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Architecture Trade Methodology for LEO Personal Communication Systems

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Architecture Trade Methodology for LEO Personal Communication Systems

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A methodology for conducting architecture trade studies for LEO communication constellations is presented. The methodology allows prediction of system performance in terms of total system capacity versus total lifecycle cost for a fixed communications quality. The architectural design decisions include the constellation type (Walker or polar), orbital altitude, satellite transmitter power and network architecture, among others. A process for quantitative comparison of system architectures is presented. Benchmarking of the simulation is conducted using the IRIDIUM and GLOBALSTAR constellations. The position of IRIDIUM and GLOBALSTAR in the LEO constellation trade space is shown and discussed in this paper. The non-dominated architectures that form the Pareto front are extracted from the full factorial search space. The methodology and simulation tool are useful as a foundation for an industry systems study of the LEO communications industry that is currently under development. The industry study will examine the interrelationships of technology, economics and policy in this context. This will allow evaluation of newly proposed LEO systems and an assessment of the effect of new technology infusion.

1 Introduction

OVER the last 15 years a number of satellite communication constellations for personal voice or data communications have been proposed. Most of these systems are based on a network of satellites operating in low Earth orbit (LEO). A small fraction of the systems that were proposed and filed with the Federal Communications Commission (FCC) have actually been deployed. A listing of 37 relevant FCC filings is shown in Appendix A. Most notable among the deployed systems are IRIDIUM (Figure 1) and GLOBALSTAR. While both of these deployed systems have met or exceeded technical requirements, both ventures did eventually file for Chapter 11 protection. Nevertheless they remain operational in niche markets. It appears that the underpinnings of system success or failure are to be found not in the details of technology implementation, but rather in the overall system architecture which is decided during conceptual design. The system architecture needs to reflect the combination of technical, economic and policy factors that will likely affect the degree to which the system can meet customer needs, comply with policy constraints and be profitable. The purpose of this paper is not to investigate the reasons for technical success or economic failure, but rather to propose a comprehensive system architecture trade methodology that will allow comparison of competing LEO concepts based on their technical performance, system capacity and lifecycle cost. The presented examples focus on voice (low-bandwidth) communications but could be extended to high-bandwidth systems.

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History of LEO Communication Constellations

The first widely used mobile satellite-based communications service was introduced by INMARSAT in early 1982 and had a capacity of 50 channels and an EIRP of 33-35 [dBW]. This service was based on a GEO satellite platform and was targeted for marine users. One of the disadvantages of GEO based satellite communications is the time delay between transmission and reception, which is due in large part to the time-of-flight to and from GEO altitude (35'800 [km]), which amounts to roughly 250 [msec] of delay.

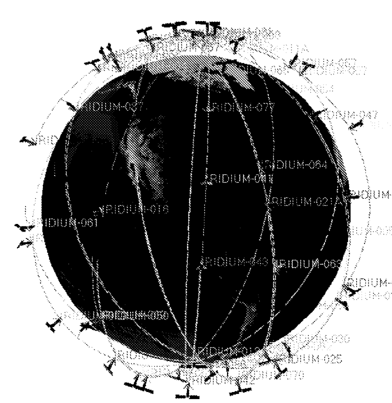

Fig. 1 IRIDIUM constellation (not drawn to scale)

Another disadvantage related to distance is the fact that signal strength decreases with $1/r^2$ and consequently that ground (terminal) transmitter power and receiver antenna need to be large. This reduces the mobility of the end user terminal. Out of these deliberations came the push for LEO based systems, where the distance between end user terminal and satellite would only be on the order of 1000 [km]. Two LEO based personal communication systems that have been launched in recent years are IRIDIUM (Figure 1) and GLOBALSTAR. While these systems were technically successful their economic performance was not as good as anticipated. As a result the future of LEO communications constellations is uncertain. The purpose of this paper is to present an architecture trade methodology that allows to show the position of existing or proposed constellations in the technical-economic-policy landscape to better understand their likelihood of success in the future.

System Architecture of LEO Constellations

A system architecture trade study is typically conducted during conceptual design and supports the concept selection process. Architectural decisions for LEO communication constellations comprise the constellation type, C, (Walker or Polar), the orbital altitude, r, the minimum acceptable elevation angle, ϵ, the satellite transmitter power, P_t, the satellite antenna (aperture) size, D_A, the per-channel bandwidth, Δf_c, and the network architecture[1]. A particularly important decision in this context is whether to implement intersatellite links (ISL's) or not. Finally the architectural "design vector" determines the expected (satellite) system lifetime, T_{sys}. Figure 2 shows the domain of system architecture decisions for a LEO satellite constellation. Lower level design decisions such as antenna type, modulation scheme or ground station transmitter power are typically made during preliminary, not during conceptual design. Also it is assumed that some parameters are fixed, i.e. the allocated frequency and bandwidth for the various links. This is a realistic assumptions, since for the most part the frequencies and bandwidth are allocated by the ITU and FCC and are not under the direct control of the LEO system architect.

Literature Review

A number of researchers have presented specific architecture and design information for particular LEO constellations such as IRIDIUM and GLOBALSTAR. Leopold has extensive knowledge of IRIDIUM as one of its original architects.[1] An overview of the IRIDIUM system was given by Fossa, Raines and coworkers.[2] In order to conduct a quantitative, relative comparison

[1]If intersatellite links are present we set $ISL = 1$, otherwise $ISL = 0$.

