BEFORE THE
FEDERAL COMMUNICATIONS COMMISSION
WASHINGTON, D.C. 20554

In re Application of: MOTOROLA SATELLITE COMMUNICATIONS, INC. For Authority to Construct, Launch and Operate a Low Earth Orbit Satellite System in the 1610-1626.5 MHz Band.	File No. 9-DSS-P-91

IRIDIUM SYSTEM APPLICATION

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EXECUTIVE SUMMARY

THE APPLICANT

Motorola, Inc., through its wholly owned subsidiary Motorola Satellite Communications, Inc., is today filing an application with the Federal Communications Commission to construct, launch and operate a global digital mobile personal communications satellite system called IRIDIUM. Motorola is a world leader in the design and manufacturing of electronic equipment, systems, and components. Its products are distributed worldwide and include two-way mobile radios, pagers, cellular telephone systems, integrated circuits, and data and information processing and handling equipment. Motorola also is in the forefront of research and development of new and improved mobile communications equipment, cellular radio technologies and satellite communications subsystems. Motorola has combined its expertise in all of these areas to develop IRIDIUM.

THE IRIDIUM SYSTEM

This past June, Motorola announced the development of its IRIDIUM mobile satellite system which envisions the use of many small low earth orbit satellites to provide worldwide cellular personal communications services. Subscribers to this system will use portable or mobile transceivers with low profile antennas to reach a constellation of 77 satellites. These satellites will be interconnected to one another by radio communications as they traverse the globe approximately 413 nautical miles above the earth in seven polar orbits. Principles of cellular diversity are used to provide continuous line-of-sight coverage from and to virtually any point on the earth's surface, with spot beams providing substantial and unprecedented frequency reuse (more than 5 times in the U.S. alone).

This application requests authority from the Commission to operate IRIDIUM for both domestic and international use. As a global communications satellite system with worldwide continuous coverage, IRIDIUM can offer the full range of mobile communications services including radiodetermination, voice and data, on land, in the air, and on water. Any subscriber unit will be able to communicate with any other IRIDIUM subscriber unit anywhere in the world, or with any telephone connected to the public switched telephone network.

Each satellite in the IRIDIUM system will be relatively small and have sophisticated electronics capable of communicating with mobile subscriber units and earth station gateways on the ground, and with other low earth orbit satellites in the constellation. IRIDIUM's innovative digital cellular design and spot beam technology is somewhat analogous to present day cellular telephone systems, except in reverse. In the case of cellular telephones, a static set of cells serves a large number of mobile units, whereas IRIDIUM's cells will move at about 7,400 meters per second while mobile units remain relatively still.

FREQUENCY SPECTRUM PLAN

In this application, Motorola is requesting authority to use the RDSS uplink band (1610-1626.5 MHz) for the provision of mobile satellite services. This 16.5 MHz of spectrum, however, will only meet expected demand for IRIDIUM services through the latter part of this decade. Ultimately, IRIDIUM will need to access up to 100 MHz of L-band spectrum worldwide to meet projected demand into the next decade. In light of the current restrictions on the use of the RDSS band, Motorola has requested a waiver from the domestic frequency allocation table to provide both two-way voice and data services on a co-primary basis with radiodetermination services. Such generic mobile satellite services in this band are fully consistent with the Commission's proposed frequency allocation plans, and are fully compatible with the use of this spectrum by other compliant RDSS systems as well as by the radio astronomy and aeronautical radio navigation communities.

In addition, IRIDIUM will need 200 MHz of spectrum in the Ka-band for its gateway feeder links and 200 MHz for the intersatellite links. Such use of the Ka-band spectrum is fully consistent with both the domestic and international table of allocations, and will be coordinated with others to avoid interference to any planned use of this band.

MARKETS AND PROPOSED SERVICES

Bulk transmission capacity on the IRIDIUM system will be provided to licensed and authorized carriers, who in turn will sell mobile communications services to the public in their authorized service areas. Due to its limited capacity and cost structure, IRIDIUM is not designed to compete with existing landline and terrestrial based cellular mobile systems. Instead, IRIDIUM will target markets not currently served by mobile communications services, such as (1) sparsely populated locations where there is insufficient demand to justify constructing terrestrial telephone systems; (2) areas in many developing countries with no existing telephone service; and (3) small urban areas that do not now have a terrestrial mobile communications structure.

IRIDIUM will offer the full range of mobile services including RDSS, paging, messaging, voice, facsimile and data services. More than half of IRIDIUM's projected six million subscribers will use RDSS and ancillary paging and messaging services.

PUBLIC INTEREST CONSIDERATIONS

IRIDIUM will provide mobile communications services to the entire United States, including all of its territories and possessions. In addition, IRIDIUM will extend the reach of modern, reliable telecommunications services to and from all worldwide locations. By supplying a full range of mobile services to many remote and underserved areas, IRIDIUM will provide critical life saving communications services to the public.

IRIDIUM also achieves highly efficient use of the frequency spectrum by reusing the bandwidth by more than five times within the U.S. and more than 200 times worldwide. IRIDIUM's innovative and flexible service will permit the constellation of satellites to shut off various frequencies and service offerings to accommodate regulatory requirements in any nation. In addition, IRIDIUM will be updated and expanded as satellites are replaced.

Motorola's considerable experience in space communications, cellular technology and private mobile services provide the necessary qualifications for constructing this innovative system. IRIDIUM will promote U.S. leadership into the 21st century in mobile, personal and satellite communications. These innovative services will enhance U.S. global telecommunications competitiveness and positively affect U.S. trade.

MOTOROLA IS READY TO PROCEED

Motorola is firmly committed to the development of IRIDIUM. To date, it has devoted substantial resources to this project. Commission action on this application by early 1991 is imperative if Motorola is going to meet the demand for satellite mobile communications service by 1997. Certain elements of the satellite design must be fixed by the third quarter of 1991 in order for IRIDIUM to become operational by 1997. In order to provide service as expeditiously as possible, Motorola concurrently requests a Section 319(d) waiver to begin construction on certain long-lead items in advance of a construction permit.

THE COMMISSION SHOULD ACT EXPEDITIOUSLY

IRIDIUM is an excellent vehicle for furthering the U.S. goal of achieving a co-primary allocation in the 1610-1626.5 MHz band for RDSS and MSS, as proposed by the Commission in its recent Second Notice of Inquiry in GEN Docket No. 89-554, F.C.C. 90-316, released October, 1990. By approving this application promptly, the Commission will promote U.S. interests and provide an innovative worldwide offering for the upcoming WARC scheduled for February 1992.

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I. INTRODUCTION

A. Overview of IRIDIUM System and Application

In June of this year, Motorola, Inc. announced the development of its IRIDIUM satellite system, a state-of-the-art global personal communications system which will provide millions of users throughout the world advanced mobile digital voice and data communications by 1997. The IRIDIUM system is composed of a constellation of 77 low earth orbit satellites circling the globe in seven polar orbits some 413 nautical miles above the earth. The satellites will use the L-band for subscriber links and will be interconnected by means of radio crosslinks in the Ka-band to form a network which provides continuous line-of-sight communications from and to any point on the earth's surface, as well as all points within an altitude of 100,000 feet above mean sea level. Figure I-1 illustrates the major components of the IRIDIUM system including its communications capabilities. Figure I-2 depicts the orbital positioning of the satellite constellation.

The IRIDIUM system will be capable of providing radiodetermination ("RDSS"), two-way digital voice and data communications between any two portable, mobile and transportable user units anywhere in the world, and interconnect any such subscriber unit to the public switched telephone network ("PSTN"). Each of the satellites contains an array of spot beams which use digital cellular technology to communicate with the subscriber units. IRIDIUM's cellular system design reuses the

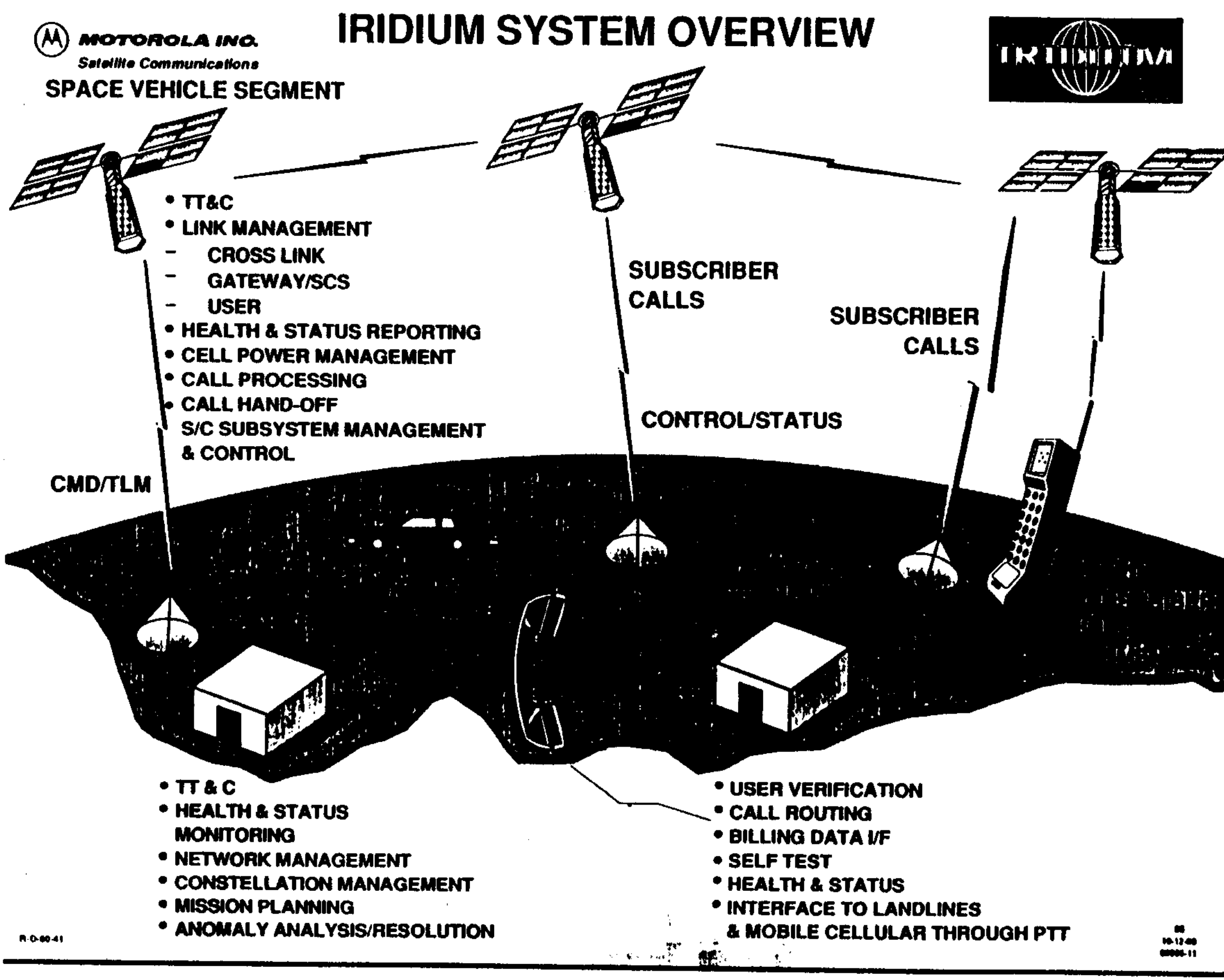

MOTOROLA INC.
Satellite Communications
IRIDIUM SYSTEM OVERVIEW
IRIDIUM
SPACE VEHICLE SEGMENT
• TT&C
• LINK MANAGEMENT
– CROSS LINK
– GATEWAY/SCS
– USER
• HEALTH & STATUS REPORTING
• CELL POWER MANAGEMENT
• CALL PROCESSING
• CALL HAND-OFF
S/C SUBSYSTEM MANAGEMENT
& CONTROL
CMD/TLM
SUBSCRIBER CALLS
CONTROL/STATUS
SUBSCRIBER CALLS
• TT & C
• HEALTH & STATUS MONITORING
• NETWORK MANAGEMENT
• CONSTELLATION MANAGEMENT
• MISSION PLANNING
• ANOMALY ANALYSIS/RESOLUTION
• USER VERIFICATION
• CALL ROUTING
• BILLING DATA I/F
• SELF TEST
• HEALTH & STATUS
• INTERFACE TO LANDLINES
& MOBILE CELLULAR THROUGH PTT

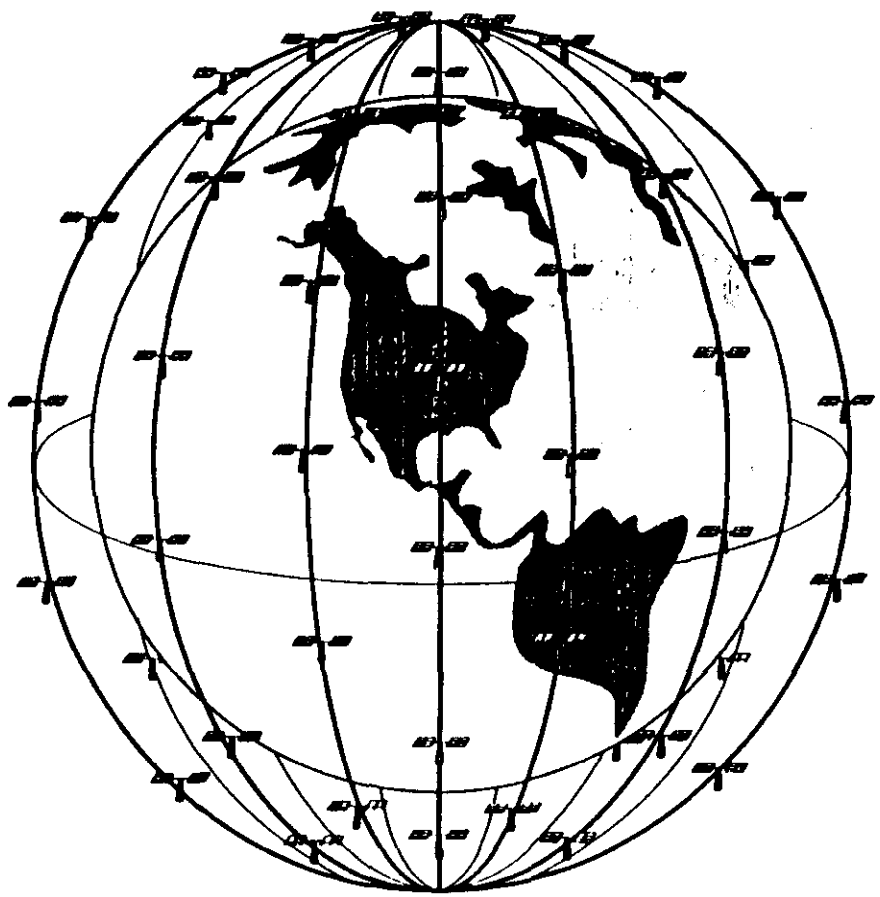
FIGURE I-1

6-1140

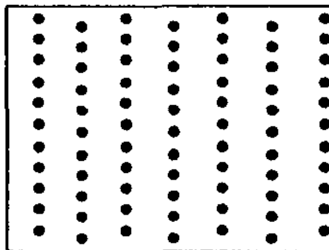
MOTOROLA INC.
Satellite Communications

IRIDIUM

MOTOROLA IRIDIUM SATELLITE SYSTEM

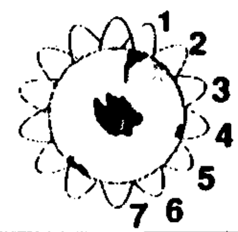


SATELLITES



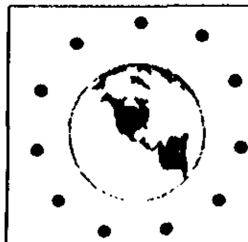
THE SYSTEM
REQUIRES
SEVENTY-SEVEN...
SATELLITES

POLAR VIEW



POSITIONED
IN SEVEN
ORBITAL
PLANES..

EQUATORIAL VIEW



CONTAINING
ELEVEN
SATELLITES
PER PLANE.

10-30-90
85812-466

FIGURE I-2 IRIDIUM SATELLITE SYSTEM

frequency spectrum far more efficiently than any other mobile satellite-based technology proposed to date.

By this application, Motorola, Inc., through its wholly owned subsidiary Motorola Satellite Communications, Inc. ("Motorola"), is taking the first domestic regulatory step toward the establishment of its IRIDIUM system. Motorola is requesting authorization to construct, launch and operate the continuously replenished 77 satellite system in low earth polar orbits in conjunction with ground stations and appropriate control facilities. This system initially will operate over all domestic United States points utilizing the available spectrum in the RDSS L-band (1610-1626.5 MHz).[1/] IRIDIUM eventually will need additional L-band spectrum by the end of the decade to meet the projected worldwide demand for services. In addition, 200 MHz of spectrum will be needed in the Ka-band for the intersatellite crosslinks (22.55-23.55 GHz); 100 MHz of bandwidth for the satellite to fixed gateway/control downlink (18.8-20.2 GHz band); and another 100 MHz for the fixed gateway/control to satellite uplink (27.5-30.0 GHz band).

Motorola understands that the domestic allocation for the RDSS band is currently limited to the provision of radiodetermination and ancillary messaging satellite services.[2/]

1/ Motorola has no need for the paired downlink RDSS spectrum, since it will provide both earth-to space and space-to-earth communications using only the 1610-1626.5 MHz band.

2/ _See_ 47 C.F.R. § 25.392(d) (1989).

Accordingly, a waiver is requested of the domestic Table of Frequency Allocations to provide both two-way digital voice and data services on a co-primary basis with RDSS.[3] Such a generic mobile satellite service is fully consistent with the Commission's proposed frequency allocation plans in this band,[4] and as demonstrated in the attached technical appendices, IRIDIUM is fully compatible with other authorized RDSS licensed systems.

Motorola does not anticipate providing any satellite services over the IRIDIUM system directly to the public. Instead, Motorola will be a wholesale supplier of IRIDIUM's transmission capacity to other carriers which in turn will offer their mobile radio services directly to users. Motorola will enter into individual arrangements with these carriers for fixed terms, subject to possible renewals, on a non-common carrier basis. Motorola and possibly others will manufacture and supply the subscriber units to vendors for sale to the public.

This application requests a domestic license to operate IRIDIUM among the United States and its territories and possessions. In addition, Motorola requests authority to provide transmission capacity between the United States and other nations for the provision of mobile services as other foreign

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[3] See 47 C.F.R. §§ 2.102 & 2.106 (1989). Additional minor technical waivers are also requested herein in order to comport IRIDIUM's innovative low earth orbit design with the Commission's existing rules in the RDSS band. See Section VI hereto.

[4] See Second Notice of Inquiry in GEN Docket No. 89-554, F.C.C. 90-316, at ¶¶ 74-76 (released Oct. 1, 1990) ("WARC-92 Second Inquiry Notice").

administrations authorize the use of the IRIDIUM system. IRIDIUM is also designed to provide mobile satellite capacity domestically within foreign countries.[5] Indeed, IRIDIUM's technical design provides for service flexibility and universal global coverage and makes it uniquely qualified to obtain such authorizations. As each projected spot beam cell passes over different geographic regions, it will have the ability to utilize only those frequencies and to provide only those services authorized by each foreign administration.

B. Regulatory and Timing Issues

At this time there is only one satellite system -- Geostar Positioning Corporation ("Geostar") -- currently licensed to operate in the domestic RDSS band.[6] As originally envisioned by the Commission when it allocated this portion of the L-band for RDSS, multiple satellite systems would provide radiodetermination and ancillary messaging services to the public. The Commission believed that up to twelve co-coverage systems could be permitted using pseudo-random CDMA modulation

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[5] It is anticipated that separate authorizations to use the IRIDIUM system in foreign countries will be obtained from their administrations as the need arises.

[6] See Geostar Corp., 60 Rad. Reg. 2d (P&F) 1725 (1986). This authorization was conditioned upon the standard RDSS construction and launch milestones, which required completion of Geostar's first satellite by August 1990, and full system implementation by August 1992. Id. at 1730. In 1989, the Commission granted Geostar a one year extension of its milestone requirements.

characteristics.[7] As the Commission recently conceded, however, in its WARC-92 Second Inquiry Notice, "[t]his service has not materialized as originally anticipated."[8] Geostar's most recent applications to modify substantially its existing authorizations raise serious questions about the economic viability of its licensed geostationary satellite system.[9] As pointed out by Motorola in Comments to Geostar's recent satellite system modification requests, it has now been more than seven years since Geostar first proposed a dedicated RDSS system, and such a system is no closer to reality today than when it was first proposed.[10]

On September 4, 1990, the Chief of the Common Carrier Bureau placed on public notice Geostar's applications to modify its authorizations and to extend the deadlines for construction

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[7] See Report and Order, 58 Rad. Reg. 2d (P&F) 1416 (1985), reconsideration 104 F.C.C.2d 637 (1986) (RDSS Allocation Order); Second Report and Order, 104 F.C.C.2d 650, 660-63 & n. 44, 60 Rad. Reg. 2d (P&F) 298 (1986) (RDSS Licensing Order).

[8] F.C.C. 90-316, at ¶ 70.

[9] See File Nos. 43-DSS-MP/ML-90, et al. To date, Geostar has only been able to provide modest interim operations using two L-band payloads on GTE Spacenet satellites which merely relay LORAN-C/GPS data from user terminals inbound to subscriber central control points. Geostar also provides outbound links to receive-only mobile units using C-band transponders on Spacenet III. See GTE Spacenet Corp., 1 F.C.C. Rcd 1163 (1986); GTE Satellite Corp., Mimeo Nos. 5175 & 1181 (released June 16, 1986, and December 2, 1985, respectively).

[10] See Comments of Motorola, Inc., filed November 5, 1990, in File Nos. 43-DSS-MP/ML-90, et al.

and launch of its dedicated RDSS satellite system.[11] In that public notice, the Commission merely requested comments to Geostar's applications and did not establish a cut-off period for accepting contemporaneous applications as required by Section 25.392(b) of the rules.[12] Ellipsat Corporation, however, submitted an application on November 2, 1990, for authority to provide a communications satellite system in the RDSS-band.[13] As of this date, that application has not been accepted for filing or placed on public notice by the Commission's staff.

With the submission of Motorola's application today for authority to construct, launch and operate its IRIDIUM system, the Commission now has before it three separate proposals for using the same frequency spectrum. Under the Commission's RDSS processing rules, all three of these proposals should now be considered in conjunction with one another and given equal treatment for purposes of considering their respective technical showings and interference analyses. Each application should be processed separately on its own merits as long as mutual compatibility is achieved. In particular, since Geostar is now proposing to construct and launch a different RDSS dedicated satellite system, none of the current applicants should have to

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11/ See Public Notice, Report No. DS-999, 5 F.C.C. Rcd 5400 (1990).

12/ 47 C.F.R. § 25.392(b) (1989).

13/ See Application of Ellipsat Corporation for Authority to Construct an Elliptical Orbit Communication Satellite System, filed November 2, 1990.

demonstrate compatibility with Geostar's licensed system.[14] Of course, each applicant still must show how it will coordinate with other RDSS systems to avoid harmful interference.[15]

The expeditious processing of Motorola's application is critical in order to ensure that necessary international radio regulatory coordination and consultation is obtained and that the United States adequately formulates and achieves its objectives at the World Administrative Radio Conference ("WARC") in February 1992.[16] Prompt processing of this application is also needed if Motorola is to meet the expected demand in the United States and worldwide for mobile communications service in those areas not adequately served by terrestrial carriers and other mobile satellite providers. Based upon the lead times required for constructing the IRIDIUM system, Motorola must fix certain elements of the satellite design by the third quarter, 1991.

C. Pioneers Preference Requested

As demonstrated throughout this application, Motorola's IRIDIUM system combines, for the first time, advanced low earth orbit satellite and cellular technologies to enable carriers to provide new and innovative mobile services in the United States and throughout the world. IRIDIUM is exactly the type of system

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[14] *See* 47 C.F.R. § 25.392(a) (1989).

[15] *See* 47 C.F.R. § 25.392(f) (1989).

[16] On this date, Motorola is submitting separately its detailed Comments in response to the WARC-92 Second Inquiry Notice.

that the Commission must have envisioned when it recently proposed the award of "pioneer's preferences" in its proposed Rule 1.402.[17]

Indeed, Chairman Sikes recently referred to Motorola's IRIDIUM system as just such a new and innovative service worthy of encouragement by the Commission.[18] The Chairman went on to emphasize "the need to develop an international regulatory framework that is not just conducive, but hospitable to innovation and technological advances," and that "[a]ll other things being equal, what the Communications Act directs is for the FCC to 'tilt' in the direction of technological advancements."[19]

D. Format and Content of Application

Motorola has set forth in detail all pertinent technical and operational aspects of its proposed satellite system as required by Section 25.392 of the Commission's rules. Motorola believes it has provided all the required information on each and every item specified in the rules, including the

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17/ See Establishment of Procedures to Provide a Preference to Applicants Proposing an Allocation for New Services, 5 F.C.C. Rcd 2766 (1990).

18/ See Remarks of Chairman Alfred C. Sikes, before the Washington Annenberg Program Conference on the 1992 World Administrative Radio Conference (Nov. 5, 1990).

19/ The Chairman cited Sections 157, 218 and 303(g) of the Communications Act of 1934, as amended, to support this view. Id.

information identified in Appendix B to the Space Station Filing Procedures, 93 F.C.C.2d 1260, 1265 (1983), and the RDSS Allocation Order and RDSS Licensing Order. In addition, Motorola has provided information in support of its rule waiver requests. To the extent the Commission requires additional information or data concerning the IRIDIUM system, Motorola would be happy to provide such information either by formal amendment or informally in communications with Commission staff.

This application is divided into eight sections and seven appendices. Section I provides a brief overview of the IRIDIUM system and this application. Section II sets forth significant public interest benefits supporting the prompt grant by the Commission of authorization for the IRIDIUM system. The most significant markets and overall demand for IRIDIUM are identified in Section III, along with the proposed service offerings. Orbital considerations are described in Section IV. The technical description of the entire IRIDIUM system is set forth in Section V. Section VI contains specific requests for waiver of the Commission's rules in order to allow the IRIDIUM system to operate in the RDSS band. Certain international considerations are discussed in Section VII. Motorola's legal, technical and financial qualifications are described in Section VIII. The appendices contain Motorola's interference and sharing analyses, further technical and operational details concerning IRIDIUM, IFRB advance publication data, supporting financial data, FCC Form 430, and the separate satellite applications.

II. PUBLIC INTEREST CONSIDERATIONS

The IRIDIUM system is an ideal example of technology serving the public interest, convenience and necessity. Motorola's pioneering efforts have resulted in a system architecture that enjoys unprecedented spectrum efficiency, unlimited service flexibility, and unmatched geographical coverage. The IRIDIUM system truly meets the Commission's statutory mandate "to make available, so far as possible, to all the people of the United States a rapid, efficient, Nation-wide, and world-wide wire and radio communication service with adequate facilities at reasonable charges ... for the purpose of promoting safety of life and property through the use of wire and radio communication ...," and "to encourage the provision of new technologies and services to the public."[20/] Authorization of the IRIDIUM system will serve as a landmark of telecommunications development for many decades to come.

A. IRIDIUM Uniquely Meets the Mobile Service Needs of Users In the United States and Throughout the World

The IRIDIUM system, with its continuous global coverage to virtually all points on the surface of the earth and up to 100,000 feet above mean sea level, will bring the benefits of digital mobile voice and data service to all those individuals in the United States and abroad currently in need of reliable

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20/ 47 U.S.C. §§ 151, 157 (1988).

telephone communications. As indicated in Section III to this application, Motorola estimates that demand for IRIDIUM in the United States will exceed 1.3 million units by 2001 with another 4.7 million units worldwide.

Those persons living or travelling in remote areas of the United States where landline and mobile radio service are minimal or nonexistent, will be able to use an IRIDIUM subscriber unit to communicate with anyone in the world connected to the PSTN or another IRIDIUM subscriber unit. Thus, for the first time, persons living or travelling in the outer reaches of Alaska will be able to communicate with offices in New York City or persons living in the U.S. Virgin Islands merely by using a handset and dialing a telephone number. Such instant communications access will greatly benefit a large number of individuals currently in need of reliable and cost-efficient telephone service. Motorola estimates that approximately 10 million Americans live in these remote locations.

Absent the development of IRIDIUM, persons living and travelling in such remote and scarcely populated areas of the country probably would never be able to obtain access to the telephone network. Insufficient demand exists for supporting the construction of a terrestrial-based telephone system in most of these locations either by means of landline or cellular radio technologies. The incremental cost for IRIDIUM to serve these remote areas is minimal once the satellite constellation is launched and operational due to IRIDIUM's global coverage. All that is required to connect a subscriber to the IRIDIUM network is a portable unit.

In addition, IRIDIUM offers every subscriber unit, no matter where it is located, immediate access to reliable and cost-effective radiodetermination and position location information, as well as associated messaging capabilities. Such services will be of significant benefit to the U.S. transportation industry.

B. No Other System Design Has Ever Been Proposed with the Orbit/Spectrum Efficiency of the IRIDIUM System

The number one problem in the satellite communications industry today is that of efficiently utilizing the available spectrum. New radio systems and subscribers are proliferating, but there remains a finite amount of frequency spectrum available for use. The IRIDIUM system has broken out of this policy bottleneck with a worldwide radio communications system that reuses its bandwidth <u>more than five times</u> within the contiguous United States and more than two hundred times worldwide. IRIDIUM will be able to serve the entire RDSS market with substantial margin using only the RDSS uplink band. IRIDIUM will not use the 16.5 MHz of spectrum in the 2483.5-2500 MHz band, which may then be allocated for other uses. No other satellite communications system either proposed or authorized by the FCC even approaches such a high level of orbit/spectrum efficiency. In fact, Motorola's understanding of the current state of the geostationary mobile satellite design is that as much as 120 MHz of uplink and downlink spectrum is required for such systems to provide the same transmission capacity over the same territory as IRIDIUM.

Such efficient usage of the limited frequency spectrum resource directly serves the public interest, convenience and necessity. Indeed, the Commission has previously recognized the United States obligation to other countries under Article 33 of the International Telecommunications Union Convention to "bear in mind that radio frequencies . . . are limited natural resources ... [which] must be used effectively and economically ...."[21/]

C. **The Unparalleled Flexibility and Innovations in the Technical Design of the IRIDIUM System Will Benefit the Public**

The digital technology of the IRIDIUM system and its innovative intersatellite radio links enable users to receive most type of mobile telecommunications service, including radiodetermination, facsimile, paging, two-way voice, or data. All of these services will be available on a 24-hour basis, seven days a week, in any country which authorizes the provision of such services. The system design, however, is also capable of

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21/ Inquiry Relating to Preparation for an International Telecommunication Union World Administrative Radio Conference on the Use of the Geostationary-Satellite Orbit and the Planning of the Space Services Utilizing It, 45 Fed. Reg. 85,126, 85,127 (1980); see also Assignment of Orbital Locations to Space Stations in the Domestic Fixed-Satellite Service, 84 F.C.C.2d 584, 592, 610 n.93 (1981) ("1980 Orbit Assignment Order").

shutting off various frequencies and limiting the types of offerings to any region which may limit IRIDIUM's authority to operate. For example, the satellites can be programmed to use only the RDSS portion of the L-band over the United States while using other L-band MSS frequencies over Europe and Africa.

There also are inherent technical and economic advantages to IRIDIUM's low earth orbit satellite design, such as minimal transmission delays and reduced subscriber unit power requirements. These advantages ultimately lead to smaller, more economical subscriber units and better quality communications.

Moreover, the IRIDIUM system will constantly be updated and expanded as satellites are replenished and new technologies are developed. For example, as new frequency allocations are authorized worldwide for IRIDIUM, satellites under construction can be modified to utilize additional spectrum.

D. The IRIDIUM System Will Save Many Lives

Central to the FCC's regulatory mission is to give priority to spectrum utilization that helps ensure the safety of life and property.[22/] With the IRIDIUM system, ambulatory patients can have access to top-flight medical advice, the injured or lost can be located, and the handicapped can live with the freedom of knowing that they are one phone call away from help should the need arise. In essence, IRIDIUM extends the

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[22/] See 47 U.S.C. § 151 (1988).

countless public health benefits of the telephone from the house or office to the outdoors.

IRIDIUM also can be used by the aviation, shipping and trucking industries as a primary or backup communications system for emergency or distress situations, such as for missing planes and for accident location determination. By accurately relaying these reports to the appropriate authorities, IRIDIUM will help save lives.

E. Motorola Is Uniquely Qualified to Operate the IRIDIUM Satellite System

All of the public interest benefits of a proposed new technology are of little value if the applicant lacks the ability or commitment to implement the proposal. Motorola is uniquely qualified to bring the benefits of low earth orbit mobile satellite technology to the public. It was a pioneer in the development of cellular technologies and today is the largest U.S. manufacturer of cellular telephones and systems. Motorola also is a world leader in the production and development of private mobile radio services. Moreover, Motorola has extensive experience with developing satellite communications subsystems based on its work for the U.S. Government. The combination of all of these technologies and resources within one company has resulted in the development of its IRIDIUM system.

Motorola is firmly committed to the development and implementation of IRIDIUM. Over seventy-five engineers and managers at Motorola currently are working on the system. Although IRIDIUM features many innovations and a state-of-the-art satellite design, there are no technological limitations which will prevent it from becoming a commercial service by 1997.

F. The IRIDIUM System Will Establish U.S. Leadership in Mobile, Personal and Satellite Communications for Many Years to Come

In today's highly competitive world, it is especially important for the FCC to take actions which help maintain and advance U.S. leadership in mobile, personal and satellite communications. The approval of IRIDIUM also will promote the expansion of U.S. private sector investment and involvement in civil space and related activities. The IRIDIUM system will establish U.S. leadership in these technologies for several decades, much as Early Bird did for the last half of the 20th century. Such leadership will provide countless public policy and economic growth benefits.

G. The IRIDIUM System Will Make a Major Contribution to U.S. Global Competitiveness in Telecommunications

RDSS technology was first developed in the United States and has since contributed positively to U.S. competitiveness in telecommunications. Now, with the satellite technological revolution represented by the IRIDIUM system, the low earth orbit concept can truly be put to work to add significantly to the U.S. Gross National Product and to enhance U.S. exports.

It is anticipated that IRIDIUM's global capabilities will be utilized abroad to provide both domestic and international mobile services. With only relatively minor incremental costs associated with additional gateways in foreign countries, IRIDIUM can offer the full range of mobile communications services to millions of individuals worldwide currently without telephone access. In addition, substantial revenues are expected from the sale in foreign countries of subscriber terminals and gateways.

H. IRIDIUM Promotes the Commission's Multiple Entry Policies for Satellite Delivered Mobile Services

IRIDIUM is fully compatible with compliant RDSS systems. As such, it will provide carriers and users with another competitive choice for obtaining satellite delivered communications. The Commission has stated on numerous occasions its preference for multiple entry in space-based communications systems, including those in the RDSS band.[23] IRIDIUM will bring the benefits of such competition, including innovative services and technologies at reduced costs, to the public in a timely manner.

Although the Commission initially may have expected multiple entrants into the RDSS band, to date only Geostar

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[23] See e.g., RDSS Licensing Order, 104 F.C.C.2d at 653-54.

retains the authority to operate a radiodetermination service. And as previously noted in Section I of this application, there are serious questions as to Geostar's long term viability. Motorola firmly believes that low-earth orbit satellite systems, like IRIDIUM, offer the only realistic possibility of achieving an economically viable RDSS system. With its global coverage and package of services, IRIDIUM will be able to achieve the revenue base necessary to justify the construction and operation of such a system.

I. IRIDIUM Promotes the International Communications and Information Policy Goals of the United States

The IRIDIUM system enjoys an unmatched ability to bring modern digital telecommunications to underserved areas in other parts of the world. Those areas may range from urban centers in developing countries and Eastern Europe to the polar regions of the world. Both this Commission and the Executive branch have articulated several U.S. policy goals which will be furthered directly and substantially by the establishment of such a global telecommunications system, including:[24]

- The promotion of the free flow of information throughout the world;
- The promotion of the development of efficient, innovative, and cost-efficient international

[24] See Establishment of Satellite Systems Providing International Communications, 101 F.C.C.2d 1046, 1064-65 (1985), citing "A White Paper on New International Satellite Systems," Senior Interagency Group on International Communication and Information Policy (February 1985).

communications services responsive to the needs of users and supportive of the expanding requirements of commerce and trade;

- The promotion of continuing evolution of an international configuration of communications services that can meet the needs of all nations, with attention toward providing such services to developing nations.

III. MARKETS AND DEMAND FOR SERVICES

A. Demand Analysis

The phenomenal growth of the public and private land mobile radio industry confirms that there is a very large market in the United States and throughout the world for mobile communications. Potential users number in the tens of millions. While the market for satellite-based mobile communications is expected to be substantial, it will amount only to a fraction of the total mobile communications market.

Satellite based mobile communications will be commercially successful in areas that cannot be served by other mobile communications services. The primary target markets include (1) sparsely populated locations where there is insufficient demand to justify constructing terrestrial telephone systems; (2) areas in many developing countries with no existing telephone service; and (3) small urban areas that do not now have a terrestrial mobile communications infrastructure.

1. Geographic Coverage

IRIDIUM will provide global telecommunications service on a continuous basis. All points from the North Pole to the South Pole will be covered. However, the IRIDIUM system will not compete with terrestrial systems with respect to transmission capacity and service costs. It will serve all international markets with RDSS, voice and data services. This unique coverage will provide service from any point in the world to any other point in the world.

This capability of worldwide service is the critical factor to IRIDIUM's commercial viability -- IRIDIUM will serve many niche user markets with a single infrastructure. Once the satellite constellation is in service, IRIDIUM can provide service to all world markets with minimal additional infrastructure investments. IRIDIUM will provide the only mobile communications services to many U.S. and global locations.

a. Rural and Non MSA Markets

IRIDIUM will serve the entire United States and its territories and possessions, including Puerto Rico, the Virgin Islands, Alaska, Hawaii and the other U.S. Pacific Islands. IRIDIUM will provide businesses and individuals in these locations with the opportunity for world-wide mobile RDSS, voice and data services.

There are also many rural portions of the U.S. that may never have terrestrial cellular telephone service because of sparse population coverage and remote location. Approximately 10 million Americans live in these areas. IRIDIUM will offer these citizens sophisticated mobile telecommunications services unavailable from terrestrial providers.

b. **Developing Countries**

Developing countries will be another major IRIDIUM market. These countries comprise approximately 3 billion people, or 60% of the world population. Inadequate telecommunications infrastructure in most developing nations is a major obstacle to their further economic development. IRIDIUM's services will promote the economies of the developing world by providing modern, reliable telecommunications service to these developing nations without the need for large indigenous infrastructure investments. For example, India has more than 500 million people in rural areas who have no access to telephone service. To ameliorate this problem, the Indian government proposes to provide portable public telephone booths in rural areas. IRIDIUM would provide an excellent solution to servicing these areas because the only infrastructure costs of providing service would be the phone booth and an IRIDIUM terminal.

c. **New Market Economies**

New market economies, including most Eastern European nations and the Soviet Union, provide a tremendous market for modern mobile telecommunications services. Although these nations have industrialized economies, their telecommunications infrastructures do not satisfy existing demand, and are not adequate for the increased commercial activity they are likely to enjoy as their economies are liberalized. The telecommunications capabilities of the IRIDIUM system will assist these nations as they democratize their political structures and liberalize their economies.

d. **Maritime and Aeronautical Coverage**

IRIDIUM will provide space segment capacity to authorized service providers which will serve domestic and worldwide maritime and aeronautical markets. This coverage will extend to aeronautical polar routes. For the first time, these markets will enjoy the full range of mobile telecommunications services, including RDSS, voice and data.

2. **RDSS and Ancillary Services**

The U.S. Department of Commerce projects that the market for radiodetermination services will exceed $1 billion annually by the late 1990s. The Commission has previously recognized that RDSS can provide substantial services for life safety, law enforcement, aviation, navigation, ground transportation and resource management markets. See RDSS Allocation Order, 58 R.R.2d at 1431-33 (Appendix B). The recent application of Orbital Communications Corporation also projects a substantial RDSS market.[25]

Each IRIDIUM subscriber unit will have RDSS capabilities. Positioning determination based on IRIDIUM will be accurate within one mile for voice units. Optional GPS or GLONASS circuitry will be offered to improve accuracy to within 100 meters.

Motorola estimates that more than 3 million subscribers, over half of the subscriber base, will use RDSS and ancillary paging and messaging services in the following categories.

a. Emergency Services

IRIDIUM will provide RDSS emergency location services for planes, boats and land vehicles that have IRIDIUM receivers for voice and data services. Market estimates for this service are included in other categories which use IRIDIUM voice and data service, such as trucks, boats, aircraft, and recreational vehicles.

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[25] Application of Orbital Communications Corporation for a Low-Orbit Mobile Satellite System, filed February, 1990, at 25-35. See Public Notice DS-953, released April 11, 1990.

b. Tracking

RDSS tracking services will be available for subscriber units. Low cost RDSS-only units will also be able to provide tracking services. Motorola will offer tracking service using IRIDIUM rather than geosynchronous satellites.

This service will be used primarily by trucking fleets in conjunction with two-way messaging. There are an estimated 3.1 million long haul trucks in the U.S.[28] Approximately ten percent of these trucks are expected to subscribe to IRIDIUM's tracking service. Other applications will be found in the tracking of hazardous wastes and military convoys. The international market is estimated at four times the U.S. market.

c. Global Paging

Motorola expects global paging to be used extensively by both domestic business people and foreign visitors travelling on business in the United States. This will be direct satellite-pager service and will allow the user to be paged instantaneously from anywhere in the world, and to receive a short message on an alphanumeric pager.

The estimated paging market in the United States for the year 1997 exceeds 23 million users. The vast majority of these users will be for local or regional pagers. The global

[28] Dittberner Associates, Inc., Radio in the Local Loop, in Project ESS Update XXV XII-11 (1990).

paging users will be most frequent among the fifty million foreign business persons travelling in foreign countries each year. Motorola estimates a three percent penetration rate, assuming approximately the same penetration of pagers among foreign business persons as the penetration of pagers among the entire United States population today. As a result, it is expected that there will be 1.5 million global pager users among business persons traveling abroad. In the U.S., there will be a 6% penetration rate among 5,000,000 potential users, or 300,000 subscribers.

3. Voice and Data Services

IRIDIUM will not compete with the public switched telephone network ("PSTN") and terrestrial cellular systems primarily because of its rate structure. Instead, IRIDIUM will provide service to locations that do not otherwise have access to the PSTN or terrestrial cellular services. Major applications of IRIDIUM will be in governmental communications, international travel, commercial air travel, business and general aircraft, marine shipping, long-haul trucking, recreational vehicles, pleasure boats, construction and oil and mineral exploration.

a. Governmental Communications

As a satellite-based communications system, IRIDIUM essentially will be disaster proof. It can be used in emergency situations such as earthquakes, hurricanes, tornados, floods, etc. Federal, state and local governments will use IRIDIUM as a secondary communications system in situations where standard communications services are inconvenient or impossible to access. Foreign governments will employ IRIDIUM extensively for emergency services as well as communication from areas without telephone service.

(1) Federal Government

The federal government has approximately 3 million civilian employees. Government agencies such as the Drug Enforcement Agency, Federal Bureau of Investigation, U.S. Customs Service, Coast Guard, and the State Department will use IRIDIUM for travel and emergency communications capabilities. United States diplomatic missions abroad also may use IRIDIUM as an emergency communications system.

Motorola estimates civilian federal government use as 10,000 subscribers. In addition, the armed forces could employ IRIDIUM for non-combat applications. Another 10,000 subscribers are estimated for this purpose.

IRIDIUM will enjoy significant use by foreign governments for communications in areas without telephone service. These foreign governments will likely purchase 400,000 units.

(2) **State Governments**

State governments in the United States have approximately 4 million employees. State governmental agencies will use IRIDIUM for law enforcement, emergency and travel applications. The penetration rate is estimated at 0.2 percent, or 8,000 subscribers. The international market for state governments is estimated at 20 times the U.S. market, or 160,000 subscribers.

(3) **Local Governments**

IRIDIUM will be used as an emergency or secondary communications system by municipalities and local governments. Individual local governments will have a limited number of units available for emergency communications in case of a natural disaster, such as the San Francisco earthquake. Police, firefighters, rescue teams, as well as the American Red Cross and other emergency organizations, will be able to use IRIDIUM units in areas where other communications are not available.

There are approximately 20,000 communities in the United States of various sizes (cities, towns, villages). The local governments in these communities employ approximately seven million people. An IRIDIUM penetration rate of 0.4% is assumed which results in 28,000 subscribers. International demand by local governments is estimated at 20 times that in the U.S., or 560,000 subscribers.

b. International Travel

Foreign business travelers in developed countries will be the main users of IRIDIUM's global paging service as discussed above. United States and foreign business people travelling to many developing countries will rely on IRIDIUM's voice and data terminals, in addition to paging units, since sophisticated and reliable communications services are not always available in these countries. An estimated 60% of the 50,000 U.S. business people travelling to developing countries will use IRIDIUM. Foreign business people travelling to developing countries will purchase an additional 120,000 units. The estimated total subscriptions for international business travel is 150,000.

c. Commercial Air Travel

IRIDIUM's global coverage will offer reliable telephone, data and RDSS services by authorized service providers to commercial aircraft at all geographic latitudes, including flights on polar air routes. The installation of terminal units will not require steerable antennas. Low gain antennas, including flush mounted antennas, may be used for this purpose. As a result, IRIDIUM will offer significant advantages over existing commercial air travel communications systems.

There are approximately 5,000 air carrier aircraft in the United States. Eventually, most of these aircraft will have in-flight public telephone service. A low-earth orbit system provides better coverage and lower cost receivers than land-based and geosynchronous-based in-flight telephones. It is assumed that IRIDIUM will capture up to fifty percent of the in-flight market, or 2,500 aircraft. This aircraft service will be available to over two hundred million passengers each year. Approximately five percent, or 10 million passengers, are expected to use IRIDIUM. Subscriptions in the international air carrier market should be approximately the same as in the U.S.

d. General Aviation

There are approximately 200,000 general aviation aircraft in the United States. The penetration rate is expected to be at least that of similarly priced equipment, such as a LORAN-C receiver, which would result in 60,000 subscribers for general aviation aircraft. The international market is expected to add another 40,000 users. These services will also be provided by authorized service providers.

e. Business Aviation

Continuous and high quality data and voice service is presently not readily available to business aircraft. IRIDIUM will fill this void by providing through authorized service providers voice, facsimile, and data services for a complete flying office.

There are approximately 10,000 turbo prop and turbo jet business aircraft in the United States. By 2001, this number is expected to increase to 14,000 aircraft. Given the need for reliable communications at all times and the generally high value of information being communicated, approximately fifty percent of these business aircraft, or 7,000 customers, will subscribe to IRIDIUM. An estimated 2,000 subscribers will be drawn from foreign owners of business aircraft.

f. <u>Recreational Vehicles</u>

There are approximately 8 million recreational vehicles in the United States. IRIDIUM service will provide owners of these vehicles with reliable telephone service in remote locations, such as camps, parks and rural roads. A hand-held phone could also be used for hiking and other recreational activities. Consumers of higher-priced recreational vehicles are prime candidates for becoming IRIDIUM subscribers. The expected penetration rate is five percent, or 400,000 subscribers. The international market is expected to contribute another 100,000 subscribers.

g. <u>Pleasure Boats</u>

There are approximately 10 million pleasure boats in the U.S. In the luxury class of boats (greater than 26 feet long) there are an estimated 300,000 pleasure boats. Approximately seventy percent of these luxury boats, or 210,000, are expected to subscribe to services carried over IRIDIUM by licensed service providers. There should be a similar subscription level in the international market.

h. Shipping

Today, ships travelling on the U.S. coast, rivers, canals, and lakes lack affordable, reliable and continuous communications service. Voice, facsimile, and data services through authorized providers will be welcome in this market.

There are approximately 30,000 ships in the United States which fall into this category. IRIDIUM will allow for a lower cost complement to other systems serving this market. A penetration rate of twenty percent, or 6,000 subscribers is anticipated. Another 40,000 coastal and inland shipping subscribers are estimated in the international market.

i. Construction and Oil and Mineral Exploration

IRIDIUM will provide critical voice and data services through authorized carriers to remote construction and natural resource exploration sites, including off-shore points. First class telecommunications services will improve the efficiency of these businesses. The U.S. market is estimated at 5,000 subscribers, with another 15,000 internationally.

j. Public Telephone

Many areas in developing countries of Asia, Africa and South America have no telephone service. In many cases, these developing countries cannot afford to install the necessary infrastructures. IRIDIUM is ideally suited for these situations since the satellite infrastructure will be provided immediately and at no cost to the host country. Only ground terminals will be needed to begin service. The estimates of people with no access to telephone service range from one to two billion people. Assuming one public phone per 2,000 people, there is a market for up to one million phones. The estimated 30% penetration rate of this market for IRIDIUM will yield 300,000 subscribers.

k. Domestic Business Travel in Developing Countries

As discussed above in Section III.B.3.b, communications in many developing countries are inadequate and create a major impediment to conducting business in these countries. In addition to serving visiting business people from developed nations, IRIDIUM will offer critical communications services to the indigenous business community. IRIDIUM'S reliable mobile voice, data and facsimile service within these nations will benefit these developing economies in all but the most industrialized countries, with combined populations of over four billion people. The potential market for use of IRIDIUM in domestic business travel is estimated to exceed one million units. A 30% penetration rate yields 300,000 subscribers.

4. Summary of Demand Analysis

Table III-1 summarizes the expected demand for IRIDIUM. The addressable market for all types of IRIDIUM applications in the U.S. exceeds 30 million users. The estimated numbers of subscribers after five years in operation will exceed 1.3 million in the U.S. and 6 million worldwide. All IRIDIUM units will be capable of receiving RDSS. Radiodetermination and two-way messaging services will be offered to the trucking market which comprises approximately 25% of the total subscriber base. Global paging will also account for 25% of the subscribers. The remaining 50% of IRIDIUM subscribers will be split among other service applications.

TABLE III-1

IRIDIUM DEMAND SUMMARY

(By Year 2001)

Market Segment	U.S. Addressable Users	U.S. Penetration Rate%	U.S. Subscribers	Foreign Subscribers	Total Subscribers
RDSS Tracking	3,100,000	10	310,000	1,240,000	1,550,000
RDSS-Global Paging	5,000,000	6	300,000	1,200,000	1,500,000
Federal Government	3,000,000	0.7	20,000	400,000	420,000
State Government	4,000,000	0.2	8,000	160,000	168,000
Local Government	7,000,000	0.4	28,000	560,000	588,000
International Travel	50,000	60	30,000	120,000	150,000
Commercial Aircraft	5,000	50	2,500	2,500	5,000
General Aviation	200,000	30	60,000	40,000	100,000
Business Aircraft	14,000	50	7,000	2,000	9,000
Recreational Vehicles	8,000,000	5	400,000	100,000	500,000
Luxury Pleasure Boats	300,000	70	210,000	210,000	420,000
Shipping	30,000	20	6,000	40,000	46,000
Construction and Oil and Mineral Exploration	10,000	50	5,000	15,000	20,000
Public Telephone	---	---	---	300,000	300,000
Domestic Business Travel	---	---	---	300,000	300,000
Totals	30,709,000	4.5	1,386,500	4,689,500	6,076,000

B. Proposed Services

IRIDIUM is a global RDSS, voice and data communications system that can provide mobile communications within the United States, and between the United States and any other location in the world. The IRIDIUM network will communicate through gateways to existing communications networks such as the public switched telephone network and terrestrial cellular telephone systems. IRIDIUM is intended to extend the coverage of existing telephone networks, not to compete with them.

All services will be offered on a global basis, as authorized in each country. The range of specific services available to any individual subscriber depends only on the type of unit selected.

1. Radiodetermination and Ancillary Services

IRIDIUM will offer RDSS services for automatic location reporting, paging and two-way messaging. These services will be available on a global basis.

a. RDSS

IRIDIUM can provide low-cost RDSS-only location reporting services. In addition, RDSS capability is integral to voice units.

b. Global Paging Services

An alphanumeric pager for instantaneous global paging will be offered. The pager unit will be similar in size and performance to the present terrestrial pagers. It is primarily intended for use in domestic and international metropolitan areas where adequate telephone service is available for timely response.

c. Two-Way Messaging

Two-way messaging will be offered in conjunction with RDSS to report unit positions and to receive and transmit short messages. The primary application for their service will be for trucking fleet management.

2. Data Services

Global data services will be available over IRIDIUM. Users can send facsimiles and other data from any point in the world to any other point.

Data will be transmitted at a rate of 2400 bits per second. IRIDIUM subscribers need only add a modem to an IRIDIUM voice terminal in order to send and receive data.

3. Digital Voice Services

IRIDIUM will provide two-way, high quality 4800 bits per second digital voice communications using handheld portable and vehicle mounted terminals. IRIDIUM mobile terminals will be available in combination with terrestrial cellular phones, with RDSS and in combination with Global Position System ("GPS") units. A terminal may be designed for in-flight telephone service on commercial aircraft and a unit to be used on general aviation and commercial aircraft.

C. Transceiver Description and Features

The IRIDIUM subscriber unit ("ISU") product family consists of hand-held portable units, the vehicular mobile units, transportable units and pager units. The ISU offers worldwide RDSS, voice and data communications, and will be lightweight, economical and as easy to use as a cellular phone. The ISU communicates with IRIDIUM's satellite constellation, which forms a practical, low-power communications link for next-generation telephony.

ISU product development at Motorola is in progress. Because Motorola has extensive design and development experience in conventional cellular telephones, digital cellular telephones and pagers, Motorola is uniquely qualified to design and develop a quality ISU product family. The economic advantages of Motorola's technical experience and volume production capabilities will cause ISU prices to follow a reduction pattern somewhat similar to that experienced with cellular phones. However, they are not expected to experience as rapid and dramatic reductions as occurred with cellular radio because fewer units will be manufactured.

It is anticipated that an "open system" functional specification will be made available, allowing other manufacturers to design and build ISU products. ISU product compliance to the ISU functional specification will be verified through rigorous "type approval" testing.

The initial introduction prices for the basic handheld telephone are expected to be in the neighborhood of $2,000 (1990 dollars), and somewhat more for more complex units. A pager is expected to cost approximately $200-300. An RDSS-only unit made by Motorola or a third-party could cost as little as $200.

1. Radiodetermination Terminals

RDSS-only units without any voice or other data capabilities are expected to become available as the market develops for such services. As an option, Global Positioning System (GPS) or GLONASS receiver circuitry can be added to provide the user with more accurate location information.

2. Paging Terminals

The pager ISU provides worldwide paging in an apparatus similar in size, weight and operation to a Motorola pager. In addition, other manufacturers are expected to offer pagers compatible with IRIDIUM.

3. __Portable Terminals__

The ISU portable user interface will emulate, as much as possible, the existing Motorola cellular telephone interface. The ISU will have many of the same programmable features found in conventional cellular telephones.

The hand-held portable ISU provides full-duplex voice communication in an apparatus similar in size, weight and operation to a Motorola DynaTAC portable cellular phone. The portable ISU will be small and lightweight. __See__ Figure III-1 for a depiction of a portable ISU.

4. __Mobile Terminals__

The vehicle mobile ISU provides voice and 2400 baud data communication in an apparatus similar in size, weight and operation to a Motorola mobile cellular phone. Mobile installation configurations include hands-free calling for driving safety, and dual antenna diversity for superior signal reception.

5. __Transportable Terminals__

Where permitted, the transportable ISU will provide full-duplex voice and full-duplex 2400 baud data communication in an apparatus similar in size, weight and operation to a Motorola mobile cellular phone. The transportable ISU can be temporarily installed in a building or at other locations.

MOTOROLA

IRIDIUM SUBSCRIBER UNIT

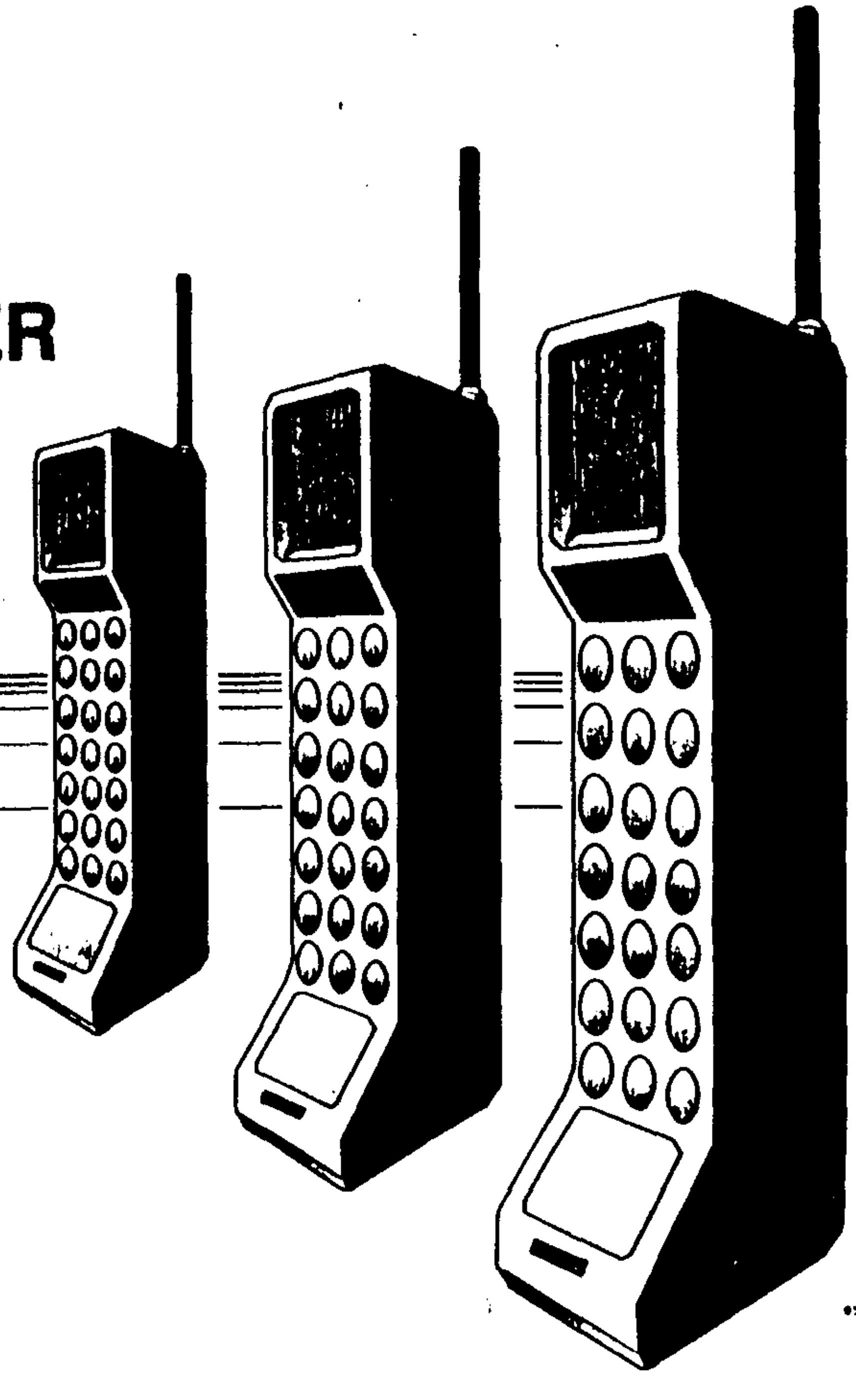

FIGURE III-1 IRIDIUM SUBSCRIBER UNIT

D. Information Concerning Sales of Communications Services

1. Proposed Sales of Communications Services

IRIDIUM will be operated on a non-common carrier basis by selling bulk transmission capacity on the satellite constellation to major authorized carriers in the United States and abroad. RDSS will be priced on a usage basis. Voice and data offerings will be priced in units of service time, rather than transponder capacity, and sold for fixed terms.

2. Nature and Principal Terms of Offerings To Be Made Available to Other Parties

Plans for the sale of IRIDIUM's communications services will take into account such factors as competition, customer demand, and flexibility in pricing and payment terms. The services will be sold in wholesale bulk units on a traffic minute basis.

IRIDIUM's unique ability to provide telecommunications service from and to anywhere in the world has already attracted considerable interest from a number of major domestic and international carriers. Proposals are being presented to a select group of customers. Final negotiations relating to business terms, technical and legal matters could occur prior to Commission approval of the IRIDIUM system. Buyers will have the right to terminate agreements should Motorola elect not to continue the program because of regulatory considerations.

3. Specific and Detailed Information Concerning Marketing Plans

In National Association of Regulatory Utility Commissioners v. F.C.C., 525 F.2d 630 (D.C. Cir. 1976), cert. denied sub nom Nat'l Association of Radiotelephone Systems v. F.C.C., 425 U.S. 992 (1976), the Court held that "the characteristic of holding oneself out to serve indiscriminately appears to be an essential element" of common carriage, and that an entity will not be a common carrier "where its practice is to make individualized decisions, in particular cases, whether and on what terms to deal." Id. at 641-42. In applying these holdings to satellite transponder sales, the Commission found that as stable one-time offerings to buyers and sellers with particularized needs, these business relationships would not be expected to be provided uniformly and indiscriminately to all potential customers on a common carrier basis.[27/] Accordingly, the Commission authorized applicants to apply for domestic satellite licenses for non-common carrier purposes.[28/] Moreover, the Commission has held that long-term leases are consistent with

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27/ See Domestic Fixed-Satellite Transponder Sales, 90 F.C.C.2d 1238, 1255-57 (1982) ("Transponder Sales Decision"), aff'd, World Communications, Inc. v. F.C.C., 735 F.2d 1466 (D.C. Cir. 1984).

28/ Id. at 1257.

the criteria established for the provision of non-common carrier offerings.[29]

IRIDIUM's offerings should similarly be classified as non-common carrier services. Motorola will negotiate individual long-term arrangements with major international carriers for wholesale bulk transmission services. These carriers will, in turn, provide telecommunications services to members of the public.

A description of the proposed markets and services that can be offered by IRIDIUM is contained elsewhere in this application. The market response to IRIDIUM's satellite system has been strong. Motorola further believes that prospective carriers will demand long-term relationships in order to ensure adequate capacity at stable prices.

4. Names of Any Purchasing Customers for Which Sales Contracts Have Been Executed

Although Motorola has not entered into definitive agreements for the sale of communications capacity, it has engaged in detailed discussions with a number of prospective customers. Market response to IRIDIUM has been very positive. Motorola has entered into Memoranda of Intent with several major international telecommunications carriers.

[29] See Satellite Business Systems, 95 F.C.C.2d 866, 869-70 (1983); Establishment of Satellite Systems Providing International Communications, 101 F.C.C.2d 1046, 1104-06 (1985) ("Separate Systems"), reconsideration, 61 Rad. Reg. 2d (P&F) 649 (1986), further reconsideration, 1 F.C.C. Rcd 439 (1986).

IV. ORBIT CONSIDERATIONS

A. Requested Orbits

The IRIDIUM system consists of a constellation of 77 low-earth orbit satellites in seven polar orbits, with eleven satellites equally spaced in each orbital plane. The selection of the operating orbits for the satellites was based on the simultaneous solution of many criteria, each of which are vital to the commercial and technological feasibility of IRIDIUM.

B. Orbit Selection Criteria

The following six criteria were considered in selecting the number of satellites and orbits:

The primary criterion for developing IRIDIUM's orbit selections was the need to provide single global coverage over the entire surface of the earth at all times to insure that any IRIDIUM subscriber unit will always have at least one satellite in view. This requirement defines the minimum number of orbital planes and number of satellites within each plane.

A second selection criterion required that some portion of each orbit be available to allow each satellite to operate in a low power environment, thereby permitting power generation subsystems to be recharged. This requirement allows the size of the power subsystem to be minimized and makes it feasible to design a "small" satellite.

A third criterion for selection required that the relative spacing and line-of-sight relationships to neighboring satellites be repeatable to allow the on-board subsystems which control crosslinks to be simplified, thus reducing the size, weight and power on the satellite design.

A fourth orbit selection criterion involved minimizing the cost of the entire constellation of satellites. This is a two-part optimization which requires that the number of satellites be minimized along with the cost of launching each satellite into its operational orbit. In general, the costs associated with launch vehicles increase as the satellite weight and orbit altitude increase.

To insure that reasonable link margins could be established for "small" satellites directly communicating with low power subscriber units, the minimum slant angle as measured from the horizon to the line of sight between subscriber units and satellites was set at 10 degrees. This criterion also impacts the orbit selection process which must still provide continuous coverage while providing a feasible link margin needed to offset the effects of slant range and foliage.

The last criterion involves the operational altitude regime. Operational altitudes above 600 nautical miles are affected more by the radiation environment which drive up hardware costs, whereas altitudes lower than 200 nautical miles create excessive on-board fuel requirements and frequency of stationkeeping maneuvers.

C. Orbit Selection

The orbit selection process focused on the satisfaction of all of the above criteria. The paper contained in Appendix C hereto provides an extensive analysis of the general topic of earth coverage provided by families of polar satellites. The selected IRIDIUM constellation is comprised of seven evenly spaced circular polar planes, with each plane containing eleven satellites in a ring. See Figure IV-1 for a view of these planes. The satellites within each plane are spaced 32.7 degrees apart, and travel in the same direction at approximately 16,669 miles per hour in a north/south direction and 900 miles per hour westward over the equator. Each satellite circles the earth every 100 minutes.

The seven planes of satellites co-rotate towards the north pole on one side of the earth and "crossover" and come down towards the south pole on the other side of the earth. Of course, the earth continues to rotate beneath the IRIDIUM constellation. The 11 satellites in each plane are equally spaced around their planar orbit, with the satellites in the odd numbered planes (1,3,5, and 7) in phase with one another, and those in the even numbered planes (2,4, and 6) in phase with each other and halfway out of phase with the odd numbered planes. In order to prevent the satellites from colliding at the poles, a minimum miss distance is maintained between the planes in phase. Each of the seven co-rotating planes are separated by slightly

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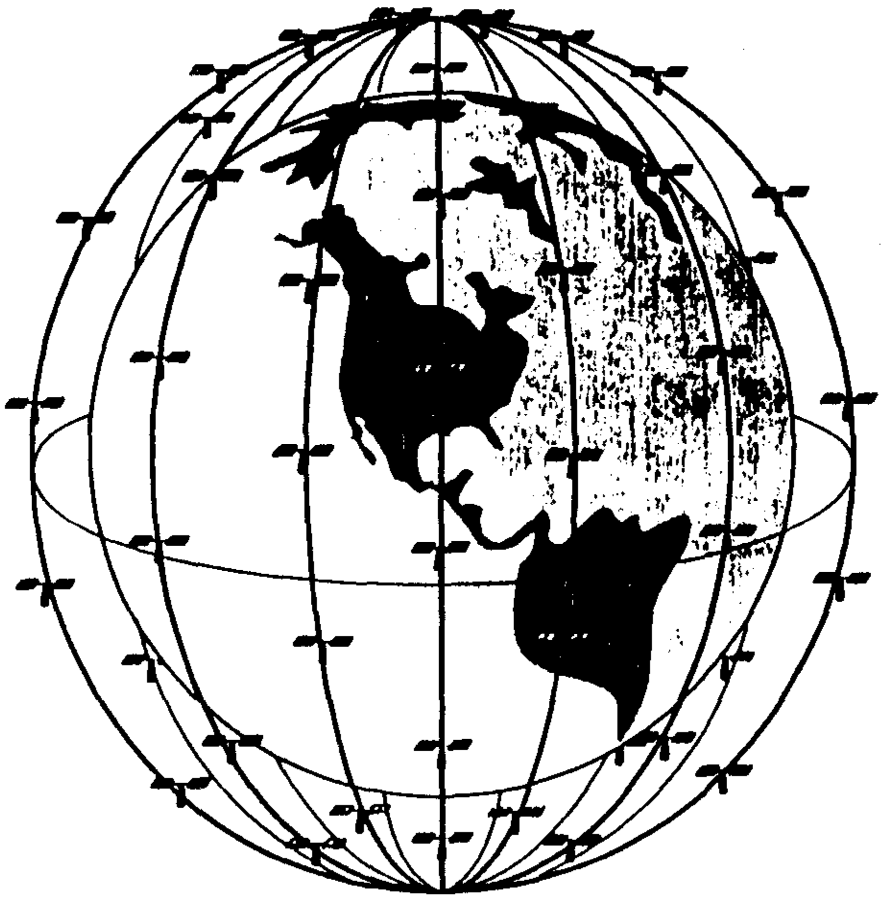
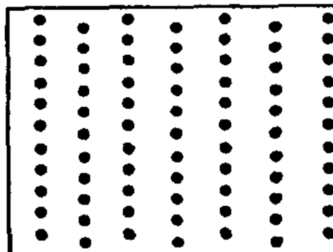
MOTOROLA IRIDIUM SATELLITE SYSTEM

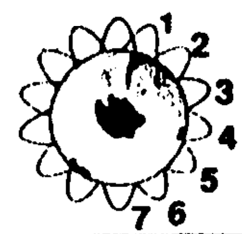


SATELLITES



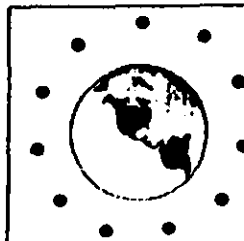
THE SYSTEM REQUIRES SEVENTY-SEVEN... SATELLITES

POLAR VIEW



POSITIONED IN SEVEN ORBITAL PLANES..

EQUATORIAL VIEW



CONTAINING ELEVEN SATELLITES PER PLANE.

FIGURE IV-1 ORBITAL PLANES

more than 27 degrees, and the "seam" between planes 1 and 7, which represents plane 1 satellites going up on one side of the earth and plane 7 satellites coming down in the adjacent plane, is separated by slightly more than 17 degrees.

This satellite constellation provides coverage over the entire surface of the earth with single coverage provided at the equator and increasing levels of coverage as the satellites move toward the poles (due to individual satellite coverages beginning to overlap). The chosen altitude of 413 nautical miles is compatible with the desired altitude regime of greater than 200 and less than 600 nautical miles, and with the need to minimize the cost of the launch vehicles needed to place the satellites into their operational orbits. Several launch vehicle suppliers should be able to place IRIDIUM satellites into the required orbits at a reasonable price.

The nearly symmetrical relationships between planes in the chosen constellation also simplifies the on-board subsystems which control inter-satellite crosslinks. Neighboring satellites slightly ahead of a reference satellite move smoothly towards the reference satellite's plane and cross over that plane at the poles. They then move smoothly away from the reference satellite as the cluster approaches the equator.

D. Deployment and Replenishment of Satellites

There are several deployment options for the constellation that are presently under evaluation. Single or multiple satellite launches are being considered.

The majority of the constellation probably will be deployed using multiple satellite launches to facilitate rapid completion of the 77 satellite constellation. Final completion of each plane will be obtained by single satellite per launch emplacement.

Replenishment of the constellation will be accomplished using single satellite launches to minimize cost and to replace rapidly non operational spacecraft.

E. Safety Considerations

The IRIDIUM constellation is designed to comply with all safety practices and procedures presently accepted in the aerospace industry. Launch safety will be assured through compliance with appropriate range safety controlling documents from the selected satellite launch complex.

An additional safety consideration for the IRIDIUM program consists of avoidance of satellite to satellite collisions in the polar areas. The constellation is designed with the assurance of clearance between satellites as they pass each other at the poles. Small deviations between actual orbit elements and pure polar orbits with exactly the same orbit phase angles are used to assure that collisions do not occur.

At the end of useful life, fuel is expended to enhance the decay of the satellite into lower orbits where natural atmospheric drag will cause it to burn up during reentry. Careful selection of materials will be made to insure complete consumption during the reentry trajectory.

Systems design includes the considerations necessary to assure user safety.

F. Public Interest Considerations

The public interest considerations noted in Section II of this application also support the assignment of these proposed low-earth orbits to IRIDIUM. By utilizing polar orbits at relatively low altitudes, IRIDIUM is able to take advantage of superior propagation characteristics and frequency reuse techniques to enable worldwide mobile communications at affordable costs. Such services also can be offered in conjunction with other terrestrial and satellite-based communications systems on an interference free basis.

To date, no commercial carriers utilize low-earth orbits to provide communications service to the public. Only fixed geostationary satellites currently provide space communications. As the geosynchronous orbit becomes more and more congested with satellites and interference considerations prevent further use of the orbital arc, low-earth orbit satellites will provide a realistic alternative for the continued and expanded use of space for global communications. Through the granting of this application for radio station licenses, this Commission can start the process of licensing and coordinating low-earth orbital assignments.

In addition, the proposed orbital assignments will provide continuous coverage to the contiguous United States as well as all noncontiguous U.S. areas, including Alaska, Hawaii, Puerto Rico, the Virgin Islands, and U.S. territories in the Pacific. The Commission has long recognized and encouraged the provision of satellite service to these offshore points in order to integrate better domestic U.S. communications services.[30]

V. IRIDIUM SYSTEM DESCRIPTION

A. General Overview of System

The IRIDIUM system is composed of: (1) a Space Segment comprised of a continuously replenished constellation of 77 small, smart satellites in low earth orbit, (2) a Gateway Segment consisting of earth stations and associated facilities distributed throughout the world to support call processing operations and to provide for PSTN interconnection, (3) a centralized System Control Facility; (4) a Launch Segment to transfer the satellites into orbit; and (5) a Subscriber Unit

[30] See, e.g., 1980 Orbit Assignment Order, 84 F.C.C.2d at 604-05 (1981); Domestic Communication-Satellite Facilities, 35 F.C.C.2d 844, 856-59 (1972) ("Domsat II").

("ISU") Segment. Figure V-1 provides a pictorial summary of the major elements of each of the system segments.

The IRIDIUM system architecture is extremely flexible and has been designed with the following objectives in mind:

- Efficient use of spectrum and RF power;
- Continuous global coverage;
- Reliable communications in nearly all environments and terrains;
- Minimizing user terminal size, weight and cost;
- Minimizing satellite production and launch costs;
- Allowing for economical upgrades to increase system capacity and to implement improvements resulting from natural technology evolution.

B. Space Segment

The Space Segment includes a constellation of 77 small satellites in low-earth orbit which are networked together as a switched digital communications system utilizing the principles of cellular diversity to provide maximum frequency reuse. Each satellite will utilize up to 37 separate spot-beams to form cells on the surface of the earth. Multiple relatively small beams allow the use of higher satellite antenna gains and reduce the RF power required in the satellite and the user terminal. The spatial separation of the beams allows increased spectral efficiency via time/frequency/spatial reuse over multiple cells, enabling many simultaneous user messages over the same frequency channel.

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IRIDIUM SEGMENTS

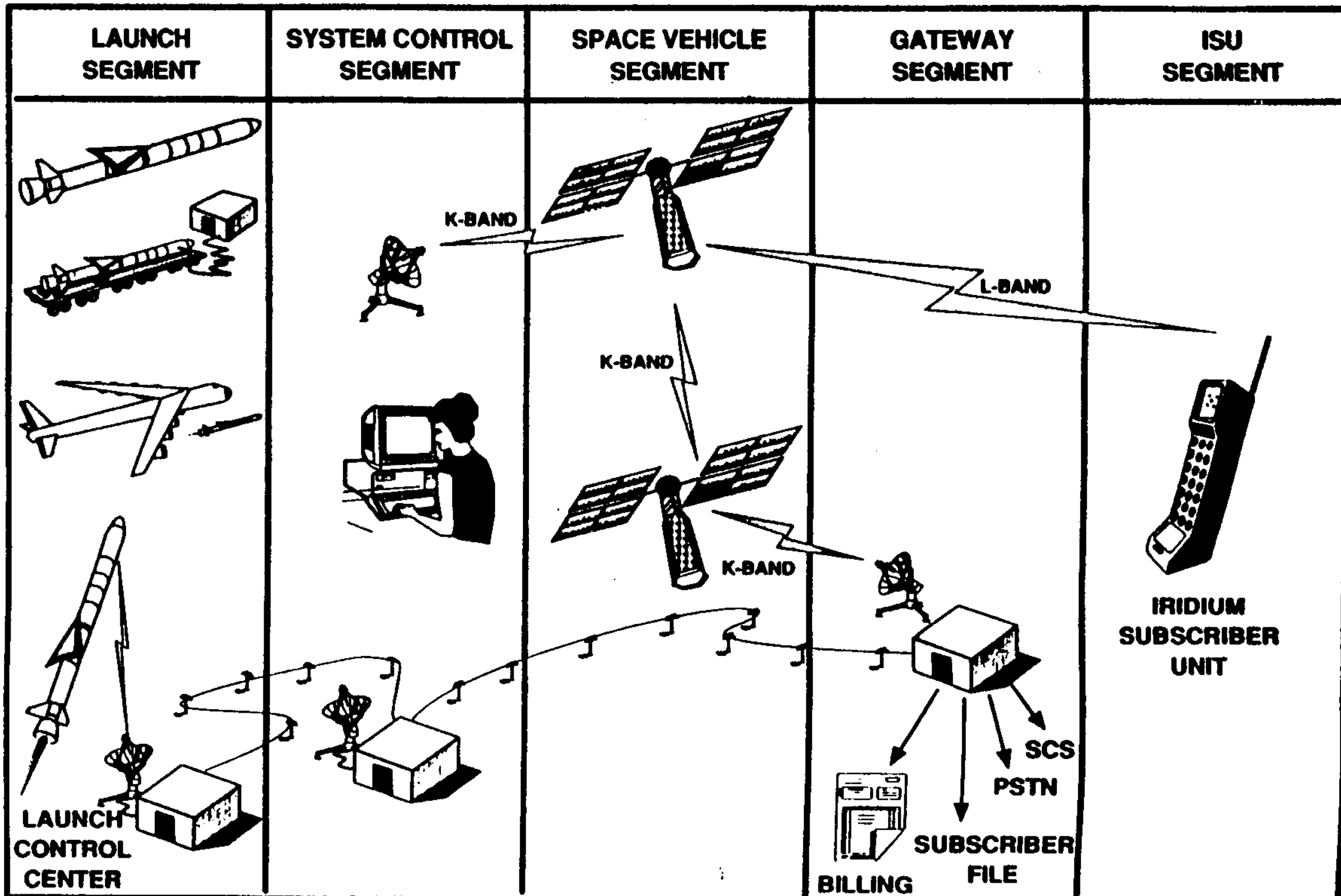

FIGURE V-1

The constellation of satellites and its projection of cells is somewhat analogous to a cellular telephone system. In the case of cellular telephones a static set of cells serves a large number of mobile users; in the case of IRIDIUM, the users move at a slow pace relative to the spacecraft, so the users appear static while the cells move. As each satellite nears the poles, the outermost spot beams are disabled to eliminate unnecessary overlap with beams from adjacent satellites. *See* Figure V-2 for a global depiction of such spot beam coverage.

Each satellite operates crosslinks as a medium used to support internetting. These crosslinks operate in the Ka-band and include both forward and backward looking links to the two adjacent satellites in the same orbital plane which are nominally at a fixed angle and 2,173 nautical miles away. Up to 4 inter-plane crosslinks are also maintained and these links vary in angle and distance from the satellite with a maximum distance of 2,200 nautical miles. Crosslink beams never intercept the earth.

Each satellite can communicate with earth-based gateways either directly or through other satellites by means of the crosslink network. The system architecture is designed to accommodate 250 independent gateways, although initially between 5 and 20 gateways will be constructed, including two in the U.S.

The initial system is sized to handle the expected demand plus some margin for the end of this decade; however, IRIDIUM allows for capacity growth in subsequent years as the need arises. Technological improvements in power available on

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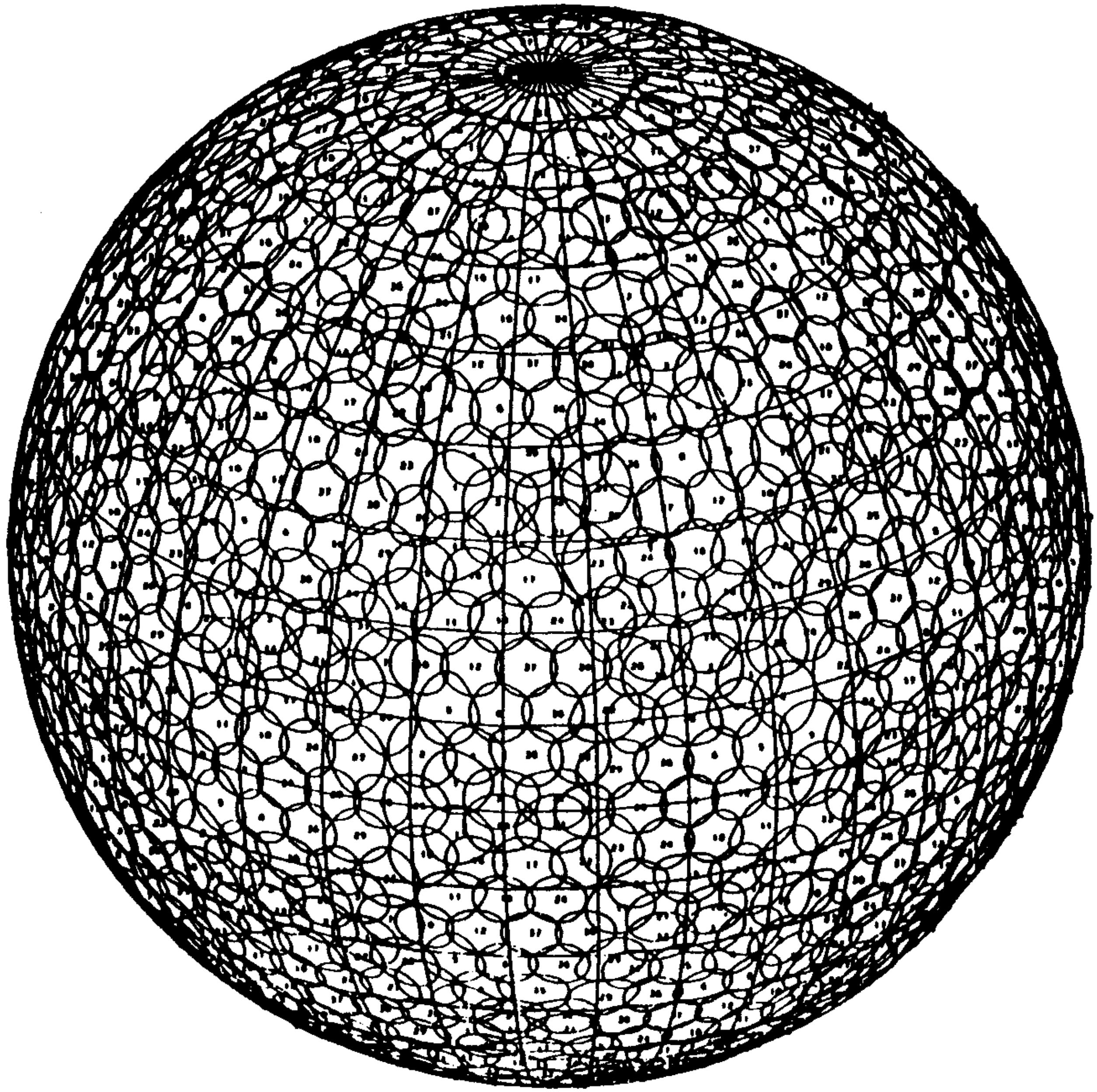

FIGURE V-2 GLOBAL SPOT BEAMS

board spacecraft, launch weights, antenna technology, electronic technology, and areas not now known will allow for system growth within the overall system design that provides for a natural evolution as IRIDIUM matures.

The IRIDIUM system has been designed to meet the technical requirements set forth in the international Radio Regulations and the applicable provisions of Part 25 of the Commission's Rules and Regulations. The system design also is fully compatible with all compliant RDSS systems, the radio astronomy community and GLONASS.

The major satellite characteristics are shown in Table V-1. The following subsections will describe in greater detail these and other aspects of the IRIDIUM system.

TABLE V-1 MAJOR IRIDIUM SATELLITE CHARACTERISTICS	
Stabilization	3-Axis
Mission Life	5 Years
Station Keeping	+/- 0.5 Degrees Attitude Accuracy +/- 20 Kilometers Position Accuracy
Frequency Bands	1610-1626.5 MHz 18.8-20.2 GHz 27.5-30.0 GHz 22.55-23.55 GHz
Earth Coverage	5 Million Square Miles Per Satellite
Max. Number of Uplink Channels per Satellite	110 per cell averaged over 37 cells
Max. Number of Downlink Channels per Satellite	110 per cell averaged over 37 cells
Number Intersatellite Channels per Satellite	3,000 Maximum
Number Gateway Channels per Satellite	2,000 Maximum
Total Occupied Bandwidth	16.5 MHz @ L-band 200 MHz @ Ka-band (crosslinks) 100 MHz @ Ka-band (gateway uplink)
Polarization	Right Circular 100 MHz @ Ka-band (gateway downlink) @ L-band & Ka-band (Gateway and TT&C links) Vertical @ Ka-band (Intersatellite links)
Transmit EIRP	12.4 to 31.2 dBw @ L-band 14.5 to 27.5 dBw @ Ka-band (Gateway) 37.9 dBw @ Ka-band (Intersatellite)
Satellite G/T	-19.6 to -5.3 dBi/K @ L-band -10.1 dBi/K @ Ka-band (Gateway) 5.3 to 7.0 dBi/K @ Ka-band (Inter-satellite)
Wet Mass with Reserve	386.2 kg.
Orbit	Polar (7 planes)

1. Cell Management and Frequency Reuse

a. Satellite L-Band Antenna Pattern

Each satellite has the capability of projecting 37 L-band spot beams on the surface of the earth. The spot beams form a continuous hexagonal pattern with one center spot beam surrounded by three rings of equally-sized beams. The three rings consist of 6, 12, and 18 spot beams, respectively. Each of the 37 spot beams is created such that they are approximately the same shape and size (372 nautical miles in diameter), and combine to cover a circular area with a diameter of about 2,200 nautical miles for each satellite. Each satellite is in view by a single ISU for approximately nine minutes.

Each satellite has 6 multiple beam phased array antennas plus one fixed beam cupped dipole antenna. The phased array antennas are located on the side panels of the hexagonal satellite, each of which forms six cellular beams. The fixed beam antenna is located on the bottom of the satellite and forms a single cellular beam in the nadir direction. Active Transmit/Receive (T/R) modules are utilized to provide power amplification for the transmit function, low noise amplification for the receive function, switch selection between transmit and receive, and digital phase control for active beam steering of both the transmit and receive beams in the phased arrays.

The composite L-band pattern is illustrated in Figure V-3 as it is projected on the surface of the earth. The six cell

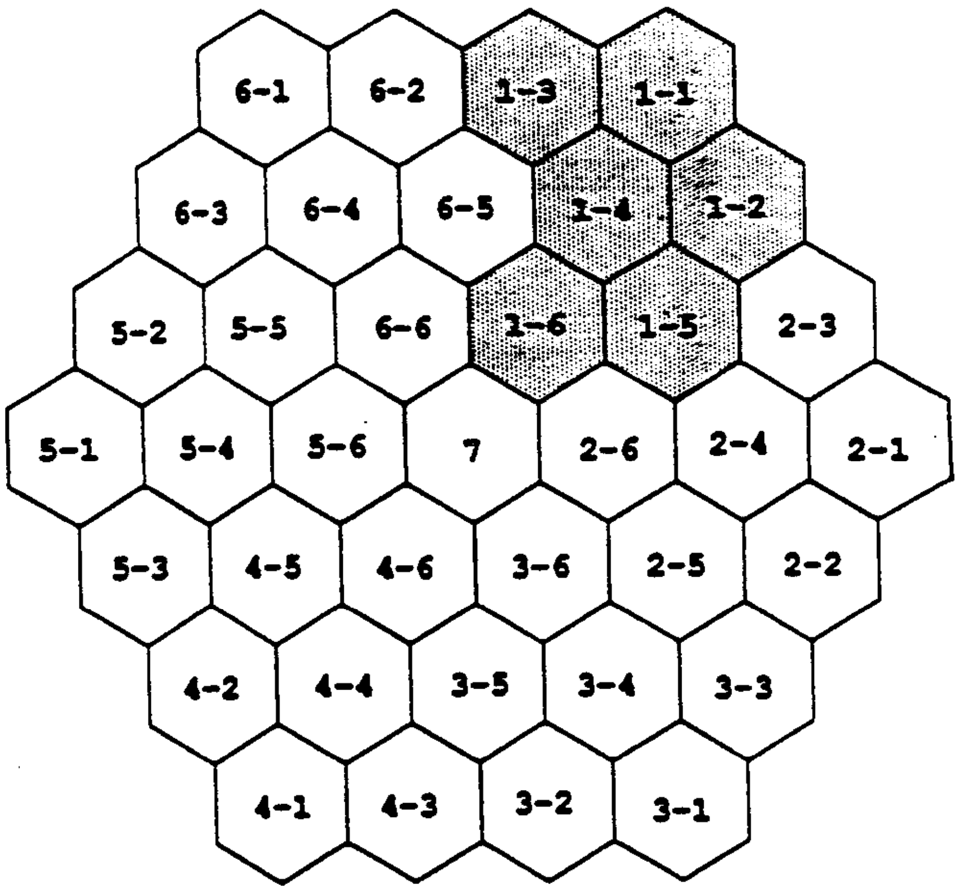

FIGURE V-3 37-CELL PATTERN

pattern of each phased array (beam types 1-6) is repeated for each of the six panels. The nadir cell (beam type 7) is served by the cupped dipole located on the nadir face of the satellite. Each of the phased array antenna beams have been optimized to provide the desired cell coverage. The antenna aperture gains (on-boresight) and beamwidths for each of the beam types are listed in Table V-2. Figures V-4 to V-10 depict the satellite L-band antenna gain contours. Tables A-2 to A-5 in Appendix A provide the peak antenna gains and specific link analyses.

