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A Parametric Communications Spacecraft Model for Conceptual Design Trade Studies

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This paper develops a parametric model for communications spacecraft intended for use in trade studies conducted during the early conceptual stages of system design. Existing models are becoming outdated and address only the most general class of communications satellites. Moreover, they do not give information about their uncertainty and range of applicability. This work concentrates specifically on communications satellites in non-geostationary orbits and is based on data from the 1990–1999 period. Model development is undertaken in three steps. The first step is to collect data from pertinent systems. Next, empirical scaling relationships are derived heuristically from this data. Finally, the model is compared against existing models and applied to trade studies. The end of the last decade saw the rise of a design tendency toward larger, more powerful communications spacecraft. Since then, it has become apparent that this trend may not be reflected in actual deployments. These larger systems, however, are taken into account in this paper. It is shown that wet mass scales less than linearly with payload power for large systems. A method of estimating propellant mass is introduced in order to improve wet mass estimates. A preliminary comparison with earlier models shows that this model improves upon their estimates for wet mass, while for satellite volume and antenna diameter in particular, more work is needed.

Nomenclature

M_{wet} = spacecraft wet mass, kg
M_{dry} = spacecraft dry mass, kg
M_{prop} = propellant mass, kg
M_{PL} = payload mass, kg
M_{pp} = primary power mass, kg
M_0 = pre-maneuver spacecraft mass, kg
V_{sat} = satellite volume, m^3
P_{PL} = payload power, W
P_{bol} = total power at beginning-of-life, W
P_{eol} = total power at end-of-life, W
T_{life} = system design lifetime, years
h = orbital altitude, km
D_T = transmitter diameter, m
f = service downlink frequency, GHz
ΔV = velocity increment, m/s
I_{sp} = specific impulse, s
g = acceleration due to gravity, m/s^2
N = number of data points
σ = RMS deviation

1 Introduction

RECENT events in the satellite communications industry have demonstrated that it is worthwhile to carefully explore the system conceptual design space before committing to a particular architecture. Iridium and Globalstar are operating examples of personal communications systems based on constellations of satellites in low Earth orbit (LEO). Although successful from a technical standpoint, in neither case were all the factors driving the profitability of the system apparent when the basic architectural concept was selected. It would be premature to conclude that space-based mobile communications services are not economically viable. However, the size of the design space for satellite communications systems presents a major difficulty. In considering a future system, it is not feasible to develop all possible design options in detail from the ground up. Relationships between payload power, spacecraft mass, total power, and spacecraft volume, among others, are key to early design trade studies.

A coherent system architecture trade methodology has been proposed by de Weck and Chang[1] which extends earlier work by Hastings, Shaw,[2] Miller, Jilla,[3] and Kashitani.[4] This methodology allows prediction of system perfomance taking into account not only the technical elements of the system but also economic and policy factors. A key part of the methodology is a tradespace exploration tool - a high-level simulation - used to quickly survey a large number of potential design options. This simulation makes use primar-

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ily of relationships derived from physical governing equations and cost estimating relationships to arrive at values for quantitative performance and cost metrics. The simulation also relies on scaling relationships (e.g. mass or power estimating relationships) derived from high-quality empirical data. This is the focus of the present paper. The scaling models currently available in the literature, however, are too general or outdated. Here, we specifically consider communications satellites in non-geostationary orbits (NGSO). Existing models also do not give information about their uncertainty and range of applicability.

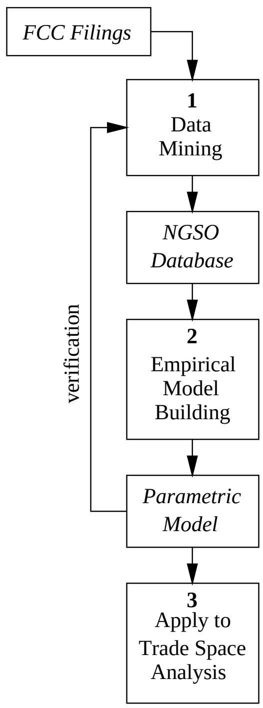

Fig. 1 Progression of model development

We therefore propose to develop new scaling models that focus specifically on NGSO satellite communications systems. Development progresses in three steps (see Figure 1). The first step is to collect empirical data on which scaling models can be based. Because the number of operational NGSO systems is so small (presently, these include only Iridium, Globalstar, and Orbcomm, although an ICO test satellite was successfully launched in June 2001), we have turned to data from systems that have been proposed but have either not launched or been abandoned altogether. The data is deemed of sufficient quality due to the rigors of the Federal Communications Commission's licensing process. The second step consists of data analysis and model building. Response surface methods are used to derive empirical scaling relationships among important system-level parameters. The third step involves integrating the scaling relationships into the larger tradespace exploration tool and exercising it according to the original intent.

Literature Review

A number of scaling models exist in the literature. Pritchard[5] (1984) originally developed a set of mass and power estimating relationships for communications satellites based on data from the 1970 and 1980 periods. Richharia[6] (1995) has reproduced this model in a more recent reference.

Larson and Wertz[7] have compiled an exhaustive set of guidelines for various aspects of space system design. These include mass and power estimating relationships as well as procedures for developing propellant, mass, and power budgets. Their identification of spacecraft configuration drivers for mass and power estimating relationships formed starting points in the development of our model. Saleh, Hastings, and Newman[8] have expanded on the work of Larson and Wertz, focusing on the effects of increasing system design lifetimes on spacecraft mass and cost.

There are a number of drawbacks to these scaling models. In some cases, the data underlying the models is out of date. Moreover, these models are applicable to a very general class of satellites. This can include spacecraft designed not only for communications, but for navigation, remote sensing, or other scientific or military purposes. It also includes spacecraft designed for geosynchronous orbits (GEO) as well as low or middle Earth orbits. In addition, very little information is available as to the uncertainty in these models or their applicability to various classes of satellites. Our aim is to develop a model focused specifically on LEO communications spacecraft that will give designers of such systems higher fidelity estimating relationships. In addition, we would like to provide quantitative measures of the uncertainty in these relationships.