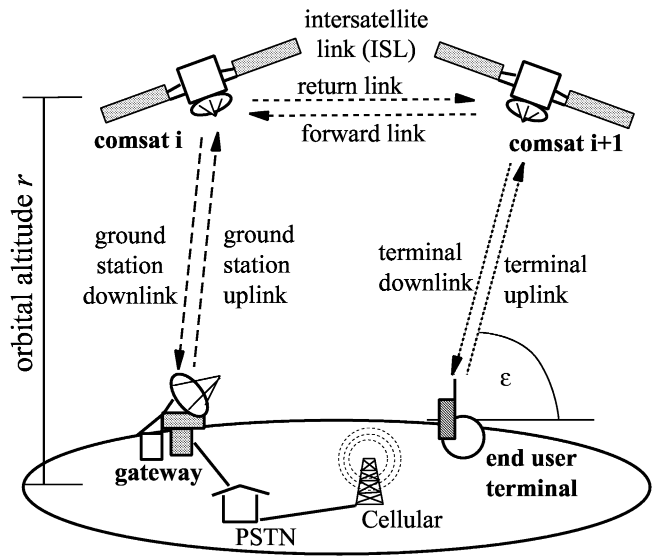

Fig. 2 LEO Communication Constellation Architecture. The end user terminal connects to a satellite comsat i+1 via the terminal up/downlink when outside of cellular coverage. Voice and data is transferred to comsat i via intersatellite link. The downlink to a ground station (gateway) provides connectivity to the Public Switched Telephone Newtork (PSTN) and wireless cellular systems.

of satellite communications constellations a number of metrics have been proposed. Kelic, Shaw and Hastings proposed a "cost per function" (CPF) metric for satellite-based internet links.[3] In this work five proposed constellations were compared based on a "cost per T1 minute" metric that took into account the life-cycle cost of a satellite-based T1 internet link at a data rate of 1.544 Mbps. The cost in this paper, however is not the cost to the operator, but rather the price of a T1-minute to the customer that will ensure a 30% internal rate of return. This important contribution built upon earlier work by Hastings, Gumbert[4] and Violet.[5] Shaw extended this work, enabling the modeling of most distributed satellite systems (DSS) as information processing networks. The methodology proposed by Shaw is called the Generalized Information Network Analysis (GINA) methodology.[6] Jilla has extended this methodology to include multidisciplinary design optimization (MDO),[7] i.e. the use of optimization to find a subset of good architectures in a very vast design space.

Larson and Wertz have compiled very useful design guidelines for space systems.[8] Extensive use of their work is made in this paper, e.g. in the area of cost modeling and use of cost estimation relationships (CER's). Very insightful and complete tables on LEO satellite constellations have been compiled, commented and maintained by Wood[9] based on various sources. This information was used for benchmarking our simulation in Section 3. Architecture trade analysis of new LEO constellations has been proposed by Suzuki and coworkers[10] for potential designs of Japan's Next-generation LEO system. This last paper is particularly interesting in the sense that it proposes to use architecture trading as a testbed for assessing the impact of new technologies such as an intersatellite optical tracking system.

2 Problem Definition and Approach

The purpose of this paper is to present a comprehensive methodology for conducting system architecture trades for LEO communications constellations using quantitative metrics. Fundamentally the architectural choices are captured by a "design vector" $\mathbf{x}$ and the metrics by which the merits of a particular LEO system architecture are assessed are contained in the objective vector $\mathbf{J}$. Other inputs are vectors containing constant parameters, $\mathbf{c}$, policy decisions, $\mathbf{p}$, and voice communications quality requirements, $\mathbf{r}$. Thus there is a mapping from decision space to objective space:

$$\mathbf{x} \mapsto \mathbf{J} = f\left(\mathbf{x},\mathbf{c},\mathbf{p},\mathbf{r}\right) \tag{1}$$

The set of feasible vectors, $\mathbf{x}$, defines a design space. The problem is to find, which corresponding objective vectors, $\mathbf{J}$, are non-dominated in objective space.

System Architecture Evaluation Framework

We propose to solve the problem in the following six steps:

1. Choose the elements and bounds of the architectural design vector $\mathbf{x}$, objective vector $\mathbf{J}$, constants vector $\mathbf{c}$, requirements vector $\mathbf{r}$ and policy vector $\mathbf{p}$.

2. Build the Mapping Matrix, subdivide the problem into modules and define the interfaces.

3. Model technological-physical,economic and policy relationships, implement the individual modules and test them in isolation from each other.

4. Integrate the modules into an overall simulation and benchmark the simulation against a reference system. Tune and refine the simulation as necessary (Loop A).

5. Conduct a systematic trade space exploration using design-of-experiments (DOE) or optimization search algorithms

6. Postprocessing of the Pareto optimal set including sensitivity and uncertainty analysis. Extract a subset of Pareto optimal architectures that are non-dominated for further study. If no acceptable architecture is found the trade space needs to be modified (Outer Loop B).

This framework has been demonstrated by Jilla[7] for other space missions such as TPF, TechSat21 and a broadband communications constellation. Figure 3 shows a block diagram of the proposed system architecture trade methodology.

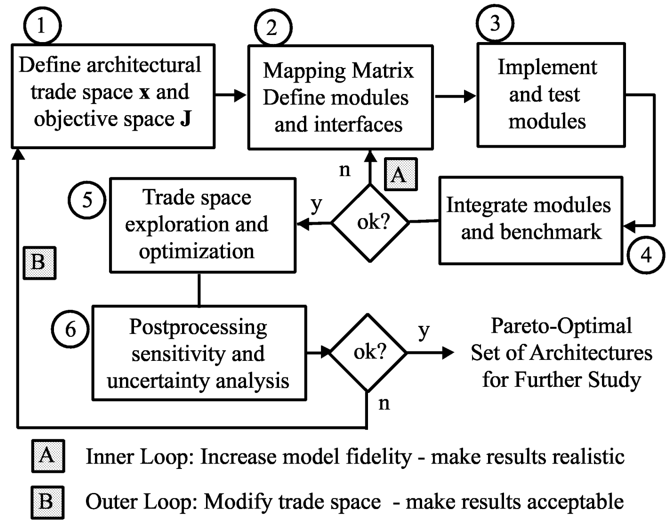

Fig. 3 System Architecture Trade Methodology

3 LEO Communications Constellation Simulation

While the proposed framework is applicable to many classes of complex systems we now turn our attention to LEO communications constellations. In this section we go through the first four steps of the methodology. This begins by clearly defining the decision variables in the design vector, $\mathbf{x}$, and ends with benchmarking the simulation against actual LEO systems.