TABLE V-2

ANTENNA APERTURE GAINS AND BEAMWIDTHS

Beam Type	Aperture Gain (dBi)	3 dB Beamwidth Azimuth	Elevation (deg)
1	25.0	19.0	5.4
2	25.0	19.0	5.4
3	25.0	19.0	5.4
4	23.9	19.0	7.0
5	23.0	19.0	8.5
6	20.0	26.0	11.5
7	12.0	45.0	45.0

b. Formation of the Cellular Pattern

IRIDIUM operates with a 7-cell frequency reuse pattern, as shown in Figure V-11. The cells denoted as A through G are scanned by the satellite antenna arrays in accordance with the timing pattern and sequence shown in Figures V-3 and V-12. During the time slot that the antenna is pointing at a cell, satellite transmissions may be made and receptions of

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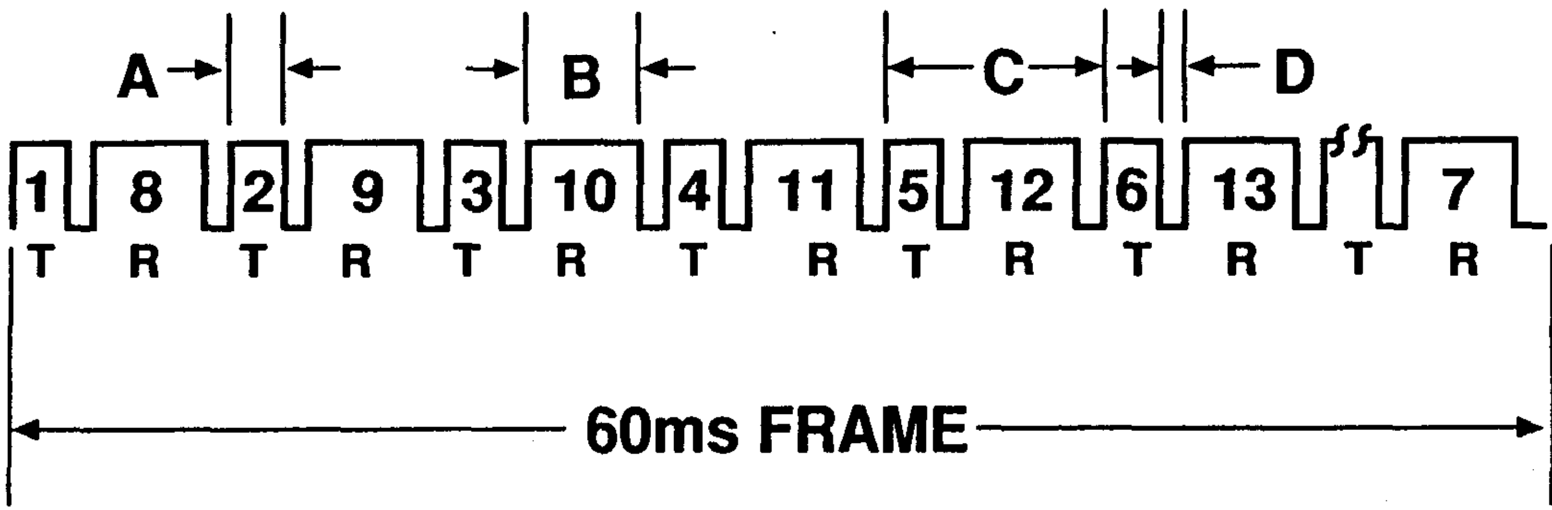
SATELLITE TDMA FORMAT

A = TRANSMIT BURST TIME = 1.3 MILLISECOND
B = RECEIVE BURST TIME = 2.9 MILLISECONDS
C = TIME BETWEEN BURSTS = 4.2857 MILLISECONDS
D = GUARD TIME = 42.857 MICROSECONDS



T = TRANSMIT TIME
R = RECEIVE TIME

FIGURE V-12 TDMA FORMAT

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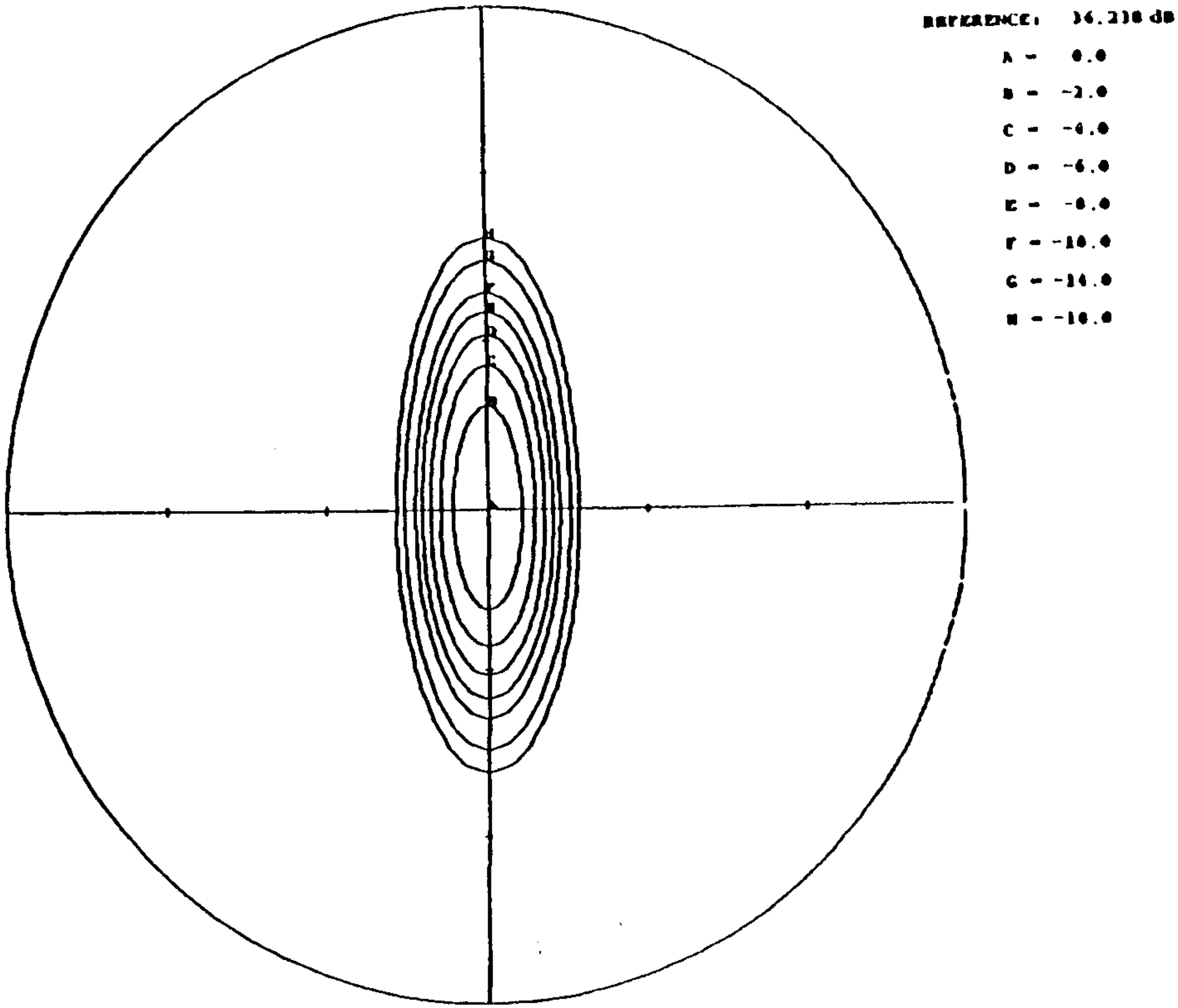

FIGURE 5 CROSS LINK ANTENNA PATTERN

EXHIBIT I (Revised)

TECHNICAL INFORMATION

Radio Frequency and Polarization Plan

L-Band (Uplink and Downlink)	1610-1626.5 MHz (16.5 MHz)
Polarization	Right Hand Circular
Center Frequency	FDMA Cross Band
Channel Bandwidth	280 KHz Downlink 126 KHz Uplink
Gateway and TT&C (Uplink)	27.5-30.0 GHz (100 MHz)
(Downlink)	18.8-20.2 GHz (100 MHz)
Polarization	Right Hand Circular
Center Frequency	6 Channels (single channel per link)
Channel Bandwidth	15 MHz
Intersatellite Link	22.55-23.55 GHz (200 MHz)
Polarization	Vertical
Center Frequency	8 Channels (single channel per link)
Channel Bandwidth	25 MHz

Final Amplifier Output Power[1/]

L-Band	
(Cells 1 - 37)	1.5 to 11.8 Burst Watts per carrier
Ka-Band	
Gateway	1.0 to 25.0 Watts per channel
Intersatellite	5.1 Burst Watts per carrier[1/]

Receiving System Noise Temperature[1/]

L-Band	553 °K
Ka-Band	
Gateway	1454 °K
Intersatellite	789 - 1114 °K

[1/] See Appendix A of IRIDIUM system application.

Gain of Each L-Band Channel	(Not a transponder)[2]
Orbital Locations[3]	
Altitude	413 Nautical Miles
Number of Planes	7 Polar Planes
Spacing of Planes	27 Degrees (except planes 1 & 7 spaced 17 Degrees)
Number of Satellites Per Plane	11 Satellites
Spacing of Satellites In Plane	32.7 Degrees
Predicted Satellite Coverage Contours	[4]
Functional Block Diagram of Satellite Communications System and Switching Capabilities	[5]
Physical Characteristics of Satellite	
Attitude Accuracy	+/- 0.5 Degrees
Position Accuracy	+/- 20 kilometers
Antenna Axis Attitude	[6]
Antenna Pointing Accuracy Toward Earth	+/- 0.5 Degrees

[2] See Appendix A of IRIDIUM system application.

[3] See Section IV to the IRIDIUM system application for the factors which support these orbital assignments.

[4] L-band cell (1 - 7) contours and Ka-band gateway and intersatellite link contours are provided in the IRIDIUM system application at Section V. See Appendix A of the IRIDIUM system application for receiving antenna gain, transmitting antenna gain, receiving system sensitivity (G/T), saturation power flux density, and effective isotropically radiated power.

[5] See Section V of the IRIDIUM system application.

[6] See Section V of the IRIDIUM system application.

Estimated Minimum Lifetime of In-Orbit Satellite[7/]	5 Years
Attitude Stabilization and Station-keeping Systems	[8/]
Electrical Energy System	[9/]

Emission Limitations (L-Band)

Channel Bandwidth	280 KHz

Spurious Emissions Attenuated

30 dB @ 100% x Channel Bandwidth from carrier
60 dB @ 200% x Channel Bandwidth from carrier

7/ The basis for this lifetime estimate is contained in Section V of the IRIDIUM system application.

8/ A description of these systems is contained in Section V of the IRIDIUM system application.

9/ A description of this system, including provision for operation during eclipse conditions, is set forth in Section V of the IRIDIUM system application.

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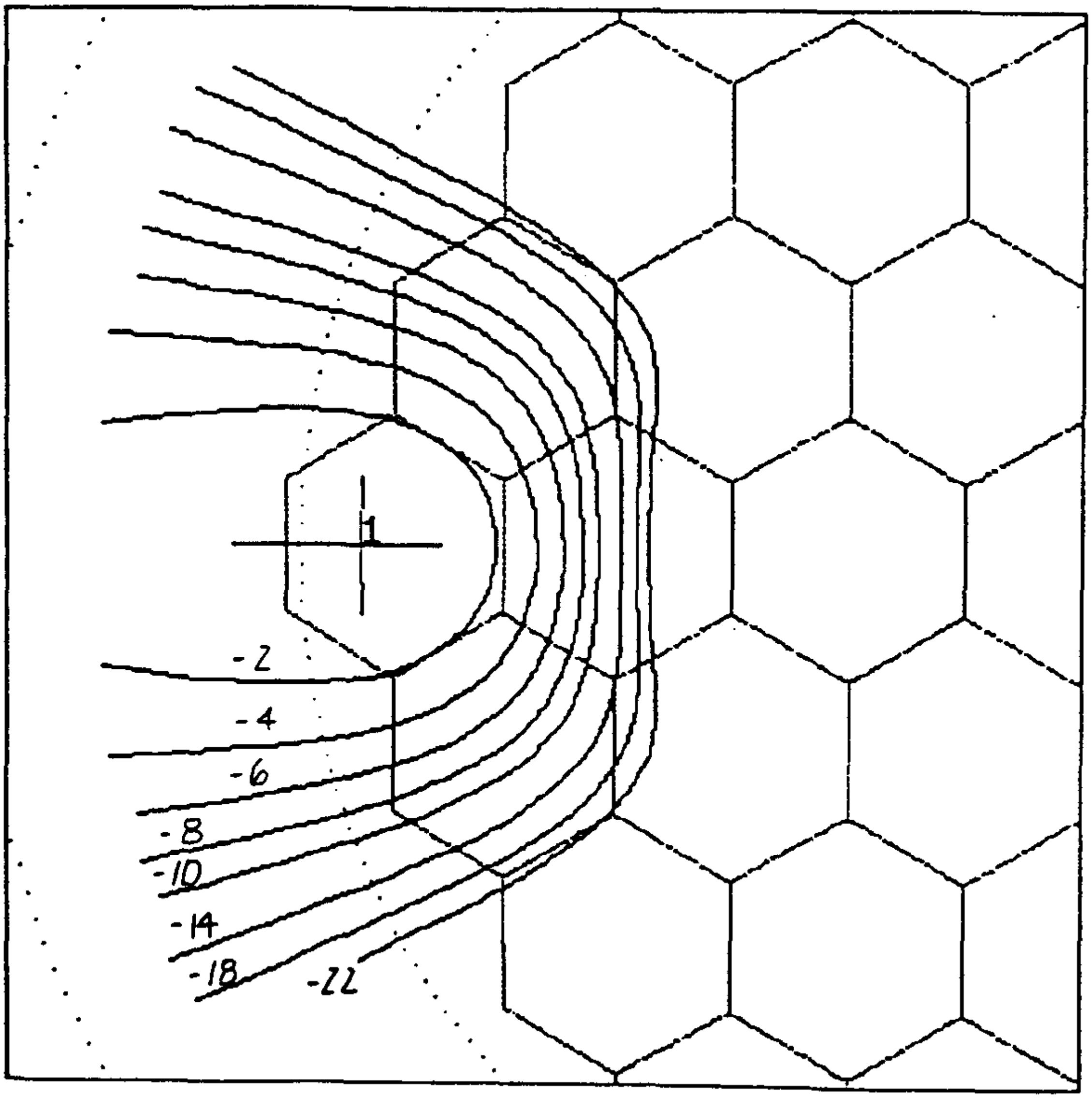

FIGURE V-4 CELL 1 PATTERN

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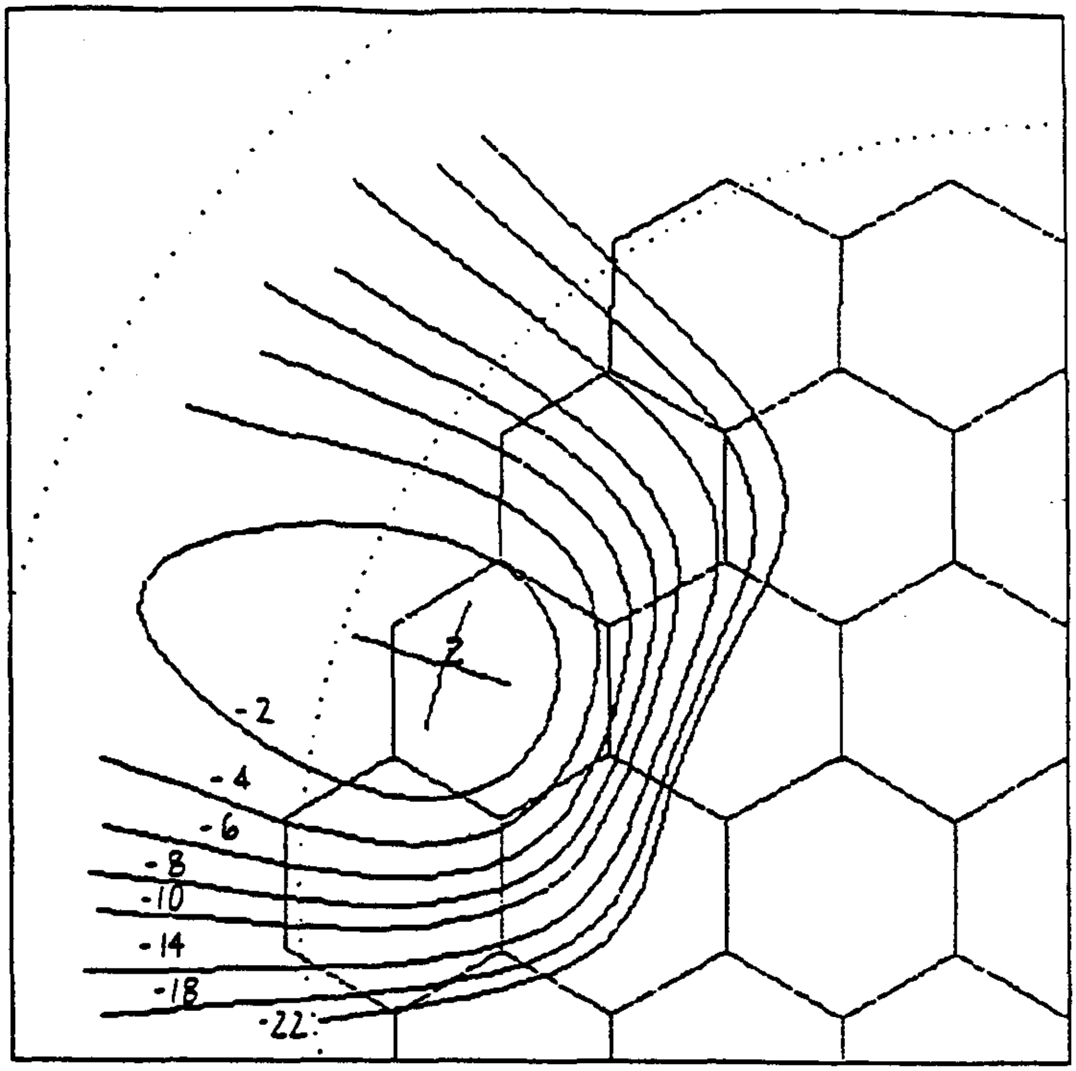

FIGURE V-5 CELL 2 PATTERN

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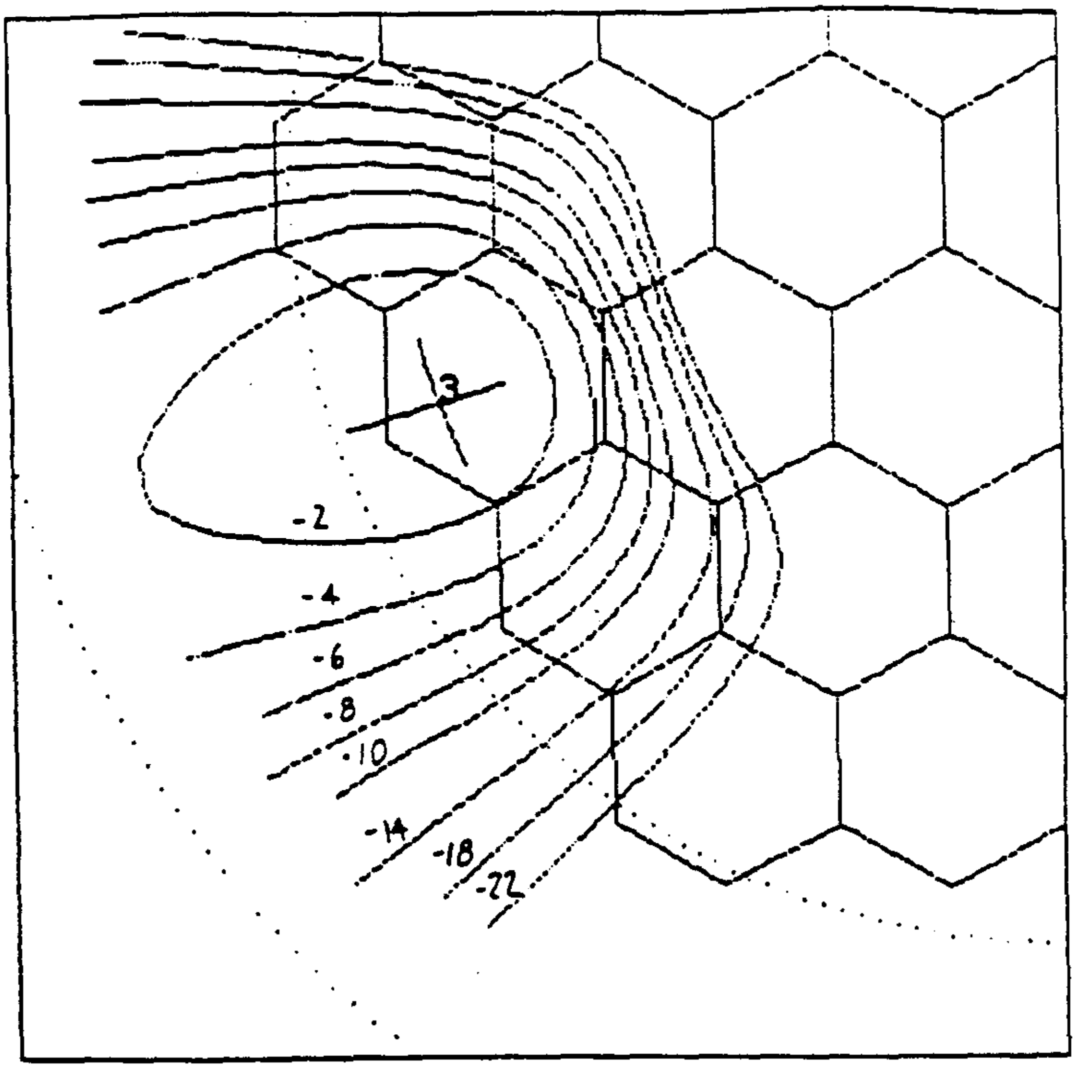

FIGURE V-6 CELL 3 PATTERN

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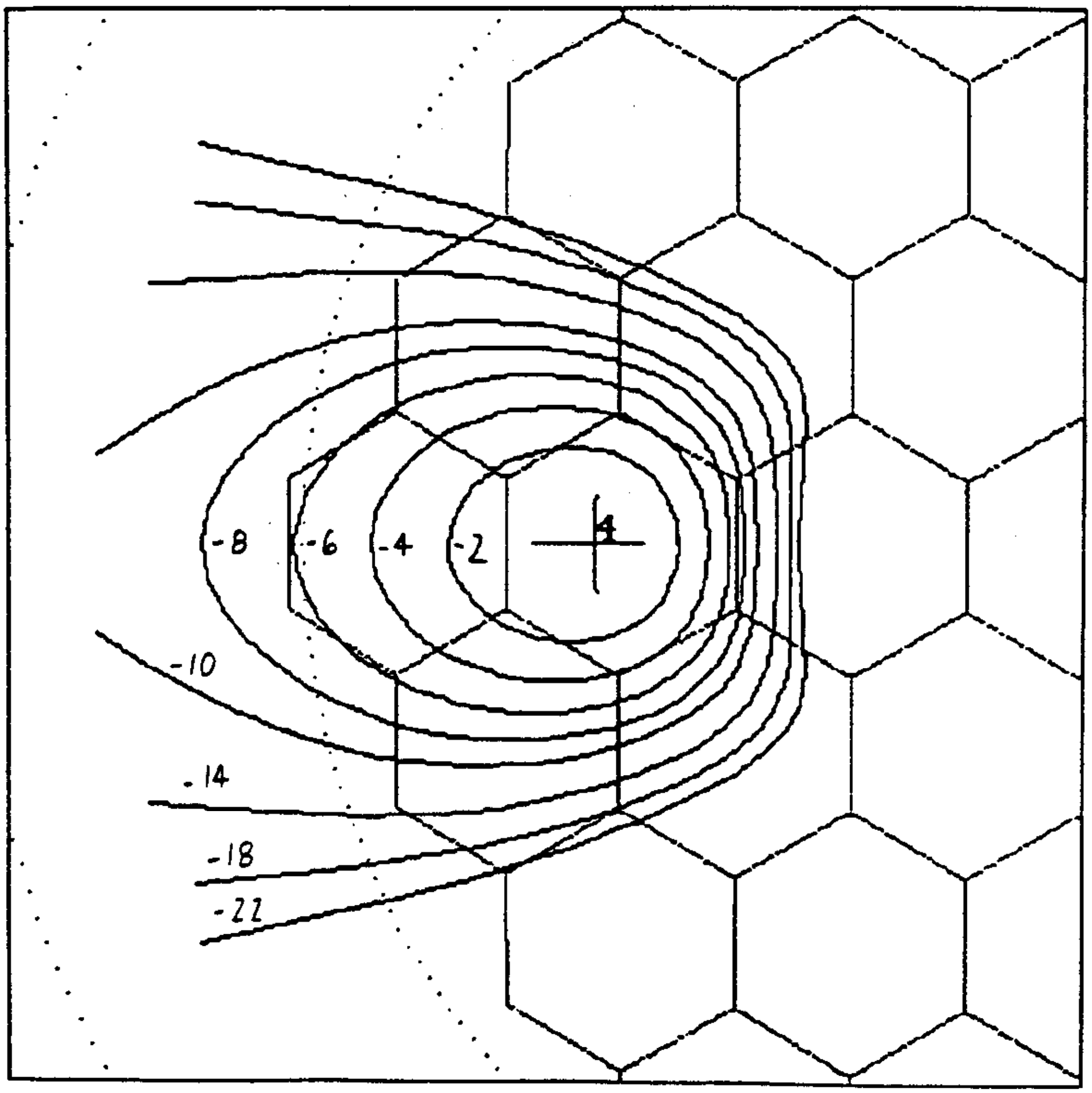

FIGURE V-7 CELL 4 PATTERN

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IRIDIUM

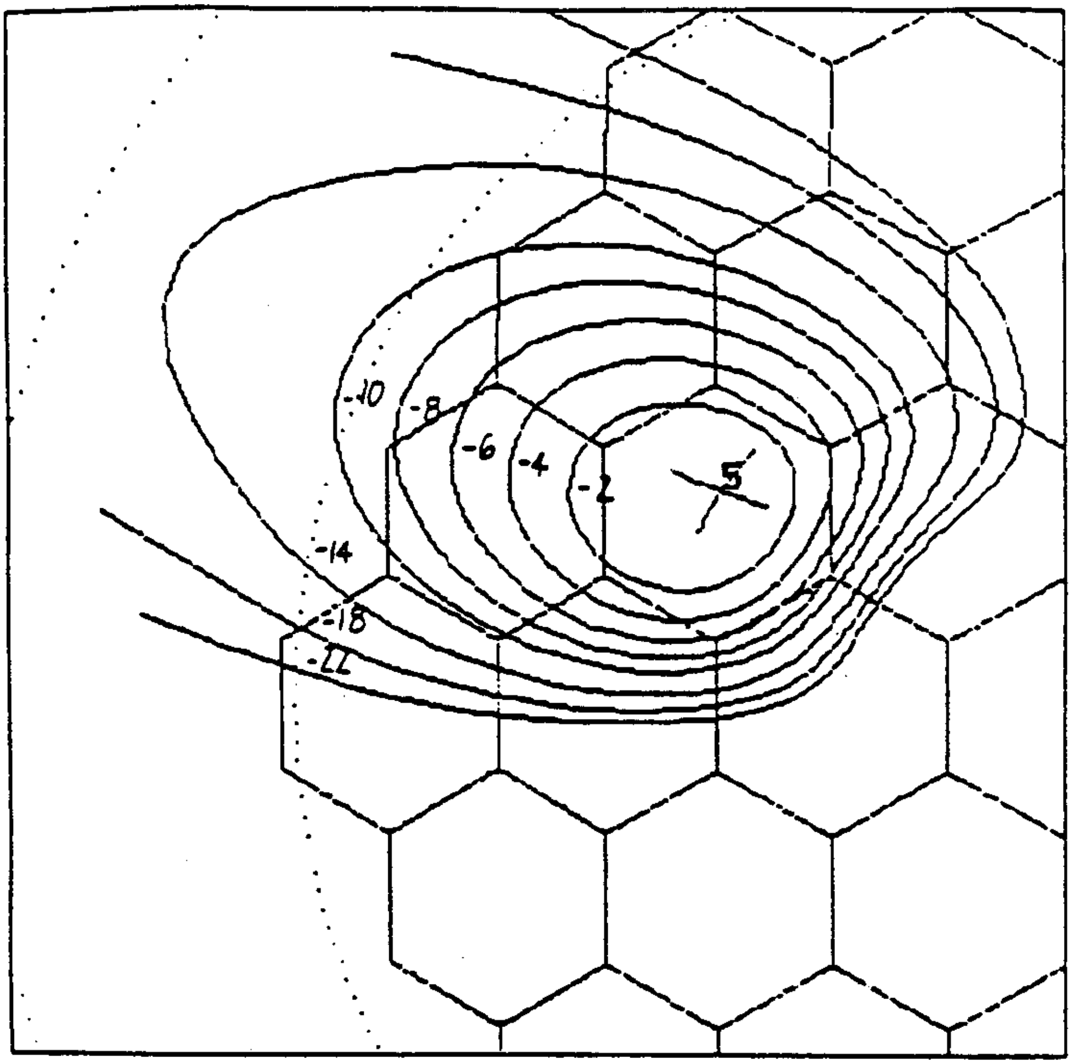

FIGURE V-8 CELL 5 PATTERN

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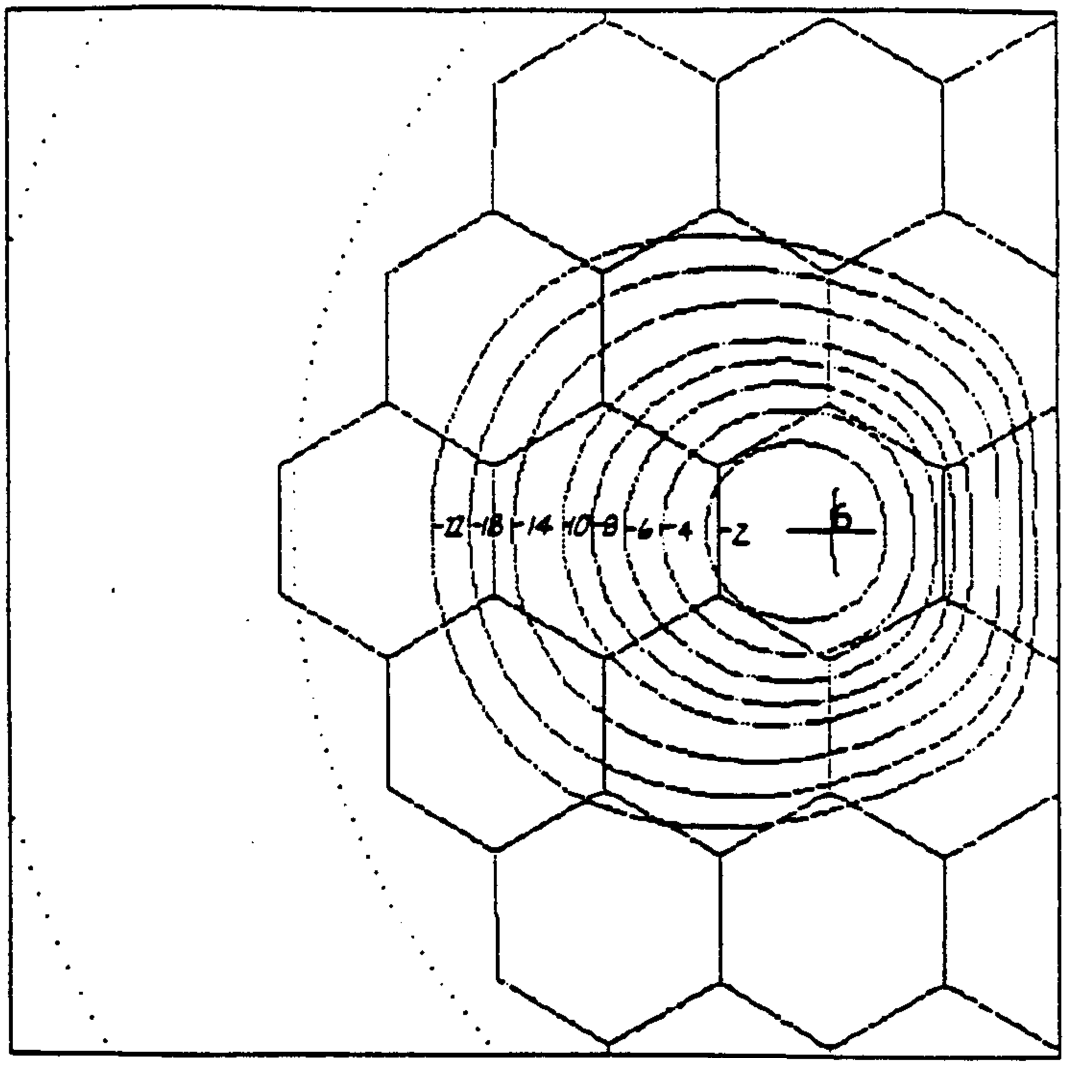

FIGURE V-9 CELL 6 PATTERN

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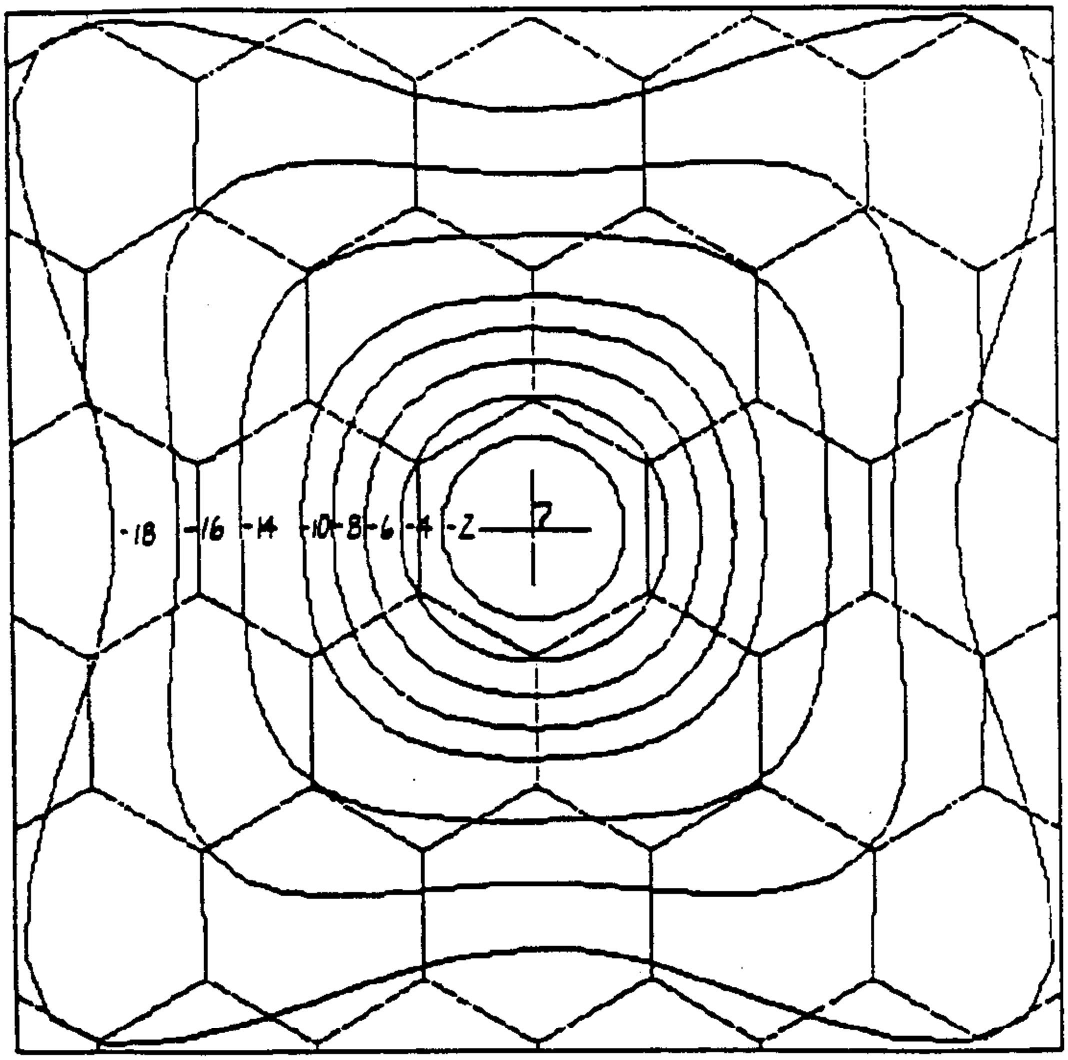

FIGURE V-10 CELL 7 PATTERN

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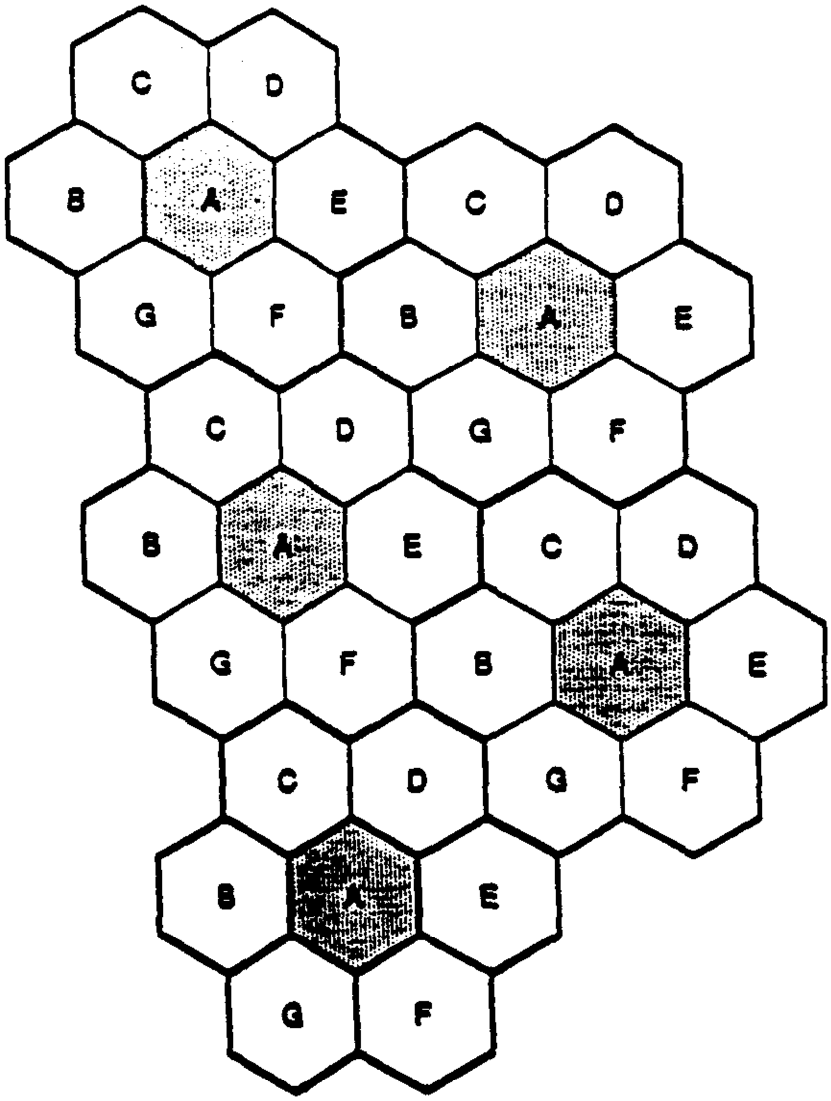

FIGURE V-11 SEVEN CELL FREQUENCY REUSE PATTERN transmissions from ISU's may occur during the respective transmit and receive intervals. Transmissions may be on the same frequency at the same time in any cells with the same letters (A, B, etc.) as shown in Figure V-11.

Each satellite has scanning beam antennas which are programmed to point at the correct cell on the earth at the right time. Figure V-13 shows the integration of the 7-cell pattern on a satellite and how it is integrated with satellites whose antenna patterns are contiguous.

The positioning of the satellites is such that the cells merge at the equator as shown in Figure V-2. As the satellites move toward a pole, the distance between satellites in adjacent planes decreases. This causes antenna patterns to overlap. As the cell patterns begin to overlap, selected spot beam antennas are deactivated to permit an orderly reconstitution of the frequency reuse pattern. This synchronized control of the cells is defined as cell management.

On a global basis, there typically are 1,628 cells and the seven-cell pattern reuses each frequency over two hundred times. Within the contiguous United States alone, IRIDIUM will achieve more than five times frequency reuse. No other existing or proposed satellite system comes close to achieving these spectrum efficiencies.

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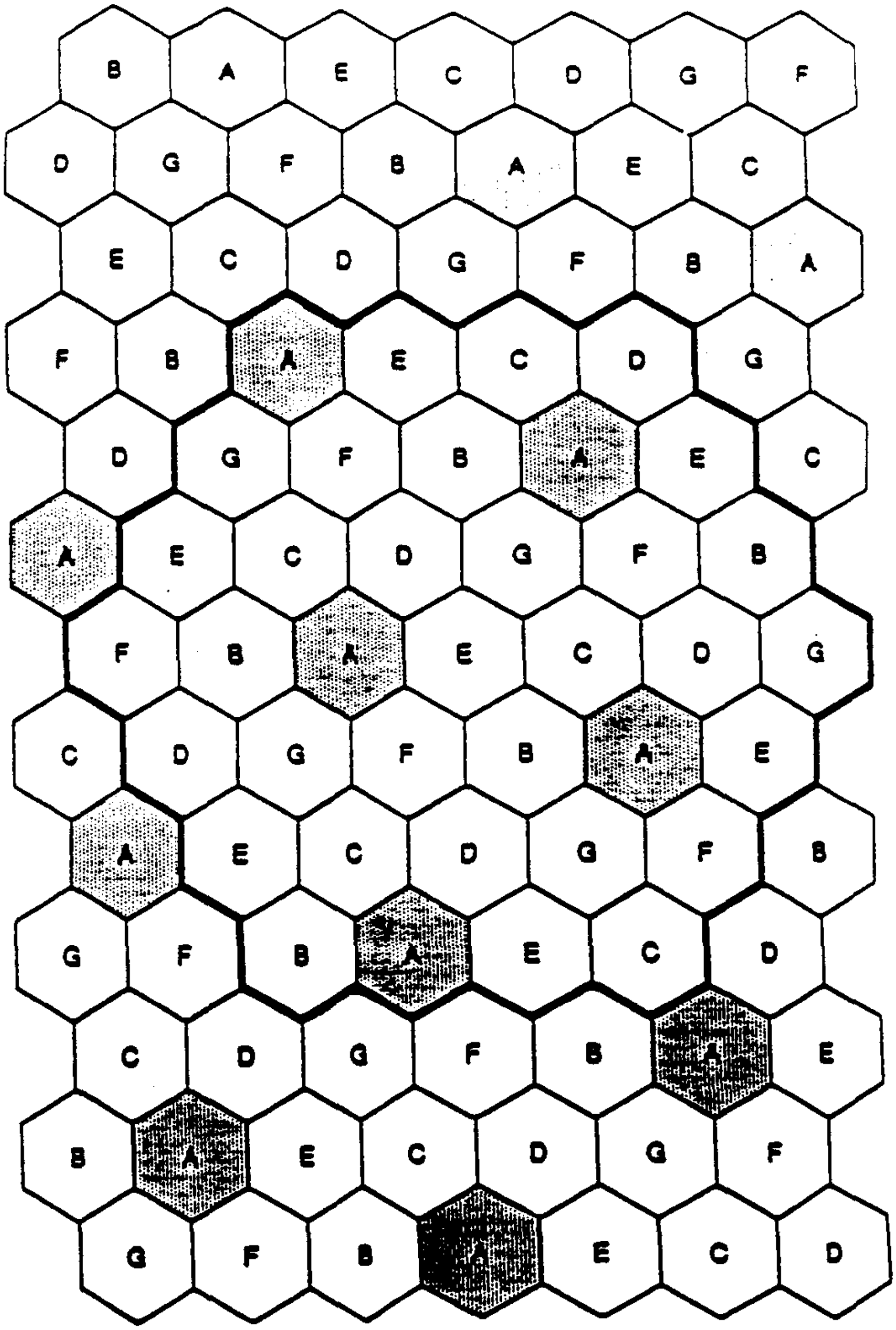

FIGURE V-13 REUSE PATTERN WITH MORE THAN ONE SATELLITE

2. Spectrum Utilization and Frequency and Polarization Plans

The IRIDIUM system will receive and transmit signals in the United States at the following frequencies:

Subscriber Unit Uplink and Downlink[31]	1610-1626.5 MHz
Gateways and Satellite Control Facilities	27.5-30.0 GHz (Uplink) 18.8-20.2 GHz (Downlink)
Intersatellite Crosslinks	22.55-23.55 GHz

The IRIDIUM system is designed for single L-band operation. This means that no frequency spacing is required between the up and down link carriers, and that the paired RDSS band (2483.5-2500 MHz) will not be needed for the proposed service.

a. Frequency Plans

The Frequency Plan for the L-band is shown in Figures V-14 and V-15. The uplink consists of up to 102 frequency channels spaced every 160 KHz. Each channel occupies a 126 KHz bandwidth. It is expected that a maximum of 64 carriers may be used, 9 of which will be control channels. The downlink consists of up to 46 carriers. The carrier spacing is every 350 KHz and each channel occupies a bandwidth of 280 KHz. It is expected

[31] The IRIDIUM system will be capable of operating in the 1610-1660.5 MHz band worldwide, but will only utilize those portions of the spectrum over any geographic region authorized by the appropriate regulatory bodies.

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DOWNLINK R.F. PLAN

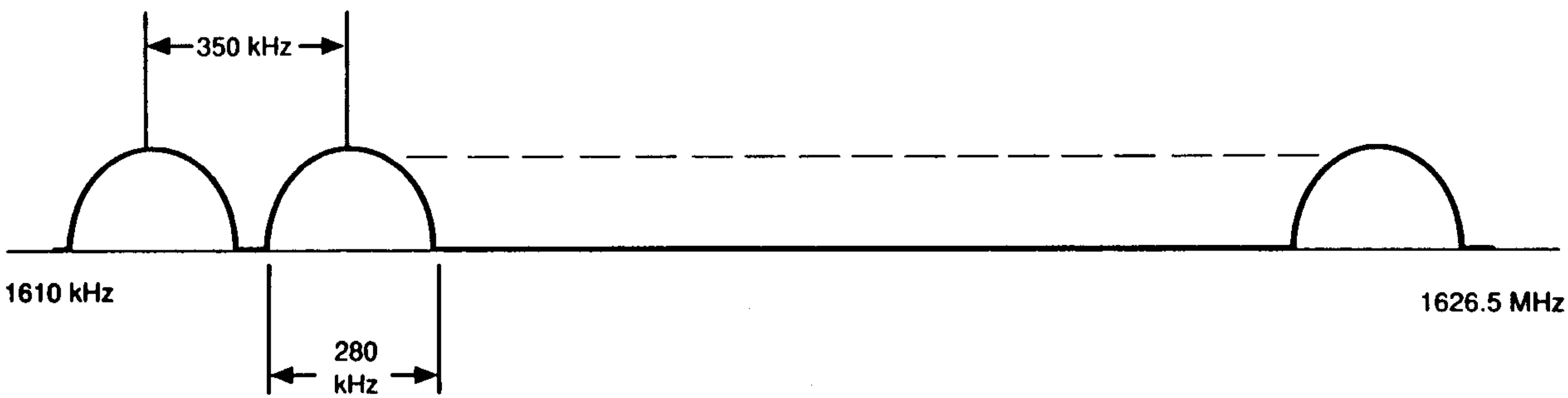

FIGURE V-14 L-BAND DOWNLINK RF PLAN

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UPLINK R.F. PLAN

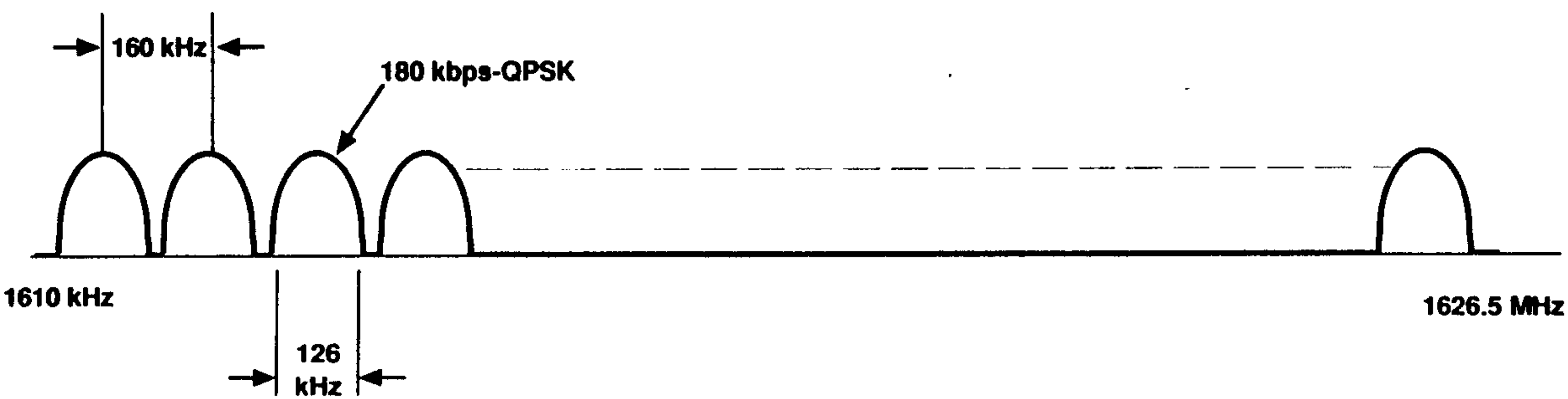

FIGURE V-15 L-BAND UPLINK RF PLAN

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that a maximum of 29 carriers may be used, 4 of which will be control channels.[32]

The downlink uses Digital Speech Interpolation (DSI) techniques to reduce its bandwidth. A 2.2:1 DSI activity compression ratio is used allowing the 25 downlink traffic carriers to handle up to 55 voice channels. The four control channels provide the DSI control information to the IRIDIUM subscriber terminal units, as well as the paging and synchronization signals.

The spectral occupancy of the carriers will be arranged to protect the radio astronomy (1610-1613.5 MHz) and GLONASS (up to 1616 MHz) frequency bands. Motorola does not anticipate any difficulties entering into memoranda of understanding with the appropriate radio astronomy parties to protect certain frequencies where necessary to avoid unacceptable interference in these bands. <u>See</u> Appendix B.

The IRIDIUM system crosslinks require 200 MHz of spectrum. The appropriate allocation for this type of service is the Intersatellite Link Service ("ISS") allocation at 22.55-23.55 GHz. This application requests the use of frequencies in these specified bands; however, it is recognized that the space research community anticipates future use of this spectrum on such systems as the ATDRSS. It is believed that because of the

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[32] These figures assume a fully-operational GLONASS system.

general geocentric isolation of the two systems the likelihood of unacceptable interference is low.[33]

Polarization for L-band links will be right circular. Polarization for the Ka-band intersatellite crosslinks will be vertical. The polarization for the Gateway links will be circular.

Spurious emissions beyond the usable bandwidth of each frequency band will be attenuated by input and output filters, and the radio frequency design.

b. Compatibility with Other RDSS Systems

IRIDIUM is fully compatible with all compliant RDSS systems and will not cause objectionable interference to any licensed system. See Appendix B hereto. Motorola agrees to coordinate with Geostar or any other licensed system operator to avoid harmful interference as required by Section 25.392(b) of the Commission's Rules. As set forth in Section VI of this application, Motorola requests a waiver of Section 25.392(f) of the Rules to provide such coordination through technical means other than the spread spectrum techniques set forth therein.

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[33] It should be noted that the FCC Industry Advisory Committee to WARC-92 is recommending additional ISS allocations in the 22 and 33 GHz part of the spectrum to accommodate possible future needs. Motorola understands that this proposed ISS allocation use and development strategy has been discussed and coordinated with cognizant U.S. space research officials.

3. **Traffic Capacity**

The multiple access format for IRIDIUM uses both time division ("TDMA") and frequency division ("FDMA") which results in a very efficient use of spectrum. A 14 slot TDMA format is used, allowing each cell to be assigned on the average two time slots. The average traffic capacity of the IRIDIUM system using the 16.5 MHz from 1610 to 1626.5 MHz is therefore 2 x 87 traffic channels or 174 full duplex voice channels per cell. The IRIDIUM system places approximately 40 cells (time variant over 10 minutes) over the continental United States and its coastal waters. The traffic capacity for the contiguous United States would then be 40 cells x 174 or 6,960 full duplex voice channels.[34/]

Other non-contiguous parts of the United States would also be served by the IRIDIUM system, including Alaska, Hawaii, the Virgin Islands, Puerto Rico and the island territories in the Pacific Ocean. At 174 full duplex voice channels per cell and 1628 operable cells worldwide, the theoretical maximum capacity of the system would be 174 x 1628, or 283,272 full duplex voice channels using just 16.5 MHz of spectrum.[35/]

For RDSS only applications, the traffic capacity would be even larger. The basic RDSS data may be transmitted in a

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34/ These capacity figures may be reduced somewhat depending upon the future deployment of GLONASS.

35/ *Id*.

single burst in the TDMA time slot. Each cell exchanges two bursts every 60 milliseconds, or 33.3 bursts per second. Therefore, the capacity per carrier per second over the continental United States would be 40 cells times 33.3 or 1333. Given the capability of 40 active RDSS traffic carriers on the downlink, the total system capacity would be over 191 million observations per hour.[36] IRIDIUM can provide observations to all subscribers. There is no limit on the number of subscribers.

4. Communications Subsystem

The IRIDIUM communications system provides L-band communications between each satellite and individual subscriber units, Ka-band communications between each spacecraft and ground-based facilities (either Gateway or System Control Facilities), and Ka-band crosslinks from satellite to satellite. The transfer of Telemetry, Tracking, and Control ("TT&C") information between the System Control Facilities and each satellite is generally provided via the a Ka-band communications links, with a dedicated link (via omni antenna) provided as a backup. Figure V-16 is a top-level block diagram for the communications subsystem.

[36] *Id.*

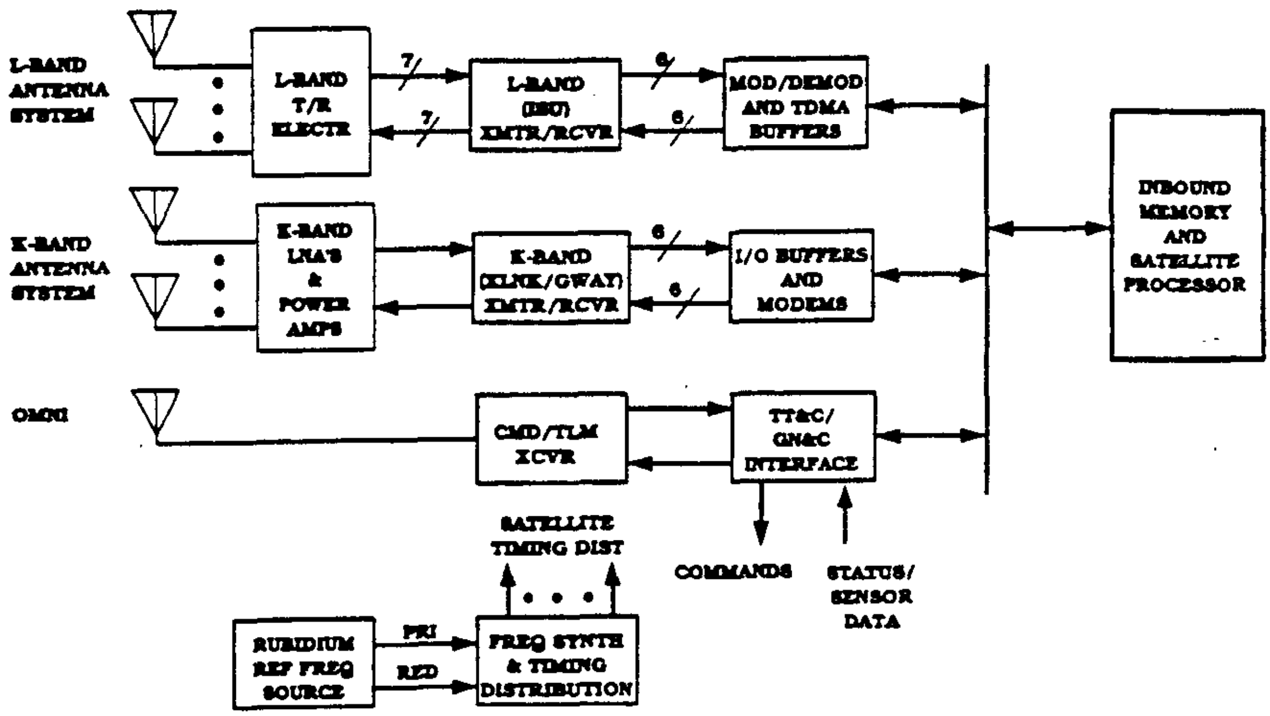

FIGURE V-16

SATELLITE ELECTRONICS TOP-LEVEL BLOCK DIAGRAM

a. L-Band Subscriber Terminal Links

The L-band communications requirement is supported by an antenna complex consisting of seven antenna panels which form 37 cellular beams. Of the seven beams that can be formed simultaneously (one from each panel), six may be active during any time slot (based on the projected overlap between the cell patterns of adjacent satellites). The L-band communications subsystem is sized to provide transmit and receive capability for up to six fully loaded cells.

Each active receive beam supports up to 87 traffic channels spaced at 160 KHz intervals. Each active transmit beam supports up to 45 traffic channels requiring a maximum of 280 TDMA modulator channels per satellite. The larger uplink channel quantity is balanced with the use of a 2.2:1 DSI voice activity compression ratio on the downlink.

The L-Band communications subsystem is designed to support bit error rates of less than 10^{-2} end-to-end for voice. The lower bit error rates required for data transfers will be supported through the use of processing hardware installed at the subscriber units to apply more robust protocols and coding in order to counter the deep fades experienced in the L-band links. The FDMA/TDMA architecture selected for use on IRIDIUM will allow growth in the capacities of future satellite launches through additional frequencies, while maintaining compatibility with the data rates, channel spacing, and slot allocations described herein.

b. Intersatellite Crosslinks

To form a transmission network that is able to transport subscriber communications around the entire earth requires that the satellites of the IRIDIUM constellation be interconnected. Each satellite will communicate and route network traffic to the two satellites that are fore and aft of the vehicle in the same orbital plane. Two separate fixed waveguide slot arrays pointing in forward and aft directions are used for the in-plane links. The gain of these arrays is approximately 36 dBi. Figure V-17 depicts a typical crosslink antenna gain contour. Table A-8 in Appendix A gives the peak antenna gains and specific link analyses.

In addition, each spacecraft will be interconnected to the satellites in the adjacent two orbital planes. Mechanically steered waveguide slot arrays are used to track the co-rotating adjacent planes (cross-plane). The gain of the cross-plane antennas are also 36 dBi. The cross-plane antennas are optimized to provide a 5 degree elevation beamwidth so that mechanical scanning is required in only the azimuth direction.

These four cross links provide both direct and practical routing between users throughout the world and provide a substantial redundancy that can continue to support traffic flow in the event of degradation to one of the satellites. These

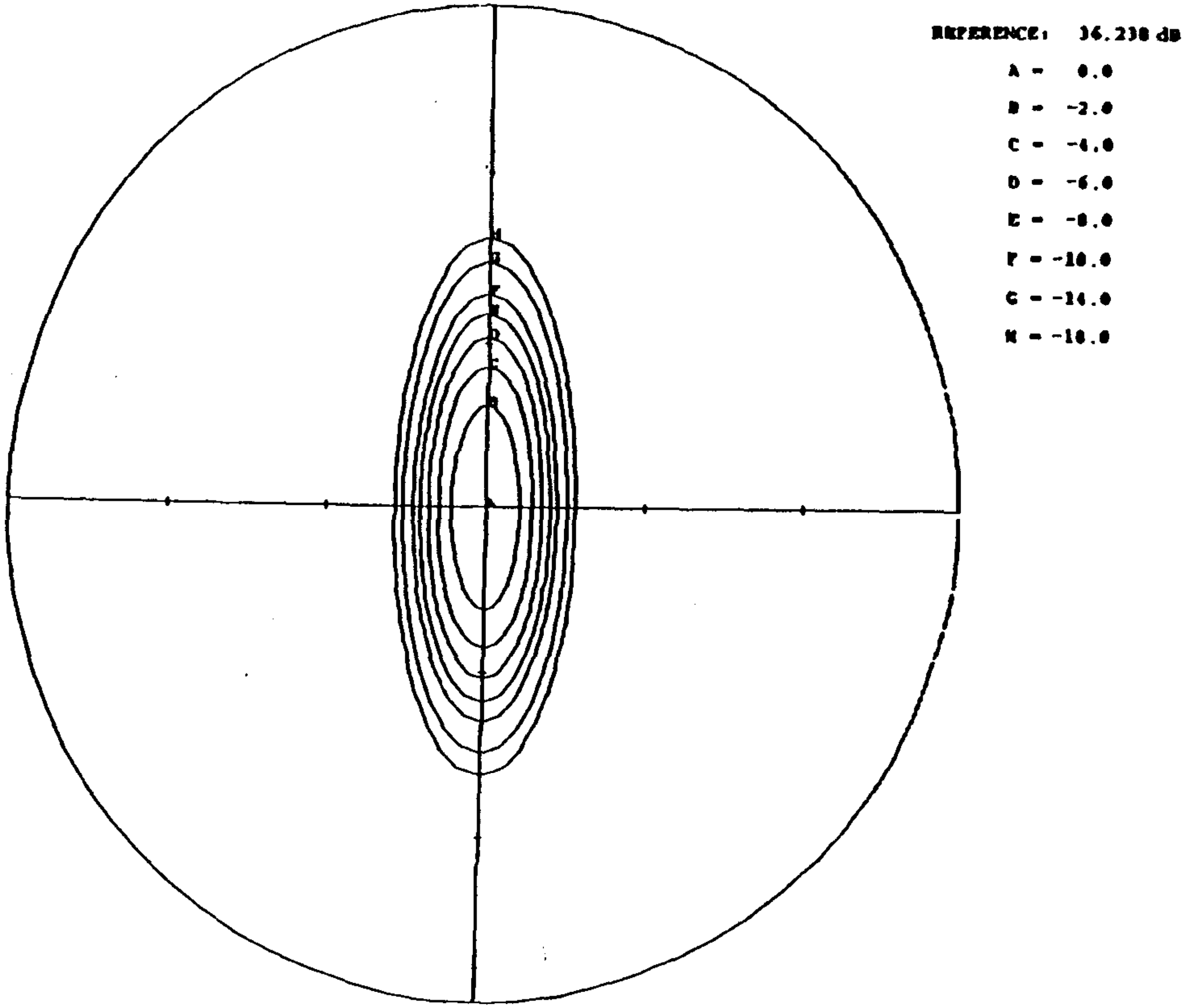

FIGURE V-17 CROSSLINK ANTENNA PATTERN

links will experience neither transmission fades nor multipath as can be seen in the link budget calculations in Appendix A. The low link margins both limit the power requirements aboard the satellites and minimize any possibility of interference originating from the satellites. Each of the four crosslinks supports 600 simultaneous circuits for an effective capacity of 1300 voice channels assuming the 2.2:1 DSI factor.

The frequency plan for these crosslinks requires the allocation of eight distinct center frequencies for crosslink communications in order to support all necessary satellite-to-satellite communications on a non-interfering basis. The burst data rate for each link is 25 Mbps and the channels are spaced at 25 MHz intervals. Each Ka-band crosslink is designed to support a bit error rate of less than 10^{-7} using rate 1/2 FEC coding.

c. <u>Gateway Links</u>

The Ka-band gateway links support simultaneous communications with two ground-based gateways (or system control facilities) per satellite. The antenna elements for the gateway subsystem are located on the nadir panel of the satellite. Satellite beam-center gains for maximum range is 18.0 dBi on the downlink and 21.5 dBi on the uplink. The transmission links are designed to function even during rainfalls that attenuate the signal by up to 13 dB in the downlink and up to 26 dB in the uplink. Multiple antennas separated by up to 34 nautical miles provide spatial diversity which avoids sun interference and helps mitigate rain attenuation. This provides link availability of 99.8% for gateways. Figures V-18 to V-27 depict the satellite to gateway downlink antenna gain contours. Figure V-28 depicts the gateway to satellite uplink antenna gain contour. Tables A-6 and A-7 in Appendix A give the peak antenna gains and specific link analyses for the gateway link.

Each of the two full-duplex gateway links supports 600 simultaneous circuits for an effective capacity of 1300 voice channels assuming the 2.2:1 DSI factor. The frequency plan requires the allocation of six distinct center frequencies each for uplink and downlink gateway links. The modulation rate in each direction is 12.5 Mbps and the channels are spaced at 15 MHz intervals. Each link is designed to support a bit error rate of less than 10^{-7} using 1/2 rate FEC.

5. Transmission Characteristics

a. Provision of RDSS and Other Services

The IRIDIUM system has been designed to provide RDSS plus voice and data services using digital transmission in a combined time and frequency division multiplexing scheme. RDSS is accomplished by performing an electronic calculation of the stationary position of the ISU relative to a satellite orbit. Given these results and a description of the satellite orbit, the position of the ISU can be determined to within one mile. Accuracy can be improved with time. The ISU measures the arrival

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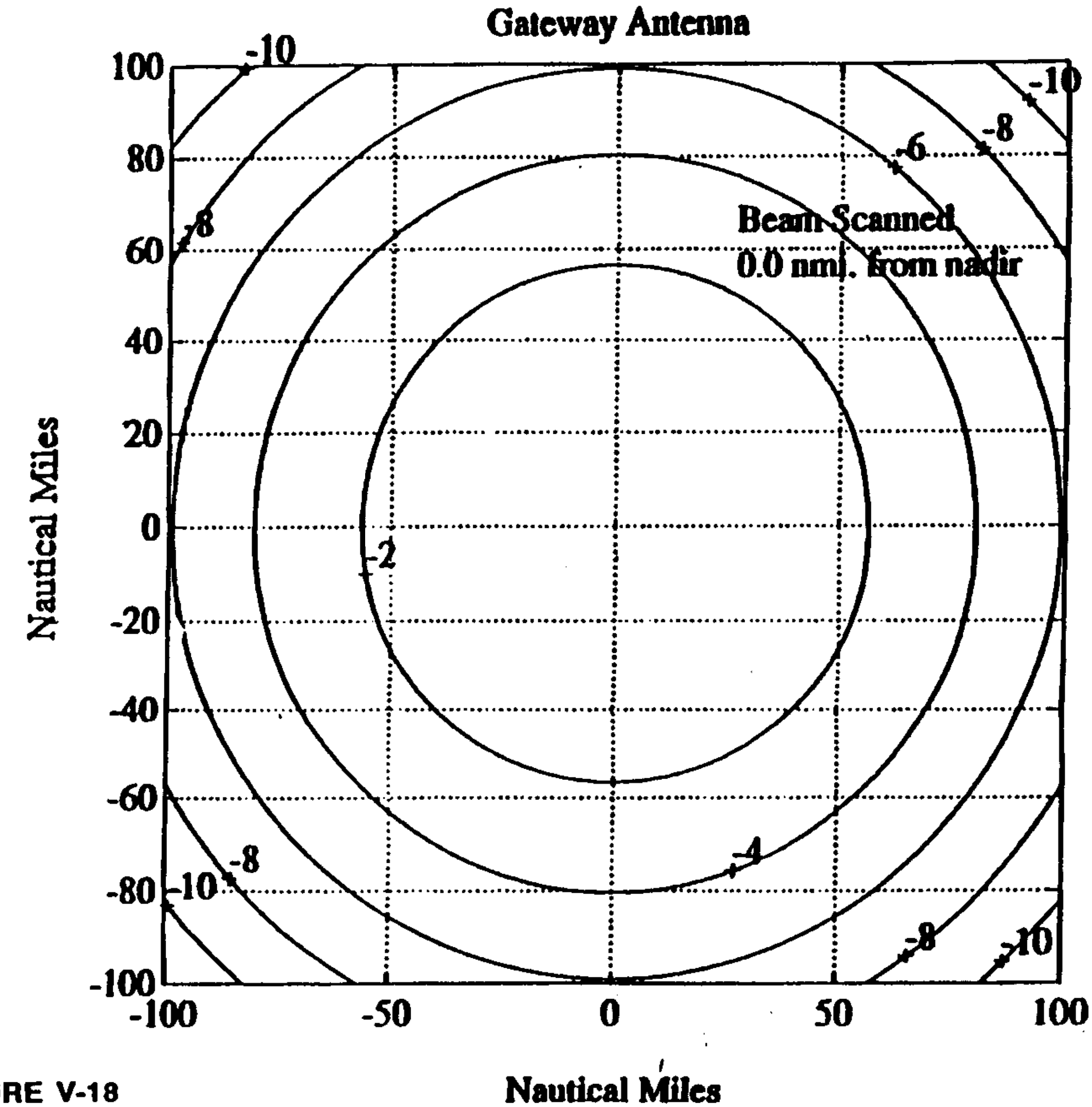

FIGURE V-18

SATELLITE GATEWAY DOWNLINK ANTENNA PATTERN - O NMI FROM NADIR

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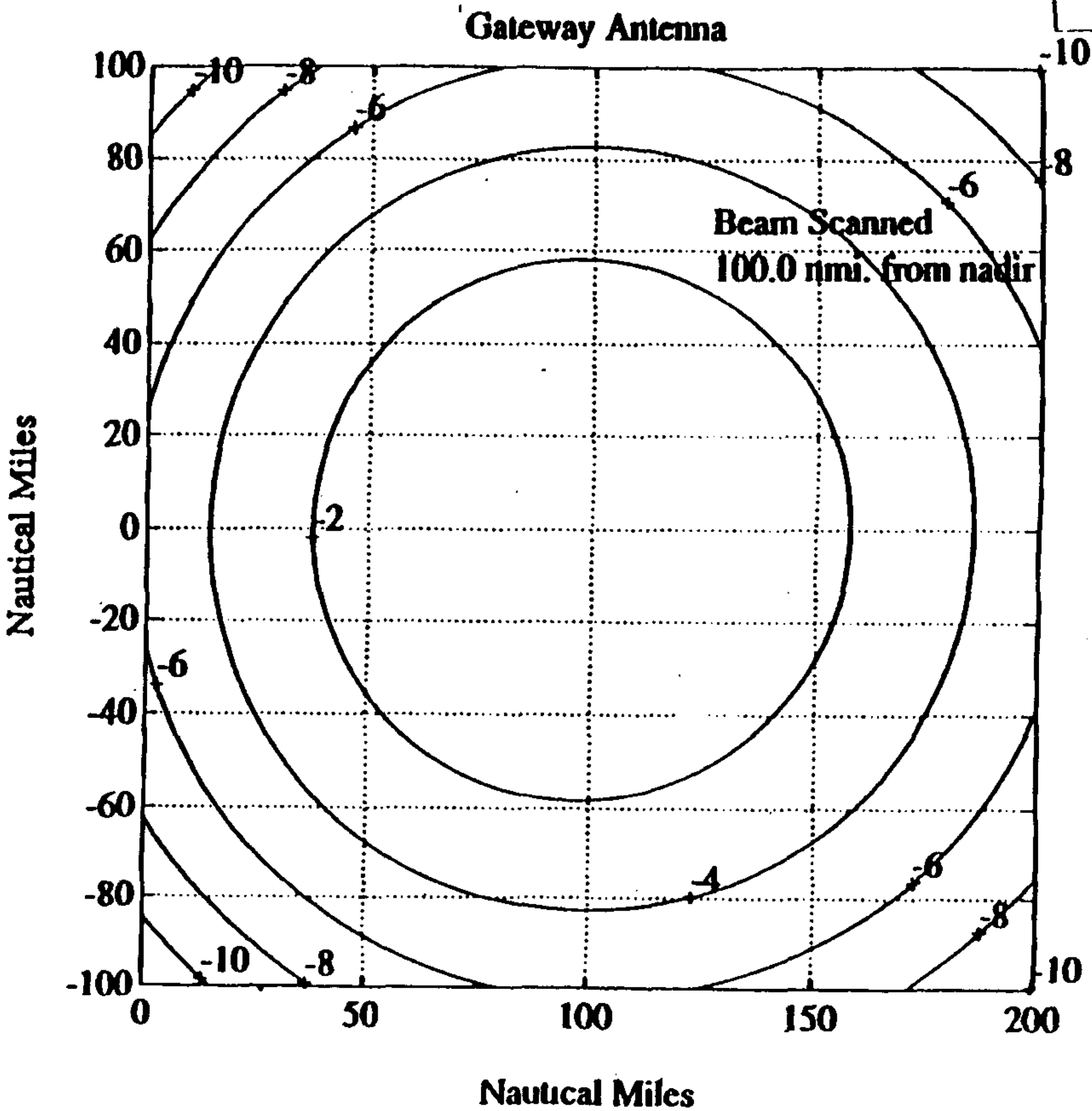

