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Schedule and Cost Estimating Analysis for LEO Satellite Constellations

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Abstract

Following the lead of commercial satellite service companies, the Department of Defense (DoD) is developing new Low Earth Orbit (LEO) megaconstellations to improve the resilience and agility of military space systems. Megaconstellations can have hundreds of satellites in multiple orbital planes ranging from 500 kilometers to 1,200 kilometers in altitude. Additional replenishment satellites are maintained on the ground, ready to launch to replace satellites lost due to planned de-orbits, reliability issues, or attrition due to natural or manmade causes. DoD planning purposes demand a clear understanding of the cost implications for developing, procuring, and operationalizing a LEO-based megaconstellation's ground system and satellites, including initial launch and replenishment costs. This paper describes robust and simple parametric cost models, with reasonable explanatory and predictive power, that we developed to estimate the costs of these megaconstellations using data from 12 LEO government and commercial constellations.

Introduction

Commercial and government space sectors see significant utility in large networked satellite constellations in low earth orbit (LEO). Networked satellites hold the promise of providing near real-time global communications, access to the internet, and remote sensing. The Department of Defense (DoD) is currently procuring one such constellation, called the Tranche 1 Transport Layer (T1TL), through the Space Development Agency (SDA). According to the SDA, the three prototype agreements combined are worth approximately $1.8 billion and will "establish the foundation for Tranche 1 Transport Layer (T1TL), a mesh network of 126 optically interconnected space vehicles (SVs) that will provide a resilient, low-latency, high-volume data transport communication system, and be ready for launch starting in September 2024" (DoD, 2022).

> SDA's Transport Layer is envisioned, modeled, and architected as a constellation varying in size from 300 to more than 500 satellites in LEO ranging from 750km to 1200km in altitude. With a full constellation, 95% of the locations on the Earth will have at least two satellites in view at any given time, while 99% of the locations on the Earth will have at least one satellite in view. This will ensure constant world-wide coverage around the globe. The constellation will be interconnected with Optical Inter-Satellite Links (OISLs)

which have significantly increased performance over existing radio frequency cross links. LEO orbits in conjunction with OISLs will reduce path loss issues but more importantly offer much lower latencies, which are deemed critical to prosecute time sensitive targets in today's wartime environment. (*Transport*, n.d.)

As part of a program review of the SDA's transport layer, and with the realization that megaconstellations in LEO are likely to proliferate, we developed an unbiased multivariate linear regression model[1] to cost the design, test, procurement, and launch of entire satellite constellations. In addition, we present a model to estimate replenishment costs as a function of satellite reliability and the number of LEO orbital planes in the constellation.

Methodology

Many sources of data were referenced to obtain the satellite program data listed below, including:

- Selected Acquisition Reports, and briefings from the SDA, the Space Force, Missile Defense Agency, and Office of the Secretary of Defense (OSD; for DoD satellites)
- President's Budget and Service/Agency Budget Justification, Federal Procurement Data System (FPDS), Defense Acquisition and Cost Information System (DACIS), Government Accounting Office reports (for U.S. government satellites, the DoD, National Aeronautics and Space Administration (NASA), and the National Oceanographic and Atmospheric Administration (NOAA)
- News and trade articles or other open sources of information (Wiki, Gunther's Space Page)

Relevant and available commercial and government space programs from the last three decades also were included in the dataset.

The following constellations of LEO satellites were used in our linear regressions for cost modeling:

- Iridium
- Iridium 2nd Gen
- Orbcomm
- Midcourse Space Experiment/Space Based Visible (MSX/SBV) sensor
- Space Based Space Surveillance (SBSS)
- Globalstar
- Globalstar 2nd Gen
- OneWeb
- COSMIC
- COSMIC-2
- Starlink
- Space Tracking and Surveillance System (STSS)

Data we collected:

- Satellite or constellation name
- Orbital configuration (LEO, MEO, HEO [low, medium, and high Earth orbit] altitudes)

[1] Standard method for regression modeling. The model uses least squares and has all of the assumptions embedded therein.