Design and Objective Vector Definition

Figure 4 shows the vector of design variables $\mathbf{x}$, constant parameters, $\mathbf{c}$, performance requirements, $\mathbf{r}$, policy decisions, $\mathbf{p}$ and objectives, $\mathbf{J}$. Note that we will focus on system capacity, lifecycle cost and cost-per-function in this paper. The assigned frequency for satellite-mobile user uplink and downlink is assumed at 1.6 [GHz] similar to IRIDIUM. No policy restrictions such as technology export controls or gateway placement and licensing have been imposed.

The design vector, $\mathbf{x}$, embodies the architectural design decisions and is subject to the bounds or discrete choices shown in Table 1.

The objective vector, $\mathbf{J}$, captures all the metrics by which the "goodness" of a particular architecture can be evaluated. The objective vector contains the average delay (propagation only), the number of simultaneous users the system can support and the total system lifetime capacity expressed as the number of total minutes at a data rate, bit-error-rate and link

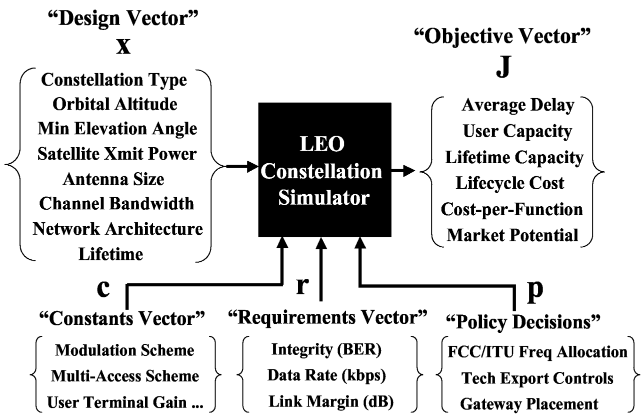

Fig. 4 Input-Output Mapping Of LEO Communication Constellation Model

Table 1 LEO Constellation Design Vector x

Symbol	Variable	x_{LB}	x_{UB}	unit
C	const. type	Walker	Polar	[-]
r	altitude	400	2000	[km]
ϵ	min elevation	5	35	[deg]
P_t	Sat Xmit Pwr	200	1800	[W]
D_A	antenna size	0.5	3.5	[m]
Δf_c	CH bandwidth	40	80	[kHz]
ISL	inter sat links	1	0	[-]
T_{sys}	sat lifetime	5	15	[years]

margin specified by **r**. The total delay is perceived directly by the customer and is a function of time-of-flight, number of inter-satellite links and switching times. The amount of delay also determines the suitability of the system for synchronous or asynchronous data communications (e.g. TCP/IP). The lifecycle cost is the sum of the research & development, test and evaluation costs (RDT&E), the manufacturing and assembly cost, the launch cost, the space and ground segment operations cost and the replacement costs. Ultimately this cost plus some profit has to be recovered from the end users. The cost-per-function (CPF) is the total system capacity divided by lifecycle cost. The market potential is the estimated global total subscriber base[2]. The objective vector is summarized in Table 2.

The comparison between architectures is made under the assumption of a fixed minimum communications quality for all end user terminals. This is captured by the requirements vector, **r**. It is assumed that the (voice) quality is determined primarily by the Bit-Error-Rate (BER) - high BER is perceived as white noise - and the data rate (R) - low R is perceived as clipping of high frequencies. Additionally the link margin, L_m, is fixed to a specified value.

[2] This metric is based on work by T. Kashitani[11] and is still under development.

Table 2 LEO Constellation Objective Vector J

J	Objective	Symbol	unit
J_1	Average Delay	τ	[msec]
J_2	Simultaneous Users	N_{user}	[-]
J_3	Lifetime Capacity	C_{tot}	[min]
J_4	Lifecycle Cost	LCC	[B$]
J_5	Cost-per-Function	CPF	[$/min]
J_6	Market Potential	MP	[# subscribers]

Simplifying Assumptions

The current simulation model makes a number of simplifying assumptions. Only circular orbits between altitudes 400 [km] and 2000 [km] are allowed. This excludes MEO and GEO systems and elliptical constellations (e.g. Molnyia orbits). The current simulation model captures the key governing equations between power, satellite mass, altitude, link budgets and so forth. Some subtle points such as the fact that satellites in lower orbits need to carry more fuel for drag compensation are ignored at this point. The same is true for the effect of increasing radiation levels for upper LEO altitudes, which could lead to shorter lifetimes or higher satellite failure rates. Nevertheless we will be able to show reasonable correspondence between simulation and the benchmarked systems, which increases confidence that the answers are not very sensitive to the simplifying assumptions.

LEO Simulation Modules

The second and third step in the architecture trade methodology from Figure 3 is to define and implement the simulation modules. The simulation architecture is shown in Figure 5. There are three macro-modules: Technical, Cost and Market. The task of the technical macro-module is to build a model of a LEO constellation architecture based on the input design vector and to predict the system objective vector. The objective of the cost macro-module is to estimate the lifecycle cost of the architecture, the task of the market module is to estimate the market potential and the CPF of a particular architecture. The technical and cost macro-modules are completed as of the writing of this paper, the market module is still in development.

Capacity and Lifecycle cost estimates

The total lifetime capacity of a LEO system, C_{tot}, is defined as the number of instantaneous users, N_{user}, the LEO system can handle multiplied by the system lifetime T_{sys} in minutes. It is to be expected that only a small percentage of the lifetime system capacity will be used for the following reasons:

- Local capacity versus local demand: at any instant in time there is large capacity over sparsely populated areas and open water. This limiting factor is referred to as market demographics.