FIGURE V-19

SATELLITE GATEWAY DOWNLINK ANTENNA PATTERN- 100 NMI FROM NADIR

Motorola

IRIDIUM

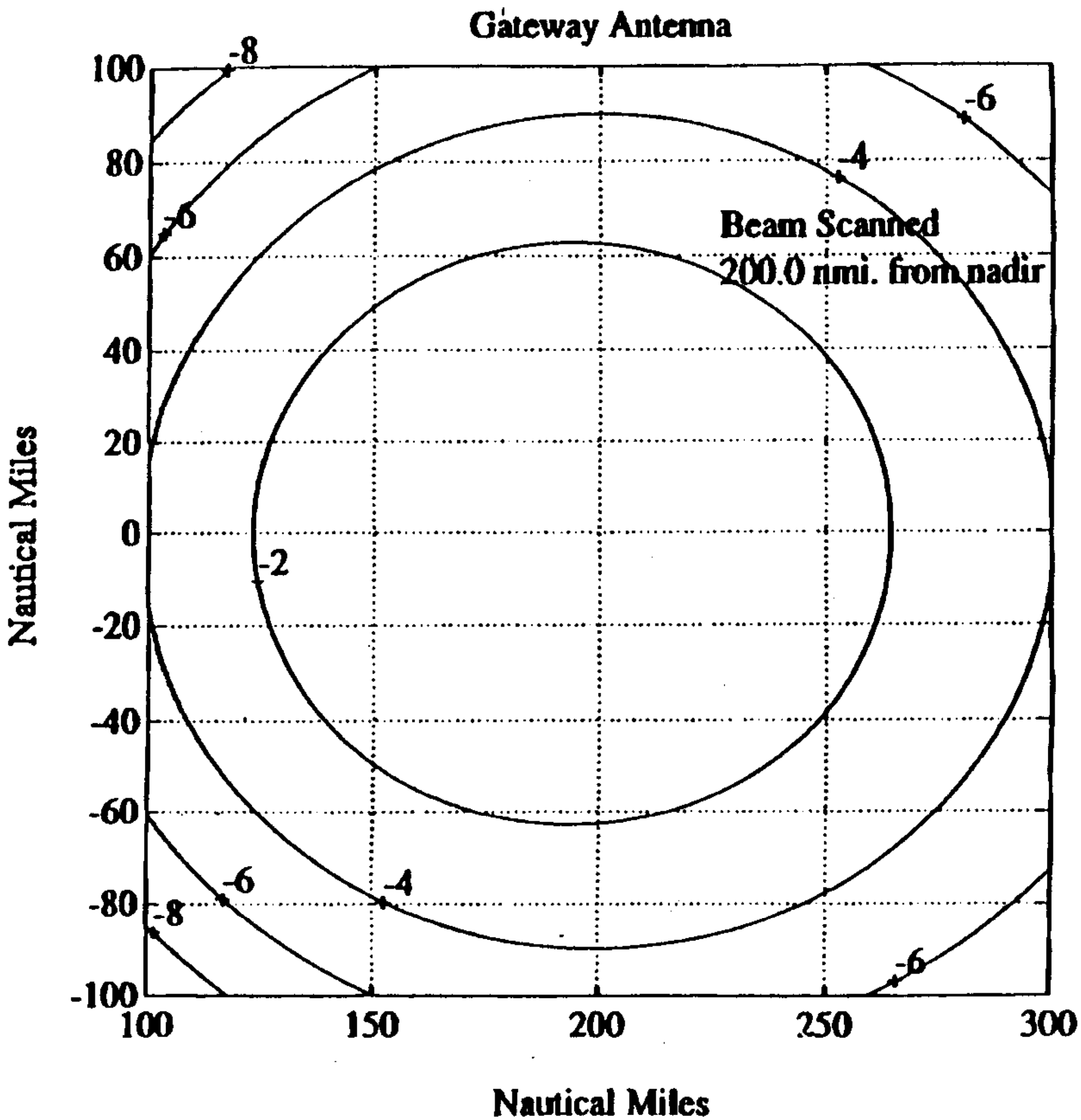

FIGURE V-20

SATELLITE GATEWAY DOWNLINK ANTENNA PATTERN- 200 NMI FROM NADIR

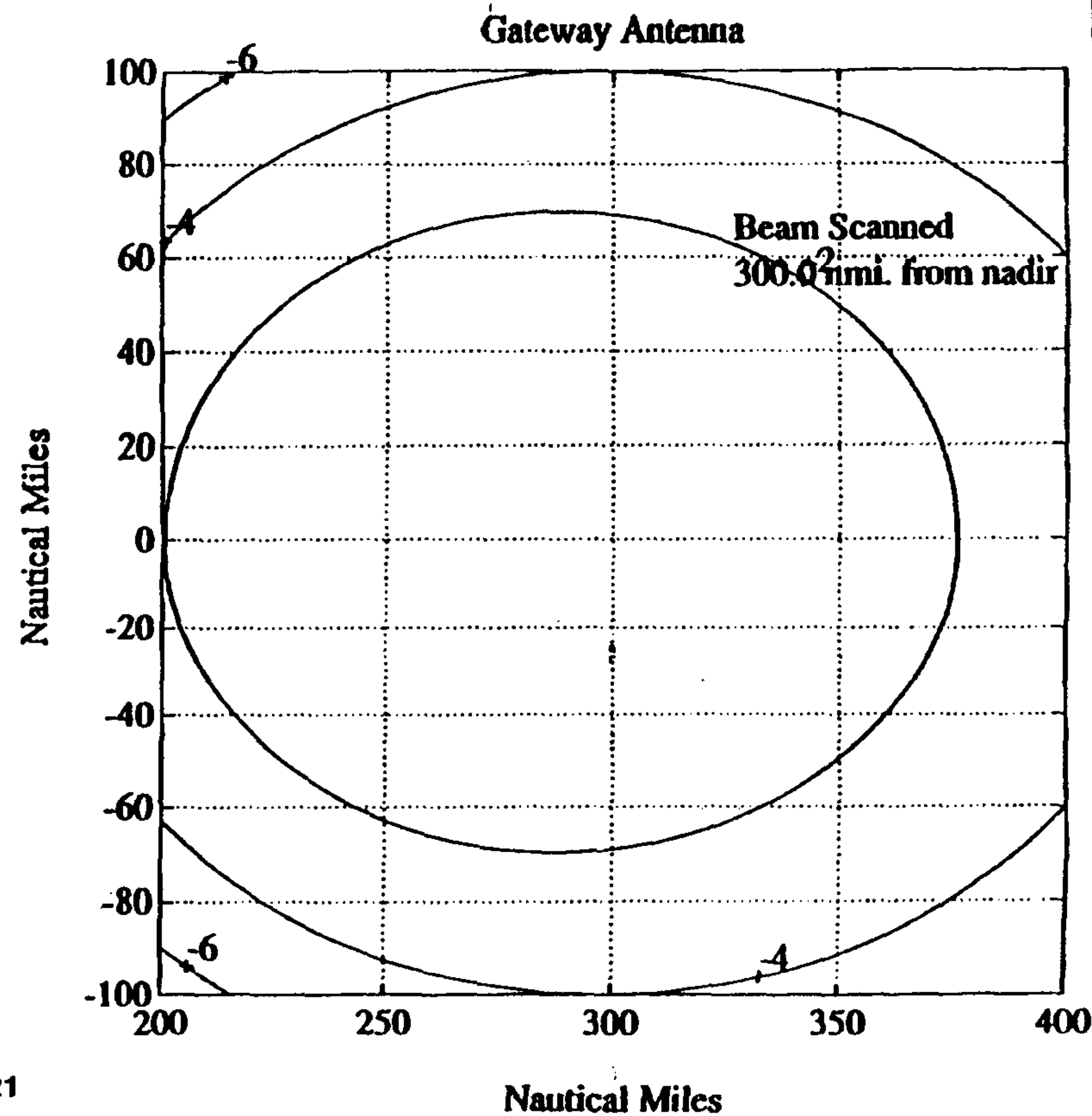

FIGURE V-21

SATELLITE GATEWAY DOWNLINK ANTENNA PATTERN- 300 NMI FROM NADIR

MOTOROLA

IRIDIUM

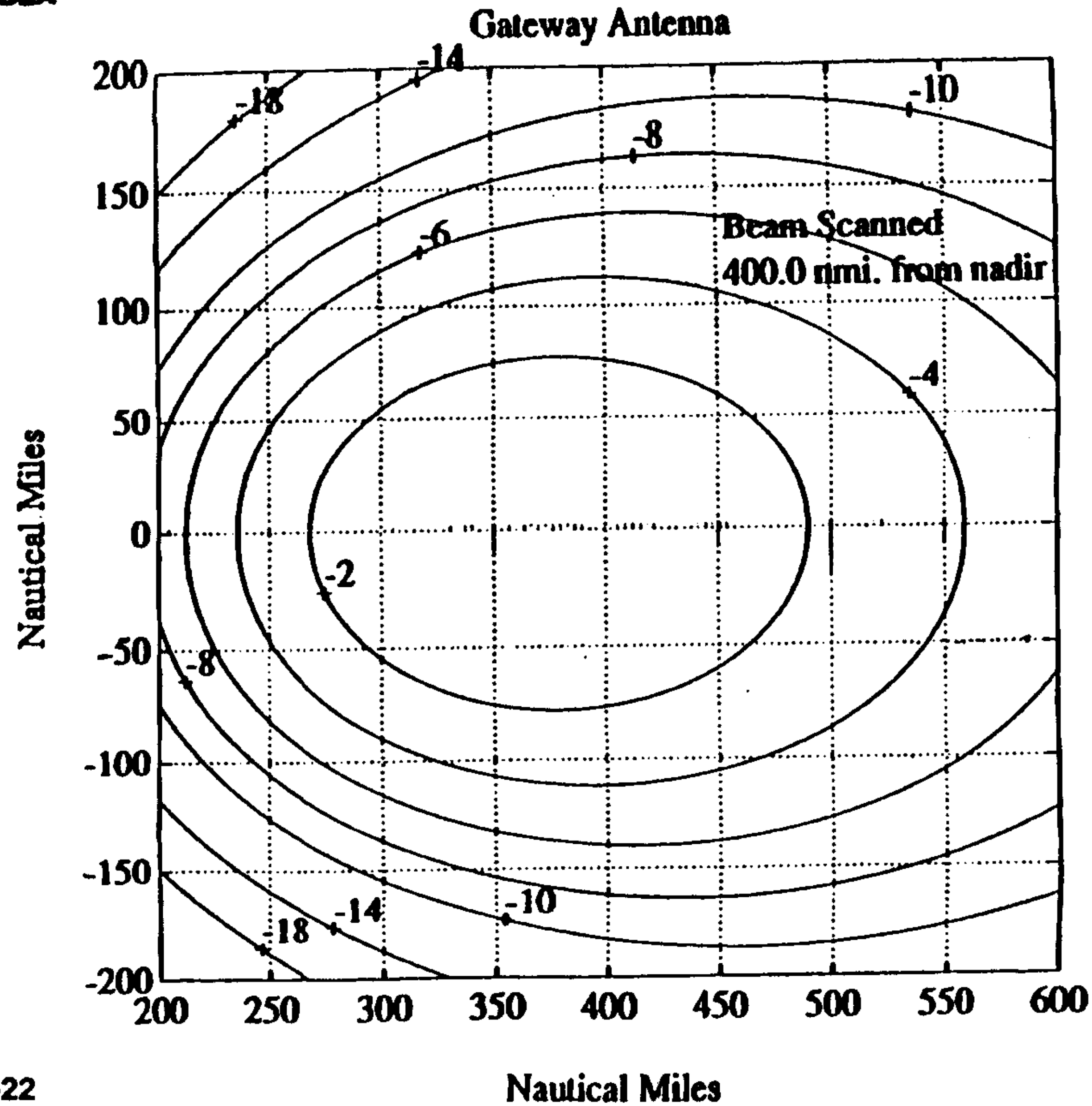

FIGURE V-22

SATELLITE GATEWAY DOWNLINK ANTENNA PATTERN - 400 NMI FROM NADIR

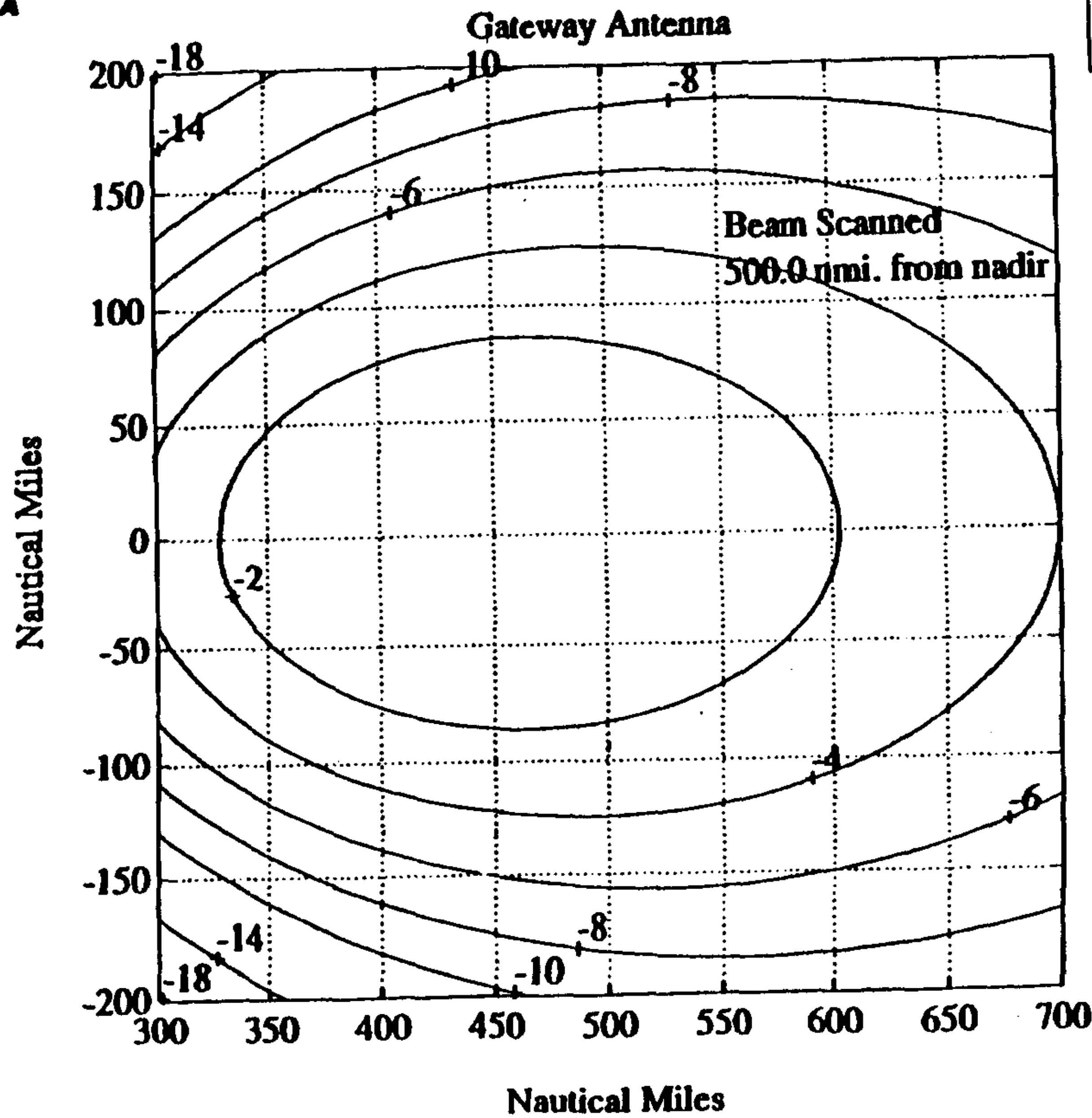

FIGURE V-23

SATELLITE GATEWAY DOWNLINK ANTENNA PATTERN- 500 NMI FROM NADIR

MOTOROLA

IRIDIUM

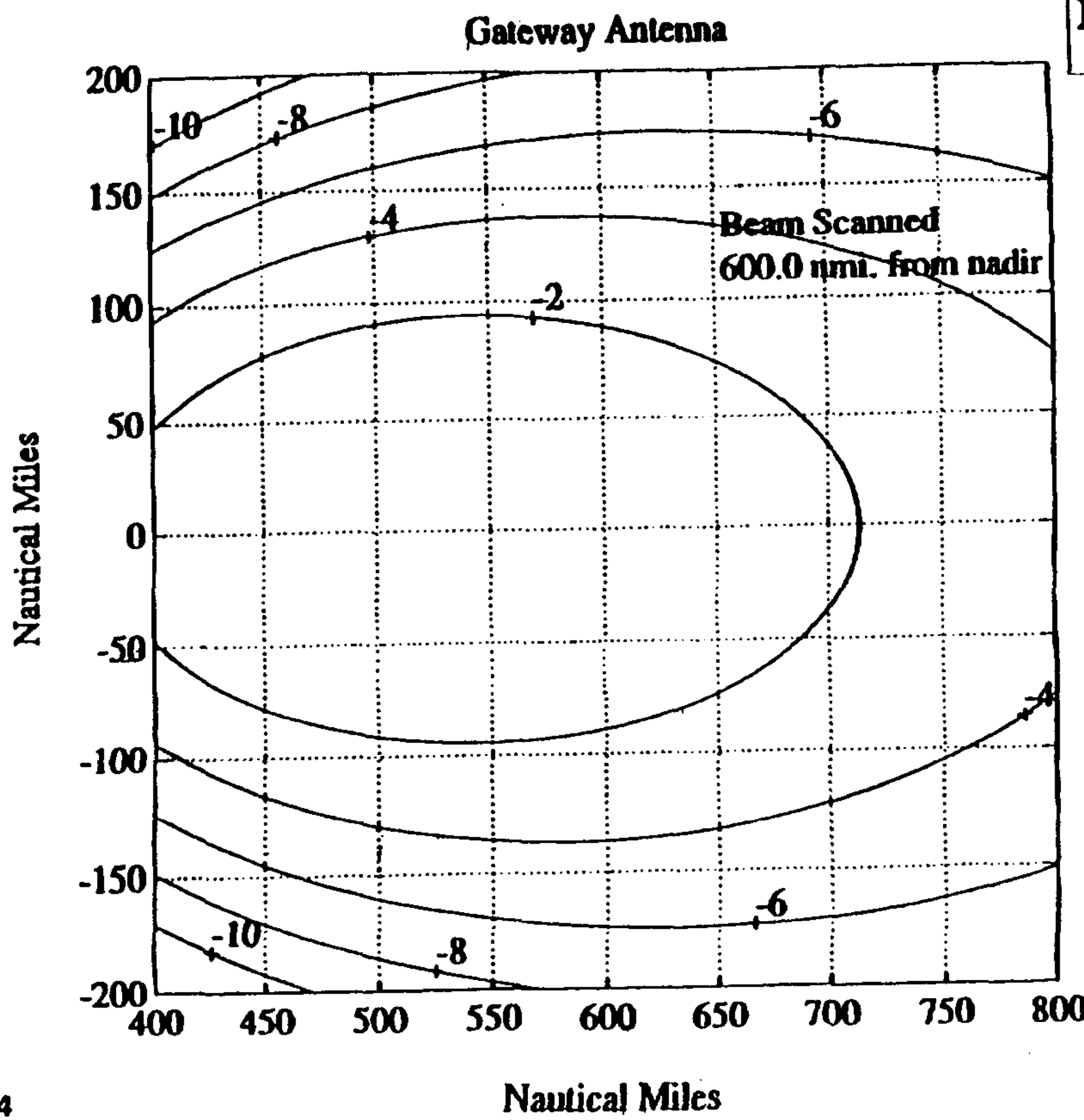

FIGURE V-24

SATELLITE GATEWAY DOWNLINK ANTENNA PATTERN - 600 NMI FROM NADIR

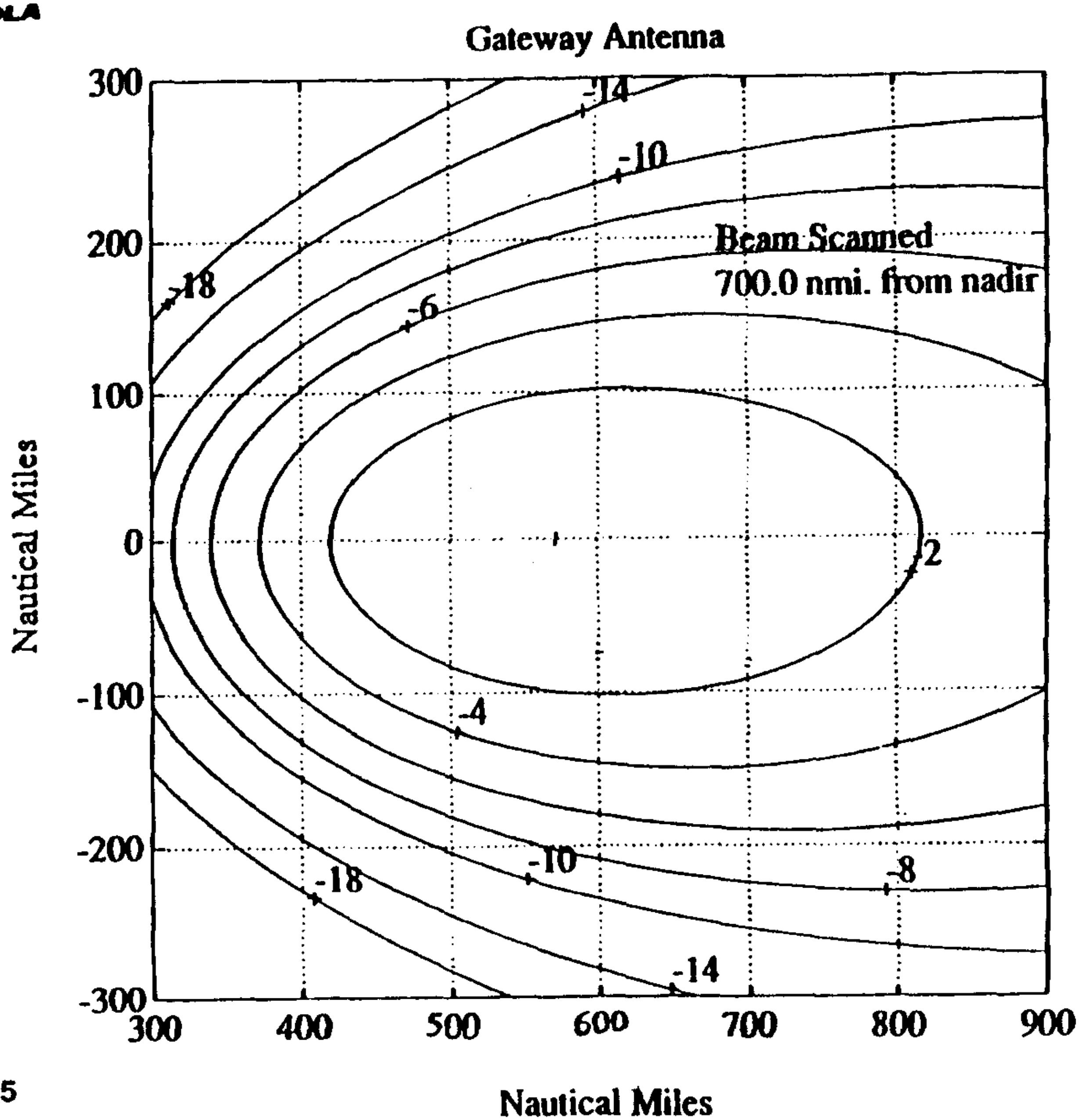

FIGURE V-25

SATELLITE GATEWAY DOWNLINK ANTENNA PATTERN- 700 NMI FROM NADIR

MOTOROLA

IRIDIUM

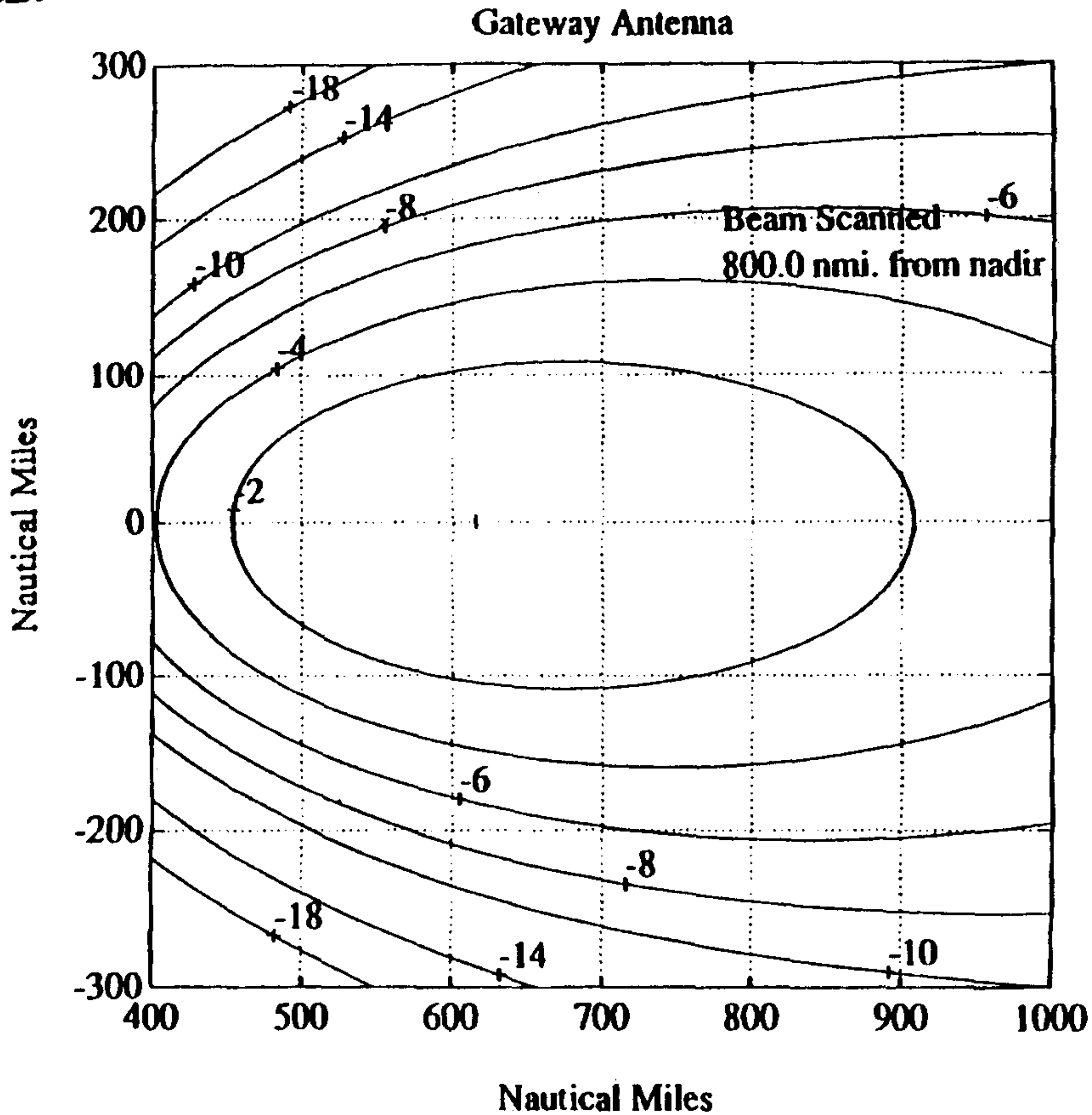

FIGURE V-26

SATELLITE GATEWAY DOWNLINK ANTENNA PATTERN - 800 NMI FROM NADIR

MOTOROLA

IRIDIUM

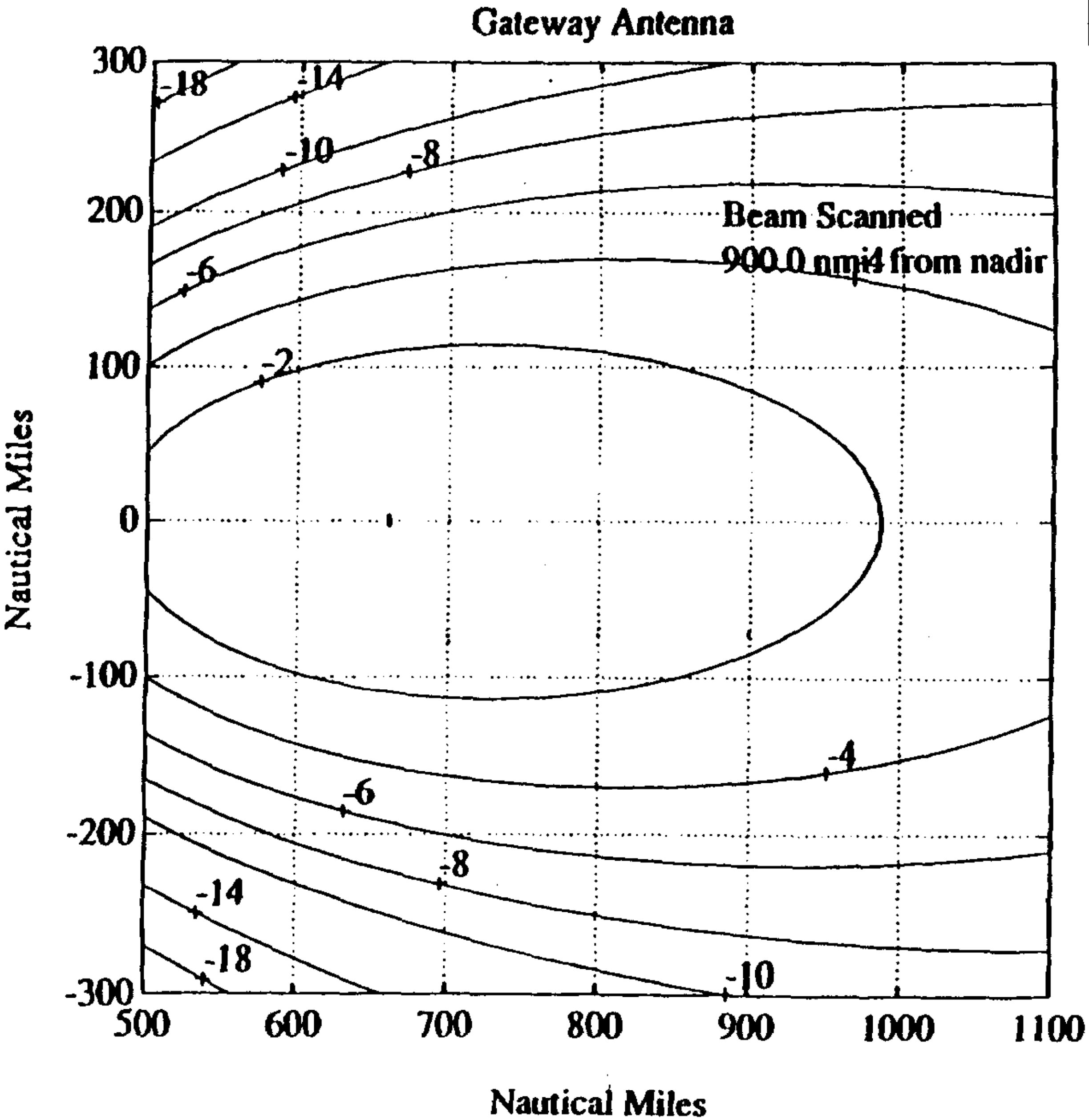

FIGURE V-27

SATELLITE GATEWAY DOWNLINK ANTENNA PATTERN - 900 NMi FROM NADIR

MOTOROLA

IRIDIUM

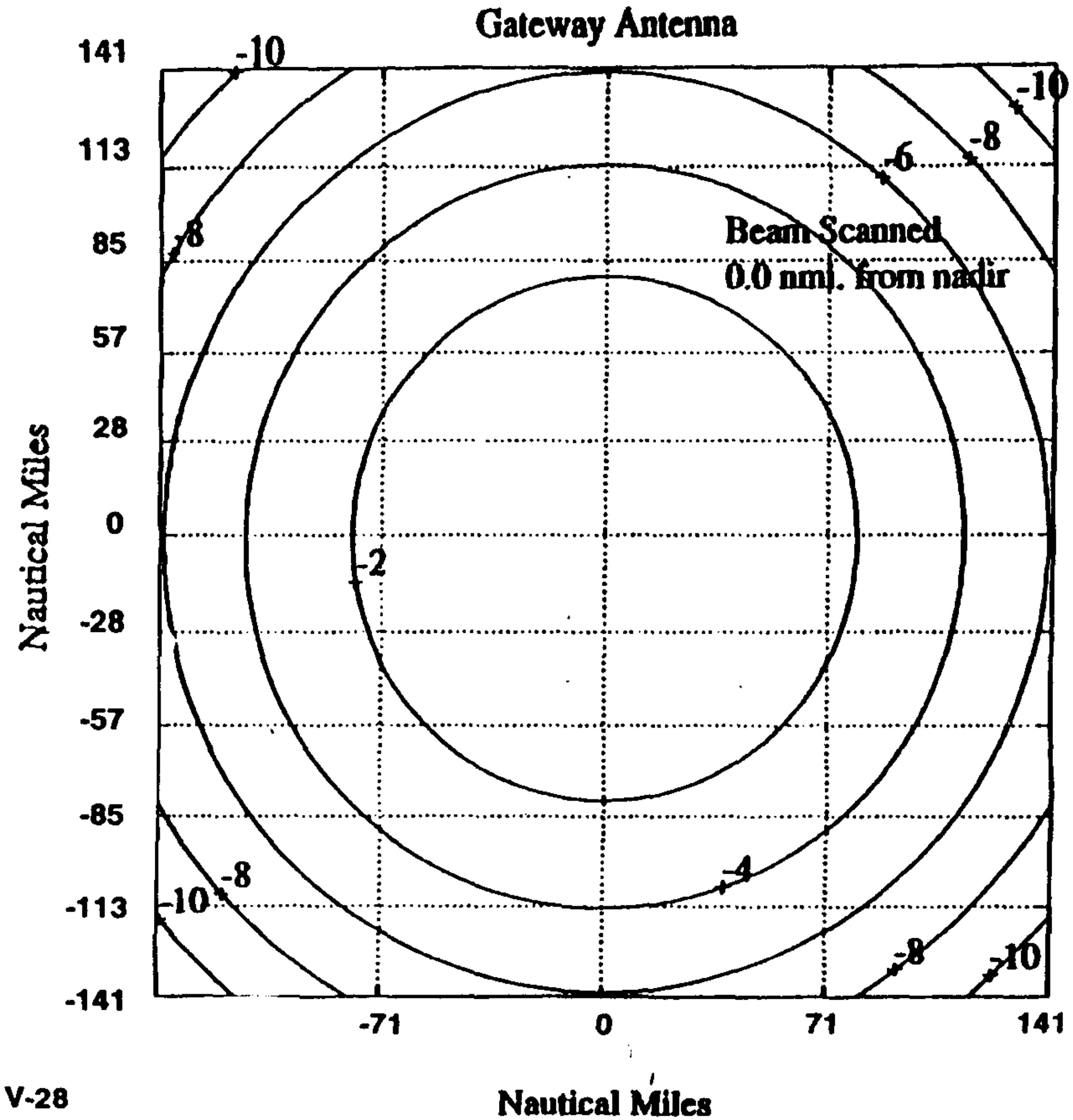

FIGURE V-28

SATELLITE GATEWAY UPLINK ANTENNA PATTERN - O NMi FROM NADIR of the start of downlink transmissions by correlation detection of the unique word which begins the event. The arrival of subsequent bursts, at once per frame are noted. The difference between actual arrival time and expected arrival time are recorded. Using these values and the ephemeris parameters of the orbit, the ISU computes an estimate of the distance and time from the satellite to the ISU when the satellite is at Point of Closest Approach ("POCA"). In an iterative process, a difference equation is solved and an estimate of pseudo range produced. Worst case, the technique will require a few minutes of passive listening to provide an answer.

Voice is provided by the transmission of the output of a VSELP 4800 BPS voice coder. Processing by this type of voice coder produces discrete blocks or packets of data at the coder framing rate. Each information packet will be protected from errors with a combination of forward error correction and error detection which increase the information bit rate of 4800 bits per second to a link transmission rate of about 8500 bits per second.

b. Modulation Characteristics

The modulation and multiple access techniques used in IRIDIUM resembles those of a terrestrial cellular system, especially the newer digital cellular systems (GSM, U.S. digital cellular, etc.). A combined frequency division and time division multiple access format is used along with data or vocoded voice and digital modulation techniques (QPSK, MSK, etc.).

Each subscriber unit operates in a burst mode using a single carrier transmission. The bursts are controlled to occur at the proper time in the TDMA frame. A typical uplink TDMA format is shown in Figure V-12. The TDMA frame has fourteen time slots. Each ISU will burst so that its transmission is received at the satellite in the proper time slot, Doppler corrected. The downlink transmission format is similar, though slightly higher in bit rate to the uplink.

This overall scheme has been chosen to maximize frequency reuse, minimize spectrum requirements, maximize the possibility of sharing spectrum, and minimize the complexity of the subscriber units, the satellites, and the gateways that interface with the terrestrial Public Switched Telephone Network ("PSTN"). Use of digital techniques also provides good communication with lower signal to noise ratios than could be achieved with analog modulation techniques. Ultimately, this permits service to be provided to more users, using less spectrum, and at lower cost.

The system will use differentially encoded, raised cosine filtered, quadrature phase shift keyed ("QPSK") modulation. This specific format has been chosen as the best compromise for the transmission channel between the satellites and the earth which may experience a combination of multipath fading and transmission impairments (shadowing) due to natural vegetation. Several competing modulation formats were considered but were not chosen because they offered no improvement and generally were more complex to implement. Raised cosine filtering of the digital signal reduces the spectral occupancy and thus permits multiple carriers to be placed close together with acceptable levels of intermodulation.

c. Performance Objectives

The IRIDIUM system is designed to provide service to virtually 100% of the earth, 99.5% of the time. However, it should be recognized that it will be economically, and at times, physically impossible to provide service to every single point on the earth. There are practical limitations to the total number of locations which will physically be within line of sight to the satellites. The end-to-end bit error rate will be better than 0.01 for voice transmissions. More typical minimum bit error rates will be between .001 and .0001.

d. Link Performance Calculations

The link budgets presented in Appendix A include the use of QPSK modulation format and sufficient bits to provide the equivalent of Rate 3/4 forward error correction.

6. Telemetry, Tracking and Control Subsystem

The Telemetry, Tracking, and Control ("TT&C") subsystem provides the functional hardware required for the reception, processing and implementation of command data, and the collection, storing, multiplexing, and transmission of satellite telemetry data. The TT&C subsystem operates with or without the simultaneous functioning of the mission communications system, and does not degrade or interfere with the mission communications operations. The spacecraft antenna arrangement and the communications hardware configuration insure that command and telemetry functions are accessible during all phases of the mission. Functional hardware redundancy will be used to ensure reliability and preclude single point failures of the TT&C subsystem. Typical functions of the TT&C subsystem are satellite attitude control, thruster control, electronic equipment redundancy switching, multiple-point system monitoring for health and status evaluation, control of system initialization and testing, and general housekeeping tasks.

When the satellite is on-station, telemetry downlink transmissions utilize the 18.8-20.2 GHz band, and telecommand uplink transmissions utilize the 27.5-30.0 GHz band. Alternatively, TT&C data may be conveyed to any gateway using the satellite crosslink network provisions. TT&C data normally are multiplexed into the wideband 20/30 GHz ground link or the crosslink transmissions during on-station operations, but during transfer orbit operations the TT&C capability is provided by transmission over independent narrowband channels at the same 20/30 GHz carrier frequencies. These narrowband channels use omnidirectional spacecraft antennas to permit direct communications with a gateway regardless of the satellite attitude. These antennas are linearly polarized. This link supports control and data communication during pre-orbit operations, de-orbit procedures, or during emergency or "lost bird" conditions where the satellite is not earth-locked.

The narrowband TT&C communication link signal margins are adequate to permit a ground station antenna of moderate beamwidth (approximately 1 degree) to receive and transmit TT&C link signals. This meets the requirements of initial acquisition and re-acquisition operations. When the narrowband transmission mode is in operation, all of the TT&C data and control signals are transmitted in digital form at a rate of 1.0 kbps each. Large signal margins and FSK modulation are used to minimize the effects of anticipated antenna pattern irregularities and grating lobes which are characteristic of the satellite omnidirectional antennas. Non-coherent modulation allows signal demodulation in the presence of the rapid phase shifts likely to occur if the satellite tumbles or spins. The TT&C satellite transmission characteristics are summarized in Table V-3.

TABLE V-3

TT&C SATELLITE TRANSMISSION CHARACTERISTICS

	On-Station Transfer Orbit (Omni Antenna)	Communications Network
Frequency/ Polarization	18.8-20.2 GHz/ Linear	18.8-20.2 GHz/ RHC (Gateway/SCS)
EIRP	9.5 dBW max.	(Uses Gateway link or Crosslink)
Modes of Operations	Sequential data, Selected data	Sequential data, Selected data
Modulation	FSK	QPSK
Data Rate	1 kbps	12.5/25 mbps (total Gateway link/Crosslink data rate)

The command subsystem is designed to maintain positive control of the spacecraft during all mission phases. It provides reliable control during launching maneuvers and for all satellite operating attitudes. It also maintains the orbital velocity of the satellite and controls housekeeping functions and communications subsystem configurations. The command messages are encrypted and authenticated to provide security, protecting the satellite control subsystem against unauthorized access.

The command transmissions received from the ground are demodulated into a digital bit stream. When the satellites receive and decode a valid command from the TT&C earth control station, the spacecraft command subsystem generates a digital command verification message which is transmitted back to the ground. The spacecraft command subsystem then executes the command in response to a subsequent verification transmission, and executes the command. Some of the attributes of the command uplink are summarized in Table V-4.

TABLE V-4

COMMAND SIGNAL CHARACTERISTICS

	Transfer Orbit	On-Station
Frequency	27.5-30 GHz	27.5-30 GHz
Ant. Polarization	Linear	RCP
Modulation	FSK	QPSK
Receive Flux Density	-60 dBW/m2 max.	(Uses Gateway link or Cross-link)
Data Rate	1 kbps	12.5 mbps (total uplink data rate)

7. Autonomous Navigation and Control Subsystem

IRIDIUM's Autonomous Navigation and Control Subsystem ("ANAC") is configured as a three axis bias momentum system. Primary attitude control of the satellite is achieved by the gyroscopic effects of a single Pitch Axis momentum wheel. The design uses the momentum of a high speed, single degree of freedom wheel to provide inherent attitude stability. Magnetic torquing and wheel speed control will be utilized for attitude error correction. The primary sensors will be a pair of Barnes Engineering Dual Cone Scanners implemented for the MANS (Microcosm Autonomous Navigation System) to provide infrared sensing of the earth and visible sensing of the Moon and Sun.

The system will be fully autonomous with ground control backup capability after the satellite is placed in its final orbit and initially attitude stabilized. The inherent gyroscopic stability of the wheel provides stable attitude control and reliable reacquisition in the event of a sensor failure or control anomaly. Figure V-29 is a representative block diagram of the system.

The ANAC System is utilized during the parking orbit and final mission orbit, and performs the following functions:

Parking Orbit: Determines altitude and position. The momentum wheel, torquers and small thrusters are used to establish and maintain three-axis stability during the parking orbit. Satellite position is reported via telemetry to the ground control.

Mission Orbit: Maintains control during deployment and mission operation. Stationkeeping can be performed autonomously or in conjunction with ground commands.

The Momentum Wheel Assembly provides gyroscopic stability of the wheel axis which is aligned to the satellite Pitch axis in inertial space. Control of the Pitch Axis to

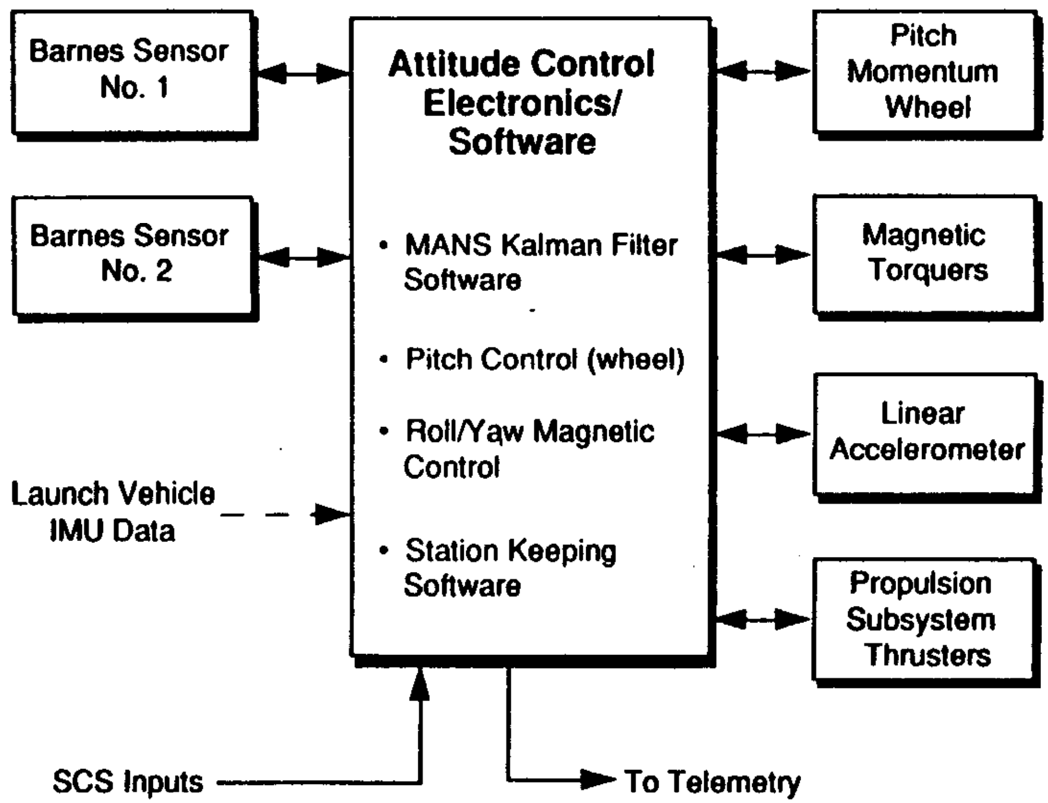

FIGURE V-29 ATTITUDE CONTROL SYSTEM

maintain nadir pointing is achieved by wheel speed control to exchange momentum with the satellite. Roll and yaw errors are both controlled utilizing magnetic torquing. Wheel speed commands and magnetic torquing currents are developed in response to error signals developed by the MANS Kalmann filter. The Barnes sensor utilizes earth, sun, and moon sensing to develop the required error signals. Torquing results from the interaction between the magnetic fields of the coils and the earth's magnetic field. Both roll and yaw errors are corrected in response to a roll error signal.

MANS employs a modified existing space qualified scanning sensor to obtain altitude, roll, and pitch using infrared detection of the earth. The same sensor obtains yaw and orbit parameters using visible light detection of the azimuth and elevation of the sun and moon. Two sensors are utilized to obtain enhanced accuracy plus provide sensor redundancy. Using this approach, fully autonomous navigation and attitude are provided independent of any external resources. A Rubidium clock is also required as part of the system to provide an accurate time reference. Position, attitude, and rates are available at 250 msec intervals and provide the following attitude and position knowledge accuracy:

- Attitude accuracy: +/- 0.5 degrees
- Position accuracy: +/- 20 kilometers

The system stationkeeping mode also utilizes an autonomous approach using an absolute stationkeeping method wherein each satellite is maintained within a prescribed "box" with position within the box determined by the MANS system. This approach requires minimal commanding. The positions of all the other satellites are known without extensive data transmission, and the system can be easily monitored from the ground as a check mode.

A low thrust hydrazine system is utilized to minimize spacecraft disturbance torques. The thrusters will always be fired in the direction of the velocity vector to ensure optimal propellant efficiency. The magnitude of the drag makeup is based on the observed drift relative to its assigned box and the required impulse computed during the ascending node of the orbit. The required command will be executed at the subsequent apogee to raise and circularize the orbit to maintain the spacecraft within the center of its designated box.

8. **Propulsion Subsystem**

The satellite uses a monopropellant hydrazine subsystem to provide all propulsive functions. This subsystem applies external torques and forces to the satellite to perform the functions of orbit insertion, orbit adjustment, maintenance, reaction control, and de-orbit. The principle components of the subsystem include propellant storage pressure vessels, catalytic thrusters, solenoid, manual, and pyrotechnically actuated valves, plumbing, and telemetry instrumentation to evaluate the in-flight performance of the subsystem.

The propulsion subsystem includes a propellant load and thrusters capable of providing the delta-velocity increment required to insert the spacecraft into the designated orbital slot and positively de-orbit the spacecraft at end-of-life. The on-orbit functions of the subsystem include, altitude, mean longitude, and orbit inclination maintenance for the duration of the operational life. The on-orbit propellant load has been sized to provide a 60% consumable reserve for on-orbit functions. Table V-5 provides a preliminary propellant budget.

The hardware implementation of the subsystem utilizes one surface tension propellant tank manifolded to redundant thrusters -- each having a series redundant propellant control valve and it's own thermal elements. Thrusters are located as to provide limited redundancy. The surface-tension device in the fuel tank ensures gas-free propellant delivery under all acceleration environments. The tank capacity provides for an 8-year mission life including the delta-velocity functions.

TABLE V-5

PRELIMINARY PROPELLANT BUDGET

Function	Propellant Mass (kg)
Orbit Insertion	17.5
Orbit Trim	2.2
Drag Makeup	3.6
EOL Decommission Maneuver	18.0
Total Propellant Mass	41.3

Each solenoid valve is controlled by a thruster I/O board which provides the interface between the propulsion subsystem and the main payload processor. A background task running on the main processor selects the proper valves and timing for whatever function is commanded from the ground or by the on-board attitude control task. The status of the subsystem and maneuver bookkeeping is monitored via telemetry. End of consumable life is detected via pressure telemetry coupled with bookkeeping information.

9. Electrical Power Subsystem

The Electrical Power Subsystem ("EPS") is depicted in simplified form in Figure V-30. The EPS provides the power to the satellite electrical loads over the expected lifetime. The bus voltage varies from 22 to 36 volts and is converted to required equipment voltages by power converters located at the loads.

The EPS is configured as a peak power tracking system with the battery always on line. The peak power trackers are adjustable and can be operated off the peak power point to reduce battery charge current when the battery reaches a full state of charge. The subsystem includes the following major elements:

- A high output photovoltaic solar array.
- Long life nickel hydrogen secondary batteries.
- Fault isolating power distribution system.

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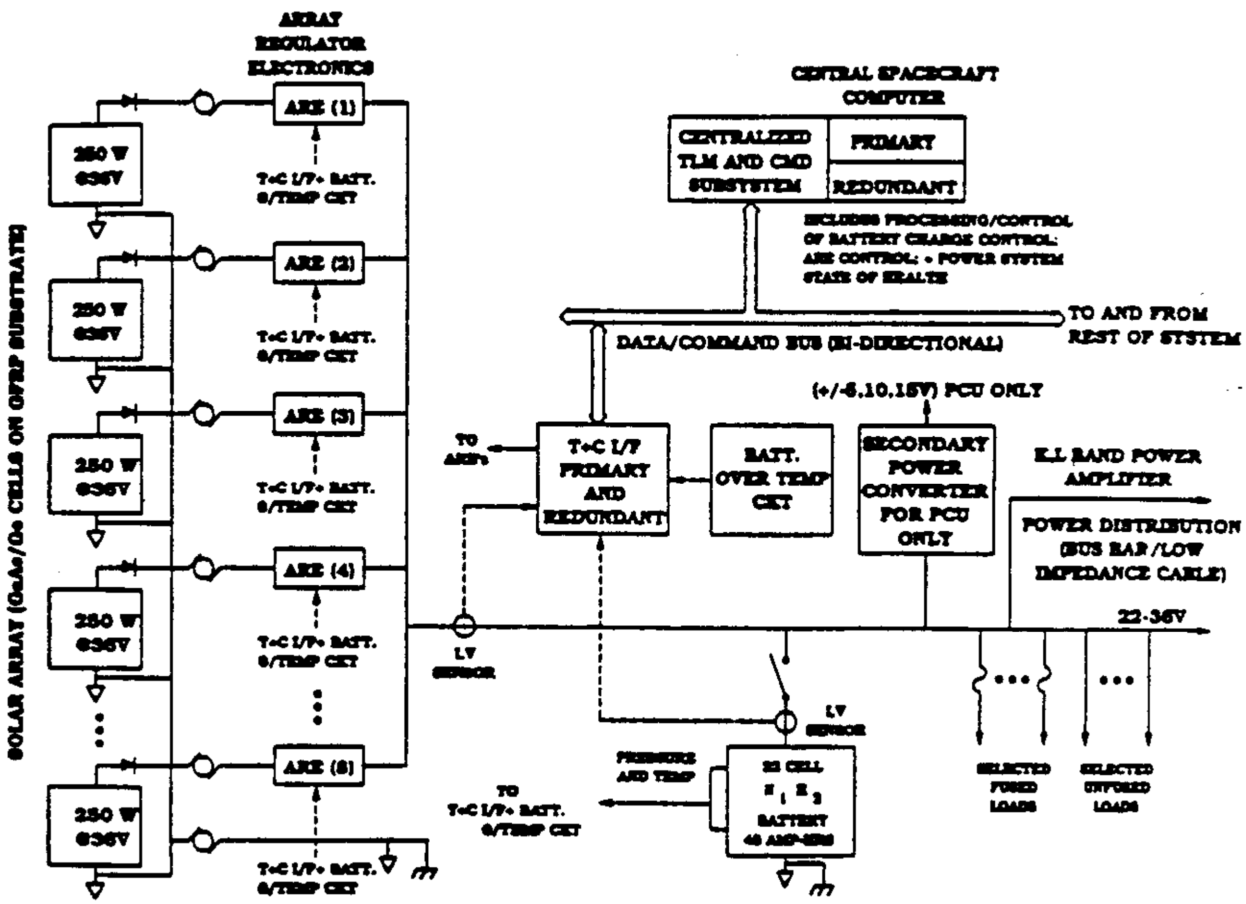

FIGURE V-30 ELECTRICAL SYSTEM BLOCK DIAGRAM

- Redundant bus regulation and battery charging controls.

The EPS contains fault protection features which automatically respond to subsystem malfunction or to excessive main bus loads. All power subsystem automatic function can be overridden in response to ground commands. Sufficient telemetry is provided to allow a comprehensive evaluation of EPS in flight performance as well as complete equipment status.

The solar array consists of 18 sun oriented planar panels with 9 panes per wing. Each wing is attached to a deployed astromast by a Graphite Fiber Reinforced Plastic ("GFRP") boom. During transfer orbit, the panels are folded and stowed by a single wrap around cable against the spacecraft body. During this time, the outermost panels are periodically illuminated by the sun and will aid in providing power to housekeeping loads. When the spacecraft reaches its operation orbit, the array is deployed and full power will be available.

The following mechanisms are used to deploy the solar array;

- Multipoint solar panel support during launch by restraint from a single wraparound cable.
- Cable release provided by redundant pyro activated cable cutter.
- Deployment sequenced using simple thermo motorized hinges.

Stepper motor drives are used for sun tracking. Two seasonal drives (one/wing) and a common orbital drive provides rotation of both wings about the deployed mast. Power from the rotating array is transferred to the main bus by slip rings. Each wing is independently oriented by redundant stepper motors.

The design incorporates high efficiency GaAs/Ge solar cells on a lightweight GFRP substrate for minimum size and weight. Array design and sizing will meet all power requirements over the satellite mission life.

One 48 amp-hour nickel hydrogen battery will comprise the battery system. Battery charge current will be controlled by adjusting the peak power tracker based on amp hour integration processed within the on board computer, with temperature backup controls within the Power Control Unit. The battery consists of 22 cells allowing for a single cell failure.

The batteries are trickle charged at a constant c/100 rate when they reach approximately 97% state of charge (actual capacity). Recharge rate occurs at a level of c/1.2 to c/1.8 in the peak power tracking mode from eclipse exit until switch to trickle charge. The battery system will be sized to provide all housekeeping loads during eclipse plus some capability for communications.

Table V-6 sets forth the electrical power budget and indicates EOL power capabilities:

TABLE V-6

POWER BUDGET

SUBSYSTEM	EOL(5 yrs,avg pwr)
Communications	
Electronics	433
K band pwr amp(PA)	21
L band pwr amp(PA)	232 (battery supplied)
Attitude Control	50
Telemetry, Tracking, and Cmd	20
Electrical power and Distrib	75
Thermal Control	20
Battery Charge	750
TOTAL LOAD	1369 (excluding L band PA)
Panel Capability	1429 watts
Margin (%)	60 watts (4%)

10. **Satellite Physical Description**

Motorola will evaluate a variety of satellite designs before selecting a final design. It will be necessary to retain the flexibility to choose a final design based on technical capability and negotiations with potential suppliers. The baseline design was developed by Motorola in conjunction with consulting satellite engineers; however, Motorola reserves the right to substitute an equivalent design at a later date if so warranted. Motorola will, of course, keep the Commission informed of its final choice in satellite design and characteristics.

The satellite will be three-axis stabilized. Figure V-31 is an illustration of its design, and Figure V-32 is a diagram of major bus subsystems.

The satellite structure will be capable of supporting the mass, volume, and heat dissipation requirements of the satellite. The structure itself will be capable of providing the required support and rigidity during all phases of launch, transfer and orbit insertion. The structure is a hexagonal tube of aluminum honeycomb panels supporting horizontal aluminum honeycomb shelves at both ends. Aluminum honeycomb stiffening ribs positioned vertically along the full length of the tube at three of the six corners support an internally mounted propellant tank. On one end of the hexagonal tube is the Zenith panel which supports two-axis articulating solar arrays on an extendable mast. The Nadir panel, on the opposite end, supports Ka-band crosslink and gateway antennas and a single L-band subscriber antenna. The remaining six subscriber antennas cover the side of the hexagonal panels. Bus, processor, and communication electronics are located on the inside of the hexagonal tube.

The structure has the following features:

- Simple structure assembly
- Interchangeable subassemblies
- Modular assembly of all subassemblies
- Low structure weight
- Grounded subassemblies to avoid space charging effects.

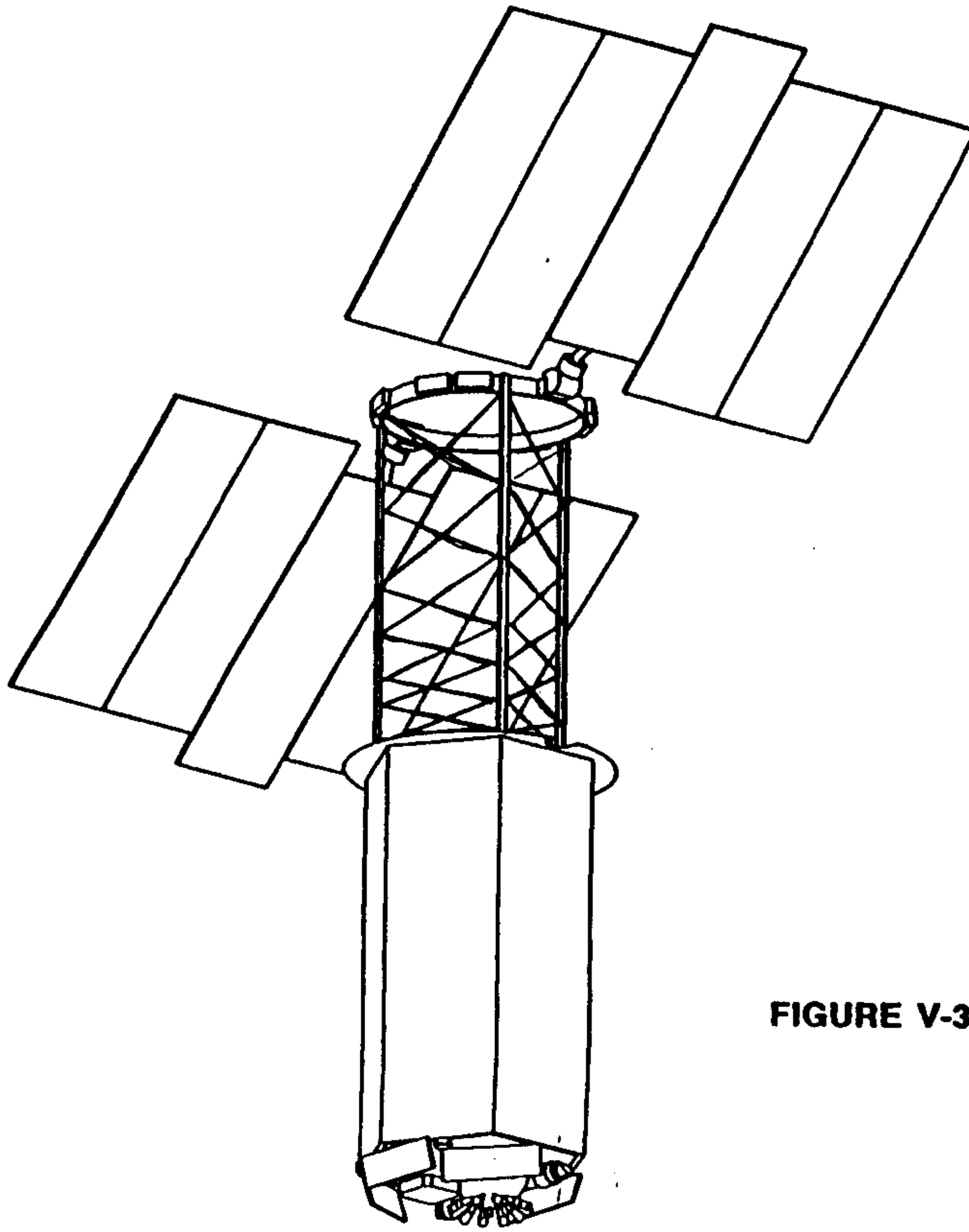

FIGURE V-31 SATELLITE DESIGN

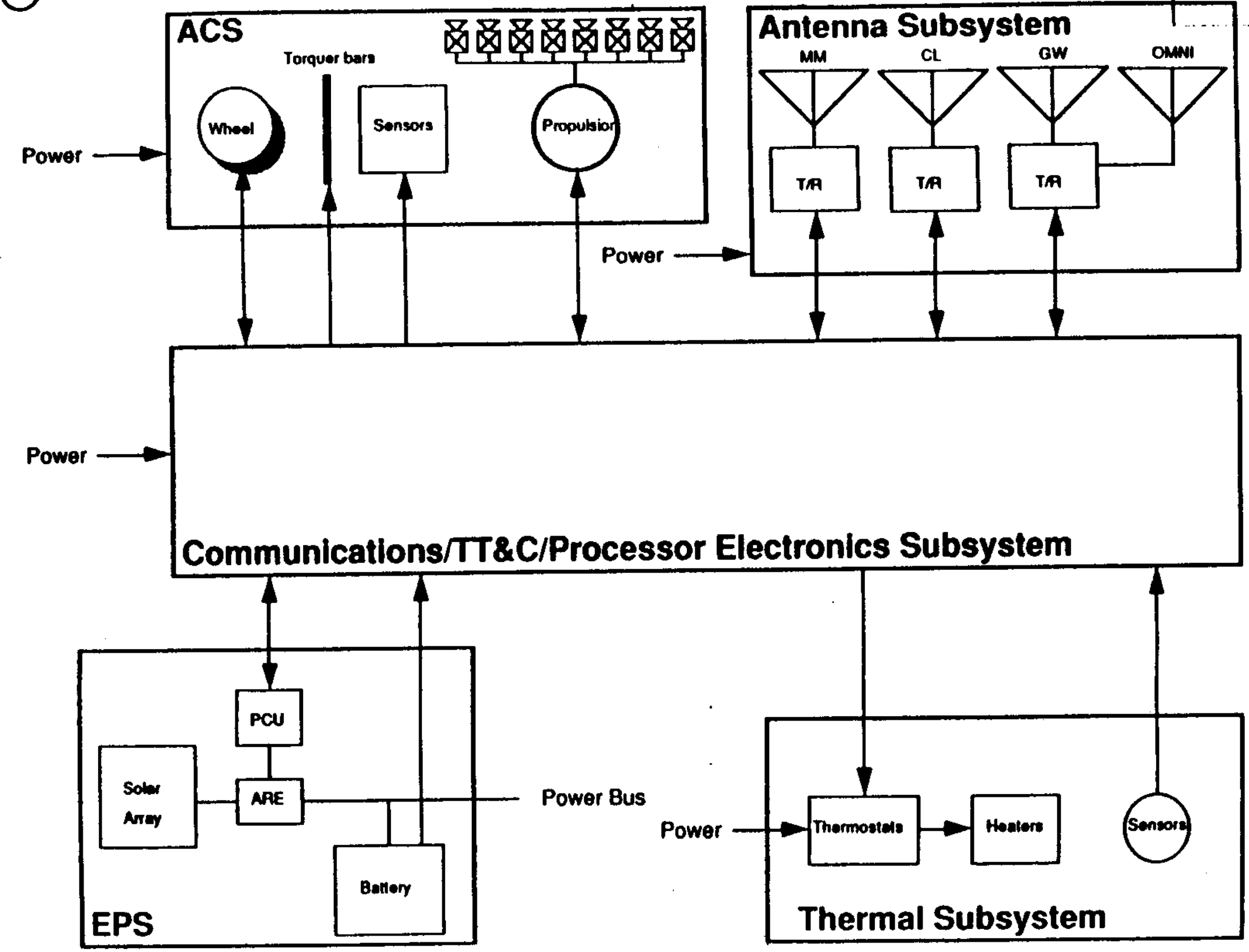

FIGURE V-32 SATELLITE BLOCK DIAGRAM

The structure will be compatible with the volume, thermal, acoustic, and vibration constraints of a variety of commercial launch vehicles, including Delta, Atlas, and Pegasus.

The Thermal Control Subsystem maintains the temperature of the spacecraft and its components within a safe operation range under the simultaneous effects of the external space environment and component thermal dissipation during the entire mission. The major elements of this system are:

- Surface finish coatings
- Thermal insulation blankets
- Thermal conducting materials
- Makeup heaters
- Temperature sensors and thermal control processing
- Heat pipes

Temperature control is performed by using passive design techniques, heat pipes, and heater augmentation. The passive surface finish, insulation, and heat pipe elements compensate for the seasonal and orbital variations in solar flux, while the heaters compensate for internal dissipation due to the variation in number of users over different areas of coverage and the state of the electrical power subsystem during eclipse and sunlight operations.

The spacecraft mass budget is as shown in Table V-7.

TABLE V-7

SPACECRAFT MASS BUDGET

Subsystem	Mass (kg)
Structure Thermal Control Subsystem Propulsion (Dry) GN&C Subsystem Electrical Power Subsystem Antenna Subsystem Communication Electronics Subsystem	24.9 12.1 8.6 9.8 78.9 83.3 81.8
Spacecraft Mass (Dry)	299.4
Consumables	41.3
Spacecraft Mass (Wet)	340.7
Spacecraft Reserve Mass	45.5
Spacecraft Wet Mass with Reserve	386.2

11. <u>Operational Lifetime and Space Segment Reliability</u>

The operational lifetime of each satellite is determined by a number of factors, including solar array degradation, stationkeeping fuel consumption, and random parts failure. The following indicates the estimated lifetime of the satellites for each of these factors:

Solar array degradation - 5 years

Stationkeeping fuel - 8 years (3 sigma orbital, insertion accuracy assumed)

Random parts failure - 5 years

Redundancy will be provided on critical hardware as determined to be necessary through reliability analyses and predictions.

C. Gateway Segment

1. Overview

The Gateway Segment controls user access and provides interconnection to the terrestrial Public Switched Telephone Network ("PSTN"). There will be multiple gateways distributed throughout the world; initially two of these gateways will be sited in the continental U.S. to provide separate coverage of both the eastern and western halves of the country. Two additional sites will be located in eastern and western Canada to provide coverage for that country as well as Alaska.[37]

Each Gateway contains an Earth Terminal and Switching Equipment necessary to support IRIDIUM's Mission Operations.

2. Earth Terminal

The key Earth Terminal parameters are summarized in Table V-8. Each earth gateway terminal contains three RF front-ends supporting continuous operations with extremely high reliability. One RF front-end is used to establish uplink and downlink communication with the "active" satellite while another

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[37] When these exact locations are identified, separate gateway applications will be filed.

is used to establish communication with the next "active" satellite. A third RF front-end provides backup capability in case of equipment failure and also provides geographic diversity against unusual sun or atmospheric conditions that would degrade service. Each RF-front-end consists of a Ka-band antenna, receiver, transmitter, demodulator, modulator, and TDMA buffers.

TABLE V-8

GATEWAY EARTH TERMINAL SUMMARY

Data Rate	12.5 Mbps
Error Correction Coding	Convolutional, Rate=1/2, K=7
Modulation	QPSK
Frequency Bands: Transmit Receive	27.5-30.0 GHz (Uplink) 18.8-20.2 GHz (Downlink)
Ground Tracking Antenna Diameter	 3.5 Meters
Gain	54.0 dB @ 20 GHz 57.5 dB @ 30 GHz
Maximum Sidelobe Level	20 dB below main beam peak
3 dB Beamwidth	0.36 Degrees @ 20 GHz 0.24 Degrees @ 30 GHz
Pointing Angle Range	360 Degrees Azimuth +5 to 90 Degrees Elevation
Ground Acquisition Antenna	Passive Array, Configuration TBA
Transmitter EIRP Clear Weather Heavy Rain	 51.4 dBW (+/- 3 dB) to 77.4 dBW Max. (+/- 3dB)
Receiver G/T	23.2 dBi
Minimum Eb/No	6.9 dB @ BER-10^{-6}

Since the orbiting satellites are in motion relative to the gateways, both primary antennas follow the track of the nearest two satellites. The communication payload being conveyed across the "active" link must be handed off periodically, from the current satellite to the next one as the active link disappears from view. This handoff process will be transparent to both IRIDIUM and PSTN users involved in active calls.

Each RF front-end is controlled by an earth terminal processor, which provides antenna pointing commands based on ephemeris data provided by the System Control Segment ("SCS"). In addition, this processor provides status and performance data to the SCS so that the gateway operations within acceptable limits can be verified. The SCS will be able to direct specific gateway hardware to be tested, diagnosed, and reconfigured as necessary. In addition, the SCS can direct the gateways to reduce or terminate their access to the IRIDIUM network or the PSTN when continued operations would result in possible harm to either one.

The RF front end High Power Amplifier power output will be controlled to compensate for atmospheric attenuation (such as rain). Received signal strength will be monitored and used to obtain information on atmospheric attenuation. The received electric field intensity at the satellite will be maintained at a constant level that is within 6 dB of the minimum required to maintain a 10^{-6} bit error rate. The vast majority of the time, this will imply that the RF front end EIRP will be within 3 dB of nominal.

Communication with the SCS will normally be achieved by using up to 1 Mb/s data rate to the "active" satellite; the information is transported by the IRIDIUM Ka-band network between each satellite and the "active" satellite serving the SCS. To insure that essential information flow is not disrupted in the face of Ka-band network anomalies, backup terrestrial communication channels conforming to CCITT V and X Series Recommendations will also be provided between the gateways and the SCS.

To provide a reliable backup method of monitoring and controlling satellite operations, the gateways will transparently relay essential Tracking, Telemetry, and Control ("TT&C") information between the overhead satellites using Ka-band channels and the SCS using terrestrial data communication channels. This equipment also performs the following functions:

- Processing of call control data packets to establish and terminate virtual circuits for IRIDIUM subscriber units.
- Processing of system control data packets to support SCS communications.

3. **Switching Equipment**

Each gateway provides switching equipment to interface between the communication payload in the Ka-band link and the voice/data channels of the PSTN for establishing, maintaining, and terminating calls. This equipment performs the following functions:

- Transferring in-band line/address signals associated with PSTN Signalling System R1 to establish and terminate circuit-switched connections.

- Transferring common channel signalling information associated with PSTN Signalling System 7 to establish and terminate circuit-switched connections.
- Supplying in-band tones and announcements to PSTN users to indicate call progress conditions
- Digital switching of PCM signals between channels derived from the earth terminal data, channels connected to the PSTN, and channels used to support in-band signalling of call control or progress information

4. Mission Operations

Each gateway provides external interfaces that allow IRIDIUM to set up connections between users and the PSTN, transfer billing information for each call, and transfer or update information in the subscriber files for its subset of registered users.

5. PSTN Interconnection

IRIDIUM will provide both voice and data connections through its satellite network, allowing information to be transferred between a subscriber terminal and any other IRIDIUM or PSTN user. Voice connections will be designed to be fully compatible with applicable ANSI T1 standards and the CCITT G and Q Series Recommendations for digital transmission systems utilizing Signaling Systems R1 and 7 (as adapted for the U.S. telephone network). It is anticipated that interconnections will be made to local exchange, inter-exchange, and international carriers to allow an IRIDIUM user to establish a connection to any destination in the world.

Data connections will be designed to be fully compatible with the Commission's OSI standards developed in the context of its Computer III Inquiry, as well as with applicable CCITT V and X Series Recommendations.

D. System Control Segment

The System Control Segment ("SCS") provides control of the satellite constellation. The SCS manages and controls all IRIDIUM system elements, insuring that service to the user is maintained in both the short term and over the long haul. Functions performed by the System Control Segment fall into two general areas: active control of the satellites, and control of the communications assets of the satellites. These tasks are performed by separate, collocated subsystems.

1. Constellation Operations

The primary functions of the constellation operations subsystem include:

- Managing each satellite orbit. Over time a satellite's orbit tends to decay because of effects such as high altitude atmosphere and solar pressure. One of the constellation operations functions is to monitor this decay and order the firing of thrusters on the satellite to correct the orbit.

- Monitoring each satellite's health. Telemetry information reflecting the status of each of the satellite's many systems is continuously telemetered to the System Control Segment. When unusual situations or failures occur it is often possible to issue commands to a satellite to "work around" the problem, and sometimes even correct it.

- Supporting satellite launch and checkout. As each satellite is launched, it must be maneuvered into its final orbit and tests must be run to verify proper functioning. These activities are performed under the control of the constellation operations subsystem.

- Removing satellites from the constellation. As each satellite reaches then end of its useful life it must be maneuvered away from the rest of the constellation and safely de-orbited.

2. Network Operations

The network operations subsystem provides the capability to manage the communications networks. Under normal conditions the functioning of the satellites in terms of communication to the subscriber units, gateways, and to each other will be autonomous. In the event of abnormal conditions such as very heavy traffic loading or node failure, the network operations subsystem will provide instructions to the network nodes on what steps to take to maintain service quality to the users. The steps may be very simple or very complex depending on the specific conditions.

3. Location of SCS Subsystems

The network operations and constellation operations subsystems will be replicated at two separate sites to provide a continuous capability in the event of some catastrophic event. By positioning the observation sites approximately 52 degrees north and spreading them in latitude, it is possible to observe every satellite every orbit with three earth terminals. The earth terminals will be nearly identical to those described in Section V.C.2. A final SCS element, the Operations and Analysis Subsystem, will be located at Chandler, Arizona. This subsystem provides long term planning and analysis for the entire IRIDIUM system. Chandler is particularly attractive as a site because access to the design engineers will be key to performing the analysis functions.

E. Subscriber Unit Segment

Communications between the ISU and the satellite is over a full-duplex FDMA channel in TDMA bursts of QPSK modulated digital data. Digitized voice is encoded and decoded using the Motorola 4800 bps VSELP vocoder algorithm (selected as the U.S. Digital Cellular competition). Subscriber 2400 baud data and 4800 bps digital voice data are protected with convolutional coding and interleaving. Table V-9 provides a technical summary of a typical subscriber unit.

TABLE V-9

SUBSCRIBER UNIT SUMMARY

Coded Date Rate: Uplink Downlink	180 Kbps 400 Kbps
Error Correction Coding	Convolutional, Rate=3/4, K=7
Modulation	QPSK
Frequency Band	1610.0-1626.5 MHz
Antenna:	
Type	Quadrifliar Helix
Gain	+1.0 to +3.0 dBi
Area of coverage	360 Degrees Azimuth +10 to 90 Degree Elevation
Transmitter EIRP: Peak Average	8.45 dBW (7.00 Watts) Maximum -4.70 dBW (338 Milliwatts) Maximum
Receiver G/T	-23.8 to -21.8 dBi
Minimum Eb/No	3.1 dB @ BER-10^{-2}

ISU uplink TDMA burst timing is synchronized to the downlink burst. The ISU compensates for changes in satellite range by timing the uplink burst transmission to arrive at the satellite with correct TDMA frame alignment. The ISU also compensates for the satellite Doppler frequency shift by adjusting the uplink transmit frequency.

F. Launch Segment

The Launch Segment encompasses the systems required to deliver each satellite to a specified parking orbit for positioning in the constellation. This segment includes the launch vehicle and all associated equipment used to support the launch, integration of the launch vehicle and satellite, and control of launch operations. Satellites will be launched one by one or several at a time. At the end of launch vehicle powered flight, the launch segment provides the satellite state vector (position and time) to the SCS which them assumes control over the satellite.

Pre-launch and launch operations are basically the same as those in practice for launches today. The SCS determines the overall launch plans and launch schedules. The launch vehicle is assembled and tested by the Launch Segment before mating with the satellite. The satellite is then mated with the launch vehicle and undergoes pre-flight integration testing and checkout.

The SCS computes and provides the Launch Segment with the parameters that specify the desired parking orbit. The Launch Segment performs all planning and targeting required for the launch vehicle to achieve the desired parking orbit. The Launch Segment computes the mission-specific data load for the LV flight computer and loads the flight computer.

Launch operations are controlled by a Launch Control Center ("LCC") under the direction of the System Control Segment.

Satellite telemetry is passed to the launch vehicle and relayed to the LCC as part of the telemetry. The LCC monitors the launch vehicle status and relays satellite telemetry to the SCS. The SCS processes and monitors telemetry to validate readiness of the satellite to launch. The LCC may recompute and upload the launch vehicle mission data load before launch.

The LCC makes a recommendation to launch based on results of satellite and launch vehicle readiness testing and environmental monitoring (weather, etc.).

The launch vehicle is monitored and controlled by the LCC. The LCC monitors range safety and can send an abort or destruct command to the launch vehicle after ignition if pre-determined range safety guidelines are violated.

The satellite provides health and status telemetry data to the launch vehicle. The launch vehicle transmits the data to the LCC, along with launch vehicle status data. The LCC provides the SCS with the satellite telemetry data received via the launch vehicle. The SCS monitors the satellite telemetry data to determine SV health and status.

The LCC determines the launch vehicle trajectory from tracking and telemetry data and generates an estimate of the parking orbit state vector. The SCS uses these parameters to determine antenna pointing angles for contacting the satellite after separation.

The SCS will nominally acquire the satellite using the estimated parking orbit vectors received from the launch vehicle.

A search may be required to be performed by the ground antennas to acquire the satellite if a nominal orbit was obtained. The SCS will update the parking orbit vectors based on ephemeris information provided by the satellite.

In the parking orbit, the satellite will deploy the satellite subsystems on ground command. The SCS will monitor the deployment sequence via telemetry when in line of sight of the SCS or Gateway earth terminals. The solar panels will then start to provide the power to allow use of the Ka-band uplink/downlink and crosslink antennas normally used for SCS/Gateway communications. The SCS determines the command sequences necessary to accomplish the transfer from the parking orbit to the mission orbit. The final sequence is actually a series of small burns which places the satellite into the right orbital "slot" relative to the other satellite in the same orbit. The satellite will execute the orbit maneuvers at the commanded times. The SCS will monitor the orbit maneuvers and continue to monitor satellite health, status and state vectors.

VI. REQUESTED WAIVERS OF COMMISSION RULES

IRIDIUM's state-of-the-art design and business plan requires certain nonconforming use and technical waivers of the Commission's rules. As demonstrated throughout this application, there are substantial public interest benefits supporting this global personal communications systems. These considerations and others clearly demonstrate good cause for granting the requested waivers.[38/]

A. Request For Waiver Of Frequency Allocation To Permit Co-Primary Voice And Data Services As A Nonconforming Use Of The RDSS Band

Motorola requests that the Commission waive Sections 2.106 and 25.392(d) of its rules to permit the IRIDIUM system to offer co-primary voice and data services as a nonconforming use of the RDSS band.[39/] A nonconforming use waiver will open up to the public the full range of advanced and innovative services the IRIDIUM system can offer, enhance the safety of lives and property worldwide, foster the international competitiveness of the United States, and significantly advance the efficient use of the 1610-1626.5 band, without interference to existing users. Additionally, use of the RDSS band for the provision of generic mobile satellite services comports with the Commission's own publicly espoused policy goal of reallocating the RDSS band for co-primary RDSS and generic MSS use.

1. Nonconforming Uses of the Frequency Spectrum Are Permitted in Appropriate Situations

Both the Commission's rules and the international Radio Regulations provide for nonconforming uses of frequencies

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[38/] 47 C.F.R. § 1.3 (1989). See also WAIT Radio v. F.C.C., 418 F.2d 1153 (D.C. Cir. 1969).

[39/] 47 C.F.R. §§ 2.106, 25.392(d) (1989).

provided that no harmful interference is caused to existing allocated services.[40] When evaluating a request for a waiver of its frequency allocations, the Commission typically considers four factors:

> (1) whether the frequencies requested are underutilized;
>
> (2) whether the proposed use of the frequencies will be detrimental to their assigned users;
>
> (3) whether any existing frequency allocation is not suited to or is insufficient to accommodate the applicant's requirements; and
>
> (4) whether the public interest will be served by a grant of the waiver.

No single factor, however, is determinative in this analysis.[41]

2. The Proposed Nonconforming Use of the RDSS Band Satisfies the Commission's Waiver Standard

a. The 1610-1626.5 Band Is Underutilized

As discussed in the RDSS Licensing Order,[42] the Commission's original intent when it allocated the RDSS band was to license multiple RDSS systems so as to foster competition in the provision of radiolocation and radionavigation services. The

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[40] 47 C.F.R. § 2.102 (1989); International Radio Regulation No. 342; DBS Systems, 92 F.C.C.2d 64, 68 (1982) (Commission generally allows nonconforming uses in appropriate situations).

[41] See Bangor and Aroostook R.R. Co., 5 F.C.C. Rcd 1199 (1990); Big Bend Telephone Co., 2 F.C.C. Rcd 3068 (1986), and cases cited therein.

[42] 104 F.C.C.2d at 653.

Commission perceived sufficient market demand for dedicated RDSS services to support several licensees.[43] It concluded that competition among those licensees would bring such services to the public quickly, without the delays attendant to comparative hearings or the establishment of a consortium.[44]

None of these predictions has come to pass. Although the Commission initially entertained three technically compatible applications, only one licensee remains. To date, however, that licensee -- Geostar -- has had very little success in bringing its radio-determination services to the public.[45]

Given Geostar's currently limited services, the decreasing likelihood of any significant increase in its capacity to serve new subscribers in the future, and the total absence of any additional proposals for the provision of dedicated RDSS services waiting in the wings, the 1610 to 1626.5 band is practically unused for its assigned purpose. In these circumstances, "the public interest would be better served by allowing [others] to use the frequencies . . . than by allowing the frequencies to lie fallow."[46]

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[43] Id. at 662-63.

[44] Id. at 653.

[45] See WARC-92 Second Inquiry Notice, F.C.C. 90-316, at ¶ 70; GTE Spacenet Corp., 1 F.C.C. Rcd at 1163; GTE Satellite Corp., Mimeo Nos. 5175 & 1181 (released June 16, 1986, and December 2, 1985, respectively); GTE Spacenet Corp., 4 F.C.C. Rcd 4538 (1989).

[46] Bangor and Aroostook R.R. Co., 5 F.C.C. Rcd at 1200.

b. Operation of IRIDIUM in the RDSS Band Will Not Interfere With the Operations of Any Other Authorized Service Providers

In its RDSS Licensing Order, the Commission indicated that nonconforming uses of the RDSS band could be permitted if there is no prospect of causing harmful interference.[47] As demonstrated in Appendix B, the IRIDIUM system has been carefully designed to share the 1610-1626.5 band with all currently licensed users. With this proposed system design, the chances of harmful interference to Geostar and other RDSS band users are virtually nonexistent.

c. The Existing Allocation for Generic MSS Is Clearly Insufficient

The Commission itself has already recognized that additional bandwidth must be allocated to the generic mobile satellite service and that the RDSS band is the most appropriate source of additional scarce bandwidth. In its WARC-92 Second Inquiry Notice, the Commission explicitly noted that the demand for generic MSS is growing at an accelerating pace and is already beginning to create "increasing pressure to accommodate more and more systems within the limited spectrum available for these services."[48] Consequently, the Commission has endorsed proposals for RDSS to share the 1610-1626.5 MHz band with compatible

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47/ 104 F.C.C.2d at 660.

48/ F.C.C. 90-316, at ¶ 65.

generic MSS systems on a co-primary basis and is planning to advocate such a reallocation at WARC-92.[49] In the past, the Commission has not hesitated to grant a waiver for a nonconforming use when, as here, the process for reallocation of the relevant band to that use is already underway.[50]

d. Granting a Waiver for Primary Voice and Data Services Will Serve the Public Interest

Granting a waiver to permit the IRIDIUM system to offer voice and data services on a co-primary basis with RDSS will serve both the policies adopted by the Commission for the 1610-1626.5 band and the public interest for several reasons. First, the requested waiver will foster the Commission's multiple entry policies. The ability to offer voice and data services on a co-primary basis will permit multiple new entrants to use capacity on IRIDIUM to make RDSS and MSS widely available in competition with Geostar and possibly other MSS service providers. Second, as demonstrated in this application, IRIDIUM's extensive reuse of the L-band and lack of need for the paired RDSS bandwidth at 2483.5-2500 MHz, is an extremely efficient use of the frequency spectrum. Third, IRIDIUM can provide both supplemental RDSS service and meet the market's growing demand for generic MSS without causing interference to other operators in the L-band.

49/ Id. at ¶ 70.

50/ See, e.g., Communications Satellite Corp., 5 F.C.C. Rcd 4117, 4118 (1990).

Fourth, the requested waiver will promote "the Commission's policy ... to encourage advancements in communication system design and to foster communications that promote the safety of life and property."[51] Finally, permitting IRIDIUM to develop to its full potential will advance U.S. competitiveness in international telecommunications generally and place the United States at the forefront of developments in low earth satellite technologies.

B. Request for Waiver of RDSS Technical Rules to Allow for Up and Downlinks in RDSS L-band and for Non-Spread Spectrum Compatibility Techniques

Motorola also requests waivers of two technical requirements contained in the RDSS rules. First, Motorola seeks a waiver of Section 25.202(a)(2) of the rules[52] to permit the IRIDIUM system to use both uplinks and downlinks in the 1610-1626.5 MHz band. Second, Motorola requests a waiver of Section 25.392(f) of the rules[53] to allow the use of non-spread spectrum techniques for ensuring IRIDIUM's compatibility with other licensed RDSS systems.[54]

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[51] Aeronautical Radio Inc., 5 F.C.C. Rcd 3038 (1990).

[52] 47 C.F.R. § 25.202(a)(2) (1989) (allocating the 1610-1626.5 MHz band for RDSS user-to-satellite communications and the 2483.5-2500 MHz band for satellite-to-user communications).

[53] 47 C.F.R. § 25.392(f) (1989).

[54] In addition, to the extent required, a wavier is requested of Section 25.392(f) of the rules, to allow for compatibility (continued...)

The Commission has consistently held that it is appropriate to waive its technical requirements whenever the requested waiver forwards the public interest and serves the policies underlying the rules.[55] Permitting IRIDIUM to use the 1610-1626.5 MHz band for both uplinks and downlinks will benefit the public and advance the Commission's policy of multiple entry into RDSS. The Commission has traditionally advocated the efficient use of the frequency spectrum, including the bands allocated to RDSS, so as to bring the maximum level of service to the public. In addition, the Commission's policy is to foster multiple entry into RDSS.[56] By using both uplinks and downlinks in the L-band, IRIDIUM conserves scarce spectrum, freeing the 2483.5-2500 MHz band for other users,[57] and, as demonstrated in Appendix B, the IRIDIUM system's use of the 1610-1626.5 MHz band for the satellite-to-user link will not cause harmful interference to other operators in the L-band.

Similarly, endorsing IRIDIUM's non-spread spectrum compatibility technology would both satisfy the rationale underlying the RDSS compatibility requirements and serve the Commission's policy favoring multiple entry. The Commission

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[54] (...continued)
techniques for radio astronomy other than those specified in Appendix D to the RDSS Licensing Order, such as those set forth in Appendix B hereto.

[55] See Aeronautical Radio, Inc., 5 F.C.C. Rcd at 3039.

[56] RDSS Licensing Order, 104 F.C.C.2d at 653-54.

[57] RDSS Allocation Order, 58 Rad. Reg. 2d (P&F) at 1420-21.

elected to require RDSS licensees to use spread spectrum techniques for avoiding interference with other RDSS licensees because it was the only technology proposed at the time which appeared to permit multiple entry.[58] As demonstrated in Appendix B, Motorola's IRIDIUM system is equally as, if not more, effective as spread spectrum techniques at ensuring compatibility with other compliant systems.

Under such circumstances, Motorola should not be prevented from utilizing this technology simply because it had not been developed at the time the technical standards for RDSS were established. Indeed, the Commission is required to adjust its rules and policies in the face of changed circumstances, including new and innovative technologies.[59]

VII. INTERNATIONAL APPLICATION

One of the significant benefits of IRIDIUM is its ability to service the entire world with the same number of satellites required to provide U.S. domestic service. Each of its 77 satellites circles the earth in approximately 100 minutes, with the entire network of satellites providing continuous, interconnected global service via a revolutionary set of intersatellite crosslinks.

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[58] RDSS Licensing Order, 104 F.C.C.2d at 661.

[59] WWHT, Inc. v. F.C.C., 656 F.2d 807, 819 (D.C. Cir. 1981); Geller v. F.C.C., 610 F.2d 973, 980 n.59 (D.C. Cir. 1979).

With this comprehensive system application, IRIDIUM is seeking from the Commission both domestic and international licensing authority for connections within the U.S. and between the United States and abroad. With respect to the requested international authorizations, Motorola recognizes that separate approvals will be needed from foreign administrations before IRIDIUM can operate within and between those countries and the United States. An authorization from the Commission, however, will be extremely helpful in obtaining such foreign government approvals. Accordingly, Motorola requests that in addition to domestic authorizations, the Commission issue it conditional international authorizations subject only to further consultations and coordination with appropriate international bodies and foreign administrators. If such an international authorization would delay significantly the approval of a domestic license, Motorola respectfully requests the Commission first grant it a domestic license and then continue to process this request for conditional international approval. Such authorizations would be consistent with Commission policies for processing international satellite and undersea cable applications.[60]

Motorola understands that it will have to coordinate IRIDIUM with INTELSAT and INMARSAT pursuant to international

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[60] Separate Systems, 101 F.C.C.2d at 1062; Tel-Optik Ltd., 100 F.C.C.2d 1033, 1042-46 (1985); Pacific Telecom Cable, Inc., 2 F.C.C. Rcd 2686, 2688-89 (1987).

agreements. Motorola firmly believes that these processes will not be an impediment to the provision of international RDSS and MSS services over IRIDIUM. In this regard, at the most recent INTELSAT Assembly of Parties meeting in Lisbon, certain truncated procedures were approved for the processing of non-technical aspects of the Article XIV(d) consultation process. The INTELSAT Board of Governors now has the authority to issue findings with respect to separate systems intended to carry other than fixed satellite services. See BG 86-98, dated September 18, 1990. And in a recent internal progress report to the Board of Governors, which was endorsed by the Board, it was recommended that "since INTELSAT has no present intention to provide mobile services, separate systems . . . offering such services, should not be subjected to significant economic harm assessment." See BG 84-81 (Rev. 1), dated March 13, 1990.

In any event, it is imperative that the Commission immediately begin the process of advance publication with the IFRB and authorize IRIDIUM well in advance of the upcoming WARC.

A. The U.S. Must Immediately Advance Publish IRIDIUM to the IFRB

Advance publication of the IRIDIUM system, and subsequent international frequency coordination in accordance with the international rules and regulations, must be an important immediate undertaking for the United States.[61] Such advance publication will enable the IFRB to circulate worldwide the IRIDIUM system characteristics, including global footprint patterns, and will further U.S. interests in obtaining primary allocation protection at WARC.

The IRIDIUM system should be advance published without delay in connection with satellite uplinks for the aeronautical radionavigation class of stations and recognition that the downlink would operate under RR 342. This class of IRIDIUM subscriber terminals enjoys worldwide primary allocation status today under ITU Footnote 732. In early 1986, prior to authorization of Geostar and other RDSS satellite systems, the Commission advance published a generic RDSS satellite system for U.S. coverage in the 1610-1626.5 MHz band using similar strategies. This early advance publication, and subsequent coordination, had the advantage of protecting under ITU rules all other classes of RDSS subscriber terminals.

B. It Is Imperative That The Commission Approve IRIDIUM In Advance Of The 1992 WARC

Perhaps the most important international aspect of this application is its nexus with the World Administrative Radio Conference in Spain scheduled for February 1992. The expeditious processing of Motorola's application will provide the

[61] Appendix D sets forth all of the information required for IFRB advance publication of IRIDIUM.

Commission with a rare opportunity to support a global mobile satellite allocation at the 1992 Conference with a concrete proposal and authorization for using that allocation to the benefit of all nations.

1. **Global Primary Allocations for IRIDIUM Are Achievable at WARC if Adopted As a Major U.S. Goal**

A global primary allocation to RDSS and MSS in the 1610-1626.5 MHz bands, as proposed by the FCC in its recent WARC-92 Second Notice of Inquiry, can be achieved much more easily if IRIDIUM is available as a reference system approved in the United States. Similar strategies have proved successful in the past for international recognition of satellite systems -- such as the fixed satellite service and the direct broadcast satellite service.

At the 1987 WARC, several countries refused to agree to a primary RDSS allocation in the 1610-1626.5 MHz band. Most of these countries saw little need for a pure position location service. The many other benefits of the IRIDIUM system architecture -- mobile telephony, digital technology, worldwide coverage, and personal telecommunications -- should be instrumental in upgrading the 1610-1626.5 MHz international allocation to primary MSS/RDSS status.

Motorola is prepared to make a major effort to assist the United States in achieving worldwide primary status for RDSS and MSS in the 1610-1626.5 MHz band. However, for this effort to achieve credibility overseas, it is extremely important for the IRIDIUM system to have already been licensed by the FCC. Otherwise, other countries will look at IRIDIUM as just a possible proposal that does not yet enjoy the backing of the U.S. government.

2. International Authorization of IRIDIUM in the RDSS Band Can Be Made Subject to the 1992 WARC Outcome

As a global satellite system, it is important for IRIDIUM to be consistent with the international table of frequency allocations. It is precisely for this reason that IRIDIUM has been designed to operate in different portions of the L-band in different parts of the world.

Motorola is willing to accept international license authority subject to the outcome of the 1992 WARC. Much work then could be done on the IRIDIUM system that would be consistent with various WARC outcomes. For example, it is likely that the 1992 WARC will adopt certain sharing constraints as a concomitant of a global allocation for the IRIDIUM system. Motorola is confident that it can engineer the IRIDIUM system to comply with any reasonable set of sharing constraints.

3. Authorization of IRIDIUM Before the WARC Will Hasten the Availability of Service to the Public

Another extremely important reason to authorize IRIDIUM prior to the 1992 WARC is to hasten the availability of life-saving IRIDIUM services to the public. Motorola will be able to initiate satellite construction activity promptly, subject to any necessary modifications based on the WARC outcome. Motorola is separately filing a request for a Section 319(d) waiver to begin certain construction activities for long-lead items prior to obtaining a license from the Commission. However, Motorola will need a U.S. license before it can proceed with final system design and construction of this project.

VIII. LEGAL, TECHNICAL AND FINANCIAL QUALIFICATIONS

A. Legal Qualifications

Motorola Satellite Communications, Inc. is a Delaware corporation wholly owned by Motorola, Inc., which is also a Delaware corporation. Motorola is a leading manufacturer of space, cellular and terrestrial communications equipment, including mobile and portable telephones, cellular telephones, and pagers. In addition, Motorola, Inc. provides a number of communications services, including private microwave, common carrier paging and general mobile radio.

Motorola Satellite Communications, Inc.'s legal qualifications are demonstrated in FCC Form 430, "Common Carrier and Satellite Radio License Qualification Report," attached to this application as Appendix F.

B. Financial Qualifications

1. Construction and Launch Schedules

Motorola has already issued a Request for Proposals ("RFP") for satellite construction, and has met with a number of potential major satellite manufacturers. The manufacturers that have studied Motorola's IRIDIUM operational plans confirm that there are no engineering or technical impediments with Motorola's proposed satellite system.

Motorola requests permission to begin preliminary construction activities prior to Commission approval of this application. A Section 319(d) waiver request is being filed concurrently with this application. Authorization to begin satellite development would enable Motorola to continue to implement its IRIDIUM program during Commission consideration of this application, and to insure that IRIDIUM is prepared to proceed expeditiously following Commission approval.

The combination of relatively light weight, small size, and low target altitude gives Motorola significant flexibility in selecting launch alternatives. For example, each satellite is sized to fit on an Orbital Sciences modified Pegasus type launch vehicle to replace single space vehicles, if required. Although this single launch option could place all 77 space vehicles into orbit, Motorola is actively reviewing several multiple launch options to populate the constellation initially. These multiple launch options include several based on modified Peacekeeper missiles, the McDonnell Douglas Delta II, and the General Dynamics Atlas II. These negotiations are currently underway with a selection of a launch supplier estimated for mid 1991.

The IRIDIUM program is off to an excellent start. Table VIII-1 shows the IRIDIUM Program Milestones. This schedule assumes FCC authorization of IRIDIUM in early 1991. As mentioned above, Motorola has already issued the RFP for satellite construction. Motorola expects to select the satellite contractor and execute a contract in 1991. Financing for the entire system is expected to be complete by 1992.

TABLE VIII-1

IRIDIUM Program Milestones	Year
Spacecraft RFP Issued	1990
Spacecraft Contractor Selected	1991
Spacecraft Contract Executed	1991
Launch Services Contract Executed	1991
Financing Completed	1992

Motorola intends to construct the initial constellation of 77 satellites plus 10 spares on an assembly line basis. Table VIII-2 shows the IRIDIUM Construction and Launch Milestones. Satellite construction will begin in 1992. The first satellites will be completed and launched in 1994. Construction and launch of the final group of satellites will be completed by 1996. The first satellite will be placed into service in 1995, and the last one in 1996. The final testing of the system will be completed in 1996, and IRIDIUM will provide communications service in 1997.

TABLE VIII-2	
Construction and Launch Milestones	Year
Satellite Construction Begins	1992
First Satellite Constructed	1994
First Satellite Launched	1994
First Satellite in Service	1995
Last Satellite Constructed	1996
Last Satellite Launched	1996
IRIDIUM Begins Operations	1996
IRIDIUM Provides Services	1997

2. Projected System Costs

The total costs for IRIDIUM to the system operator for the period through 1997, the first full year of operation, are itemized in Table VIII-3 below. The pre-operating expenses include marketing, finance and administrative services.

The research and development costs will be heaviest in the 1992-1994 period. Motorola intends to sub-contract some of the research and development work.

The satellite construction and launch service costs cover 77 satellites, 10 ground spares and launch insurance.

Satellite construction will begin in 1992. Construction of the System Control Facility ("SCF") will begin in 1992 and be completed by 1994.

The interest expenses are for loans to construct and launch the system. These estimates are based on an eleven percent interest rate.

Spacecraft depreciation will start in 1995 as the satellites are placed into orbit. Depreciation estimates are calculated by a straight line method over six years.

The gateways will be owned and operated by independent gateway operators. These gateway operators will be the telecommunications carriers using IRIDIUM to provide service. The construction costs for the gateways, estimated as $16 million apiece, are not included in Table VIII-3 because they will be borne by the independent gateway operators.

TABLE VIII-3

PROJECTED TOTAL SYSTEM COSTS ($ MILLIONS)

	1990	1991	1992	1993	1994	1995	1996	1997
Pre-Operating Expenses	3	10	20	23	52	61	83	42
Research and Development	8	43	130	133	97	46	46	46
Satellite Construction			83	273	352	257	141	
Launch Services and Insurance					51	260	260	
System Control Facility			25	41	15			
Interest		4	5	34	63	102	136	154
Depreciation						47	216	385
Total Costs	11	57	263	504	630	773	882	627

3. Sources of Funds

Motorola, Inc. is firmly committed to meeting all IRIDIUM construction and operating expenses with internal resources. Motorola, Inc. has adequate internal resources to finance the entire IRIDIUM system. The company's 1989 retained earnings exceeded $2.5 billion. Sales revenues for 1989 were $9.6 billion. At the end of the 1990 third quarter, Motorola's assets exceeded $8.4 billion.

Donald R. Jones, Motorola, Inc.'s Executive Vice President and Chief Financial Officer, confirms that Motorola, Inc. "is fully committed to meet[ing] the construction and operating expenses" of the IRIDIUM project. Mr. Jones' statement and excerpts from Motorola, Inc.'s most recent quarterly and annual reports are contained in Appendix E to this application.

Motorola, Inc. is firmly committed to financing 100% of the total cost of the IRIDIUM system out of internal funds if necessary. However, Motorola, Inc. intends to seek additional equity and debt placements. Motorola is confident that debt financing for IRIDIUM can be obtained.

4. Revenue Requirements

As a non-common carrier, Motorola need not address revenue requirements. Motorola does not expect any financing of the construction or launch of IRIDIUM to be generated by operating revenues.

C. Technical Qualifications

Motorola is a world-wide leader in space communications, telecommunications, semiconductors, global positioning, computer systems, electronics, and related technologies. Motorola's IRIDIUM team consists of management and professional staff taken from its corporate-wide resources. There are more than 75 managers and engineers dedicated to the

IRIDIUM project. These engineers specialize in communications and space technologies and systems.

Motorola has provided vital space communications technology for the Department of Defense, NASA and other government agencies. For example, Motorola supplied technologically advanced space equipment to NASA for the Ranger, Mariner, Viking, Voyager, Mercury, Gemini, Apollo and Magellan programs.

The IRIDIUM team can draw on Motorola Inc.'s corporate resources as necessary. Motorola, Inc. has more than 20,000 engineers corporate-wide.

D. Waiver of Use of Spectrum

Pursuant to Section 304 at the Communications Act of 1934, as amended, Motorola hereby waives any claim to the use of any particular frequency or of the ether against the regulatory power of the United States because of the previous use of the same, whether by license or otherwise.

E. Certificate

Motorola certifies that all of the statements contained herein are true, complete and accurate to the best of its information, belief and knowledge.

IX. CONCLUSIONS

For all of the above reasons, Motorola respectfully requests that the Commission expeditiously grant this comprehensive IRIDIUM system application.

Respectfully submitted,

MOTOROLA SATELLITE
COMMUNICATIONS, INC.

By:

Title: President, Motorola Satellite Communications, Inc.

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Counsel to
Motorola Satellite
Communications, Inc.

December 3, 1990

ENGINEERING CERTIFICATE

I hereby certify that I am the technically qualified person responsible for preparation of the engineering information contained in this application, that I am familiar with Part 25 of the Commission's Rules, that I have either prepared or reviewed the engineering information submitted in the application, and, that it is complete and accurate to the best of my knowledge and belief.

Gerald M. Munson

Title: Spectrum Utilization Manager
Motorola Satellite Communications

Date: December 3, 1990

APPENDIX A

IRIDIUM TRANSMISSION CHARACTERISTICS

1.0 RF PLAN AND LINK BUDGETS

Tables A-1 through A-8 summarize the key RF parameters of the communication links. Transmitter RF output electronic power control will be utilized on the subscriber and gateway links to compensate for vegetative shadowing and inclement weather. Tables A-2, A-3 & A-6 are with minimum transmitter power levels, representing clear sky, line of sight operation. Tables A-4, A-5 & A-7 reflect maximum transmitter power levels with the highest tolerable amount of shadowing and rain.

Table A-8 shows two conditions of operation: "normal" and "into sun". The latter occurs when two linked-satellite's orbital positions are such that the receiving antenna of one must point directly into the sun, resulting in an increase in received thermal noise.