- Mission (SATCOM/Other)
- Commercial/other
- Generation (1st/2nd)
- Program/company information
- Program cost
- Program start and end dates
- Contract cost
- Contract number
- Contractor/builder
- Contract award date, end date, or period of performance (POP)
- Other milestone dates (i.e., Milestone B, Preliminary Design Review, Critical Design Review, Available for Launch [AFL] date, Initial Operational Test and Evaluation [IOT&E] complete date)
- Number of satellites in the constellation
- Constellation launch dates
- Mass (kg)
- Operational lifetime
- Ground station (descriptions, development schedule, cost, contractor, etc.)
- Time (years) to launch of first mission-capable satellite as a proxy for development time
- Time to complete launching the constellation

Calculations:

- Mass * Orbital Altitude * Number of Satellites (MAN) is a synthetic variable used in our linear regressions, based on the physics of putting a constellation in its operational orbit.

Regressions: Independent variables considered:

- Satellite generation
- Number of satellites in the constellation
- Mission (SATCOM/Other)
- Commercial/other
- Generation (1st/2nd)
- Mass (kg)
- Time (years) to launch of first mission-capable satellite as a proxy for development time
- Year first mission-capable satellite launched
- Lifetime (years)
- Orbital altitude (km)

We modeled total constellation cost using multiple linear regression techniques with various combinations of logical independent variables selected (from Table 1), along with a synthetic variable, MAN, that is going to be correlated with the total "work," in a physics sense, to get the constellation in its operational orbit:

- Mass (kg) * Orbital Altitude * Number of Satellites in the Constellation (MAN)

The resulting equations were evaluated using statistical parameters, and the robustness of the methodology was evaluated by determining how much data could be excluded from the regression while maintaining both a good fit of the remaining data and a strong prediction of the data that were excluded. In this paper, we discuss the simplest and best equation, as defined by these measures.

We also developed a replenishment cost model for LEO satellite constellations as a function of the number of orbital planes in the constellation, an assumed reliability of the satellites (where reliability equals 1- the number of satellites that need to be replaced annually/number of satellites), and a premium for high-priority launches. Launch vehicle costs were based on inflation-adjusted Falcon 1 and Falcon 9 rocket launch costs in open-source literature.

Schedule Analysis

Figure 1 depicts the amount of time it took to launch the first satellite for 22 programs. Year 1 is the year of program initiation, and the last year illustrated is the year of the first launch of a *mission-capable* space vehicle. Space vehicles are organized by increasing mass, with the lightest vehicles appearing at the bottom of the chart. Satellites with different orbits (e.g., LEO, MEO, Geosynchronus Earth orbit [GEO], and Sun-synchronous orbit [SSO]) are included in the dataset and labelled on the vertical axis next to mass. The green bars in Figure 1 represent commercial programs, whereas the blue bars are government/military and scientific. The rust-shaded bar in the background represents the average development time ranging between +/- 1 SD.