2 Data Mining

FCC Filings

As noted earlier, data from proposed NGSO communications systems is needed because the number of operational systems is so small that insufficient data on physical hardware exists. Over the last fifteen years, a number of organizations have filed with the Federal Communications Commission (FCC) for licenses to operate NGSO satellite communications systems. These filings[1] are publicly available based on the Freedom of Information Act of 1966, commonly known as the FOIA (5 U.S.C. §552). The filings serve two purposes. First, they are an integral part of the FCC/ITU licensing process and as such must demonstrate the technical feasibility of a particular project. Second, they help the FCC assign specific frequency bands for service, feeder, and inter-satellite links. Obtaining FCC approval and acquiring the right to use desired

[1] obtained via http://www.fccfilings.com

Table 1 Chracteristics of LEO Market Segments

Market Segment	Terrestrial Equivalent	Example System	Typical Range: Operational Frequency	Typical Range: Bandwidth
Little LEO (8)	paging	Orbcomm	below 1 GHz	< 1 MHz
Big LEO (9)	cellular	Iridium	1–7 GHz	10–100 MHz
Broadband LEO (19)	fiber optic	Teledesic	12–50 GHz	500–3000 MHz

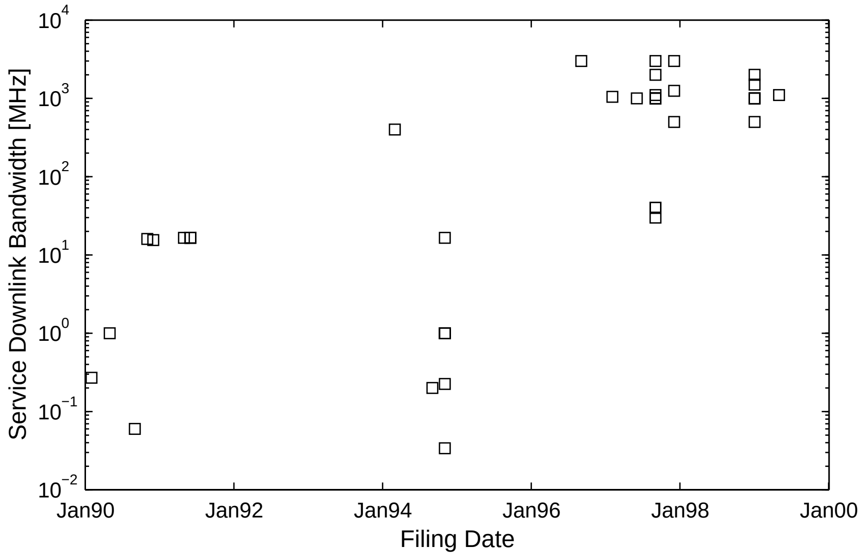

Fig. 2 Emergence of broadband systems during the 1990's

frequency bands has become a major hurdle that new and existing communications satellite operators need to clear. A substantial amount of effort goes into the development of a license application. The key idea of this research is to understand a representative range of proposed satellite systems based on their FCC filings and to generate useful empirical, parametric models from them.

The FCC filings typically begin with a description of the service(s) to be offered by the proposed system and an appraisal of the market for those services, as well as a justification for operation of the system with regard to the public interest. They also detail the legal and financial qualifications of the applicant and outline a schedule for construction and operation of the proposed system. Most importantly, each filing contains a technical description of the space, ground, and user segments of the proposed system. Because it must be established that the proposed system is viable, numerical values for important system-level parameters are provided. This has allowed us to systematically extract numerical data on communications system and network design, constellation architecture, spacecraft bus design, system cost, and setup of gateways and user terminals for thirty-six proposed NGSO satellite communications systems. The data pertinent to this paper is contained in Tables 6, 7, and 8 in Appendix A. What follows is a brief summary of this data and a look at some apparent trends in communications satellite design.

LEO Communications Systems

The Federal Aviation Administration's Associate Administrator for Commercial Space Transport divides the LEO satellite communications market into three segments termed Little LEO, Big LEO, and Broadband LEO[2]. The basic characteristics of each segment are summarized in Table 1. The number of each type of system surveyed as part of our work is shown in parentheses.

Little LEO systems like Orbcomm operate at frequencies below 1 GHz using less than 1 MHz of bandwidth. Their capabilities are limited to paging, data acquisition, asset monitoring, and the like. Often these systems neither require nor provide continuous global coverage. Big LEO systems are more or less analogous to terrestrial cellular networks, offering personal voice and in some cases low-rate data communications services. Iridium and Globalstar both fall into this segment. Big LEO systems generally operate at frequencies between 1 and 7 GHz and utilize 10–100 MHz of bandwidth. Finally, Broadband LEO systems offer

[2]LEO is used loosely here - approximately one third of the systems surveyed actually employ MEO constellations

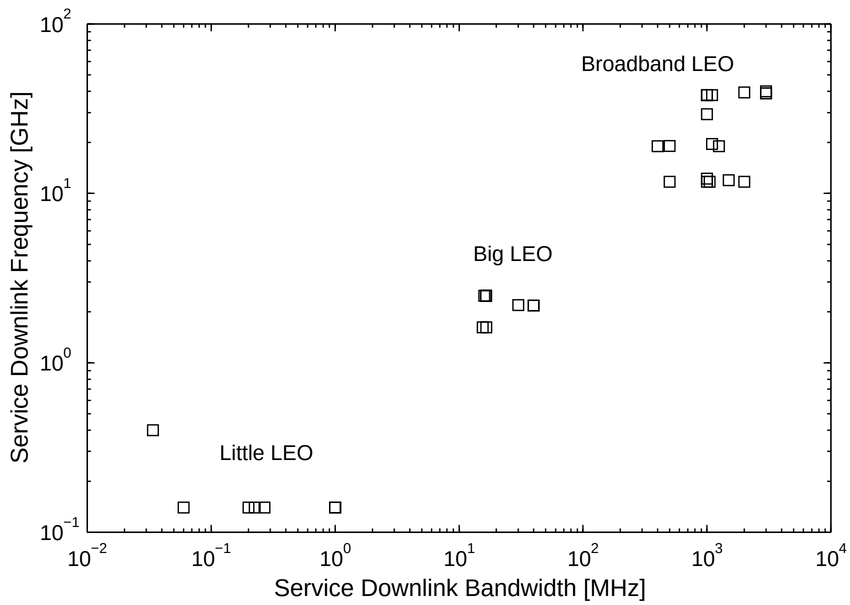

Fig. 3 Service downlink center frequency plotted against service downlink bandwidth requirement

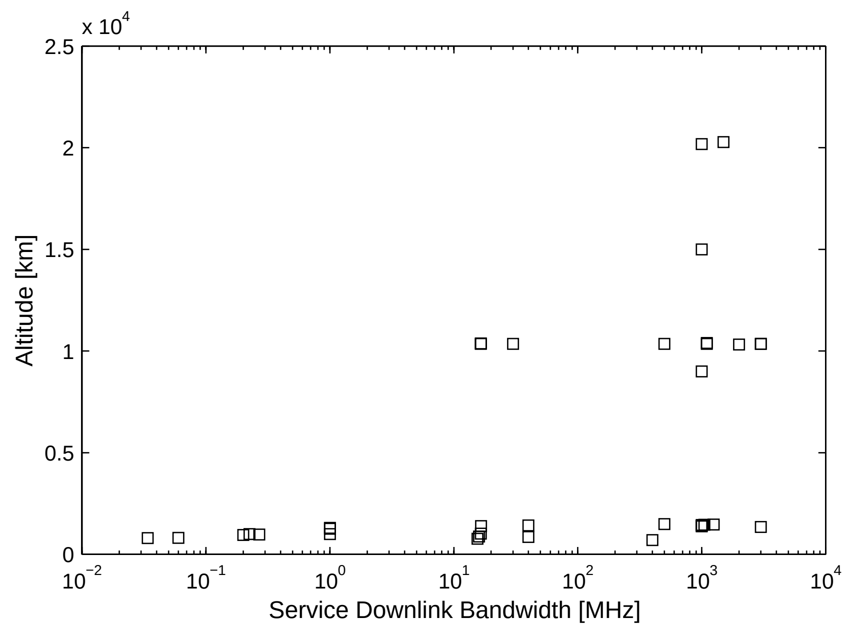

Fig. 4 Design altitude vs. service downlink bandwidth requirement

high speed data and multimedia services operating in the Ku, Ka, Q, and V bands and utilizing up to 3 GHz of bandwidth.