TABLE A-1

SPACE VEHICLE RF SUMMARY

	SV-USER DOWNLINK	USER-SV UPLINK	GATEWAY DOWNLINK	GATEWAY UPLINK	CROSS LINK
CENTER FREQ (GHz)	1.618	1.618	20.00	30.00	23.05
CHANNEL SPACING (MHz)	0.35	0.16	15.00	15.00	25.00
MAX # CARRIERS	46	64	2	2	4
RF PWR TO ANTENNA	1.5 min	1.2 min	1.0 min	0.55 min	2.5nom.
(Peak Watts Per Carrier)	11.5 max	7.0 max	20.0 max	217 max	----
MODULATION	QPSK	QPSK	QPSK	QPSK	QPSK
CODING RATE	3/4	3/4	1/2	1/2	1/2
CODED DATA RATE (Mbps)	0.40	0.18	12.50	12.50	25.00
MULTIPLEXING	T/FDMA	T/FDMA	T/FDMA	T/FDMA	T/FDMA
USER CALL CAPACITY PER SATELLITE	4070	4070	2000	2000	3000

TABLE A-2

SV-USER DOWNLINK, LINE OF SIGHT

	UNITS	CELL1	CELLS 2 & 3	CELL4	CELL 5	CELL6	CELL 7
AZIMUTH ANGLE	Deg	5.39	19.75	6.59	30.00	10.89	30.00
GROUND RANGE FROM NADIR	NMi	1108.0	1026.9	810.7	744.0	492.1	186.0
NADIR ANGLE	Deg	61.56	60.82	57.69	56.26	47.58	23.98
GRAZING ANGLE	Deg	10.00	12.09	18.82	21.36	34.23	62.93
SLANT RANGE	NMi	1238.4	1157.8	949.9	887.3	664.2	457.5
XMTR BURST PWR INTO ANT	Watts	1.55	1.51	1.73	2.42	3.13	3.56
(Per Carrier)	dBm	31.89	31.79	32.38	33.83	34.95	35.51
PEAK ANT GAIN	dBi	24.99	24.99	23.87	23.02	20.00	12.04
EDGE LOSS	dB	0.50	0.50	1.70	1.50	2.60	3.80
SCAN LOSS	dB	0.95	1.43	1.42	3.00	3.61	0.00
TAPER LOSS	dB	1.00	1.00	1.00	1.00	1.00	0.00
XMTR NET ANT GAIN	dBi	22.54	22.06	19.75	17.52	12.79	8.24
XMT FEED/CKT LOSS	dB	1.30	1.30	1.30	1.30	1.30	1.30
EIRP	**dBmi**	**53.13**	**52.55**	**50.83**	**50.05**	**46.44**	**42.45**
PATH LOSS	dB	163.84	163.25	161.53	160.94	158.43	155.19
POLARIZATION LOSS	dB	0.50	0.50	0.50	0.50	0.50	0.50
GASEOUS LOSS	dB	0.30	0.30	0.30	0.30	0.30	0.30
MEAN VEGETATION LOSS	dB	0.00	0.00	0.00	0.00	0.00	0.00
TOT PROPAGATION LOSS	dB	164.64	164.05	162.33	161.74	159.23	155.99
RCVR NET ANT GAIN	dBi	1.00	1.00	1.00	1.00	2.18	3.01
ANT NOISE TEMP	^{o}K	150.00	150.00	150.0	150.00	150.00	150.00
RCV FEED/CKT LOSS	dB	1.00	1.00	1.00	1.00	1.00	1.00
LNA NOISE FIGURE	dB	0.80	0.80	0.80	0.80	0.80	0.80
SYST NOISE TEMP, Ts	^{o}K	298.93	298.93	298.93	298.93	298.93	298.93
G/Ts	dBi/^{o}K	-23.76	-23.76	-23.76	-23.76	-22.57	-21.74
BOLTZMANN'S, k	dBm/Hz^{o}K	-198.60	-198.60	-198.60	-198.60	-198.60	-198.60
C/I	dB	18.00	18.00	18.00	18.00	18.00	18.00
RCV'D C/No	**dBHz**	**62.87**	**62.87**	**62.87**	**62.87**	**62.87**	**62.87**
REQUIRED Eb/No	dB	3.10	3.10	3.10	3.10	3.10	3.10
CHANNEL DATA RATE	dBHz	54.77	54.77	54.77	54.77	54.77	54.77
IMPLEMENTATION LOSS	dB	2.00	2.00	2.00	2.00	2.00	2.00
REQUIRED C/No	**dBHz**	**59.87**	**59.87**	**59.87**	**59.87**	**59.87**	**59.87**
LINK MARGIN	**dB**	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**
FLUX DENSITY per 4KHz BW	dBW/m^2	-132.1	-132.1	-132.1	-132.3	-133.4	-134.1

TABLE A-3

USER-SV UPLINK, LINE OF SIGHT

	UNITS	CELL 1	CELLS 2 & 3	CELL 4	CELL 5	CELL 6	CELL 7
AZIMUTH ANGLE	Deg	5.39	19.75	6.59	30.00	10.89	30.00
GROUND RANGE FROM NADIR	NMi	1108.0	1026.9	810.7	744.0	492.1	186.0
NADIR ANGLE	Deg	61.56	60.82	57.69	56.26	47.58	23.98
GRAZING ANGLE	Deg	10.00	12.09	18.82	21.36	34.23	62.93
SLANT RANGE	NMi	1238.4	1157.8	949.9	887.3	664.2	457.5
XMTR BURST PWR INTO ANT	Watts	1.27	1.24	1.43	1.99	2.58	2.93
	dBm	31.05	30.95	31.54	32.99	34.11	34.67
XMTR NET ANT GAIN	dBi	1.00	1.00	1.00	1.00	2.18	3.01
XMT FEED/CKT LOSS	dB	0.70	0.70	0.70	0.70	0.70	0.70
EIRP	dBmi	31.35	31.25	31.84	33.48	35.69	37.00
PATH LOSS	dB	163.84	163.25	161.53	160.94	158.43	155.19
POLARIZATION LOSS	dB	0.50	0.50	0.50	0.50	0.50	0.50
GASEOUS LOSS	dB	0.30	0.30	0.30	0.30	0.30	0.30
MEAN VEGETATION LOSS	dB	0.00	0.00	0.00	0.00	0.00	0.00
TOT PROPAGATION LOSS	dB	164.64	164.05	162.33	161.74	159.23	155.99
PEAK ANT GAIN	dBi	24.99	24.99	23.87	23.02	20.00	12.04
EDGE LOSS	dB	0.50	0.50	1.70	1.50	2.60	3.80
SCAN LOSS	dB	0.95	1.43	1.42	3.00	3.61	0.00
TAPER LOSS	dB	1.00	1.00	1.00	1.00	1.00	0.00
XMTR NET ANT GAIN	dBi	22.54	22.06	19.75	17.52	12.79	8.24
ANT NOISE TEMP	^oK	290.00	290.00	290.00	290.00	290.00	290.00
RCV FEED/CKT LOSS	dB	1.80	1.80	1.80	1.80	1.80	1.80
LNA NOISE FIGURE	dB	1.00	1.00	1.00	1.00	1.00	1.00
SYST NOISE TEMP, Ts	^oK	552.58	552.58	552.58	552.58	552.58	552.58
G/Ts	$dBi/^oK$	-5.52	-5.26	-7.59	-9.64	-14.49	-19.58
BOLTZMANN'S, k	dBm/Hz^oK	-198.60	-198.60	-198.60	-198.60	-198.60	-198.60
C/I	dB	18.00	18.00	18.00	18.00	18.00	18.00
RCV'D C/No	dBHz	59.90	59.90	59.90	59.90	59.90	59.90
REQUIRED Eb/No	dB	3.60	3.60	3.60	3.60	3.60	3.60
CHANNEL DATA RATE	dBHz	51.30	51.30	51.30	51.30	51.30	51.30
IMPLEMENTATION LOSS	dB	2.00	2.00	2.00	2.00	2.00	2.00
REQUIRED C/No	dBHz	56.90	56.90	56.90	56.90	56.90	56.90
LINK MARGIN	dB	3.00	3.00	3.00	3.00	3.00	3.00
FLUX DENSITY per 4KHz BW	dBW/m^2	-150.4	-149.9	-147.6	-145.4	-140.7	-136.1

TABLE A-4

SV-USER DOWNLINK, WITH MODERATE SHADOWING

	UNITS	CELL 1	CELLS 2&3	CELL 4	CELL 5	CELL 6	CELL 7
AZIMUTH ANGLE	Deg	5.39	19.75	6.59	30.00	10.89	30.00
GROUND RANGE FROM NADIR	NMi	1108.0	1026.9	810.7	744.0	492.1	186.0
NADIR ANGLE	Deg	61.56	60.82	57.69	56.26	47.58	23.98
GRAZING ANGLE	Deg	10.00	12.09	18.82	21.36	34.23	62.93
SLANT RANGE	NMi	1238.4	1157.8	949.9	887.3	664.2	457.5
XMTR BURST PWR INTO ANT	Watts	11.51	9.59	6.00	7.43	6.90	6.73
(Per Carrier)	dBm	40.61	39.82	37.78	38.71	38.39	38.28
PEAK ANT GAIN	dBi	24.99	24.99	23.87	23.02	20.00	12.04
EDGE LOSS	dB	0.50	0.50	1.70	1.50	2.60	3.80
SCAN LOSS	dB	0.95	1.43	1.42	3.00	3.61	0.00
TAPER LOSS	dB	1.00	1.00	1.00	1.00	1.00	0.00
XMTR NET ANT GAIN	dBi	22.54	22.06	19.75	17.52	12.79	8.24
XMT FEED/CKT LOSS	dB	1.30	1.30	1.30	1.30	1.30	1.30
EIRP	**dBmi**	**61.21**	**60.68**	**56.31**	**55.19**	**50.02**	**44.82**
PATH LOSS	dB	163.84	163.25	161.53	160.94	158.43	155.19
POLARIZATION LOSS	dB	0.50	0.50	0.50	0.50	0.50	0.50
GASEOUS LOSS	dB	0.30	0.30	0.30	0.30	0.30	0.30
MEAN VEGETATION LOSS	dB	12.00	11.62	9.00	8.48	7.09	6.17
TOT PROPAGATION LOSS	**dB**	176.64	174.81	170.98	169.94	166.21	162.14
RCVR NET ANT GAIN	dBi	1.00	1.00	1.00	1.00	2.18	3.01
ANT NOISE TEMP	^{0}K	150.00	150.00	150.00	150.00	150.00	150.00
RCV FEED/CKT LOSS	dB	1.00	1.00	1.00	1.00	1.00	1.00
LNA NOISE FIGURE	dB	0.80	0.80	0.80	0.80	0.80	0.80
SYST NOISE TEMP, Ts	^{0}K	298.93	298.93	298.93	298.93	298.93	298.93
G/Ts	**dBi/^{0}K**	-23.76	-23.76	-23.76	-23.76	-22.57	-21.74
BOLTZMANN'S, k	dBm/Hz^{0}K	-198.60	-198.60	-198.60	-198.60	-198.60	-198.60
C/I	dB	18.00	18.00	18.00	18.00	18.00	18.00
RCV'D C/No	**dBHz**	**59.87**	**59.87**	**59.87**	**59.87**	**59.87**	**59.87**
REQUIRED Eb/No	dB	3.10	3.10	3.10	3.10	3.10	3.10
CHANNEL DATA RATE	dBHz	54.77	54.77	54.77	54.77	54.77	54.77
IMPLEMENTATION LOSS	dB	2.00	2.00	2.00	2.00	2.00	2.00
REQUIRED C/No	**dBHz**	**59.87**	**59.87**	**59.87**	**59.87**	**59.87**	**59.87**
LINK MARGIN	**dB**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
FLUX DENSITY per 4KHz BW	dBW/m^2	-123.3	-124.6	-126.7	-127.3	-129.6	-131.2

TABLE A-5

USER-SV UPLINK, WITH MODERATE SHADOWING

	UNITS	CELL 1	CELLS 2&3	CELL 4	CELL 5	CELL 6	CELL 7
AZIMUTH ANGLE	Deg	5.39	19.75	6.59	30.00	10.89	30.00
GROUND RANGE FROM NADIR	NMi	1108.0	1026.9	810.7	744.0	492.1	186.0
NADIR ANGLE	Deg	61.56	60.82	57.69	56.26	47.58	23.98
GRAZING ANGLE	Deg	10.00	12.09	18.82	21.36	34.23	62.93
SLANT RANGE	NMi	1238.4	1157.8	949.9	887.3	664.2	457.5
XMTR BURST PWR INTO ANT	Watts	7.00	7.00	5.52	6.82	6.35	6.19
	dBm	38.45	38.45	37.42	38.34	38.03	37.92
XMTR NET ANT GAIN	dBi	1.00	1.00	1.00	1.00	2.18	3.01
XMT FEED/CKT LOSS	dB	0.70	0.70	0.70	0.70	0.70	0.70
EIRP	dBmi	38.75	38.75	37.72	38.64	39.51	40.23
PATH LOSS	dB	163.84	163.25	161.53	160.94	158.43	155.19
POLARIZATION LOSS	dB	0.50	0.50	0.50	0.50	0.50	0.50
GASEOUS LOSS	dB	0.30	0.30	0.30	0.30	0.30	0.30
MEAN VEGETATION LOSS	dB	12.00	11.62	9.00	8.48	7.09	6.17
TOT PROPAGATION LOSS	dB	176.64	174.81	170.98	169.94	166.21	162.14
PEAK ANT GAIN	dBi	24.99	24.99	23.87	23.02	20.00	12.04
EDGE LOSS	dB	0.50	0.50	1.70	1.50	2.60	3.80
SCAN LOSS	dB	0.95	1.43	1.42	3.00	3.61	0.00
TAPER LOSS	dB	1.00	1.00	1.00	1.00	1.00	0.00
XMTR NET ANT GAIN	dBi	22.54	22.06	19.75	17.52	12.79	8.24
ANT NOISE TEMP	^{o}K	290.00	290.00	290.00	290.00	290.00	290.00
RCV FEED/CKT LOSS	dB	1.80	1.80	1.80	1.80	1.80	1.80
LNA NOISE FIGURE	dB	1.00	1.00	1.00	1.00	1.00	1.00
SYST NOISE TEMP, Ts	^{o}K	552.58	552.58	552.58	552.58	552.58	552.58
G/Ts	dBi/^{o}K	-5.52	-5.26	-7.59	-9.64	-14.49	-19.58
BOLTZMANN'S, k	dBm/Hz^{o}K	-198.60	-198.60	-198.60	-198.60	-198.60	-198.60
C/I	dB	18.00	18.00	18.00	18.00	18.00	18.00
RCV'D C/No	dBHz	55.64	56.90	56.90	56.90	56.90	56.90
REQUIRED Eb/No	dB	3.60	3.60	3.60	3.60	3.60	3.60
CHANNEL DATA RATE	dBHz	51.30	51.30	51.30	51.30	51.30	51.30
IMPLEMENTATION LOSS	dB	2.00	2.00	2.00	2.00	2.00	2.00
REQUIRED C/No	dBHz	56.90	56.90	56.90	56.90	56.90	56.90
LINK MARGIN	dB	-1.26	0.00	0.00	0.00	0.00	0.00
FLUX DENSITY per 4KHz BW	$dBW/_{m}2$	-143.0	-142.4	-142.2	-140.4	-136.9	-133.2

TABLE A-6

GATEWAY LINKS, CLEAR WEATHER

(MAXIMUM RANGE)

	UNITS	DOWNLINK	UPLINK
GROUND RANGE FROM NADIR	NMi	1108.0	1108.0
NADIR ANGLE	Deg	61.56	61.56
GRAZING ANGLE	Deg	10.00	10.00
SLANT RANGE	NMi	1238.4	1238.4
CENTER FREQUENCY	GHz	20.00	30.00
XMTR BURST PWR INTO ANT	Watts	1.00	0.55
(Per Carrier)	dBm	30.00	27.37
PEAK ANT GAIN	dBi	20.00	57.50
OFF-PEAK LOSSES	dB	2.00	0.00
XMTR NET ANT GAIN	dBi	18.00	57.50
XMT FEED/CKT LOSS	dB	3.50	3.50
EIRP	dBmi	44.50	81.37
PATH LOSS	dB	185.67	189.19
POLARIZATION LOSS	dB	0.50	0.50
GASEOUS LOSS	dB	3.30	3.30
RAIN LOSS	dB	0.00	0.00
TOT PROPAGATION LOSS	dB	189.47	192.99
PEAK ANT GAIN	dBi	54.00	23.50
OFF-PEAK LOSSES	dB	0.00	2.00
RCVR NET ANT GAIN	dBi	54.00	21.50
ANT NOISE TEMP	^{o}K	30.00	290.00
RCV FEED/CKT LOSS	dB	4.00	4.00
LNA NOISE FIGURE	dB	3.00	3.00
SYST NOISE TEMP, Ts	^{o}K	1193.44	1453.44
G/Ts	dBi/^{o}K	23.23	-10.12
BOLTZMANN'S, k	dBm/Hz^{o}K	-198.60	-198.60
RCV'D C/No	dBHz	76.86	76.86
REQUIRED Eb/No	dB	6.90	6.90
CHANNEL DATA RATE	dBHz	67.96	67.96
IMPLEMENTATION LOSS	dB	2.00	2.00
REQUIRED C/No	dBHz	76.86	76.86
LINK MARGIN	dB	0.00	0.00
FLUX DENSITY per 4KHz BW	dBW/$_{m}$2	-155.7	-118.8

TABLE A-7

GATEWAY LINKS, WITH MODERATELY HEAVY RAIN*

(MAXIMUM RANGE)

	UNITS	DOWNLINK	UPLINK
GROUND RANGE FROM NADIR	NMi	1108.0	1108.0
NADIR ANGLE	Deg	61.56	61.56
GRAZING ANGLE	Deg	10.00	10.00
SLANT RANGE	NMi	1238.4	1238.4
CENTER FREQUENCY	GHz	20.00	30.00
XMTR BURST PWR INTO ANT	Watts	20.00	217.27
(Per Carrier)	dBm	42.99	53.37
PEAK ANT GAIN	dBi	20.00	57.50
OFF-PEAK LOSSES	dB	2.00	0.00
XMTR NET ANT GAIN	dBi	18.00	57.50
XMT FEED/CKT LOSS	dB	3.50	3.50
EIRP	**dBmi**	**57.50**	**107.37**
PATH LOSS	dB	185.67	189.19
POLARIZATION LOSS	dB	0.50	0.50
GASEOUS LOSS	dB	3.30	3.30
RAIN LOSS*	dB	13.00	26.00
TOT PROPAGATION LOSS	**dB**	**202.47**	**218.99**
PEAK ANT GAIN	dBi	54.00	23.50
OFF-PEAK LOSSES	dB	0.00	2.00
RCVR NET ANT GAIN	dBi	54.00	21.50
ANT NOISE TEMP	^{o}K	30.00	290.00
RCV FEED/CKT LOSS	dB	4.00	4.00
LNA NOISE FIGURE	dB	3.00	3.00
SYST NOISE TEMP, Ts	**^{o}K**	**1193.44**	**1453.44**
G/Ts	**dBi/^{o}K**	**23.23**	**-10.12**
BOLTZMANN'S, k	dBm/Hz^{o}K	-198.60	-198.60
RCV'D C/No	**dBHz**	**76.86**	**76.86**
REQUIRED Eb/No	dB	6.90	6.90
CHANNEL DATA RATE	dBHz	67.96	67.96
IMPLEMENTATION LOSS	dB	2.00	2.00
REQUIRED C/No	**dBHz**	**76.86**	**76.86**
LINK MARGIN	**dB**	**0.00**	**0.00**
FLUX DENSITY per 4KHz BW	**dBW/m^2**	**-155.7**	**-118.8**

* CRANE RAIN MODEL, REGION "G", 0.5% OUTAGE

TABLE A-8

CROSSLINKS

(@ MAXIMUM RANGE)

	UNITS	NORMAL	INTO SUN
RANGE	NMi	2200	2200
CENTER FREQUENCY	GHz	23.05	23.05
XMTR BURST PWR INTO ANT	Watts	2.46	2.46
(Per Carrier)	dBm	33.91	33.91
PEAK ANT GAIN	dBi	36.00	36.00
OFF-PEAK LOSSES	dB	0.00	0.00
XMTR NET ANT GAIN	dBi	36.00	36.00
XMT FEED/CKT LOSS	dB	2.00	2.00
EIRP	**dBmi**	**67.91**	**67.91**
PATH LOSS	dB	191.47	191.47
POLARIZATION LOSS	dB	0.50	0.50
TOT PROPAGATION LOSS	**dB**	**191.97**	**191.97**
PEAK ANT GAIN	dBi	36.00	36.00
OFF-PEAK LOSSES	dB	0.00	0.00
RCVR NET ANT GAIN	dBi	36.00	36.00
ANT NOISE TEMP	^{o}K	50.00	428.11
RCV FEED/CKT LOSS	dB	2.50	2.50
LNA NOISE FIGURE	dB	3.00	3.00
SYST NOISE TEMP, Ts	**^{o}K**	**788.96**	**1167.07**
G/Ts	**dBi/^{o}K**	**7.03**	**5.33**
BOLTZMANN'S, k	dBm/Hz^{o}K	-198.60	-198.60
RCV'D C/No	**dBHz**	**81.57**	**79.87**
REQUIRED Eb/No	dB	6.90	6.90
CHANNEL DATA RATE	dBHz	70.97	70.97
IMPLEMENTATION LOSS	dB	2.00	2.00
REQUIRED C/No	**dBHz**	**79.87**	**79.87**
LINK MARGIN	**dB**	**1.70**	**0.00**
FLUX DENSITY per 4KHz BW	**dBW/$_{m}$2**	**-140.2**	**-140.2**

APPENDIX B

SPECTRUM UTILIZATION AND SHARING ANALYSIS

1. INTRODUCTION

This paper evaluates the potential for a personal communication low earth orbit mobile satellite system (IRIDIUM) to share the 1610 to 1626.5 MHz frequency band with other services, including the Radio Determination Satellite Service (RDSS), GLONASS, Aeronautical Public Correspondence (APC) and Radio Astronomy (RA). An example of sharing with RDSS services is given for the IRIDIUM system to share the spectrum with the GEOSTAR system in the contiguous United States (CONUS). The IRIDIUM system is designed for bi-directional, i.e. single band, operation. This means that the satellite transmits and receives in the same frequency band.

2. CONCLUSIONS

This analysis establishes that the IRIDIUM system may share this band with each of these systems without harmful interference to their operations.

In sharing with RDSS systems, the IRIDIUM system will not interfere with the operation of the GEOSTAR system. As presently licensed, the GEOSTAR system will not interfere with the IRIDIUM system. An extension of this conclusion is that the system can share this spectrum with RDSS systems on a worldwide basis.

IRIDIUM will share the GLONASS, Radio Astronomy and APC bands by band segmentation. That is IRIDIUM will not use frequencies that would interfere with GLONASS, Radio Astronomy or APC operations..

The spectral efficiency and frequency reuse of the IRIDIUM system is such that it can provide for a theoretical maximum capacity of approximately 4400 full duplex voice channels across the CONUS using 10.5 MHz of the 16.5 MHz frequency band. The remaining 6.0 MHz is assumed to be not used due to sharing with GLONASS and RA. The GLONASS system is not yet fully operational. IRIDIUM may use these frequencies until the GLONASS satellites are operational in these frequency bands.

3. RF PLAN

The following describes the RF plan for the up and down links.

3.1 Uplink

The uplink would contain up to 102 carriers. These are 180 KBPS QPSK modulated carriers that are spaced at 160 KHz and occupy a 126 KHz bandwidth. Each carrier is based on TDMA carriers with one channel per burst and 14 bursts per TDMA frame. Due to sharing with GLONASS and RA, it is expected that only a maximum of 64 of the carriers may be used when the GLONASS system is in full operation. Of these 64 carriers, 9 are control and 55 are traffic channels.

3.2 Downlink

The downlink consists of up to 46 carriers. These are 400 KBPS offset keyed QPSK carriers that are spaced at 350 KHz and each occupies a 280 KHz bandwidth. These are also TDMA carriers, with one channel per burst and 14 bursts per TDMA frame. Due to sharing with GLONASS, it is expected that only a maximum of 29 carriers may be used. Of these 29 carriers, 4 are control and 25 are traffic channels. Voice activity compression techniques are used to reduce the number of carriers required in the downlink. Using 2.2:1 digital speech interpolation (DSI) compression, 55 voice channels can use the 25 downlink traffic channels.

4.0 TRAFFIC CAPACITY

The multiple access format for the IRIDIUM system uses both time and frequency division. This is described in Annex A. A 14 slot TDMA format is used. Since a 7 cell reuse pattern is used, each cell may be assigned 2 time slots. The traffic capacity of the IRIDIUM system using 10.5 MHz of the 16.5 MHz from 1610 to 1626.5 MHz is therefore 2 X 55 or 110 full duplex voice channels per cell. The voice and data capacity is developed in Section 4.1. The RDSS capacity is developed in Section 4.2.

4.1 Voice and Data Capacity

The IRIDIUM system places 40 cells over the CONUS and its coastal waters. The traffic capacity for the CONUS would then be 40 X 110 or 4400 full duplex voice channels (theoretical maximum). This is a very efficient use of spectrum. This corresponds to an equivalent 1.2 kHz per channel for the up and down link. A 2400 bits/s data channel may be used in place of a voice channel.

The worldwide capacity of the system may be calculated as follows. Approximately 1628 cells are active over the world. At 110 full duplex voice channels per cell, the theoretical maximum worldwide capacity would be 110 X 1628 or 179,080 full duplex voice channels. An estimate of the capacity for Land Mobile operations would be approximately 30% of this or 53,724 full duplex channels.

4.2 RDSS Capacity

The traffic capacity of the IRIDIUM system operating as an RDSS system is very large. Each cell exchanges two bursts in every carrier slot every 60 ms. Maximum traffic would be 33.33 bursts per second/carrier. There are 40 cells that cover the CONUS and 29 carriers/cell. Assuming the average RDSS data exchange may be transmitted in ten bursts, the theoretical maximum capacity of the system is:

Capacity = 40 X 33.33 X 29 X 0.1 X 3600 = 13.9 million/hour

5. SYSTEM CHARACTERISTICS

The system characteristics of the IRIDIUM and GEOSTAR systems are listed in Tables 1 and 2. These characteristics are used in the sharing analysis of the following sections.

TABLE 1

IRIDIUM SYSTEM CHARACTERISTICS

	DOWNLINK	UPLINK
CHANNEL SPACING (KHz)	350	160
CHANNEL BANDWIDTH (KHZ)	280	126
MAX # CARRIERS (10.5 MHZ)	29	64
MODULATION	QPSK	QPSK
CODING RATE	3/4	3/4
CODED DATA RATE (kbits/s)	400	180
MULTIPLE ACCESS	T/FDMA	T/FDMA
POLARIZATION	RCP	RCP
EIRP/CARRIER (dBw)	ANNEX C	ANNEX C

TABLE 2

GEOSTAR SUBSCRIBER TERMINAL CHARACTERISTICS

a. EIRP = 17 to 18 dBw
b. Burst time = 20 to 80 ms
c. Transmit polarization: LCP
d. Multiple access: CDMA
e. Chip Rate: 8 Mcps
f. Modulation: BPSK
g. Spread ratio: 512

6. SHARING

This section analyses the sharing of IRIDIUM with RDSS (GEOSTAR), GLONASS, Aeronautical Public Correspondence and Radio Astronomy.

6.1 SHARING WITH THE GEOSTAR SYSTEM

Since the IRIDIUM satellites and subscriber terminals transmit in the receive band of the GEOSTAR system satellites, each of these is a potential source of harmful interference. The basis of this sharing analysis is the CCIR Document US IWP-8/15-USA-6. Annex 1 of that paper is included as Annex B of this paper. The referenced sharing analysis defines the procedure for determining the effect of a mobile satellite system sharing with the GEOSTAR satellites.

Table 1 is a summary of the sharing between RDSS (as represented by GEOSTAR) and IRIDIUM. The interference of IRIDIUM into GEOSTAR is represented as the percent loss of GEOSTAR satellite capacity. This is consistent with the CCIR analysis of Annex B. The interference of GEOSTAR into IRIDIUM is represented by the Carrier-to-Interference ratio (C/I) in the IRIDIUM satellite. This calculation is performed in Annex D.

A calculation has been included for both the peak and average transmitter powers of the IRIDIUM satellite constellation and the subscriber terminals. The average power calculations are considered to be the more accurate estimate of the interference. The peak bursts arrive at the GEOSTAR satellite with variable time delay which has a tendency to average the bursts.

Table 3 shows that the IRIDIUM satellite constellation and subscriber terminals will cause a maximum of 2.4 % and 3.0 % loss of capacity to the GEOSTAR satellite system. The CCIR report in Annex B indicates that up to 20 % loss of capacity would be acceptable for sharing so the loss is well within the acceptable range.

Table 3 also shows that the GEOSTAR system would result in a 14.0 dB C/I ratio in the IRIDIUM satellite. This is considered to be acceptable.

The conclusion can be drawn that the systems are mutually compatible and can share the spectrum.

TABLE 3

SHARING ANALYSIS

SOURCE	% LOSS OF GEOSTAR SATELLITE CAPACITY	C/I IN IRIDIUM SATELLITE (DB)
IRIDIUM satellite constellation		
a. Average burst power	1.0	----
b. Peak burst power	2.4	----
IRIDIUM subscriber terminals		
a. Average burst power	2.5	----
b. Peak burst power	3.0	----
GEOSTAR subscriber terminals	----	14.0

The following sections are a more detailed description of the analysis and the results.

6.1.1 IRIDIUM Satellites Sharing with the GEOSTAR Satellites

A potential source of interference is the IRIDIUM satellite constellation transmitting its downlink carriers. Because of their orbits, the main beam of the IRIDIUM satellites will not transmit directly into the main beam of the GEOSTAR satellites.The side and back lobes of the IRIDIUM satellite constellation would transmit energy up into the GEOSTAR satellite. An estimate of the energy from a global IRIDIUM system that would be transmitted up to the GEOSTAR satellite is calculated in Tables 3 and 4 of Annex C.

The equations of Annex B are evaluated for 29 carriers, each with a power of 5.1 dBw for the average burst power and 10.2 dBW for the peak burst power. A channel spacing of 350 KHz and a channel bandwidth of 280 KHz is used.. The results show that a 1.0 % and 2.4 % loss of capacity for the GEOSTAR satellite would result from this. This is negligible since, as indicated in Annex B, 20 % would be considered acceptable. Since GEOSTAR uses a spot beam rather than a global beam antenna, the results are probably conservative since the assumption is that all of the interfering carriers are in the 3 dB beamwidth of the GEOSTAR satellite, which they are not.

6.1.2 IRIDIUM Subscriber Terminals Sharing with the GEOSTAR Satellite

A second potential source of interference is the IRIDIUM subscriber terminal uplink carriers. An estimate of the interference energy, from the subscriber terminals of a global IRIDIUM system, is calculated in Table 5 and 6 of Annex C again for average and peak burst power. The equations of Annex B are evaluated for 64 carriers, each with a power of 5.7 and 6.5 dBW, a channel spacing of 160 KHz and a channel bandwidth of 126 KHz. The results show a 2.5 % and 3.0 % loss of GEOSTAR satellite capacity would result, which should be acceptable. Again, the results are probably conservative since only a portion of the subscriber terminals would be in the 3 dB beamwidth of the GEOSTAR satellites.

6.1.3 GEOSTAR Subscriber Terminals Sharing with the IRIDIUM Satellite

The derivation of the uplink C/I in the IRIDIUM satellite due to the GEOSTAR subscriber terminals is contained in Annex D. The spread spectrum modulation and short pulse duration, used on the GEOSTAR transmissions, allow the IRIDIUM satellites to share the spectrum with GEOSTAR transmissions. A GEOSTAR subscriber terminal transmits a 17 to 18 dBw burst that has an approximate duration of 20 to 80 ms and is spread over a 16 MHz frequency band. The resulting 14 dB C/I is considered to be acceptable to the IRIDIUM system.

6.1.4 GEOSTAR Subscriber Terminal Sharing with the IRIDIUM Subscriber Terminals

The GEOSTAR subscriber terminals transmit into the receive band of the IRIDIUM system subscriber terminal. The probability of interference is low due to the short burst length and geographical dispersion of the GEOSTAR subscriber terminals.

The IRIDIUM subscriber terminal combats this interference in the following ways:

1. Pulse blankers: The GEOSTAR burst has a duration of 20 to 80 milliseconds. The subscriber terminal will blank this pulse if it is strong enough to exceed a threshold signal level. This prevents pulse stretching and damage to the receiver.

2. Error detection and correction: The packet format contains error correction and detection coding. Missing packets are detected. The voice vocoder will interpolate across missing packets. The vocoder uses the same technology as the U.S. digital cellular system and can interpolate across 6 missing voice frames. Automatic repeat request is used to request retransmission of missing data packets.

6.2 Sharing with GLONASS

GLONASS is the Soviet satellite navigation system. The satellite constellation may have up to 24 satellites in subsynchronous polar orbit. . Each of these satellites has a separate frequency. The satellite frequencies are spaced 562.5 KHz and extend up to 1615.5 MHz. The bandwidth occupancy of each satellite is approximately 1 MHz. IRIDIUM will not use the frequency bands from 1610 to 1616 MHz that are actually being used by GLONASS.

6.3 Sharing with Radio Astronomy

The Radio Astronomy band extends from 1610.5 to 1613.5 MHz. The Radio Astronomy sites are fixed. Sharing would be accomplished by not using the frequencies in the cells that include the Radio Astronomy sites.

6.4 Sharing with Aeronautical Public Correspondence

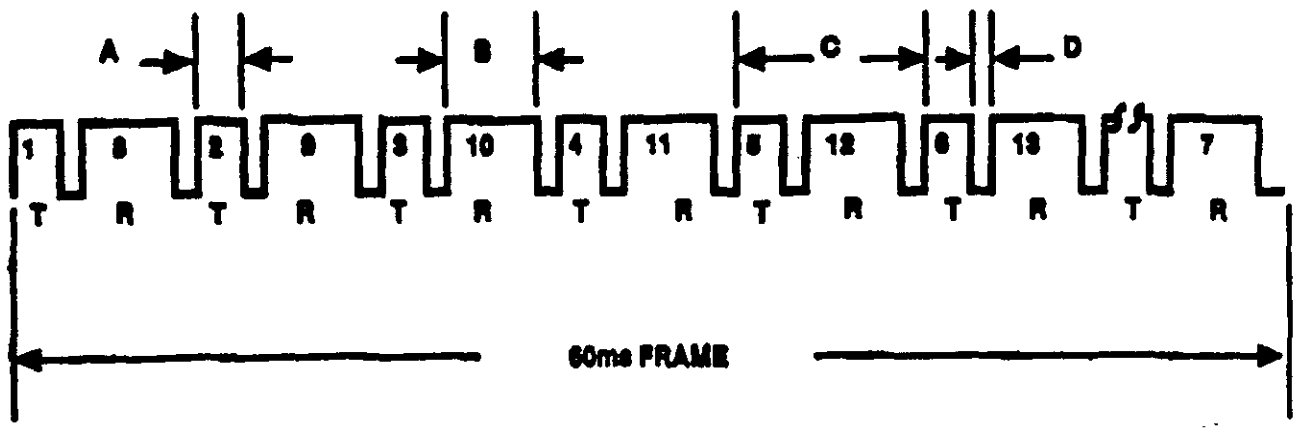
There is an Aeronautical Public Correspondence band from 1625.5 to 1626.5 MHz, which is not widely used. The IRIDIUM system would share this band by not using these frequencies in the cells that would interfere with the operation of the service.

ANNEX A

Multiple Access Format

IRIDIUM uses a combination of time and frequency division multiple access to efficiently use spectrum, maintain subscriber equipment that is both affordable and simple, and to provide a network which is flexible and responsive to changing environments and applications. The time division multiple access is evident in a 60 ms repetitive frame which is established for the system and repeats ad infinitum. The time waveform at the space station is shown in Figure 1. The shorter intervals, each 1.3 milliseconds, are the transmit times for the space craft, while the longer 2.9 millisecond intervals are the receive intervals aboard the space craft . Each frame begins with a transmit time for the first time slot, labeled 1, which is followed by the receive time slot which corresponds to the transmit time slot 8. Downlink burst transmissions occur during the space craft transmit interval while uplink communication bursts occurs during the space craft receive bursts. Thirteen additional pairs of transmit and receive time slots complete the frame, each of which is a couplet of a transmit time and a receive time corresponding to a transmit time slot a half frame away. This half frame separation eases the processing burden in the ground subscriber units by providing time between the receipt of a down link message and the initiation of an uplink transmission. The interleaving of the transmit and receive pairs provides the full guard interval both in front of and behind the receive bursts. The guard is the means by which range change accumulations are buffered until a handshaking exchange between the subscriber units and the satellite recenters the uplink burst in the receive window. The time slots also provide time separation which implements frequency reuse. The downlink carriers may all be in use in each of the time slots as all of the uplink carrier frequencies may be occupied during the uplink intervals.

A = TRANSMIT BURST TIME	= 1.3 MILLISECOND
B = RECEIVE BURST TIME	= 2.9 MILLISECONDS
C = TIME BETWEEN BURSTS	= 4.2857 MILLISECONDS
D = GUARD TIME	= 42.857 MICROSECONDS



T = TRANSMIT TIME

R = RECEIVE TIME

FIGURE 1 - SATELLITE TDMA FORMAT

ANNEX B

This Annex consists of an extract from Document No. US IWP 8/15-USA-6

Document Title

Possibilities for Frequency Sharing Between Mobile-Satellite Services Using Geostationary Satellites and Other Services in Approximate Range 1-3 GHz

The Authors are:

Tom Sullivan: AMSC
Jeff Binkes: COMSAT
Ron Lepkowski: GEOSTAR

The part that has been extracted is Annex I, MSS/RDSS sharing in the 1610-1626.5 MHz Band.

MSS/RDSS Sharing in the 1610-1626.5 MHz Band

The capacity of an RDSS inbound (mobile terminal to central earth station) transponder is limited by external interference and by the code noise caused by other spread spectrum signals passing through the transponder at the same time. The effect of a number (K) of such simultaneous spread spectrum transmissions carried over the transponder can be estimated from the following formula presented in Section 3.6.1 of CCIR Report 1050:

$$[E_b/N_o]^{-1}_{req} = [E_b/N_o]^{-1}_{single} + (K-1)\,[E_b/N_o]^{-1}_{code\ noise}$$

and, assuming the the effects of code noise are about 2/3 the effects of thermal noise,

$$[E_b/N_o]_{code\ noise} = 1.5 \cdot R_s$$

where:

$[E_b/N_o]_{req}$ =	E_b/N_o required to achieve desired BER;
$[E_b/N_o]_{single}$ =	predicted link E_b/N_o in absence of code noise;
R_s =	spread ratio, i.e. ratio of chip rate to data rate.

For the Geostar RDSS system, typical values are 4.9 (6.9 dB), 11.7 (10.7 dB) (unfaded condition), and 512 (27.1 dB) for $[E_b/N_o]$req, $[E_b/N_o]$single, and R_s, respectively. This results in an upper limit on RDSS transponder capacity of approximately 92 simultaneous RDSS signals passing through the inbound transponder at any instant.

The effects of interference from an external MSS system can be estimated by calculating the equivalent number of simultaneous RDSS transmissions that would be displaced by the aggregate noise produced by the MSS transmitters in the RDSS bandwidth using the following formula adapted from equation (5) of Section 1.4.1 of Annex II to CCIR Report 1050:

$$10 \log_{10} [N_{rdss}] = EIRP_{mss} + 10 \log_{10} [N_{mss}] - EIRP_{rdss} - DG_{sat} + FBW$$

where:

N_{rdss} = equivalent number of simultaneous RDSS users suppressed by the aggregate MSS interference

$EIRP_{mss}$ = EIRP of an MSS channel (dBW)

N_{mss} = number of MSS channels within the RDSS satellite receiver bandwidth

$EIRP_{rdss}$ = EIRP of a typical RDSS transmitter (dBW)

DG_{sat} = RDSS space station antenna discrimination towards the MSS service area (dB) (assumed to be 0 dB for the co-coverage case considered here)

FBW = effective attenuation of the MSS signals by the RDSS demodulation (dB).

For the case of a narrowband interfering MSS carrier, the correlation process used in the spread spectrum RDSS receiving process results in a spreading of the MSS carrier into a $\sin^2(x)/x^2$ spectrum, reducing the amount of interfering power falling within the passband of the demodulator in the RDSS ssystem. For multiple interfering MSS carriers evenly spaced across the RDSS transponder bandwidth, this interference reduction effect is reflected in the value of the FBW factor, which can be calculated from the following formula derived as an extension of formula (6) in Section 1.4.1 of Annex II to CCIR Report 1050:

$$FBW = 10\log 10\left[\frac{1}{N_{mss}}\sum_{k=0}^{N_{mss}-1}\left\{\frac{\sin\left(\pi\,\frac{-8.25+BW_{mss}/2+k\cdot\Delta BW}{8}\right)}{\left(\pi\,\frac{-8.25+BW_{mss}/2+k\cdot\Delta BW}{8}\right)}\right\}^2\right]$$

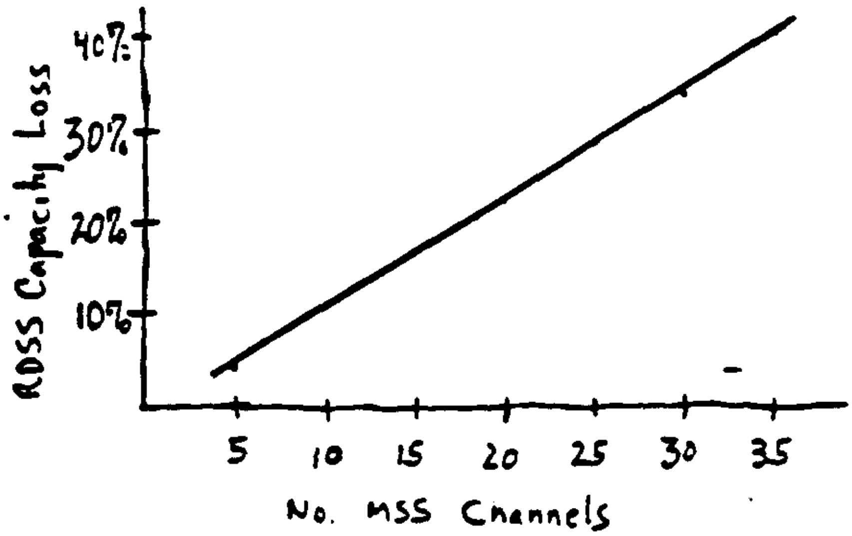
where:

BW_{mss} = banwidth of MSS channel (MHz)

ΔBW = frequency separation between MSS channels (MHz)

and 8 mcps is the transmission rate of the direct sequence pseudorandom noise code of the Geostar RDSS system.

The following figure plots the loss of RDSS capacity as a function of the number of MSS channels with an EIRP of 22 dBW (corresponding to an Inmarsat-M land mobile earth station channel) using the formulas given above.



In satellite sharing studies, it is generally accepted that no more than 20% of the noise in a channel should be produced by other satellite systems. In the case of interference from an MSS system into a spread spectrum RDSS system, this can be approximated by a 20% loss of RDSS capacity using the formulas given above. For the assumptions used in this analysis, a narrowband MSS system would have to be limited to about 17 or 18 channels to satisfy this criterion.

ANNEX C

Derivation of Up and Downlink Power for Sharing Analysis

The purpose of this Annex is to derive average and peak burst power for sharing calculations. Tables 1 and 2 show the link calculations for the up and down link. Tables 3 and 4 derive the average and peak burst satellite downlink sidelobe power. Tables 5 and 6 derive the average and peak burst uplink power for the subscriber terminals.

TABLE 1

DOWNLINK CALCULATIONS

	UNITS	CELL 1	CELLS 2&3	CELL4	CELL 5	CELL6	CELL 7
AZIMUTH ANGLE	Deg	5.39	19.75	6.59	30.00	10.89	30.00
GROUND RANGE FROM NADIR	NMi	1108.0	1026.9	810.7	744.0	492.1	186.0
NADIR ANGLE	Deg	61.56	60.82	57.69	56.26	47.58	23.98
GRAZING ANGLE	Deg	10.00	12.09	18.82	21.36	34.23	62.93
SLANT RANGE	NMi	1238.4	1157.8	949.9	887.3	664.2	457.5
XMTR BURST PWR INTO ANT	Watts	1.55	1.51	1.73	2.42	3.13	3.56
(Per Carrier)	dBm	31.89	31.79	32.38	33.83	34.95	35.51
PEAK ANT GAIN	dBi	24.99	24.99	23.87	23.02	20.00	12.04
EDGE LOSS	dB	0.50	0.50	1.70	1.50	2.60	3.80
SCAN LOSS	dB	0.95	1.43	1.42	3.00	3.61	0.00
TAPER LOSS	dB	1.00	1.00	1.00	1.00	1.00	0.00
XMTR NET ANT GAIN	dBi	22.54	22.06	19.75	17.52	12.79	8.24
XMT FEED/CKT LOSS	dB	1.30	1.30	1.30	1.30	1.30	1.30
EIRP	dBm	53.13	52.55	50.83	50.05	46.44	42.45
PATH LOSS	dB	163.84	163.25	161.53	160.94	158.43	155.19
POLARIZATION LOSS	dB	0.50	0.50	0.50	0.50	0.50	0.50
GASEOUS LOSS	dB	0.30	0.30	0.30	0.30	0.30	0.30
MEAN VEGETATION LOSS	dB	0.00	0.00	0.00	0.00	0.00	0.00
TOT PROPAGATION LOSS	dB	164.64	164.05	162.33	161.74	159.23	155.99
RCVR NET ANT GAIN	dBi	1.00	1.00	1.00	1.00	2.18	3.01
ANT NOISE TEMP	^{o}K	150.00	150.00	150.0	150.00	150.00	150.00
RCV FEED/CKT LOSS	dB	1.00	1.00	1.00	1.00	1.00	1.00
LNA NOISE FIGURE	dB	0.80	0.80	0.80	0.80	0.80	0.80
SYST NOISE TEMP, Ts	^{o}K	298.93	298.93	298.93	298.93	298.93	298.93
G/Ts	dBi/^{o}K	-23.76	-23.76	-23.76	-23.76	-22.57	-21.74
BOLTZMANN'S, k	dBm/Hz^{o}KdB	-198.60	-198.60	-198.60	-198.60	-198.60	-198.60
C/I		18.00	18.00	18.00	18.00	18.00	18.00
RCV'D C/No	dBHz	62.87	62.87	62.87	62.87	62.87	62.87
REQUIRED Eb/No	dB	3.10	3.10	3.10	3.10	3.10	3.10
CHANNEL DATA RATE	dBHz	54.77	54.77	54.77	54.77	54.77	54.77
IMPLEMENTATION LOSS	dB	2.00	2.00	2.00	2.00	2.00	2.00
REQUIRED C/No	dBHz	59.87	59.87	59.87	59.87	59.87	59.87
LINK MARGIN	dB	3.00	3.00	3.00	3.00	3.00	3.00
FLUX DENSITY per 4KHz BW	dBW/m^2	-132.1	-132.1	-132.1	-132.3	-133.4	-134.1

TABLE 2

UPLINK CALCULATIONS

	UNITS	CELL 1	CELLS 2&3	CELL4	CELL 5	CELL6	CELL 7
AZIMUTH ANGLE	Deg	5.39	19.75	6.59	30.00	10.89	30.00
GROUND RANGE FROM NADIR	NMi	1108.0	1026.9	810.7	744.0	492.1	186.0
NADIR ANGLE	Deg	61.56	60.82	57.69	56.26	47.58	23.98
GRAZING ANGLE	Deg	10.00	12.09	18.82	21.36	34.23	62.93
SLANT RANGE	NMi	1238.4	1157.8	949.9	887.3	664.2	457.5
XMTR BURST PWR INTO ANT	Watts	1.27	1.24	1.43	1.99	2.58	2.93
	dBm	31.05	30.95	31.54	32.99	34.11	34.67
XMTR NET ANT GAIN	dBi	1.00	1.00	1.00	1.00	2.18	3.01
XMT FEED/CKT LOSS	dB	0.70	0.70	0.70	0.70	0.70	0.70
EIRP	dBm	31.35	31.25	31.84	33.48	35.69	37.00
PATH LOSS	dB	163.84	163.25	161.53	160.94	158.43	155.19
POLARIZATION LOSS	dB	0.50	0.50	0.50	0.50	0.50	0.50
GASEOUS LOSS	dB	0.30	0.30	0.30	0.30	0.30	0.30
MEAN VEGETATION LOSS	dB	0.00	0.00	0.00	0.00	0.00	0.00
TOT PROPAGATION LOSS	dB	164.64	164.05	162.33	161.74	159.23	155.99
PEAK ANT GAIN	dBi	24.99	24.99	23.87	23.02	20.00	12.04
EDGE LOSS	dB	0.50	0.50	1.70	1.50	2.60	3.80
SCAN LOSS	dB	0.95	1.43	1.42	3.00	3.61	0.00
TAPER LOSS	dB	1.00	1.00	1.00	1.00	1.00	0.00
XMTR NET ANT GAIN	dBi	22.54	22.06	19.75	17.52	12.79	8.24
ANT NOISE TEMP	^{o}K	290.00	290.00	290.00	290.00	290.00	290.00
RCV FEED/CKT LOSS	dB	1.80	1.80	1.80	1.80	1.80	1.80
LNA NOISE FIGURE	dB	1.00	1.00	1.00	1.00	1.00	1.00
SYST NOISE TEMP, Ts	^{o}K	552.58	552.58	552.58	552.58	552.58	552.58
G/Ts	dBi/^{o}K	-5.52	-5.26	-7.59	-9.64	-14.49	-19.58
BOLTZMANN'S, k	dBm/Hz^{o}KdB	-198.60	-198.60	-198.60	-198.60	-198.60	-198.60
C/I		18.00	18.00	18.00	18.00	18.00	18.00
RCV'D C/No	dBHz	59.90	59.90	59.90	59.90	59.90	59.90
REQUIRED Eb/No	dB	3.60	3.60	3.60	3.60	3.60	3.60
CHANNEL DATA RATE	dBHz	51.30	51.30	51.30	51.30	51.30	51.30
IMPLEMENTATION LOSS	dB	2.00	2.00	2.00	2.00	2.00	2.00
REQUIRED C/No	dBHz	56.90	56.90	56.90	56.90	56.90	56.90
LINK MARGIN	dB	3.00	3.00	3.00	3.00	3.00	3.00
FLUX DENSITY per 4KHz BW	dBW/m^2	-150.4	-149.9	-147.6	-145.4	-140.7	-136.1

TABLE 3

RDSS SHARING ANALYSIS

DERIVATION OF AVERAGE DOWNLINK SIDELOBE POWER

	Units	Cell 1	Cells 2 & 3	Cell 4	Cell 5	Cell 6	Cell 7
Peak EIRP	dBm	53.1	52.6	50.8	50.1	46.4	42.5
Avg to Peak Ratio	dB	-13.6	-13.6	-13.6	-13.6	-13.6	-13.6
Avg EIRP on Axis	dBm	39.5	39.0	37.2	36.5	32.8	28.9
Sidelobe Reduction	dB	-20.0	-20.0	-20.0	-20.0	-20.0	-20.0
Avg EIRP Off-Axis	dBm	19.5	19.0	17.2	16.5	12.8	8.9
Avg EIRP Off-Axis	watts	0.089	0.079	0.052	0.045	0.019	0.009
Weighting		6	12	6	6	6	1
EIRP X Wtg		0.535	0.953	0.315	0.268	0.114	0.009

Avg EIRP/spot beam/carrier = (summation of EIRP X WTG) / 37

= 0.059 watts/carrier = - 12.3 dBw/carrier

Nt = Total number of cells (spot beams) worldwide = 1628

LM % = Land Mobile spot beams (% of total) = 30 %

LOS % = Number of IRIDIUM satellites in line of sight to GEOSTAR satellite = 57 % (44 of 77)

L % = Average cell loading (% of peak) = 50 %

N = Number of active Land Mobile spot beams in view of the GEOSTAR satellite

= Nt X LM % X LOS % X L % = 1628 X 0.3 X .57 X .5 = 139

Pl = Polarization loss = 4 dB

EIRP(sat) = Average sidelobe/backlobe EIRP/carrier

= EIRP(sat) + 10 Log (N) - Pl

= -12.3 + 21.4 - 4.0 = 5.1 dBW/carrier

TABLE 4

RDSS SHARING ANALYSIS

DERIVATION OF PEAK DOWNLINK SIDELOBE POWER

	Units	Cell 1	Cells 2 & 3	Cell 4	Cell 5	Cell 6	Cell 7
Peak EIRP	dBm	53.1	52.6	50.8	50.1	46.4	42.5
Sidelobe Reduction	dB	-20.0	-20.0	-20.0	-20.0	-20.0	-20.0
Peak EIRP Off-Axis	dBm	33.1	32.6	30.8	30.1	26.4	22.5
Peak EIRP Off-Axis	watts	2.04	1.82	1.20	1.02	0.44	0.18
Weighting		6	12	6	6	6	1
EIRP X Wtg		12.25	21.84	7.21	6.14	2.62	0.18

Peak EIRP/spot beam/carrier = (summation of EIRP X WTG) / 37

= 1.36 watts/carrier = 1.3 dBw/carrier

Nt = Total number of cells (spot beams) worldwide = 1628

LM % = Land Mobile spot beams (% of total) = 30 %

LOS % = Number of IRIDIUM satellites in line of sight to GEOSTAR satellite = 57 % (44 of 77)

RU % = % of cells active due to the 7 cell reuse pattern = 1/7 = 14 %

L % = Average cell loading (% of peak) = 50 %

N = Number of active Land Mobile spot beams in view of the GEOSTAR satellite

= Nt X LM % X LOS % X RU % X L % = 1628 X 0.3 X .57 X .14 X .5 = 19

Pl = Polarization loss = 4 dB

Peak EIRP(sat) = Peak sidelobe/backlobe EIRP/carrier

= Peak EIRP/spot beam + 10 Log (N) - Pl

= 1.3 + 12.9 - 4.0 = 10.2 dBW/carrier

TABLE 5

DERIVATION OF AVERAGE UPLINK POWER

	Units	Cell 1	Cells 2 & 3	Cell 4	Cell 5	Cell 6	Cell 7
Peak EIRP	dBm	31.4	31.3	31.8	33.5	35.7	37.0
Avg to Peak Ratio	dB	-10.1	-10.1	10.1	10.1	10.1	10.1
Avg EIRP	dBm	21.3	21.2	21.7	23.4	25.6	26.9
Avg EIRP	mw	0.135	0.132	0.148	0.219	0.363	0.490
Weighting		6	12	6	6	6	1
EIRP X Wtg		0.809	1.582	0.887	1.313	2.178	0.490

Avg subscriber EIRP = (summation of EIRP X WTG) / 37

= 0..196 watts/carrier = - 7.1 dBW/ subscriber unit

Nt = Total number of cells worldwide = 1628

LM % = Land Mobile spot beams (% of total) = 30 %

LOS % = Number of Land Mobile cells visable to RDSS satellite (% of total) = 50 %

L % = Average cell loading (% of peak) = 50 %

VA % = Voice activity of each carrier = 40 %

N = Number of active Land Mobile subscriber terminal transmitters visable to the RDSS satellite/carrier slot

= Nt X LM % X LOS % X L % X VA % = 1628 X 0.3 X 0.5 X 0.5 X 0.4 = 48

Pl = Polarization loss = 4 dB

Avg EIRP(sub) = Average EIRP for the subscriber units/carrier slot

= Avg EIRP(sub) + 10 Log (N) + Pl

= - 7.1 + 16.8 - 4.0 = 5.7 dBW/ carrier slot

TABLE 6

DERIVATION OF PEAK UPLINK POWER

	Units	Cell 1	Cells 2 & 3	Cell 4	Cell 5	Cell 6	Cell 7
Peak EIRP	dBm	31.4	31.3	31.8	33.5	35.7	37.0
Peak EIRP	watts	1.38	1.35	1.51	2.24	3.72	5.0
Weighting		6	12	6	6	6	1
EIRP X Wtg		8.28	16.19	9.08	13.43	22.23	5.0

Peak EIRP/spot beam = (summation of EIRP X WTG) / 37

= 2.0 watts/carrier = 3.0 dBW/ spot beam

Nt = Total number of cells worldwide = 1628

LM % = Land Mobile spot beams (% of total) = 30 %

LOS % = Number of Land Mobile cells visable to RDSS satellite (% of total) = 50 %

RU % = % of cells active due to the 7 cell reuse factor = 1/7 = 14 %

L % = Average cell loading (% of peak) = 50 %

VA % = Voice activity of each carrier = 40 %

N = Number of active Land Mobile subscriber terminal transmitters visable to the RDSS satellite/carrier slot

= Nt X LM % X LOS % X RU % X L % X VA % = 1628 X 0.3 X 0.5 X .14 X 0.5 X 0.4 = 7

Pl = Polarization loss = 4 dB

Peak EIRP(sub) = Peak EIRP for the subscriber units/carrier slot

= Peak EIRP/spot beam + 10 Log (N) + Pl

= 2.0 + 8.5 - 4.0 = 6.5 dBW/ carrier slot

ANNEX D

DERIVATION OF THE UPLINK C/I RATIO IN THE IRIDIUM SATELLITE DUE TO THE RDSS SUBSCRIBER TERMINALS

The RDSS subscriber terminals transmit a 20 to 80 ms spread spectrum burst at a power between 17 and 18 dBW. This power is spread over a 16 MHz bandwidth. The IRIDIUM subscriber terminal transmits a 2.9 ms burst with an occupied bandwidth of 126 KHZ.

The carrier-to-interference (C/I) ratio in the IRIDIUM satellite may be estimated as follows:

C/I = EIRP(irid) - BW(irid) - EIRP(rdss) + BW(rdss) + Pl (all in dB)

where:

EIRP(irid) = Peak burst power of the IRIDIUM subscriber terminal (dBW)
= 6.5 dBW
BW(irid) = Occupied bandwidth of the uplink IRIDIUM transmission
= 126 kHz = 51 dB
EIRP(rdss) = Peak burst power of the RDSS subscriber terminal
= 17.5 dBW
BW(rdss) = Occupied bandwidth of the uplink RDSS transmission
= 16 MHz = 72 dB
Pl = Polarization loss = 4 dB

solving:

C/I = 6.5 - 51 - 17.5 + 72 + 4
= 14.0 dB

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Circular Polar Constellations Providing Continuous Single or Multiple Coverage Above a Specified Latitude[1]

W. S. Adams[2] and L. Rider[3]

Abstract

Arbitrarily and optimally phased polar orbit constellations using minimum total numbers of satellites to achieve continuous single or multiple coverage above a specified latitude are derived using a street-of-coverage technique. The first fifty members of families of minimal constellations are provided for single, double, triple, and quadruple coverage above 0, 30, 45, and 60 degrees. Approximations are derived which relate the total number of satellites in a constellation to the size of the Earth coverage cap associated with each satellite in the constellation.

Introduction

A primary activity of systems planners in designing potential navigation, communication, surveillance, and defense systems is to perform those conceptual trade studies which lead to the identification of minimal-cost, low-risk preliminary system architectures that satisfy a given performance requirement while utilizing a projected technological capability. In many cases when such systems employ a space-based segment, to meet this goal requires the identification of families of satellite constellations which exemplify the trade-off between total number of satellites and the Earth coverage required from each satellite of the constellation such that a specified continuous Earth coverage criterion is met. Consequently, the identification of "minimal" constellations is an important aspect of system architecture selection deliberations.

This article addresses the problem of synthesizing circular polar orbit constellations with the fewest number of satellites at a common altitude that provide continuous single or multiple coverage above an arbitrary geocentric latitude. Prior analyses [1–4] have

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already addressed some aspects of this problem: In [1] minimal constellations were determined which provide *single* global and zonal coverage using *arbitrary* phasing between satellites in different orbital planes; the "star patterns" discussed in [2] utilize *optimal* inter-plane satellite phasing to find minimal constellations which provide *single* or *double global* coverage; optimal inter-plane satellite phasing was also used in [3] to determine constellations providing single and triple global and polar cap coverage; and the analysis [4] compares arbitrarily phased and optimally phased polar constellations for multiple global coverage, provides arbitrarily phased polar constellation data for multiple polar cap coverage, but does not provide *optimally phased* polar constellation data for multiple polar cap coverage.

The present study augments the analysis of polar orbit constellations by characterizing the complete families of minimal polar orbit constellations that provide continuous single or multiple coverage above an arbitrary geocentric latitude using either arbitrary[4] or optimal inter-plane satellite phasing. As is the case with [1], [3], [4], and [5], this study utilizes a "street-of-coverage" technique and assumes that all orbital planes have the same number of satellites with the satellites symmetrically distributed in each orbital plane. Unlike [3] and [4], certain simplifications are avoided, so the results achieved herein are more precise than those found in [3] and [4].

Streets-of-Coverage

The "street-of-coverage" technique was first used in [1] and generalized in [4]. The latter formulation, also used herein, requires that the coverage circles for the symmetrically distributed satellites in each orbital plane overlap to provide a continuous band, or "street," of coverage along the orbital projection. This condition is illustrated in Fig. 1. As shown, the half-street width of coverage c_j is a function of the satellite radius of coverage — identified by an Earth-central angle θ — and j, an integer which indicates the multiple level of coverage to be provided by satellites from the same orbital plane. The magnitude of c_j is given by

$$c_j = \arccos[\cos\theta/\cos(j\pi/s)] \qquad (1)$$

where s is the number of satellites in each orbital plane. For finite constellation altitudes, no satellite is able to cover a complete hemisphere, and thus, the minimum value of s considered will be 3.

Multiple coverage can be provided not only by redundant coverage ensured by satellites from the same orbital plane but also by overlapping streets-of-coverage from different orbital planes. If n is the desired level of multiple coverage, n can be factored into $j \times k$, where j is defined as above, and k is the level of multiple coverage provided by overlapping streets-of-coverage.

Arbitrarily Phased Constellations

If inter-plane satellite phasing is not to be exploited, ensuring continuous n-fold coverage above the lower latitude bound ϕ of a polar cap region by satellites from inter-

[4]As far as this article is concerned, "arbitrary" phasing means that no single inter-plane satellite phasing angle needs to be maintained among the satellites in the various orbital planes which comprise the constellation.

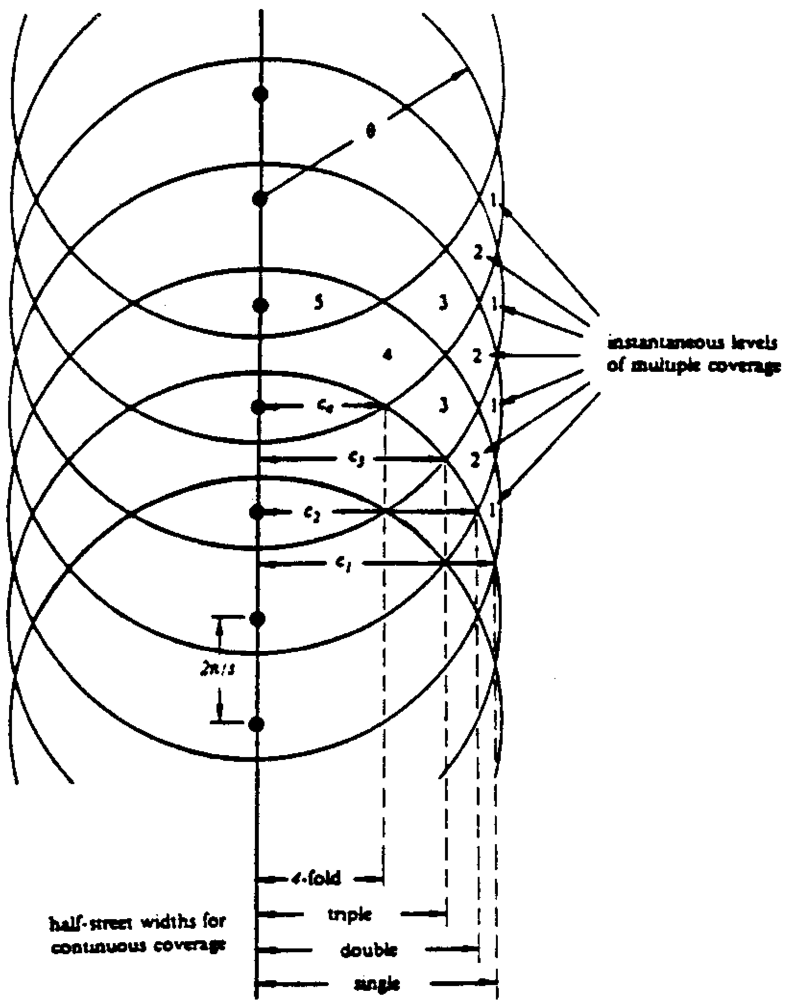

FIG. 1. Streets of Coverage.

facing orbital planes requires that the worst case coverage interface be determined by the half-street widths c_1 and c_j, as pictured in Fig. 2.

In [4] the constraint relation identified for n-fold global coverage using arbitrary inter-plane satellite phasing was found to be

$$p(c_1 + c_j) \geq k\pi \tag{2}$$

where p is the number of orbital planes in the constellation. From Fig. 2 and an application of the law of sines for spherical triangles, the generalization to n-fold coverage above an arbitrary latitude ϕ is seen to be

$$p[\arcsin(\sin c_1/\cos \phi) + \arcsin(\sin c_j/\cos \phi)] \geq k\pi \tag{3}$$

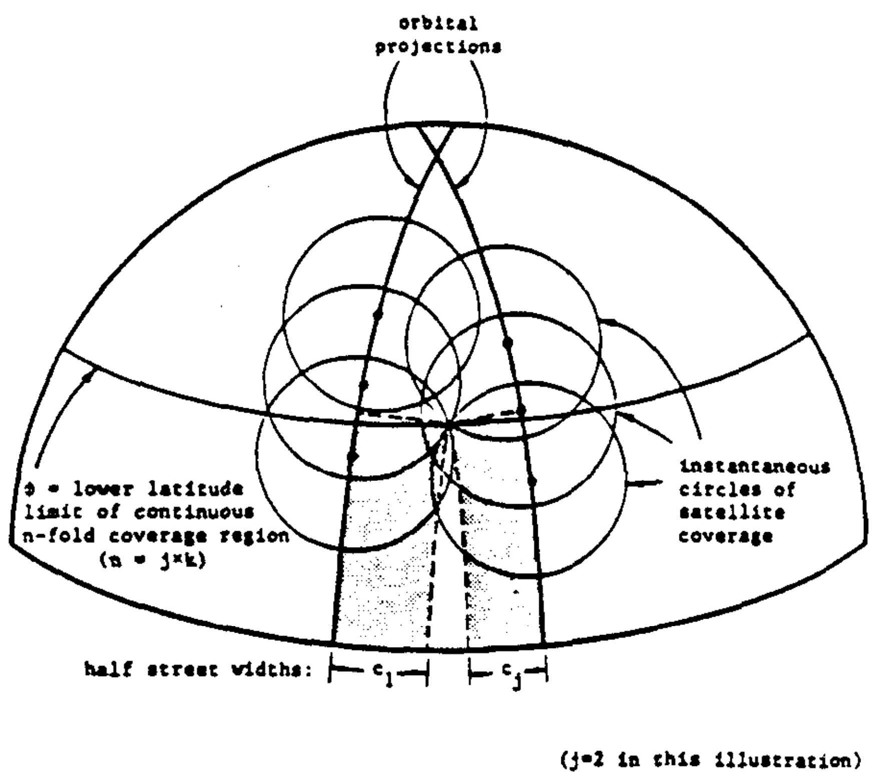

FIG. 2. Coverage Interface for Arbitrary Phasing

The inequality (3) holds for all values of j, k, and p such that $p > k$. When $p = k$, each orbital plane is required to provide continuous j-fold coverage independent of the other planes in the constellation, and therefore, the distance c_j must equal the co-latitude $\pi/2 - \phi$. The constraint relation which reflects this condition is given by

$$\theta \geq \arccos[\sin\phi\cos(j\pi/s)] \tag{4}$$

and follows directly from equation (1).

For arbitrary phasing the interfaces between adjacent orbital planes are independent of both the inter-plane satellite phasing and the relative sense of travel of the satellites in these planes. Consequently, the ascending nodes of the orbital planes can be equally spaced along half the equator using a separation angle of $\alpha = \pi/p$ radians.

Phased Coverage Interfaces

Suppose the streets-of-coverage from two orbital planes interface to provide continuous coverage above the latitude ϕ for the region that lies between the two planes. When the satellites in the two planes are moving in the same relative direction along the coverage interface, the interface is called a *co-rotating* interface, and when the satellites move in opposite directions along the interface, the interface is called a *counter-rotating* interface. Constraints which must be satisfied to ensure continuous coverage along an interface depend upon whether the interface is co-rotating or counter-rotating. Constraints for each type of interface are discussed below.

Co-rotating Interface

Since satellites move in the same relative direction along a common co-rotating interface, it is enough to determine constraints which will ensure coverage at the lower latitude limit of coverage ϕ. Let ω denote the inter-plane satellite phasing angle between satellites in two orbital planes A and B, and let $\delta = j(\text{mod } 2)$. The narrowest width of a j-fold street-of-coverage occurs at the cusp which is associated with the half-street width c_j. As illustrated in Fig. 3, when such a cusp from plane A is at the lower latitude limit ϕ, there is a satellite in plane A at latitude ζ, where

$$\zeta = \arcsin(\sin \phi/\cos c_j) + \delta\pi/s \tag{5}$$

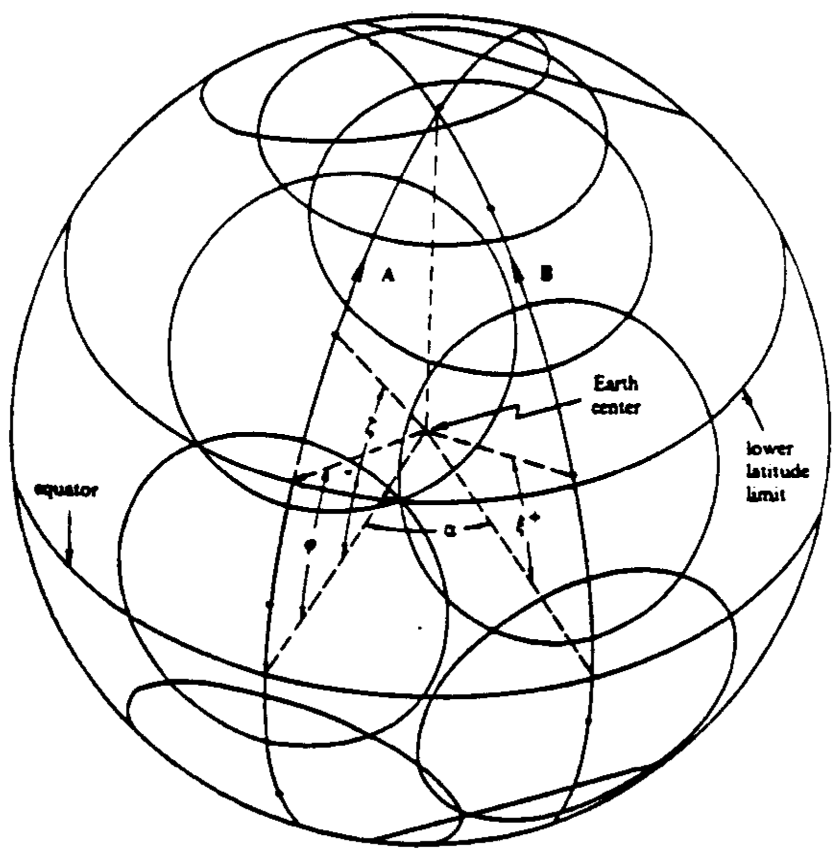

FIG. 3. Co-Rotating Interface.

Consequently, the latitude of satellites in plane B can be determined from the angular distances $\zeta + \omega + m(2\pi/s)$ measured from their ascending node, where the integer m ranges from 0 to $s - 1$. One of these satellites, having latitude ξ^+, will be closest to the plane A cusp at latitude ϕ. For continuous coverage along the interface, then, the angular separation α between the ascending nodes of planes A and B must satisfy the following constraint

$$\alpha \le \arcsin(\sin c_j/\cos\phi) + \arccos[(\cos\theta - \sin\xi^+ \sin\phi)/(\cos\xi^+ \cos\phi)] \tag{6}$$

Similarly, when a cusp from plane B is at the lower latitude limit ϕ, the latitude of satellites in plane A can be determined from the angular distances $\zeta - \omega + m(2\pi/s)$ measured from their ascending node, where again the integer m ranges from 0 to $s - 1$, and ζ is defined by equation (5). If the satellite in plane A that is closest to the plane B cusp has latitude ξ^-, then α must also satisfy

$$\alpha \le \arcsin(\sin c_j/\cos\phi) + \arccos[(\cos\theta - \sin\xi^- \sin\phi)/(\cos\xi^- \cos\phi)] \tag{7}$$

The determination of the latitude ξ^+ (or ξ^-) can be made by evaluating the expression $\arccos[(\cos\theta - \sin\xi \sin\phi)/(\cos\xi \cos\phi)]$ for all satellites in plane B (or A) where the satellite latitude ξ satisfies $|\xi - \zeta| \le \theta$; ξ^+ (or ξ^-) will correspond to the value of ξ which maximizes this expression.

Counter-rotating Interface

To provide continuous coverage along a counter-rotating interface, it is necessary to satisfy constraints which will ensure coverage at the lower latitude bound ϕ. As was the case for co-rotating interfaces, the critical situation occurs when a cusp from one plane's street-of-coverage lies at the latitude ϕ. Suppose such a cusp from plane A is at latitude ϕ and a satellite in plane A is at an angular distance of ζ from its ascending node, where ζ is again given by equation (1). If, as before, ω denotes the inter-plane satellite phasing angle at which satellites in plane B lead satellites in plane A, then the angular distances $\pi - [\zeta + \omega + m(2\pi/s)]$ measured from plane B's *descending* node, m ranging from 0 to $s - 1$, characterize the positions of the satellites in plane B. One of these satellites, having latitude ξ^+, will be closest to the plane A cusp at latitude ϕ. If α' denotes the angular separation between the ascending node of one orbital plane and the descending node of the other, then $\alpha' = \pi - \alpha$, and a necessary constraint that must be satisfied for continuous coverage at latitude ϕ along the counter-rotating interface is the following

$$\alpha' \le \arcsin(\sin c_j/\cos\phi) + \arccos[(\cos\theta - \sin\xi^+ \sin\phi)/(\cos\xi^+ \cos\phi)] \tag{8}$$

Likewise, an analogous constraint must be satisfied when the roles of planes A and B are reversed. When a cusp from plane B is at latitude ϕ, the positions of satellites in plane A are determined from the angular distances $\pi - [\zeta - \omega + m(2\pi/s)]$ measured from plane A's *descending* node, m again ranging from 0 to $s - 1$. One of these satellites, having latitude ξ^-, will be closest to the plane B cusp at latitude ϕ. The other constraint on α' can then be expressed as follows

$$\alpha' \leq \arcsin(\sin c_j/\cos \phi) + \arccos[(\cos \theta - \sin \xi^- \sin \phi)/(\cos \xi^- \cos \phi)] \tag{9}$$

The determination of the latitudes ξ^+ and ξ^- can be accomplished in a manner completely analogous to that used in the case of a co-rotating interface discussed previously.

The constraints (8) and (9) given above, which when satisfied, ensure that continuous coverage will always exist *at* latitude ϕ. However, those constraints alone are not sufficient to ensure continuous coverage everywhere *above* latitude ϕ along a counter-rotating interface. Since satellites move in opposite directions along such an interface, it is possible for a hole in coverage to open up above latitude ϕ even though coverage at latitude ϕ is continuous. This situation is depicted in Fig. 4. A necessary and sufficient condition for no such hole to occur along a counter-rotating interface is that α' be small enough so that whenever a c_j cusp from one plane's street-of-coverage is

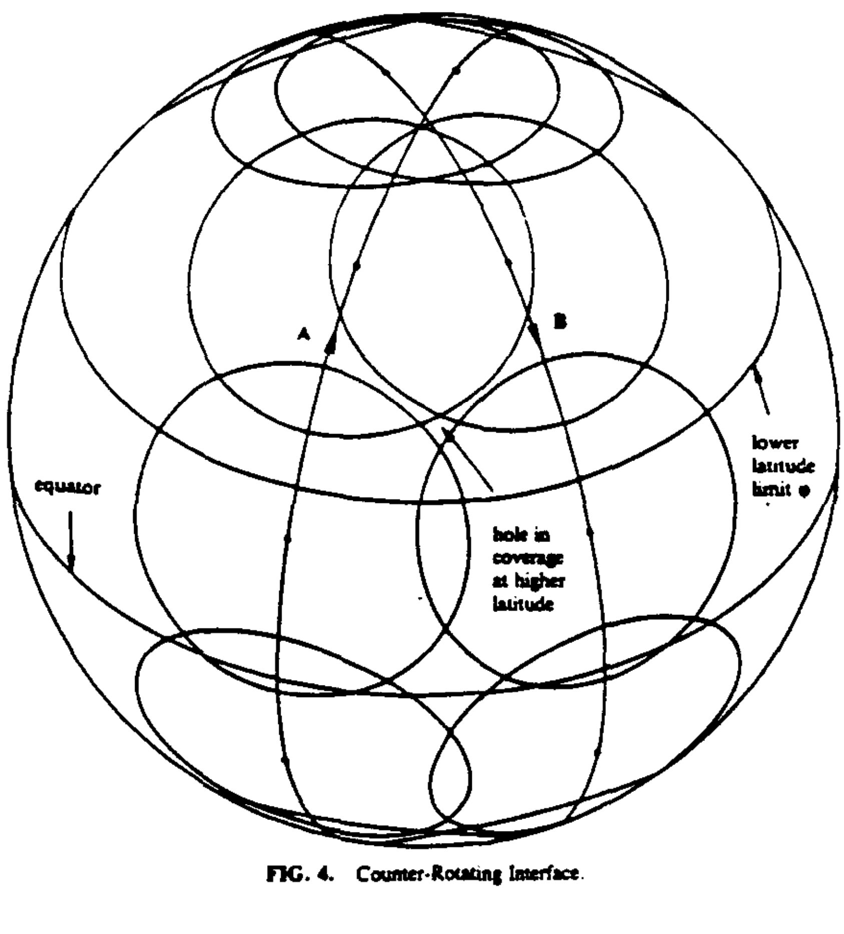

FIG. 4. Counter-Rotating Interface.

at the same latitude as a c_1 cusp from the other, the streets-of-coverage intersect. If ψ is the lowest latitude greater than or equal to ϕ at which this situation occurs, the constraint on α' can be given as

$$\alpha' \leq \arcsin(\sin c_i/\cos \psi) + \arcsin(\sin c_1/\cos \psi) \tag{10}$$

An explicit determination of ψ is given in Appendix A.

Phased Constellation Orientations

The *orientation* of a polar orbit constellation is determined by the inter-plane satellite phasing angle ω and the angular separation α between ascending nodes of successive orbital planes whose satellites possess this phasing. Ascending nodes can be placed so that the numbers of co-rotating and counter-rotating interfaces vary. Since the goal of this analysis is to arrive at minimal constellations, for a given choice of ϕ, θ, and ω, it is prudent to maximize the number of one type of interface over the other, depending upon which type is less constraining to the coverage problem. Constellations with a maximal number of co-rotating interfaces will be called *co-oriented*, and those with a maximal number of counter-rotating interfaces will be called *counter-oriented*. If p is the number of orbital planes in a constellation, there will be p coverage interfaces. It will be shown that at least $p - 1$ of these interfaces can be made either all co-rotating or all counter-rotating. The exceptional interface is the one between the pth and first planes. It should be noted that the inter-plane satellite phasing angle along this interface is $(p - 1)\omega \pmod{2\pi/s}$. Since this phasing angle possibly differs from ω, it is likely that the angular separation between the ascending nodes for the pth and first orbital planes may differ from α: for this reason this angular separation will be denoted β, and β' will be defined as $\pi - \beta$. The coverage constraints for α and α' previously discussed also apply to β and β' with $(p - 1)\omega \pmod{2\pi/s}$ taking the role of ω.

Co-oriented Constellations

Recall that in the factorization $j \times k$ of the level of coverage n, k is the minimum number of streets-of-coverage which must overlap every point in the covered region. When k equals 1, ascending nodes can be distributed over π radians with an approximate value for α being π/p. From the example illustrated in Fig. 5A, note that all coverage interaces will be co-rotating except the last one between the pth and first orbital planes. There is no manner of distributing ascending nodes in order to have all co-rotating interfaces when k equals 1. When k equals 2, ascending nodes can be distributed over 2π radians with an approximate value for α being $2\pi/p$. An example of this situation is depicted in Fig. 5B. In this case all interfaces will be co-rotating; however, the exceptional interface between the pth and first orbital planes has a potentially different inter-plane satellite phasing angle than the other interfaces. In general, to maximize the number of co-rotating interfaces characterized by the angle α, ascending nodes should be distributed over $k\pi$ radians with an approximate value for α being $k\pi/p$. When k is odd, the exceptional interface is counter-rotating and is characterized by the angle β'; when k is even, the exceptional interface is co-rotating and is characterized by the angle β. It should be noted that when k and p are not relatively prime, there is a possibility of co-incidence of orbital planes; this situation will not be considered for viable constellations.

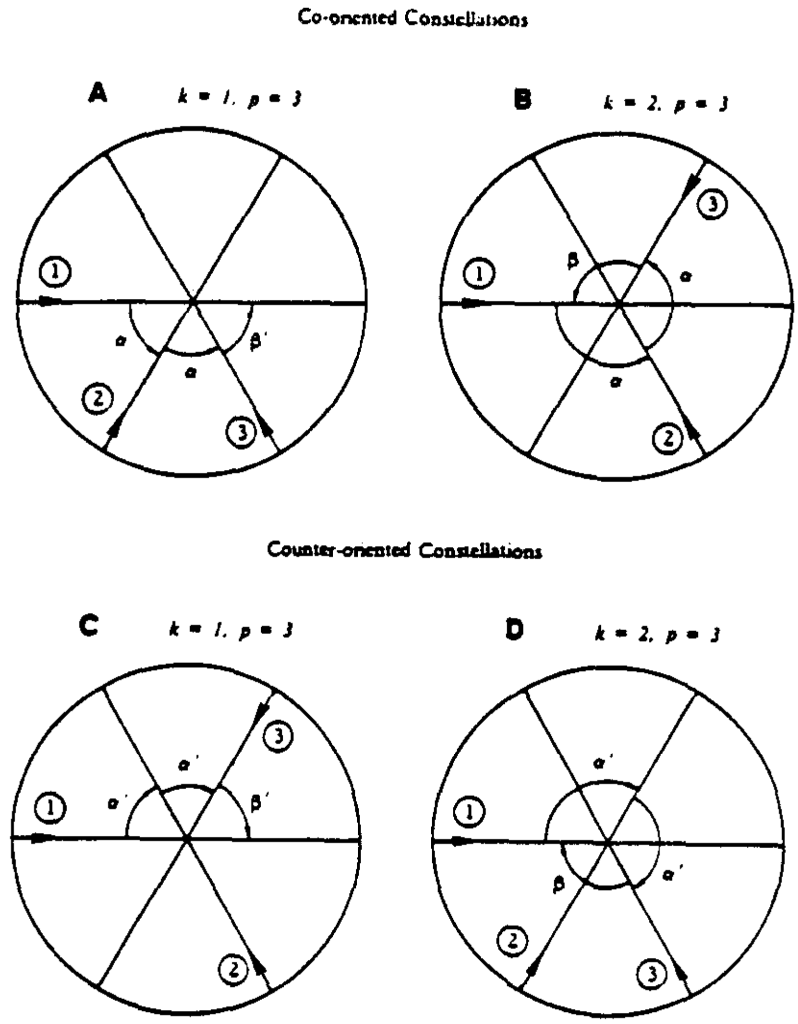

FIG. 5. Constellation Orientation Examples.

For a co-oriented constellation, a constraint which must be satisfied to ensure continuous coverage above latitude ϕ is given by

$$(p - 1)\alpha + \beta' \geq k\pi \tag{11}$$

when k is odd, or

$$(p - 1)\alpha + \beta \geq k\pi \tag{12}$$

when k is even. Naturally, α must satisfy the inequalities given in (6) and (7), and when k is even, β must satisfy the appropriate analogs of these same inequalities. If k is odd, β' must satisfy the analogs of (8), (9), and (10).

Counter-oriented Constellations

Generalizing from the examples in Figs. 5C and 5D, the number of counter-rotating interfaces characterized by the angle α' can be maximized by distributing ascending nodes over $(p-k)\pi$ radians with an approximate value for α being $(p-k)\pi/p$. When both p and k are odd, all interfaces will be counter-rotating with the exceptional interface between the pth and first orbital planes being characterized by the angle β'. When either p or k is even, the exceptional interface will be co-rotating and will be characterized by the angle β. When p and $p-k$ are not relatively prime, there is a possibility of co-incidence of orbital planes, and again, this situation will not be allowed in determining potential constellations.

For a counter-oriented constellation, a constraint which must be satisfied to ensure continuous coverage above latitude ϕ is given by

$$(p-1)\alpha' + \beta' \geq k\pi \tag{13}$$

when k and p are both odd, or

$$(p-1)\alpha' + \beta \geq k\pi \tag{14}$$

when either k or p is even. The angle α' must satisfy the inequalities given in (8), (9), and (10), and when k and p are both odd, β' must satisfy the appropriate analogs of these same inequalities. If either k or p is even, β must satisfy the analogs of (6) and (7).

Minimal Constellations

The determination of polar orbit constellations with the fewest number of satellites that provide continuous n-fold coverage above latitude ϕ has been facilitated by developing iterative computational procedures that calculate minimum θ-values which satisfy the appropriate coverage constraint. For arbitrarily phased constellations this implies solving (3) when equality holds; such a solution is obtained by employing Newton's method of approximating roots to differentiable functions. When inter-plane satellite phasing is to be exploited, the iterative procedure is more complicated since it must determine a minimum θ for which a phasing angle ω exists such that equality will hold in the applicable coverage constraint given by (11), (12), (13), or (14). These computational procedures are incorporated into the minimal constellation selection process in the following manner: ϕ and n are given. Potential values of T, the total number of satellites in a constellation, are examined in increasing order. For a selected value of T, all factorizations of both $T = p \times s$ and $n = j \times k$ are considered. When optimal phasing is to be considered, both co-oriented and counter-oriented constellations are examined. A minimum value for θ is determined using the applicable iterative computational procedure so that equality will hold in the appropriate coverage constraint; for optimally phased constellations an associated phasing ω is also found. If the value of θ so determined is larger than a previous value of θ computed either for a smaller value of T or for a different factorization of either the current T or n, then the constellation cannot be minimal and is discarded. If, on the other hand, the value of θ is smaller than that determined for a previous constellation consisting of T satellites, then the previous constellation cannot be minimal and is discarded. The constellations which remain after this discarding process are precisely the minimal constellations as a function of the satellite radius of coverage θ.

The first fifty members of families of arbitrarily phased and optimally phased minimal constellations are given in Tables 1–4 and Tables 5–8, respectively, for values of n ranging from 1 to 4, and for values of ϕ equal to 0, 30, 45, and 60 degrees. It should be noted that when ϕ is greater than zero, continuous j-fold coverage is possible using satellites in a single orbital plane. Since inter-plane satellite phasing need not be a concern in these cases, minimal constellations providing continuous n-fold coverage, where each plane provides continuous j-fold coverage, have been included only in the tables pertaining to arbitrary phasing. The $j \times k$ factorizations of n are given in Tables 1–4 for arbitrarily phased constellations; however, due to space restrictions, *such factorizations are not given for the optimally phased constellations*. Nevertheless, it is possible to easily determine the integers j and k: the j-value for a constellation is the greatest factor of n less than $s\theta/180°$, where θ is given in degrees, and the integer k must equal n/j. Inspection will reveal that all factorizations of n appear in the tables; however, the factorization with $j = n$ is the predominant one.

It is interesting to note that for optimally phased constellations and the values of n considered, counter-oriented constellations are never minimal for global coverage, unless one considers two plane constellations as being counter-oriented. (Two plane constellations are both co-oriented and counter-oriented.) However, for higher values of ϕ, some minimal constellations are counter-oriented (e.g., $\phi = 30°$, $n = 2$, and $T = 12$). A determination of the integers j and k as indicated above will reveal whether a constellation is co-oriented or counter-oriented: using a constellation's α-value given in degrees, *if $k \approx p\alpha/180°$, the constellation will be co-oriented, and if $k \approx p - p\alpha/180°$*, the constellation will be counter-oriented.

Comparison with Prior Results

As was noted in the introduction, prior studies have addressed various special cases of the general problem treated herein. A comparison of those previous results with the ones that have been presented here is in order.

In [1] Lüders showed that an arbitrarily phased minimal constellation supplying continuous single coverage above a specified latitude ϕ must have a satellite radius of coverage which in the terminology of the present study is characterized by the following

$$\theta = \arccos[\cos(\pi/s)\sqrt{1 - \cos^2 \phi \sin^2(\pi/2p)}] \tag{15}$$

It can easily be shown that equation (15) follows immediately from (3) by setting $j = k = 1$.

The polar orbit "star patterns" used by Walker in [2] yield essentially the same results as those obtained herein for continuous single global coverage using optimal inter-plane satellite phasing. The results for continuous double global coverage in [2], however, can be improved upon; this is apparent by noting that the $p = 3$, $s = 3$ constellation given there required a satellite radius of coverage equal to 74.0 degrees, whereas the value in Table 5 here indicates that by using a different distribution of satellites, a θ equal to 71.253 degrees is sufficient.