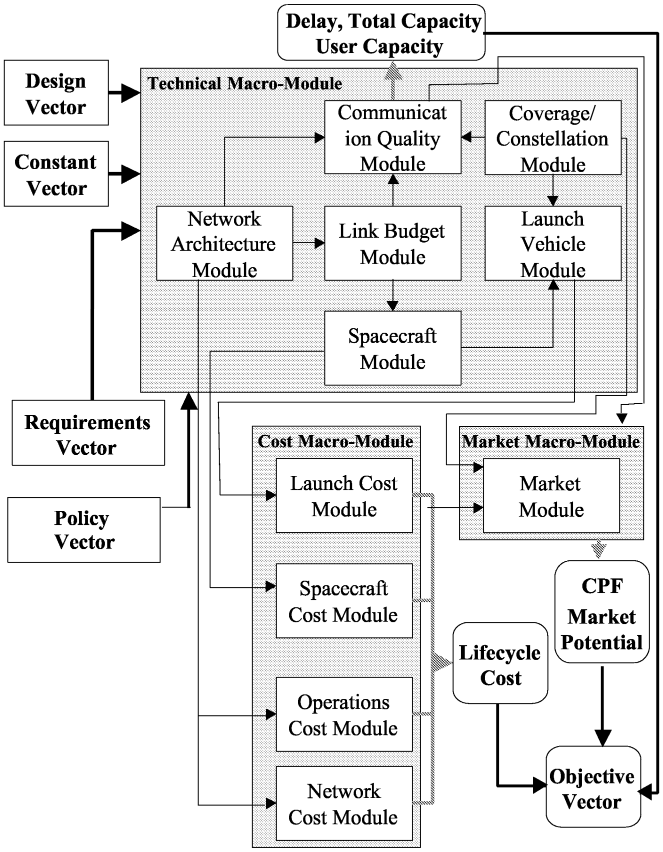

Fig. 5 LEO Communications Constellation Simulation Block Diagram

- The usage of communication systems is strongly depended on time-of-day distributions, see[3] (Fig.3)
- Competing space, air and land-based communication systems limit the market share of mobile satellite services
- System downtimes due to unexpected failures or planned maintenance activities

Since any of these four aspects are highly probabilistic and difficult to model, we will compare systems based on the system capacity metric, C_{tot}, mentioned above. This is the maximum theoretical capacity of the system.

Integration and Benchmarking

The fourth step of the framework consists of integrating all the modules and benchmarking. Benchmarking is a critical step, since it ensures that the simulation predicts the technical performance and costs of *actual deployed* systems with reasonable accuracy. This gives confidence that the predicted responses for other systems within the trade space will not be off by orders of magnitude. The IRIDIUM and GLOBALSTAR constellations were chosen as reference systems for benchmarking of the LEO constellation simulator. These are logical choices since the systems are currently operational, extensive literature describing their characteristics exists[9] and they represent sufficiently different architectures to be of use[3]. A picture of a single Iridium satellite, including the characteristic three-panel phased array antenna, is shown in Figure 6.

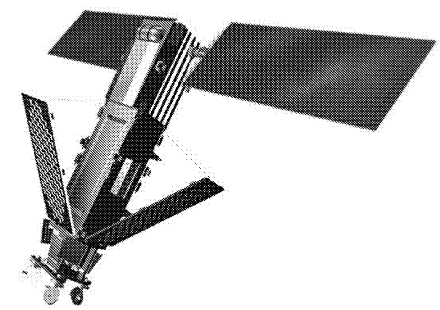

Fig. 6 Individual IRIDIUM satellite

Benchmarking in this context means selecting the same design vector that was implemented in the real reference system, performing the simulation and comparing the objective vector between the real system and the simulated system. The design vector for IRIDIUM is:

$$\mathbf{x}_I = \begin{bmatrix} C \\ r \\ \varepsilon \\ P_t \\ D_A \\ \Delta f_c \\ ISL \\ T_{sys} \end{bmatrix} = \begin{bmatrix} \text{polar} \\ 780 \\ 8.2 \\ 1400 \\ 1.5 \\ 41.67 \\ 1 \\ 5 \end{bmatrix} \begin{matrix} [-] \\ [\text{km}] \\ [\text{deg}] \\ [\text{W}] \\ [\text{m}] \\ [\text{kHz}] \\ [1/0] \\ [\text{y}] \end{matrix} \quad (2)$$

Aside from the design vector a number of constants are fixed in the constants vector, $\mathbf{c}$. Examples are the transmitter efficiencies at $\eta_T = 0.55$ and the user terminal uplink frequency at 1.62 [GHz]. The voice communications requirements are set to: BER=1E-3, $R = 4.8$ [kbps] and $L_m = 16$ [dB]. The results of the benchmarking are values for the objective vector. In the case of IRIDIUM a comparison between the real objective vector $\mathbf{J}_{Ireal}$ and the one returned by the simulator, $\mathbf{J}_{Isim}$, yields the following results:

[3] It is likely that some implementation details of these systems have changed somewhat since the benchmarking references were published.

$$
\mathrm{J_{Isim}}=\begin{bmatrix} 0.0054 \\ 1.0116\mathrm{E}+5 \\ 2.6584\mathrm{E}+11 \\ 3.6608 \\ 0.0138 \\ 5.3967\mathrm{E}+4 \end{bmatrix}\begin{bmatrix} \text{delay} \\ \text{usercap} \\ \text{capacity} \\ \text{LCC} \\ \text{CPF} \\ \text{subscribers} \end{bmatrix}\begin{matrix} [m\,\text{sec}] \\ [-] \\ [\text{min}] \\ [\text{B\$}] \\ [\text{\$/min}] \\ [-] \end{matrix} \tag{3}
$$

$$
\mathrm{J_{Ireal}}=\begin{bmatrix} 0.0054 \\ 1.72\mathrm{E}+5 \\ 4.5202\mathrm{E}+11 \\ 5.5 \\ 0.0122 \\ 6.0\mathrm{E}+4 \end{bmatrix}\begin{bmatrix} \text{delay} \\ \text{usercap} \\ \text{capacity} \\ \text{LCC} \\ \text{CPF} \\ \text{subscribers} \end{bmatrix}\begin{matrix} [m\,\text{sec}] \\ [-] \\ [\text{min}] \\ [\text{B\$}] \\ [\text{\$/min}] \\ [-] \end{matrix} \tag{4}
$$