As noted by Saleh, Hastings, and Newman,[8] more recent communications satellite system designs have tended toward the Broadband LEO segment. To some extent, this trend owes to the emergence of terrestrial cellular networks over the last decade, which caused the market for satellite-based voice communications to shrink significantly. Figure 2 shows how service downlink bandwidth requirements for proposed NGSO systems evolved between 1990 and 2000. Growing bandwidth requirements have forced these systems to operate at increasingly higher frequencies where such requirements can be satisfied, as seen in Figure 3.

The nature of broadband services has also allowed the use of constellations in middle Earth orbit (MEO). This is illustrated in Figure 4. The time delay between transmission and reception associated with higher orbits is an issue for voice users (if delays exceed 400 ms) and can be an issue for data transmission using the TCP/IP protocol, but generally is barely perceptible to users of high speed data services.

On the whole, proposed communications spacecraft have become larger and more powerful in the last ten years, in step with the trend toward broadband systems. The highest launch masses belong to large broadband systems, however, other factors such as payload power and onboard propellant contribute more directly to this than increasing bandwidth requirements. Other factors contributing to the increasing size and power of communications spacecraft include more ambitious service requirements as well as increasing orbital altitudes and design lifetimes. While system design lifetimes have not increased uniformly over the past decade, design lifetimes of ten years or more have become more common since 1997. The same is true for orbital altitudes - MEO designs are much more prevalent after 1997.

The majority of the systems surveyed employ phased array service antennas. This allows flexible forming of spot beams within a satellite's area of coverage. Approximately half of the systems surveyed have a bent-pipe architecture, while the others use inter-satellite links, although 70% of the systems designed after 1995 fall into the latter category. Iridium, which filed for an FCC license at the end of 1990, was the first commercial system to use inter-satellite links. Iridium's inter-satellite links operate at a frequency around 23 GHz, while the most recent systems are designed with optical intersatellite links. Although some Little LEO systems rely on passive stabilization schemes (i.e. gravity gradient), almost all newer systems - with or without inter-satellite links - utilize 3-axis stabilization. Inter-satellite links necessitate 3-axis attitude control.

Limitations

Although we consider this data a suitable basis for an empirical model, the use of what amounts to hypothetical data has some limitations. First, it is to be expected that some of the parameter estimates in the FCC filings are overly optimistic. The degree to which these estimates are realistic varies. Some of the filings do include margins in their mass and power budgets, while others do not. In any case, it is difficult to systematically correct for overly hopeful estimates. This is one source of uncertainty in the models.

Due to the nature of the FCC filings, data for certain parameters for which scaling laws are very useful is inconsistent. Satellite volume is one example. The folded volume of a satellite is an important quantity because it in part determines potential launch vehicles as well as the number of satellites that can be launched at once, most often into the same orbital plane.[9] Some filings explicitly state the folded dimensions of the satellite, others give approximate dimensions of the spacecraft bus, and still others list no dimensions at all. This is reflective of the fact that spacecraft dimensions are less essential to the viability of the system than other parameters and therefore of lesser consequence to the FCC. In the particular case of satellite volume, we show the results of our analysis on a subset of the systems surveyed. Still, in order to develop a complete set of scaling models, the current database will need to be supplemented with data from other sources, or other modeling approaches will have to be employed.

3 Empirical Model Building

In this section, response surfaces are used to model system-level parameters as functions of design variables. Modeling proceeds in a heuristic manner. Given a logical starting point, an initial model is fit to the data and evaluated. It is then refined and re-evaluated until a satisfactory model is achieved.

Response Surface Methodology

For our purposes, response surface methodology (RSM) is a set of techniques that encompasses designing a set of experiments that will yield adequate and reliable measurements of the response of interest and determining a mathematical model that best fits the data collected, in order to obtain a better understanding of a system. RSM is similar to regression analysis, in that relationships between explanatory and response variables are established empirically.

What follows is a brief review of the mathematics underlying empirical modeling.[10] Consider the model

$$y = f(\mathbf{x}, \theta) + \varepsilon \qquad (1)$$

where $\mathbf{x} = [x_1, x_2, ..., x_k]^T$ are independent variables, $\theta = [\theta_1, \theta_2, ..., \theta_k]^T$ are unknown parameters, and ε is a random error term. The least squares estimate of θ is obtained by minimizing the function

$$S(\theta) = \sum (f(\mathbf{x}, \theta) - \hat{\mathbf{y}}_{\mathbf{u}})^2 \qquad (2)$$

where $\hat{y}_{ui}$ is the observed value of the response at the point $x_{u1}, x_{u2}, .., x_{uk}$; $u = 1, 2, ..., N$. The root mean square (RMS) deviation, one measure of model uncertainty, is the square root of the sum of residual squares divided by the number of observations:

$$\sigma = \sqrt{\frac{S(\hat{\theta})}{N}} \qquad (3)$$

Wet Mass

We begin our analysis by looking at spacecraft mass. Designers rely a great deal on mass estimating relationships because obtaining a bottom-up estimate for the mass of a spacecraft requires very detailed knowledge about its design. In general, the dry mass of a satellite is influenced primarily by the mass of its payload, which in turn is driven by the payload power. On