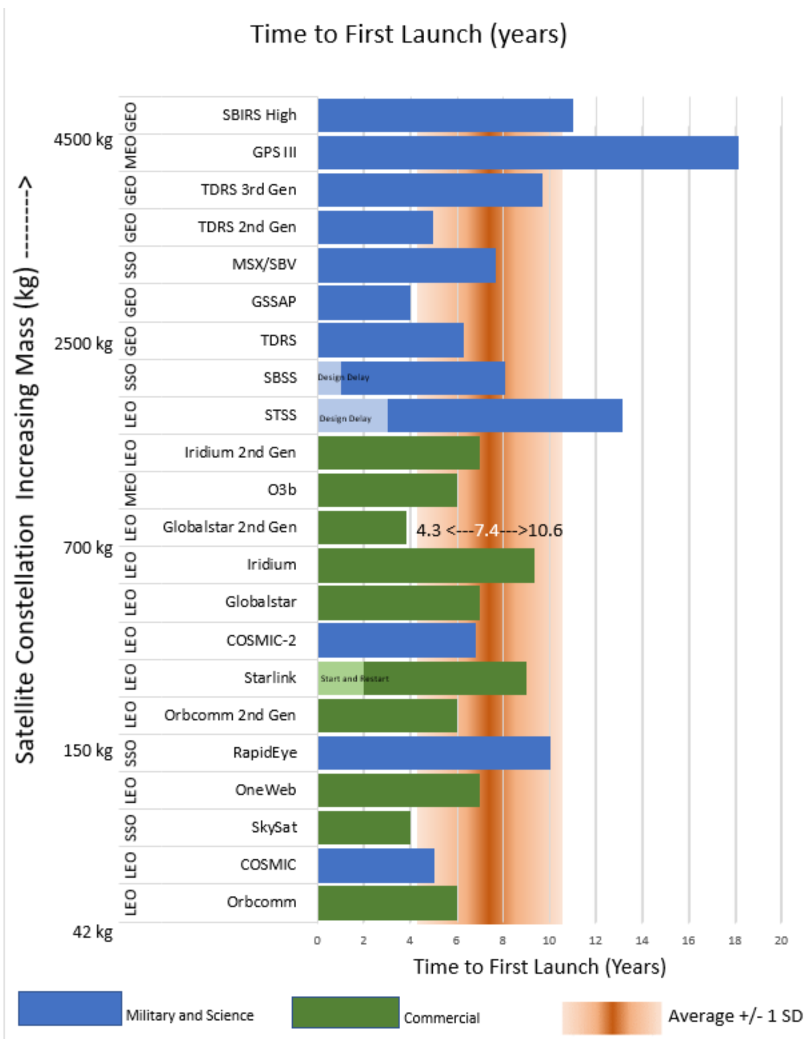

Figure 1. Historical Commercial and Government Space Development Schedules

Figure 2 compares the development times for the 22 constellations shown in Figure 1 and the subsets of 11 commercial, 6 DoD, and 13 LEO constellations. The average development time for all 22 systems in Figure 1 is 7.4 years. The average development time for the 13 LEO constellations is 7.2 years.

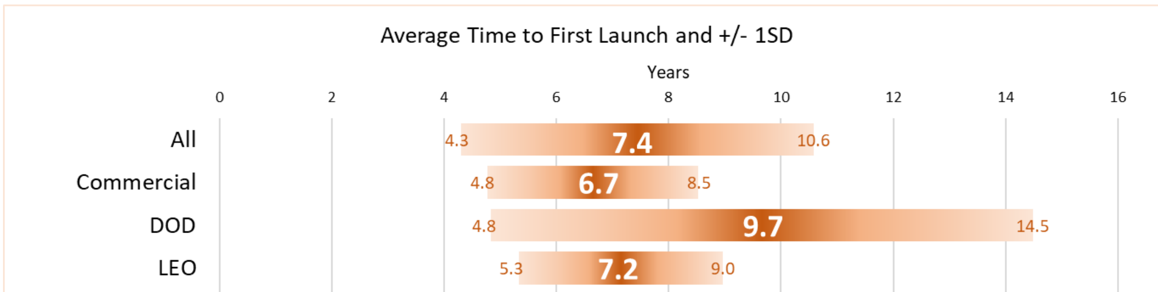

Figure 2. Average Time to Launch the First Mission-Capable Satellite

Cost Analysis

Table 1 shows the cost data collected for 12 LEO constellations. Commercial, military, and scientific constellations are represented. All costs are in $ million calendar year 2022 ($M CY 2022). We used the time from the program start (or contract award in its absence) to the launch of the first *mission-capable* satellite as a proxy for development time.

Table 1. Cost Data for LEO Constellations

Constellations	Generation	Number of satellites	SATCOM	Commercial	Mass (kg)	Time to first launch (years)	Year of 1st launch	Lifetime (years)	Orbital Altitude (km)	Cost (CY22 $M)
COSMIC	1	5	0	0	70	5.0	2006	5	700	111
COSMIC-2	0	6	0	0	278	6.8	2019	5	710	233
Orbcomm	1	28	1	1	42	6.0	1995	4	661	514
Globalstar 2nd Ger	0	24	1	1	700	3.8	2010	15	1,410	934
SBSS	1	11	0	0	1,031	7.1	2010	7	630	1,167
MSX/SBV	1	1	0	0	2,700	7.6	1996	26	898	1,514
STSS	1	2	0	0	1,000	10.1	2009	12	1,350	2,342
Globalstar	1	52	1	1	450	7.0	1998	8	1,410	2,976
Iridium 2nd Gen	0	81	1	1	860	7.0	2017	13	780	3,202
OneWeb	1	428	1	1	147	7.0	2019	7	1,200	4,011
Iridium	1	98	1	1	689	9.3	1997	8	780	7,488
Starlink	1	1,737	1	1	260	7.0	2018	6	550	10,400