In [3] Beste was the first in external publications to consider optimal inter-plane satellite phasing using both polar orbits and a street-of-coverage technique. His analysis

TABLE I. Arbitrarily Phased Polar Constellations Providing Continuous Coverage Above 0 Degrees Geocentric Latitude

Single Coverage							Double Coverage							Triple Coverage							Quadruple Coverage						
j	*k*	*p*	*s*	*T*	theta	alpha	*j*	*k*	*p*	*s*	*T*	theta	alpha	*j*	*k*	*p*	*s*	*T*	theta	alpha	*j*	*k*	*p*	*s*	*T*	theta	alpha
1	1	2	3	6	69.295	90.000	1	2	3	3	9	75.522	60.000	1	3	4	3	12	78.969	45.000	2	2	3	5	15	77.496	60.000
1	1	2	4	8	60.000	90.000	2	1	2	5	10	73.221	90.000	3	1	2	7	14	77.524	90.000	2	2	3	6	18	71.744	60.000
1	1	2	5	10	55.106	90.000	2	1	2	6	12	64.341	90.000	1	3	5	3	15	72.909	36.000	2	2	3	7	21	68.502	60.000
1	1	3	4	12	52.239	60.000	2	1	2	7	14	59.156	90.000	3	1	2	8	16	69.295	90.000	4	1	2	11	22	67.591	90.000
1	1	2	7	14	50.425	90.000	2	1	2	8	16	55.839	90.000	3	1	2	9	18	63.806	90.000	4	1	2	12	24	63.638	90.000
1	1	3	5	15	45.522	60.000	2	1	2	9	18	53.576	90.000	3	1	2	10	20	60.000	90.000	4	1	2	13	26	60.639	90.000
1	1	3	6	18	41.410	60.000	2	1	2	10	20	51.959	90.000	3	1	2	11	22	57.256	90.000	4	1	2	14	28	58.314	90.000
1	1	3	7	21	38.715	60.000	2	1	2	11	22	50.761	90.000	3	1	2	12	24	55.210	90.000	4	1	2	15	30	56.477	90.000
1	1	4	6	24	36.860	45.000	2	1	3	8	24	47.462	60.000	3	1	2	13	26	53.644	90.000	4	1	2	16	32	55.000	90.000
1	1	3	9	27	35.531	60.000	2	1	3	9	27	43.958	60.000	3	1	2	14	28	52.415	90.000	4	1	2	17	34	53.794	90.000
1	1	4	7	28	33.655	45.000	2	1	3	10	30	41.420	60.000	3	1	2	15	30	51.434	90.000	4	1	2	18	36	52.796	90.000
1	1	4	8	32	31.400	45.000	2	1	3	11	33	39.519	60.000	3	1	2	16	32	50.637	90.000	4	1	2	19	38	51.961	90.000
1	1	5	7	35	31.033	36.000	2	1	3	12	36	38.057	60.000	3	1	3	11	33	50.150	60.000	2	2	5	8	40	50.393	36.000
1	1	4	9	36	29.754	45.000	2	1	3	13	39	36.908	60.000	3	1	2	17	34	49.981	90.000	4	1	2	22	44	50.132	90.000
1	1	5	8	40	28.519	36.000	2	1	3	14	42	35.988	60.000	3	1	3	12	36	46.920	60.000	2	2	5	9	45	47.450	36.000
1	1	4	11	44	27.569	45.000	2	1	4	11	44	35.111	45.000	3	1	3	13	39	44.408	60.000	4	1	3	16	48	46.752	60.000
1	1	5	9	45	26.658	36.000	2	1	4	12	48	33.226	45.000	3	1	3	14	42	42.418	60.000	2	2	5	10	50	45.331	36.000
1	1	5	10	50	25.243	36.000	2	1	4	13	52	31.735	45.000	3	1	3	15	45	40.814	60.000	4	1	3	17	51	44.796	60.000
1	1	6	9	54	24.814	30.000	2	1	4	14	56	30.536	45.000	3	1	3	16	48	39.504	60.000	4	1	3	18	54	43.162	60.000
1	1	5	11	55	24.142	36.000	2	1	4	15	60	29.556	45.000	3	1	3	17	51	38.419	60.000	4	1	3	19	57	41.785	60.000
1	1	6	10	60	23.270	30.000	2	1	4	16	64	28.744	45.000	3	1	3	18	54	37.510	60.000	4	1	3	20	60	40.613	60.000
1	1	5	13	65	22.569	36.000	2	1	4	17	68	28.064	45.000	3	1	3	19	57	36.741	60.000	4	1	3	21	63	39.608	60.000

1	1	6	11	66	22.059	30.000	2	1	5	14	70	27.850	36.000	3	1	3	20	60	36.085	60.000	4	1	3	22	66	38.740	60.000
1	1	7	10	70	21.996	25.714	2	1	4	18	72	27.490	45.000	3	1	3	21	63	35.521	60.000	4	1	3	23	69	37.985	60.000
1	1	6	12	72	21.091	30.000	2	1	5	15	75	26.673	36.000	3	1	4	16	64	35.364	45.000	4	1	3	24	72	37.324	60.000
1	1	7	11	77	20.701	25.714	2	1	5	16	80	25.695	36.000	3	1	3	22	66	35.032	60.000	4	1	3	25	75	36.742	60.000
1	1	6	13	78	20.305	30.000	2	1	5	17	85	24.874	36.000	3	1	4	17	68	33.922	45.000	4	1	3	26	78	36.227	60.000
1	1	7	12	84	19.660	25.714	2	1	5	18	90	24.178	36.000	3	1	4	18	72	32.710	45.000	4	1	3	27	81	35.769	60.000
1	1	6	15	90	19.123	30.000	2	1	5	19	95	23.582	36.000	3	1	4	19	76	31.682	45.000	2	2	7	12	84	35.156	25.714
1	1	7	13	91	18.809	25.714	2	1	5	20	100	23.067	36.000	3	1	4	20	80	30.802	45.000	4	1	3	29	87	34.993	60.000
1	1	8	12	96	18.672	22.500	2	1	5	21	105	22.621	36.000	3	1	4	21	84	30.043	45.000	4	1	4	22	88	34.451	45.000
1	1	7	14	98	18.106	25.714	2	1	6	18	108	22.269	30.000	3	1	4	22	88	29.383	45.000	2	2	7	13	91	33.828	25.714
1	1	8	13	104	17.771	22.500	2	1	5	22	110	22.231	36.000	3	1	4	23	92	28.807	45.000	4	1	4	23	92	33.434	45.000
1	1	7	15	105	17.518	25.714	2	1	6	19	114	21.579	30.000	3	1	4	24	96	28.300	45.000	4	1	4	24	96	32.542	45.000
1	1	8	14	112	17.022	22.500	2	1	6	20	120	20.983	30.000	3	1	4	25	100	27.852	45.000	4	1	4	25	100	31.754	45.000
1	1	7	17	119	16.599	25.714	2	1	6	21	126	20.464	30.000	3	1	4	26	104	27.454	45.000	4	1	4	26	104	31.056	45.000
1	1	8	15	120	16.392	22.500	2	1	6	22	132	20.009	30.000	3	1	5	21	105	27.418	36.000	4	1	4	27	108	30.433	45.000
1	1	9	14	126	16.236	20.000	2	1	6	23	138	19.609	30.000	3	1	4	27	108	27.099	45.000	4	1	4	28	112	29.877	45.000
1	1	8	16	128	15.858	22.500	2	1	6	24	144	19.255	30.000	3	1	5	22	110	26.605	36.000	4	1	4	29	116	29.377	45.000
1	1	9	15	135	15.573	20.000	2	1	7	21	147	19.109	25.714	3	1	5	23	115	25.892	36.000	4	1	4	30	120	28.926	45.000
1	1	8	17	136	15.402	22.500	2	1	6	25	150	18.940	30.000	3	1	5	24	120	25.265	36.000	4	1	4	31	124	28.519	45.000
1	1	9	16	144	15.009	20.000	2	1	7	22	154	18.596	25.714	3	1	5	25	125	24.710	36.000	4	1	4	32	128	28.148	45.000
1	1	10	15	150	14.960	18.000	2	1	7	23	161	18.144	25.714	3	1	5	26	130	24.216	36.000	4	1	4	33	132	27.812	45.000
1	1	8	19	152	14.668	22.500	2	1	7	24	168	17.743	25.714	3	1	5	27	135	23.775	36.000	4	1	4	34	136	27.504	45.000
1	1	9	17	153	14.525	20.000	2	1	7	25	175	17.386	25.714	3	1	5	28	140	23.379	36.000	4	1	4	35	140	27.222	45.000
1	1	10	16	160	14.371	18.000	2	1	7	26	182	17.067	25.714	3	1	5	29	145	23.022	36.000	4	1	4	36	144	26.964	45.000
1	1	9	18	162	14.106	20.000	2	1	7	27	189	16.780	25.714	3	1	5	30	150	22.700	36.000	4	1	5	29	145	26.656	36.000
1	1	10	17	170	13.863	18.000	2	1	8	24	192	16.732	22.500	3	1	5	31	155	22.408	36.000	4	1	5	30	150	26.093	36.000
1	1	9	19	171	13.742	20.000	2	1	7	28	196	16.521	25.714	3	1	5	32	160	22.142	36.000	4	1	5	31	155	25.584	36.000
1	1	10	18	180	13.423	18.000	2	1	8	25	200	16.336	22.500	3	1	6	27	162	21.895	30.000	4	1	5	32	160	25.122	36.000

TABLE 2. Arbitrarily Phased Polar Constellations Providing Continuous Coverage Above 30 Degrees Geocentric Latitude

Single Coverage							Double Coverage							Triple Coverage							Quadruple Coverage						
j	*k*	*p*	*s*	*T*	theta	alpha	*j*	*k*	*p*	*s*	*T*	theta	alpha	*j*	*k*	*p*	*s*	*T*	theta	alpha	*j*	*k*	*p*	*s*	*T*	theta	alpha
1	1	1	3	3	75.522	n/a	2	1	1	5	5	81.112	n/a	3	1	1	7	7	83.612	n/a	4	1	1	9	9	85.019	n/a
1	1	1	4	4	69.295	n/a	1	2	2	3	6	75.522	90.000	3	1	1	8	8	78.969	n/a	2	2	2	5	10	81.112	90.000
1	1	1	5	5	66.140	n/a	2	1	1	7	7	71.836	n/a	1	3	3	3	9	75.522	60.000	4	1	1	11	11	78.012	n/a
1	1	1	6	6	64.341	n/a	1	2	2	4	8	69.295	90.000	3	1	1	10	10	72.909	n/a	1	4	4	3	12	75.522	45.000
1	1	1	7	7	63.225	n/a	2	1	1	9	9	67.479	n/a	3	1	1	11	11	70.887	n/a	4	1	1	13	13	73.499	n/a
1	1	2	4	8	56.012	90.000	1	2	2	5	10	66.140	90.000	1	3	3	4	12	69.295	60.000	2	2	2	7	14	71.836	90.000
1	1	2	5	10	50.239	90.000	2	1	1	11	11	65.126	n/a	3	1	1	13	13	68.022	n/a	4	1	1	15	15	70.454	n/a
1	1	2	6	12	46.792	90.000	2	1	2	6	12	61.045	90.000	3	1	1	14	14	66.989	n/a	1	4	4	4	16	69.295	45.000
1	1	2	7	14	44.579	90.000	2	1	2	7	14	55.025	90.000	1	3	3	5	15	66.140	60.000	4	1	1	17	17	68.315	n/a
1	1	3	5	15	43.177	60.000	2	1	2	8	16	51.112	90.000	1	3	4	4	16	64.902	45.000	2	2	2	9	18	67.479	90.000
1	1	2	8	16	43.081	90.000	2	1	2	9	18	48.407	90.000	3	1	1	17	17	64.842	n/a	4	1	1	19	19	66.761	n/a
1	1	3	6	18	38.682	60.000	2	1	2	10	20	46.452	90.000	3	1	2	9	18	60.429	90.000	1	4	4	5	20	66.140	45.000
1	1	3	7	21	35.696	60.000	2	1	2	11	22	44.991	90.000	3	1	2	10	20	56.012	90.000	2	2	3	7	21	60.443	60.000
1	1	3	8	24	33.615	60.000	2	1	2	12	24	43.870	90.000	3	1	2	11	22	52.790	90.000	2	2	3	8	24	57.803	60.000
1	1	3	9	27	32.110	60.000	2	1	2	13	26	42.990	90.000	3	1	2	12	24	50.364	90.000	4	1	2	13	26	56.757	90.000
1	1	4	7	28	31.783	45.000	2	1	3	9	27	41.786	60.000	3	1	2	13	26	48.488	90.000	2	2	3	9	27	55.944	60.000
1	1	3	10	30	30.988	60.000	2	1	3	10	30	38.906	60.000	3	1	2	14	28	47.006	90.000	4	1	2	14	28	54.037	90.000
1	1	4	8	32	29.347	45.000	2	1	3	11	33	36.741	60.000	3	1	2	15	30	45.813	90.000	4	1	2	15	30	51.869	90.000
1	1	4	9	36	27.553	45.000	2	1	3	12	36	35.070	60.000	3	1	2	16	32	44.839	90.000	4	1	2	16	32	50.113	90.000
1	1	4	10	40	26.194	45.000	2	1	3	13	39	33.751	60.000	3	1	2	17	34	44.032	90.000	4	1	2	17	34	48.668	90.000
1	1	4	11	44	25.141	45.000	2	1	3	14	42	32.691	60.000	3	1	2	18	36	43.356	90.000	4	1	2	18	36	47.466	90.000
1	1	5	9	45	25.120	36.000	2	1	3	15	45	31.826	60.000	3	1	2	19	38	42.785	90.000	4	1	2	19	38	46.454	90.000
1	1	4	12	48	24.309	45.000	2	1	3	16	48	31.111	60.000	3	1	3	13	39	42.473	60.000	4	1	2	20	40	45.594	90.000

1	1	5	10	50	23.599	36.000	2	1	3	17	51	30.513	60.000	3	1	2	20	40	42.296	90.000	4	1	2	21	42	44.857	90.000
1	1	5	11	55	22.408	36.000	2	1	4	13	52	29.914	45.000	3	1	3	14	42	40.177	60.000	4	1	2	22	44	44.219	90.000
1	1	5	12	60	21.457	36.000	2	1	4	14	56	28.563	45.000	3	1	3	15	45	38.327	60.000	2	2	5	9	45	44.135	36.000
1	1	5	13	65	20.687	36.000	2	1	4	15	60	27.457	45.000	3	1	3	16	48	36.813	60.000	4	1	2	23	46	43.665	90.000
1	1	5	14	70	20.054	36.000	2	1	4	16	64	26.539	45.000	3	1	3	17	51	35.557	60.000	4	1	2	24	48	43.179	90.000
1	1	6	12	72	19.721	30.000	2	1	4	17	68	25.769	45.000	3	1	3	18	54	34.503	60.000	2	2	5	10	50	41.685	36.000
1	1	5	15	75	19.529	36.000	2	1	4	18	72	25.116	45.000	3	1	3	19	57	33.609	60.000	4	1	3	18	54	41.100	60.000
1	1	6	13	78	18.873	30.000	2	1	4	19	76	24.558	45.000	3	1	3	20	60	32.845	60.000	2	2	5	11	55	39.848	36.000
1	1	6	14	84	18.172	30.000	2	1	4	20	80	24.076	45.000	3	1	3	21	63	32.187	60.000	4	1	3	19	57	39.501	60.000
1	1	6	15	90	17.587	30.000	2	1	4	21	84	23.658	45.000	2	1	3	22	66	31.615	60.000	4	1	3	20	60	38.140	60.000
1	1	6	16	96	17.093	30.000	2	1	5	17	85	23.346	36.000	3	1	3	23	69	31.115	60.000	4	1	3	21	63	36.972	60.000
1	1	7	14	98	16.931	25.714	2	1	4	22	88	23.293	45.000	3	1	3	24	72	30.676	60.000	4	1	3	22	66	35.962	60.000
1	1	6	17	102	16.672	30.000	2	1	5	18	90	22.565	36.000	3	1	3	25	75	30.288	60.000	4	1	3	23	69	35.083	60.000
1	1	7	15	105	16.298	25.714	2	1	5	19	95	21.895	36.000	3	1	4	19	76	29.969	45.000	4	1	3	24	72	34.312	60.000
1	1	7	16	112	15.761	25.714	2	1	5	20	100	21.317	36.000	3	1	3	26	78	29.943	60.000	4	1	3	25	75	33.632	60.000
1	1	7	17	119	15.302	25.714	2	1	5	21	105	20.813	36.000	3	1	4	20	80	28.961	45.000	4	1	3	26	78	33.030	60.000
1	1	7	18	126	14.906	25.714	2	1	5	22	110	20.372	36.000	3	1	4	21	84	28.091	45.000	4	1	3	27	81	32.494	60.000
1	1	8	16	128	14.831	22.500	2	1	5	23	115	19.984	36.000	3	1	4	22	88	27.335	45.000	4	1	3	28	84	32.014	60.000
1	1	7	19	133	14.563	25.714	2	1	5	24	120	19.641	36.000	3	1	4	23	92	26.673	45.000	4	1	3	29	87	31.584	60.000
1	1	8	17	136	14.340	22.500	2	1	5	25	125	19.335	36.000	3	1	4	24	96	26.091	45.000	4	1	3	30	90	31.195	60.000
1	1	7	20	140	14.263	25.714	2	1	6	21	126	19.157	30.000	3	1	4	25	100	25.575	45.000	4	1	3	31	93	30.844	60.000
1	1	8	18	144	13.916	22.500	2	1	5	26	130	19.062	36.000	3	1	4	26	104	25.117	45.000	4	1	3	32	96	30.526	60.000
1	1	8	19	152	13.546	22.500	2	1	6	22	132	18.648	30.000	3	1	4	27	108	24.707	45.000	2	2	7	14	98	30.226	25.714
1	1	8	20	160	13.222	22.500	2	1	6	23	138	18.199	30.000	3	1	4	28	112	24.340	45.000	4	1	4	25	100	30.100	45.000
1	1	9	18	162	13.193	20.000	2	1	6	24	144	17.802	30.000	3	1	4	29	116	24.009	45.000	4	1	3	34	102	29.971	60.000
1	1	8	21	168	12.937	22.500	2	1	6	25	150	17.447	30.000	3	1	4	30	120	23.710	45.000	4	1	4	26	104	29.295	45.000
1	1	9	19	171	12.801	20.000	2	1	6	26	156	17.130	30.000	3	1	4	31	124	23.439	45.000	2	2	7	15	105	29.235	25.714

TABLE 3. Arbitrarily Phased Polar Constellations Providing Continuous Coverage Above 45 Degrees Geocentric Latitude

Single Coverage							Double Coverage							Triple Coverage							Quadruple Coverage						
j	*k*	*p*	*s*	*T*	theta	alpha	*j*	*k*	*p*	*s*	*T*	theta	alpha	*j*	*k*	*p*	*s*	*T*	theta	alpha	*j*	*k*	*p*	*s*	*T*	theta	alpha
1	1	1	3	3	69.295	n/a	2	1	1	5	5	77.379	n/a	3	1	1	7	7	80.947	n/a	4	1	1	9	9	82.947	n/a
1	1	1	4	4	60.000	n/a	1	2	2	3	6	69.295	90.000	3	1	1	8	8	74.300	n/a	2	2	2	5	10	77.379	90.000
1	1	1	5	5	55.106	n/a	2	1	1	7	7	63.840	n/a	1	3	3	3	9	69.295	60.000	4	1	1	11	11	72.918	n/a
1	1	1	6	6	52.239	n/a	1	2	2	4	8	60.000	90.000	3	1	1	10	10	65.441	n/a	1	4	4	3	12	69.295	45.000
1	1	1	7	7	50.425	n/a	2	1	1	9	9	57.202	n/a	3	1	1	11	11	62.415	n/a	4	1	1	13	13	66.317	n/a
1	1	1	8	8	49.211	n/a	1	2	2	5	10	55.106	90.000	1	3	3	4	12	60.000	60.000	2	2	2	7	14	63.840	90.000
1	1	1	9	9	48.359	n/a	2	1	1	11	11	53.498	n/a	3	1	1	13	13	58.043	n/a	4	1	1	15	15	61.761	n/a
1	1	2	5	10	45.522	90.000	1	2	2	6	12	52.239	90.000	3	1	1	14	14	56.438	s/s	1	4	4	4	16	60.000	45.000
1	1	2	6	12	41.410	90.000	2	1	1	13	13	51.236	n/a	1	3	3	5	15	55.106	60.000	4	1	1	17	17	58.496	n/a
1	1	2	7	14	38.715	90.000	1	2	2	7	14	50.425	90.000	3	1	1	16	16	53.989	n/a	2	2	2	9	18	57.202	90.000
1	1	2	8	16	36.860	90.000	2	1	1	15	15	49.761	n/a	3	1	1	17	17	53.045	n/a	4	1	1	19	19	56.082	n/a
1	1	2	9	18	35.531	90.000	2	1	2	8	16	46.551	90.000	1	3	3	6	18	52.239	60.000	1	4	4	5	20	55.106	45.000
1	1	2	10	20	34.549	90.000	2	1	2	9	18	43.348	90.000	3	1	1	19	19	51.546	n/a	4	1	1	21	21	54.251	n/a
1	1	3	7	21	32.565	60.000	2	1	2	10	20	40.999	90.000	3	1	1	20	20	50.947	n/a	2	2	2	11	22	53.498	90.000
1	1	3	8	24	30.207	60.000	2	1	2	11	22	39.221	90.000	1	3	3	7	21	50.425	60.000	4	1	1	23	23	52.831	n/a
1	1	3	9	27	28.478	60.000	2	1	2	12	24	37.840	90.000	3	1	1	22	22	49.969	n/a	1	4	4	6	24	52.239	45.000
1	1	3	10	30	27.173	60.000	2	1	2	13	26	36.747	90.000	3	1	1	23	23	49.566	n/a	4	1	1	25	25	51.710	n/a
1	1	3	11	33	26.166	60.000	2	1	2	14	28	35.865	90.000	1	3	4	6	24	49.029	45.000	2	2	2	13	26	51.236	90.000
1	1	4	9	36	25.226	45.000	2	1	2	15	30	35.145	90.000	1	3	5	5	25	48.428	36.000	4	1	1	27	27	50.810	n/a
1	1	3	13	39	24.738	60.000	2	1	2	16	32	34.549	90.000	3	1	2	13	26	43.445	90.000	1	4	4	7	28	50.425	45.000
1	1	4	10	40	23.712	45.000	2	1	3	11	33	34.094	60.000	3	1	2	14	28	41.668	90.000	4	1	1	29	29	50.077	n/a
1	1	4	11	44	22.527	45.000	2	1	2	17	34	34.050	90.000	3	1	2	15	30	40.224	90.000	2	2	3	10	30	45.802	60.000
1	1	4	12	48	21.582	45.000	2	1	3	12	36	32.117	60.000	3	1	2	16	32	39.034	90.000	2	2	3	11	33	44.554	60.000

1	1	4	13	52	20.817	45.000	2	1	3	13	39	30.554	60.000	3	1	2	17	34	38.041	90.000	4	1	2	17	34	43.660	90.000
1	1	5	11	55	20.560	36.000	2	1	3	14	42	29.294	60.000	3	1	2	18	36	37.203	90.000	4	1	2	18	36	42.222	90.000
1	1	5	14	56	20.190	45.000	2	1	3	15	45	28.262	60.000	3	1	2	19	38	36.490	90.000	4	1	2	19	38	41.002	90.000
1	1	5	12	60	19.510	36.000	2	1	3	16	48	27.406	60.000	3	1	2	20	40	35.877	90.000	4	1	2	20	40	39.957	90.000
1	1	4	16	64	19.232	45.000	2	1	3	17	51	26.687	60.000	3	1	2	21	42	35.348	90.000	4	1	2	21	42	39.056	90.000
1	1	5	13	65	18.652	36.000	2	1	3	18	54	26.077	60.000	3	1	2	22	44	34.886	90.000	4	1	2	22	44	38.272	90.000
1	1	5	14	70	17.942	36.000	2	1	3	19	57	25.556	60.000	3	1	2	23	46	34.482	90.000	4	1	2	23	46	37.586	90.000
1	1	5	15	75	17.348	36.000	2	1	3	20	60	25.106	60.000	3	1	2	24	48	34.125	90.000	4	1	2	24	48	36.982	90.000
1	1	6	13	78	17.342	30.000	2	1	3	21	63	24.716	60.000	3	1	2	25	50	33.810	90.000	4	1	2	25	50	36.448	90.000
1	1	5	16	80	16.846	36.000	2	1	4	16	64	24.320	45.000	3	1	3	17	51	32.874	60.000	4	1	2	26	52	35.973	90.000
1	1	6	14	84	16.572	30.000	2	1	4	17	68	23.414	45.000	3	1	3	18	54	31.591	60.000	4	1	2	27	54	35.548	90.000
1	1	5	17	85	16.419	36.000	2	1	4	18	72	22.645	45.000	3	1	3	19	57	30.506	60.000	4	1	2	28	56	35.167	90.000
1	1	6	15	90	15.924	30.000	2	1	4	19	76	21.985	45.000	3	1	3	20	60	29.577	60.000	4	1	2	29	58	34.824	90.000
1	1	5	19	95	15.735	36.000	2	1	4	20	80	21.415	45.000	3	1	3	21	63	28.777	60.000	2	2	5	12	60	34.253	36.000
1	1	6	16	96	15.373	30.000	2	1	4	21	84	20.920	45.000	3	1	3	22	66	28.000	60.000	4	1	2	31	62	34.233	90.000
1	1	6	17	102	14.901	30.000	2	1	4	22	88	20.485	45.000	3	1	3	23	69	27.471	60.000	4	1	2	32	64	33.977	90.000
1	1	6	18	108	14.494	30.000	2	1	4	23	92	20.103	45.000	3	1	3	24	72	26.935	60.000	2	2	5	13	65	32.912	36.000
1	1	7	16	112	14.403	25.714	2	1	4	24	96	19.764	45.000	3	1	3	25	75	26.460	60.000	4	1	3	23	69	32.370	60.000
1	1	6	19	114	14.140	30.000	2	1	4	25	100	19.463	45.000	3	1	3	26	78	26.037	60.000	2	2	5	14	70	31.832	36.000
1	1	7	17	119	13.897	25.714	2	1	4	26	104	19.194	45.000	3	1	3	27	81	25.660	60.000	4	1	3	24	72	31.422	60.000
1	1	6	20	120	13.831	30.000	2	1	5	21	105	18.948	36.000	3	1	3	28	84	25.321	60.000	4	1	3	25	75	30.587	60.000
1	1	7	18	126	13.458	25.714	2	1	5	22	110	18.432	36.000	3	1	3	29	87	25.016	60.000	4	1	3	26	78	29.849	60.000
1	1	6	22	132	13.319	30.000	2	1	5	23	115	17.976	36.000	3	1	3	30	90	24.740	60.000	4	1	3	27	81	29.191	60.000
1	1	7	19	133	13.075	25.714	2	1	5	24	120	17.571	36.000	3	1	4	23	92	24.617	45.000	4	1	3	28	84	28.603	60.000
1	1	7	20	140	12.739	25.714	2	1	5	25	125	17.211	36.000	3	1	3	31	93	24.489	60.000	4	1	3	29	87	28.074	60.000
1	1	8	18	144	12.737	22.500	2	1	5	26	130	16.888	36.000	3	1	4	24	96	23.914	45.000	4	1	3	30	90	27.597	60.000
1	1	7	21	147	12.442	25.714	2	1	5	27	135	16.599	36.000	3	1	4	25	100	23.292	45.000	4	1	3	31	93	27.166	60.000

TABLE 4. Arbitrarily Phased Polar Constellations Providing Continuous Coverage Above 60 Degrees Geocentric Latitude

Single Coverage							Double Coverage							Triple Coverage							Quadruple Coverage						
j	*k*	*p*	*s*	*T*	theta	alpha	*j*	*k*	*p*	*s*	*T*	theta	alpha	*j*	*k*	*p*	*s*	*T*	theta	alpha	*j*	*k*	*p*	*s*	*T*	theta	alpha
1	1	1	3	3	64.341	n/a	2	1	1	5	5	74.478	n/a	3	1	1	7	7	78.889	n/a	4	1	1	9	9	81.351	n/a
1	1	1	4	4	52.239	n/a	1	2	2	3	6	64.341	90.000	3	1	1	8	8	70.645	n/a	2	2	2	5	10	74.478	90.000
1	1	1	5	5	45.522	n/a	2	1	1	7	7	57.319	n/a	1	3	3	3	9	64.341	60.000	4	1	1	11	11	68.915	n/a
1	1	1	6	6	41.410	n/a	1	2	2	4	8	52.239	90.000	3	1	1	10	10	59.400	n/a	1	4	4	3	12	64.341	45.000
1	1	1	7	7	38.715.	n/a	2	1	1	9	9	48.439	n/a	3	1	1	11	11	55.450	n/a	4	1	1	13	13	60.531	n/a
1	1	1	8	8	36.860	n/a	1	2	2	5	10	45.522	90.000	1	3	3	4	12	52.239	60.000	2	2	2	7	14	57.319	90.000
1	1	1	9	9	35.531	n/a	2	1	1	11	11	43.235	n/a	3	1	1	13	13	49.592	n/a	4	1	1	15	15	54.586	n/a
1	1	1	10	10	34.549	n/a	1	2	2	6	12	41.410	90.000	3	1	1	14	14	47.384	n/a	1	4	4	4	16	52.239	45.000
1	1	1	11	11	33.804	n/a	2	1	1	13	13	39.930	n/a	1	3	3	5	15	45.522	60.000	4	1	1	17	17	50.208	n/a
1	1	1	12	12	33.226	n/a	1	2	2	7	14	38.715	90.000	3	1	1	16	16	43.939	n/a	2	2	2	9	18	48.439	90.000
1	1	1	13	13	32.769	n/a	2	1	1	15	15	37.707	n/a	3	1	1	17	17	42.582	n/a	4	1	1	19	19	46.889	n/a
1	1	1	14	14	32.402	n/a	1	2	2	8	16	36.860	90.000	1	3	3	6	18	41.410	60.000	1	4	4	5	20	45.522	45.000
1	1	1	15	15	32.102	n/a	2	1	1	17	17	36.143	n/a	3	1	1	19	19	40.390	n/a	4	1	1	21	21	44.312	n/a
1	1	2	8	16	30.207	90.000	1	2	2	9	18	35.531	90.000	3	1	1	20	20	39.499	n/a	2	2	2	11	22	43.235	90.000
1	1	2	9	18	28.478	90.000	2	1	1	19	19	35.005	n/a	1	3	3	7	21	38.715	60.000	4	1	1	23	23	42.273	n/a
1	1	2	10	20	27.173	90.000	1	2	2	10	20	34.549	90.000	3	1	1	22	22	38.023	n/a	1	4	4	6	24	41.410	45.000
1	1	2	11	22	26.166	90.000	2	1	1	21	21	34.152	n/a	3	1	1	23	23	37.408	n/a	4	1	1	25	25	40.632	n/a
1	1	2	12	24	25.373	90.000	1	2	2	11	22	33.804	90.000	1	3	3	8	24	36.860	60.000	2	2	2	13	26	39.930	90.000
1	1	2	13	26	24.738	90.000	2	1	1	23	23	33.497	n/a	3	1	1	25	25	36.369	n/a	4	1	1	27	27	39.294	n/a
1	1	3	9	27	24.515	60.000	2	1	2	12	24	31.460	90.000	3	1	1	26	26	35.929	n/a	1	4	4	7	28	38.715	45.000
1	1	2	14	28	24.222	90.000	2	1	2	13	26	30.061	90.000	1	3	3	9	27	35.531	60.000	4	1	1	29	29	38.188	n/a
1	1	3	10	30	22.948	60.000	2	1	2	14	28	28.916	90.000	3	1	1	28	28	35.172	n/a	2	2	2	15	30	37.707	90.000
1	1	3	11	33	21.717	60.000	2	1	2	15	30	27.968	90.000	3	1	1	29	29	34.846	n/a	4	1	1	31	31	37.265	n/a

1	1	3	12	36	20.731	60.000	2	1	2	16	32	27.173	90.000	1	3	3	10	30	34.549	60.000	1	4	4	8	32	36.860	45.000
1	1	3	13	39	19.930	60.000	2	1	2	17	34	26.500	90.000	3	1	1	31	31	34.279	n/a	4	1	1	33	33	36.487	n/a
1	1	3	14	42	19.271	60.000	2	1	2	18	36	25.926	90.000	3	1	1	32	32	34.031	n/a	2	2	2	17	34	36.143	90.000
1	1	3	15	45	18.722	60.000	2	1	2	19	38	25.432	90.000	1	3	3	11	33	33.804	60.000	4	1	1	35	35	35.826	n/a
1	1	3	16	48	18.261	60.000	2	1	2	20	40	25.004	90.000	3	1	1	34	34	33.595	n/a	1	4	4	9	36	35.531	45.000
1	1	3	17	51	17.869	60.000	2	1	2	21	42	24.631	90.000	3	1	1	35	35	33.403	n/a	4	1	1	37	37	35.259	n/a
1	1	4	13	52	17.636	45.000	2	1	2	22	44	24.304	90.000	1	3	3	12	36	33.226	60.000	2	2	2	19	38	35.005	90.000
1	1	3	18	54	17.534	60.000	2	1	2	23	46	24.015	90.000	3	1	1	37	37	33.062	n/a	4	1	1	39	39	34.769	n/a
1	1	4	14	56	16.880	45.000	2	1	3	16	48	23.578	60.000	3	1	2	19	38	29.729	90.000	1	4	4	10	40	34.549	45.000
1	1	4	15	60	16.245	45.000	2	1	2	25	50	23.532	90.000	3	1	2	20	40	28.932	90.000	4	1	1	41	41	34.344	n/a
1	1	4	16	64	15.706	45.000	2	1	3	17	51	22.633	60.000	3	1	2	21	42	28.235	90.000	2	2	2	21	42	34.152	90.000
1	1	4	17	68	15.245	45.000	2	1	3	18	54	21.831	60.000	3	1	2	22	44	27.623	90.000	4	1	1	43	43	33.972	n/a
1	1	4	18	72	14.847	45.000	2	1	3	19	57	21.143	60.000	3	1	2	23	46	27.082	90.000	1	4	4	11	44	33.804	45.000
1	1	4	19	76	14.502	45.000	2	1	3	20	60	20.548	60.000	3	1	2	24	48	26.602	90.000	2	2	3	15	45	31.152	60.000
1	1	4	20	80	14.201	45.000	2	1	3	21	63	20.029	60.000	3	1	2	25	50	26.173	90.000	2	2	3	16	48	30.591	60.000
1	1	4	21	84	13.937	45.000	2	1	3	22	66	19.574	60.000	3	1	2	26	52	25.789	90.000	2	2	3	17	51	30.104	60.000
1	1	5	17	85	13.792	36.000	2	1	3	23	69	19.173	60.000	3	1	2	27	54	25.444	90.000	4	1	2	26	52	29.056	90.000
1	1	4	22	88	13.704	45.000	2	1	3	24	72	18.817	60.000	3	1	2	28	56	25.132	90.000	4	1	2	27	54	28.500	90.000
1	1	5	18	90	13.349	36.000	2	1	3	25	75	18.500	60.000	3	1	2	29	58	24.850	90.000	4	1	2	28	56	27.997	90.000
1	1	5	19	95	12.963	36.000	2	1	3	26	78	18.216	60.000	3	1	2	30	60	24.594	90.000	4	1	2	29	58	27.541	90.000
1	1	5	20	100	12.623	36.000	2	1	3	27	81	17.961	60.000	3	1	2	31	62	24.360	90.000	4	1	2	30	60	27.126	90.000
1	1	5	21	105	12.324	36.000	2	1	3	28	84	17.731	60.000	3	1	2	32	64	24.147	90.000	4	1	2	31	62	26.747	90.000
1	1	5	22	110	12.058	36.000	2	1	3	29	87	17.523	60.000	3	1	2	33	66	23.952	90.000	4	1	2	32	64	26.401	90.000
1	1	6	19	114	12.022	30.000	2	1	4	22	88	17.498	45.000	3	1	2	34	68	23.773	90.000	4	1	2	33	66	26.084	90.000
1	1	5	23	115	11.822	36.000	2	1	3	30	90	17.334	60.000	3	1	2	35	70	23.608	90.000	4	1	2	34	68	25.792	90.000
1	1	5	24	120	11.610	36.000	2	1	4	23	92	16.997	45.000	3	1	3	24	72	23.178	60.000	4	1	2	35	70	25.523	90.000
1	1	5	25	125	11.420	36.000	2	1	4	24	96	16.554	45.000	3	1	3	25	75	22.520	60.000	4	1	2	36	72	25.275	90.000

TABLE 5. Optimally Phased Polar Constellations Providing Continuous Coverage Above 0 Degrees Geocentric Latitude

Single Coverage						Double Coverage						Triple Coverage						Quadruple Coverage					
p	*s*	*T*	theta	alpha	omega	*p*	*s*	*T*	theta	alpha	omega	*p*	*s*	*T*	theta	alpha	omega	*p*	*s*	*T*	theta	alpha	omega
2	3	6	66.716	104.478	60.000	3	3	9	71.253	120.000	40.000	4	3	12	76.197	136.790	40.000	3	5	15	76.949	120.000	0.000
2	4	8	56.946	96.469	45.000	2	6	12	63.702	91.317	0.000	5	3	15	68.529	111.471	60.000	3	6	18	70.893	120.000	0.000
2	5	10	53.219	95.480	36.000	2	7	14	58.613	91.964	0.000	2	9	18	63.621	90.919	20.000	7	3	21	66.385	102.857	51.429
3	4	12	48.590	69.295	45.000	2	8	16	55.116	91.135	0.000	2	10	20	59.691	90.535	18.000	2	12	24	63.492	90.285	0.000
3	5	15	42.072	65.502	36.000	2	9	18	53.069	91.409	0.000	2	11	22	57.019	90.792	16.364	2	13	26	60.520	90.487	0.000
3	6	18	38.682	64.341	30.000	5	4	20	49.450	72.000	36.000	2	12	24	54.895	90.477	15.000	2	14	28	58.138	90.288	0.000
4	5	20	38.029	51.212	36.000	3	8	24	46.785	61.233	0.000	2	13	26	53.416	90.642	13.846	2	15	30	56.345	90.428	0.000
3	7	21	36.301	62.858	25.714	5	5	25	44.431	72.000	28.800	7	4	28	51.620	79.820	37.500	2	16	32	54.823	90.263	0.000
4	6	24	33.511	49.194	30.000	3	9	27	43.266	61.354	0.000	2	15	30	51.232	90.518	12.000	2	17	34*	53.665	90.367	0.000
4	7	28	30.782	48.313	25.714	3	10	30	40.658	60.989	0.000	8	4	32	48.899	70.511	45.000	9	4	36	51.608	80.000	40.000
4	8	32	28.853	47.406	22.500	3	11	33	38.839	61.037	0.000	7	5	35	46.746	78.859	36.000	5	8	40	49.287	72.000	0.000
5	7	35	27.927	39.215	25.714	7	5	35	38.148	51.428	30.857	3	12	36	46.672	60.646	15.000	11	4	44	47.705	65.455	40.909
4	9	36	27.607	47.043	20.000	3	12	36	37.367	60.772	0.000	3	13	39	44.100	60.482	13.846	5	9	45	46.334	72.000	0.000
5	8	40	25.740	38.580	22.500	3	13	39	36.312	60.801	0.000	8	5	40	43.412	69.340	30.857	5	10	50	44.268	72.000	0.000
5	9	45	24.153	37.983	20.000	7	6	42	34.268	51.429	25.714	3	14	42	42.121	60.552	12.857	3	18	54	42.987	60.257	0.000
6	8	48	23.985	32.520	22.500	4	12	48	32.532	45.747	0.000	3	15	45	40.487	60.419	12.000	11	5	55	42.090	65.455	32.727
5	10	50	23.046	37.682	18.000	7	7	49	31.957	51.429	22.041	3	16	48	39.206	60.466	11.250	3	19	57	41.620	60.300	0.000
6	9	54	22.206	32.059	20.000	4	13	52	31.067	45.744	0.000	3	17	51	38.104	60.358	10.588	3	20	60	40.431	60.231	0.000
5	11	55	22.171	37.341	16.364	4	14	56	29.867	45.607	0.000	3	18	54	37.230	60.393	10.000	3	21	63	39.442	60.264	0.000
6	10	60	20.880	31.643	18.000	4	15	60	28.935	45.602	0.000	3	19	57	36.452	60.306	9.474	13	5	65	39.088	55.385	33.231
6	11	66	19.907	31.402	16.364	9	7	63	28.183	40.000	22.857	10	6	60	35.496	55.427	30.000	3	22	66	38.562	60.207	0.000
7	10	70	19.574	27.393	18.000	4	16	64	28.139	45.497	0.000	3	21	63	35.260	60.263	8.571	3	23	69	37.824	60.233	0.000
6	12	72	19.134	31.152	15.000	4	17	68	27.511	45.493	0.000	4	16	64	35.098	45.360	11.250	3	24	72	37.155	60.184	0.000

7	11	77	18.450	27.091	16.364	5	14	70	27.243	36.564	0.000	11	6	66	33.955	50.659	30.000	3	25	75	36.590	60.206	0.000
7	12	84	17.595	26.899	15.000	9	8	72	26.241	40.000	20.000	4	17	68	33.648	45.380	10.588	7	11	77	35.864	51.429	0.000
8	11	88	17.527	23.895	16.364	5	15	75	26.066	36.551	0.000	10	7	70	33.266	55.027	22.857	13	6	78	35.504	55.385	27.692
7	13	91	16.908	26.709	13.846	5	16	80	25.084	36.472	0.000	4	18	72	32.417	45.317	10.000	7	12	84	34.194	51.429	0.000
8	12	96	16.562	23.667	15.000	9	9	81	24.917	40.000	17.778	4	19	76	31.396	45.331	9.474	15	6	90	33.176	48.000	28.000
7	14	98	16.371	26.593	12.857	5	17	85	24.286	36.461	0.000	4	20	80	30.507	45.278	9.000	7	13	91	32.904	51.429	0.000
8	13	104	15.809	23.513	13.846	11	8	88	24.059	32.727	20.454	4	21	84	29.762	45.288	8.571	4	24	96	32.380	45.176	0.000
8	14	112	15.196	23.366	12.857	5	18	90	23.601	36.398	0.000	4	22	88	29.101	45.244	8.182	7	14	98	31.888	51.429	0.000
9	13	117	15.048	21.001	13.846	5	19	95	23.037	36.388	0.000	13	7	91	28.928	42.655	25.714	4	25	100	31.596	45.187	0.000
8	15	120	14.705	23.268	12.000	11	9	99	22.429	32.727	18.182	4	23	92	28.541	45.252	7.826	4	26	104	30.891	45.159	0.000
9	14	126	14.380	20.876	12.857	5	21	105	22.126	36.330	0.000	4	24	96	28.035	45.214	7.500	15	7	105	30.689	48.000	24.000
8	16	128	14.293	23.167	11.250	6	18	108	21.721	30.373	0.000	4	25	100	27.604	45.221	7.200	4	27	108	30.275	45.169	0.000
9	15	135	13.831	20.759	12.000	11	10	110	21.267	32.727	16.364	13	8	104	27.036	42.434	22.500	4	28	112	29.715	45.144	0.000
10	14	140	13.803	18.867	12.857	6	19	114	21.040	30.361	0.000	4	27	108	26.870	45.195	6.667	4	29	116	29.223	45.152	0.000
9	16	144	13.382	20.676	11.250	6	20	120	20.450	30.321	0.000	5	22	110	26.349	36.243	8.182	17	7	119	28.846	42.353	24.202
10	15	150	13.207	18.765	12.000	11	11	121	20.410	32.727	14.876	14	8	112	26.017	39.435	22.500	4	30	120	28.771	45.131	0.000
9	17	153	13.003	20.594	10.588	6	21	126	19.950	30.311	0.000	5	23	115	25.630	36.214	7.826	4	31	124	28.371	45.138	0.000
10	16	160	12.712	18.670	11.250	13	10	130	19.671	27.692	16.615	5	24	120	25.007	36.216	7.500	9	14	126	28.145	40.000	0.000
9	18	162	12.688	20.538	10.000	6	22	132	19.508	30.278	0.000	5	25	125	24.450	36.191	7.200	4	32	128	28.000	45.119	0.000
10	17	170	12.302	18.600	10.588	6	23	138	19.130	30.270	0.000	5	26	130	23.964	36.193	6.923	4	33	132	27.671	45.125	0.000
11	16	176	12.224	17.037	11.250	13	11	143	18.653	27.692	15.105	5	27	135	23.524	36.171	6.667	19	7	133	27.584	37.894	24.361
10	18	180	11.952	18.532	10.000	7	21	147	18.621	26.004	0.000	5	28	140	23.138	36.173	6.429	9	15	135	27.076	40.000	0.000
11	17	187	11.776	16.959	10.588	6	25	150	18.499	30.236	0.000	16	9	144	22.957	34.466	20.000	17	8	136	27.018	42.353	21.176
10	19	190	11.658	18.483	9.474	7	22	154	18.110	25.977	0.000	5	29	145	22.784	36.154	6.207	9	16	144	26.204	40.000	0.000
11	18	198	11.399	16.900	10.000	13	12	156	17.881	27.692	13.846	5	30	150	22.472	36.155	6.000	5	30	150	25.949	36.122	0.000
12	17	204	11.386	15.598	10.588	7	23	161	17.668	25.968	0.000	17	9	153	22.328	32.464	20.000	19	8	152	25.530	37.895	21.316
11	19	209	11.077	16.843	9.474	15	11	165	17.563	24.000	15.273	5	31	155	22.184	36.139	5.806	9	17	153	25.484	40.000	0.000

TABLE 6. Optimally Phased Polar Constellations Providing Continuous Coverage Above 30 Degrees Geocentric Latitude

Single Coverage						Double Coverage						Triple Coverage						Quadruple Coverage					
p	*s*	*T*	theta	alpha	omega	*p*	*s*	*T*	theta	alpha	omega	*p*	*s*	*T*	theta	alpha	omega	*p*	*s*	*T*	theta	alpha	omega
2	3	6	62.474	100.894	60.000	3	3	9	66.947	120.000	40.000	4	3	12	68.427	138.989	60.000	3	6	18	64.341	121.925	30.000
2	4	8	50.131	88.794	45.000	3	4	12	58.474	60.000	28.362	5	3	15	64.799	116.371	60.000	5	4	20	63.454	143.020	33.750
2	5	10	47.541	96.735	36.000	2	7	14	53.971	91.554	25.714	4	4	16	60.963	135.325	45.000	3	7	21	59.354	120.000	17.143
2	6	12	44.042	92.922	30.000	4	4	16	50.008	89.412	45.000	2	9	18	60.801	101.514	20.000	3	8	24	56.609	120.000	15.000
2	7	14	41.608	89.873	25.714	2	9	18	47.252	89.687	20.000	5	4	20	54.205	72.000	36.000	2	13	26	56.503	89.787	0.000
3	5	15	38.934	64.068	36.000	2	10	20	45.589	89.868	0.000	2	11	22	52.402	89.339	16.364	3	9	27	54.958	60.200	7.976
3	6	18	35.121	63.445	30.000	2	11	22	44.087	89.641	0.000	2	12	24	49.893	90.379	0.000	7	4	28	52.883	76.791	37.500
3	7	21	32.791	59.460	13.914	2	12	24	43.148	89.632	15.000	2	13	26	47.937	90.003	0.000	2	15	30	51.570	89.968	0.000
3	8	24	30.698	60.938	22.500	5	5	25	41.291	72.000	28.800	2	14	28	46.620	90.533	0.000	2	16	32	49.874	89.944	11.240
3	9	27	29.760	61.101	20.000	3	9	27	41.108	119.542	20.000	2	15	30	45.433	90.382	0.000	2	17	34	48.389	89.918	10.588
4	7	28	28.318	47.162	25.714	3	10	30	37.921	120.000	0.000	2	16	32	44.387	89.971	0.000	4	9	36	47.212	89.842	20.000
4	8	32	26.690	47.557	19.129	3	11	33	35.986	119.097	16.364	2	17	34	43.666	90.118	0.000	2	19	38	46.210	90.128	9.474
4	9	36	25.005	46.876	20.000	5	7	35	35.985	72.000	20.571	7	5	35	42.253	77.703	36.000	2	20	40	45.319	89.993	9.000
4	10	40	23.655	45.627	18.000	3	12	36	34.289	60.351	0.000	3	13	39	42.225	60.548	0.000	2	21	42	44.653	90.211	8.571
4	11	44	23.269	45.710	11.619	3	13	39	32.803	120.000	0.000	8	5	40	40.224	68.344	30.857	2	22	44	44.033	90.223	8.182
5	9	45	22.486	38.229	20.000	3	14	42	32.008	119.553	12.857	7	6	42	39.312	77.767	30.000	5	9	45	43.112	107.778	20.000
5	10	50	21.230	37.320	14.747	3	15	45	31.165	60.342	0.000	3	15	45	37.921	120.000	0.000	2	24	48	42.973	90.062	7.500
6	9	54	21.108	32.413	20.000	3	16	48	30.335	120.000	0.000	3	16	48	36.486	120.000	7.500	5	10	50	40.601	107.809	0.000
5	11	55	20.153	37.192	16.364	7	7	49	29.613	51.429	22.041	3	17	51	35.205	60.052	0.000	9	6	54	40.194	80.000	26.667
5	12	60	19.474	37.146	15.000	4	13	52	29.173	134.983	0.000	3	18	54	34.080	120.000	0.000	5	11	55	38.954	72.000	0.000
5	13	65	18.902	36.502	10.670	7	8	56	27.830	51.429	19.286	3	19	57	33.295	119.693	9.474	5	12	60	37.486	107.928	15.000
6	11	66	18.563	31.663	15.341	4	15	60	26.772	45.282	0.000	3	20	60	32.530	119.934	9.000	3	21	63	36.783	120.000	5.714
5	14	70	18.367	36.633	12.857	7	9	63	26.609	51.429	17.143	3	21	63	31.797	120.000	0.000	5	13	65	36.441	107.947	0.000

6	12	72	17.638	31.291	15.000	4	16	64	25.797	45.004	0.000	3	22	66	31.327	119.833	8.182	3	22	66	35.742	60.060	8.182
7	11	77	17.450	27.297	16.364	4	17	68	25.170	134.634	10.588	3	23	69	30.834	119.881	7.826	3	23	69	34.850	120.000	0.000
6	13	78	16.879	30.829	13.846	4	18	72	24.493	45.223	0.000	10	7	70	30.226	54.366	25.714	3	24	72	34.127	120.000	5.000
6	14	84	16.463	30.923	11.451	4	19	76	23.898	45.001	0.000	3	25	75	30.033	60.071	7.200	3	25	75	33.429	60.047	7.200
6	15	90	15.969	30.783	12.000	4	20	80	23.562	134.678	9.000	4	19	76	29.663	134.903	9.474	3	26	78	32.803	120.000	0.000
7	13	91	15.738	26.948	13.846	9	9	81	23.061	40.000	17.778	11	7	77	29.063	49.631	23.143	3	27	81	32.324	119.851	6.667
6	16	96	15.532	30.466	11.250	5	17	85	22.812	36.170	1.953	4	20	80	28.660	134.905	0.000	3	28	84	31.840	60.046	6.429
7	14	98	15.076	26.628	12.857	4	22	88	22.727	134.997	0.000	4	21	84	27.816	134.943	0.000	3	29	87	31.372	120.000	0.000
8	13	104	14.889	23.609	13.846	9	10	90	21.947	40.000	16.000	4	22	88	27.002	134.943	8.182	3	30	90	31.037	119.916	6.000
7	15	105	14.595	26.569	12.000	5	19	95	21.267	36.043	0.000	4	23	92	26.377	134.898	0.000	7	13	91	30.572	128.541	0.000
7	16	112	14.189	26.349	9.924	9	11	99	21.123	40.000	14.546	4	24	96	25.820	45.088	7.500	3	32	96	30.335	120.000	0.000
7	17	119	13.809	26.293	10.588	5	20	100	20.791	36.017	2.250	4	25	100	25.252	134.963	7.200	7	14	98	29.367	128.541	12.857
8	15	120	13.660	23.398	12.000	5	21	105	20.262	36.193	0.000	4	26	104	24.849	134.904	0.000	13	8	104	28.971	55.384	20.769
7	18	126	13.539	26.282	10.000	5	22	110	19.795	36.031	0.000	4	27	108	24.453	45.090	6.667	7	15	105	28.450	51.429	0.000
8	16	128	13.164	23.179	11.250	5	23	115	19.502	36.009	1.957	4	28	112	24.041	134.975	6.429	4	27	108	28.403	134.978	6.667
9	15	135	13.020	20.935	12.000	5	24	120	19.148	36.154	0.000	4	29	116	23.765	45.077	6.207	7	16	112	27.634	128.556	0.000
8	17	136	12.829	23.218	10.032	11	11	121	18.878	32.727	14.876	13	9	117	23.604	42.249	20.000	4	29	116	27.202	45.001	6.207
8	18	144	12.478	23.105	10.000	5	25	125	18.823	36.021	0.000	4	30	120	23.479	134.907	0.000	7	17	119	27.002	128.566	10.588
8	19	152	12.169	22.946	9.474	6	21	126	18.649	30.211	0.000	4	31	124	23.169	134.984	5.806	4	30	120	26.661	134.968	6.000
9	17	153	12.067	20.680	10.588	5	26	130	18.632	36.003	1.731	5	25	125	23.010	144.000	5.760	4	31	124	26.190	134.955	0.000
8	20	160	11.980	22.981	8.241	6	22	132	18.107	30.053	0.000	14	9	126	22.779	39.322	20.000	4	32	128	25.793	134.996	5.625
9	18	162	11.715	20.635	10.000	6	23	138	17.728	30.090	1.472	5	26	130	22.402	144.000	0.000	4	33	132	25.378	134.961	5.455
10	17	170	11.566	18.777	10.588	11	13	143	17.522	32.727	12.587	5	27	135	21.929	36.047	6.667	4	34	136	25.023	134.970	0.000
9	19	171	11.414	20.517	8.657	6	24	144	17.314	30.170	0.000	5	28	140	21.484	144.000	5.143	4	35	140	24.725	45.003	0.000
9	20	180	11.131	20.472	9.000	6	25	150	16.938	30.041	0.000	5	29	145	21.037	144.000	0.000	4	36	144	24.407	134.957	5.000
9	21	189	10.913	20.454	8.571	13	12	156	16.677	27.692	13.846	5	30	150	20.702	36.039	6.000	4	37	148	24.133	134.981	0.000
10	19	190	10.808	18.531	9.474	7	23	161	16.668	25.901	0.786	5	31	155	20.378	144.000	4.645	4	38	152	23.898	45.001	0.000

TABLE 7. Optimally Phased Polar Constellations Providing Continuous Coverage Above 45 Degrees Geocentric Latitude

Single Coverage						Double Coverage						Triple Coverage						Quadruple Coverage					
p	*s*	*T*	theta	alpha	omega	*p*	*s*	*T*	theta	alpha	omega	*p*	*s*	*T*	theta	alpha	omega	*p*	*s*	*T*	theta	alpha	omega
2	4	8	47.820	98.434	45.000	3	5	15	47.311	120.000	24.000	4	5	20	48.705	137.229	36.000	3	9	27	46.546	124.480	20.000
2	5	10	40.193	87.757	36.000	2	8	16	46.965	91.761	0.000	4	6	24	46.049	135.543	30.000	3	10	30	44.820	120.000	12.000
2	6	12	37.157	89.506	30.000	2	9	18	41.901	89.716	20.000	5	5	25	44.457	72.000	28.800	3	11	33	43.383	59.048	12.070
2	7	14	36.419	94.966	25.714	4	5	20	39.989	88.861	36.000	2	13	26	43.143	89.175	0.000	7	5	35	42.989	77.143	30.128
2	8	16	34.935	93.828	22.500	2	11	22	38.318	88.075	0.000	2	14	28	41.163	89.059	0.000	4	9	36	41.884	89.861	20.000
3	6	18	32.405	65.448	30.000	2	12	24	36.822	90.382	15.000	2	15	30	39.762	89.934	0.000	2	19	38	40.788	90.815	0.000
3	7	21	28.824	61.056	25.714	2	13	26	35.759	89.807	13.846	2	16	32	38.591	89.289	11.250	2	20	40	39.696	90.481	0.000
3	8	24	27.203	62.051	22.500	2	14	28	35.069	90.089	12.857	2	17	34	37.614	90.343	0.000	2	21	42	38.740	90.048	0.000
3	9	27	26.112	58.440	10.147	5	6	30	34.136	72.000	24.000	2	18	36	36.716	89.984	0.000	2	22	44	37.975	90.009	0.000
3	10	30	24.968	61.647	18.000	2	16	32	33.910	89.612	0.000	2	19	38	36.039	90.061	0.000	2	23	46	37.369	89.763	7.826
4	8	32	24.376	48.675	22.500	3	11	33	33.474	61.420	16.364	2	20	40	35.554	90.524	0.000	2	24	48	36.747	89.777	7.500
3	11	33	23.800	120.000	0.000	5	7	35	31.465	105.577	1.807	7	6	42	34.901	78.617	30.000	2	25	50	36.239	89.977	0.000
4	9	36	22.387	46.719	20.000	3	12	36	31.381	119.126	15.000	2	22	44	34.545	90.187	0.000	4	13	52	35.738	89.903	13.846
4	10	40	21.283	47.007	18.000	3	13	39	29.687	120.000	0.000	2	23	46	34.124	89.999	0.000	2	27	54	35.366	90.117	6.667
4	11	44	20.439	45.226	10.909	3	14	42	28.432	120.000	0.000	8	6	48	32.997	68.777	30.000	5	11	55	34.980	72.575	16.364
4	12	48	19.606	46.383	15.000	3	15	45	27.606	119.311	12.000	7	7	49	32.049	102.857	0.000	2	28	56	34.953	89.966	6.429
5	10	50	19.491	38.603	18.000	3	16	48	26.745	119.327	11.250	3	18	54	31.269	60.054	3.479	2	29	58	34.617	89.983	6.207
4	13	52	18.821	45.388	13.846	3	17	51	25.986	120.000	0.000	8	7	56	30.396	67.195	22.041	5	12	60	33.260	107.550	15.000
5	11	55	18.231	37.582	16.364	3	18	54	25.343	120.000	0.000	3	19	57	30.163	60.284	0.000	9	7	63	32.912	99.970	3.214
5	12	60	17.435	37.661	15.000	7	8	56	25.124	51.429	19.286	3	20	60	29.190	60.003	0.000	5	13	65	32.074	72.191	13.846
5	13	65	16.804	36.876	10.850	3	19	57	25.007	60.202	0.000	3	21	63	28.409	60.064	0.000	5	14	70	30.931	107.751	0.000
5	14	70	16.178	37.179	12.857	3	20	60	24.545	120.000	6.000	3	22	66	27.768	120.000	5.454	5	15	75	30.224	107.937	0.000
5	15	75	15.614	36.600	12.000	7	9	63	23.605	51.429	17.143	3	23	69	27.167	60.217	0.000	11	7	77	29.904	65.455	23.377

6	13	78	15.350	31.331	13.846	4	17	68	22.734	134.855	0.000	3	24	72	26.587	120.000	0.000	3	26	78	29.655	60.089	6.923
5	16	80	15.328	36.793	11.250	7	10	70	22.513	51.429	15.429	3	25	75	26.129	120.000	0.000	5	16	80	29.439	107.862	11.250
6	14	84	14.752	31.343	12.857	4	18	72	22.051	45.067	0.000	3	26	78	25.779	119.779	6.923	3	27	81	28.973	120.000	0.000
6	15	90	14.264	31.034	10.518	4	19	76	21.376	134.646	9.474	10	8	80	25.659	55.105	22.500	3	28	84	28.403	60.081	6.429
6	16	96	13.783	30.994	11.250	4	20	80	20.872	45.218	0.000	3	27	81	25.406	119.739	6.667	3	29	87	27.890	60.000	4.133
6	17	102	13.355	30.629	10.588	4	21	84	20.297	134.936	0.000	3	28	84	25.046	120.000	0.000	3	30	90	27.407	60.105	6.000
7	15	105	13.245	26.816	12.000	4	22	88	19.936	45.043	0.000	3	29	87	24.718	120.000	0.000	3	31	93	26.958	60.003	5.806
6	18	108	13.101	30.730	10.000	9	10	90	19.870	40.000	16.000	11	8	88	24.676	50.265	22.500	3	32	96	26.580	60.042	5.625
7	16	112	12.780	26.806	11.250	4	23	92	19.601	134.691	7.826	10	9	90	24.059	54.241	20.000	3	33	99	26.258	60.013	3.625
7	17	119	12.392	26.641	9.700	4	24	96	19.298	45.204	0.000	4	24	96	23.639	134.967	0.000	3	34	102	25.927	60.119	5.294
7	18	126	12.013	26.553	10.000	9	11	99	18.853	40.000	14.546	11	9	99	23.097	49.465	18.000	13	8	104	25.831	55.384	20.769
7	19	133	11.675	26.309	9.474	4	26	104	18.720	45.016	0.000	4	25	100	23.040	134.800	7.200	3	35	105	25.608	60.007	5.143
8	17	136	11.643	23.415	10.588	5	21	105	18.379	144.000	0.000	4	26	104	22.471	134.878	6.923	3	36	108	25.340	60.007	5.000
7	20	140	11.453	26.362	9.000	9	12	108	18.077	40.000	13.333	4	27	108	21.978	134.969	0.000	3	37	111	25.121	60.115	4.865
8	18	144	11.271	23.398	10.000	5	22	110	17.939	36.150	0.000	11	10	110	21.943	49.785	18.000	7	16	112	24.870	128.543	11.250
7	21	147	11.251	26.144	7.233	5	23	115	17.477	143.786	6.887	4	28	112	21.524	134.940	0.000	13	9	117	24.424	55.384	18.461
8	19	152	10.956	23.281	8.798	9	13	117	17.472	40.000	12.308	4	29	116	21.151	134.945	6.207	7	17	119	23.999	128.500	0.000
8	20	160	10.649	23.211	9.000	5	24	120	17.098	36.171	0.000	4	30	120	20.773	134.925	6.000	7	18	126	23.388	128.555	0.000
8	21	168	10.375	23.040	8.571	5	25	125	16.675	144.000	0.000	4	31	124	20.473	134.962	0.000	4	33	132	23.154	45.042	5.455
8	22	176	10.182	23.069	8.182	5	26	130	16.425	36.106	0.000	4	32	128	20.157	134.924	0.000	7	19	133	22.778	128.531	9.474
9	20	180	10.000	20.750	9.000	5	27	135	16.140	143.874	5.707	4	33	132	19.915	134.986	5.455	15	9	135	22.733	48.000	18.667
8	23	184	10.007	22.946	6.941	5	28	140	15.911	36.140	0.000	4	34	136	19.641	134.949	5.294	8	17	136	22.721	134.927	0.000
9	21	189	9.819	20.663	8.036	11	13	143	15.706	32.727	12.587	4	35	140	19.461	45.033	5.143	7	20	140	22.323	128.557	9.000
9	22	198	9.566	20.608	8.182	5	29	145	15.630	144.000	0.000	13	11	143	19.195	41.939	16.364	4	36	144	21.947	134.991	5.000
9	23	207	9.339	20.483	7.826	6	25	150	15.453	30.003	0.000	4	37	148	19.058	45.013	4.865	7	21	147	21.896	128.553	0.000
9	24	216	9.170	20.499	7.500	11	14	154	15.126	32.727	11.688	5	30	150	19.017	143.922	6.000	4	37	148	21.622	45.022	4.865
10	22	220	9.117	18.634	8.182	6	26	156	15.112	30.156	0.000	4	38	152	18.850	134.965	4.737	15	10	150	21.582	48.000	16.800

TABLE 8. Optimally Phased Polar Constellations Providing Continuous Coverage Above 60 Degrees Geocentric Latitude

Single Coverage						Double Coverage						Triple Coverage						Quadruple Coverage					
p	*s*	*T*	theta	alpha	omega	*p*	*s*	*T*	theta	alpha	omega	*p*	*s*	*T*	theta	alpha	omega	*p*	*s*	*T*	theta	alpha	omega
2	6	12	32.394	97.281	30.000	3	7	21	33.421	114.623	12.857	5	6	30	34.350	116.413	30.000	3	14	42	31.172	124.964	12.857
2	7	14	28.617	88.608	25.714	3	8	24	31.656	115.780	11.250	4	8	32	32.576	137.606	22.500	3	15	45	30.475	124.077	12.000
2	8	16	26.545	87.519	22.500	2	13	26	28.851	89.317	13.846	5	7	35	31.679	114.461	25.714	3	16	48	29.894	120.000	7.500
2	9	18	25.334	88.410	20.000	2	14	28	27.733	89.745	12.857	4	9	36	31.428	136.414	20.000	3	17	51	29.407	120.000	7.059
2	10	20	24.754	90.832	18.000	2	15	30	27.010	91.312	12.000	2	19	38	29.655	89.681	0.000	4	13	52	28.822	89.656	13.846
2	11	22	24.621	94.364	16.364	4	8	32	26.374	88.747	22.500	2	20	40	28.672	88.999	0.000	2	27	54	28.236	89.365	0.000
3	8	24	23.833	110.331	22.500	2	17	34	25.848	87.747	0.000	2	21	42	27.866	88.784	0.000	4	14	56	27.722	89.877	12.857
2	13	26	23.439	92.649	13.846	2	18	36	25.228	91.199	10.000	2	22	44	27.215	88.973	0.000	2	29	58	27.328	90.409	0.000
3	9	27	21.964	64.489	20.000	2	19	38	24.704	90.374	9.474	2	23	46	26.702	89.516	0.000	2	30	60	26.952	89.065	6.000
3	10	30	20.296	61.471	18.000	2	20	40	24.290	89.950	9.000	2	24	48	26.228	89.808	7.500	2	31	62	26.552	90.571	0.000
3	11	33	19.024	120.000	0.000	2	21	42	23.972	89.872	8.571	2	25	50	25.816	89.437	7.200	2	32	64	26.172	90.225	0.000
3	12	36	18.572	61.246	15.000	2	22	44	23.741	90.099	8.182	2	26	52	25.477	89.351	6.923	2	33	66	25.841	90.040	0.000
3	13	39	18.359	58.681	6.923	5	9	45	23.391	72.000	16.000	2	27	54	25.128	90.208	0.000	2	34	68	25.556	90.000	0.000
3	14	42	17.636	120.000	8.571	3	16	48	22.955	60.494	11.250	7	8	56	24.750	102.858	19.286	2	35	70	25.312	90.095	0.000
4	11	44	17.597	45.192	10.909	5	10	50	22.212	72.000	14.400	2	29	58	24.512	89.934	0.000	9	8	72	25.064	99.528	19.687
3	15	45	17.232	61.490	12.000	3	17	51	22.107	120.000	7.059	2	30	60	24.282	90.040	0.000	2	37	74	24.886	89.663	4.865
4	12	48	16.544	48.045	15.000	3	18	54	21.255	118.757	10.000	2	31	62	24.099	90.291	0.000	2	38	76	24.674	89.725	4.737
3	17	51	16.354	120.000	0.000	5	11	55	20.992	107.755	3.695	7	9	63	23.881	101.569	20.000	2	39	78	24.484	90.116	0.000
4	13	52	15.632	46.712	13.846	3	19	57	20.539	60.319	9.474	8	8	64	23.671	112.049	22.500	5	16	80	24.103	71.999	9.000
4	14	56	14.859	45.491	12.857	3	20	60	19.888	120.000	0.000	2	34	68	23.564	90.380	0.000	4	21	84	23.963	89.936	8.571
4	15	60	14.545	46.487	12.000	3	21	63	19.358	120.000	0.000	7	10	70	22.642	77.172	18.000	5	17	85	23.341	72.674	10.588
4	16	64	14.283	45.229	7.500	3	22	66	19.024	120.000	0.000	8	9	72	22.453	68.208	20.000	5	18	90	22.676	107.464	10.000
4	17	68	13.821	44.811	7.302	3	23	69	18.707	119.374	7.826	3	25	75	22.231	120.000	0.000	5	19	95	22.108	107.558	9.474

4	18	72	13.506	46.128	10.000	3	24	72	18.288	120.000	5.000	7	11	77	21.634	102.857	0.000	5	20	100	21.673	72.285	9.000
5	15	75	13.241	38.178	12.000	3	25	75	18.043	119.617	7.200	8	10	80	21.402	67.428	15.429	5	21	105	21.236	107.739	0.000
4	19	76	13.144	45.430	9.474	3	26	78	17.750	120.000	0.000	3	27	81	21.167	60.464	0.000	3	36	108	21.120	120.000	0.000
5	16	80	12.671	37.484	11.250	3	27	81	17.444	120.000	0.000	3	28	84	20.679	120.000	4.286	5	22	110	20.838	107.731	0.000
5	17	85	12.175	36.832	10.588	7	12	84	17.200	51.428	12.857	3	29	87	20.268	60.322	0.000	3	37	111	20.795	60.071	4.865
5	18	90	11.920	37.309	10.000	3	29	87	17.148	60.089	0.000	8	11	88	20.232	112.388	2.216	3	38	114	20.464	120.000	3.158
5	19	95	11.699	36.622	7.105	4	22	88	17.041	134.845	8.182	3	30	90	19.863	60.090	0.000	3	39	117	20.166	119.765	4.615
5	20	100	11.360	36.154	6.750	3	30	90	17.001	120.000	4.000	3	31	93	19.512	120.000	0.000	3	40	120	19.874	60.052	4.500
5	21	105	11.132	36.960	8.571	7	13	91	16.515	51.428	11.868	3	32	96	19.213	60.046	0.000	3	41	123	19.598	120.000	0.000
6	18	108	11.026	31.626	10.000	4	23	92	16.504	134.730	7.826	3	33	99	18.962	60.229	0.000	3	42	126	19.358	120.000	0.000
5	22	110	10.875	36.555	8.182	4	24	96	16.112	134.853	7.500	3	34	102	18.720	120.000	3.529	3	43	129	19.148	60.069	4.186
6	19	114	10.636	31.222	9.474	7	14	98	15.969	51.429	11.020	3	35	105	18.491	60.310	0.000	3	44	132	18.962	60.226	4.091
6	20	120	10.291	30.837	9.000	4	25	100	15.696	134.894	0.000	3	36	108	18.246	60.102	0.000	3	45	135	18.758	120.000	2.667
6	21	126	10.087	31.092	8.571	4	26	104	15.311	134.830	0.000	3	37	111	18.030	120.000	0.000	3	46	138	18.568	60.107	3.913
6	22	132	9.907	30.830	6.855	4	27	108	15.042	134.946	0.000	3	38	114	17.842	120.000	0.000	3	47	141	18.384	60.024	3.830
6	23	138	9.662	30.390	6.261	4	28	112	14.789	134.798	6.429	3	39	117	17.696	60.052	0.000	3	48	144	18.219	120.000	0.000
6	24	144	9.476	30.819	7.500	4	29	116	14.500	134.708	6.207	10	12	120	17.553	54.890	15.000	3	49	147	18.075	60.029	3.673
7	21	147	9.440	26.970	8.571	4	30	120	14.307	134.770	6.000	3	41	123	17.398	120.000	2.927	3	50	150	17.948	60.115	3.600
6	25	150	9.283	30.565	7.200	4	31	124	14.090	45.005	0.000	3	42	126	17.281	119.865	4.286	3	51	153	17.814	60.007	2.309
7	22	154	9.157	26.715	8.182	4	32	128	13.859	134.922	0.000	3	43	129	17.135	60.009	0.000	3	52	156	17.695	60.000	2.076
6	26	156	9.107	30.318	6.923	4	33	132	13.708	134.964	0.000	10	13	130	16.827	54.304	13.846	3	53	159	17.562	60.054	3.396
7	23	161	8.904	26.471	7.826	9	15	135	13.592	40.000	10.667	11	12	132	16.814	49.965	15.000	7	23	161	17.308	128.427	7.826
7	24	168	8.738	26.618	7.500	4	35	140	13.438	134.742	5.143	4	34	136	16.660	45.151	0.000	7	24	168	16.939	128.471	7.500
7	25	175	8.590	26.521	6.430	9	16	144	13.142	40.000	10.000	10	14	140	16.267	125.998	12.857	7	25	175	16.665	128.562	0.000
7	26	182	8.405	26.173	5.790	5	30	150	12.965	36.166	0.000	11	13	143	16.153	49.478	12.462	15	12	180	16.606	48.000	14.000
7	27	189	8.253	26.413	6.667	9	17	153	12.767	40.000	9.412	4	36	144	16.031	134.974	0.000	7	26	182	16.277	128.484	0.000
8	24	192	8.251	23.497	7.500	5	31	155	12.646	144.000	0.000	4	37	148	15.780	45.029	0.000	4	47	188	16.254	45.088	3.830

did, however, take a conservative approach to the constraint dealing with counter-rotating interfaces by assuming that the latitude ϕ discussed in the present analysis was equal to the lower latitude limit of coverage ϕ. The constraint relation used in [3] for optimally phased polar constellations providing continuous single polar cap coverage, and expressed in the terminology of this paper, is

$$(p - 1)(\theta + c_1) + 2c_1 = \pi \cos \phi \tag{16}$$

Using cos ϕ as a multiplier of π in (16) is equivalent to trying to solve a spherical triangle with one side being a minor circle arc. Consequently, solutions obtained from equation (16) will be sufficiently accurate, when compared with those obtained herein, only if the quantity ($\sin \theta/\cos \phi$) is small. It should also be noted that [3] did not recognize that different $j \times k$ factorizations of n could be beneficial in determining minimal constellations.

In [4] Rider examined arbitrarily phased polar constellations providing n-fold polar cap coverage. However, the results obtained in this regard used an "average" half-street width $c = (c_1 + c_j)/2$ to arrive at the following constraint equation

$$2p \arcsin(\sin c/\cos \phi) = k\pi \tag{17}$$

Comparing equation (17) with the constraint in (3) will reveal for $n > 1$ that equation (17) produces slightly conservative results for large θ and essentially equivalent results for small θ. The treatment in [4] of optimally phased constellations that provide global coverage also takes the same conservative approach to counter-rotating interfaces as done in [3].

There are other types of constellations which can satisfy different portions of the general Earth coverage problem with fewer satellites than those reported here. In [6] Walker was the first to show that continuous coverage of the Earth could be achieved with five satellites in inclined circular orbits. In [7] Ballard extended the results of [6], and his inclined orbit constellations as reported there with twenty four or fewer satellites are more efficient than the polar constellations discussed in this paper for the total number of satellites he has considered. For some lower latitudes and some redundancies of coverage, arbitrarily phased inclined orbit constellations providing *polar cap* coverage as reported by Rider in [5] provide more efficient constellations than those given here. The results of [5] also show that mixed constellations employing two orthogonal polar planes and one equatorial plane provide more efficient constellations for *double and quadruple global* coverage when $\theta \geq 55.11$ degrees than the purely polar orbit constellations that have been used in this analysis.

Collision Avoidance

The approach to the coverage problem presented here has not as yet addressed the practical aspects of satellite collision avoidance. Since this analysis has been solely concerned with circular polar orbit constellations, and since coincidence of orbital planes has been specifically avoided, collisions are possible only above the poles. This implies that if the satellites were all in perfectly circular orbits at the same altitude, a collision would occur if and only if satellites in two or more planes crossed their ascending nodes simultaneously. This is equivalent to $i\omega$ (mod $2\pi/s$) equaling zero for some integer i ranging from 1 to $p - 1$. For arbitrarily phased constellations, an inter-plane phasing ω can always be selected so that $i\omega \pmod{2\pi/s}$ never equals zero. For optimally phased constellations, however, an examination of Tables 5–8 will reveal that $i\omega \pmod{2\pi/s}$ does equal zero for some integer i between 1 and $p - 1$ for many of the constellations listed there, most notably those with $\omega = 0$, and those with $\omega = \pi/s$ where $p > 2$.

Another means of avoiding collisions for arbitrarily phased constellations is by placing the satellites in each orbital plane at a common altitude which differs from the common altitude used for satellites in any other plane but which still ensures the same radius of coverage θ for all satellites. However, for optimally phased constellations this method is not applicable since the orbital period (and hence the semi-major axis) of each satellite in the constellation must be a common value to maintain the optimal phasing. Small adjustments to other orbital parameters including the inclination, eccentricity, and argument of perigee could result in constellation designs that were free of potential collisions. Arriving at such designs, however, would not be a trivial task, and the constellations obtained could not be both circular and polar, which are constraints that have been addressed herein.

An approach to the collision avoidance problem, which preserves orbits that are both circular and polar, is to deviate slightly from the optimal phasing so that no two satellites are at their ascending nodes simultaneously. An apparent concern that arises when approaching the problem in this manner is how much a deviation in phasing will affect the minimum satellite radius of coverage applicable for a constellation, if the same angular distances between successive ascending nodes are maintained. Let $\Delta\omega$ denote the deviation from the optimal inter-plane satellite phasing angle. It will be shown that $\Delta\theta$ — the necessary increase in a constellation's minimum applicable satellite radius of coverage — is bounded from above, as indicated in the following inequality

$$\Delta\theta \leq \max[|\Delta\omega|, (p - 1)|\Delta\omega| \pmod{2\pi/s}] \tag{18}$$

Typically, the analyst will wish to determine the minimum constellation for a specific value of θ. By using data like those given in Tables 5–8, a determination can be made of both that constellation and the minimum θ-value which is applicable for the constellation. By comparing the two θ-values and by using (18), the analyst can determine the freedom he has in perturbing the phasing from its optimal value in order to avoid collision.

Example: An analyst determines a satellite's radius of coverage to be 12.3°. He wishes to find the minimal polar constellation that will provide continuous single coverage above 45° latitude. Looking in Table 7, he finds that the appropriate constellation has $T = 126$, $p = 7$, $s = 18$, and a minimum applicable θ-value of 12.013° if the optimal phasing ω of 10° were used. Since the spacing between satellites in the same orbital plane is $360°/18 = 20°$, and since $2\omega = 20°$, the optimal phasing is judged impractical from collision avoidance considerations. The analyst's θ-value exceeds the minimum applicable θ-value for the constellation by 0.287°. Therefore, this same constellation will be appropriate for the analyst's needs as long as the deviation $\Delta\omega$ from the optimal phasing is such that $\max[|\Delta\omega|, 6|\Delta\omega| \pmod{20°}] \leq 0.287°$, which implies that $|\Delta\omega| \leq 0.047°$.

To verify (18), begin by re-examining the constraint given in (6). Consider a spherical triangle ABB' whose vertices are A — a c_i cusp at latitude ϕ from plane A's street-of-coverage, B — a satellite's position in plane B at latitude ξ^* when the optimal phasing is used, and B' — a satellite's position in plane B at latitude $\xi^* + \Delta\omega$ when the perturbed inter-plane phasing is used. The distance from A to B' is $\theta + \Delta\theta$ and must be less than or equal to $\theta + |\Delta\omega|$, which is the sum of the distances from A to B and from B to B'. Therefore, to ensure coverage along an interface governed by constraint (6), the necessary increase in a satellite's radius of coverage is no greater than $|\Delta\omega|$. This same argument works for interfaces governed by constraints (7), (8), and (9) as well. Also, the same argument applies to the counterparts of these constraints which involve the angles β and β'; in this case, however, $(p - 1)|\Delta\omega| \pmod{2\pi/s}$ represents the displacement in phasing. Consequently, for coverage interfaces governed by constraints of the types given in (6) through (9), the necessary increase in a satellite's radius of coverage is bounded from above, as indicated in (18).

It is also necessary to consider the effects a deviation from the optimal phasing has on constraints of the type given in (10). A change $\Delta\omega$ will cause both a change $\Delta\psi$ in the latitude ψ appearing in such a constraint and a change in the corresponding displacement $\Delta\zeta$ of a satellite in the plane on the c_i side of the co-rotating interface implied by the constraint. By differentiating equations (A6), (A8), and (A9) given in Appendix A, an upper bound on both $\Delta\psi$ and $\Delta\zeta$ is found to be $|\Delta\omega|/2$. Consider the spherical quadrilateral $ABB'A'$, where A and A' are the c_i cusp's positions at latitudes ψ and $\psi + \Delta\psi$, and B and B' are points in the orbital projection closest to the cusps when at those latitudes. The distance from A' to B' corresponds to the increased half-street width $c_i + \Delta c_i$. The distances from A to B, A to A', and B to B' have values of c_i, $\Delta\psi$, and $\Delta\zeta$, respectively. Therefore, $c_i + \Delta c_i \le \Delta\psi + c_i + \Delta\zeta$, or $\Delta c_i \le \Delta\psi + \Delta\zeta$. By differentiating equation (1), it is apparent that $\Delta\theta \le \Delta c_i$. Combining all these inequalities yields

$$\Delta\theta \le \Delta c_i \le \Delta\psi + \Delta\zeta \le |\Delta\omega|/2 + |\Delta\omega|/2 = |\Delta\omega| \tag{19}$$

Consequently, for a counter-rotating coverage interface characterized by the angle α', the necessary increase in θ is bounded from above by $|\Delta\omega|$. Similarly, for a counter-rotating interface characterized by the angle β', $\Delta\theta$ is bounded from above by $(p - 1)|\Delta\omega| \pmod{2\pi/s}$. Therefore, (18) holds for interfaces governed by constraints of type (10) as well.

Approximate Relations for Large Constellations

For those missions requiring large total numbers of satellites, simple approximate equations relating the major constellation parameters — n, ϕ, p, s, T, and θ — can provide both insight into the fundamental character of minimal constellations as well as expedite the accomplishment of preliminary system trade studies. The purpose of this section is to determine such approximate relations for large constellations that utilize either optimal or arbitrary inter-plane satellite phasing. Of primary interest is to observe the behavior of T as θ tends to zero.

A starting point for determining this behavior for optimally phased constellations is an examination of the inter-plane coverage constraints given by (6) through (10). Begin with the constraint given in (6). Let α_1 and α_2 denote the arcsin and arccos terms, respectively, on the right-hand side of (6). For a fixed θ, upper and lower bounds on α_2 can easily be determined by allowing the phasing angle ω to vary. Clearly, α_2 would be greatest if the phasing were such that the satellite latitude ξ^* shown in Fig. 3 corresponded to the point along plane B's orbital projection closest to the c_i cusp at latitude ϕ of plane A's street-of-coverage. Likewise, α_2 would be smallest if the phasing were such that a midpoint between satellites was the point in plane B's orbital projection closest to this cusp. From the law of sines for spherical triangles, these facts can be expressed as follows

$$\arcsin(\sin c_1/\cos \phi) \leq \alpha_2 \leq \arcsin(\sin \theta/\cos \phi) \tag{20}$$

The difference between the bounds on α_2 goes to zero as θ tends to zero. Consequently, $\arcsin(\sin \theta/\cos \phi)$ will be a good approximation for α_2 for small values of θ. Since $\theta \approx \sin \theta$ for small θ(and thus, $x \approx \arcsin x$ for small x), it follows that $\theta/\cos \phi$ is also a good approximation for α_2 when $\theta/\cos \phi$ is small. Likewise, $c_j/\cos \phi$ will be a good approximation for α_1 when $\theta/\cos \phi$ is small. This same argument will work for constraints (7), (8), and (9) as well, where again α_1 and α_2 correspond to the arcsin and arccos terms, respectively, on the right-hand side of these inequalities.

For constraint (10) the situation is somewhat different. In this case, let the parameter $\alpha_1 = \arcsin(\sin c_j/\cos \psi)$ and let $\alpha_2 = \arcsin(\sin c_1/\cos \psi)$. The definition of the latitude ψ implies that $\phi \leq \psi \leq \phi + \pi/s$. Consequently,

$$\arcsin(\sin c_j/\cos \phi) \leq \alpha_1 \leq \arcsin[\sin c_j/\cos(\phi + \pi/s)] \tag{21}$$

The difference between the bounds on α_1 given in (21) goes to zero as s increases. Therefore, $\arcsin(\sin c_j/\cos \phi)$ will be a good approximation for α_1 for small values of θ, since s must increase if θ decreases. Similarly, $\arcsin(\sin c_1/\cos \phi)$ will be a good approximation for α_2 as θ tends to zero. Since the difference on the bounds of α_2 given in (20) tends to zero, $\arcsin(\sin \theta/\cos \phi)$ will also be a good approximation for α_2 as θ tends to zero. Therefore, employing the same reasoning used for (6) through (9) above, it follows that $c_j/\cos \phi$ and $\theta/\cos \phi$ are good approximations for α_1 and α_2, respectively, when $\theta/\cos \phi$ is small.

Equality in the coverage constraints (11) through (14) is considered when determining minimal constellations. From the preceding arguments, the α, α', β, and β' parameters that appear in these constraints can all be approximated by $c_j/\cos \phi + \theta/\cos \phi$ for small values of $\theta/\cos \phi$. Consequently, an approximate constraint that characterizes minimal optimally phased constellations for small values of $\theta/\cos \phi$ is

$$p(\theta + c_j) \approx k\pi \cos \phi \tag{22}$$

The small angle approximations that have been used in the above analysis for optimally phased constellations can also be applied to (3) to arrive at the following constraint for arbitrarily phased constellations when $\theta/\cos \phi$ is small:

$$p(c_1 + c_j) \approx k\pi \cos \phi \tag{23}$$

Two other small angle approximations which will be useful in determining the approximate behavior of T for small values of θ are

$$\theta^2 \approx (\pi/s)^2 + c_1^2 \tag{24}$$

and

$$\theta^2 = (j\pi/s)^2 + c_j^2 \tag{25}$$

A Lagrangian undetermined multiplier technique can be used to find a minimum value of $T = p \times s$ subject to the constraints (22) through (25) given above. Appendix B outlines how this determination is made. The desired approximations for T are found to be

$$T \approx (4\sqrt{3}/9)n(\pi/\theta)^2 \cos\phi \tag{26}$$

for optimally phased constellations, and

$$T \approx [(2/\sqrt{3})(1 + n^2 + d)/(\sqrt{2n^2 - 1 + 2d} + \sqrt{2 - n^2 + 2d})](\pi/\theta)^2 \cos\phi \tag{27}$$

for arbitrarily phased constellations, where $d = \sqrt{1 - n^2 + n^4}$.

The accuracy of the approximations (26) and (27) has been verified by comparing actual T-values for minimal constellations with approximate values derived from these equations. Like the data given in Tables 1–8, the levels of coverage n tested ranged from 1 to 4, and the values of ϕ considered were equal to 0, 30, 45, and 60 degrees. For each minimal constellation with a total number of satellites between 100 and 1000, an approximate value of T, denoted T_{ap}, was calculated using (26) or (27) and then rounded to the nearest integer. A percent deviation in T was then determined by computing $(|T_{ap} - T|/T) \times 100\%$. Average and maximum values of this deviation are indicated in Table 9. The approximate values of T as a function of θ are seen to be

TABLE 9. Accuracy of Approximations for $100 \le T \le 1000$

		% deviation for optimal phasing		% deviation for arbitrary phasing	
ϕ	n	average	maximum	average	maximum
0	1	2.569	6.429	0.643	3.333
	2	0.680	2.857	0.325	1.818
	3	0.711	3.704	0.448	2.857
	4	0.344	1.754	0.539	3.472
30	1	2.861	6.731	0.311	1.429
	2	0.762	4.615	0.454	2.308
	3	0.609	2.419	0.553	3.125
	4	0.484	2.400	0.611	3.922
45	1	2.459	5.442	0.486	2.586
	2	0.453	2.885	0.507	2.500
	3	0.556	2.667	0.591	3.125
	4	0.596	2.941	0.767	3.175
60	1	2.556	4.762	0.470	2.000
	2	0.458	2.586	0.624	2.778
	3	0.752	4.902	0.928	4.902
	4	1.272	6.000	1.296	5.691

reasonably precise for large constellations; in a large majority of instances the approximate values of T underestimate the actual values by just a small amount.

When $\theta/\cos\phi$ is small enough for the approximations given in equations (26) and (27) to be valid, it is interesting to note that as the level of coverage n increases, the number of satellites in a constellation which is to provide continuous n-fold coverage using arbitrary phasing asymptotically approaches the number required if optimal phasing were to be utilized. This can be seen analytically by using a simple ratio test to show that as n tends to infinity, the "normalized coefficient," defined by $T/[(\pi/\theta)^2 \cos\phi]$, for arbitrarily phased constellations approaches $(4\sqrt{3}/9)n$ — which is the corresponding normalized coefficient for optimally phased constellations. This asymptotic behavior is depicted graphically in Fig. 6, which plots $T/[(\pi/\theta)^2 \cos\phi]$ as a function of n. Solid lines have been used to connect data points in the same "family" for arbitrarily phased constellations, where a family is characterized by a common k-value in the $j \times k$ factorizations of the different values of n. From the figure, it is apparent that the factorization of n with $j = n$ and $k = 1$ is associated with minimum constellations using arbitrary phasing. Data points related to optimally phased constellations have been connected by the dotted line shown. For $n \geq 5$ and a

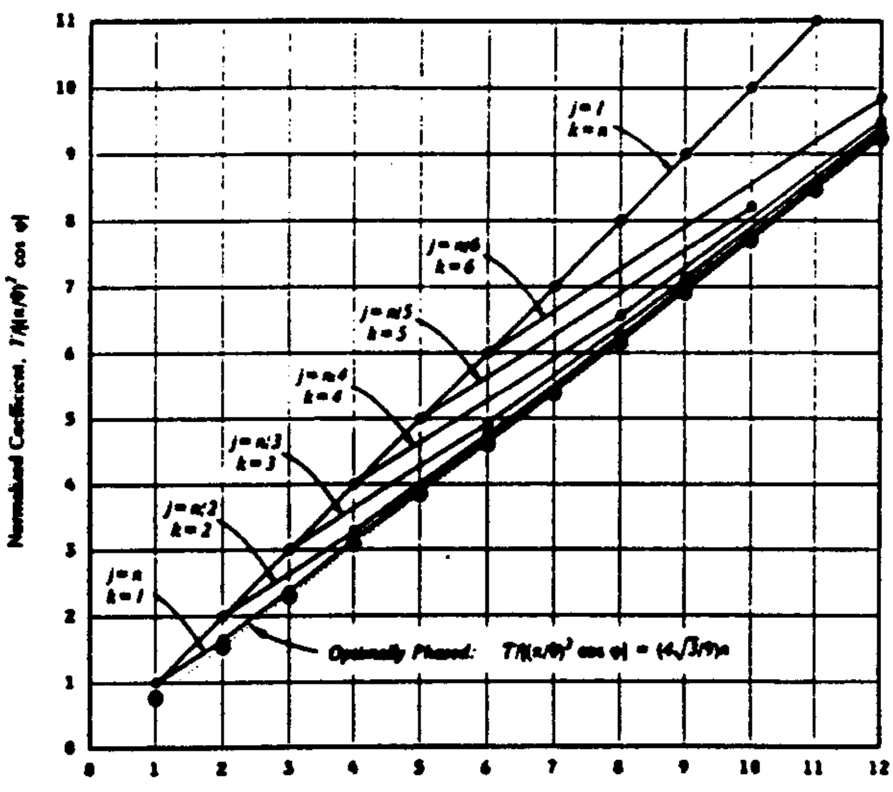

FIG. 6. Approximate Relations for Large Constellations.

fixed small θ-value, the approximations (26) and (27) predict that the difference between the required number of satellites in constellations using arbitrary or optimal phasing is less than or equal to 1.01%. Conversely, for $n \geq 5$ and a fixed total number of satellites, equations (26) and (27) predict the difference in the required θ between the best arbitrarily phased and optimally phased constellations to be less than 0.51%.

There is a fundamental difference in the character of the approximate solutions for optimally versus arbitrarily phased minimal constellations. This can be made evident by eliminating (π/θ) from equations (B18) and (B19) while using the optimal $j = n$, $k = 1$ factorization of n to obtain the approximate relation

$$(s/p)_{\alpha\varphi} = (\sqrt{2n^2 - 1 + 2d} + \sqrt{2 - n^2 + 2d})/(\sqrt{3}\cos\phi) \qquad (28)$$

for large arbitrarily phased minimal constellations. In a similar manner, equations (B7) and (B8) can be utilized to obtain the approximation

$$(s/p)_{o\varphi} = \sqrt{3}(j/k)/\cos\phi \qquad (29)$$

for large optimally phased minimal constellations. For given values of n and ϕ, equation (28) indicates that generally there is a unique approximate (s/p) ratio associated with minimal constellations employing arbitrary phasing. However, equations (26) and (29) indicate that minimal constellations using optimal phasing may be associated with several different approximate (s/p) ratios — one for each possible factorization of n. Both these cases can be verified by examining the minimal constellations listed in Tables 1–8. For small θ it should be noted that for given values of T and $(s/p)_{\varphi}$, an approximation to the number of orbital planes can be obtained from the closest integer to $p = \sqrt{T/(s/p)_{\varphi}}$. The approximate number of satellites in each orbital plane is then obtained by choosing s such that $p \times s$ is closest to T.

Summary

This article has addressed the problem of determining minimal circular polar orbit constellations which provide continuous n-fold coverage above a specified latitude ϕ when subject to the constraints of the street-of-coverage technique. Both arbitrary and optimal inter-plane satellite phasing have been considered. Inequality constraints have been derived which must be satisfied if a constellation is to provide such coverage. When solving for equality in these constraints, minimal constellations can be determined by an iterative computational procedure. The first fifty members of families of minimal constellations have been tabulated using this procedure for values of n ranging from 1 to 4, and for values of ϕ equal to 0, 30, 45, and 60 degrees. The utility of counter-oriented optimally phased constellations, which have heretofore not been considered, is apparent upon examination of these families for values of ϕ greater than zero. A comparison of the tabulated data with prior results has been made, and instances of where these prior results are conservative have been noted. The problem of collision avoidance has been treated by deriving inequalities which relate the deviation in phasing from optimal to the required increase in the satellite radius of coverage θ. Also, small angle approximations have been used in conjunction with a Lagrangian undetermined multiplier technique to derive approximate relations between the total number of satellites in large constellations and the required θ-value necessary for supplying the desired level of coverage.

Appendix A
Determination of the Latitude ψ

In the discussion of a counter-rotating interface, it was noted that a hole in coverage could result above the lower latitude limit ϕ even though coverage at latitude ϕ was continuous. By examining Fig. 3, it is apparent that such a hole would not occur if the angular separation between the ascending node of one orbital plane and the descending node of the other was sufficiently small so that the streets-of-coverage always intersect. It is enough for intersection to occur whenever a c_j cusp from one street is at the same latitude as the c_1 cusp from the other street, where the only latitudes that need to be considered are those greater than ϕ. This appendix is concerned with determining what those latitudes are. Once the determination has been made, it is an easy matter to determine the latitude ψ involved in (7), which is the constraint that places an upper bound on α'. A similar constraint with $(p - 1)\omega \pmod{2\pi/s}$ taking the role of ω applies to the angle β'.

Suppose ω is the inter-plane satellite phasing angle between satellites in two planes A and B that form a counter-rotating interface. Then satellites in B lead their counterparts in A by the angle ω. In general, four latitudes need to be determined: these are ψ_a, when a c_j cusp on the ascending side of A is at the same latitude as a c_1 cusp on the descending side of B; ψ_b, when a c_1 cusp on the ascending side of A is at the same latitude as a c_j cusp on the descending side of B; ψ_c, when a c_j cusp on the ascending side of B is at the same latitude as a c_1 cusp on the descending side of A; and ψ_d, when a c_1 cusp on the ascending side of B is at the same latitude as a c_j cusp on the descending side of A. Note that when $j = 1$, ψ_b is the same as ψ_a, and ψ_d is the same as ψ_c. It can also be seen that if ω equals π/s, then ψ_c equals ψ_a, and ψ_d equals ψ_b.