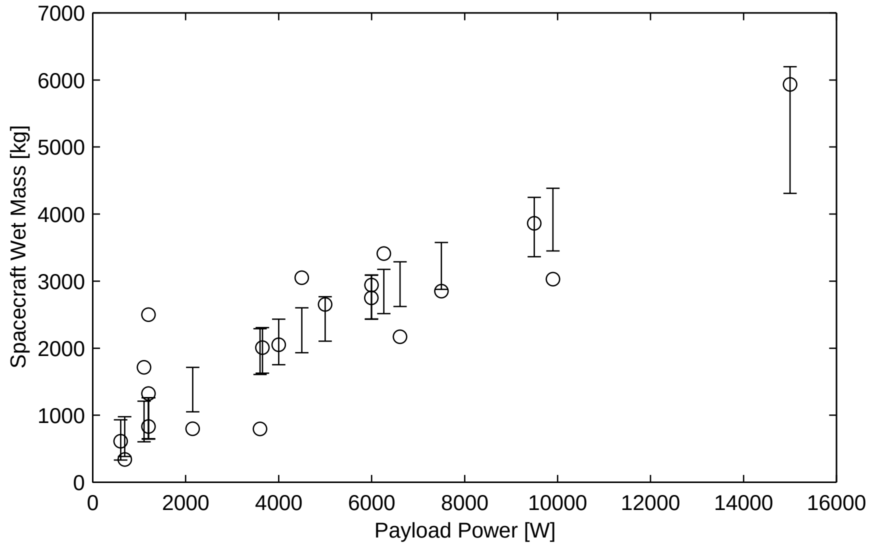

Fig. 5 Wet mass estimates using Equation (4) with 95% confidence intervals

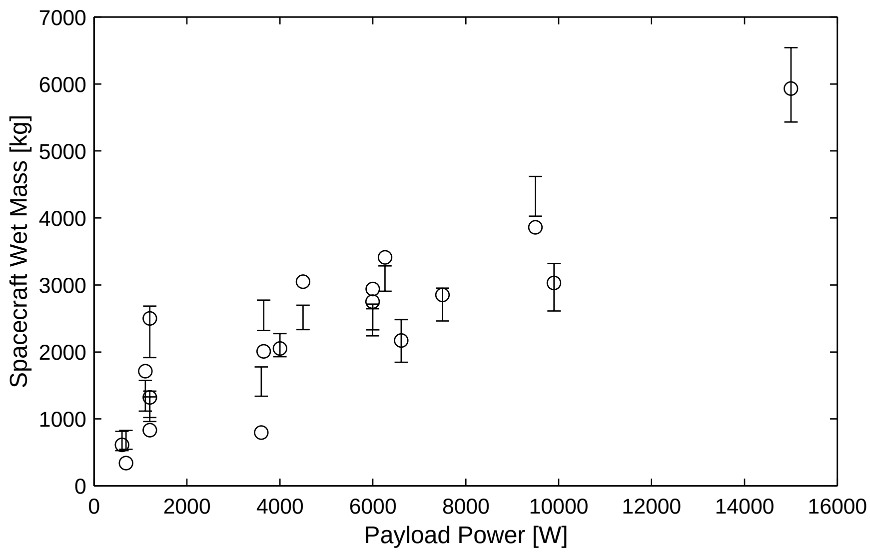

Fig. 6 Wet mass estimates using Equation (5) with 95% confidence intervals

a communications satellite, the bulk of the payload power requirement owes to the power of the transmitters, transponders, and receivers comprising the payload.[6]

The data shows a slightly better correlation between wet mass and payload power than dry mass and payload power; the relationship appears to be best described by a power law model of the form:

$$M_{wet} = 4.6{P_{PL}}^{0.73} + 140 \tag{4}$$

This (as well as each of the other scaling relations) is valid as long as the quantities are used in the units shown in the nomenclature. Wet mass estimates (for clarity excluding the smallest systems) computed for the systems in the database using the model in Equation (4) are superimposed over the actual data values in Figure 5. The error bars show 95% confidence intervals for these estimates.

The estimates from Equation (4) can be improved if another explanatory variable, propellant mass, is introduced into the model:

$$M_{wet} = 38(0.14P_{PL} + M_{prop})^{0.51} \tag{5}$$

Propellant can account for anywhere from a very small portion to as high as 35-45% of a spacecraft's wet mass, depending more fundamentally on the design altitude, design lifetime, and stabilization scheme of the system. Estimates computed using this improved relationship are shown with their corresponding data points and 95% confidence intervals in Figure 6. This is a first

Table 2 Comparison of wet mass models before and after inclusion of propellant mass

Eqn.	Ind. Variables	RMS Dev. [kg]	Avg. 95% CI [kg]
(4)	P_{PL}	551	±382
(5)	P_{PL}, M_{prop}	301	±199

attempt at modeling wet mass as a function of two variables, and it represents an improvement over modeling wet mass as a function of payload power alone. The two wet mass models are summarized in Table 2.

In each of the models so far, wet mass is estimated using a power law rather than a linear relationship. One might hypothesize that the shallowing nature (i.e. an exponent smaller than 1) of the mass-estimating relationships is due to economies of scale for large systems.

Propellant Mass

If propellant mass is to be used to improve a wet mass estimate, the designer must be able to accurately estimate the propellant mass requirement from more fundamental design variables. We were able to duplicate over half of the propellant mass estimates in the FCC filings to within 25% using an initial wet mass estimate, design altitude, design lifetime, and method of attitude control, despite making several major simplifying assumptions.

The first step toward estimating propellant mass is establishing a ΔV budget. This budget includes allowances for orbit injection, drag compensation, attitude control, and deorbit at end of life. Once the ΔV budget is established, the required propellant mass is given by:

$$M_{prop} = M_0[1 - e^{-(\frac{\Delta V}{I_{sp} g})}] \tag{6}$$

In Equation (6), M_0 is the spacecraft mass before a maneuver is completed. For example, it is the launch mass of the system if the propellant mass for orbit injection is being calculated.

In our calculations, a solid rocket apogee kick motor ($I_{sp} = 290$ s) was assumed for orbit injection, and monopropellant hydrazine (mono H, $I_{sp} = 210$ s) was assumed for all maneuvers following orbit injection. In addition, we assumed a transfer orbit with a perigee at an altitude of 150 km and an apogee at the design altitude. In computing the required ΔV, it was assumed that the apogee kick motor would circularize the transfer orbit at the design altitude. Somewhat arbitrary but reasonable parameters were used to compute ΔV's for drag compensation and attitude control - these are summarized in Table 3. In future work, antenna size and solar panel size might be used along with altitude to estimate the required ΔV for drag compensation. Finally, it was assumed that deorbit would be accomplished by changing the cirular orbit to an elliptical one with a perigee at the surface of the Earth.

Table 3 M_{prop} Estimation Parameters

Drag Compensation	
Altitude [km]	ΔV [m/s per year]
< 500	12
500–600	5
600–1,000	2
$> 1,000$	0
Attitude Control	
Type	ΔV
Gravity Gradient	0
3-Axis	10
Margin	22%

Figure 7 shows our propellant mass estimates with the estimates provided in the FCC filings. Thirty-two of the 36 systems are shown in the figure; three filings provided no estimate for propellant mass and we did not make an estimate for one other system (Pentriad). The names corresponding to the system numbers in Figure 7 are found in Table 7. Our estimates were within 25% of the provided estimates in 16 of the 27 cases where the provided estimate was not zero. For the five cases where the provided estimate was zero, our estimates ranged from 1–16 kg, averaging 8.2. In the case of system 10 in Figure 7, it appears that orbit injection is not considered separately in the estimate provided in the FCC filing. This is also likely true for systems 16, 18, 21, 23–26, and 29. The system names corresponding to these numbers can be found in Table 7 in Appendix A.