A critical comparison of these results is appropriate at this point. The average propagation delay (arithmetic mean between propagation delay of 2.60 [msec] at nadir and 8.22 [msec] at maximum slant range) matches exactly. The total instantaneous user capacity is predicted as 101160 by the simulation based on the power limitation of individual satellites (from link budget). References about the real system show a power limitation of 1100 voice circuits per satellite, resulting in 72600 simultaneous users,[9] but a maximum capacity of 3840 voice circuits per satellite based on 48 spot beams, 20 FDMA channels and 4 TDMA frames, which results in a total IRIDIUM capacity of 172000, when beam reductions during polar crossings are accounted for, see Reference.[2] The total instantaneous capacity, N_{user}, predicted by the LEO simulator can therefore be deemed to be reasonable. The lifecycle cost of IRIDIUM is predicted to be 3.66 [B$] by the simulator. The actual lifecycle cost of IRIDIUM is not easy to know since the system is still operating and one has to distinguish between the pre- and post-bankruptcy period. Nevertheless a rough order estimate is the 5.5 [B$] that were invested in IRIDIUM based on the IPO and debt financing. It is remarkable to note that Wood[9] quotes the system cost of IRIDIUM as 3.7 [B$]. Again we conclude that the simulator gives at least a reasonable estimate. The number of subscribers (market potential) is another area of considerable ambiguity. Originally IRIDIUM had hoped for roughly 1 million subscribers in order to reach the break-even point. This subscriber number turned out to be unrealistic given 3 [$/min] connection fees and a 2500-3000 [US$] purchase cost per mobile terminal. Kashitani's market model[11] predicts a subscriber market potential of 53,967. This is amazingly close to the 60,000 subscribers that the new Iridium Satellite LLC is hoping to realistically capture[12][4].

A better idea of model fidelity can be obtained by considering some intermediate variables. The following vectors compare items such as antenna gain [dB] and satellite mass [kg] between the actual IRIDIUM system and the simulation.

$$
\underbrace{\begin{bmatrix} 66 \\ 1.6212 \\ 11 \\ 780 \\ 100.1 \\ - \\ 10^{10}[\text{Jy}] \\ 24.3 \\ 1400 \\ - \\ 10.5 \\ 240 \\ 2.4/4.8 \\ \text{QPSK} \\ 1100/3840 \\ 11(15-20) \\ 700 \end{bmatrix}}_{\substack{\text{actual} \\ \text{IRIDIUM}}}\underbrace{\begin{bmatrix} 66 \\ 1.6212 \\ 11 \\ 780 \\ 100.3 \\ 57.04 \\ 4.24\mathrm{E}-11 \\ 25.6 \\ 1400 \\ 8.6353 \\ 10.5 \\ 240 \\ 4.8 \\ \text{QPSK} \\ 1532 \\ 12 \\ 699 \end{bmatrix}}_{\substack{\text{simulated} \\ \text{IRIDIUM}}}\begin{matrix} \#\text{ of sats}[-] \\ \text{frequency[GHz]} \\ \#\text{ orbital planes} \\ \text{altitude[km]} \\ \text{period[min]} \\ \text{EIRP[dBW]} \\ \text{power flux}[\text{W/m}^2] \\ \text{transmit gain[dBi]} \\ \text{transmit power[W]} \\ \text{beamwidth[deg]} \\ \text{bandwidth[MHz]} \\ \text{FDMA channels}[-] \\ \text{data rate[kbps]} \\ \text{modulation} \\ \text{voice circuits/sat} \\ \#\text{gateways} \\ \text{satellite mass[kg]} \end{matrix} \tag{5}
$$

One can see that there is no significant difference between the characteristics of the real system and the ones predicted by the simulator. Unfortunately, the largest uncertainties lie in the area of estimating the system capacity and lifecycle cost.

To verify that the simulation is valid beyond a single point design, we benchmarked the LEO simulator against GLOBALSTAR, following the same process as for IRIDIUM. A picture of a GLOBALSTAR satellite is shown in Figure 7.

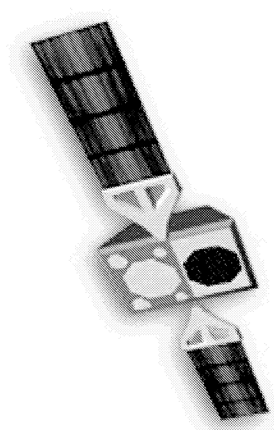

Fig. 7 Individual GLOBALSTAR satellite

[4] The underlying assumption is a global wireless communications market of 600 million users with a 2.5% market share for mobile satellite services

The (input) design vector for GLOBALSTAR is as follows:

$$\mathbf{x}_G = \begin{bmatrix} C \\ r \\ \varepsilon \\ P_t \\ D_A \\ \Delta f_c \\ ISL \\ T_{sys} \end{bmatrix} = \begin{bmatrix} \text{Walker} \\ 1414 \\ 10 \\ 1000 \\ 0.75 \\ 1.25 \\ 0 \\ 8 \end{bmatrix} \begin{matrix} [-] \\ [\text{km}] \\ [\text{deg}] \\ [\text{W}] \\ [\text{m}] \\ [\text{MHz}] \\ [1/0] \\ [\text{y}] \end{matrix} \quad (6)$$

The largest differences between Iridium and Globalstar are that Globalstar operates at twice the altitude (1400 [km]), uses a CDMA multi-access strategy and does not rely on intersatellite links. This significantly shifts lifecycle costs from the space segment to the ground segment, a characteristic of a "bent-pipe" architecture. A comparison of the objective vectors for Globalstar yields:

$$\mathrm{J}_{\mathrm{Gsim}} = \begin{bmatrix} 0.0082 \\ 4.8712\mathrm{E}+4 \\ 2.0482\mathrm{E}+11 \\ 3.1725 \\ 0.0155 \\ 2.7295\mathrm{E}+4 \end{bmatrix} \begin{bmatrix} \text{delay} \\ \text{usercap} \\ \text{capacity} \\ \text{LCC} \\ \text{CPF} \\ \text{subscribers} \end{bmatrix} \begin{matrix} [m\,\text{sec}] \\ [-] \\ [\text{min}] \\ [\text{B\$}] \\ [\text{\$/min}] \\ [-] \end{matrix} \quad (7)$$

$$\mathrm{J}_{\mathrm{Greal}} = \begin{bmatrix} 0.0082 \\ 1.344\mathrm{E}+5 \\ 5.2980\mathrm{E}+11 \\ 2.2 \\ 0.00415 \\ 6.7\mathrm{E}+4 \end{bmatrix} \begin{bmatrix} \text{delay} \\ \text{usercap} \\ \text{capacity} \\ \text{LCC} \\ \text{CPF} \\ \text{subscribers} \end{bmatrix} \begin{matrix} [m\,\text{sec}] \\ [-] \\ [\text{min}] \\ [\text{B\$}] \\ [\text{\$/min}] \\ [-] \end{matrix} \quad (8)$$