We conducted regression analysis with this data as described in the methodology section. Dummy variables were used for the generation of the constellation (1 for first, 0 for second), those that were SATCOM (1 for SATCOM, 0 for other), and those that were commercial (1 for commercial, 0 for other.) The single best performing equation, however, excluded all variables except the proxy for the development schedule and the product of mass, orbital altitude, and number of satellites in the constellation (MAN).

Table 2 shows the regression results that we obtained with the equation that had the best statistical parameters and most statistically significant of the independent variables. The equation is a function of the time to first launch (development time) and the physics-based synthetic variable that is the product of satellite mass, orbital altitude, and the number of satellites in the constellation.

The resulting cost estimating relationship (CER) in CY22 $M is

$$CER = Development\ Time * 213 + MAN * 3.78 * 10^{-5}$$

where MAN is the physics-based synthetic variable mass*altitude*number of satellites.

Table 2. Best Regression Result

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.96
R Square	0.92
Adjusted R Square	0.81
Standard Error	1303
Observations	12

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	1.93E+08	9.64E+07	5.68E+01	7.86E-06
Residual	10	1.70E+07	1.70E+06		
Total	12	2.10E+08			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
MAN	3.78E-05	5.60E-06	6.76E+00	4.98E-05	2.54E-05	5.03E-05	2.54E-05	5.03E-05
Time to first launch (ye	2.13E+02	6.17E+01	3.45E+00	6.20E-03	7.56E+01	3.51E+02	7.56E+01	3.51E+02

RESIDUAL OUTPUT

Actual	*Predicted Cost (CY22 $M)*	*Residuals*	*Standard Residuals*
111	1075	-9.63E+02	-8.10E-01
233	1495	-1.26E+03	-1.06E+00
514	1308	-7.94E+02	-6.67E-01
934	1708	-7.74E+02	-6.51E-01
1167	1778	-6.10E+02	-5.13E-01
1514	1719	-2.05E+02	-1.72E-01
2342	2259	8.34E+01	7.02E-02
2976	2741	2.36E+02	1.98E-01
3202	3548	-3.46E+02	-2.91E-01
4011	4350	-3.38E+02	-2.84E-01
7488	3986	3.50E+03	2.95E+00
10400	10893	-4.93E+02	-4.15E-01

Figure 3 shows the predicted versus actual cost values using the CER above. The regression results are displayed as blue dots with vertical standard error bars.