Fuel type or method of orbit injection or deorbit are examples of parameters that could be changed without making the computation substantially more difficult. Our estimates could no doubt have been improved across the board if our assumptions were corrected on a case-by-case basis. Thus, it is reasonable to expect to be able to accurately estimate the propellant mass requirement. Beginning with an initial wet mass estimate made using Equation (4), an estimate of the propellant mass requirement can be obtained (Table 3) and the wet mass estimate in turn refined using Equation (5).

Inter-satellite Links

It was hypothesized that the effect of inter-satellite links (ISL) on spacecraft mass was significant and

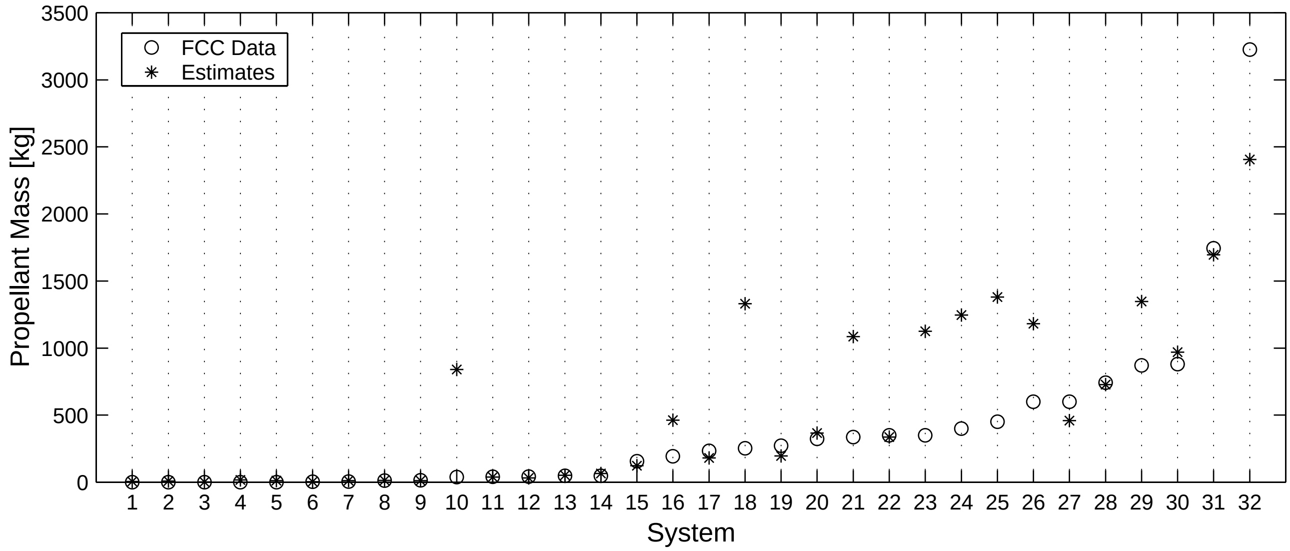

Fig. 7 Propellant mass estimates

could be deduced from the FCC data. However, no statistically significant effect was found. This is most likely due to variation in ISL implementations; that is, the number of intersatellite links on each spacecraft and the type of link employed (e.g. RF, optical) varied among the systems surveyed.

Subsystem Masses

If both wet mass and propellant mass are known, the dry mass of a satellite is given by:

$$M_{dry} = M_{wet} - M_{prop} \tag{7}$$

Payload and other subsystem masses are best estimated as percentages of the spacecraft dry mass. Data from the FCC filings is too sparse to provide a reasonable basis for estimating the mass percentages of subsystems other than payload. The percentages compiled by Saleh, Hastings, and Newman (2002) appear to be most helpful. These are summarized in Table 4. It is of note that our analysis found the average dry mass percentage of the payload to be 36% with a standard deviation of 11%, both somewhat higher than the values in Table 4.

Power

The total power requirement drives the size and mass of the solar arrays. Starting with a value for spacecraft power at end of life, the beginning of life requirement can be computed along with the surface area and mass of the solar array. Total spacecraft power at end of life appears to scale linearly with payload power:

$$P_{eol} = 1.3P_{PL} + 261 \tag{8}$$

This relationship is shown in Figure 8. The RMS deviation is 970 [W]. The total power requirement at end of life is related to the beginning of life requirement by

Table 4 Typical Subsystem Masses as Percentages of Spacecraft Dry Mass (adapted from Ref. 8)

Subsystem	% M_{dry} (Std. Dev.)
Payload	27 (4)
Attitude Control	7 (2)
Electrical Power	32 (5)
Propulsion	4 (1)
Structure	21 (3)
Thermal	4 (2)
Tracking and Command	5 (2)
TOTAL	100

$$P_{eol} = P_{bol} \times L_d \tag{9}$$

Life degradation, L_d, is a function of the system design lifetime as well as the degradation per year. The degradation per year, in turn, depends on a number of other factors, including orbital parameters and properties of the solar array. A more complete discussion of life degradation can be found in Ref. 8.

Volume

In the final two sections of analysis, we consider parameters for which relationships are based on a smaller subset of the FCC data ($N \approx 10$). First, we consider satellite volume. In the early stages of design, the volume of a spacecraft is typically estimated by dividing its launch (wet) mass by an appropriate density value.[7] Figure 9 shows spacecraft volume plotted against wet mass. The slope of the regression line suggests an average density of 285 kg/m^3, significantly higher than the typical range of 20–172 given in Ref. 7. One possible hypothesis is that a miniaturization of components has led to higher spacecraft densities.