Latitude ψ_a shall be determined first. Suppose a c_j cusp from plane A's street-of-coverage is at latitude ϕ on the ascending side. Then there is a satellite in plane A at latitude ζ, as given by equation (5). Consequently, there is a satellite in plane B at an angular distance of $\pi - (\zeta + \omega)$ from its descending node: angular distances of the other satellites in B from their descending node can be determined by adding integer multiples of $2\pi/s$ to this quantity. A c_1 cusp from plane B would be at latitude ϕ on the descending side if there were a satellite in B at latitude ξ^*, where

$$\xi^* = \arcsin(\sin\phi/\cos c_1) + \pi/s \tag{A1}$$

Usually, a satellite in plane B will not be at latitude ξ^* at the same time a satellite in plane A is at latitude ζ. There will, however, be a satellite in plane B having latitude ξ such that $\xi \geq \xi^*$ and such that $\xi - \xi^*$ is minimal. It is known that for some integer m,

$$\xi = \pi - (\zeta + \omega) + m(2\pi/s) \tag{A2}$$

Since $0 \leq \xi - \xi^* < 2\pi/s$, it follows that

$$(m - 1)(2\pi/s) < \xi^* + \zeta + \omega - \pi \leq m(2\pi/s) \tag{A3}$$

and therefore, the integer m is completely determined by the inequalities

$$m - 1 < (\xi^* + \zeta + \omega - \pi)(s/2\pi) \leq m \tag{A4}$$

Along the counter-rotating interface, as satellites in plane A move up in latitude, those in plane B decrease in latitude by the same amount. If ζ' and ξ' represent the latitudes of satellites in planes A and B, respectively, when a c_j cusp from plane A is at the same latitude ψ_a as a c_1 cusp from plane B, then there must be a constant κ such that

$$\xi' = \kappa - \zeta' \tag{A5}$$

Since at some points in time a satellite in plane B will have latitude ξ on its descending side, the constant κ must equal $\xi + \zeta$, or

$$\kappa = \pi - \omega + m(2\pi/s) \tag{A6}$$

From the law of cosines for spherical triangles, it follows that

$$\sin(\zeta' - \delta\pi/s)\cos\ c_j = \sin\psi_a = \sin(\xi' - \pi/s)\cos c_1 \tag{A7}$$

Let $\kappa' = \kappa - (1 - \delta)\pi/s$. Solving equations (A5) and (A7) for ζ' yields

$$\zeta' = \arctan[(\sin\kappa'\cos j\pi/s)/(\cos\pi/s + \cos\kappa'\cos j\pi/s)] + \delta\pi/s \tag{A8}$$

The latitude ψ_a can then be determined from (A7) as

$$\psi_a = \arcsin[\sin(\zeta' - \delta\pi/s)\cos c_j] \tag{A9}$$

The latitude ψ_b is determined in a similar manner by reversing the roles of c_j and c_1 everywhere. When this is done, the roles of ζ and ξ^* (and thus $\delta\pi/s$ and π/s) are also reversed. The latitude ζ'' of a satellite in plane A when its c_1 cusp is at the same latitude ψ_b as a c_j cusp from plane B is given as

$$\zeta'' = \arctan[(\sin\kappa''\cos\pi/s)/(\cos j\pi/s + \cos\kappa''\cos\pi/s)] + \pi/s \tag{A10}$$

where $\kappa'' = \kappa - (\delta - 1)\pi/s$. The latitude ψ_b is then found to be

$$\psi_b = \arcsin[\sin(\zeta'' - \pi/s)\cos c_1] \tag{A11}$$

The latitudes ψ_c and ψ_d are determined in the same manner as ψ_b and ψ_a, respectively, by interchanging the roles of A and B and by noting that this is equivalent to replacing ω everywhere with $-\omega$.

The latitude ψ can then be determined as $\psi = \min(\psi_a, \psi_b, \psi_c, \psi_d)$, and the constraint (7) follows by applying the law of sines for spherical triangles.

Appendix B
Approximate Solutions for Large Constellations

This appendix details how the approximations given by equations (26) and (27) have been determined.

Approximation for T for Large Optimally Phased Constellations

Using equations (22) and (25) given in the text, the optimization problem can be formulated as follows: Minimize $T = p \times s$ subject to the constraints

$$g_1 = p(\theta + c_j) - k\pi\cos\phi = 0 \tag{B1}$$

$$g_2 = \theta^2 - (j\pi/s)^2 - c_j^2 = 0 \tag{B2}$$

Employing a Lagrangian undetermined multiplier technique and considering p, s, and c_j as the independent variables, the solution can be obtained by the simultaneous solution of (B1), (B2), and the three following equations

$$\partial T/\partial p + \lambda_1 \partial g_1/\partial p + \lambda_2 \partial g_2/\partial p = 0 \tag{B3}$$

$$\partial T/\partial s + \lambda_1 \partial g_1/\partial s + \lambda_2 \partial g_2/\partial s = 0 \tag{B4}$$

$$\partial T/\partial c_j + \lambda_1 \partial g_1/\partial c_j + \lambda_2 \partial g_2/\partial c_j = 0 \tag{B5}$$

where the five variables are p, s, c_j, λ_1, and λ_2. After the partial derivatives are obtained and the Lagrangian multipliers λ_1 and λ_2 are eliminated, the three equations in the three variables p, s, and c_j that result are given by (B1), (B2), and

$$\theta + c_j = (j\pi/s)^2/c_j \tag{B6}$$

Solving (B1), (B2), and (B6) for p and s yields

$$p = (2/3)k(\pi/\theta)\cos\phi \tag{B7}$$

$$s = (2/\sqrt{3})j(\pi/\theta) \tag{B8}$$

Using $n = j \times k$, equations (B7) and (B8) can be multiplied to obtain

$$T = (4\sqrt{3}/9)n(\pi/\theta)^2\cos\phi \tag{B9}$$

Approximation for T for Large Arbitrarily Phased Constellations

Using equations (23), (24) and (25) as given in the text, the optimization problem can be formulated as follows: Minimize $T = p \times s$ subject to the constraints

$$g_1 = p(c_1 + c_j) - k\pi\cos\phi = 0 \tag{B10}$$

$$g_2 = \theta^2 - (\pi/s)^2 - c_1^2 = 0 \tag{B11}$$

$$g_3 = \theta^2 - (j\pi/s)^2 - c_j^2 = 0 \tag{B12}$$

Again employing a Lagrangian undetermined multiplier technique and considering p, s, c_1, and c_j as the independent variables, the solution can be obtained by the simultaneous solution of (B10), (B11), (B12), and the four following equations

$$\partial T/\partial p + \lambda_1 \partial g_1/\partial p + \lambda_2 \partial g_2/\partial p + \lambda_3 \partial g_3/\partial p = 0 \tag{B13}$$

$$\partial T/\partial s + \lambda_1 \partial g_1/\partial s + \lambda_2 \partial g_2/\partial s + \lambda_3 \partial g_3/\partial s = 0 \tag{B14}$$

$$\partial T/\partial c_1 + \lambda_1 \partial g_1/\partial c_1 + \lambda_2 \partial g_2/\partial c_1 + \lambda_3 \partial g_3/\partial c_1 = 0 \tag{B15}$$

$$\partial T/\partial c_j + \lambda_1 \partial g_1/\partial c_j + \lambda_2 \partial g_2/\partial c_j + \lambda_3 \partial g_3/\partial c_j = 0 \tag{B16}$$

where the seven variables are p, s, c_1, c_j, λ_1, λ_2, and λ_3. After the partial derivatives are obtained and the Lagrangian multipliers λ_1, λ_2, and λ_3 are eliminated, the four equations in the four variables p, s, c_1, and c_j that result are given by (B10), (B11), (B12), and

$$c_1 + c_j = (\pi/s)^2(1/c_1 + j^2/c_j) \tag{B17}$$

Let $e = \sqrt{1 - j^2 + j^4}$. The equations (B11), (B12), (B13), and (B17) can be solved for p and s to yield

$$p = \sqrt{2}k[\sqrt{1 + j^2 + e}/(\sqrt{2j^2 - 1 + 2e} + \sqrt{2 - j^2 + 2e})](\pi/\theta) \cos \phi \tag{B18}$$

$$s = \sqrt{2(1 + j^2 + e)/3}(\pi/\theta) \tag{B19}$$

Equations (B18) and B(19) can be multiplied to obtain

$$T = [(2/\sqrt{3})k(1 + j^2 + e)/(\sqrt{2j^2 - 1 + 2e} + \sqrt{2 - j^2 + 2e})](\pi/\theta)^2 \cos \phi \tag{B20}$$

As depicted graphically in Fig. 6, it can be shown that T is minimized when the $j = n$, $k = 1$ factorization of n is utilized.

Acknowledgment

The authors wish to express their thanks to the reviewers of this article. A special acknowledgment is due to the late A. H. Ballard whose insight has led to significant improvements in the manuscript as originally submitted.

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[5] RIDER, L. "Analytic Design of Satellite Constellations for Zonal Earth Coverage Using Inclined Circular Orbits," *Journal of the Astronautical Sciences*, Vol. 34, January-March 1986, pp. 31–64.

[6] WALKER, J. G. "Continuous Whole-Earth Coverage By Circular-Orbit Satellite Patterns," Royal Aircraft Establishment, Technical Report 77044, March 24, 1977.

[7] BALLARD, A. H. "Rosette Constellations of Earth Satellites," *IEEE Transactions on Aerospace and Electronic Systems*, Vol. AES-16, September 1980, pp. 656-673.

APPENDIX D

ADVANCE PUBLICATION INFORMATION FOR THE IRIDIUM SYSTEM

Section A - General Information

The Administration of the United States of America informs the members of the ITU of its intention to authorize the operation of the IRIDIUM Satellite Network. The RDSS system will operate in the RDSS band 1610-1626.5 MHz, in both the Earth-to-Space and Space-to-Earth directions. The last will operate in accordance with RR 342.

Section B - General Characteristics

1. **Identity of the Satellite Network**

   The Iridium Satellite Network is the same as the System. It consists of 77 identical interconnected satellites positioned in non-geostationary orbit, in seven equally spaced planes.

2. **Date of Bringing into Use**

   1994 Initial launches

3. **Administration or Group Submitting**

   United States of America
   Federal Communications Commission
   Washington, DC 20554
   Fed COMCOM
   Washington, DC

4. **Orbital Information Relating to Space Station(s)**

   There are seven polar, co-rotating planes, separated by slightly more than 27 degrees. Each plane has 11 satellites. The 11 satellites in each plane are equally spaced around their planar orbit. Satellites in planes 1, 3, 5 and 7 are in phase with each other, while those in planes 2, 4 and 6 are in phase with each other and halfway out of phase with those in planes 1, 3, 5 and 7. The earth center angel is 18.45 degrees. The system (network) satellites are at a constant altitude of 413 nautical miles. The total number of satellites having these characteristics is 77.

Section C - Characteristics of the Satellite Network in the Earth to Space Direction

1. **Earth-to-Space Service Area(s)**

   Initially Earth Stations will be used in the territory of the United States; two Gateway Stations are anticipated. The system has the capability of providing service to entire surfaces of the Earth from Pole to Pole and everywhere in between. Earth stations will be used in accordance with individual administration authorization. See Figure 1.

2. **Class of Station and Nature of Service**

   TF, TC, TL, TR

3. **Frequency Range**

   1610.0-1626.5 MHz - Subscriber Terminal
   27.5-30 GHz - Gateway link (Feederlink)

4. **Power Characteristics of Transmitter Use**

   a. Subscriber Terminal

      1) Peak EIRP (per burst):
         Total = 1.25 to 10.23 dBW
         Spectral Density = -48.3 to -40.8 dBW/Hz

      2) Average EIRP (per 60 ms frame):
         Total = 11.91 to -4.41 dBW
         Spectral Density = -61.5 to -53.9 dBW/Hz

   b. Gateway Link (Feederlink)

      EIRP:
         Total = 51.4 to 77.4 dBW
         Spectral Density = -16.6 to +9.4 dBW/Hz

5. **Characteristics of Space Station Receiving Antenna**

   a. Subscriber Link

      Gain: 22.5 dBi at 61.6 deg angle from nadir (max range)

      See Figures 2a-2g

   b. Gateway Link (Feeder)

      Gain: 21.5 dBi

      See Figure 3

6. **Noise Temperature of Space Station Receiving System**

   a. Subscriber Link

      553 degrees K

   b. Gateway Link (Feeder)

      1454 degrees K

7. **Necessary Bandwidth**

   a. Subscriber Link

      Total = 16.5 MHz
      Per Channel = 126 KHz

   b. Gateway Link (Feeder)

      15 MHz

8. **Modulation Characteristics**

   a. Subscriber Link

      Digital voice and data, QPSK with TDMA/FDMA multiplexing

   b. Gateway Link (Feeder)

      Digital voice and data, QPSK with TDMA multiplexing

Section D - Characteristics of Satellite Network in the Space to Earth Direction

1. **Space-to-Earth Service Areas**

   The receiving earth stations, both subscriber units (portable, mobile, and transportable) and Gateways, may be located in the U.S. initially. The service areas will be expanded in accordance with agreements with other countries. See Figure 1.

2. **Class of Stations and Nature of Service**

   ES, EC, EF

3. **Frequency Range**

1610-1626.5 MHz	Subscriber Terminal
18.8-20.2 GHz	Gateway Link (Feederlink)

4. **Power Characteristics of Transmitter Use**

a. Subscriber Link

1) Peak EIRP (per burst per carrier):
Total = 12.45 to 31.21 dBW
Spectral Density = -40.6 to -21.8 dBW/Hz

2) Average EIRP (per carrier per 60 ms frame):
Total = -4.2 to +14.6 dBW
Spectral Density = -57.2 to -38.4 dBW/Hz

b. Gateway Link (Feederlink)

EIRP:
Total = 14.5 to 27.5 dBW
Spectral Density = -53.5 to -40.5 dBW/Hz

5. **Space Station Transmitting Antenna**

a. Subscriber Link

Gain: 22.5 dBi at 61.6 deg angle from nadir (max range)

See Figures 2a-2g

b. Gateway Link (Feederlink)

Gain: 18.0 dBi

See Figures 4a-4j

6. **System Noise Temperature of Space Station Receiver**

a. Subscriber Link

553 degrees K

b. Gateway Link (Feederlink)

1193 degrees K

7. **Necessary Bandwidth**

a. Subscriber Link

Total = 16.5 MHz
Per Channel = 280 KHz

b. Gateway Link (Feederlink)

15 MHz

8. Modulation Characteristics

a. Subscriber Link

Digital voice and data, QPSK with TDMA/FDMA multiplexing

b. Gateway Link (Feederlink)

Digital voice and data, QPSK with TDMA multiplexing

Section E - Characteristics to be Furnished for Space-to-Space Relays

a) The 77 IRIDIUM satellites in seven planes, with 11 identical satellites each are all interconnected to each other.

b) 22.55-23.55 GHz

c) Emission: QPSK, FDMA/TDMA

d) Burst EIRP: 37.9 dBW (-33.1 dBW/Hz)

e) Crosslink antenna pattern: See Figure 5

Section F - Supplementary Information

Refer to Appendix A for power flux densities.

MOTOROLA

IRIDIUM

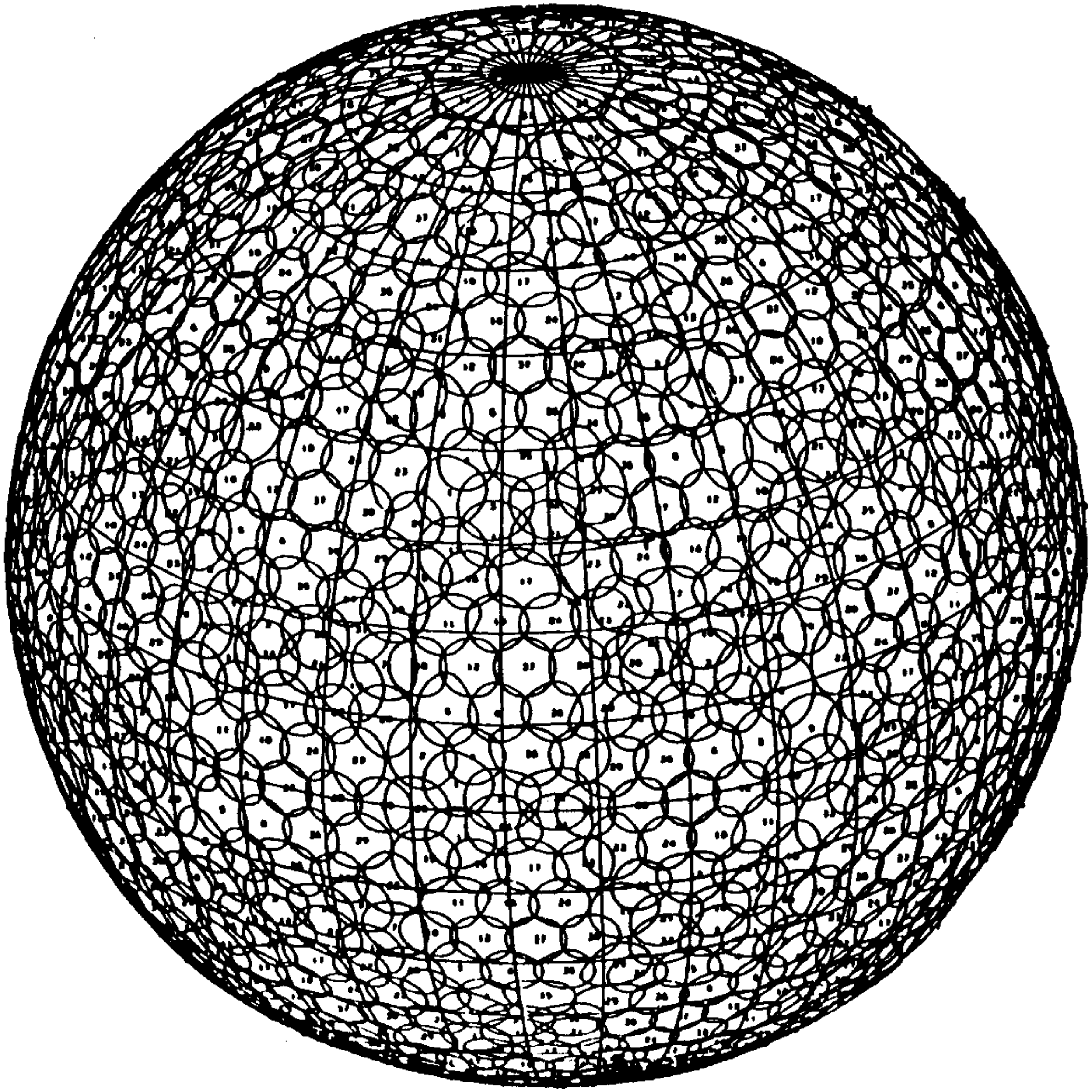


FIGURE 1 POTENTIAL IRIDIUM SERVICE AREAS

MOTOROLA

IRIDIUM

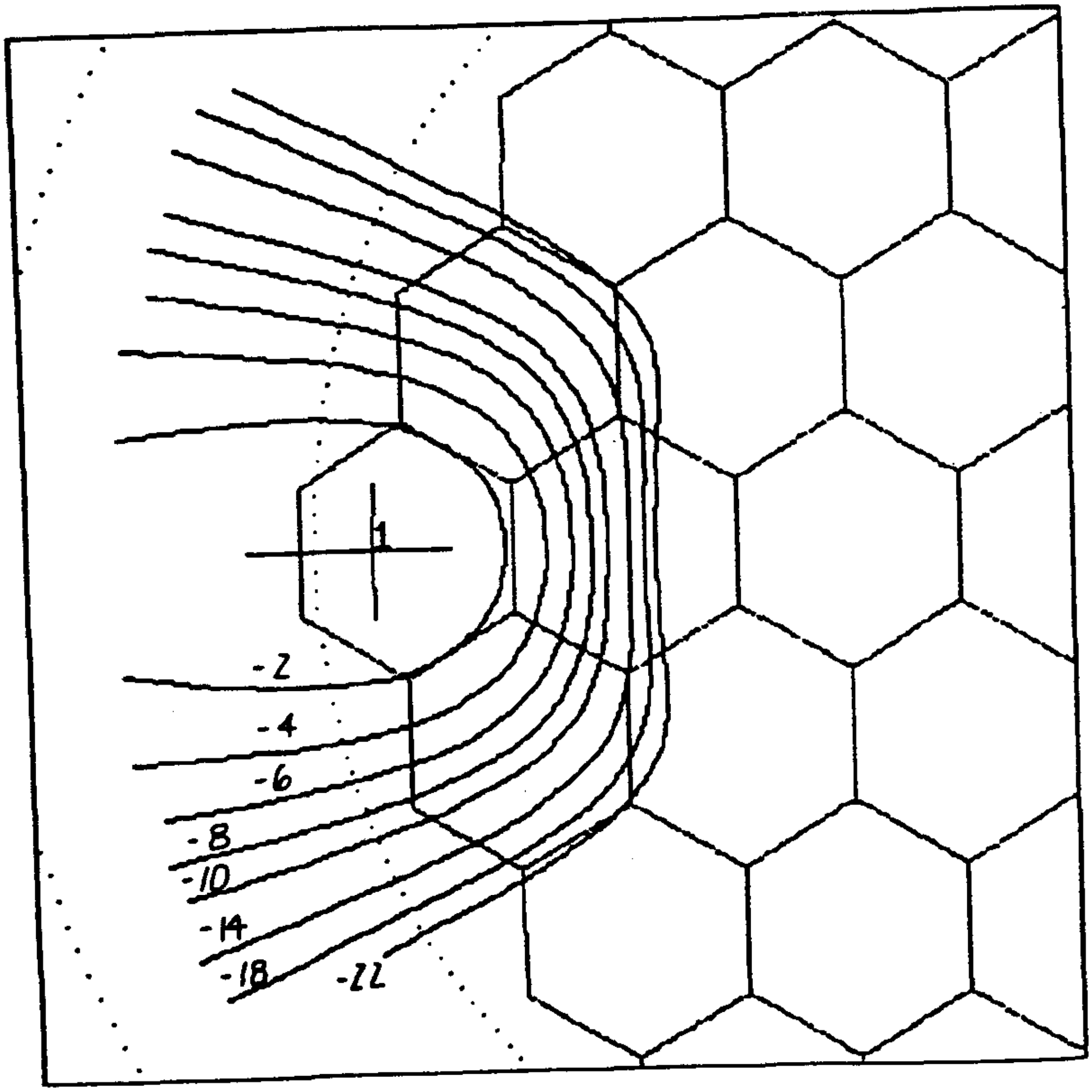


FIGURE 2a

CHARACTERISTIC OF SPACE STATION RECEIVE AND TRANSMIT ANTENNAS

MOTOROLA

IRIDIUM

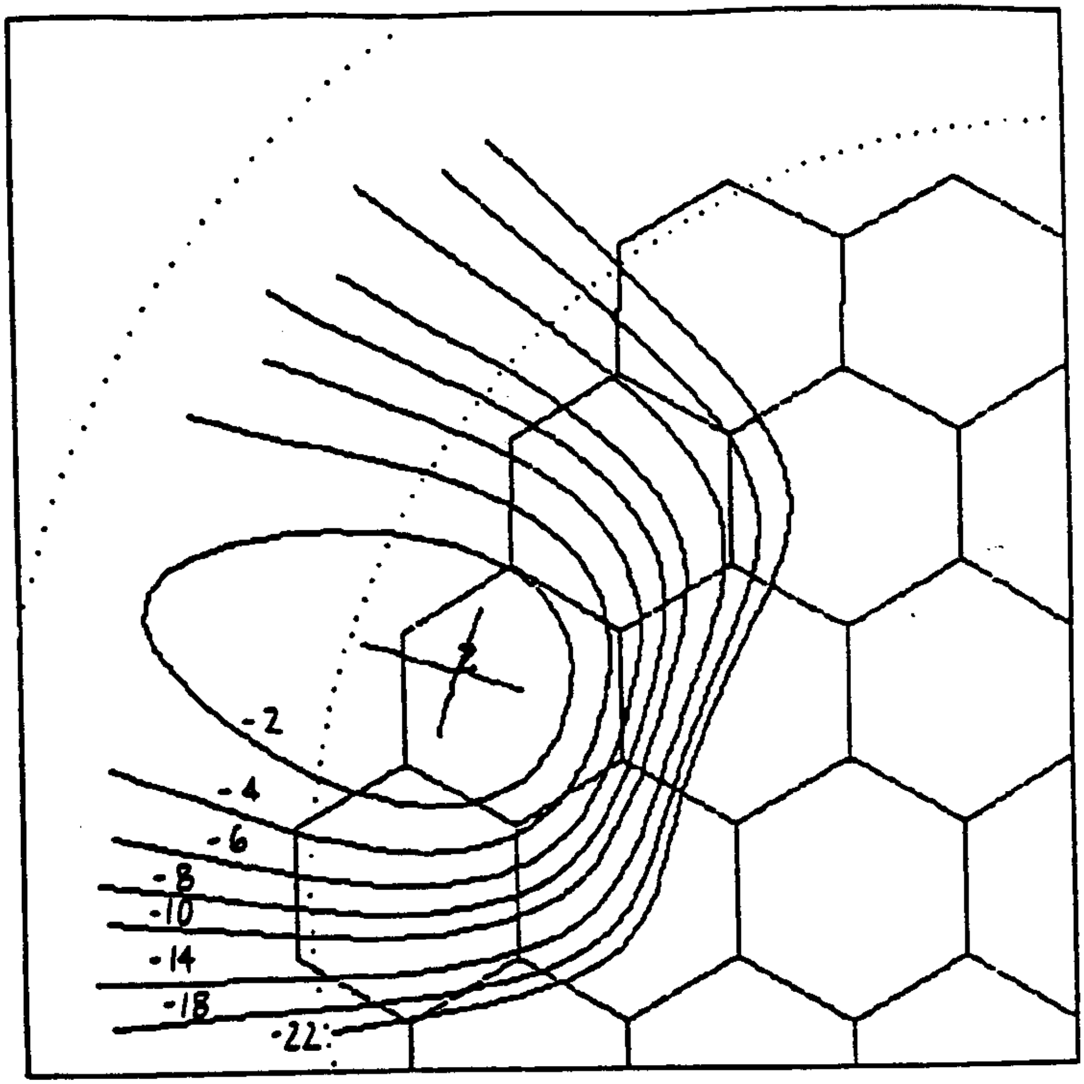


FIGURE 2b

CHARACTERISTIC OF SPACE STATION RECEIVE AND TRANSMIT ANTENNAS

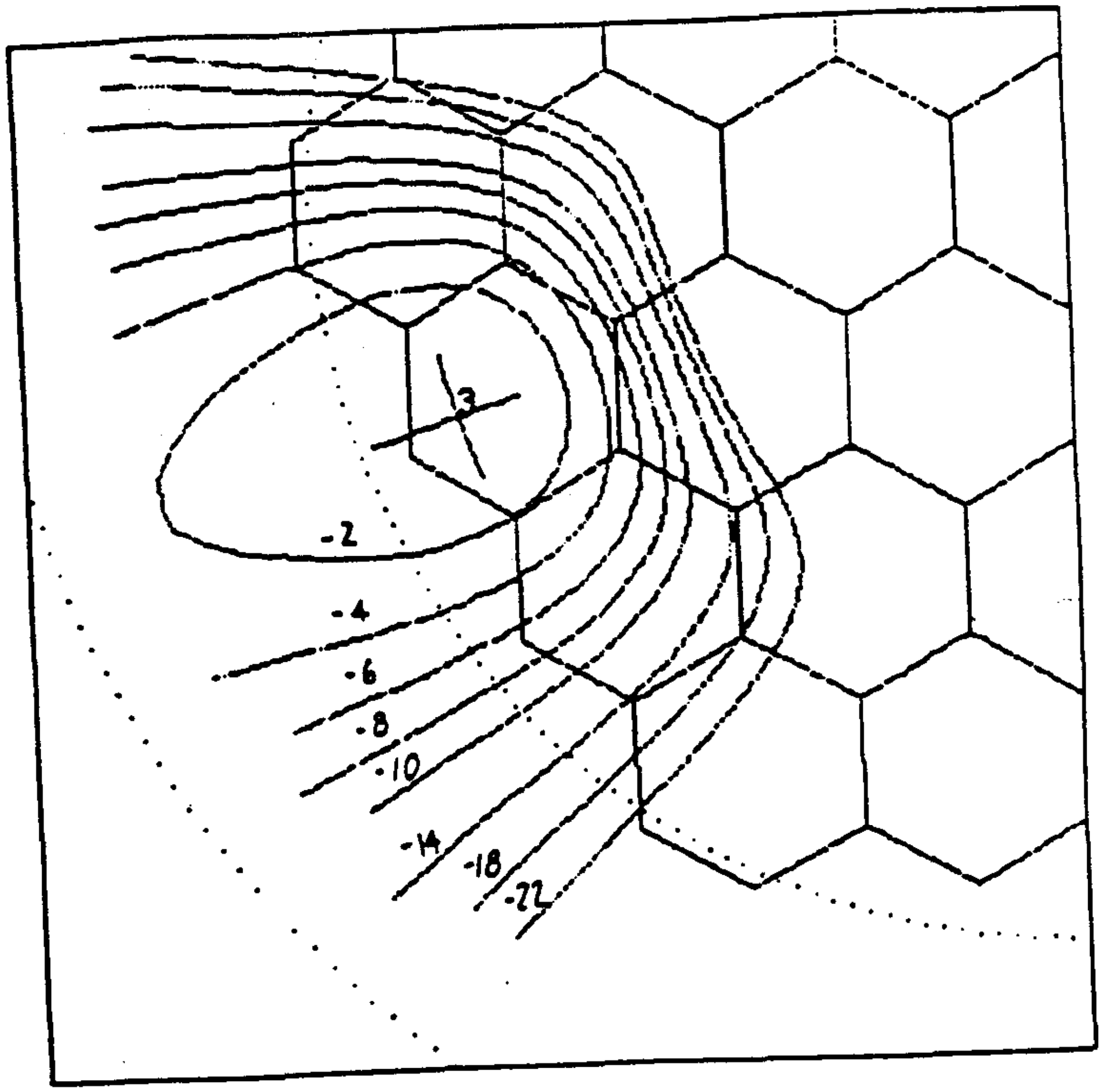


FIGURE 2c

CHARACTERISTIC OF SPACE STATION RECEIVE AND TRANSMIT ANTENNAS

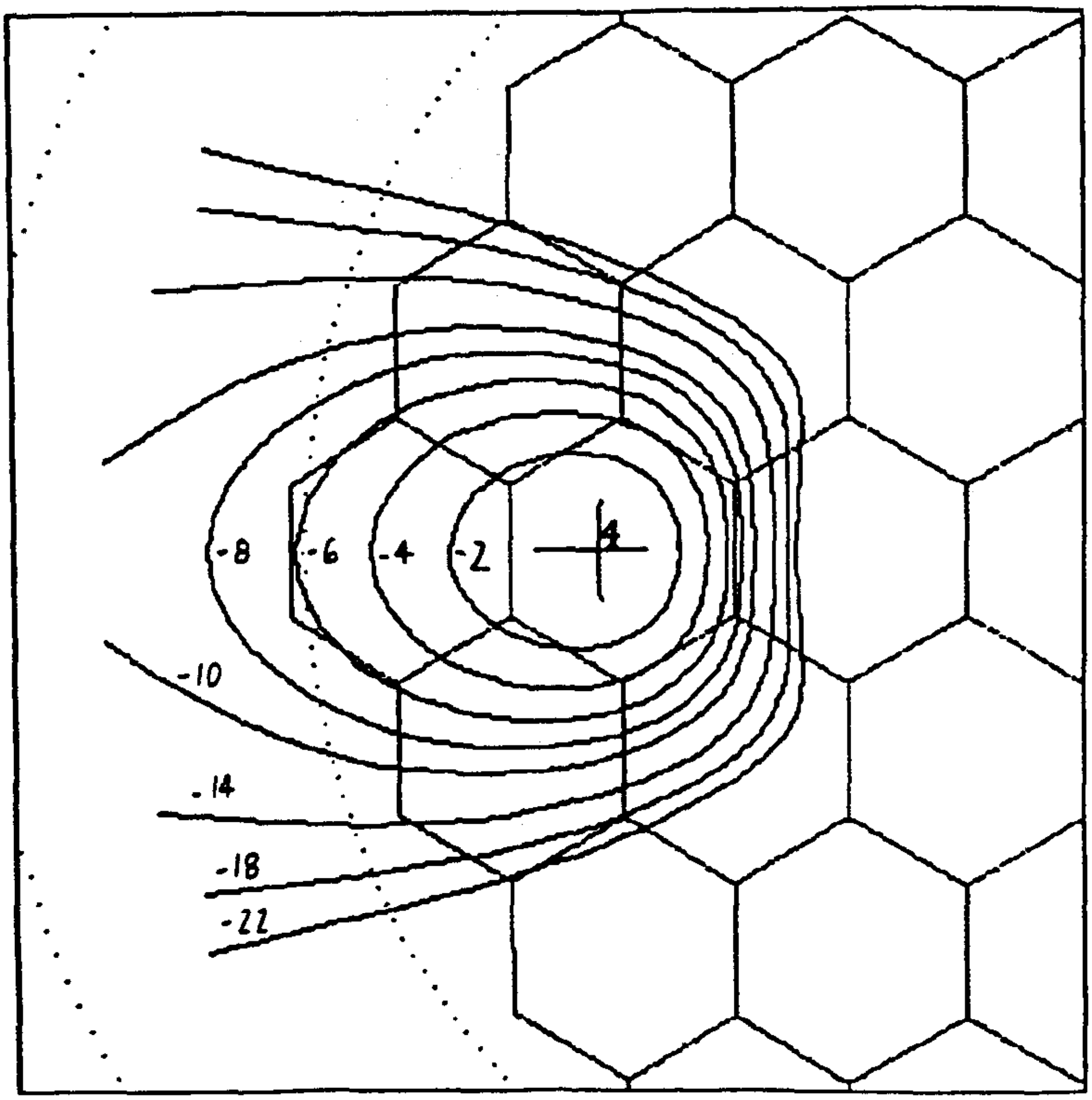


FIGURE 2d

CHARACTERISTIC OF SPACE STATION RECEIVE AND TRANSMIT ANTENNAS

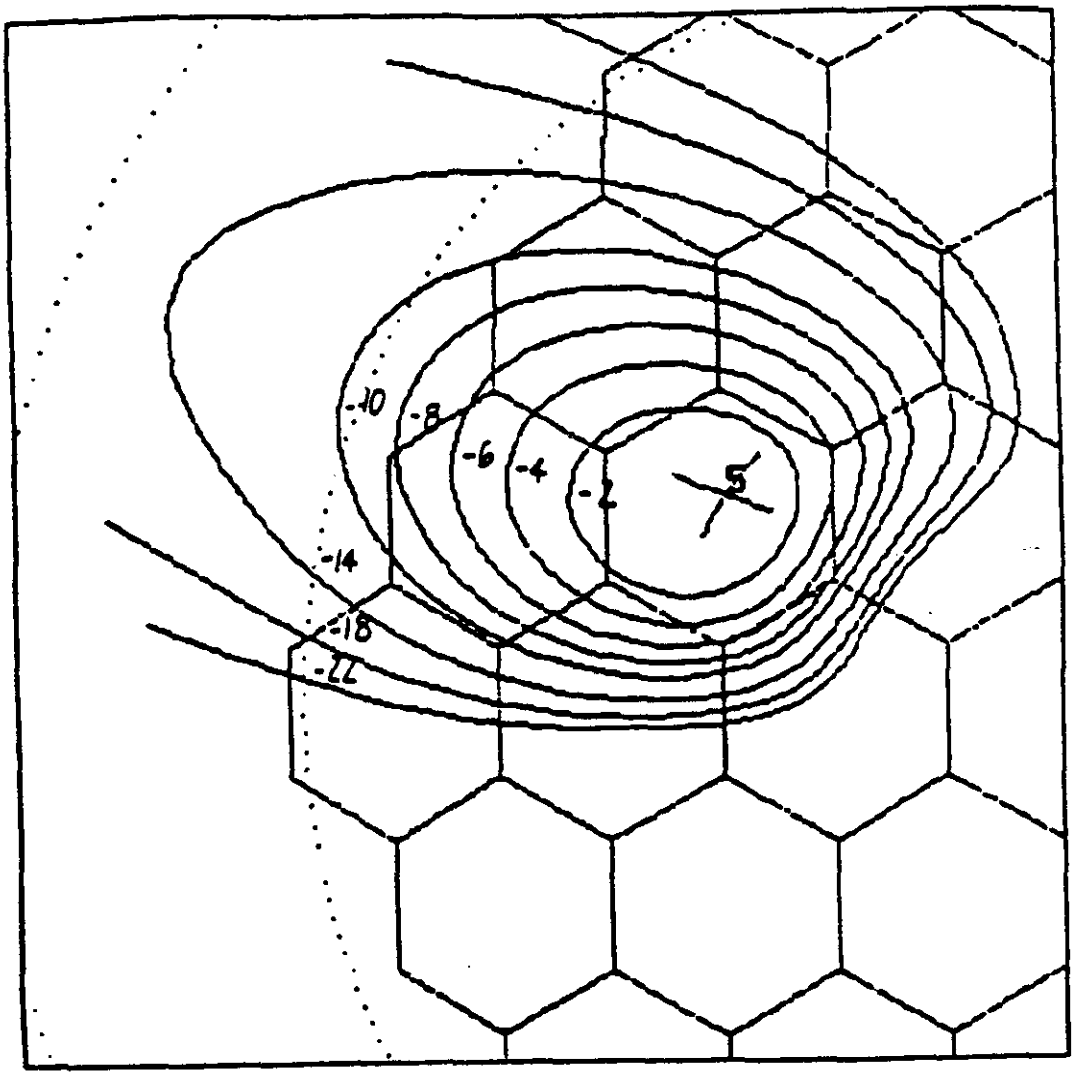


FIGURE 2e

CHARACTERISTIC OF SPACE STATION RECEIVE AND TRANSMIT ANTENNAS

MOTOROLA

IRIDIUM

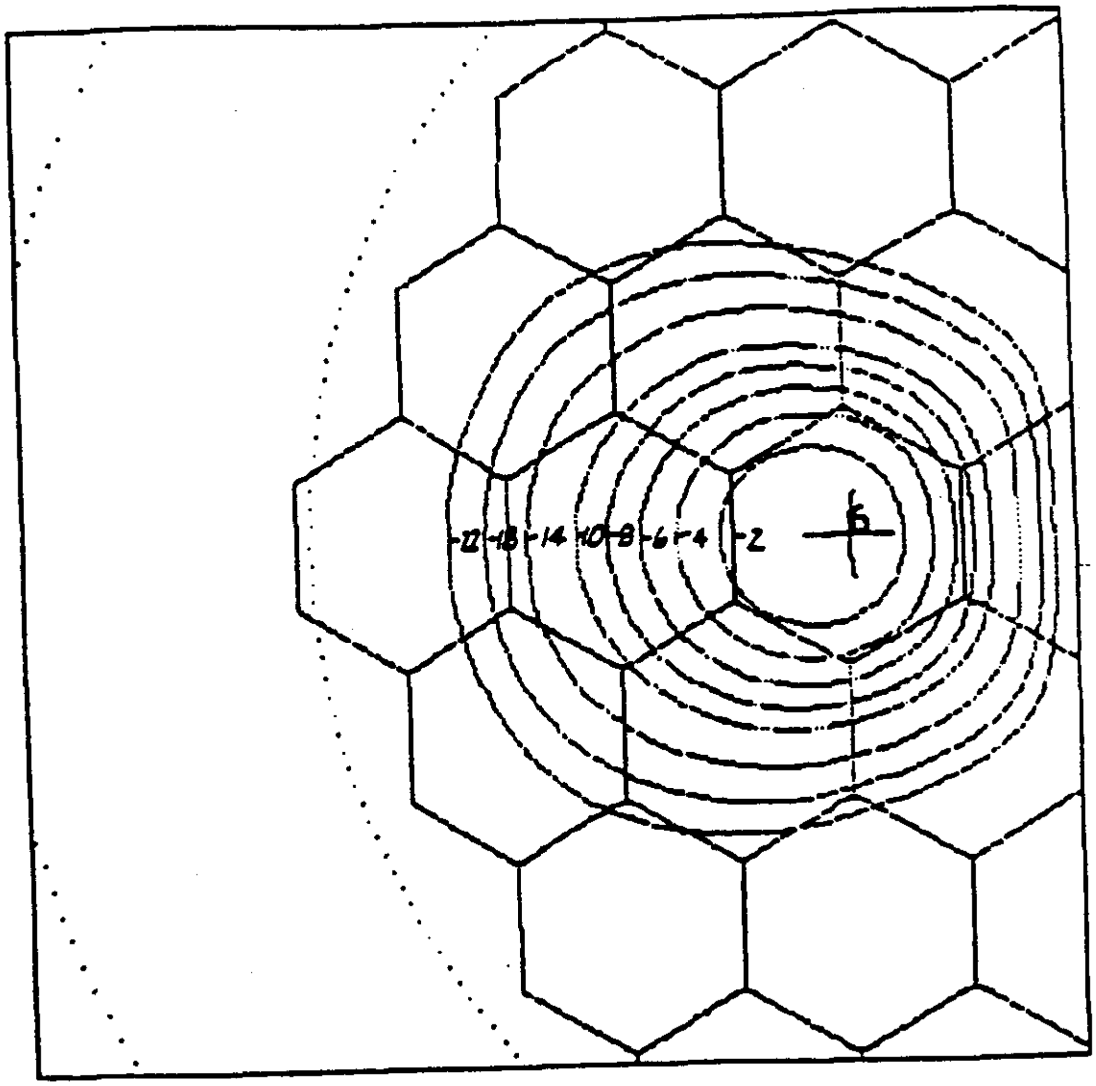


FIGURE 21

CHARACTERISTIC OF SPACE STATION RECEIVE AND TRANSMIT ANTENNAS

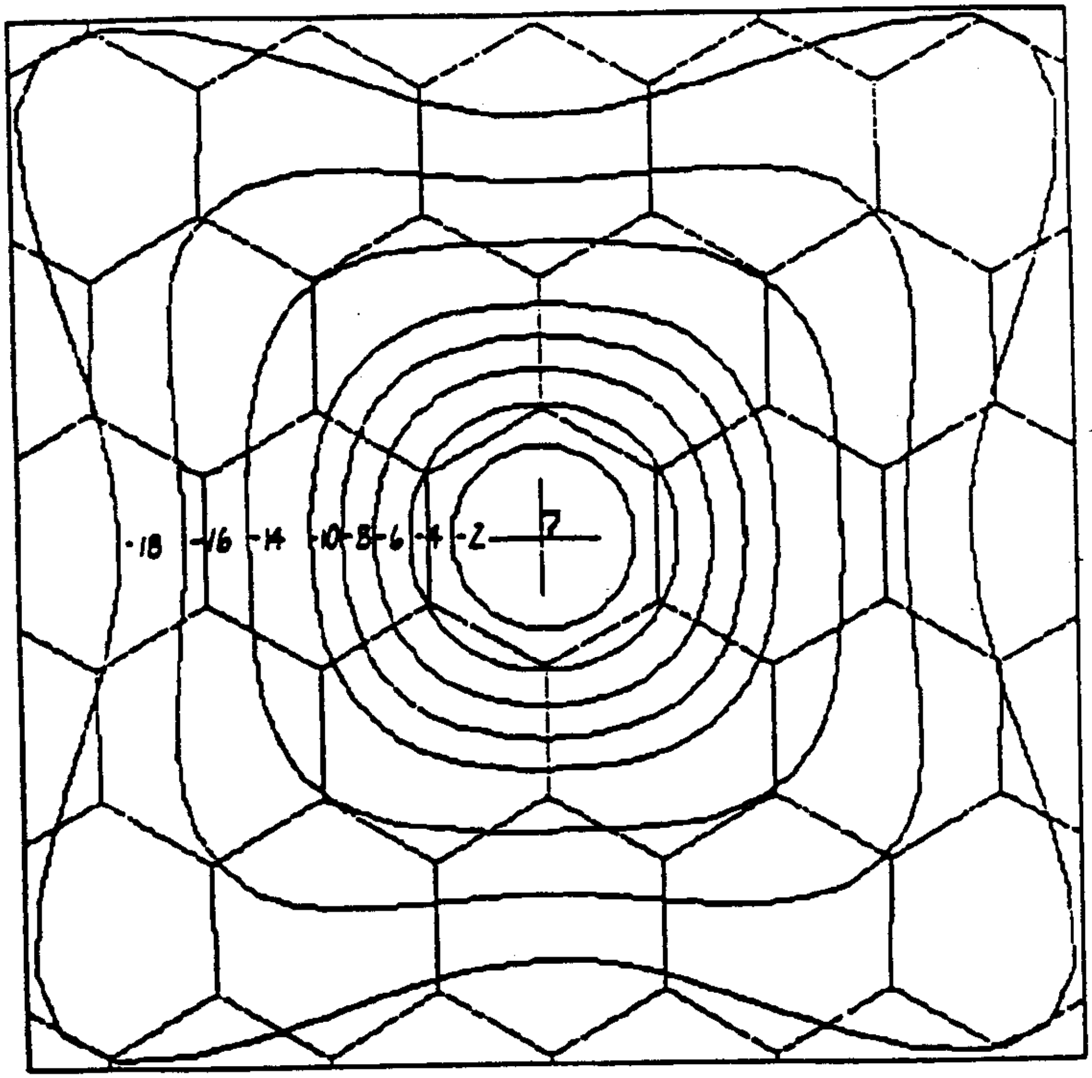


FIGURE 2g

CHARACTERISTIC OF SPACE STATION RECEIVE AND TRANSMIT ANTENNAS

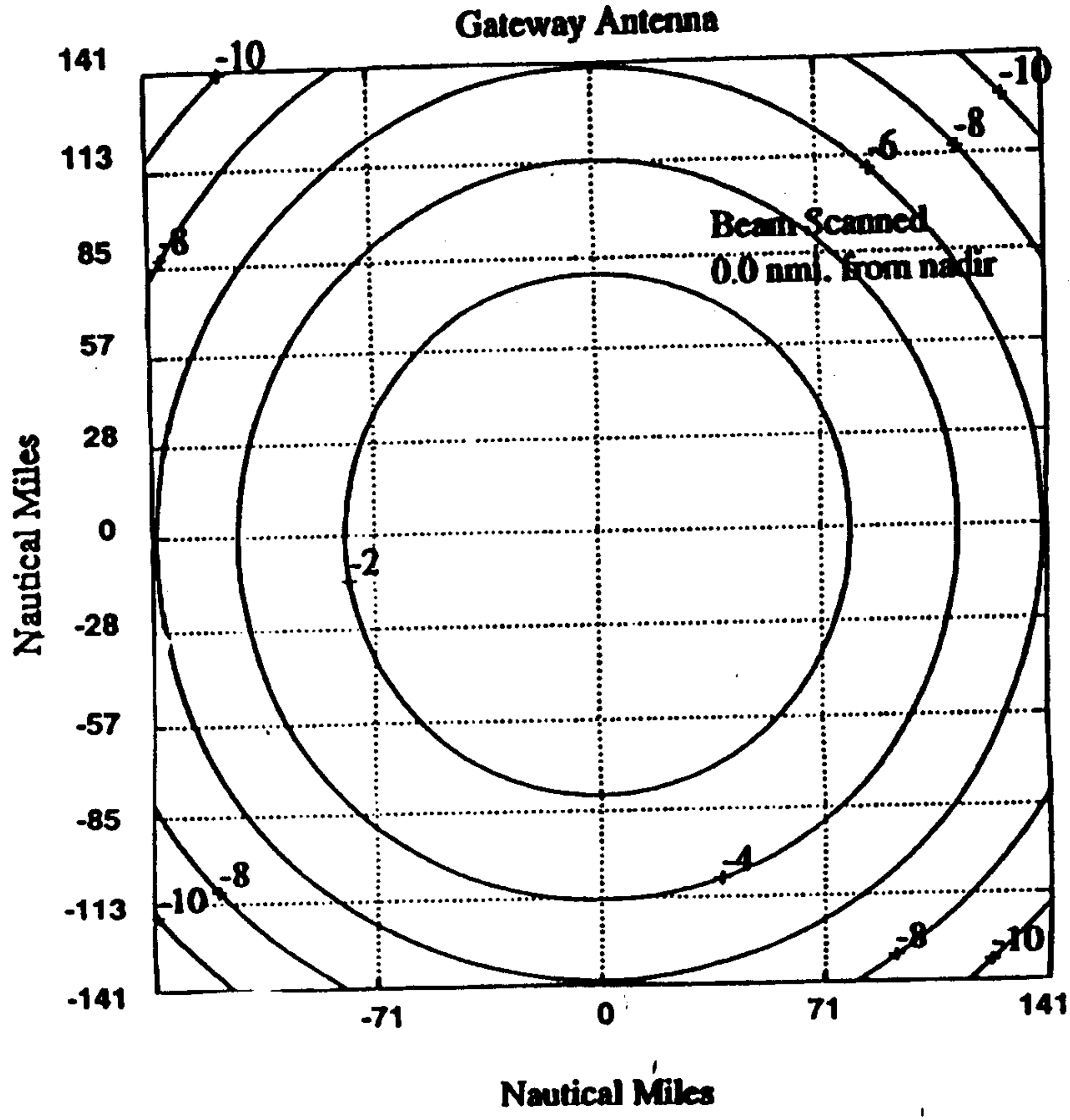


FIGURE 3 GATEWAY SPACE STATION RECEIVE PATTERN

MOTOROLA

IRIDIUM

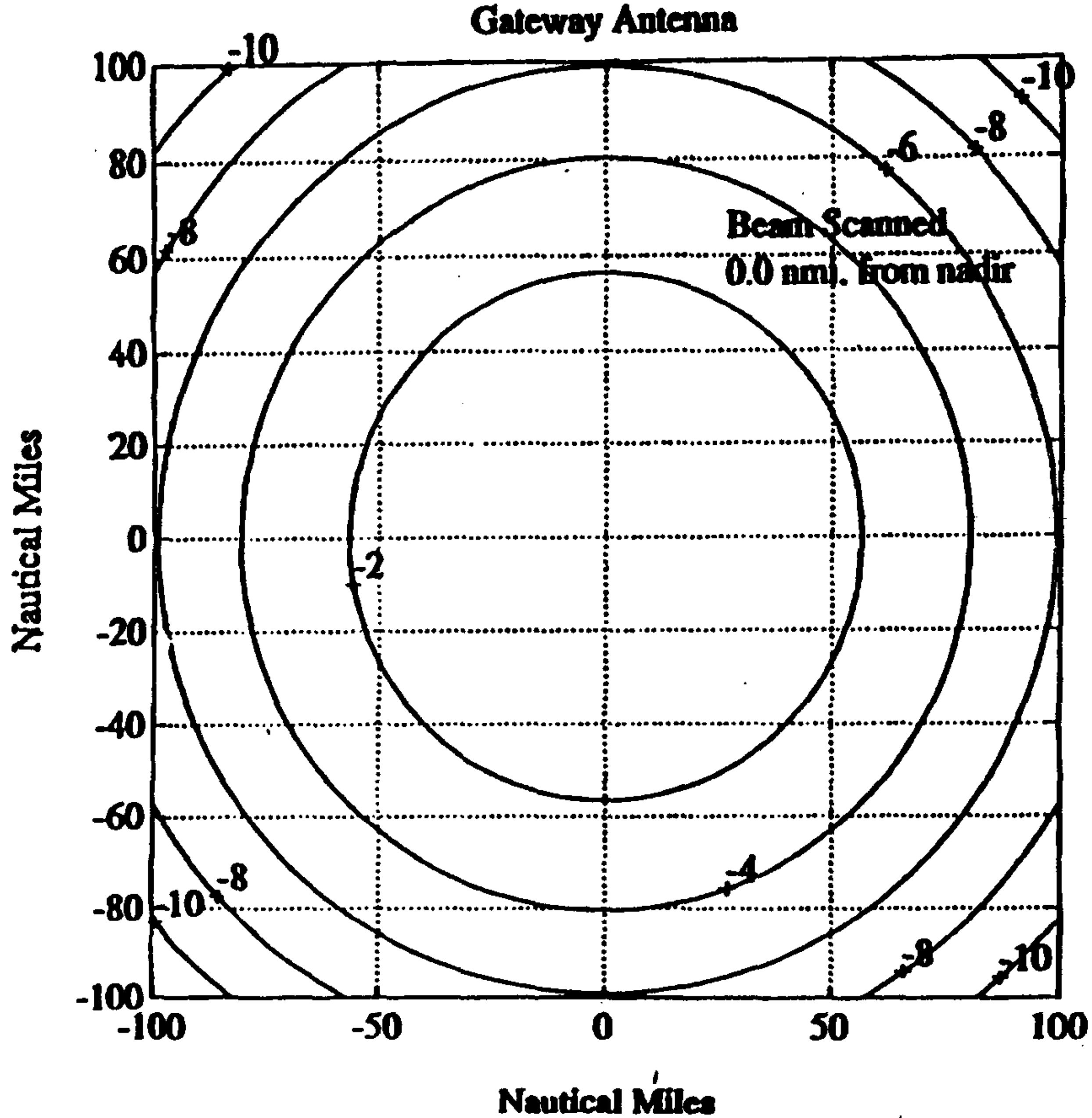


FIGURE 4a GATEWAY SPACE STATION TRANSMIT PATTERN O NMI FROM NADIR

MOTOROLA

IRIDIUM

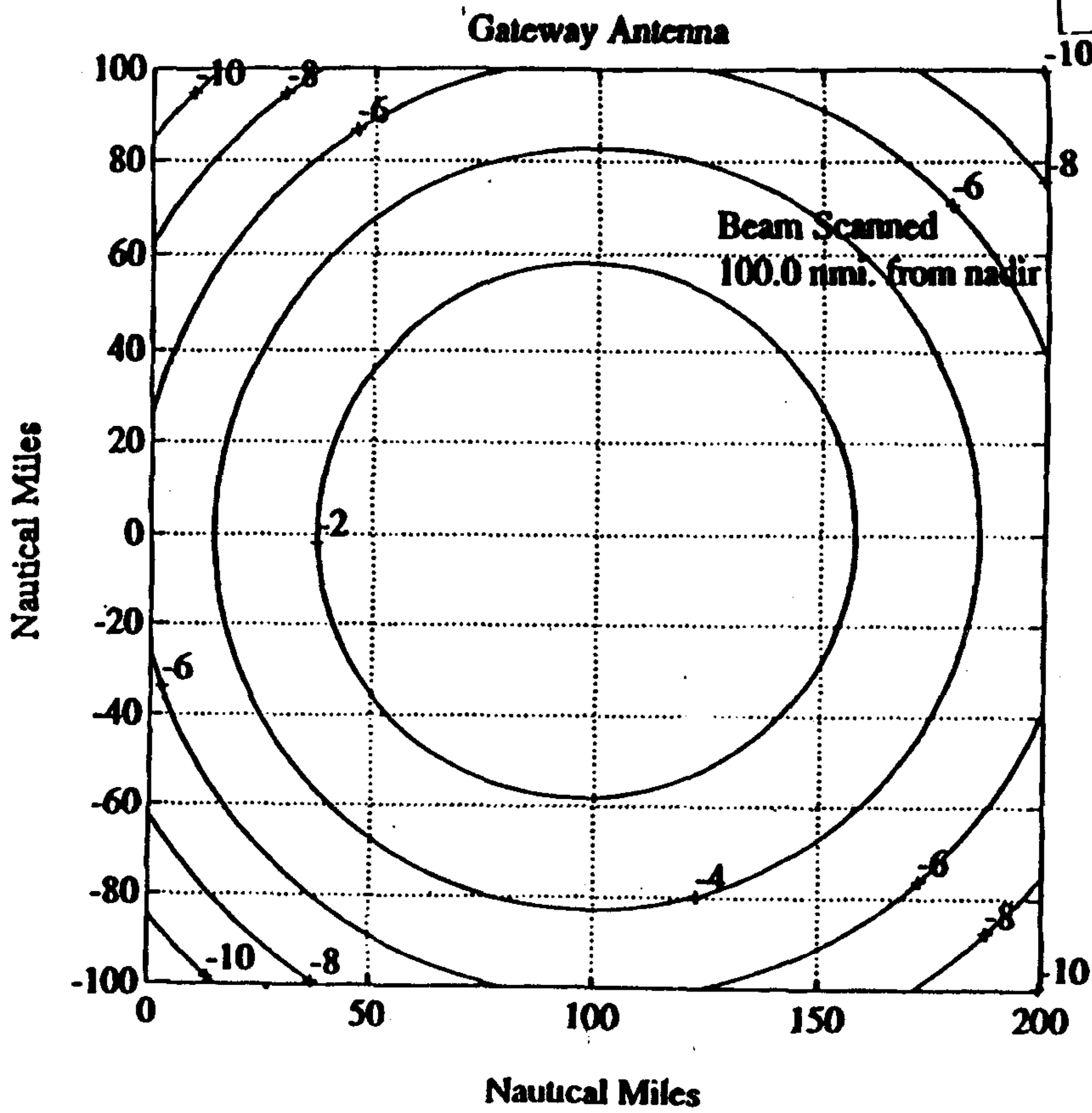


FIGURE 4b GATEWAY SPACE STATION TRANSMIT PATTERN 100 NMI FROM NADIR

MOTOROLA

IRIDIUM

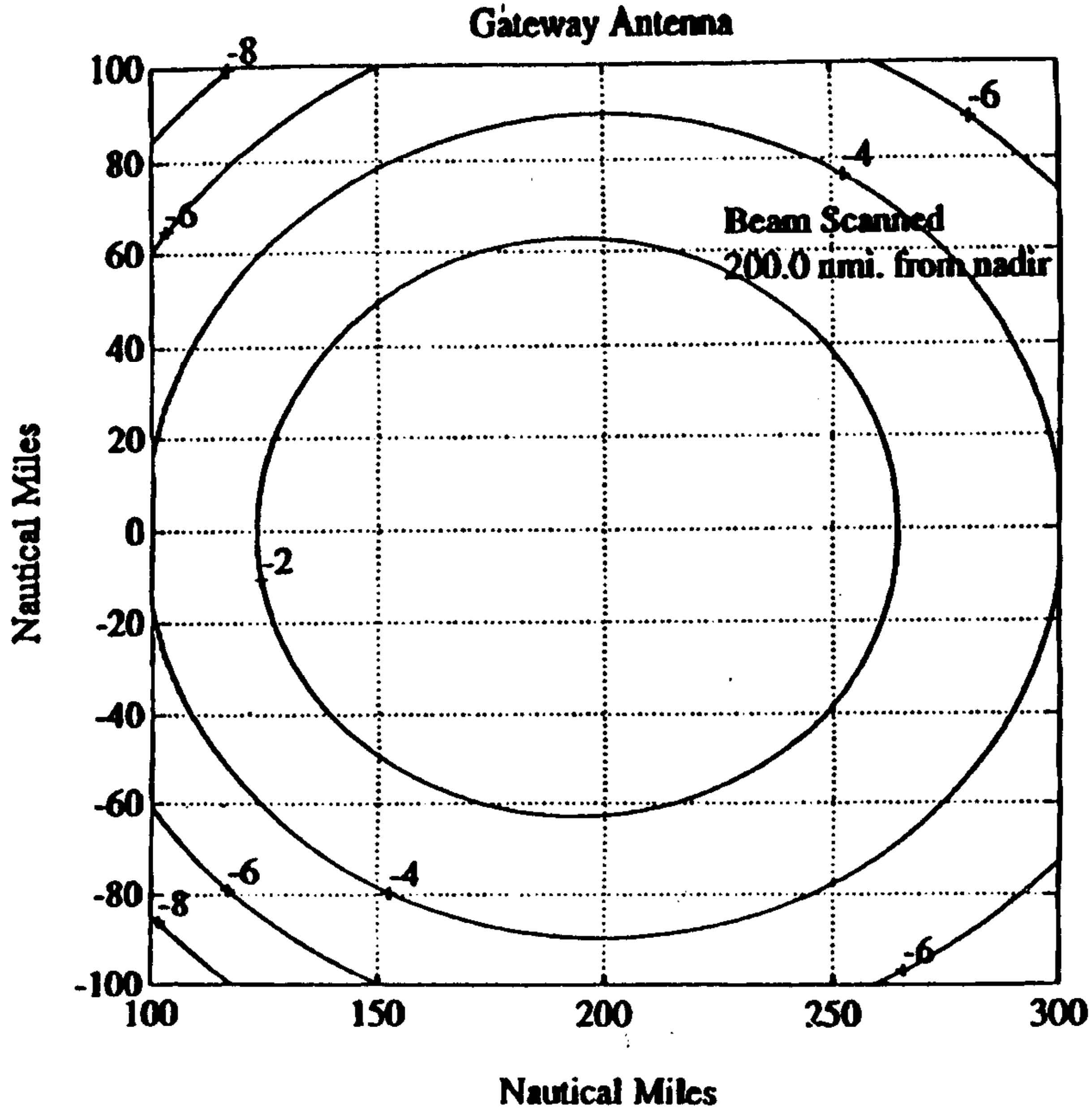


FIGURE 4c GATEWAY SPACE STATION TRANSMIT PATTERN 200 NMI FROM NADIR

MOTOROLA

IRIDIUM

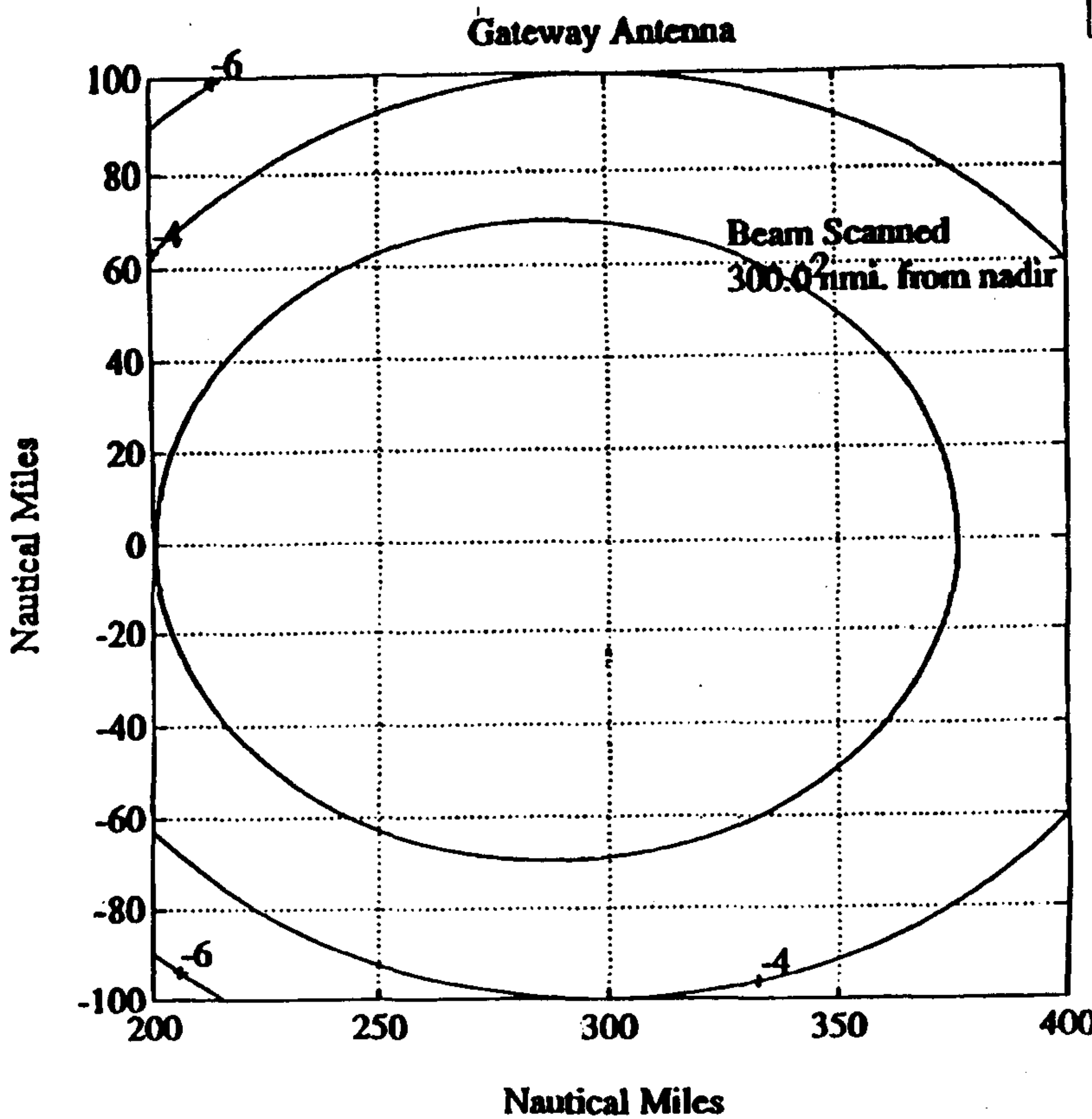


FIGURE 4d GATEWAY SPACE STATION TRANSMIT PATTERN 300 NMI FROM NADIR

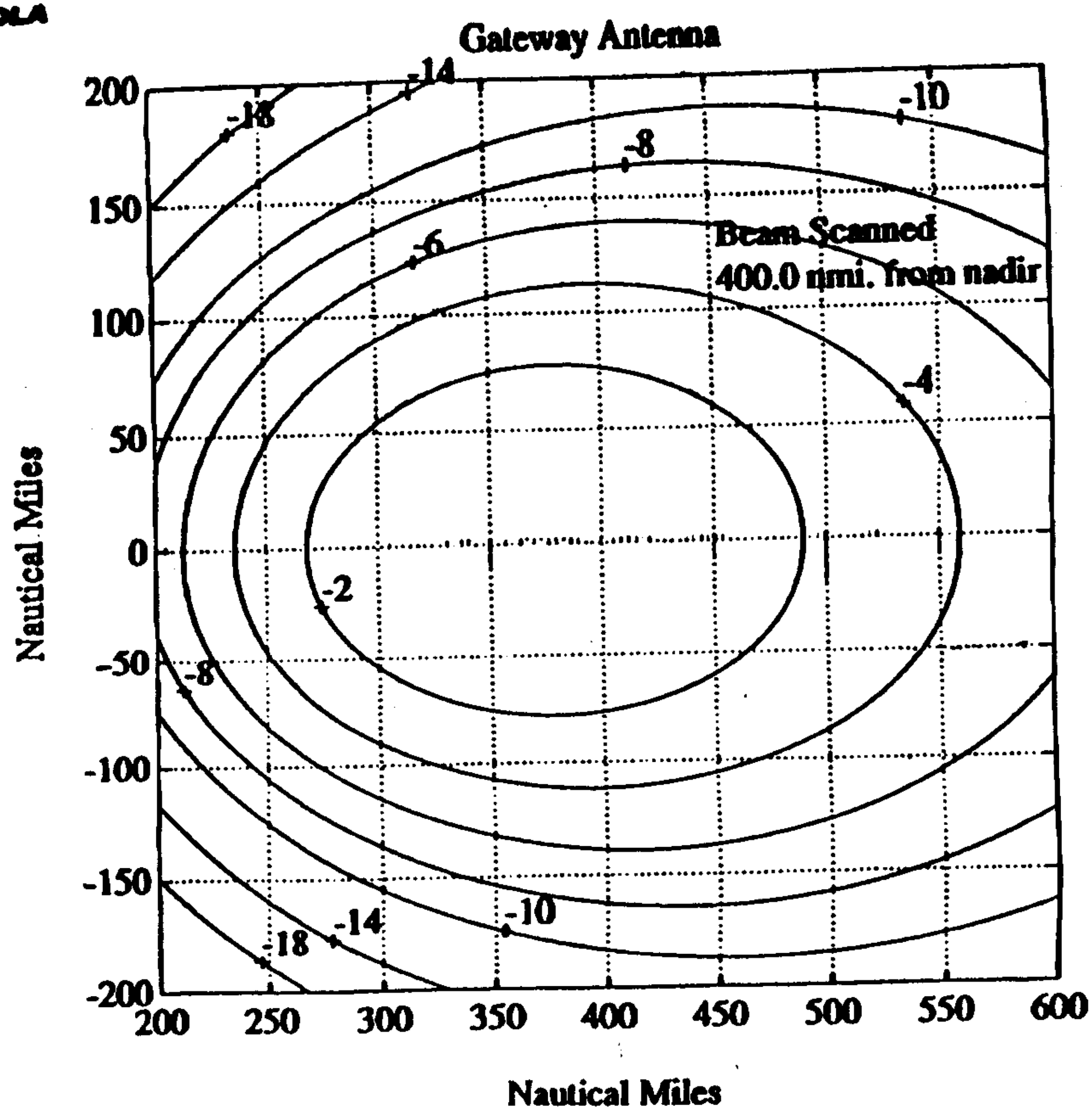


FIGURE 4e GATEWAY SPACE STATION TRANSMIT PATTERN 400 NMI FROM NADIR

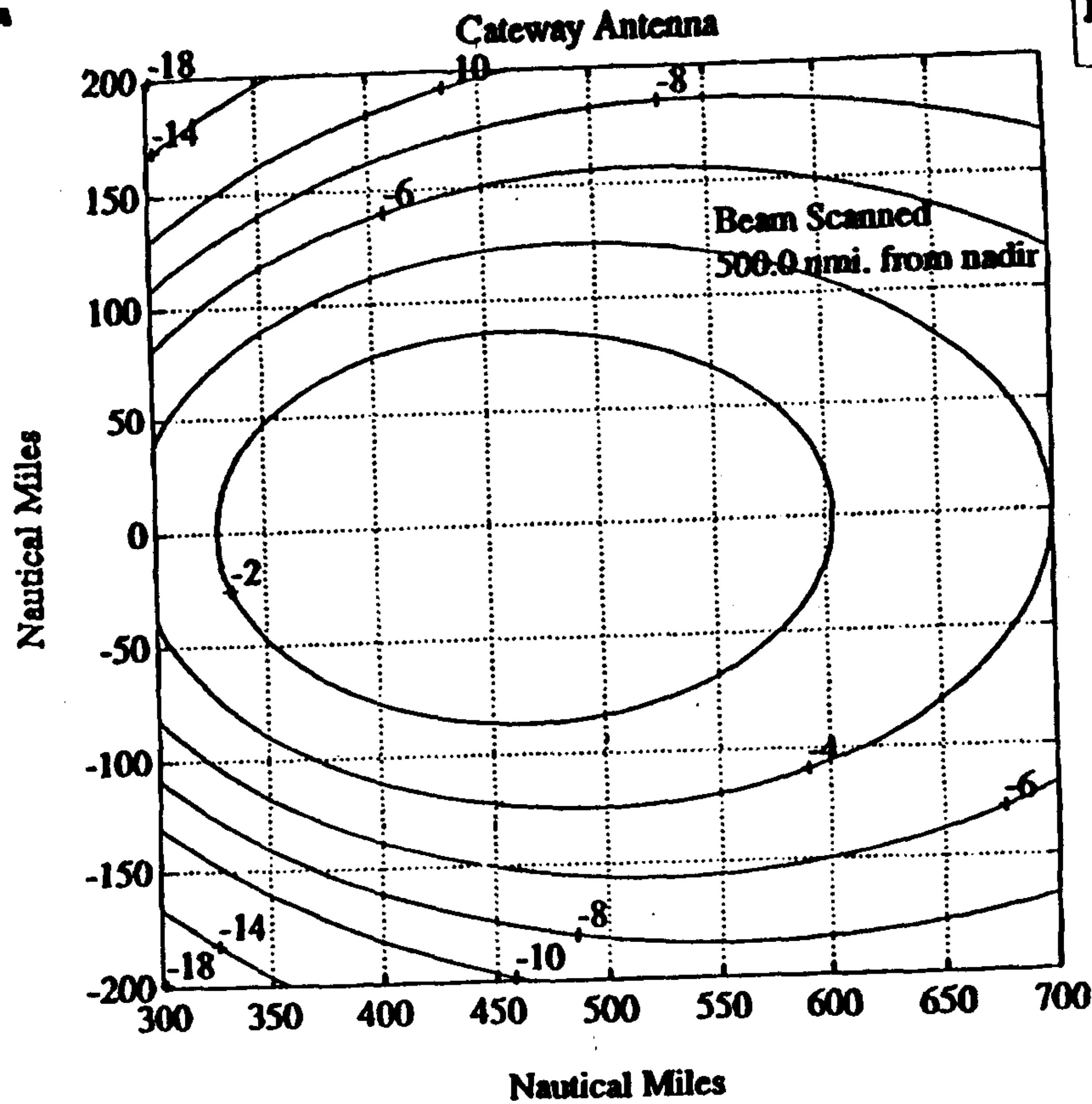


FIGURE 4f GATEWAY SPACE STATION TRANSMIT PATTERN 500 NMI FROM NADIR

MOTOROLA

IRIDIUM

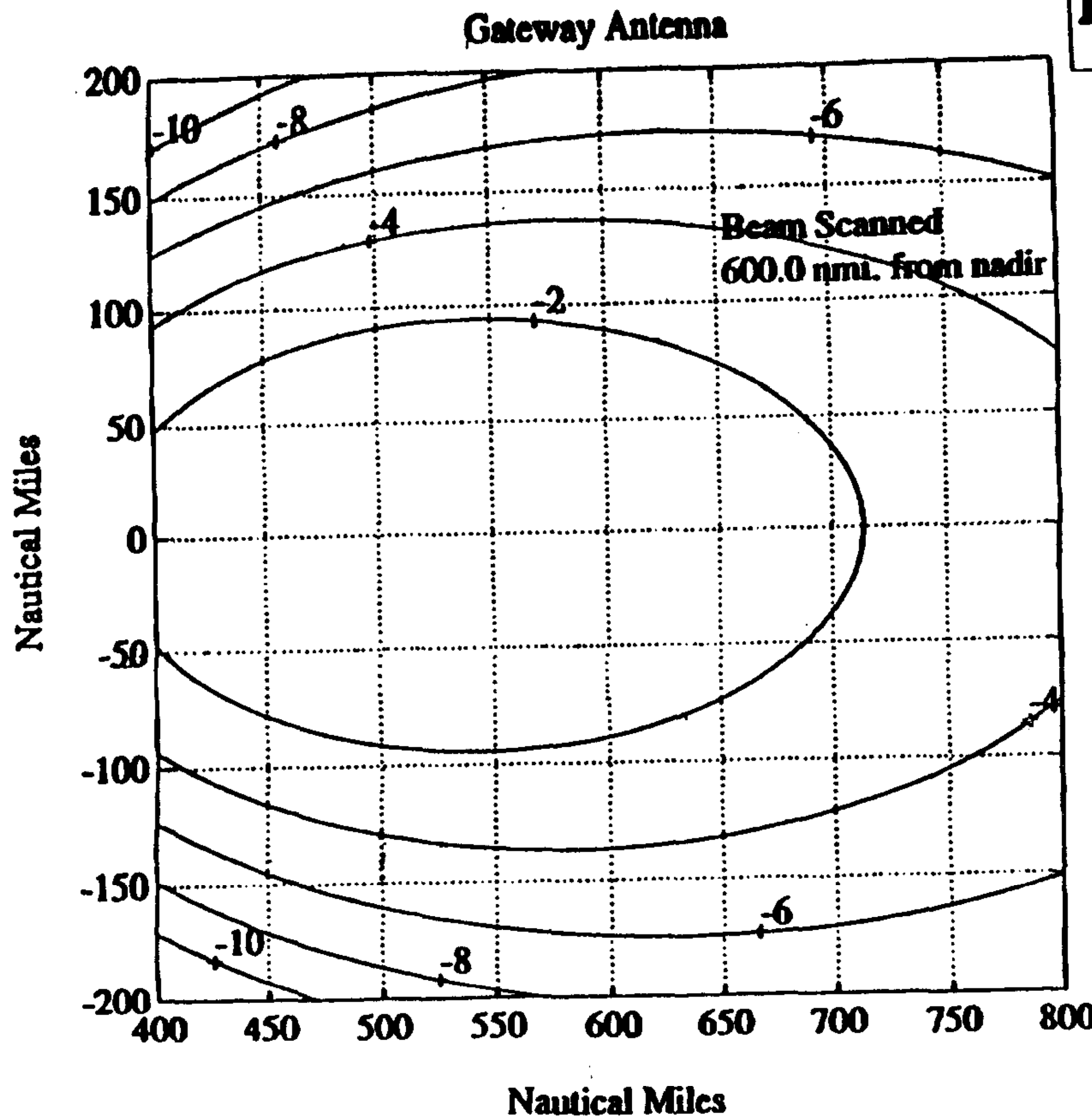


FIGURE 4g GATEWAY SPACE STATION TRANSMIT PATTERN 600 NMI FROM NADIR

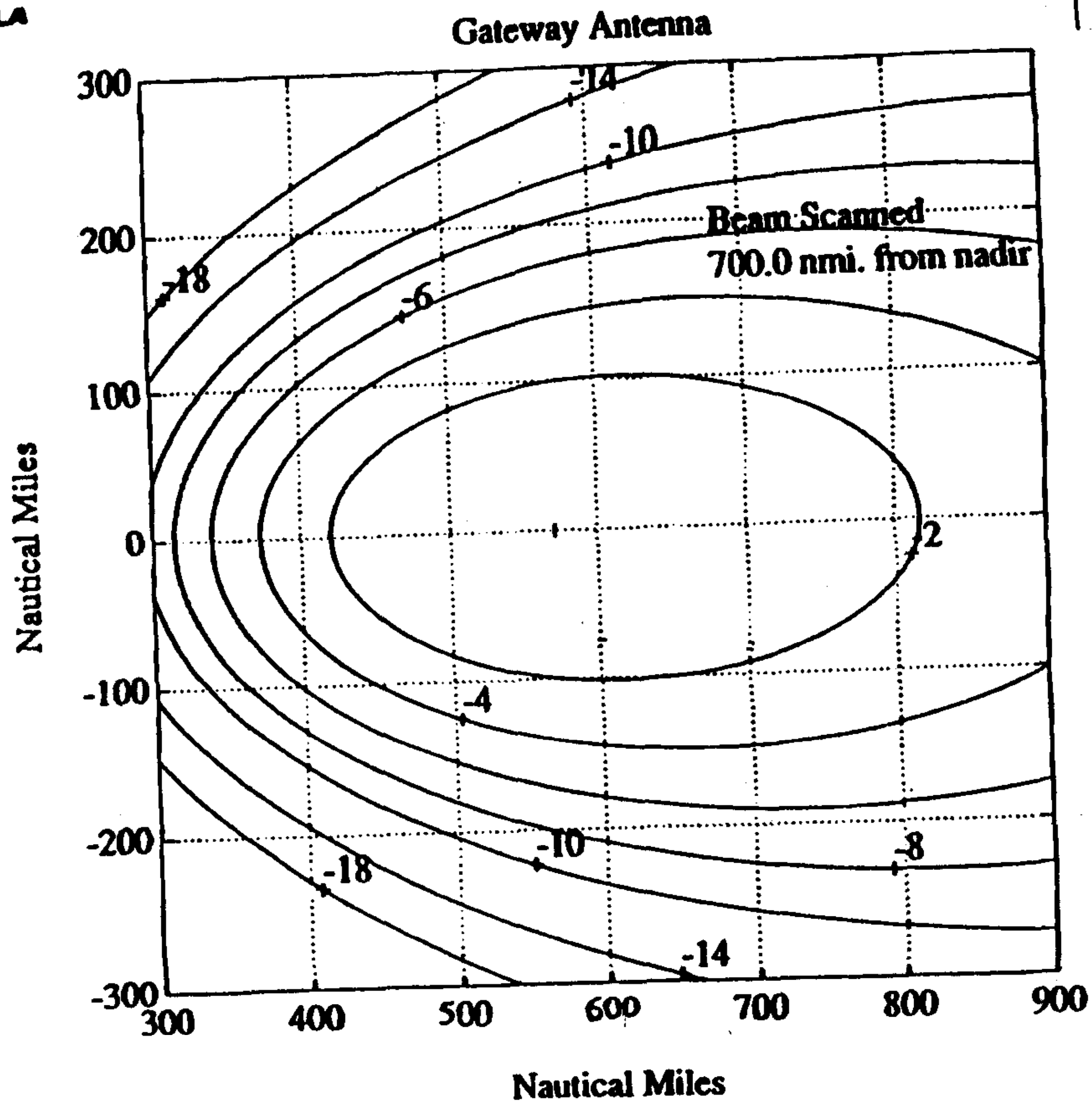


FIGURE 4h GATEWAY SPACE STATION TRANSMIT PATTERN 700 NMI FROM NADIR

MOTOROLA

IRIDIUM

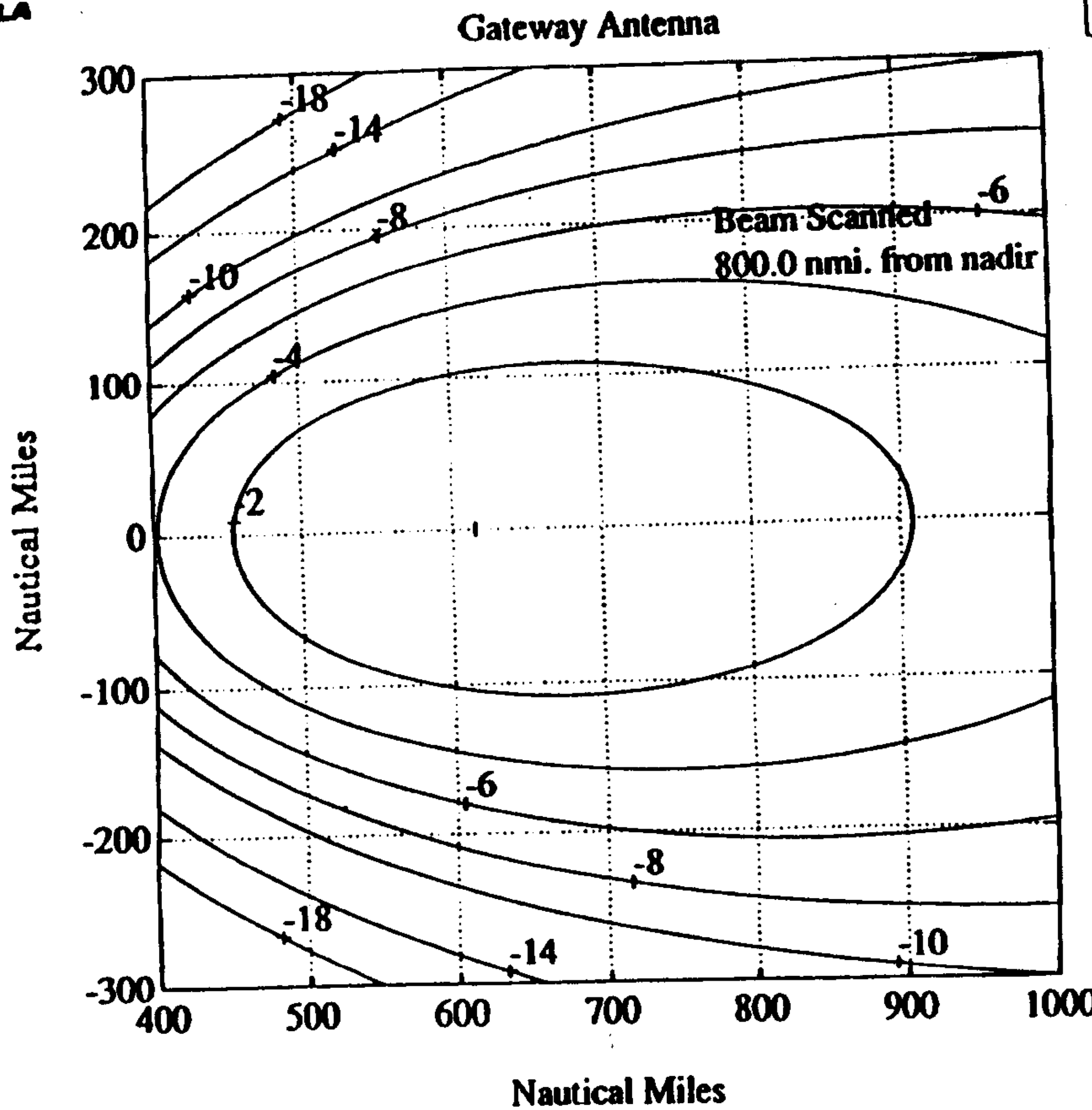


FIGURE 4I GATEWAY SPACE STATION TRANSMIT PATTERN 800 NMI FROM NADIR

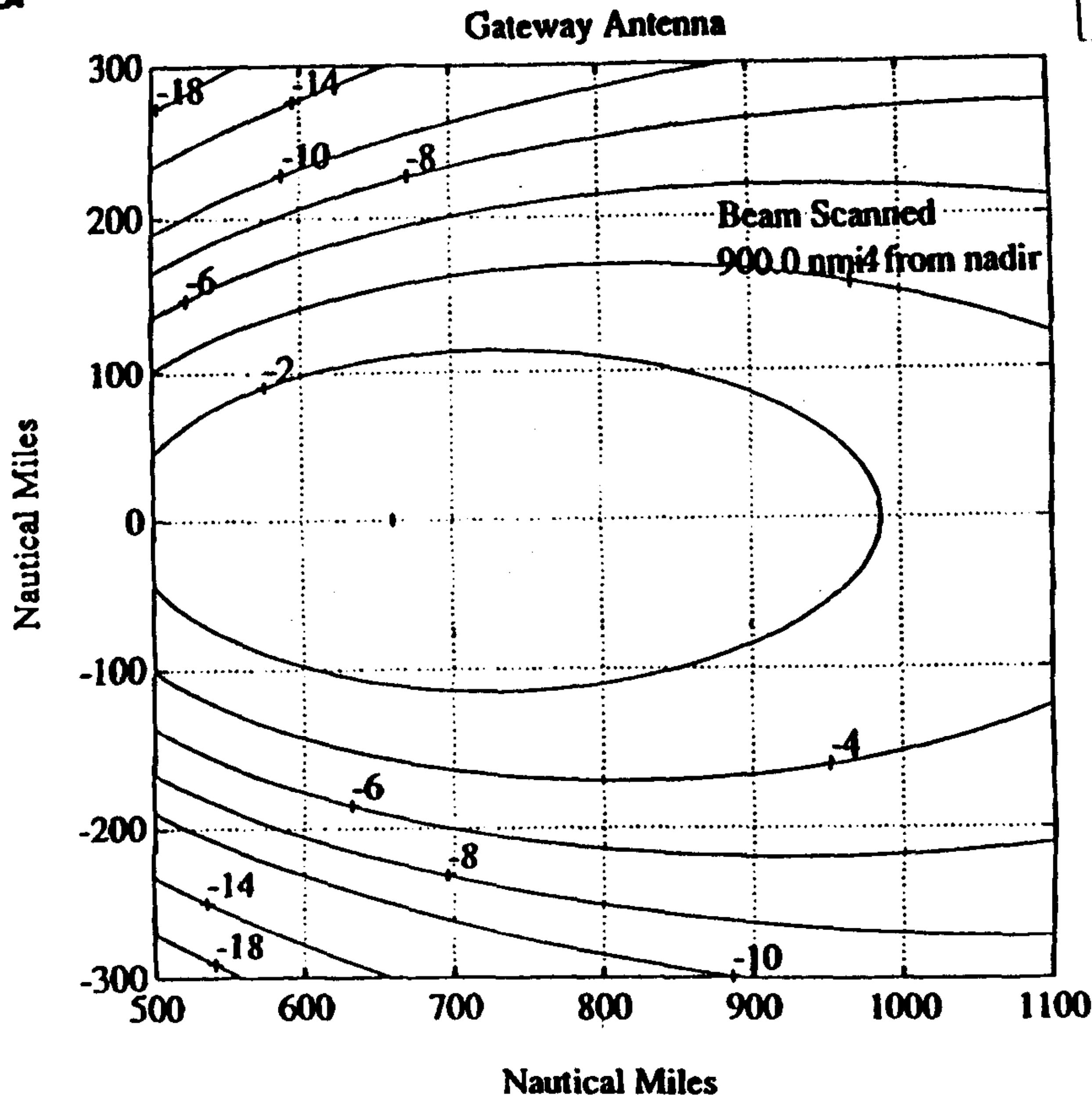
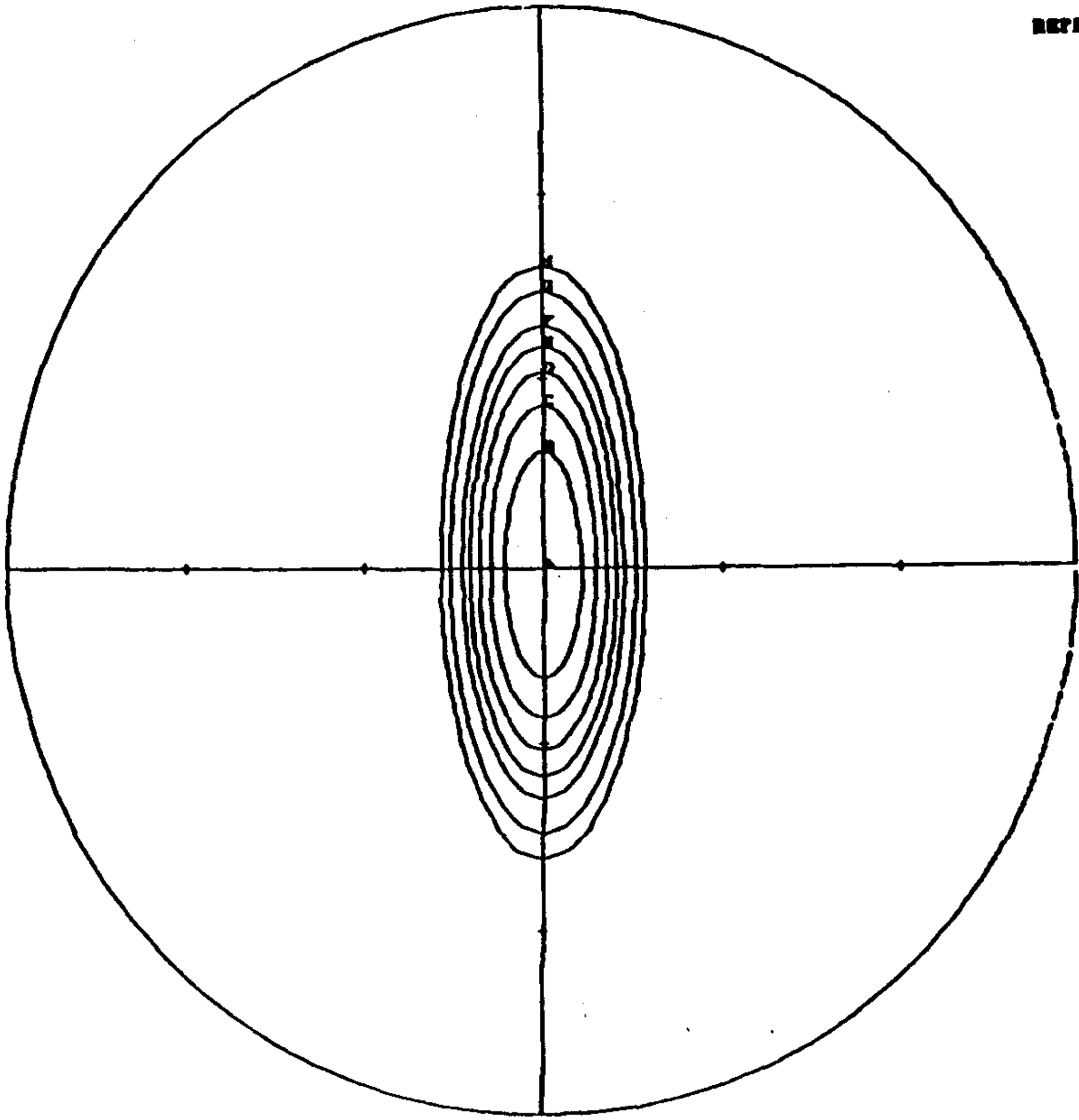


FIGURE 4j GATEWAY SPACE STATION TRANSMIT PATTERN 900 NMI FROM NADIR

6-1140

MOTOROLA

IRIDIUM



REFERENCE: 36.238 dB

A = 0.0

B = -2.0

C = -4.0

D = -6.0

E = -8.0

F = -10.0

G = -14.0

H = -18.0

FIGURE 5 CROSS LINK ANTENNA PATTERN

3

MOTOROLA INC.