A critical analysis of these results reveals that benchmarking for GLOBALSTAR appears somewhat more difficult. While the delay is modeled accurately there is a discrepancy in the number of voice circuits predicted between the simulation (1218) versus reality (2800). This is mainly due to the way in which spectrum sharing (CDMA) is handled in the simulation. Also the published lifecycle cost of 2.2 [B$] does not include the cost of third party ground stations. This explains part of the difference with the predicted lifecycle cost of 3.17 [B$] from the simulation. The satellite masses, however, are relatively close (503.5 [kg] simulated versus 450 [kg] on orbit). While IRIDIUM and GLOBALSTAR have significantly different architectures they are relatively close in objective space in terms of total lifetime capacity, C_{tot}, and lifecycle cost, LCC. Now that benchmarking has been concluded we can begin exploring the LEO architectural trade space with some confidence.

4 Architecture Trade Study Results

The fifth step of the framework, see Figure 3, consists of exploring the architectural trade space using design-of-experiments (DOE) or optimization techniques. First the trade space is defined by discretizing the continuous elements of the design vector, **x**. This has been done based on Table 1 as follows:

Table 3 LEO Constellation Trade Space x

Symbol	Variable	*values*	unit
C	'Polar'	[-]	
r	400,800,1200,1600,2000	[km]	
ϵ	5,20,35	[deg]	
P_t	200,600,1000,1400,1800	[W]	
D_A	0.5,1.5,2.5,3.5	[m]	
Δf_c	40	[kHz]	
ISL	1 , 0	[-]	
T_{sys}	5,10,15	[y]	

This results in a total of 1800 possible architectures, i.e. the "size" of the tradespace is 1800. Due to the relatively fast simulation of a single architecture (ca. 10 min for the entire tradespace on a Pentium 4 machine), we can attempt a full factorial search and don't need to resort to sampling (e.g. parameter study, orthogonal arrays etc...) or optimization. For larger tradespaces the methods proposed by Jilla appear to be most helpful.[7]

System Capacity versus Lifecycle Cost

A key aspect of successful LEO communication constellation design is that the system capacity has to be matched to the likely system demand.[7] System demand is highly uncertain due to the unknown actual market size for space based communications, the effects of competition from land based PSTN and cellular systems as well as the unknown market penetration (market share). Nevertheless it is worthwile to examine the tradeoff between lifetime capacity C_{tot} [min] versus total lifecycle cost LCC in [B$]. This is done by evaluating the objective vector **J** for all possible architectures in Table 3 and plotting C_{tot} (capacity) versus LCC (lifecycle cost), see Figure 8. Each dot represents a specific architecture.

In this plot we can see that higher total lifetime capacity generally comes at the expense of higher lifecycle cost. It appears, however that some architectures provide a better tradeoff than others. Since we can consider this a multiobjective problem we can find the subset of architectures that constitute the Pareto front. These architectures are non-dominated according to the definition offered by Sawaragi.[13] A number of interesting observations are appropriate at this point.