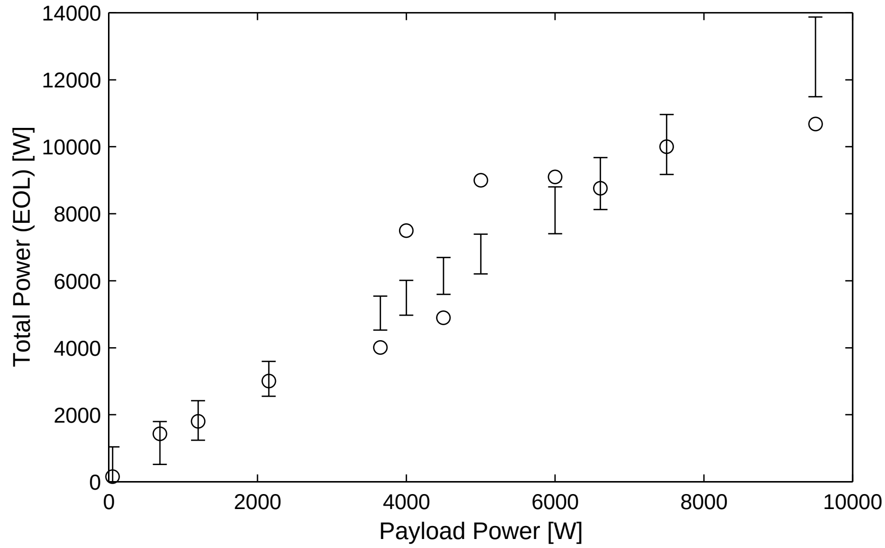

Fig. 8 P_{eol} **estimates using Equation 8 with 95% confidence intervals**

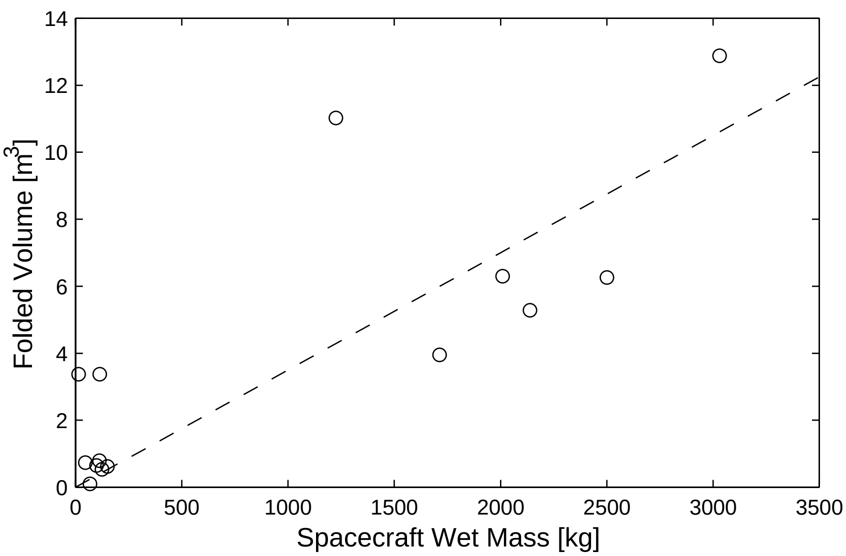

Fig. 9 Spacecraft volume plotted against wet mass

Transmit Antenna Diameter

The square of the transmit antenna diameter (analogous to the total area of the service downlink antenna) appears to scale linearly with design altitude and transmit frequency. Transmit antenna diameter is plotted in Figure 10 against a dummy variable, u, where

$$u = \frac{f}{12.5} + \frac{h}{2500} \tag{10}$$

The complete scaling model is

$$D_T{}^2 = \frac{f}{12.5} + \frac{h}{2500} + 0.85 \tag{11}$$

It is apparent that the scaling models for volume and antenna diameter are substantially more uncertain than the models for mass or power. In addition to being based on small subsets of the FCC data, a good portion of the data points in Figures 9 and 10 are significant outliers of the regression line. Nevertheless, these models could still be of use for first order estimates before a detailed link budget can be established.

Applicability

The models developed in this paper appear to be most useful in the design of larger spacecraft, namely where $P_{PL} \in [1, 16]$ kW, as the confidence intervals will be a smaller percentage of the estimates for larger systems. However, it is of note that in the cases of the mass and power estimating relationships there were no serious outliers (i.e. $|y_u - \hat{y}_u| > 2\sigma$). This suggests

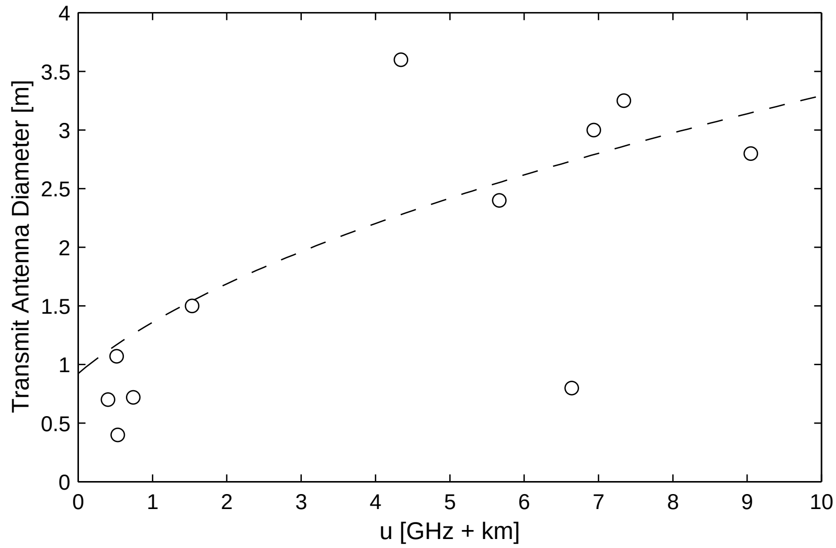

Fig. 10 Service downlink antenna diameter as a function of design altitude and service downlink center frequency

Table 5 Comparison of wet mass model with earlier models

Model	Figure 11	Avg.% Error	RMS Deviation [kg]
Equation (12,13)	(a)	-4.4	727
Equation (14)	(b)	14.4	955
Equation (5)	(c)	1.6	301

that the models are still of at least limited use over all sizes of communications satellites.

4 Comparison with Earlier Models

We now proceed to examine the wet mass model developed in Section 3 with earlier models. Specifically, we consider models presented in Refs. 6 and 7. Each of these includes estimating relationships for several parameters other than wet mass.

Richharia[6] estimates wet mass in the following manner. First, dry mass is estimated as a function of the payload mass, M_{PL}, and the primary power mass, M_{pp}:

$$M_{dry} = 2.0(M_{PL} + M_{pp} - 10) \tag{12}$$

This relationship is valid for 3-axis stabilized spacecraft. The primary power mass includes solar arrays, batteries, and power control hardware. Our data yielded a rough estimate of the primary power mass as approximately 24% of the dry mass. We substitute this for M_{pp} into Equation (12) in our calculations. Wet mass is then estimated using:

$$M_{wet} = M_{dry} e^{\frac{(100+5T_{life})}{gI_{sp}}} \tag{13}$$

A nominal I_{sp} of 260 s was used in our calculations.

The "model" presented by Larson and Wertz[7] is really better described as a set of guidelines for system design. It was not intended for specific application to communications satellites. Nevertheless, we include it here for completeness. Dry mass is estimated as 1.3 times the payload mass, and propellant mass is estimated as between 0–25% of the dry mass. We take the high end of the latter estimate (25%) and from Equation (7), arrive at:

$$M_{wet} \approx 4M_{PL} \tag{14}$$

Estimates using Equations (12,13), (14), and (5) are shown in Figure 11 with the FCC data. A numerical comparison is shown in Table 5. We see that Equations (12,13) tend to underestimate while Equation (14) tends to overestimate. On the basis of both average percent error and RMS deviation, our model represents an improvement over Refs. 6 and 7.