1990
Third Quarter
Report

MOTOROLA INC.

October 31, 1990

FINANCIAL QUALIFICATION SHOWING
RDSS Application,
Motorola Satellite Communications Inc.

To Whom It May Concern:

This will confirm that Motorola Satellite Communications Inc. is a 100 percent-owned subsidiary of Motorola, Inc. and that the parent corporation is fully committed to meet the construction and operating expenses of the subsidiary. The parent corporation's assets are more than adequate to meet these expenses, as evidenced by the attached Annual Report and Quarterly Report updates.

Donald R. Jones 10-31-90

Donald R. Jones
Executive Vice President and
Chief Financial Officer

Corporate Offices
1303 E. Algonquin Road, Schaumburg, IL 60196-1065 • (708) 576-5000


MOTOROLA
VOYAGER AT NEPTUNE

Exhibit III
Form 430

In March 1988, the filer's corporate owner entered guilty pleas to three counts of making false statements to the U.S. Government. The pleas involved the Government Electronics Group (GEG) of Motorola, Inc. A penalty of $10,000 per count was imposed. In addition, Motorola paid approximately $17 million to the government in final settlement of this matter. Motorola was not suspended or debarred from business with the U.S. Government because of these guilty pleas. At the time of the guilty pleas, Motorola entered into an Administrative Settlement Agreement with the Defense Logistics Agency ("DLA"). DLA specifically determined that the terms of the Administrative Settlement Agreement "provide adequate assurance that future dealing with Motorola and GEG will be conducted with the high degree of integrity that the Government expects of its business partners and that suspension or debarment is not necessary at this time to protect the Government's interests." (Preamble, paragraph 7)

Exhibit IV
Form 430

Motorola, Inc. v. Howard B. Chapman and Robert Cole v. Hal Brock v. Mason McCloud, Civil Action No. H-89-2706, U. S. District Court for the Souther District, Houston. The case includes a general allegation involving a claim of an illegal tying arrangement and is currently in the discovery stage.

Exhibit V
Form 430

The filer's corporate owner, Motorola, Inc., holds numerous licenses throughout the United States for repeater operations and/or base-mobile operations under Part 90 of the Rules.

Motorola owns and holds licenses for numerous trunked SMR systems (Rules Part 90) throughout the United States and has applications pending for new SMR systems in additional markets.

Motorola holds numerous private multiple address microwave licenses nationwide licensed under Part 94. The company also holds a few private microwave licenses to link its manufacturing plants in Phoenix, Arizona.

Motorola holds various GMRS radio systems licensed under Rules Part 95.

Motorola holds developmental and experimental licenses in a number of frequency bands associated with equipment development.

Motorola holds a number of common carrier Digital Termination System licenses in various markets throughout the country. The company also holds common carrier paging licenses on the island of Guam and in Puerto Rico. Additionally, the company has received a construction permit for a rural cellular system for the Kossuth, Iowa, RSA.

Exhibit VI
Form 430

The filer is wholly owned by Motorola, Inc., which is a publicly traded corporation. To the best of its knowledge, no individual or entity owns 10 per cent or more of the filer company's stock.

Exhibit VII
Form 430

The names of the officers and directors of the filer corporation are set forth below. Each may be contacted in care of the filer's principal place of business, given below:

Durrell Hillis	President
Donald R. Jones	Vice President
Carl Koenemann	Vice President
Garth L. Milne	Treasurer
Victor R. Kopidlansky	Secretary
Kevin Gilbert	Assistant Secretary
Ray A. Dybala	Assistant Secretary

Directors:

Carl Koenemann
Durrell Hillis
John F. Mitchell

Principal Place of Business:
2501 S. Price Road
Chandler, Arizona 85248-2899

Exhibit VIII
Form 430

The filer corporation is a wholly-owned subsidiary of Motorola, Inc., which is a publicly traded corporation. The parent company is a leading manufacturer of electronic and telecommunications equipment, particularly land mobile RF equipment. See exhibit V for a listing of telecommunications systems operated by the company. To the best of its knowledge, no individual or entity owns 10 per cent or more of Motorola, Inc's., stock. The names of the president and directors of Motorola, Inc., are set forth below. Each individual may be contacted at Motorola's corporate headquarters, 1303 East Algonquin Road, Schaumburg, Illinois 60196.

George M. C. Fisher
Chairman of the Board and CEO

Gary L. Tooker
President and COO

Christopher B. Galvin
Director, Sr. Exec. VP, Asst. COO

Robert W. Galvin
Director, Chairman of Exec. Committee

John F. Mitchell
Director, Vice Chairman of the Board

William J. Weisz
Director, Vice Chairman of the Board

David R. Clare, Director

Wallace C. Doud, Director

John T. Hickey, Director

Lawrence Howe, Director

Anne P. Jones, Director

Donald R. Jones, Director

Stephen L. Levy, Director

Walter E. Massey, Director

William G. Salatich, Director

Gardiner L. Tucker, Director

B. Kenneth West, Director

Exhibit IX
Form 430

The filer's corporate parent, Motorola, Inc., is a global corporation with operations in a number of other countries. In some of these countries, business operations are managed by corporate officers which are aliens. For example, Wilhelm Braxmeier, a German citizen, is Corporate Vice President and Director of Eastern Europe Operations. Toshiaki Irie, a Japaneze citizen, is Corporate Vice President and Chairman, Nippon Motorola Limited. None of these latter officers has any relationship with the filer or is involved with the business operations of the filer. None of these officers holds or votes stock of the filer, and none holds 10 per cent or more of the stock of the parent corporation.

Before the
FEDERAL COMMUNICATIONS COMMISSION
Washington, D.C. 20554

In re Application of: MOTOROLA SATELLITE COMMUNICATIONS, INC. For Authority to Construct, Launch and Operate a Low Earth Orbit Satellite as Part of the IRIDIUM System (IRIDIUM 1)	File No.

APPLICATION

Motorola Satellite Communications, Inc. ("Motorola" or "Applicant") hereby applies for authority to construct, launch and operate a low earth orbit satellite designated as IRIDIUM 1.

I.

PURPOSE OF APPLICATION

A. Authorization Requested

Motorola requests authority from the Commission to construct, launch and operate its IRIDIUM global personal communications system comprised of a constellation of 77 low earth orbit satellites. Each satellite will operate in the 1610-1626.5 MHz band and the Ka-band, in a polar orbit some 413 nautical miles above the earth's surface. This application covers all pertinent technical and operational information for authority to construct, launch and operate one of the IRIDIUM satellites. Separate applications for the other in orbit and spare satellites are being filed concurrently herewith. Much of the information about this satellite and the IRIDIUM system is provided in the comprehensive system application also filed contemporaneously with this application, which is incorporated herein by reference.

B. Summary of Proposed Service

The applicant will offer bulk air time over IRIDIUM to others on a non-common carrier basis. Service that can be provided to the public include RDSS, paging, voice and data. IRIDIUM provides continuous coverage to virtually all points on the surface of the earth and within 100,000 feet above mean sea level, including all U.S. domestic locations.

C. Applicant Information

The applicant's name and address is:

Motorola Satellite Communications, Inc.
2501 South Price Road
Chandler, AZ 85248

Correspondence and communications concerning this application should be addressed to:

Leonard Kolsky
Vice President and Director
Regulatory Affairs
Motorola, Inc.
1350 I Street, N.W.
Washington, D.C. 20005
(202) 371-6932

with copies directed to:

Philip L. Malet, Esquire
Alfred M. Mamlet, Esquire
Steptoe & Johnson
1330 Connecticut Avenue, N.W.
Washington, D.C. 20036
(202) 429-6239

II.

TECHNICAL INFORMATION

Technical and other information about this satellite is provided in Exhibit I hereto. It is anticipated that construction, launch and operation of this satellite will be in accordance with the milestones set forth in Table VIII-2 in the comprehensive system application, which is incorporated herein by reference.

III.

WAIVERS AND CERTIFICATIONS

Pursuant to Section 304 of the Communications Act of 1934, as amended, Motorola hereby waives any claim to the use of any particular frequency or of the ether against the regulatory power of the United States because of the previous use of the same, whether by license or otherwise.

This application reflects a good faith effort to address all of the Commission's filing requirements as fully and completely as possible. While the applicant believes that it has fully complied with all pertinent rules and policies, and has supplied all the information required by the Commission, it hereby requests that, to the extent it has not satisfied the applicable requirements, appropriate waivers be granted.

The applicant certifies that all of the statements made in this application are true, complete and accurate to the best of its belief and knowledge, and are made in good faith.

IV.

CONCLUSION

Wherefore, Motorola requests that the Commission grant this application expeditiously and in conjunction with the other IRIDIUM satellite applications.

Respectfully submitted,

MOTOROLA SATELLITE
COMMUNICATIONS, INC.

By: [signature]

Title: President, Motorola Satellite Communications, Inc.

Philip L. Malet
Alfred Mamlet
Steptoe & Johnson
1330 Connecticut Avenue, N.W.
Washington, D.C. 20036
(202) 429-6239

Counsel to Motorola Satellite
Communications, Inc.

December 3, 1990

Gain of Each L-Band Channel	(Not a transponder)[2/]
Orbital Locations[3/]	
Altitude	413 Nautical Miles
Number of Planes	7 Polar Planes
Spacing of Planes	27 Degrees (except planes 1 & 7 spaced 17 Degrees)
Number of Satellites Per Plane	11 Satellites
Spacing of Satellites In Plane	32.7 Degrees
Predicted Satellite Coverage Contours	[4/]
Functional Block Diagram of Satellite Communications System and Switching Capabilities	[5/]
Physical Characteristics of Satellite	
Attitude Accuracy	+/- 0.5 Degrees
Position Accuracy	+/- 20 kilometers
Antenna Axis Attitude	[6/]
Antenna Pointing Accuracy Toward Earth	+/- 0.5 Degrees

2/ See Appendix A of IRIDIUM system application.

3/ See Section IV to the IRIDIUM system application for the factors which support these orbital assignments.

4/ L-band cell (1 - 7) contours and Ka-band gateway and intersatellite link contours are provided in the IRIDIUM system application at Section V. See Appendix A of the IRIDIUM system application for receiving antenna gain, transmitting antenna gain, receiving system sensitivity (G/T), saturation power flux density, and effective isotropically radiated power.

5/ See Section V of the IRIDIUM system application.

6/ See Section V of the IRIDIUM system application.

Estimated Lifetime of In-Orbit Satellite[7]	5 Years
Attitude Stabilization and Station-keeping Systems	[8]
Electrical Energy System	[9]

Emission Limitations (L-Band)

Channel Bandwidth	280 KHz

Spurious Emissions Attenuated

30 dB @ 100% x Channel Bandwidth from carrier
60 dB @ 200% x Channel Bandwidth from carrier

---

[7] The basis for this lifetime estimate is contained in Section V of the IRIDIUM system application.

[8] A description of these systems is contained in Section V of the IRIDIUM system application.

[9] A description of this system, including provision for operation during eclipse conditions, is set forth in Section V of the IRIDIUM system application.

EXHIBIT I

TECHNICAL INFORMATION

Radio Frequency and Polarization Plan

L-Band (Uplink and Downlink)	1610-1626.5 MHz (16.5 MHz)
Polarization	Right Hand Circular
Center Frequency	FDMA Cross Band
Channel Bandwidth	280 KHz Downlink 126 KHz Uplink
Gateway and TT&C (Uplink)	27.5-30.0 GHz (100 MHz)
(Downlink)	18.8-20.2 GHz (100 MHz)
Polarization	Right Hand Circular
Center Frequency	6 Channels (single channel per link)
Channel Bandwidth	15 MHz
Intersatellite Link	22.55-23.55 GHz (200 MHz)
Polarization	Vertical
Center Frequency	8 Channels (single channel per link)
Channel Bandwidth	25 MHz

Final Amplifier Output Power[1/]

L-Band	
(Cells 1 - 37)	1.5 to 11.5 Burst Watts per carrier
Ka-Band	
Gateway	1.0 to 20.0 Watts per channel
Intersatellite	2.5 Burst Watts per carrier[1/]

Receiving System Noise Temperature[1/]

L-Band	553 °K
Ka-Band	
Gateway	1454 °K
Intersatellite	789 - 1167 °K

1/ See Appendix A of IRIDIUM system application.

The individual satellite applications for IRIDIUM 1 through IRIDIUM 87 are enclosed in separately bound appendices G-1 and G-2.

RECEIVED

DEC 5 1990

Domestic Facilities Division
Satellite Radio Branch

APPENDIX G-1 TO

APPLICATION OF

MOTOROLA SATELLITE COMMUNICATIONS, INC.

FOR

IRIDIUM

A LOW EARTH ORBIT MOBILE SATELLITE SYSTEM

BEFORE THE

FEDERAL COMMUNICATIONS COMMISSION

WASHINGTON, D.C.

DECEMBER 1990

Before the
FEDERAL COMMUNICATIONS COMMISSION
Washington, D.C. 20554

In re Application of: **MOTOROLA SATELLITE COMMUNICATIONS, INC.** **For Authority to Construct, Launch and Operate a Low Earth Orbit Satellite as Part of the IRIDIUM System (IRIDIUM 1)**	)	**File No.**

APPLICATION

Motorola Satellite Communications, Inc. ("Motorola" or "Applicant") hereby applies for authority to construct, launch and operate a low earth orbit satellite designated as IRIDIUM 1.

I.

PURPOSE OF APPLICATION

A. Authorization Requested

Motorola requests authority from the Commission to construct, launch and operate its IRIDIUM global personal communications system comprised of a constellation of 77 low earth orbit satellites. Each satellite will operate in the 1610-1626.5 MHz band and the Ka-band, in a polar orbit some 413 nautical miles above the earth's surface. This application covers all pertinent technical and operational information for authority to construct, launch and operate one of the IRIDIUM satellites. Separate applications for the other in orbit and spare satellites are being filed concurrently herewith. Much of the information about this satellite and the IRIDIUM system is provided in the comprehensive system application also filed contemporaneously with this application, which is incorporated herein by reference.

B. Summary of Proposed Service

The applicant will offer bulk air time over IRIDIUM to others on a non-common carrier basis. Service that can be provided to the public include RDSS, paging, voice and data. IRIDIUM provides continuous coverage to virtually all points on the surface of the earth and within 100,000 feet above mean sea level, including all U.S. domestic locations.

C. Applicant Information

The applicant's name and address is:

Motorola Satellite Communications, Inc.
2501 South Price Road
Chandler, AZ 85248

Correspondence and communications concerning this application should be addressed to:

Leonard Kolsky
Vice President and Director
Regulatory Affairs
Motorola, Inc.
1350 I Street, N.W.
Washington, D.C. 20005
(202) 371-6932

with copies directed to:

Philip L. Malet, Esquire
Alfred M. Mamlet, Esquire
Steptoe & Johnson
1330 Connecticut Avenue, N.W.
Washington, D.C. 20036
(202) 429-6239

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CONCLUSION

Wherefore, Motorola requests that the Commission grant this application expeditiously and in conjunction with the other IRIDIUM satellite applications.

Respectfully submitted,

MOTOROLA SATELLITE COMMUNICATIONS, INC.

By:

Title: President, Motorola Satellite Communications, Inc.

Philip L. Malet
Alfred Mamlet
Steptoe & Johnson
1330 Connecticut Avenue, N.W.
Washington, D.C. 20036
(202) 429-6239

Counsel to Motorola Satellite Communications, Inc.

December 3, 1990

ENGINEERING CERTIFICATE

I hereby certify that I am the technically qualified person responsible for preparation of the engineering information contained in this application, that I am familiar with Part 25 of the Commission's Rules, that I have either prepared or reviewed the engineering information submitted in the application, and, that it is complete and accurate to the best of my knowledge and belief.

Gerald M. Munson

Title: Spectrum Utilization Manager
Motorola Satellite Communications

Date: December 3, 1990

EXHIBIT I

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1/ See Appendix A of IRIDIUM system application.

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---

[2] See Appendix A of IRIDIUM system application.

[3] See Section IV to the IRIDIUM system application for the factors which support these orbital assignments.

[4] L-band cell (1 - 7) contours and Ka-band gateway and intersatellite link contours are provided in the IRIDIUM system application at Section V. See Appendix A of the IRIDIUM system application for receiving antenna gain, transmitting antenna gain, receiving system sensitivity (G/T), saturation power flux density, and effective isotropically radiated power.

[5] See Section V of the IRIDIUM system application.

[6] See Section V of the IRIDIUM system application.

Estimated Lifetime of In-Orbit Satellite[7]	5 Years
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30 dB @ 100% x Channel Bandwidth from carrier
60 dB @ 200% x Channel Bandwidth from carrier

7/ The basis for this lifetime estimate is contained in Section V of the IRIDIUM system application.

8/ A description of these systems is contained in Section V of the IRIDIUM system application.

9/ A description of this system, including provision for operation during eclipse conditions, is set forth in Section V of the IRIDIUM system application.

#1

RECEIVED

FEB 2 2 1991

Federal Communications Commission
Office of the Secretary

BEFORE THE
FEDERAL COMMUNICATIONS COMMISSION
WASHINGTON, D.C. 20554

In re Application of: MOTOROLA SATELLITE COMMUNICATIONS, INC. For Authority to Construct, Launch and Operate a Low Earth Orbit Satellite System in the 1610-1626.5 MHz Band.	)	File No. 9-DSS-P-91(87)

SUPPLEMENTAL INFORMATION to IRIDIUM SYSTEM APPLICATION

Leonard S. Kolsky
Vice President and
Director of Regulatory Affairs
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1350 I Street, N.W.
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(202) 429-6239

Attorneys for
Motorola Satellite
Communications, Inc.

The undersigned officer of the applicant hereby certifies that all of the attached information submitted in support of Motorola Satellite Communications' application for a low earth orbit satellite system is true, complete and accurate to the best of my belief and knowledge, and is made in good faith.

Respectfully submitted,

MOTOROLA SATELLITE
COMMUNICATIONS, INC.

Durrell Hillis
President

CERTIFICATION OF PERSON RESPONSIBLE FOR PREPARING ENGINEERING INFORMATION

I hereby certify that I am the technically qualified person responsible for preparation of the attached engineering information submitted in support of Motorola Satellite Communications' application for a low earth orbit satellite system, that I am familiar with Part 25 of the Commission's Rules and Regulations, that I have either prepared or reviewed the attached engineering information, and that it is complete and accurate to the best of my knowledge.

Gerald M. Munson

Gerald M. Munson
Spectrum Utilization Manager

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APPENDIX E	Financial Certification and Financial Data
	Statement from Donald R. Jones, Motorola, Inc., Executive Vice President and Chief Financial Officer
	Excerpts from Motorola, Inc.'s 1989 Annual Report
	Excerpts from Motorola, Inc.'s 1990 Third Quarter Report
APPENDIX F	FCC Form 430 "Common Carrier and Satellite Radio Licensee Qualification Report"
APPENDIX G	Individual Satellite Application - IRIDIUM 1 (Exhibit I Revised)
APPENDIX G-1	Individual Satellite Applications - IRIDIUM 1-43 (Bound Separately)
APPENDIX G-2	Individual Satellite Applications - IRIDIUM 44-87 (Bound Separately)

the criteria established for the provision of non-common carrier offerings.[29]

IRIDIUM's offerings should similarly be classified as non-common carrier services. Motorola will negotiate individual long-term arrangements with major domestic and international carriers for wholesale bulk transmission services. These carriers will, in turn, provide telecommunications services to members of the public.

A description of the proposed markets and services that can be offered by IRIDIUM is contained elsewhere in this application. The market response to IRIDIUM's satellite system has been strong. Motorola further believes that prospective carriers will demand long-term relationships in order to ensure adequate capacity at stable prices.

4. Names of Any Purchasing Customers for Which Sales Contracts Have Been Executed

Although Motorola has not entered into definitive agreements for the sale of communications capacity, it has engaged in detailed discussions with a number of prospective customers. Market response to IRIDIUM has been very positive. Motorola has entered into Memoranda of Intent with several major international telecommunications carriers.

---

[29] See Satellite Business Systems, 95 F.C.C.2d 866, 869-70 (1983); Establishment of Satellite Systems Providing International Communications, 101 F.C.C.2d 1046, 1104-06 (1985) ("Separate Systems"), reconsideration, 61 Rad. Reg. 2d (P&F) 649 (1986), further reconsideration, 1 F.C.C. Rcd 439 (1986).

TABLE V-1

MAJOR IRIDIUM SATELLITE CHARACTERISTICS

Stabilization	3-Axis
Mission Life	5 Years
Station Keeping	+/- 0.5 Degrees Attitude Accuracy +/- 20 Kilometers Position Accuracy
Frequency Bands	1610-1626.5 MHz 18.8-20.2 GHz 27.5-30.0 GHz 22.55-23.55 GHz
Earth Coverage	5 Million Square Miles Per Satellite
Max. Number of Uplink Channels per Satellite	110 per cell averaged over 37 cells
Max. Number of Downlink Channels per Satellite	110 per cell averaged over 37 cells
Number Intersatellite Channels per Satellite	3,000 Maximum
Number Gateway Channels per Satellite	2,000 Maximum
Total Occupied Bandwidth	16.5 MHz @ L-band 200 MHz @ Ka-band (crosslinks) 100 MHz @ Ka-band (gateway uplink)
Polarization	Right Circular 100 MHz @ Ka-band (gateway downlink) @ L-band & Ka-band (Gateway and TT&C links) Vertical @ Ka-band (Intersatellite links)
Transmit EIRP	12.3 to 31.7 dBw @ L-band 15.1 to 28.1 dBw @ Ka-band (Gateway) 39.6 dBw max @ Ka-band (Intersatellite)
Satellite G/T	-5.1 to -19.2 dBi/K @ L-band -10.1 dBi/K @ Ka-band (Gateway) 4.0 to 6.2 dBi/K @ Ka-band (Inter-satellite)
Wet Mass with Reserve	386.2 kg.
Orbit	Polar (7 planes)

pattern of each phased array (beam types 1-6) is repeated for each of the six panels. The nadir cell (beam type 7) is served by the cupped dipole located on the nadir face of the satellite. Each of the phased array antenna beams have been optimized to provide the desired cell coverage. The antenna aperture gains (on-boresight) and beamwidths for each of the beam types are listed in Table V-2. Figures V-4 to V-10 depict the satellite L-band antenna gain contours. Tables A-2 to A-5 in Appendix A provide the peak antenna gains and specific link analyses.

TABLE V-2

ANTENNA APERTURE GAINS AND BEAMWIDTHS

Beam Type	Aperture Gain (dBi)	3 dB Beamwidth (deg) Azimuth	Elevation
1	25.0	19.0	5.4
2	25.0	19.0	5.4
3	25.0	19.0	5.4
4	23.9	19.0	7.0
5	23.0	19.0	8.5
6	20.0	26.0	11.5
7	12.0	45.0	45.0

b. <u>Formation of the Cellular Pattern</u>

IRIDIUM operates with a 7-cell frequency reuse pattern, as shown in Figure V-11. The cells denoted as A through G are scanned by the satellite antenna arrays in accordance with the timing pattern and sequence shown in Figures V-3 and V-12. During the time slot that the antenna is pointing at a cell, satellite transmissions may be made and receptions of

The spacecraft mass budget is as shown in Table V-7.

TABLE V-7

SPACECRAFT MASS BUDGET

Subsystem	Mass (kg)
Structure	24.9
Thermal Control Subsystem	12.1
Propulsion (Dry)	8.6
GN&C Subsystem	9.8
Electrical Power Subsystem	78.9
Antenna Subsystem	83.3
Communication Electronics Subsystem	81.8
Spacecraft Mass (Dry)	299.4
Consumables	41.3
Spacecraft Mass (Wet)	340.7
Spacecraft Reserve Mass	45.5
Spacecraft Wet Mass with Reserve	386.2

11. Operational Lifetime and Space Segment Reliability

The operational lifetime of each satellite is determined by a number of factors, including solar array degradation, stationkeeping fuel consumption, and random parts failure. The fcllowing indicates the estimated minimum lifetime of the satellites for each of these factors:

Solar array degradation - 5 years

Stationkeeping fuel - 8 years (3 sigma orbital, insertion accuracy assumed)

Random parts failure - 5 years

TABLE V-8

GATEWAY EARTH TERMINAL SUMMARY

Data Rate	12.5 Mbps
Error Correction Coding	Convolutional, Rate=1/2, K=7
Modulation	QPSK
Frequency Bands: Transmit Receive	27.5-30.0 GHz (Uplink) 18.8-20.2 GHz (Downlink)
Ground Tracking Antenna Diameter	 3.5 Meters
Gain	53.7 dB @ 20 GHz 57.6 dB @ 30 GHz
Sidelobe Level	Will meet the criterion of 47 CFR § 25.209(a)(2)
3 dB Beamwidth	0.36 Degrees @ 20 GHz 0.24 Degrees @ 30 GHz
Pointing Angle Range	360 Degrees Azimuth +5 to 90 Degrees Elevation
Ground Acquisition Antenna	Passive Array, Configuration TBA
Transmitter EIRP Clear Weather Heavy Rain	 51.6 dBW (+/- 3 dB) to 77.6 dBW Max. (+/- 3dB)
Receiver G/T	22.9 dB/K
Required Eb/No	6.7 dB @ BER 10^{-6}

Since the orbiting satellites are in motion relative to the gateways, both primary antennas follow the track of the nearest two satellites. The communication payload being conveyed across the "active" link must be handed off periodically, from the current satellite to the next one as the active link

MOTOROLA

IRIDIUM

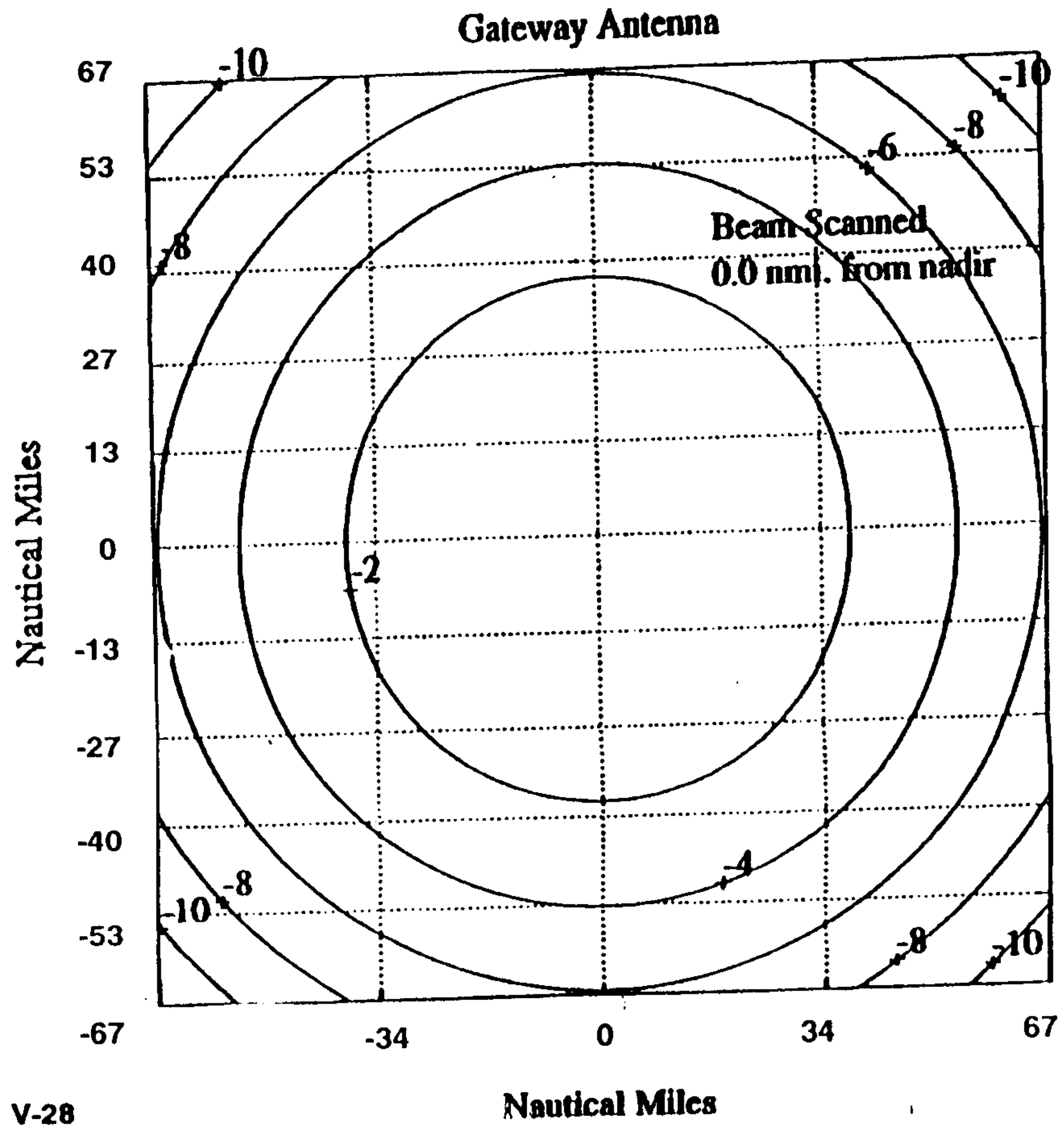

FIGURE V-28

ANTENNA PATTERN - O NMI FROM NADIR

vegetation. Several competing modulation formats were considered but were not chosen because they offered no improvement and generally were more complex to implement. Raised cosine filtering of the digital signal reduces the spectral occupancy and thus permits multiple carriers to be placed close together with acceptable levels of intermodulation.

c. Performance Objectives

The IRIDIUM system is designed to provide service to virtually 100% of the earth, 99.5% of the time. However, it should be recognized that it will be economically, and at times, physically impossible to provide service to every single point on the earth. There are practical limitations to the total number of locations which will physically be within line of sight to the satellites. The end-to-end bit error rate will be better than 0.01 for voice transmissions. More typical minimum bit error rates will be between .001 and .0001.

d. Link Performance Calculations

The L-band link budgets presented in Appendix A include the use of QPSK modulation format and sufficient bits to provide the equivalent of Rate 3/4 forward error correction.

6. Telemetry, Tracking and Control Subsystem

The Telemetry, Tracking, and Control ("TT&C") subsystem provides the functional hardware required for the reception,

TABLE V-3 TT&C SATELLITE TRANSMISSION CHARACTERISTICS		
	Transfer Orbit (Omni Antenna)	On-Station Communications Network
Frequency/ Polarization	18.8-20.2 GHz/ Linear	18.8-20.2 GHz/ RHC (Gateway/SCS)
EIRP	9.5 dBW max.	(Uses Gateway link or Crosslink)
Modes of Operations	Sequential data, Selected data	Sequential data, Selected data
Modulation	FSK	QPSK
Data Rate	1 kbps	12.5/25 mbps (total Gateway link/Crosslink data rate)

The command subsystem is designed to maintain positive control of the spacecraft during all mission phases. It provides reliable control during launching maneuvers and for all satellite operating attitudes. It also maintains the orbital velocity of the satellite and controls housekeeping functions and communications subsystem configurations. The command messages are encrypted and authenticated to provide security, protecting the satellite control subsystem against unauthorized access.

The command transmissions received from the ground are demodulated into a digital bit stream. When the satellites

APPENDIX A

IRIDIUM TRANSMISSION CHARACTERISTICS

1. RF PLAN AND LINK BUDGETS

Tables A-1 through A-7 summarize the key RF parameters of the communication links. Transmitter RF output electronic power control will be utilized on the subscriber and gateway links to compensate for vegetative shadowing and inclement weather. Tables A-2, A-3 & the identified portion of table A-6 reflect maximum transmitter power levels with the highest tolerable amount of shadowing and rain. Tables A-4, A-5 & the identified portion of A-6 are with minimum transmitter power levels, representing clear sky, line of sight operation.

Table A-7 shows two conditions of operation: "normal" and "in-plane link into the sun". The latter occurs when two linked-satellite's orbital positions are such that the receiving antenna of one must point directly into the sun, resulting in an increase in received thermal noise.

TABLE A-1

SYSTEM PARAMETER SUMMARY

	SV-USER		SV-GW		
	DOWN	UP	DOWN	UP	SV-SV
MULTIPLEXING	***********	TDMA	& FDMA		**************
MODULATION	**************		QPSK		****************
BASEBAND FILTERING	*********	40%	RAISED COSINE		************
FEC RATE	3/4	3/4	1/2	1/2	1/2
CODED DATA RATE (Mbps)	0.40	0.20	12.50	12.50	25.00
OCCUPIED BW PER CHAN (KHz)	280	126	8750	8750	17500
CENTER FREQUENCY (GHz)	1.61825	1.61825	19.950	29.750	23.275
TOTAL BANDWIDTH (MHz)	16.5	16.5	100.0	100.0	200.0
CARRIER SPACING (MHz)	0.350	0.160	15.0	15.0	25.0

TABLE A-2
SV-ISU DOWNLINK, WITH SHADOWING

	CELL 1	CELL 2 / 3	CELL 4	CELL 5	CELL 6	CELL 7
AZIMUTH ANGLE (DEG)	5.4	21.1	6.6	30.0	10.9	30.0
GROUND RANGE (Km)	2052.0	1917.9	1501.4	1377.9	911.4	344.5
NADIR ANGLE (DEG)	61.6	60.9	57.7	56.3	47.6	24.0
GRAZING ANGLE (DEG)	10.0	11.9	18.8	21.4	34.2	62.9
SLANT RANGE (Km)	2293.5	2160.2	1759.2	1643.3	1229.9	847.3
HPA Burst Power (Watts)	11.8	8.6	5.7	7.2	7.1	6.7
(dBW)	10.7	9.4	7.6	8.6	8.5	8.2
XMTR Peak Ant Gain (dBi)	25.0	25.0	23.9	23.0	20.0	12.0
Edge Loss (dB)	0.8	0.6	1.7	1.5	2.6	3.8
Scan Loss (dB)	1.0	1.4	1.4	3.0	3.6	0.0
Taper Loss (dB)	1.0	1.0	1.0	1.0	1.0	0.0
NET XMTR ANT GAIN (dBi)	22.3	22.0	19.8	17.5	12.8	8.2
XMTR Feed/Ckt Loss (dB)	1.3	1.3	1.3	1.3	1.3	1.3
EIRP (dBWi)	31.7	30.1	26.0	24.8	20.0	15.2
Path Loss (dB)	163.8	163.3	161.5	160.9	158.4	155.2
Polarization Loss (dB)	0.5	0.5	0.5	0.5	0.5	0.5
Atmos Absorption Loss (dB)	0.3	0.3	0.3	0.3	0.3	0.3
Mean Vegetation Loss (dB)	12.0	10.9	8.7	8.2	7.0	6.2
TOT PROPAGATION LOSS (dB)	176.6	175.0	171.0	169.9	166.2	162.2
RCVR Ant Net Gain (dBi)	1.0	1.0	1.0	1.2	2.3	3.0
RCV'D SIG LEVEL, C (dBW)	-143.9	-143.9	-143.9	-143.9	-143.9	-143.9
RCVR Antenna N-Temp (K)	150.0	150.0	150.0	150.0	150.0	150.0
RCVR Feed/Ckt Loss (dB)	1.0	1.0	1.0	1.0	1.0	1.0
LNA Noise Figure (dB)	0.8	0.8	0.8	0.8	0.8	0.8
RCV SYS NOISE TEMP, Ts (K)	298.9	298.9	298.9	298.9	298.9	298.9
G/Ts (dBi/K)	-23.8	-23.8	-23.8	-23.6	-22.5	-21.7
RCVR NOISE BW, B (KHz)	280.0	280.0	280.0	280.0	280.0	280.0
Sensitivity = kTsB (dBW)	-149.4	-149.4	-149.4	-149.4	-149.4	-149.4
RCV'D C/N (dB)	5.4	5.4	5.4	5.4	5.4	5.4
C/I (dB)	18.0	18.0	18.0	18.0	18.0	18.0
RCV'D C/(N+I) (dB)	5.2	5.2	5.2	5.2	5.2	5.2
RCV'D C/(Jo+Io) (dB)	59.7	59.7	59.7	59.7	59.7	59.7
Required Eb/No (dB)	3.2	3.2	3.2	3.2	3.2	3.2
Modem Impl Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
REQUIRED C/(N+I) (dB)	5.2	5.2	5.2	5.2	5.2	5.2
LINK MARGIN (dB)	0.0	0.0	0.0	0.0	0.0	0.0
FLUX DENS (dBW/sq-m, 4KHz)	-123.5	-124.6	-126.9	-127.5	-129.8	-131.4

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UNITED STATES OF AMERICA

Proposed Modification to Section 6.1.1.4.1.3 to the JIWP Report

Concerning proposed LEO mobile-satellite systems which would use spectrum above about 1 GHz, new aspects of spectrum sharing must be addressed. The potential of such a system to share with geostationary orbit mobile-satellite systems is now under study. The characteristics of the LEO earth stations along with the low orbit of the LEO satellites and cellular nature of the systems provides a potential for frequency sharing.~~that has not yet been explored.~~ An analysis has been performed of the potential for sharing between LEO systems and RDSS systems in the GSO in the vicinity of 1.6 GHz. LEO system elements will not cause unacceptable interference to uplink carriers operating with RDSS single beam or multi-beam GSO satellites. LEO system elements are able to accommodate potentially harmful interference from RDSS uplink burst packets by means of error detection and packet interpolation techniques. Mutual harmful interference between LEO systems and RAS, APC and RNSS will not occur because the LEO systems will avoid co-frequency use on the basis of dynamic time and geographical channel assignment techniques. Analyses are required to consider sharing with other services that use this band.

The technical basis for this modification is in Annex 1, attached.

ANNEX 1 TO JIWP-USA-6A

SHARING BETWEEN LEO AND GSO SYSTEMS IN THE RADIO DETERMINATION SATELLITE, RADIO ASTRONOMY, RADIO NAVIGATION SATELLITE AND AERONAUTICAL CORRESPONDENCE SERVICES in the Vicinity of 1.6 GHz

(QUESTIONS 82-1/8)

1. INTRODUCTION

One of the considerations at WARC '92 will be to provide additional spectrum for Mobile Satellite applications in the 1-3 GHz part of the spectrum. This contribution provides the technical bases that show how a Personal Communication Low Earth Orbit Mobile Satellite System (PCLEO) can share the uplink frequency band allocation of the Radio Determination Satellite Service (RDSS) in the 1-2 GHz part of the spectrum. It also establishes the basis for sharing of this spectrum with other services, i.e., Radio Navigation Satellite Services (RNSS), Aeronautical Public Correspondence (APC), and Radio Astronomy (RA).

The PCLEO system operates in a bi-directional, single band mode, i.e., the PCLEO satellite transmits and receives using the same frequencies on a time shared basis. In order to assist in sharing of spectrum, the PCLEO system controls the number and location of its active cells, the transmitter powers of the subscriber terminals, the satellite transmitter power and the frequencies used. This capability is necessary to the performance of the system and provides assurance that the PCLEO system will not cause unacceptable interference to other services and systems.

2. SYSTEM CHARACTERISTICS

The characteristics of the RDSS and PCLEO systems, are given in the following paragraphs.

2.1 RDSS System Characteristics

The significant characteristics of a typical RDSS system operating in the GSO are given in Table 1.

TABLE 1

RDSS SYSTEM CHARACTERISTICS

A. SUBSCRIBER TERMINAL EIRP: 18.5 dBW
B. BURST TIME: 20 TO 80 MS
C. TRANSMIT POLARIZATION: LCP
D. MULTIPLE ACCESS: CDMA
E. CHIP RATE: 8 MCPS
F. MODULATION: BPSK
G. SPREAD RATIO: 512

2.2 PCLEO System Characteristics

The characteristics of the PCLEO system are summarized in Table 2. The radio frequency carriers of the PCLEO system will operate within a maximum of 10.5 MHz of bandwidth within the RDSS band. A more detailed description of significant characteristics that enter into sharing consideration are given in the following sections.

TABLE 2

PCLEO SYSTEM CHARACTERISTICS

	DOWNLINK	UPLINK
MULTIPLE ACCESS	F/TDMA	F/TDMA
CHANNEL SPACING (KHz)	350	160
CHANNEL BANDWIDTH (KHz)	280	126
TOTAL BANDWIDTH ASSUMED (MHz)	10.5	10.5
MAX # ACTIVE CARRIERS (10.5 MHz)	29	29
MAX # VOICE CHANNELS (10.5 MHz)		
PER CELL	110	110
PER TDMA FRAME	770	770
BURST TIMES (MS)	1.3	2.9
MODULATION	QPSK	QPSK
CODING RATE	3/4	3/4
CODED DATA RATE (KBPS)	400	180
POLARIZATION	RCP	RCP
EIRP/CARRIER (dBW)	APPX A	APPX A

The following sections expand on the PCLEO system description to aid in evaluating the sharing analysis.

2.2.1 RF Plan

This section describes the RF plan for the PCLEO subscriber up- and downlinks. The system uses multiple TDMA/FDMA carriers for both the up- and downlinks. Since the PCLEO satellites do not transmit and receive at the same time, the up- and downlink transmissions will both be able to use the entire frequency band that is employed by the system.

2.2.1.1 Downlink

The downlink consists of multiple TDMA carriers, each of which is QPSK modulated at a channel rate of 400 kbps and each of which occupies a bandwidth of 280 KHz.

In order to provide protection to other services and systems, only 10.5 MHz of the 16.5 MHz allocated to RDSS uplinks will be utilized by the PCLEO system. A total of 29 downlink carriers may use this bandwidth, 4 of these are for control and 25 are for traffic channels. Voice activity compression techniques are used to reduce the number of carriers required in the downlink. Using 2.2 to 1 digital speech interpolation (DSI) compression, 55 voice channels can use the 25 traffic downlink channels.

The TDMA frame may contain 14 voice channels thus providing 55 X 14 or 770 channels per frame in a 7-cell cluster. With a 7 cell frequency reuse pattern, each frame will service 7 cells resulting in 110 voice channels per cell, assuming uniform distribution of traffic among the cells in a 7-cell cluster.

2.2.1.2 Uplink

The uplink also utilizes multiple TDMA carriers. These are QPSK modulated at a channel rate of 180 kbps and occupy a 126 KHz bandwidth. Although a total of 64 carriers may occupy the 10.5 MHz of bandwidth, only 29 of these are active at any time due to the use of voice activity control on the transmitter. Therefore, the number of active uplink carriers will be constrained to be the same as the number of downlink carriers.

2.3 Multiple Access Format

The PCLEO System uses a combination of time and frequency division multiple access. The time division multiple access scheme employs a 60 millisecond (ms) repetitive frame which is established for the system and repeats continuously. The timing diagram at the satellite is shown in Figure 1. The shorter intervals, each 1.3 milliseconds long, are the transmit (i.e. downlink) bursts from the satellite, while the longer 2.9 millisecond intervals are for reception of the uplink bursts. 'Guardband' time is also shown.

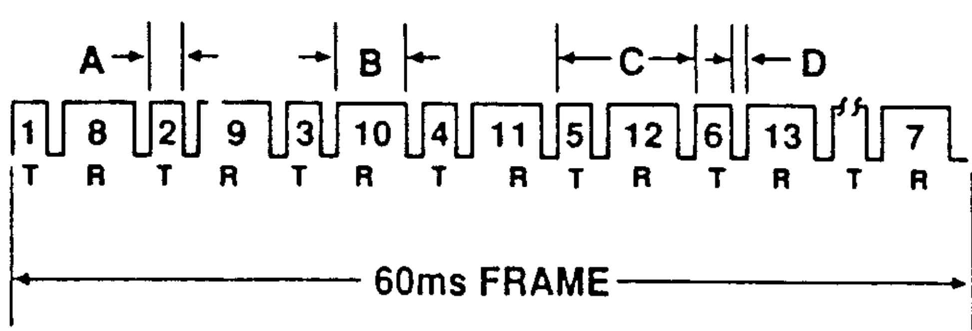
Each frame begins with a satellite transmission for the first time slot, labeled 1, which is followed by the receive time slot which corresponds to the transmit time slot 8 (transmit slot number + 7). Thirteen additional pairs of transmit and receive time slots complete the frame, each of which is a couplet of a transmit time and a receive time corresponding to a transmit time slot half a frame away.

On the downlink, the satellite transmitter is active 30.3% of the time. This corresponds to 14, 1.3 millisecond bursts in the 60 millisecond frame.

On the uplink, the subscriber unit transmitters are active 67.6% of the time. This corresponds to 14, 2.9 millisecond bursts in the 60 millisecond frame.

SATELLITE TDMA FORMAT

A = TRANSMIT BURST TIME = 1.3 MILLISECOND
B = RECEIVE BURST TIME = 2.9 MILLISECONDS
C = TIME BETWEEN BURSTS = 4.2857 MILLISECONDS
D = GUARD TIME = 42.857 MICROSECONDS



T = TRANSMIT TIME
R = RECEIVE TIME

FIGURE 1.

2.4 Earth Coverage

A PCLEO system, operating with polar, low orbits can provide simultaneous full Earth coverage using 1628 cells. A GSO RDSS satellite, on the other hand, provides coverage of only a portion of the Earth. In order to evaluate the potential for sharing between these two types of systems it is necessary to define the portion of the Earth which they will mutually cover. It has been useful to define the coverage of the GSO RDSS satellite in terms of the number of cells of the PCLEO system.

Thus, a single beam RDSS satellite covering North America is assumed to receive interference from some 80 PCLEO cells. Similarly, in a multi-beam RDSS satellite serving North America, about 12 PCLEO cells are assumed to be within the coverage of one of the beams.

2.5 Transmitter Powers

The PCLEO system provides dynamic control of the transmitted power of both the subscriber terminals and the satellites. To preserve battery power of the satellites and subscriber terminals, the system elements are operated at the power levels necessary to satisfy the communication link bit error requirements. These power levels are to be controlled in 1 dB steps. The "maximum" transmitter power is needed to overcome the effect of vegetative shadowing. This power level is also the maximum that the satellite and subscriber terminal will be able to transmit. The "nominal" transmitter power is based on a 3 db link margin.

Because of the number of cells in the PCLEO system, more than one satellite transmitter or subscriber terminal will be transmitting at the same time using the same frequency but because of a number of factors, the powers are not simply additive. Further, the PCLEO and the RDSS transmission systems are orthogonally polarized, and it is assumed in this analysis that the PCLEO uplink transmissions that potentially interfere with RDSS satellites can be reduced by a polarization isolation factor. This assumption, however, may be investigated further to assess the effects of multipath on the available cross polarization isolation. If the PCLEO interfering carrier powers were simply additive, the net interfering power per carrier (Pt) of the PCLEO system may be calculated as follows:

$$Pt = P + 10 \log (N) - PL$$

where:

P = Power/carrier for a single frequency use

N = Number of frequency reuses of the PCLEO within the coverage of the GEO RDSS satellite

PL = Polarization loss

However, the PCLEO transmitted power (EIRP) associated with almost all of the cells in each seven-cell cluster is different, both in the uplink and downlink. In addition, the PCLEO system controls both uplink and downlink transmitter power to overcome the effects of vegetative shadowing in a variable, non-linear manner adjusting for the amount of individual fades, the specifics of cell geometry, and available power. Further, the duration of a transmit burst associated with any PCLEO cell is quite short compared to the burst length of an uplink RDSS packet transmission, i.e., 1.3 and 2.9 ms compared to 20 to 80 ms, thus the potentially interfering power levels of PCLEO carriers change during the RDSS uplink pulse. Moreover, each of the PCLEO cells can accommodate 29 simultaneous burst carriers but it is virtually impossible that all 29 carriers in all the geographically dispersed, co-frequency cells will be utilized at the same time --- in other words, an occupancy factor must be considered. Finally, the transmitted packets of the PCLEO cells and satellites are geographically distributed, having significantly different propagation times to the GSO --- thereby causing the potentially interfering PCLEO burst transmissions to be not simply additive in terms of interference power.

The above described variable factors have been considered to arrive at a weighted peak carrier EIRP to employ in the interference evaluations below. One of more conservative weighting factors was that half (50%) of all carriers were operated at maximum power to overcome vegetative shadowing. The Maximum Average Peak Powers per PCLEO carrier that will be used are:

Uplink	7.89	dBW
Downlink	26.46	dBW

It is assumed that the PCLEO system operates in accordance with the parameters used in the following interference calculations. That is, it may be necessary to control the aggregate power level of the PCLEO carriers so that the required BER performance of the RDSS system is achieved. Moreover, it is assumed that the PCLEO signalling and control system is capable of controlling access to the system in a manner that ensures that the aggregate interference power produced at the geosynchronous orbit at any instant by all transmissions within the PCLEO system will not cause unacceptable interference to RDSS system. It also assumed that other operational characteristics of the PCLEO system, such as the accuracy of satellite attitude control and the sidelobe performance of the satellite phased array antennas are in fact being maintained within their specified limits.

3. SHARING

This section analyzes the sharing of the PCLEO system with RDSS systems and other services such as Radio Navigation Satellite, Aeronautical Public Correspondence and Radio Astronomy.

3.1 Sharing with RDSS

3.1.1 General

Since the PCLEO satellites and subscriber terminals both transmit in the uplink band of the RDSS system satellites, there is a potential for mutual harmful interference between the networks. The basis for this sharing analysis is the calculation of Carrier-to-Interference Density ratios (C/Io). For the case of interference into RDSS satellite receivers, the C/Io caused by PCLEO system elements is evaluated versus C/Io caused by other co-coverage RDSS systems as well as intra-RDSS system interference. The interference levels of RDSS systems into like RDSS systems serving North America are also represented by C/Io ratios calculated in Table A-1 of Appendix A. Both single and multiple beam RDSS systems are considered, as well as intra-RDSS system interference.

3.1.2 PCLEO Satellites Sharing with the RDSS Satellites

A potential source of interference to the geostationary orbit (GSO) RDSS system is the PCLEO satellite constellation transmitting its downlink carriers. This can result from the side- and backlobes of the PCLEO satellite antennas transmitting energy into the RDSS satellite receivers. This is the source of interference that is used to calculate the downlink PCLEO interference.

A second potential source of interference from the PCLEO satellite constellation could be from the main beam of PCLEO satellite antennas scanning through the geosynchronous orbit and directly illuminating RDSS satellite antennas. This potential interference will be avoided by shutting down PCLEO cells which graze the Earth's limb and illuminate the GSO.

The C/Io of RDSS satellites caused by the downlinks of a PCLEO satellite constellation are calculated in Table A-2 of Appendix A. In addition, Table A-3 includes link budgets which incorporate the effect of intra- and intersystem interference[1]. Table 3 is a summary of Table A-2 of Appendix A which shows how the interference from the PCLEO satellite transmissions will affect the uplink performance of the RDSS system in the presence of interference from

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[1] The link budgets do not include significant interference contributions from other sources, such as terrestrial transmissions and other satellite networks in the RDSS feederlink band, and is based on the data-like performance of the RDSS link.

TABLE 3

=======

Effects of PCLEO Downlinks

		MultiBeam RDSS	SingleBeam RDSS
Uplink RDSS C/No (thermal)	dB	58.20	52.70
C/Io (in-beam RDSS)	dB	59.52	61.82
C/Io (adj beam RDSS)	dB	66.00	NA
C/Io (3 other RDSS systems)	dB	54.91	56.75
C/Io due to PCLEO downlink	dB	62.16	64.12
RDSS Uplink C/(No+Io)	dB	52.08	50.69

TABLE 4

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Effects of PCLEO Uplinks

		MultiBeam RDSS	SingleBeam RDSS
Uplink RDSS C/No (thermal)	dB	58.20	52.70
C/Io (in-beam RDSS)	dB	59.52	61.82
C/Io (adj beam RDSS)	dB	66.00	NA
C/Io (3 other RDSS systems)	dB	54.91	56.75
C/Io due to PCLEO uplink	dB	70.40	66.68
RDSS Uplink C/(No+Io)	dB	52.08	50.78

TABLE A-3
SV-ISU UPLINK, WITH SHADOWING

	CELL 1	CELL 2 / 3	CELL 4	CELL 5	CELL 6	CELL 7
AZIMUTH ANGLE (DEG)	5.4	21.1	6.6	30.0	10.9	30.0
GROUND RANGE (Km)	2052.0	1917.9	1501.4	1377.9	911.4	344.5
NADIR ANGLE (DEG)	61.6	60.9	57.7	56.3	47.6	24.0
GRAZING ANGLE (DEG)	10.0	11.9	18.8	21.4	34.2	62.9
SLANT RANGE (Km)	2293.5	2160.2	1759.2	1643.3	1229.9	847.3
HPA Burst Power (Watts)	7.0	7.0	5.5	6.9	6.7	6.3
(dBW)	8.5	8.5	7.4	8.4	8.3	8.0
NET XMTR ANT GAIN (dBi)	1.0	1.0	1.0	1.2	2.3	3.0
XMTR Feed/Ckt Loss (dB)	0.7	0.7	0.7	0.7	0.7	0.7
EIRP (dBWi)	8.8	8.8	7.7	8.9	9.9	10.3
Path Loss (dB)	163.8	163.3	161.5	160.9	158.4	155.2
Polarization Loss (dB)	0.5	0.5	0.5	0.5	0.5	0.5
Atmos Absorption Loss (dB)	0.3	0.3	0.3	0.3	0.3	0.3
Mean Vegetation Loss (dB)	12.0	10.9	8.7	8.2	7.0	6.2
TOT PROPAGATION LOSS (dB)	176.6	175.0	171.0	169.9	166.2	162.2
RCVR Peak Ant Gain (dBi)	25.0	25.0	23.9	23.0	20.0	12.0
Edge Loss (dB)	0.8	0.6	1.7	1.5	2.6	3.8
Scan Loss (dB)	1.0	1.4	1.4	3.0	3.6	0.0
Taper Loss (dB)	1.0	1.0	1.0	1.0	1.0	0.0
NET RCVR ANT GAIN (dBi)	22.3	22.0	19.8	17.5	12.8	8.2
RCV'D SIG LEVEL, C (dBW)	-145.6	-144.2	-143.6	-143.6	-143.6	-143.6
RCVR Antenna N-Temp (K)	290.0	290.0	290.0	290.0	290.0	290.0
RCVR Feed/Ckt Loss (dB)	1.8	1.8	1.8	1.8	1.8	1.8
LNA Noise Figure (dB)	1.0	1.0	1.0	1.0	1.0	1.0
RCV SYS NOISE TEMP, Ts (K)	552.6	552.6	552.6	552.6	552.6	552.6
G/Ts (dBi/K)	-5.1	-5.4	-7.7	-9.9	-14.6	-19.2
RCVR NOISE BW, B (KHz)	126.0	126.0	126.0	126.0	126.0	126.0
Sensitivity = kTsB (dBW)	-150.2	-150.2	-150.2	-150.2	-150.2	-150.2
RCV'D C/N (dB)	4.6	5.9	6.6	6.6	6.6	6.6
C/I (dB)	18.0	18.0	18.0	18.0	18.0	18.0
RCV'D C/(N+I) (dB)	4.4	5.7	6.3	6.3	6.3	6.3
RCV'D C/(No+Io) (dB)	55.4	56.7	57.3	57.3	57.3	57.3
Required Eb/No (dB)	4.3	4.3	4.3	4.3	4.3	4.3
Modem Impl Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
REQUIRED C/(N+I) (dB)	6.3	6.3	6.3	6.3	6.3	6.3
LINK MARGIN (dB)	-1.9	0.0	0.0	-0.6	0.0	-0.4
FLUX DENS (dBW/sq-m, 4KHz)	-143.0	-143.4	-142.8	-142.5	-143.5	-138.9

TABLE A-4
SV-ISU DOWNLINK, NO SHADOWING

	CELL 1	CELL 2 / 3	CELL 4	CELL 5	CELL 6	CELL 7
AZIMUTH ANGLE (DEG)	5.4	21.1	6.6	30.0	10.9	30.0
GROUND RANGE (Km)	2052.0	1917.9	1501.4	1377.9	911.4	344.5
NADIR ANGLE (DEG)	61.6	60.9	57.7	56.3	47.6	24.0
GRAZING ANGLE (DEG)	10.0	11.9	18.8	21.4	34.2	62.9
SLANT RANGE (Km)	2293.5	2160.2	1759.2	1643.3	1229.9	847.3
HPA Burst Power (Watts)	1.6	1.5	1.7	2.3	3.0	3.4
(dBW)	2.0	1.7	2.2	3.7	4.8	5.3
XMTR Peak Ant Gain (dBi)	25.0	25.0	23.9	23.0	20.0	12.0
Edge Loss (dB)	0.8	0.6	1.7	1.5	2.6	3.8
Scan Loss (dB)	1.0	1.4	1.4	3.0	3.6	0.0
Taper Loss (dB)	1.0	1.0	1.0	1.0	1.0	0.0
NET XMTR ANT GAIN (dBi)	22.3	22.0	19.8	17.5	12.8	8.2
XMTR Feed/Ckt Loss (dB)	1.3	1.3	1.3	1.3	1.3	1.3
EIRP (dBWi)	23.0	22.4	20.6	19.9	16.3	12.3
Path Loss (dB)	163.8	163.3	161.5	160.9	158.4	155.2
Polarization Loss (dB)	0.5	0.5	0.5	0.5	0.5	0.5
Atmos Absorption Loss (dB)	0.3	0.3	0.3	0.3	0.3	0.3
Mean Vegetation Loss (dB)	0.0	0.0	0.0	0.0	0.0	0.0
TOT PROPAGATION LOSS (dB)	164.6	164.1	162.3	161.7	159.2	156.0
RCVR Ant Net Gain (dBi)	1.0	1.0	1.0	1.2	2.3	3.0
RCV'D SIG LEVEL, C (dBW)	-140.7	-140.7	-140.7	-140.7	-140.7	-140.7
RCVR Antenna N-Temp (K)	150.0	150.0	150.0	150.0	150.0	150.0
RCVR Feed/Ckt Loss (dB)	1.0	1.0	1.0	1.0	1.0	1.0
LNA Noise Figure (dB)	0.8	0.8	0.8	0.8	0.8	0.8
RCV SYS NOISE TEMP, Ts (K)	298.9	298.9	298.9	298.9	298.9	298.9
G/Ts (dBi/K)	-23.8	-23.8	-23.8	-23.6	-22.5	-21.7
RCVR NOISE BW, B (KHz)	280.0	280.0	280.0	280.0	280.0	280.0
Sensitivity = kTsB (dBW)	-149.4	-149.4	-149.4	-149.4	-149.4	-149.4
RCV'D C/N (dB)	8.7	8.7	8.7	8.7	8.7	8.7
C/I (dB)	18.0	18.0	18.0	18.0	18.0	18.0
RCV'D C/(N+I) (dB)	8.2	8.2	8.2	8.2	8.2	8.2
RCV'D C/(No+Io) (dB)	62.7	62.7	62.7	62.7	62.7	62.7
Required Eb/No (dB)	3.2	3.2	3.2	3.2	3.2	3.2
Modem Impl Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
REQUIRED C/(N+I) (dB)	5.2	5.2	5.2	5.2	5.2	5.2
LINK MARGIN (dB)	3.0	3.0	3.0	3.0	3.0	3.0
FLUX DENS (dBW/sq-m, 4KHz)	-132.3	-132.3	-132.3	-132.5	-133.6	-134.3

TABLE A-5
SV-ISU UPLINK, NO SHADOWING

	CELL 1	CELL 2/3	CELL 4	CELL 5	CELL 6	CELL 7
AZIMUTH ANGLE (DEG)	5.4	21.1	6.6	30.0	10.9	30.0
GROUND RANGE (Km)	2052.0	1917.9	1501.4	1377.9	911.4	344.5
NADIR ANGLE (DEG)	61.6	60.9	57.7	56.3	47.6	24.0
GRAZING ANGLE (DEG)	10.0	11.9	18.8	21.4	34.2	62.9
SLANT RANGE (Km)	2293.5	2160.2	1759.2	1643.3	1229.9	847.3
HPA Burst Power (Watts)	1.5	1.4	1.6	2.2	2.9	3.3
(dBW)	1.8	1.6	2.0	3.5	4.6	5.2
NET XMTR ANT GAIN (dBi)	1.0	1.0	1.0	1.2	2.3	3.0
XMTR Feed/Ckt Loss (dB)	0.7	0.7	0.7	0.7	0.7	0.7
EIRP (dBWi)	2.1	1.9	2.3	4.0	6.2	7.5
Path Loss (dB)	163.8	163.3	161.5	160.9	158.4	155.2
Polarization Loss (dB)	0.5	0.5	0.5	0.5	0.5	0.5
Atmos Absorption Loss (dB)	0.3	0.3	0.3	0.3	0.3	0.3
Mean Vegetation Loss (dB)	0.0	0.0	0.0	0.0	0.0	0.0
TOT PROPAGATION LOSS (dB)	164.6	164.1	162.3	161.7	159.2	156.0
RCVR Peak Ant Gain (dBi)	25.0	25.0	23.9	23.0	20.0	12.0
Edge Loss (dB)	0.8	0.6	1.7	1.5	2.6	3.8
Scan Loss (dB)	1.0	1.4	1.4	3.0	3.6	0.0
Taper Loss (dB)	1.0	1.0	1.0	1.0	1.0	0.0
NET RCVR ANT GAIN (dBi)	22.3	22.0	19.8	17.5	12.8	8.2
RCV'D SIG LEVEL, C (dBW)	-140.2	-140.2	-140.2	-140.2	-140.2	-140.2
RCVR Antenna N-Temp (K)	290.0	290.0	290.0	290.0	290.0	290.0
RCVR Feed/Ckt Loss (dB)	1.8	1.8	1.8	1.8	1.8	1.8
LNA Noise Figure (dB)	1.0	1.0	1.0	1.0	1.0	1.0
RCV SYS NOISE TEMP, Ts (K)	552.6	552.6	552.6	552.6	552.6	552.6
G/Ts (dBi/K)	-5.1	-5.4	-7.7	-9.9	-14.6	-19.2
RCVR NOISE BW, B (KHz)	126.0	126.0	126.0	126.0	126.0	126.0
Sensitivity = kTsB (dBW)	-150.2	-150.2	-150.2	-150.2	-150.2	-150.2
RCV'D C/N (dB)	9.9	9.9	9.9	9.9	9.9	9.9
C/I (dB)	18.0	18.0	18.0	18.0	18.0	18.0
RCV'D C/(N+I) (dB)	9.3	9.3	9.3	9.3	9.3	9.3
RCV'D C/(No+Io) (dB)	60.3	60.3	60.3	60.3	60.3	60.3
Required Eb/No (dB)	4.3	4.3	4.3	4.3	4.3	4.3
Modem Impl Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
REQUIRED C/(N+I) (dB)	6.3	6.3	6.3	6.3	6.3	6.3
LINK MARGIN (dB)	3.0	3.0	3.0	3.0	3.0	3.0
FLUX DENS (dBW/sq-m, 4KHz)	-149.6	-149.4	-147.1	-144.9	-140.1	-135.6

TABLE A-6
SV-GATEWAY LINKS

MAX SLANT RANGE = 2293.5 Km

	DOWNLINK		UPLINK	
	CLEAR	RAIN	CLEAR	RAIN
CENTER FREQ (GHz) =	20.0	20.0	29.8	29.8
XMTR: HPA Output Power(dBW)	0.6	13.6	-2.1	24.0
Peak Ant Gain (dBi)	20.0	20.0	57.6	57.6
Off-Peak Loss (dB)	2.0	2.0	0.5	0.5
Net Antenna Gain (dB)	18.0	18.0	57.1	57.1
XMIT Circuit Losses (dB)	3.5	3.5	3.5	3.5
EIRP (dBWi)	15.1	28.1	51.6	77.6
Path Loss (dB)	185.7	185.7	189.1	189.1
Polarization Loss (dB)	0.5	0.5	0.5	0.5
Atmos Loss (dB)	3.3	3.3	3.3	3.3
Rain Loss (dB)	0.0	13.0	0.0	26.0
TOT PROPAGATION LOSS (dB)	189.5	202.5	192.9	218.9
RCVR: Ant Peak Gain (dBi)	54.2	54.2	23.5	23.5
Blockage/Off-Pk Loss (dB)	0.5	0.5	2.0	2.0
NET ANT GAIN (dB)	53.7	53.7	21.5	21.5
NOM RCV'D POWER (dBW)	-120.7	-120.7	-119.9	-119.9
Net Ant Noise Temp (K)	30.0	30.0	290.0	290.0
Diplxr/FLT/Lim Losses (dB)	4.0	4.0	4.0	4.0
LNA Noise Fig (dB)	3.0	3.0	3.0	3.0
SYST NOISE TEMP,Ts (K)	1193.4	1193.4	1453.4	1453.4
G/Ts (dBi/K)	22.9	22.9	-10.1	-10.1
Boltzmann's (dBW/HzK)	-228.6	-228.6	-228.6	-228.6
RCV'D C/No (dB)	77.1	77.1	77.1	77.1
Required Eb/No (dB)	5.7	5.7	5.7	5.7
RCVR Noise BW (dBHz)	69.4	69.4	69.4	69.4
Modem Impl Loss (dB)	2.0	2.0	2.0	2.0
REQUIRED C/No (dBHz)	77.1	77.1	77.1	77.1
LINK MARGIN (dB)	0.0	0.0	0.0	0.0
FLUX DENS (dBW/sq-m, 4KHz)	-155.1	-155.1	-118.6	-118.6

TABLE A-7
SV-SV INTERSATELLITE LINKS

	ADJACENT-PLANE LINKS NOM	ADJACENT-PLANE LINKS Looking into sun	IN-PLANE LINKS NOM	IN-PLANE LINKS Looking into sun
MAX SLANT RANGE (Km)	3885.5	3885.5	4023.8	4023.8
Center Frequency (GHz)	23.05	23.05	23.05	23.05
XMTR: Output Power(Watts)	**5.1**	**5.1**	**4.0**	**4.0**
XMTR: HPA Output Power(dBW)	7.1	7.1	6.0	6.0
Peak Ant Gain (dBi)	36.0	36.0	36.0	36.0
Off-Peak Losses (dB)	1.5	1.5	0.8	0.8
XMIT Circuit Losses (dB)	2.0	2.0	2.0	2.0
EIRP (dBWi)	**39.6**	**39.6**	**39.2**	**39.2**
Path Loss (dB)	191.6	191.6	191.9	191.9
Polarization Loss (dB)	0.5	0.5	0.5	0.5
TOT PROPAGATION LOSS (dB)	192.1	192.1	192.4	192.4
	0.0	0.0	0.0	0.0
RCVR: Ant Peak Gain (dBi)	36.0	36.0	36.0	36.0
Off-Peak Loss (dB)	1.5	1.5	0.8	0.8
NET ANT GAIN (dB)	34.5	34.5	35.2	35.2
NOM RCV'D POWER (dBW)	-118.0	-118.0	-118.0	-118.0
Ant Earth Noise (K)	30.0	30.0	30.0	30.0
Ant Sun Noise (K)	20.0	345.2	20.0	345.2
Diplxr/FLT/Lim Losses (dB)	2.5	2.5	2.5	2.5
LNA Noise Fig (dB)	3.0	3.0	3.0	3.0
SYST NOISE TEMP,Ts (K)	789.0	1114.1	789.0	1114.1
G/Ts (dBi/K)	**5.5**	**4.0**	**6.2**	**4.7**
Boltzmann's, k (dBW/HzK)	-228.6	-228.6	-228.6	-228.6
RCV'D C/No (dBHz)	**81.6**	**80.1**	**81.6**	**80.1**
Required Eb/No (dB)	5.7	5.7	5.7	5.7
RCVR Noise BW (dBHz)	72.4	72.4	72.4	72.4
Modem Impl Loss (dB)	2.0	2.0	2.0	2.0
REQUIRED C/No (dBHz)	**80.1**	**80.1**	**80.1**	**80.1**
LINK MARGIN (dB)	**1.5**	**0.0**	**1.5**	**0.0**
FLUX DENS (dBW/sq-m, 4KHz)	-138.5	-138.5	-138.9	-138.9

CCIR FACT SHEET

Study Group: U.S. JIWP
Doc. No. U.S. JIWP-6A

Date: February 5, 1991
Ref: Report of IWP 8/15 to the JIWP

DOCUMENT TITLE

SHARING BETWEEN LEO AND GSO SYSTEMS IN THE RADIO DETERMINATION SATELLITE, RADIO ASTRONOMY, RADIO NAVIGATION SATELLITE, AND AERONAUTICAL PUBLIC CORRESPONDENCE SERVICES IN THE VICINITY OF 1.6 GHz

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PURPOSE/OBJECTIVE:

The report of IWP 8/15 to the JIWP indicated a need for further study on sharing a Personal Communication Low Earth Orbit Mobile Satellite System (PCLEO) with other services in the vicinity of 1.6 GHz.

ABSTRACT:

This report describes the basis upon which a PCLEO system can share this frequency band with other services. Specifically the Radio Determination Satellite (RDSS), Aeronautical Public Correspondence (APC), Radio Astronomy (RAS), and Radio Navigation Satellite Services (RNSS) are evaluated. An example of active sharing is given for a representative RDSS system serving the contiguous United States (CONUS). Sharing between the PCLEO and RAS, APC, and RNSS will occur on the basis of dynamic time and geograpical channel assignment techniques. The PCLEO system operates in a bi-directional single band mode.

This analysis establishes that the PCLEO system may share this band with each of these systems without harmful interference to their operations.

other cocoverage RDSS systems as well as from the "target" RDSS system itself. As can be seen from Table 3 and the link budget in Table A-3, PCLEO can operate compatibly with RDSS. However, the impact of interference on RDSS acquisition performance requires further study. Further study is also needed to optimize the example RDSS link budget in terms of RDSS system capacity and the several types of external interference.

3.1.3 PCLEO Subscriber Terminals Sharing with the RDSS Satellites

The PCLEO subscriber terminals are also a potential source of interference to the RDSS system. The C/Io of RDSS satellites caused by PCLEO subscriber terminal uplinks are calculated in Table A-2 of Appendix A. Table 4 is a summary of the calculated results of Appendix A. Table 4 and Table A-3 of Annex A show that a PCLEO System will operate compatibly with RDSS.

3.1.4 RDSS Subscriber Terminal Sharing with the PCLEO Satellites and Subscriber Terminals

The RDSS subscriber terminals will transmit into the receive band of the PCLEO satellites and subscriber terminals. The probability of interference is low due to the short burst length and geographical dispersion of the RDSS subscriber terminals. Moreover, the PCLEO satellite and subscriber terminals compensate for potential interference from the RDSS terminal in several ways:

1. Pulse blankers: The RDSS burst has a duration of 20 to 80 milliseconds. This will include, at most, two PCLEO bursts associated with a single voice channel. The PCLEO

subscriber terminal will blank out the adversely affected PCLEO bursts if the RDSS pulse is strong enough to exceed a threshold signal level. This prevents RDSS pulses from causing damage to the PCLEO receiver.

2. Error detection and correction: The PCLEO packet format contains error detection and correction coding. Missing packets are detected. The PCLEO voice vocoder will interpolate across missing packets. The vocoder uses the same technology as the U.S. digital cellular system and can interpolate across six missing voice frames. Automatic repeat request is used to request retransmission of missing data packets.

Because of the above factors, the PCLEO system will be able to accept any interference caused to it, including to its subscriber terminals that arise from transmissions of RDSS subscriber terminals operating in conformance with their published characteristics.

3.2 Sharing with RNSS

One typical RNSS system employs a satellite constellation with up to 24 satellites in subsynchronous polar orbit. Each of these satellites operates on a different frequency. The satellite center frequencies are separated by 562.5 KHz. The bandwidth occupancy of each satellite is approximately 1 MHz.

Although the PCLEO system has the capability to use the same frequency bands as those used by the RNSS system, it can selectively turn off transmissions in these bands and could share the allocation in the vicinity of 1.6 GHz by band segmentation on a dynamic time and geographical basis.

3.3 Sharing with Radio Astronomy

The Radio Astronomy Service (RAS) seeks protection in the 1610.6 to 1613.8 MHz portion of the spectrum. The radio astronomy sites are fixed. Sharing can be accomplished by having the PCLEO system control the use of frequencies in this band so that the power flux density does not exceed -238 dBW/square meter/Hz at radio observatory sites during the periods of radio astronomy observations. Since the radio astronomy need is not full time, scheduling can be used to allow the use of RA frequencies by the PCLEO system when they are not being used by the Radio Astronomy Service.

3.4 Sharing with Aeronautical Public Correspondence

There is also a small Aeronautical Public Correspondence band in this part of the spectrum which is not widely used. The PCLEO system can share this band by not using the indicated frequencies in the specific cells that would interfere with the operation of the service.

4. CONCLUSIONS

This analysis establishes that a PCLEO system having dynamic control characteristics can share allocations with several other services (including RDSS, APC, RAS and RNSS) without causing unacceptable interference to their operations.

In sharing with GSO RDSS systems, the PCLEO system will not cause unacceptable interference to the operation of the RDSS systems. It can accomplish this by controlling the number of its active carriers and cells as well as the power levels to be similar to those employed herein or as agreed to during coordination. As a result, no real-time cooperation between the PCLEO and RDSS systems and services is required. The PCLEO system is able to accept any interference caused to it by an RDSS system operating normally.

The PCLEO system will share with RNSS, Radio Astronomy and Aeronautical Public Correspondence by band segmentation, i.e., PCLEO will not use frequencies in the vicinity of 1.6 GHz that would interfere with their operations in the geographic areas of interest.

APPENDIX A

PCLEO/RDSS System Interference

This appendix establishes baseline information regarding interference levels into an RDSS uplink carrier. This baseline information relates to two types of RDSS satellites that are being considered for use in North America, i.e., employing satellite antennas that cover the region with either single or multiple (8) beams in the 1.6 GHz band. PCLEO interference levels are also calculated.

Table A-1 lists the assumptions and (for both types of systems) shows the calculations for RDSS intra- and inter-system interference Table A-2 shows that arising from a PCLEO system. Table A-3 presents detailed RDSS link budgets showing the effects of intra-system, other RDSS, and PCLEO interference. Table A-4 lists the PCLEO terminal and satellite EIRPs associated with each cell type.

These calculations assume that the PCLEO system is providing 4,400 voice channels within North America. Weighted values are used for the PCLEO r.f. carrier EIRP in these calculations which assume that one-half of the carriers are operating at maximum power due to heavy vegetative shadowing and the other half are operating at their nominal values. These conservative assumptions might be relaxed in the coordination process as more detailed information on traffic distribution statistics in the PCLEO system becomes available.

TABLE A-1

INTRA- & INTERSYSTEM INTERFERENCE FROM OTHER COCOVERAGE RDSS SYSTEMS

Assumptions:

- All RDSS user uplink powers equal
- All RDSS systems are copolarized
- Desired RDSS user is at EOC
- Carrier bandwidth= 16 MHz = 72.04 dBHz
- Gold code advantage= 0.67 = 1.74 dB

	MultiBeam	SingleBeam	MultiBeam into SingleBeam	
Intra-Beam Case				
Other users per beam	14	14		
Ave.relative gain interferor	2.8	0.5		dB
C/I	-14.26	-11.96		dB
C/Io (w. Gold code)	59.52	61.82		dBHz
Intra-System, Inter-Beam Case				
Users per beam	15	NA		
No. of adjacent beams	4	NA		
Ave.relative gain interferor	-10	NA		dB
C/I	-7.78			dB
C/Io (w. Gold code)	66.00			dBHz
Tot intra-sys C/Io(w Gold code)	58.6	61.82		dBHz
Single Inter-System Case				
In beam, other system users	15	15	120	
Ave.relative gain interferor	2	0.5	0.5	dB
No. of other systm, adj beams	4	NA		
Ave.relative gain interferor	-15			dB
Tot inter-system C/I(one system)	-14.09	-12.26	-21.29	dB
C/Io (w. Gold code)	59.69	61.52	52.49	dBHz
Multiple Inter-System Case				
Number other interfer RDSS sys	3	3	3	
Tot inter-system C/I(one system)	-18.87	-17.03	-26.06	
C/Io (w. Gold code)	54.91	56.75	47.72	

TABLE A-2

PCLEO INTERFERENCE INTO RDSS

PCLEO Parameters: Voice channels for North America = 4400
Time slot factor = 1/14 = 0.07
Voice activity/DSI factor = 0.5
Average PCLEO EIRP: uplink = 7.89 dBW ;downlink = 26.45 dBW

RDSS System Parameters: Bandwidth = 72.0 dBHz;EIRP= 18.3 dBW(up & down)

Interferer ---> PCLEO Uplink Carriers

	RDSS MultiBeam	RDSS SingleBeam
No. PCLEO channels in RDSS beam	1100	4400
Time slot factor	0.07	0.07
Voice activity/DSI factor	0.50	0.50
Active xmitters/time slot	39	157
EIRP per carrier (dBW)	7.89	7.89
CUM PCLEO PEAK EIRP to RDSS beam	23.83	29.85
Polarization isolation (dB)	4	4
FBW (29 carriers in 10.5 MHZ)(in dB)	-2.69	-2.69
RDSS satellite ant relative gain(dB)	2.8	0.5
RDSS EIRP (dBW)	18.3	18.3
RDSS C/I due to PCLEO	-1.64	-5.36
RDSS C/Io due to PCLEO	70.40	66.67

Interferer ---> PCLEO Downlink Carriers

	RDSS MultiBeam	RDSS SingleBeam
No. PCLEO channels in RDSS beam	4070 *	4400
Time slot factor	0.07	0.07
Voice activity/DSI factor	0.50	0.50
Active xmitters/time slot	145	157
EIRP per carrier (dBW)	26.45	26.45
Relative gain PCLEO satellite antenna	-20	-20
CUM PCLEO PEAK EIRP to RDSS beam	28.07	28.41
FBW (29 carriers in 10.5 MHZ)	-2.69	-2.69
RDSS satellite ant relative gain	2.8	0.5
RDSS EIRP (dBW)	18.3	18.3
RDSS C/I due to PCLEO	-9.88	-7.92
RDSS C/Io due to PCLEO	62.16	64.11

TABLE A-3

RDSS LINK BUDGETS --INCLUDING INTERFERENCE EFFECTS

	Units	MultiBeam RDSS		SingleBeam RDSS	
Uplink RDSS C/No (thermal)	dB	58.20	58.20	52.70	52.70
C/Io (in-beam RDSS)	dB	59.52	59.52	61.82	61.82
C/Io (adj beam RDSS)	dB	66.00	66.00	NA	NA
C/Io (other RDSS systems)	dB	54.91	54.91	56.75	56.75
C/Io due to PCLEO downlink	dB	NA	62.16	NA	64.12
C/Io due to PCLEO uplink	dB	70.40	NA	66.68	NA
RDSS Uplink C/(No+Io)	dB	52.08	51.73	50.78	50.69
Downlink RDSS C/No(thermal)	dB	76.80	76.80	71.90	71.90
Downlink RDSS C/(No+Io)	dB	76.80	76.80	71.90	71.90
Total Link C/(No+Io)	dB	52.06	51.72	50.75	50.66
Info rate	dBHz	41.94	41.94	41.94	41.94
Eb/No received	dB	10.12	9.78	8.81	8.72
FEC coding gain	dB	5.20	5.20	5.20	5.20
Implementation loss	dB	2.50	2.50	2.50	2.50
Eb/No for 10E-5 BER	dB	9.60	9.60	9.60	9.60
Link Margin	dB	3.22	2.88	1.91	1.82
Required link margin	dB	3.00	3.00	2.00	2.00
Excess link margin	dB	0.22	-0.12	-0.09	-0.18

Note: Small negative values of excess margin can be resolved in the coordination process

CCIR FACT SHEET

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DOC. NO. U.S. JIWP-26

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TO THE JIWP

DOCUMENT TITLE

SHARING BETWEEN MAIN BEAM DOWNLINK LEO AND UPLINK GSO SATELLITES IN THE 1-3 GHz ALLOCATIONS

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PURPOSE/OBJECTIVE:

The report of IWP 8/15 to the JIWP indicated a need for further study on sharing between a Personal Communication Low Earth Orbit Mobile Satellite System (PCLEO) with Geostationary Orbit (GSO) Mobile Satellite Service (MSS) systems in the vicinity of 1-3 GHz.

ABSTRACT:

This report examines the potential for interference via mainbeam coupling of downlink emissions from a PCLEO satellite with a GSO satellite and indicates how interference from this coupling mechanism can be avoided. The potential interference will be avoided by shutting down PCLEO cells which could graze the Earth's limb and illuminate the GSO.

Documents
CCIR Study Groups
Period 1990-1994

JIWP-26
28 Jan 1991
Original: English

<u>Additional Sentences for 6.1.1.4.1.3</u>

"<u>An analysis has been performed of potential interferences through main beam coupling of PCLEO downlink emissions with receiving GSO satellites. This potential interference will be avoided by shutting down PCLEO cells which could graze the Earth's limb and thereby illuminate the GSO</u>."

The basis for this addition may be found in Annex I.

Sharing Between Main Beam Downlink Leo

and Uplink GSO Satellites

in the 1-3 GHz Allocations

1.0 INTRODUCTION

IWP 8/15 has prepared text for section 6.1.1.4.1.3, Sharing Involving Low Earth Orbit Systems which states:

> " The potential of such a system (LEO) to share with geostationary orbit mobile-satellite systems is now under study. The characteristics of the LEO Satellites and cellular nature of the systems provides a potential for frequency sharing that has not yet been explored."

This is of concern with respect to fulfilling the provisions of RR2613. Several other contributions have addressed the question of LEO and GEO sharing in the present RDSS and MMS allocations in the 1-3 Ghz range, and in the FSS feederlink bands. This contribution examines the potential for interference via mainbeam coupling of downlink emissions from a PCLEO satellite with a receiving geostationary satellite, and indicates how interference from this coupling mechanism can be avoided. The question of cumulative level of interference that may occur to a geostationary satellite from PCLEO downlink emissions by way of the PCLEO satellite antenna sidelobes has been dealt with in another contribution.

2.0 SYSTEM/INTERFERENCE CONFIGURATION

Figure 1 shows the coverage provided by the 37 cells of a PCLEO satellite. Each cell has approximately an equal area projection on the Earth. The circle that encompasses the cells represents a 10° horizon toward GSO. The cell pattern consists of a center cell, surrounded by three rings of cells: A, B, and C. A has six, B has 12 and C has 18 cells, respectively. Of the latter there are six "key" cells which protrude beyond the 10° horizon.

Figure 2 shows the relative geometry between a PCLEO satellite, the Earth and a satellite in the GSO. The GSO satellite is assumed to have a full earth coverage beam, i.e, an 8.7° degree half angle. For the PCLEO to have a line of sight interference path with the GSO it must be on the backside of the Earth. This condition exists when the angle between a vector to the PCLEO satellite and a vector to the GSO is

$81.3° + 1/2 \cdot 53.52° = 108°$

A detailed diagram of this interference geometry is shown in Figure 3, and illustrates how energy inside the 3 dB beamwidth of the PCLEO will "splash over" the horizon. Table 1 below shows the Perimeter (C ring) Cell Boresight Angle from NADIR. The key perimeter cells are those that extend beyond the 10° horizon. From Figure 2, the angle from nadir to the horizon is 63.24° (one half of angle "b")1

TABLE 1

Perimeter Cell Boresight Angle From Nadir

Cell Type	Boresight	3 Db Beamwidth	Angle from Nadir
Key Perimeter	60.7°	5.8°	63.6°
Regular Perimeter	59.9°	5.8°	62.8°

The only RF energy from a PCLEO which will go into outer space from behind the earth are those perimeter cells where the sum of their boresight angle and half the 3 dB beamwidth are greater than the angle from nadir to the 0° horizon, i.e. 63.24. For the Key cells this value is + 0.36; for the Regular Cells this is -0.44. In other words the 6 Key cells of 37 of each PCLEO are the only ones which will radiate into space.

3.0 INTERFERENCE ANALYSIS

To determine the potential for interference it is necessary to determine: 1) the specific locations within the PCLEO orbit where the above interference geometry exists; 2) the frequency with which these occur, and 3) whether they occur for more than one PCLEO at a time.

Figures 4a and 4b show the beginning and end of the period when the PCLEO horizon target can illuminate the GSO. The question becomes when, and which of the six Key cells of a PCLEO satellite can cause interference. Figure 5 shows the six perimeter cells in a PCLEO at the equator. The cells are active (turned on) only within specific latitude bands of the satellite nadir point. When these are correlated with the geometric constraint that the 0° horizon circle be target to the GSO field of view, it should be apparent that only the cells at 3 o'clock and 9 o'clock have the potential to cause interference, and that only one of these will be in position to interfere at a time.

A further analysis of Figure 5 shows that the coverages of the neighboring satellites overlap the coverages of the perimeter cells. e.g. the 3 o'clock cell of P1 SAT 1 is covered by the 7 o'clock cell of P2 SAT 11, and the 11 o'clock cell of P2 SAT 1.

Internal system coverage analysis indicates that one of these three can be turned off and still provide service.

Thus, through the operational choice of shutting off the 3 o'clock cell, (and by symmetry the 9 o'clock cell) it is assured that no RF energy will be radiated toward the GSO.

4.0 CONCLUSION

An analysis has been performed of potential interferences through main beam coupling of PCLEO downlink emissions with receiving GSO satellites. This potential interference will be avoided by shutting down PCLEO cells which could graze the Earth's limb and thereby illuminate the GSO.

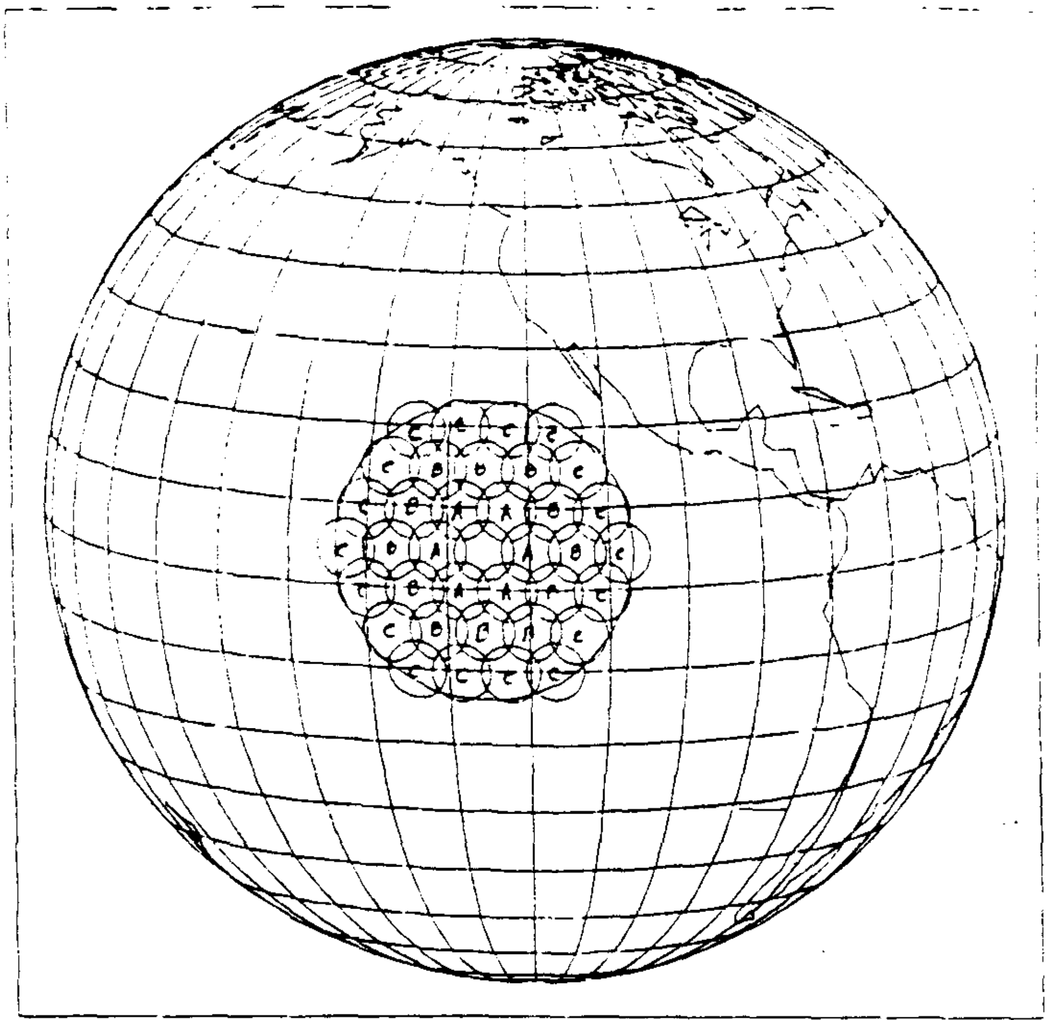

Figure 1. PCLEO Cell Pattern Projected On The Earth's Surface

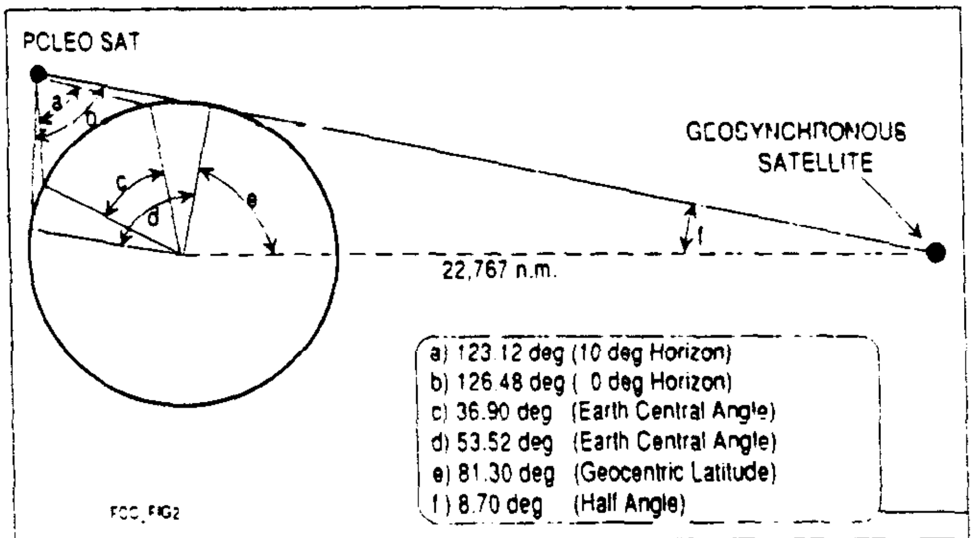

Figure 2. Interference Geometry

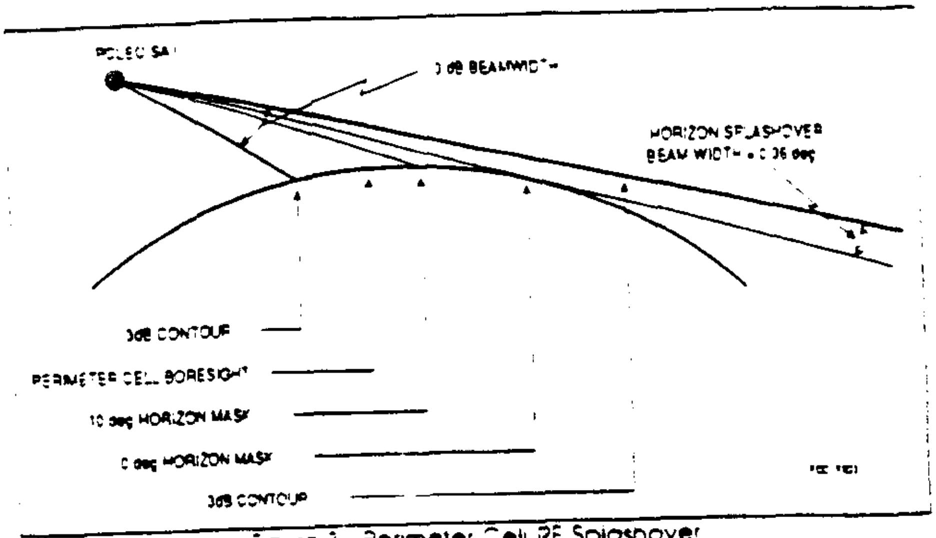

Figure 3. Perimeter Cell RF Splashover

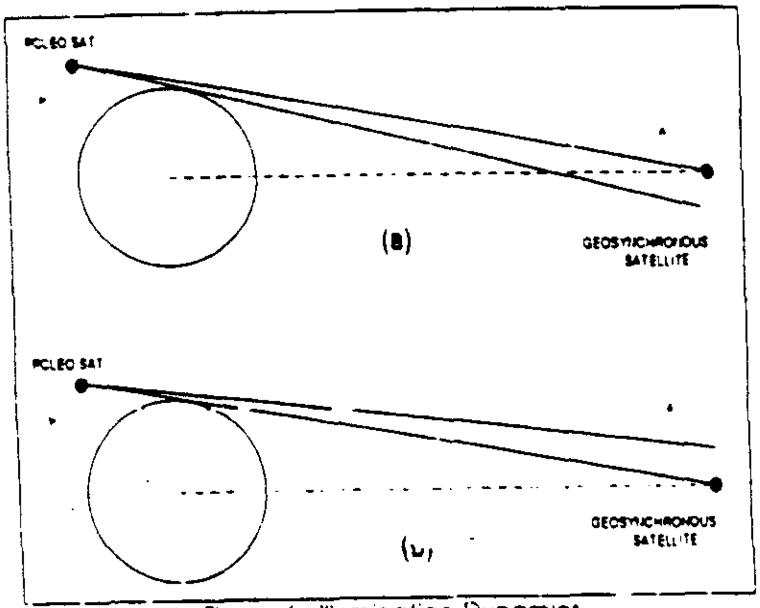

Figure 4. Illumination Dynamics

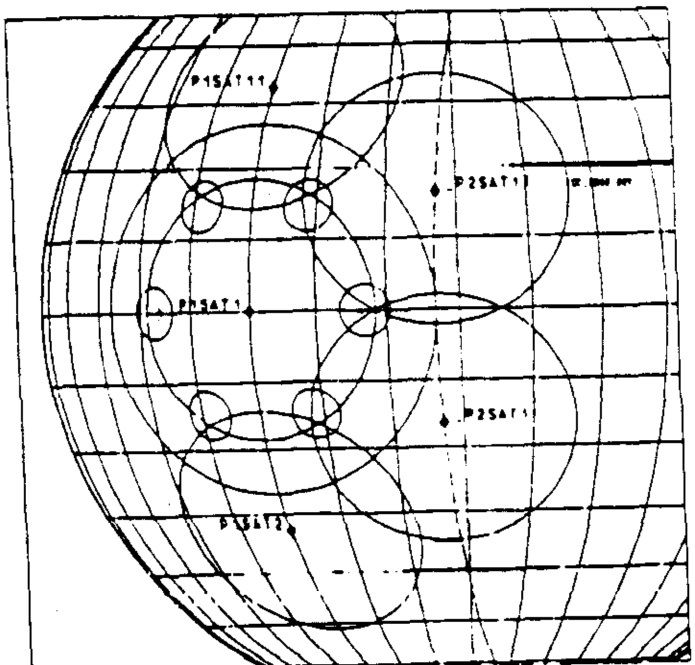

Figure 5
Interference Geometry At The Equator

CCIR FACT SHEET

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DOCUMENT TITLE

LEO FEEDERLINK AVOIDANCE OF THE GSO IN THE FIXED SATELLITE SERVICE (FSS)

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PURPOSE/OBJECTIVE:

The report of IWP 4/1 to the JIWP indicated a need for further study on sharing a Low Earth Orbit Mobile Satellite System (LEO) with geostationary orbit (GSO) systems in the Fixed Satellite Service (FSS).