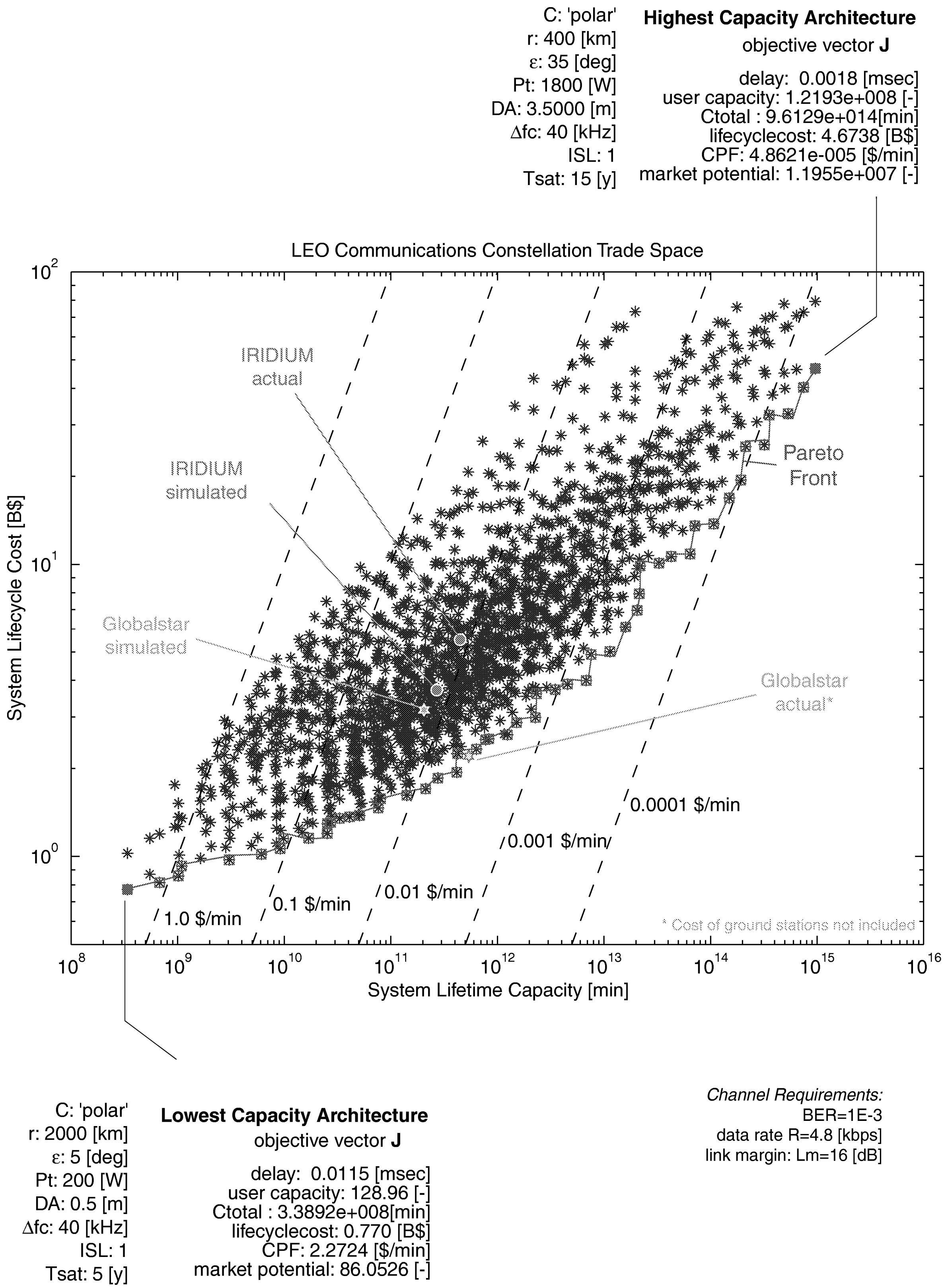

Fig. 8 LEO Constellation Trade Space

Pareto Optimal Set of Architectures

From the trade space shown in Figure 8, the Pareto optimal set of non-dominated solutions can be extracted. This is the sixth and last step in the framework of Figure 3. These architectures are shown with small squares and tend towards the lower right of the figure (high capacity and low LCC corner). The architecture with the largest capacity is a system at the lowest altitude (400 [km]) with 1215 satellites, and maximal transmitter power (P_t=1800 [W]), antenna size (D_A=3.5 [m]) and long lifetime (T_{sys}=15 [years]). The lowest capacity architecture is at the highest allowable orbit (r=2000 [km]) and has low transmitter power (P_t=200 [W]), small antenna size (D_A=0.5 [m]) and a short design lifetime (T_{sys}=5 [years]). All other Pareto-optimal architectures fall in between these two extremes. The trend that higher capacity, more expensive systems are in lower orbits and feature large numbers of satellites was also observed by Jilla[7] and Kashitani[11] in their broadband studies. There, GEO systems appear in the lower left, followed by MEO systems, small LEO's and big LEO's in the upper right. A listing of all 51 Pareto optimal architectures is shown in Table 4. Note that all non-dominated architectures appear to be favoring the use of intersatellite links.

The position of IRIDIUM and GLOBALSTAR in this trade space is shown in Figure 8. Both systems are not too far from each other in this space and provide medium lifetime capacity. For IRIDIUM it can be said that it does not appear to be Pareto optimal as it is dominated by other architectures. The non-dominated architecture that comes closest to IRIDIUM (actual) in terms of providing a similar capacity is in a 800 [km] orbit with 54 satellites, uses a power of 600 [W] at a minimum elevation angle of 5 [deg] and is underlined in Table 4. The higher capacity is achieved mainly due to a larger antenna (2.5 versus 1.5 [m]) and an extended lifetime (10 versus 5 [years]). The lower lifecycle cost is likely due to the slightly lower number of satellites (66 versus 54) and the smaller power per satellite (1400 versus 600 [W]), which results in smaller, cheaper satellites. This architecture is indeed very similar to IRIDIUM and with an extended on-orbit lifetime[12] the actual Iridium would approach this architecture. The actual GLOBALSTAR appears to be non-dominated, however, this is an artifact of the missing ground station costs in the published cost estimates for this system.

The diagonal lines in Figure 8 represent the lines of constant cost-per-minute, they are the iso-CPF lines. As expected the large systems have the lowest CPF due to economy of scale and learning curve effects. This does not mean that such an architecture should actually be chosen, since it is more important that the implemented system's capacity is well matched with

Table 4 Set of Pareto Optimal LEO Architectures

r [km]	N_{sat} [ ]	ϵ [deg]	P_t [W]	C_{tot} 10^{12} [min]	LCC [B$]
2000	24	5	200	0.0003	0.7702
2000	24	5	200	0.0007	0.8142
2000	24	5	200	0.0010	0.8581
1600	28	5	200	0.0011	0.9271
2000	24	5	200	0.0030	0.9733
2000	24	5	200	0.0061	1.0173
2000	24	5	200	0.0091	1.0612
1600	28	5	200	0.0098	1.1498
2000	24	5	200	0.0169	1.1546
2000	24	5	200	0.0254	1.1986
800	54	5	200	0.0255	1.2949
1600	28	5	200	0.0273	1.3061
2000	24	5	200	0.0331	1.3492
1600	28	5	200	0.0410	1.3639
800	54	5	200	0.0509	1.3805
800	54	5	200	0.0764	1.4660
1600	28	5	200	0.0803	1.5770
800	54	5	200	0.1414	1.6184
800	54	5	200	0.2121	1.7040
800	54	5	200	0.2769	1.8521
800	54	5	200	0.4153	1.9376
800	54	5	600	0.4242	2.2436
800	54	5	600	0.6363	2.3292
400	112	5	200	0.7751	2.5065
800	54	5	600	0.8307	2.5216
800	54	5	600	1.2460	2.6071
400	112	5	200	1.5178	2.8715
400	112	5	200	2.2767	2.9847
400	112	5	600	2.3254	3.6012
400	112	5	600	3.4881	3.7145
400	112	5	600	4.5533	3.8839
400	112	5	600	6.8300	3.9972
400	112	5	1000	7.5889	4.9016
400	112	5	1000	11.3833	5.0149
400	112	5	1400	15.9366	6.1016
400	112	5	1800	20.4899	6.9636
400	416	20	200	21.4394	7.9389
400	416	20	600	21.8986	9.8665
400	416	20	600	32.8479	10.0906
400	416	20	600	42.8788	10.6385
400	416	20	600	64.3182	10.8626
400	416	20	1000	71.4647	13.5371
400	416	20	1000	107.1971	13.7612
400	416	20	1400	150.0759	16.8561
400	416	20	1800	192.9547	19.4380
400	1215	35	600	213.6195	25.2568
400	1215	35	600	320.4292	25.6335
400	1215	35	1000	356.0325	32.3542
400	1215	35	1000	534.0487	32.7308
400	1215	35	1400	747.6682	40.2958
400	1215	35	1800	961.2877	46.7385

the actual market demand. So it appears that one of the major reasons of economic failure for IRIDIUM and GLOBALSTAR might not have been a poor technical architecture, but a mismatch between the system capacity and actual market demand.