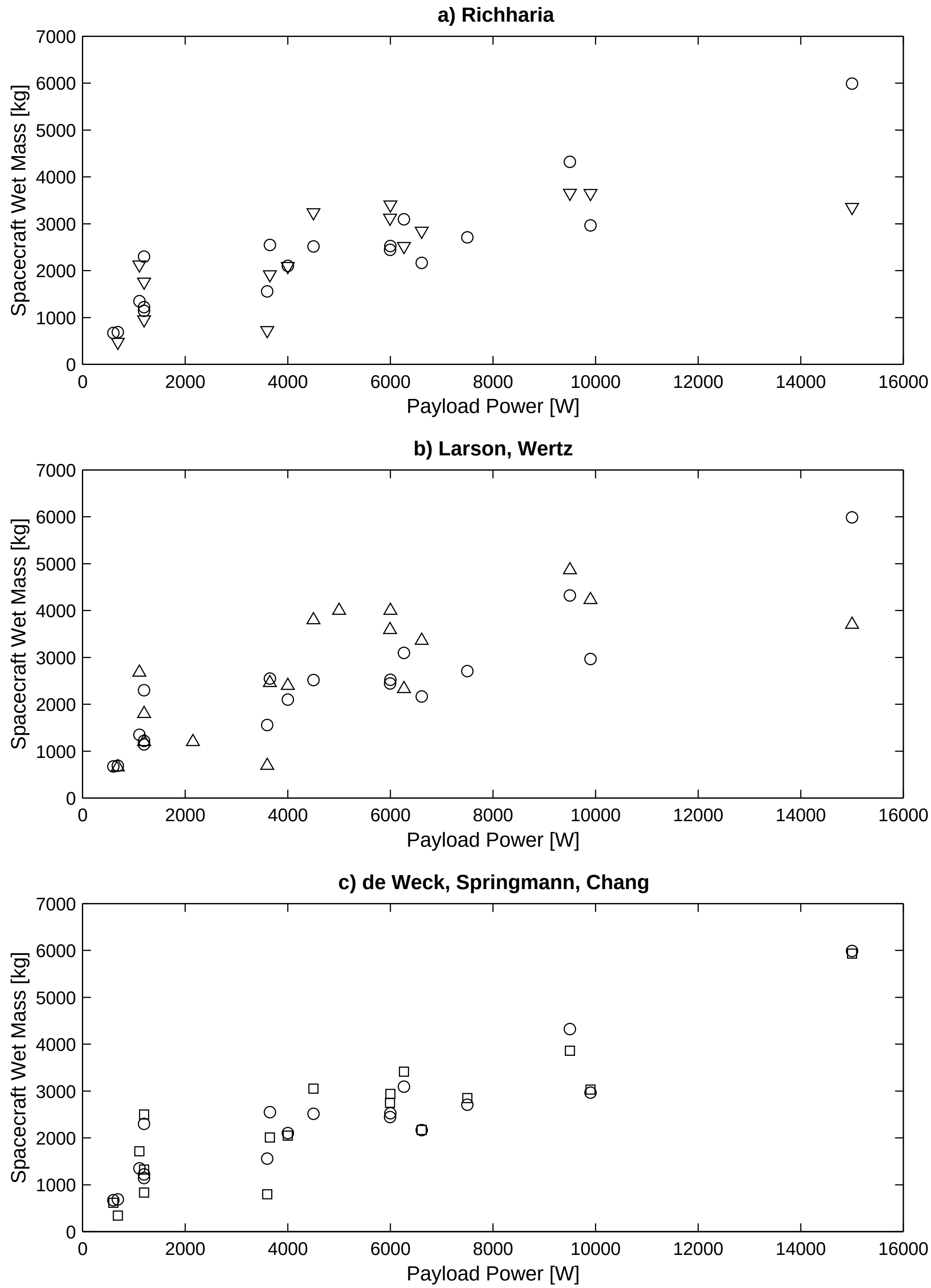

Fig. 11 Graphical comparison of our wet mass model with earlier models; (a), (b), and (c) show estimates using Equations (12,13), (14), and (5) respectively

5 Conclusions and Future Work

A parametric model for communications spacecraft was developed in Section 3 using the data in Appendix A. Though not a comprehensive overview, Figure 12 illustrates the fundamental dependence of trade studies on scaling models. Intermediate parameters like mass, power, and volume directly influence performance and cost. Certain intermediate parameters can be traded against one another (e.g. antenna size and payload power), so it is important to understand how they scale with design inputs. Dependable models are essential to the ability to accurately survey the system architecture design space and anticipate the success of a satellite communications venture.

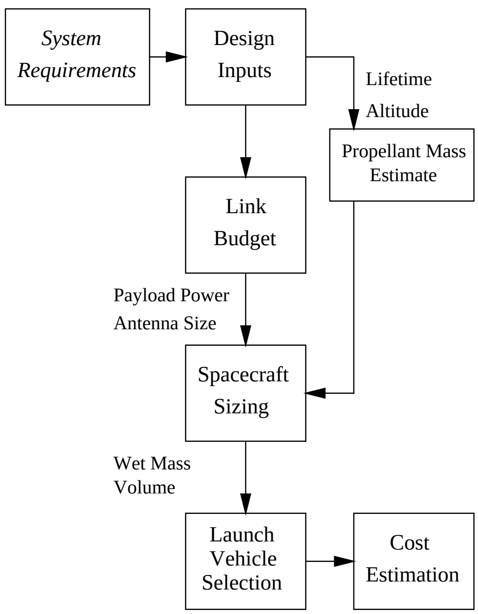

Fig. 12 Application of scaling models to trade studies

In order to further demonstrate the improvement our wet mass model makes over earlier models, we note that the actual wet mass of an Iridium satellite is 689 kg,[11] including 115 kg of propellant, both more than twice the figure in Iridium's FCC filing. Since the actual total power requirement is very close to the figure in the filing ($\approx$ 1400 W), it can be assumed that the same is true for the actual payload power requirement. Using Equation (5), the wet mass estimate at the filing date would have been 467 kg (vs. 340.7 kg in the FCC filing). This estimate would have been 582 kg for the deployed spacecraft (vs. the actual value of 689 kg). While the estimates are off in both cases, the inclusion of propellant mass in Equation (5) allowed changes to the design lifetime and design altitude made between license application and deployment to be taken into account.

FCC Database

Riching the database will require an ongoing effort. A larger data set would presumably result in higher fidelity models with less uncertainty, and would facilitate identification of outlying systems. There are important parameters that we have not been able to model well using the FCC filings, particularly spacecraft volume and transmit antenna size. Development of more reliable models for such parameters will require additional data. Future work specific to antenna size might focus on phased array antennas, since their use is now widespread.