ABSTRACT:

This report provides the basis for LEO systems to share the FSS allocations in the 20/30 GHz part of the spectrum with GSO systems. Several avoidance techniques are listed for the LEO systems to use which can achieve compatibility with GSO systems and meet the objective of RR 2613. These techniques include the LEO operating at non-interfering frequencies, operating at power levels which result in interference below the acceptable level determined by CCIR recommendations, and not transmitting to LEO satellites whenever there is insufficient angular separation between the LEO satellite and the GSO satellite.

Documents
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<u>Proposed Modification to Section 6.1.1.4.1.3</u>

<u>of the JIWP Report</u>

The second sentence in this paragraph should be replaced with the following:

<u>Certain techniques to permit compatible operations between gateway feederlinks of LEO systems and GSO systems using allocations in the 20/30 GHz part of the spectrum have been identified. LEO systems should utilize appropriate avoidance technique(s) when transmitting and receiving signals to and from its associated LEO satellite(s) to achieve compatibility with GSO systems and to meet the objective of RR 2613.</u>

The basis for this proposed modification is in Annex I.

Annex I

LEO Feederlink Avoidance of the GSO

in the Fixed Satellite Service (FSS)

1.0 Introduction

The Report of IWP 4/1 to JIWP (WARC-92), contains proposed text for section 6.1.1.4.1.3, Sharing Between LEO Feeder Links and GSO Systems in the FSS. This text states:

> "Article 29 RR 2613 specifies the inter alia relationship between geostationary and non-geostationary satellite systems in the FSS Further study is needed to evaluate the potential interference and optimum sharing arrangements which would provide compatible operations between the LEO and GSO systems in the FSS bands."

The purpose of this contribution is to provide the information to indicate how such compatible sharing is established between LEO and GSO Systems.

2.0 System considerations

Although the principal use of the FSS has been for GSO communication satellites in the 4/5 GHz and 11-12/14 GHz part of the spectrum, the technology and associated systems are now being considered for 20/30 GHz. Table A.2.1.2, from IWP 4/1's contribution to the JIWP contains above 10 GHz FSS System parameters. These are indicated in the table below.

Organization	Tran BW (MHz)	Coverage	EIRP (dB)	G/T	Rec. Ant. (dB)	X Power dBW/Mz	PFD (W/M²)
Deutsche Bund.	90	Germany	48	7.7	39.7	20	-92-
Italy	110	Italy	47/55.5	68/18.8	38/50	20	[illegible]

In addition, proposals have been made for LEO systems, which would use the 20/30 GHz bands, as feederlinks or gateways. The gateway links are intended to interconnect the LEO system to the PCN. They would use 100 MHz of bandwidth in each direction. There would be six center frequencies for the uplink and downlink. The channels will be spaced at 15 MHz intervals. The modulation rate in each direction is 12.5 Mbps. The link characteristics of this system may be found in the table in Appendix I. These links are between earth stations and satellites which are in seven equal spaced polar orbits which are at an altitude of approximately 765 Km.

It is LEO and GSO systems with characteristics such as those described above which will be the subject of the subsequent sharing analysis.

3.0 Options for FSS GSO/LEO Sharing at 20/30 GHz

Article 29, Section II, Control of Interference to Geostationary-Satellite Systems, in RR 2613 states:

"Non-geostationary space stations shall cease or reduce to a negligible level their emissions and their associated earth stations shall not transmit to them, whenever there is insufficient angular separation between non-geostationary satellites and geostationary satellites, and whenever there is unacceptable interference to geostationary-satellite space stations in the fixed satellite service operating in accordance with these Regulations." A footnote indicates that the level of interference should be determined in accordance with CCIR Recommendations.

Several methods exist which can be employed by the LEO system to avoid causing harmful interference to co-frequency GSO communications satellites. These methods fall in the following categories:

3.1 Operation at non-interfering frequencies. The LEO satellites will have the capability of operating at six 15 MHz channels within the 100 MHz band. The channels may be used in such a way that the frequency is different for any pass where the LEO may point at the GSO satellite.

3.2. Operation at levels which result in interference below the acceptable level determined by CCIR Recommendations. The range to the GSO is 18 to 54 times the range to the LEO. This is 25 to 34 dB additional free space path loss attenuation of the LEO signal. Therefore, depending on the calculation of signal level for the individual case the GSO may not be affected.

3.3. Associated LEO earth stations would not transmit to LEO satellites, whenever there is insufficient angular separation between the LEO satellite and the GSO satellite. The third category has several options:

3.3.1 The LEO earth terminal may simply turn off during the period of possible interference. Due to the relatively fixed position of the GSO satellite. The period of possible impingement by the LEO main beam is relatively small. These outage periods last for no more than a few seconds (2 to 4 depending on latitude and differential longitude).

3.3.2 The LEO may use a link to another LEO satellite in view. At the moderate latitudes which are more populated, there is a high probability (40% at 30 deg to 100% at 52 deg) that more than one satellite is in view.

3.3.3 Traffic may be routed to one or more gateways and connected in the terrestrial network. This is a normal back-up for gateway failure.

The LEO earth feederlink stations can be located such that the down-link beam will not interfere with the GSO stations.

4.0 Summary

LEO systems using FSS feederlinks in the 20/30 GHz part of the spectrum can achieve the objective of RR 2613. Sufficiently diminished mutual interference between LEO and GSO systems can be achieved by a variety of methods. The LEO can utilize operating scenarios from the above options or others to accomplish this.

APPENDIX I

GATEWAY LINKS, WITH MODERATELY HEAVY RAIN*

(MAXIMUM RANGE)

	UNITS	DOWNLINK	UPLINK
GROUND RANGE FROM NADIR	NMi	1108.0	1108.0
NADIR ANGLE	Deg	61.56	61.56
GRAZING ANGLE	Deg	10.00	10.00
SLANT RANGE	NMi	1237.0	1237.0
CENTER FREQUENCY	GHz	20.00	30.00
XMTR BURST PWR INTO ANT	Watts	20.00	217.27
(Per Carrier)	dBm	42.99	53.37
PEAK ANT GAIN	dBi	20.00	57.50
OFF-PEAK LOSSES	dB	2.00	0.00
XMTR NET ANT GAIN	dBi	18.00	57.50
XMT FEED/CKT LOSS	dB	3.50	3.50
EIRP	dBmI	57.50	107.37
PATH LOSS	dB	185.67	189.19
POLARIZATION LOSS	dB	0.50	0.50
GASEOUS LOSS	dB	3.30	3.30
RAIN LOSS*	dB	13.00	26.00
TOT PROPAGATION LOSS	dB	202.47	218.99
PEAK ANT GAIN	dBi	54.00	23.50
OFF-PEAK LOSSES	dB	0.00	2.00
RCVR NET ANT GAIN	dBi	54.00	21.50
ANT NOISE TEMP	°K	30.00	290.00
RCV FEED/CKT LOSS	dB	4.00	4.00
LNA NOISE FIGURE	dB	3.00	3.00
SYST NOISE TEMP, Ts	°K	1193.44	1453.44
G/Ts	dBi/°K	23.23	-10.12
BOLTZMANN'S, k	dBm/Hz°K	-198.60	-198.60
RCV'D C/No	dBHz	76.86	76.86
REQUIRED Eb/No	dB	6.90	6.90
CHANNEL DATA RATE	dBHz	67.96	67.96
IMPLEMENTATION LOSS	dB	2.00	2.00
REQUIRED C/No	dBHz	76.86	76.86
LINK MARGIN	dB	0.00	0.00
FLUX DENSITY per 4KHz BW	dBW/m^2	-155.7	-118.8

* CRANE RAIN MODEL, REGION "G", 0.5% OUTAGE

APPENDIX D

ADVANCE PUBLICATION INFORMATION FOR THE IRIDIUM NETWORK

Section A - General Information

The Administration of the United States of America informs the members of the ITU of its intention to authorize the operation of the IRIDIUM Satellite Network. The Subscriber-to-Space Station link of the network will operate in the RDSS band 1610-1626.5 MHz, in both the Earth-to-Space and Space-to-Earth directions. In the latter direction the network will operate in accordance with RR 342. The Feederlink and Space-to-Space relay of the network will operaye in the appropriately allocated portions of the band 18.8 to 30 GHz.The Space Station of the network does not employ simple frequency changing transponders.

Section B - General Characteristics

1. Identity of the Satellite Network

The Iridium Satellite Network is the same as the System. The Network includes of 77 identical interconnected satellites positioned in non-geostationary orbit, in seven equally spaced planes.

2. Date of Bringing into Use

Initial launches in 1995

Period of Validity of Frequency Assignments of the Space Stations

15 Years

3. Administration or Group Submitting the Advance Information

United States of America

Federal Communications Commission Washington, DC 20554	FEDCOMCOM Washington,DC

4. Orbital Information Relating to Space Stations

There are seven polar, co-rotating planes, separated by slightly more than 27 degrees. Each plane has 11 satellites. The 11 satellites in each plane are equally spaced around their planar orbit. Satellites in planes 1, 3, 5 and 7 are in phase with each other, while those in planes 2, 4 and 6 are in phase with each other and halfway out of phase with those in planes 1, 3, 5 and 7. The system (network) satellites are at a constant altitude of 765 Kilometers. The total number of operational satellites having these characteristics is 77.

Section C - Characteristics of the Satellite Network in the Earth-to-Space Direction

1. Earth-to-Space Service Area(s)

Initially, Subscriber Terminals and Gateway Earth Stations will be used in the territory of the United States; two Gateway EarthStations are anticipated. The system has the capability of providing service to the entire surface of the Earth from Pole to Pole and everywhere in between. See Figure 1. Subscriber Terminals and Gateway Earth stations will be used in accordance with individual administration authorization.

2. Class of Station and Nature of Service

TF, TC, TL, TR, TU

3. Frequency Range

1610.0-1626.5 MHz - Subscriber Terminal
27.5-30.0 GHz - Gateway Link (Feederlink)

4. Power Characteristics of the Transmitted Wave Into the Transmit Antenna

a. Subscriber Terminal

Peak Spectral Power Density = -42.5 dBW/Hz

b. Gateway Earth Station (Feederlink)

Peak Spectral Power Density = -45.4 dBW/Hz

5. **Characteristics of Space Station Receiving Antenna**

a. Subscriber Link

Peak Gain: +25.0 dBi
See Figures 2a-2g

b. Gateway Link (Feeder)

Peak Gain: +23.5 dBi
See Figure 3

6. **Noise Temperature of Space Station Receiving System**

a. Subscriber Link

553 degrees K

b. Gateway Link (Feeder)

1453 degrees K

7. **Necessary Bandwidth**

a. Subscriber Link

Total: 16.5 MHz
Per Channel: 160 KHz

b. Gateway Link (Feeder)

15 MHz

8. **Modulation Characteristics**

a. Subscriber Link

Digital voice and data, QPSK with TDMA/FDMA multiplexing

b. Gateway Link (Feeder)

Digital voice and data, QPSK with TDMA multiplexing

Section D - Characteristics of Satellite Network in the Space-to-Earth Direction

1. Space-to-Earth Service Areas

Same as the Earth-to-Space Service Area. See Figure 1.

2. Class of Stations and Nature of Service

ES, EC, EF, EU

3. Frequency Range

1610.0-1626.5 MHz	Subscriber Terminal
18.8-20.2 GHz	Gateway Link (Feederlink)

4. Power Characteristics of the Transmitted Wave Into the Space Station Transmit Antenna

a. Subscriber Link

Peak Spectral Power Density = -43.8 dBW/Hz

b. Gateway Link (Feederlink)

Peak Spectral Power Density = -55.8 dBW/Hz

5. Characteristics of the Space Station Transmitting Antenna

a. Subscriber Link

Peak Gain: +25.0 dBi
See Figures 2a-2g

b. Gateway Link (Feederlink)

Peak Gain: +20.0 dBi
See Figures 4a-4j

6. Characteristics of the Receiving Earth Stations

a. Subscriber Terminal

Noise Temperature:	553 degrees K
Peak Antenna Gain:	+3 dBi

b. Gateway Earth Station

Noise Temperature:	1193 degrees K
Peak Antenna Gain:	+54.2 dBi

7. **Necessary Bandwidth**

a. Subscriber Link

Total: 16.5 MHz
Per Channel: 350 KHz

b. Gateway Link (Feederlink)

15 MHz

8. **Modulation Characteristics**

a. Subscriber Link

Digital voice and data, QPSK with TDMA/FDMA multiplexing

b. Gateway Link (Feederlink)

Digital voice and data, QPSK with TDMA multiplexing

Section E - Characteristics to be Furnished for Space-to-Space Relays

a. The 77 IRIDIUM satellites in seven planes, with 11 identical satellites each are all interconnected to each other.

b. Frequency of Operation: 22.55-23.55 GHz

c. Modulation: QPSK, FDMA/TDMA

d. Peak EIRP: +39.6 dBW

e. Peak Spectral Power Density: -65.3 dBW/Hz

f. Crosslink antenna pattern: See Figure 5

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IRIDIUM

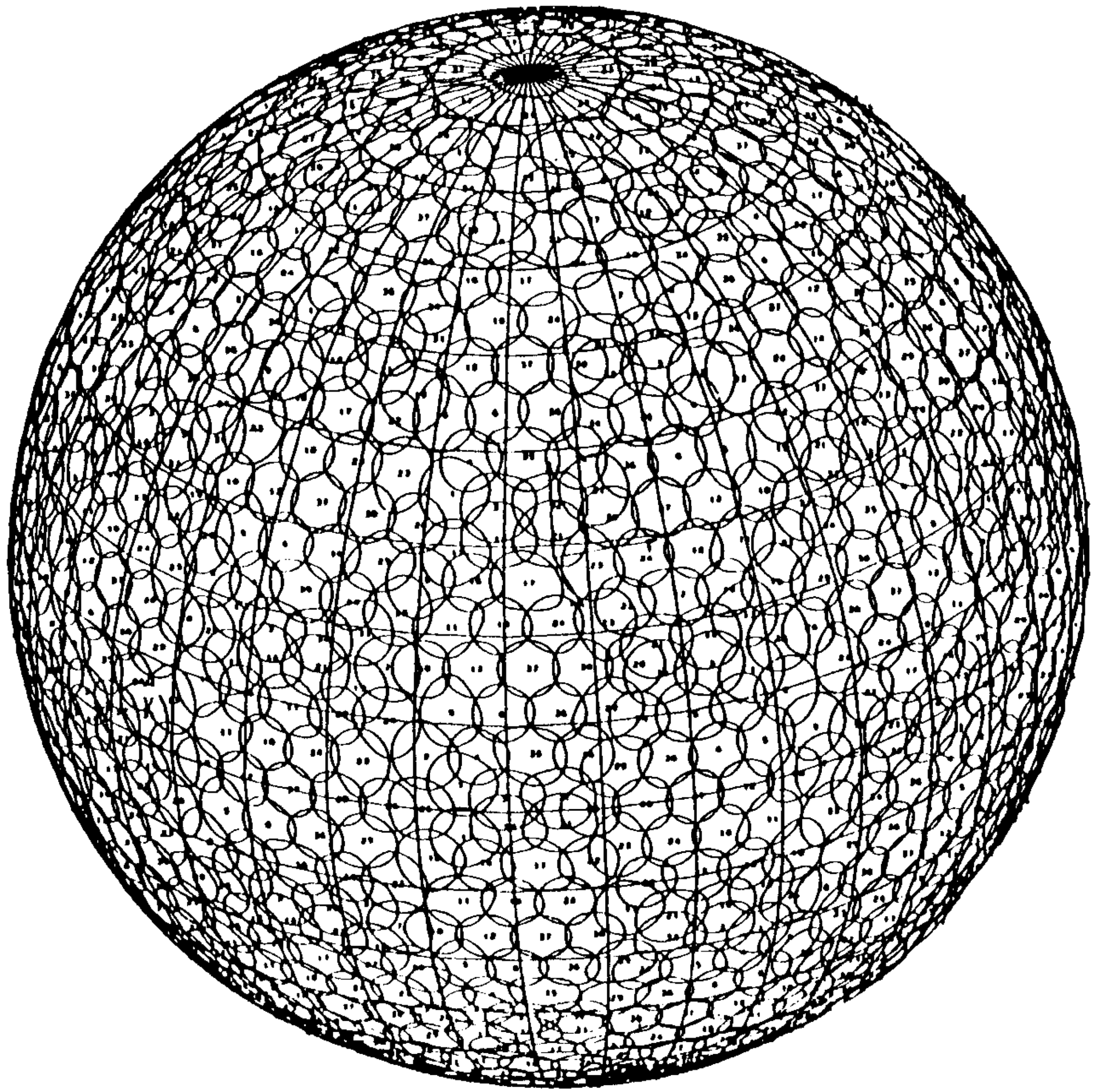

FIGURE 1 POTENTIAL IRIDIUM SERVICE AREAS

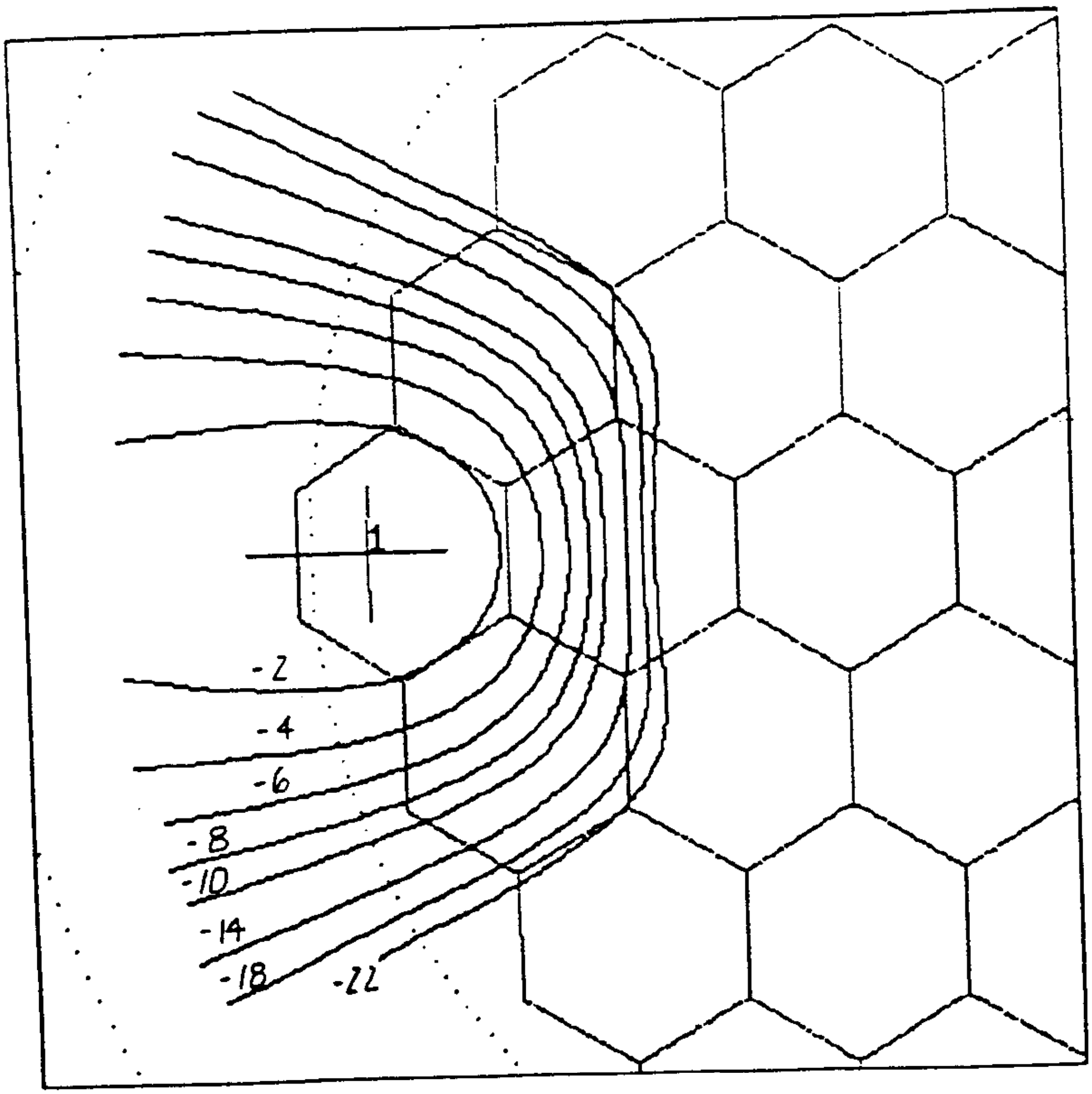

FIGURE 2a

CHARACTERISTIC OF SPACE STATION RECEIVE AND TRANSMIT ANTENNAS

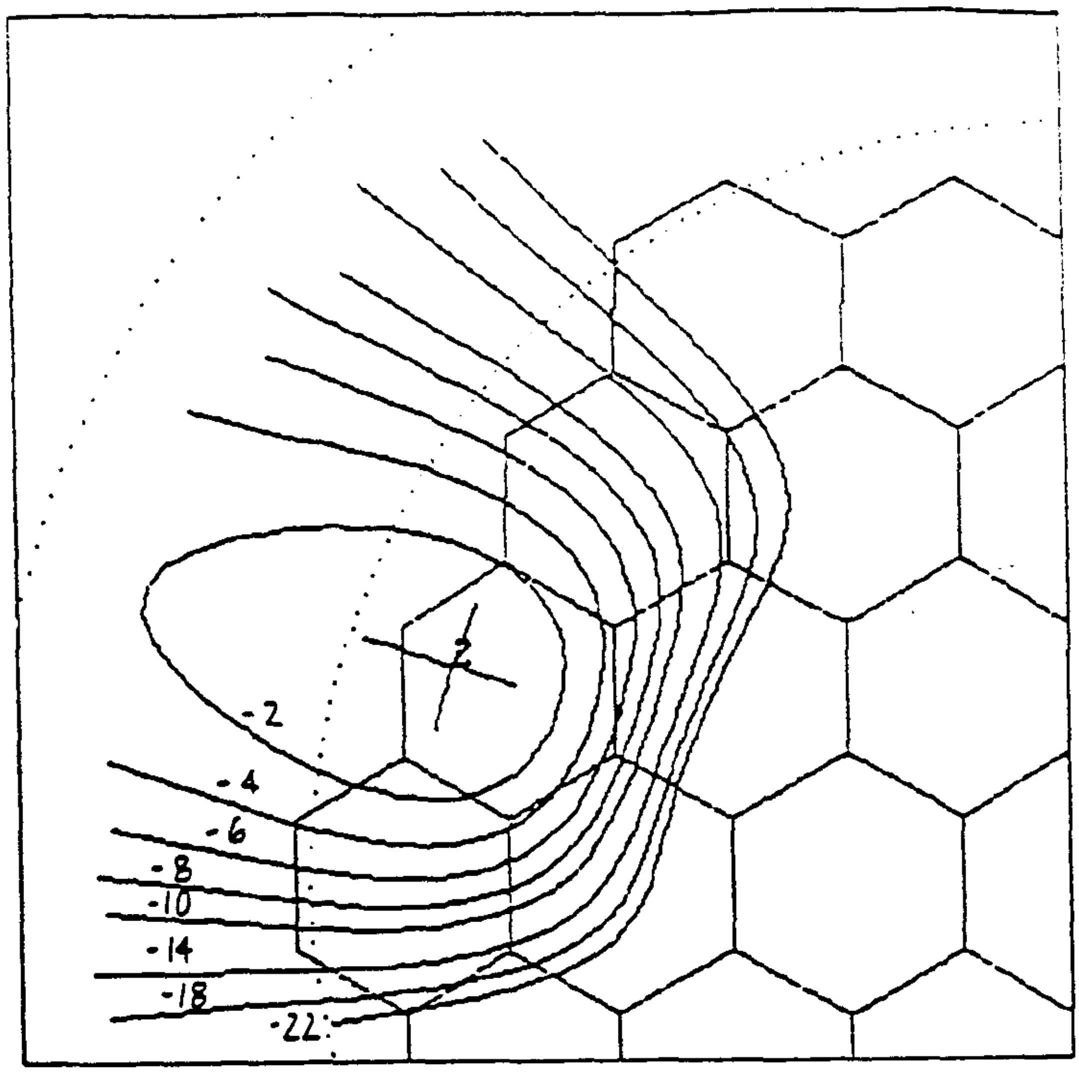

FIGURE 2b

CHARACTERISTIC OF SPACE STATION RECEIVE AND TRANSMIT ANTENNAS

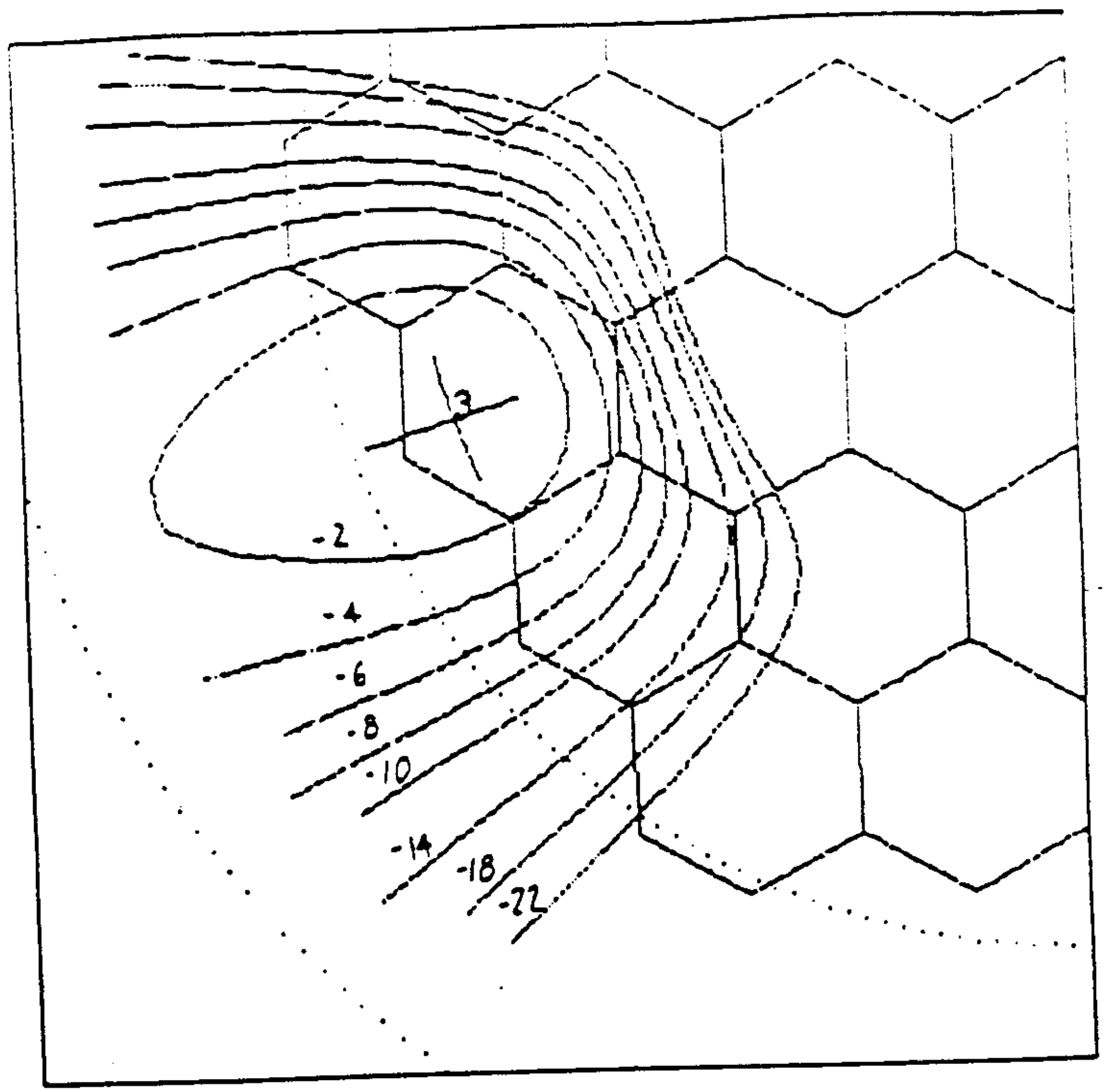

FIGURE 2c

CHARACTERISTIC OF SPACE STATION RECEIVE AND TRANSMIT ANTENNAS

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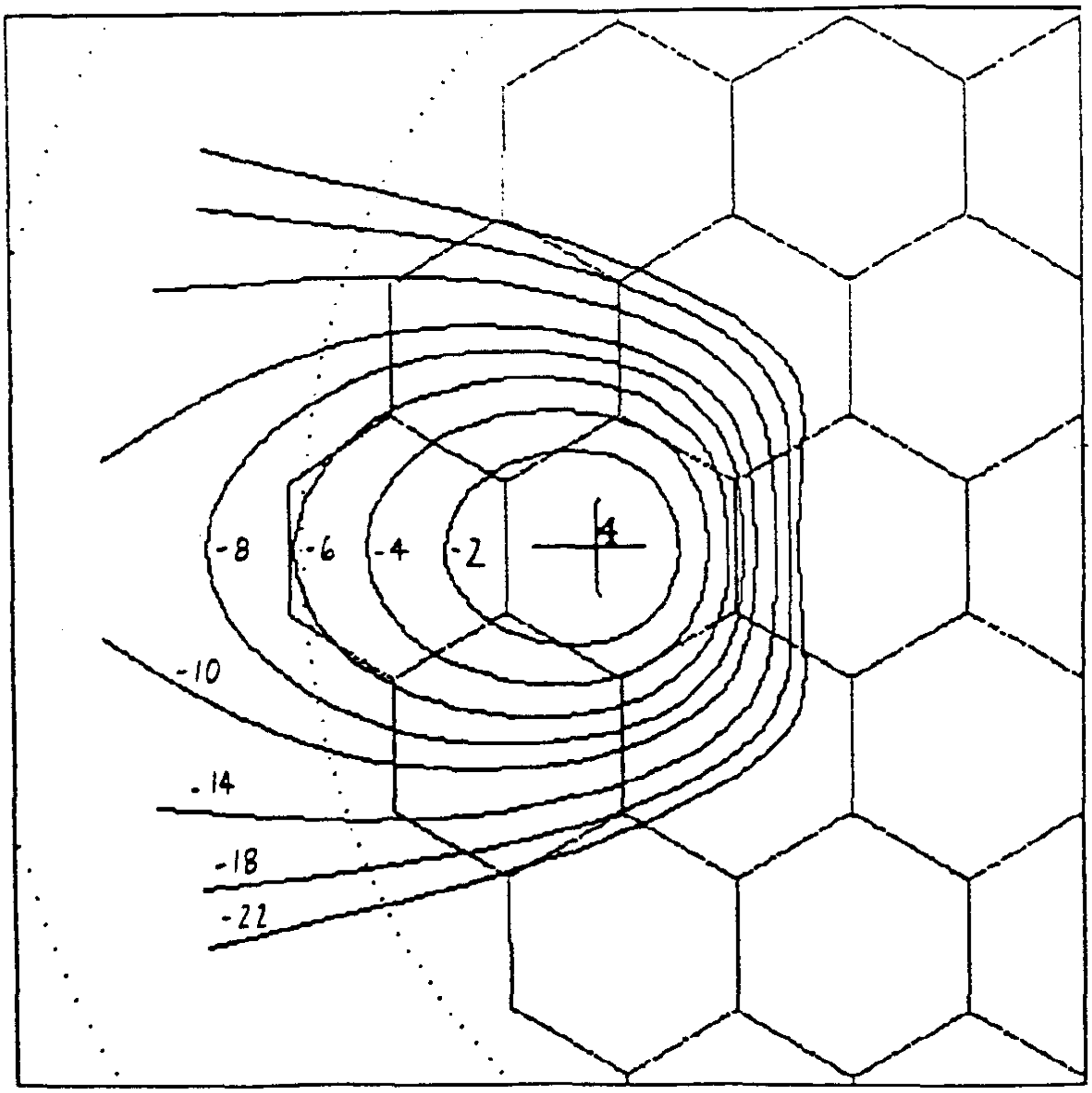

FIGURE 2d

CHARACTERISTIC OF SPACE STATION RECEIVE AND TRANSMIT ANTENNAS

MOTOROLA

IRIDIUM

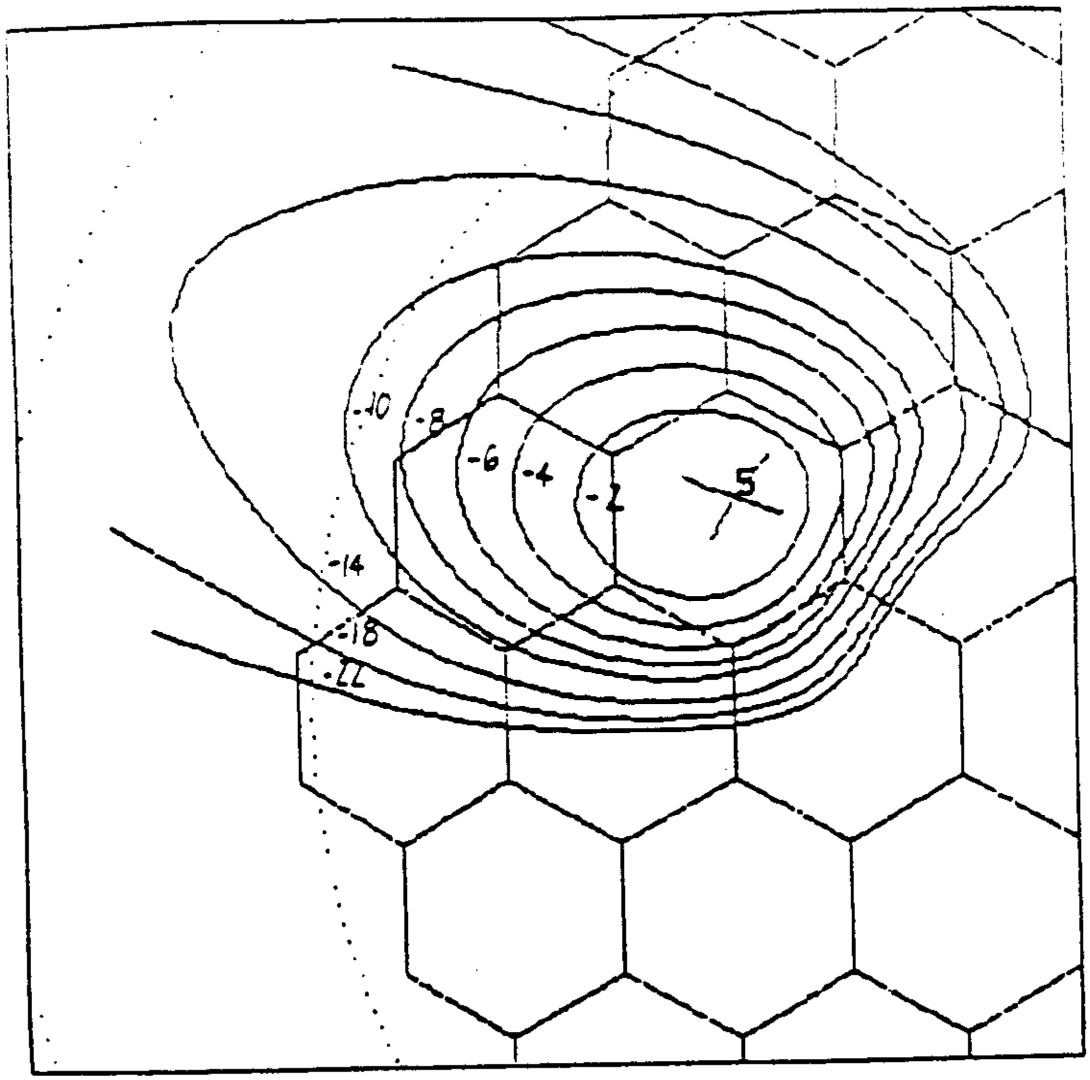

FIGURE 2e

CHARACTERISTIC OF SPACE STATION RECEIVE AND TRANSMIT ANTENNAS

MOTOROLA

IRIDIUM

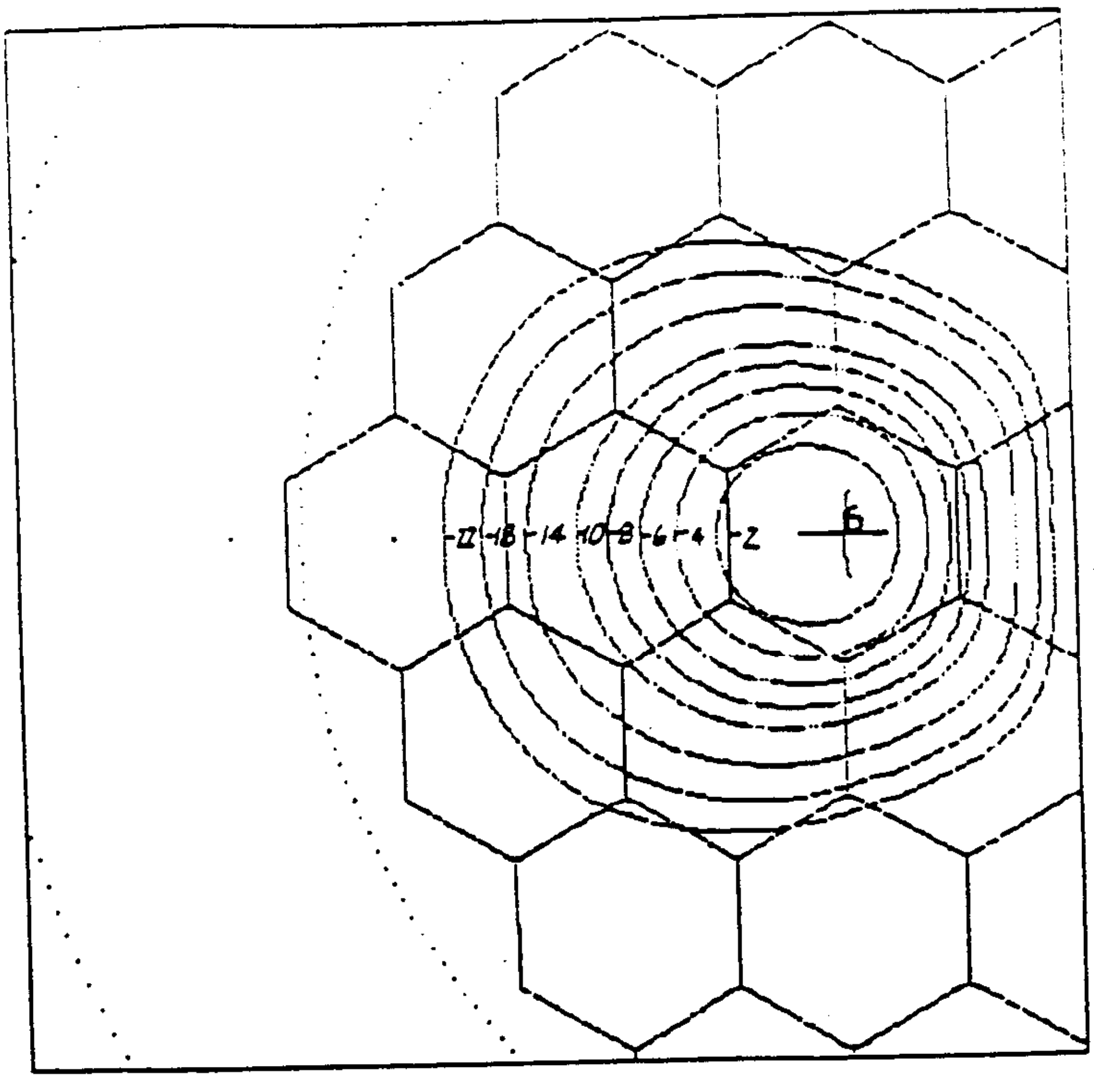

FIGURE 2f

CHARACTERISTIC OF SPACE STATION RECEIVE AND TRANSMIT ANTENNAS

MOTOROLA

IRIDIUM

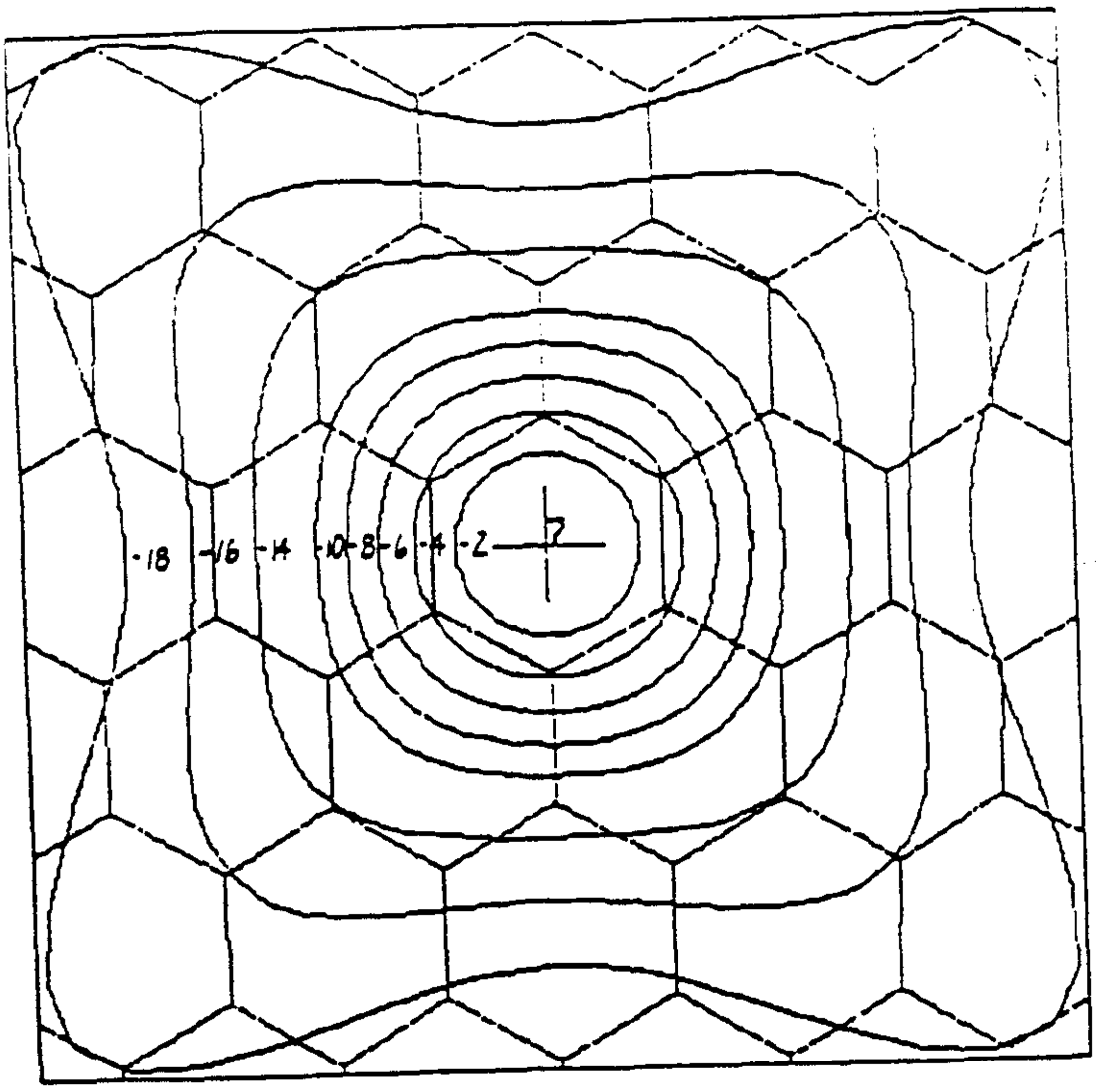

FIGURE 2g

CHARACTERISTIC OF SPACE STATION RECEIVE AND TRANSMIT ANTENNAS

MOTOROLA

IRIDIUM

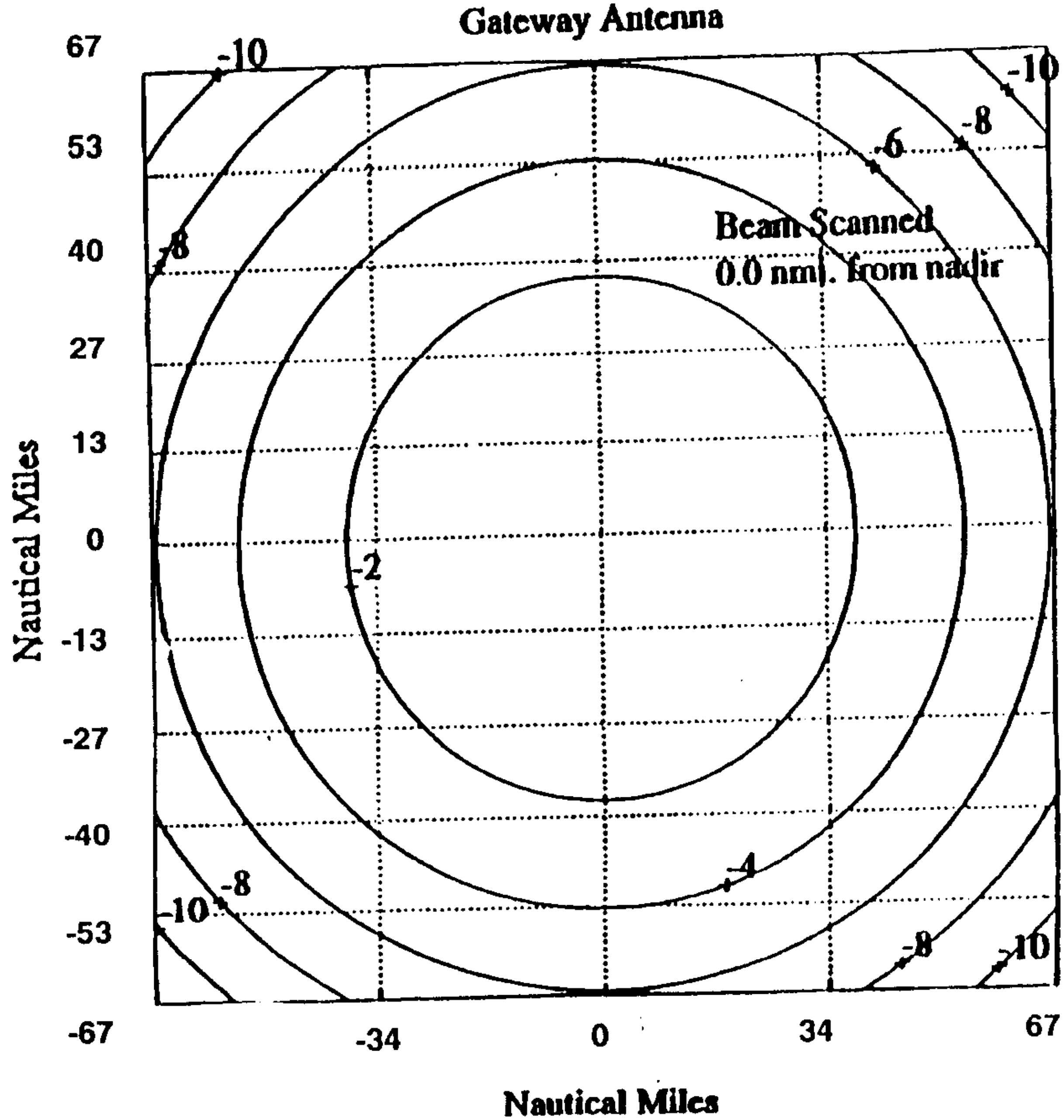

FIGURE 3 GATEWAY SPACE STATION RECEIVE PATTERN

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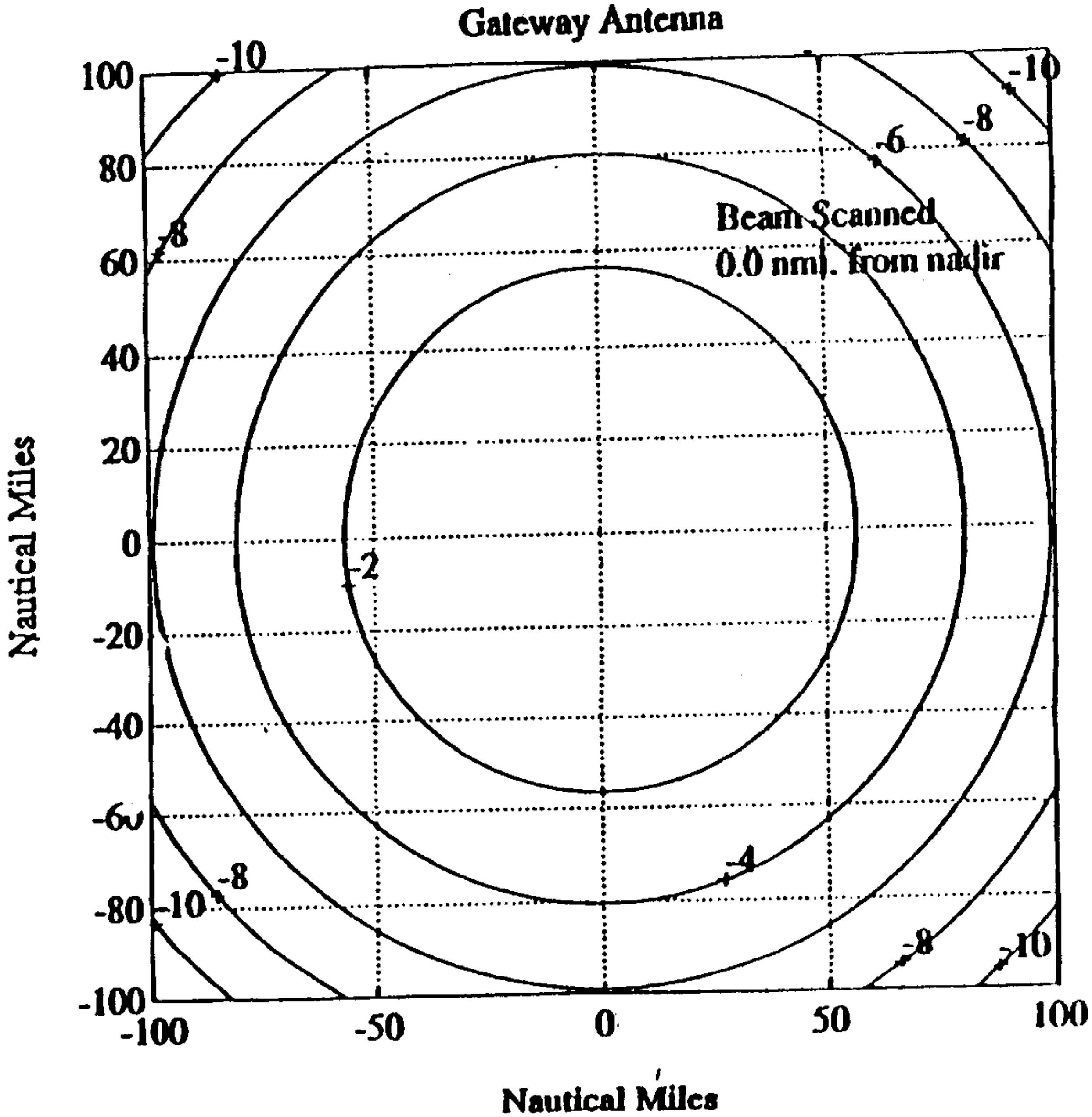

FIGURE 4a GATEWAY SPACE STATION TRANSMIT PATTERN O NMI FROM NADIR

MOTOROLA

IRIDIUM

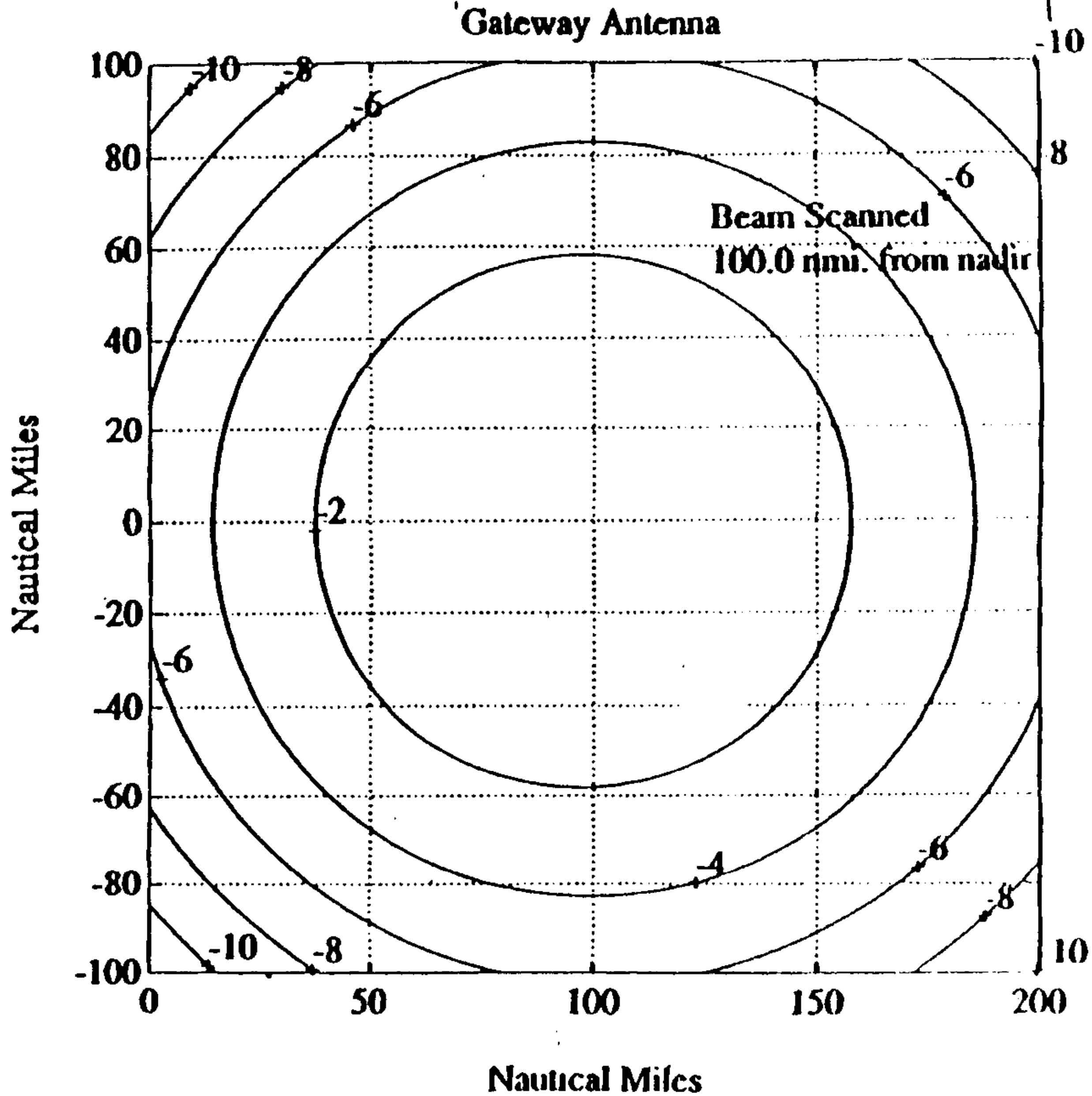

FIGURE 4b GATEWAY SPACE STATION TRANSMIT PATTERN 100 NMI FROM NADIR

MOTOROLA

IRIDIUM

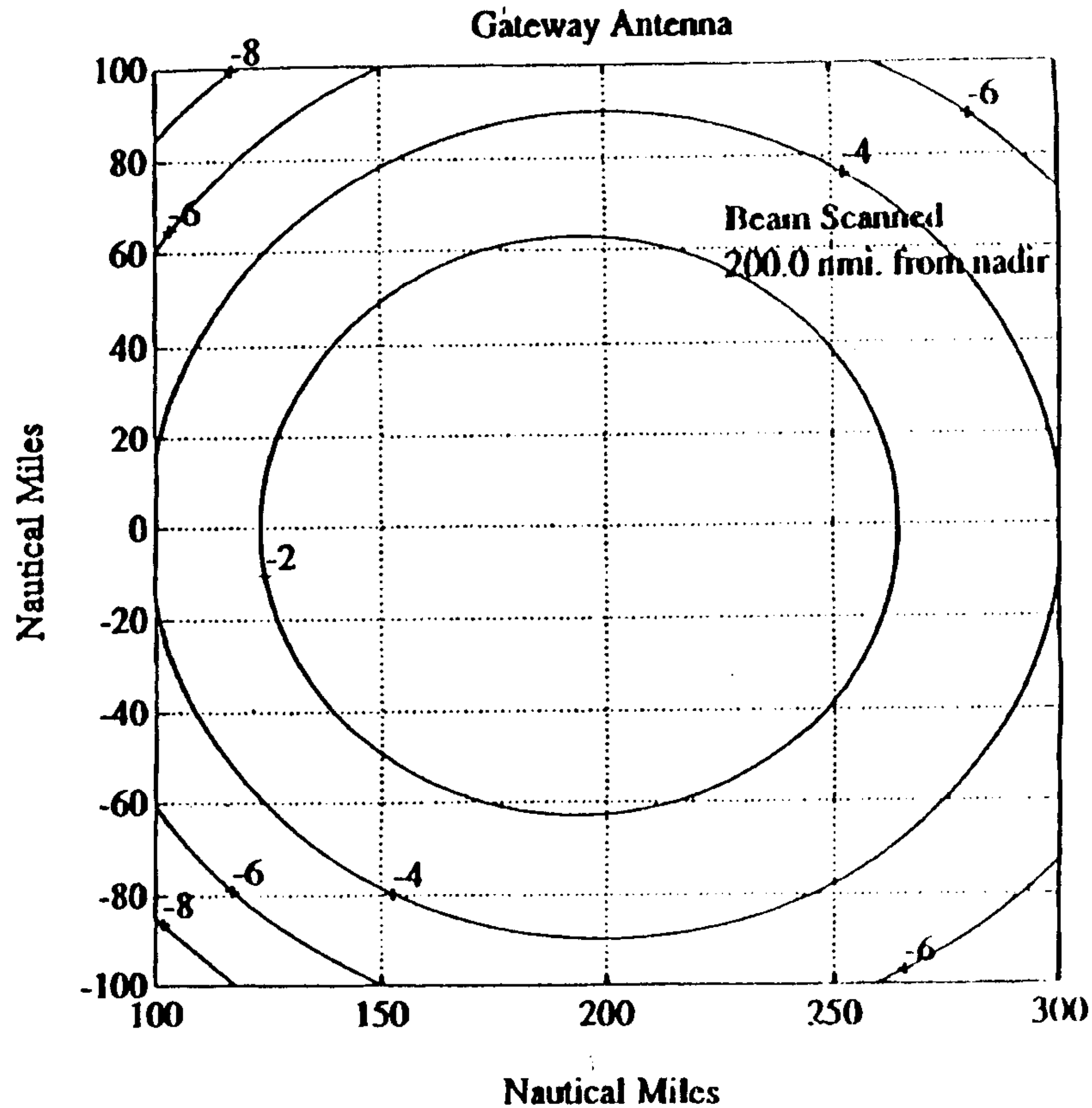

FIGURE 4c GATEWAY SPACE STATION TRANSMIT PATTERN 200 NMI FROM NADIR

MOTOROLA

IRIDIUM

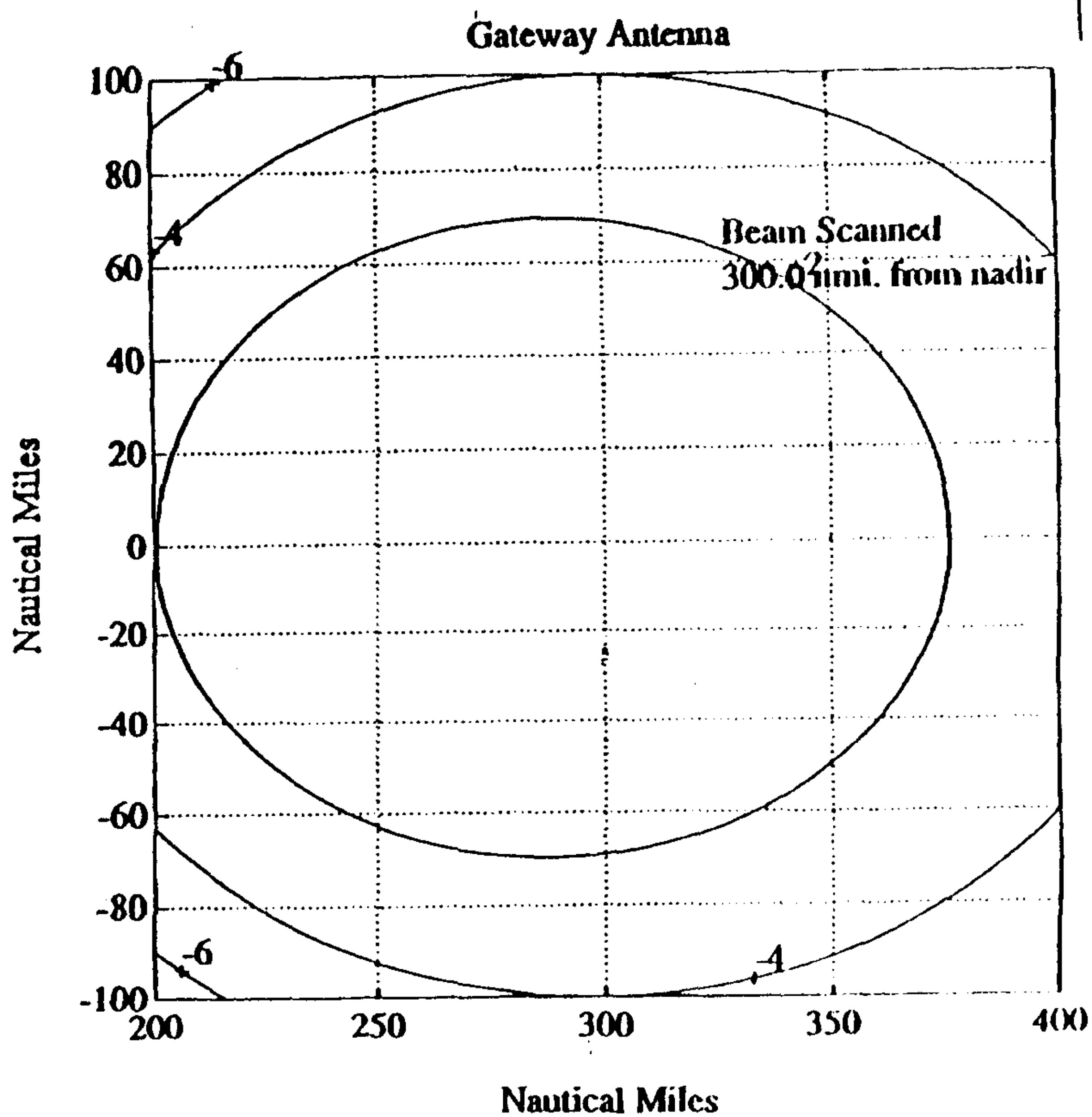

FIGURE 4d GATEWAY SPACE STATION TRANSMIT PATTERN 300 NMI FROM NADIR

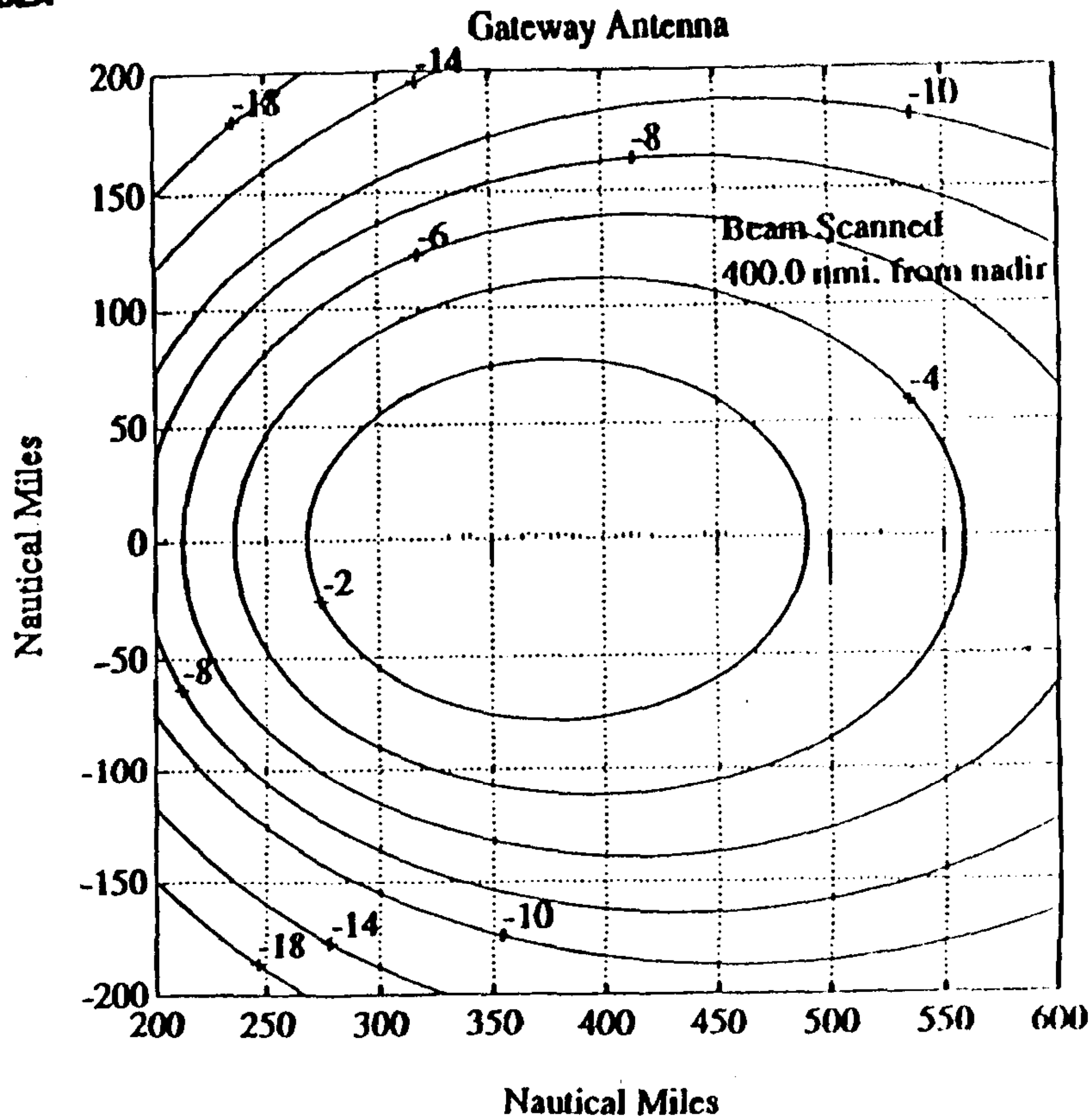

FIGURE 4e GATEWAY SPACE STATION TRANSMIT PATTERN 400 NMI FROM NADIR

MOTOROLA

IRIDIUM

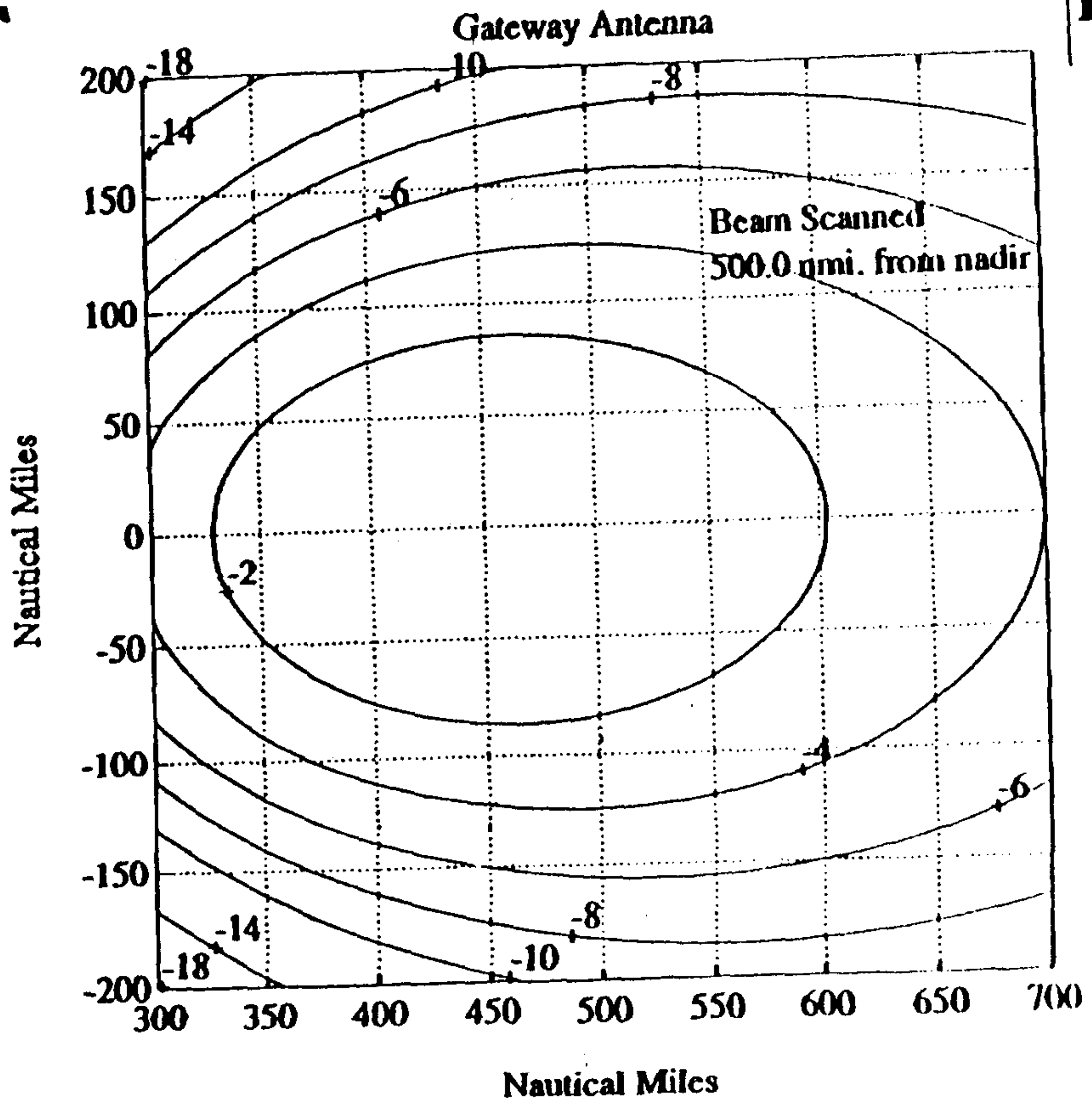

FIGURE 4f GATEWAY SPACE STATION TRANSMIT PATTERN 500 NMI FROM NADIR

MOTOROLA

IRIDIUM

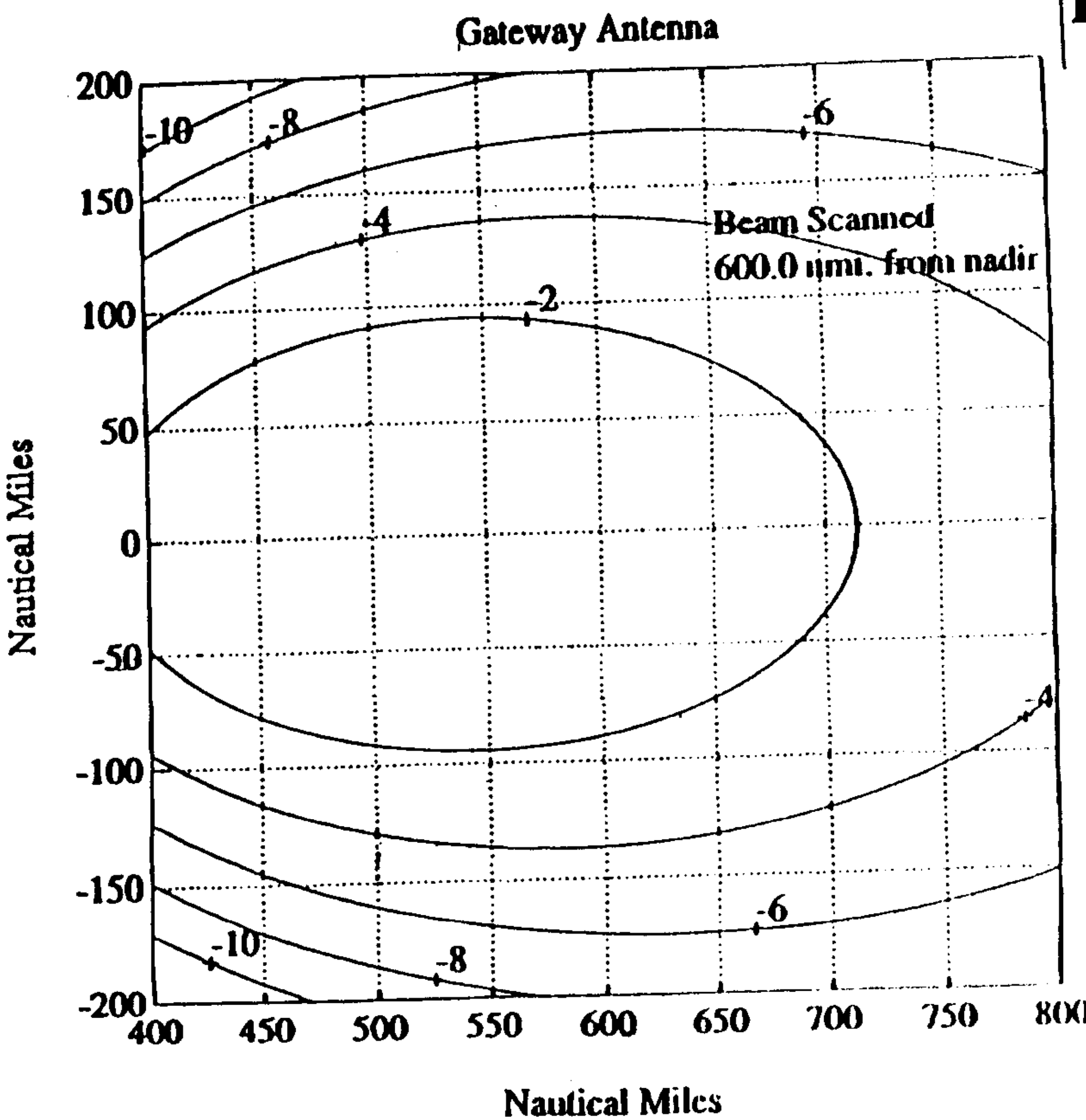

FIGURE 4g GATEWAY SPACE STATION TRANSMIT PATTERN 600 NMI FROM NADIR

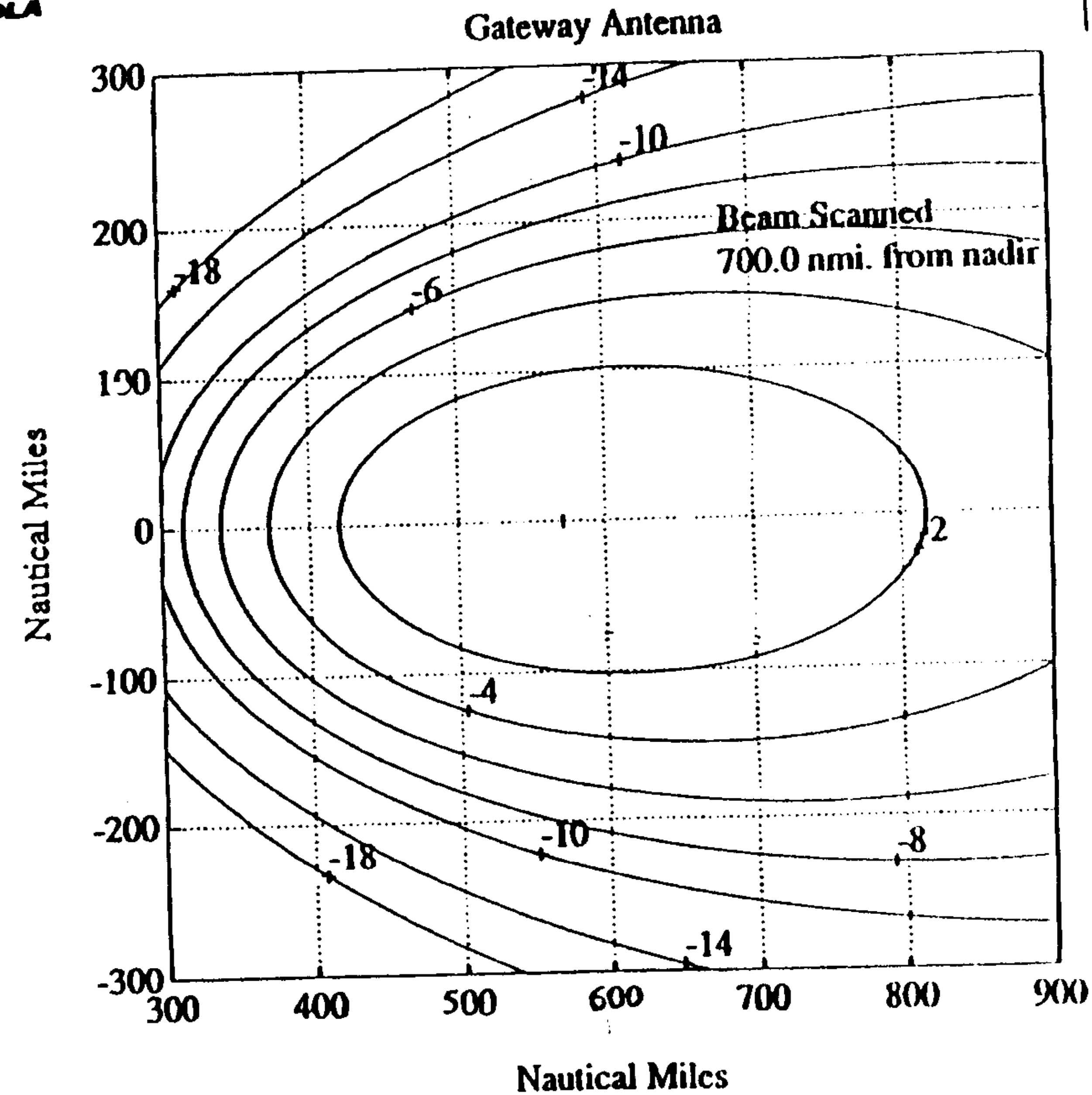

FIGURE 4h GATEWAY SPACE STATION TRANSMIT PATTERN 700 NMI FROM NADIR

MOTOROLA

IRIDIUM

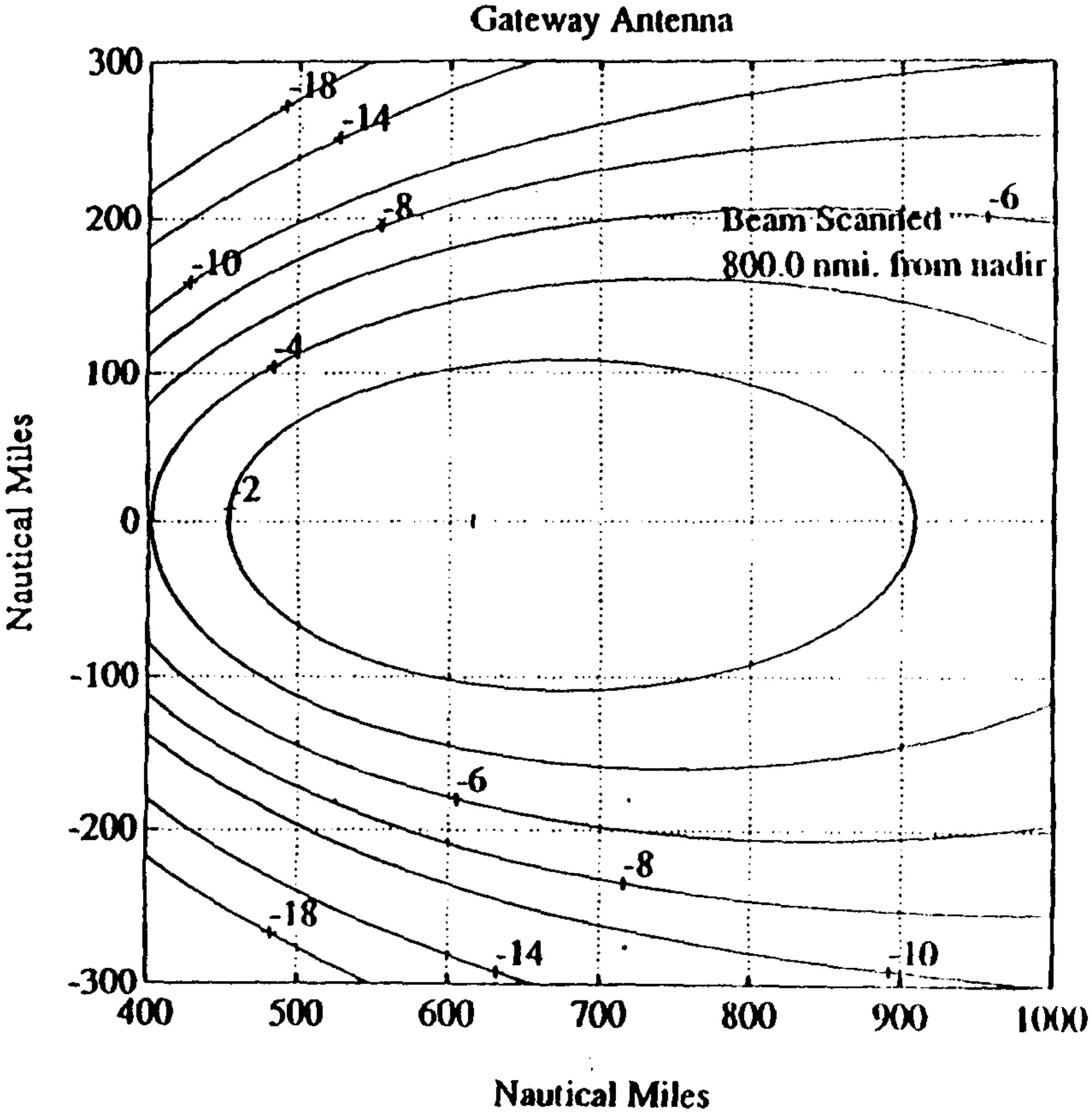

FIGURE 4I GATEWAY SPACE STATION TRANSMIT PATTERN 800 NMI FROM NADIR

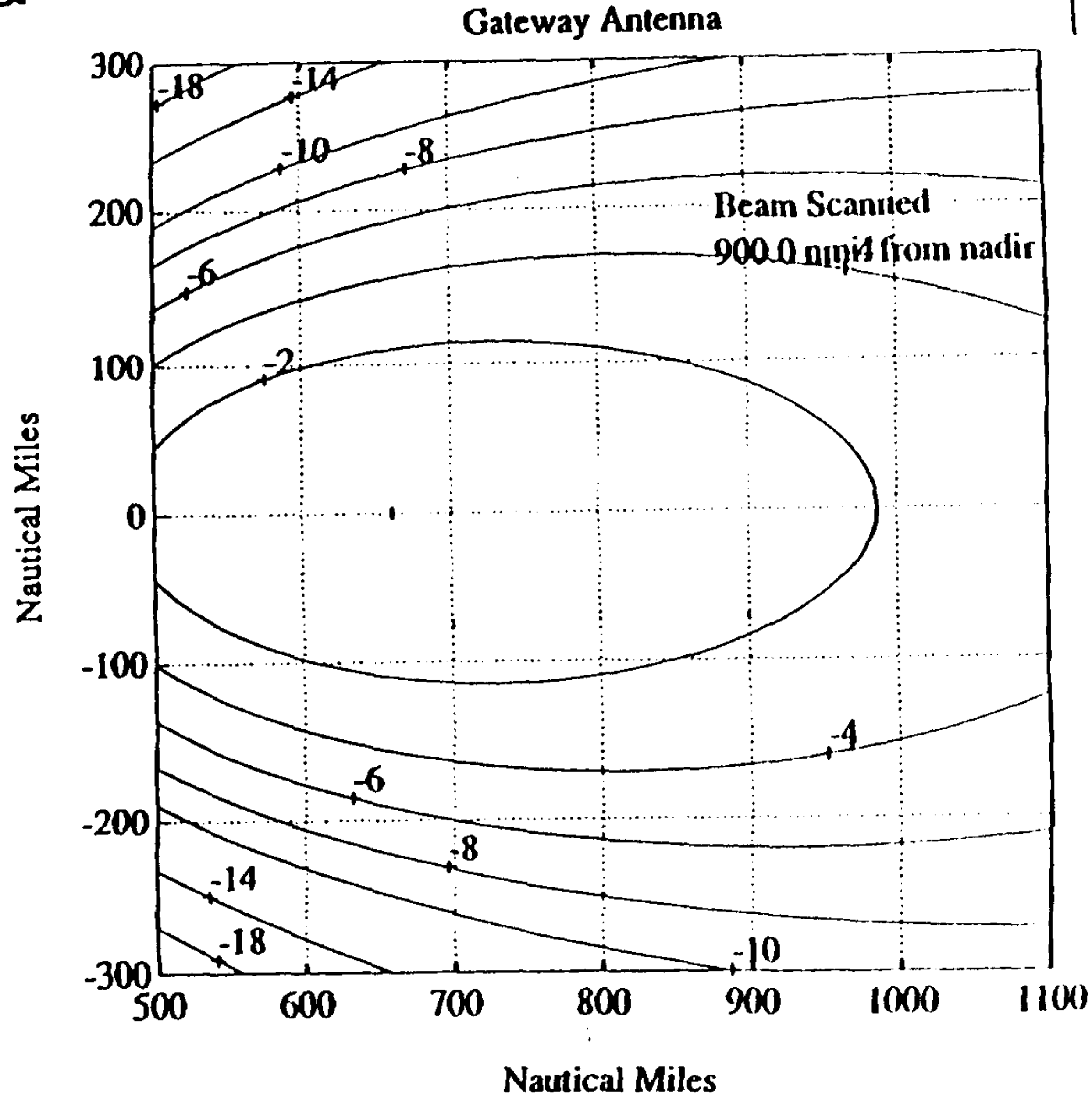

FIGURE 4J GATEWAY SPACE STATION TRANSMIT PATTERN 900 NMI FROM NADIR