In previous work by Kelic, Shaw and Hastings[3] the *cost per function* was based on an achievable system capacity. This achievable capacity was based on the satellite system design and the "available market". In this paper the system capacity is only a function of system design, since the past has shown that any kind of market prediction is highly uncertain. If the market-driven CPF (cost to the customer !) metric were employed here with actual market data from the 1998-2002 time frame, the iso-CPF lines would likely shift in favor of smaller systems.

5 Conclusions and Future Work

This paper focuses on presenting a coherent system architecture trade methodology for LEO communications constellations. A six step procedure has been proposed which allows architectural trades to be conducted. Benchmarking is a key step in ensuring that the simulation results can be trusted. The Pareto front of architectures shows the best tradeoff between system capacity and lifecycle cost. IRIDIUM and GLOBALSTAR are mapped into this trade space and appear at some distance from the Pareto-front. Nevertheless it appears that a mismatch between system capacity and market demand is a larger problem for these systems than a poorly chosen architecture.

Subsequent papers will discuss trade space results between some other components of the objective vector (e.g. CPF versus subscriber base/user capacity) as well as economical, policy and technology insertion impact on the Pareto front in more detail. Also it is our ambition to further refine the technical fidelity of the modules shown in Figure 5. Figure 9 shows the triangle between technology, policy and economics that can be better explored with the presented framework.

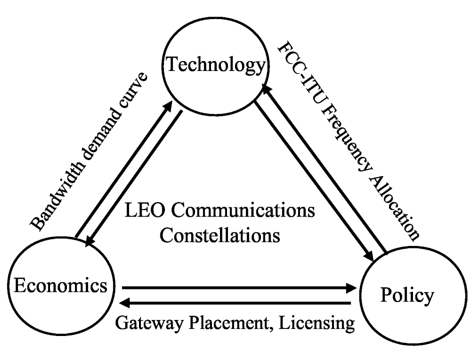

Fig. 9 Technology-Policy-Economics Relationships for LEO Communications Constellations

Industry Systems Study

One of the goals of this research is to synthesize a high-quality industry systems study at the intersection of aerospace and communications that can be used to enhance education in Engineering Systems. In particular the LEO constellation simulation can serve as a testbed to explore lessons learned for large complex systems. This systems study is part of a series, developed by MIT's Engineering Systems Learning Center. The study will eventually be comprised of four modules:

Module 1: Technological Success and Economic Failure

In this module the learners familiarize themselves with the telecommunications and satellite industries, analyze original market predictions, recreate the Iridium and Globalstar constellations using a computer simulation and read newspaper and journal articles documenting system design, deployment and ultimate economic failure. They will analyze discrepancies between actual performance and lifecycle cost predictions and reality, explore potential reasons for failure and negotiate recovery (post bankruptcy) options in stakeholder groups.

Module 2: Exploring System Architecture and Design Spaces

This module shows that both Iridium and Globalstar are point designs and merely represent discrete choices that were made within a large design space. This design space is explored using the computer simulation over a range of options, including orbital altitude, constellation type, satellite transmitter power and system design lifetime, among others. For each the learners will compute performance in terms of system capacity (expected total lifetime minutes available), lifecycle cost (development, manufacture, test, launch and operations) for a fixed voice channel communications quality. From this trade space the students will identify and analyze the Pareto-optimal subset with respect to system capacity and lifecycle cost.

Module 3: Embedding Robustness and Flexibility

Iridium, Globalstar and the set of Pareto optimal designs found in the previous module all have fixed total capacity and offer essentially only one type of low bandwidth service (voice at 4.8 [kbps] per channel). Here, the students will learn that such systems are vulnerable to uncertainties in actual market demand and to new disruptive technologies (e.g. GSM terrestrial networks). This is particularly true if the time between conception and deployment is long as is the case for LEO systems. Robustness to uncertain market demand will be investigated in the form of an alternative variable capacity design. Flexibility will be investigated in terms of system designs that could offer a mix of high and low bandwidth voice, data and multimedia communications services, whereby the exact mix might not be known during conceptual design. The students will learn how to value robustness and flexibility during early design using real options theory.

Module 4: Impact of Policy Decisions and Technology Insertion

This module will allow the learners to critically assess relationships in the triangle between Technology-Policy-Economics. The basic assumptions of available technologies used in Module II will be challenged in this module. The potential effect of revolutionary, but as yet unproven, technologies on the Pareto optimal front of designs will be investigated. Examples of such technologies are smart auto-tracking antennas for end user stations and optical laser inter-satellite links. The second area pertains to policy impact on architectures. Both frequency and bandwidth allocation by the FCC and ITU and technology export control restrictions (restricting the choice of available launch sites and vehicles) will be considered. These technology disruptions and policy decisions will be simulated using the LEO simulation model. This will allow the learners to quantify and visualize the impact of such events on their previous "optimal" design decisions.

The work presented in this paper will assist in synthesizing modules I and II. Modules III and IV remain as future work.

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Appendix A: FCC Filing Database

The following filings for satellite communications constellations with the Federal Communications Commission (FCC) were used as a basis for the spacecraft simulation module and for benchmarking purposes:

@contact, AMSC, NGSO, Boeing NGSO FSS, Celestri, Constellation, Ellipso, E-Sat, Final Analysis, GE LEO, GEMnet, Globalstar, Globalstar 2 GHz, Globalstar GS-40, HughesLINK, HughesNET, ICO, Iridium, Iridium Macrocell, Leo One, LM MEO, M Star, Odyssey, Orbcomm, Orblink, Pentriad, Sky Station, Skybridge, Skybridge II, Spaceway NGSO, StarLynx, StarSys, Teledesic, Teledesic KuBS, Teledesic V-band, TRW EHF, Virgo, VITA

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