In parametric modeling there is an implicit assumption that future systems will follow historical trends. It is difficult to speculate as to the number and type of commercial LEO or MEO constellations that will be launched in the next 20–30 years. Many systems were proposed during the 1990's, but it seems unlikely that any - other than those already in operation - will ultimately be deployed. Maintenance of the database will be key to ensuring that emerging technologies or changing design trends do not render existing scaling models useless. Special attention will need to be paid to trends in the market for space-based communications and how they might affect NGSO spacecraft design.

Neural Networks

Neural networks show promise as multivariable function approximators. Provided that the data available is aqequate for training, this approach could be applied to the development of scaling models, particularly where nonlinear multivariable relationships arise. Future work might take this approach and compare the results with the more traditional statistical approach.

Trade Space Exploration Tool

One of the goals of this work is to support the development of an integrated trade space exploration tool. We intend to to reanalyze our previous work in view of this new parametric model.

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Appendix A

Table 6 FCC Constellation Data

System	Filing Date	T_{life} [years]	h [km]	Service Downlink Bandwidth [MHz]	Service Downlink Center Frequency [GHz]
@contact	May-99	12	10400	1100	19.55
AMSC NGSO	Nov-94	10	10355	16.5	2.49
Boeing NGSO	Jan-99	12	20182	1000	12.20
Celestri	Jun-97	8	1400	1000	29.30
Constellation	Jun-91	5	1018.6	16.5	2.49
Ellipso	Nov-90	5	875	16	2.49
E-Sat	Nov-94	10	1261	1	0.14
Final Analysis	Nov-94	7	1000	0.225	0.14
GE LEO	Nov-94	5	800	0.034	0.40
GEMnet	Nov-94	5	1000	1	0.14
Globalstar	Jun-91	7.5	1389	16.6	1.62
Globalstar 2 GHz	Sep-97	7.5	1420	40	2.18
Globalstar GS-40	Sep-97	7.5	1440	1000	38.00
HughesLINK	Jan-99	12	15000	1000	11.73
HughesNET	Jan-99	10	1490	500	11.73
ICO	Sep-97	12	10355	30	2.19
Iridium	Dec-90	5	765	15.5	1.62
Iridium Macrocell	Sep-97	7.5	853	40	2.18
Leo One	Sep-94	5	950	0.2	0.14
LM MEO	Dec-97	10	10352	3000	40.00
M Star	Sep-96	8	1350	3000	39.00
Odyssey	May-91	10	10371	16.5	2.49
Orbcomm	Feb-90	7	970	0.27	0.14
Orblink	Sep-97	7	9000	1000	38.00
Pentriad	Sep-97			2000	39.50
SkyBridge	Feb-97	8	1457	1050	11.73
SkyBridge II	Dec-97	10	1468	1250	19.00
Spaceway NGSO	Dec-97	12	10352	500	19.05
StarLynx	Sep-97	12	10352	1100	38.05
StarSys	May-90	5	1300	1	0.14
Teledesic	Mar-94	10	700	400	19.00
Teledesic KuBS	Jan-99	7	10320	2000	11.70
Teledesic V-band	Sep-97	7	1375	1000	38.00
TRW EHF	Sep-97	15	10355	3000	39.00
Virgo	Jan-99	12	20281	1500	11.95
VITA	Sep-90	5	805.5	0.06	0.14

Table 7 FCC Mass and Volume Data

System	M_{dry} [kg]	M_{prop} [kg]	M_{wet} [kg]	M_{pl} [kg]	M_{pp} [kg]	V_{sat} [m^3]	Figure 7 Ref.
@contact	2542	870	3412	583			29
AMSC NGSO	2450	600	3050	950			26
Boeing NGSO	2118	1743	3861	1217	352		31
Celestri	2500	600	3100				27
Constellation	113.4	11.3	124.7	34.5	26.3	2.12	8
Ellipso	68	0	68			0.10	1
E-Sat	100	14	114			3.38	9
Final Analysis	98.5	0	98.5			0.65	2
GE LEO	15	0	15		6	3.38	3
GEMnet			45				-
Globalstar	222	40	262	60	12		11
Globalstar 2 GHz	676	156	832	300	253	17.33	15
Globalstar GS-40	992	234	1226			11.03	17
HughesLINK	2540	400	2940	1000			24
HughesNET	1650	350	2050	600			22
ICO	2413.8	336.2	2750	898	601.6		21
Iridium	299.4	41.3	340.7	165.1	78.9		12
Iridium Macrocell	1442	271	1713	670		3.95	19
Leo One	154	0	154	26	31		4
LM MEO	2133	38	2171	840			10
M Star	2210	323	2535				20
Odyssey	1620	880	2500	450		6.26	30
Orbcomm	145	5	150			2.47	7
Orblink	1268	742	2010	615	350	6.30	28
Pentriad	1455	684	2139	592		5.28	-
SkyBridge			800	300			-
SkyBridge II			2650	1000			-
Spaceway NGSO	2500	350	2850				23
StarLynx	3050	450	3500				25
StarSys	112	0	112	24	2	0.79	5
Teledesic	747	48	795	173	239	72.04	13
Teledesic KuBS	1132	192	1324				16
Teledesic V-band	566	48	614				14
TRW EHF	2707	3227	5934	926			32
Virgo	2778	252	3030	1058	936		18
VITA	43	2.5	45.5				6

Table 8 FCC Antenna and Power Data

System	D_T [m]	P_{PL} [W]	P_{bol} [W]	P_{eol} [W]
@contact		6264		
AMSC NGSO	3.6	4500		4900
Boeing NGSO	2.8	9500	14201	10678
Celestri			13600	4600
Constellation		49	250	49
Ellipso			360	120
E-Sat	1.07			200
Final Analysis		29.5	59	47
GE LEO		11	10.56	9.1
GEMnet				
Globalstar		50	875	150
Globalstar 2 GHz	0.72	1200	3000	1520
Globalstar GS-40			4500	2280
HughesLINK	3	6000	10500	9100
HughesNET	1.5	4000	8200	7500
ICO		5994		9000
Iridium		686		1429
Iridium Macrocell		1105	7300	
Leo One		158		290
LM MEO	3.25	6610		8760
M Star			3100	1530
Odyssey		1200		1800
Orbcomm	0.7	325	450	360
Orblink	0.8	3650		4010
Pentriad		100	10247	7684
SkyBridge		2150		3000
SkyBridge II		5000		9000
Spaceway NGSO	2.4	7500	13800	10000
StarLynx			17000	15000
StarSys	0.4	84		125
Teledesic		3600	11595	6626
Teledesic KuBS		1200	6500	1500
Teledesic V-band		600	5000	800
TRW EHF		15000		15500
Virgo		9900		10593
VITA			42	25.3