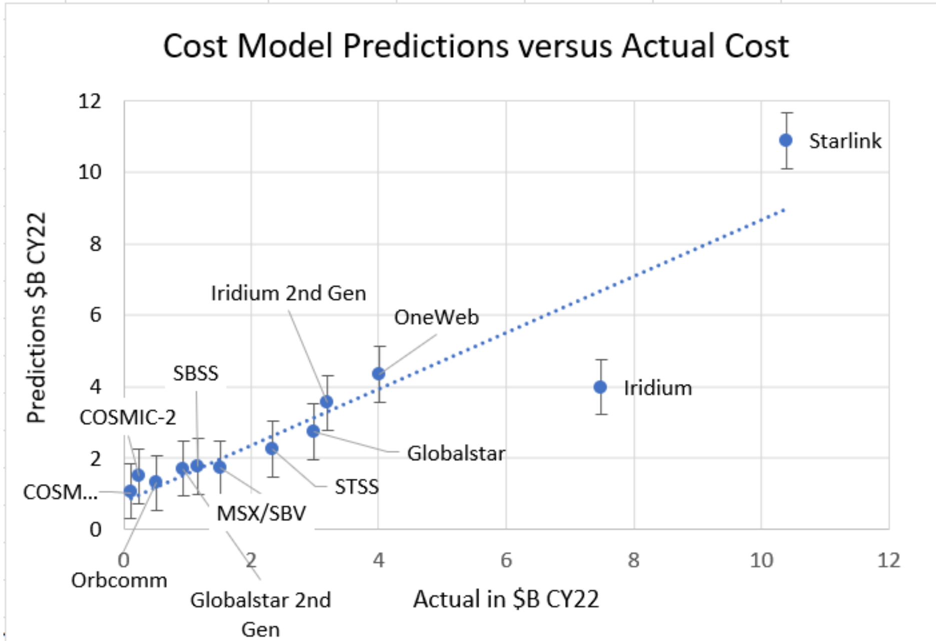

Figure 3. Sensitivity Analysis

The robustness of the methodology was evaluated by determining how much data could be excluded from the regression while maintaining both a good fit of the remaining data and a strong prediction of the data that were excluded. Figure 4 shows the regression results excluding the top three data points (left) and the lower six data points (right). Both the regression and variables for each “degraded” model below remained significant. However, excluding the highest cost constellations from the regression on the left led to a model that was less predictive for higher cost constellations. For the right-hand chart, the methodology still leads to a reasonable predictive model for the five lower points that were excluded from the regression.

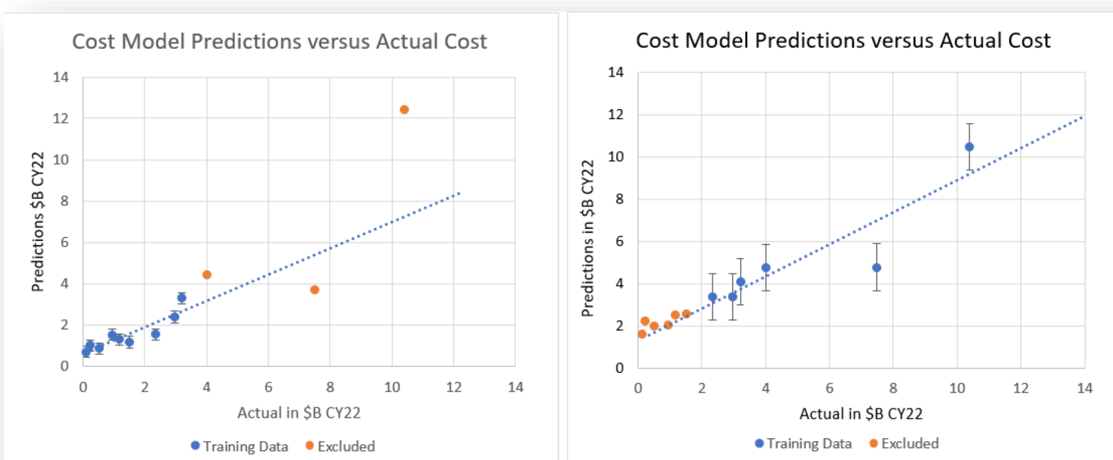

Figure 4. Sensitivity Analysis

Replenishment Costs

In order to maintain operational readiness of LEO constellations, additional replenishment satellites will be maintained on the ground, ready to replace satellites lost due to planned de-orbits, reliability issues, or attrition due to natural or manmade causes.

We developed a replenishment cost model to estimate the cost of maintaining LEO constellations in multiple orbital planes as a function of satellite reliability and launch priority.

The model calculates launch costs for the annual replenishment of an orbital plane using a series of launch vehicles that have different payload weights and cost. It then selects the launch vehicle configurations that provide the lowest cost under two conditions. When the replacement time is not critical (low priority), the rocket launch costs are allocated to the replenishment satellites by weight (sharing the cost of the launch with other satellite programs). Conversely, when the replacement time is critical (high priority), the replenishment satellites incur the full cost of the launch, oftentimes with a launch vehicle that has additional unused capacity. Next, the model adds the cost of the replenishment satellites and multiplies that cost by the number of orbital planes.

Figure 5 shows the annual replenishment costs for a 126- (500 kg, $13 million each) constellation in six orbital planes as a function of reliability (1-the number of satellites that need to be replaced annually/number of satellites). The figure demonstrates how replenishment costs are driven by the cost of the replenishment satellites and how launch priority affects it.

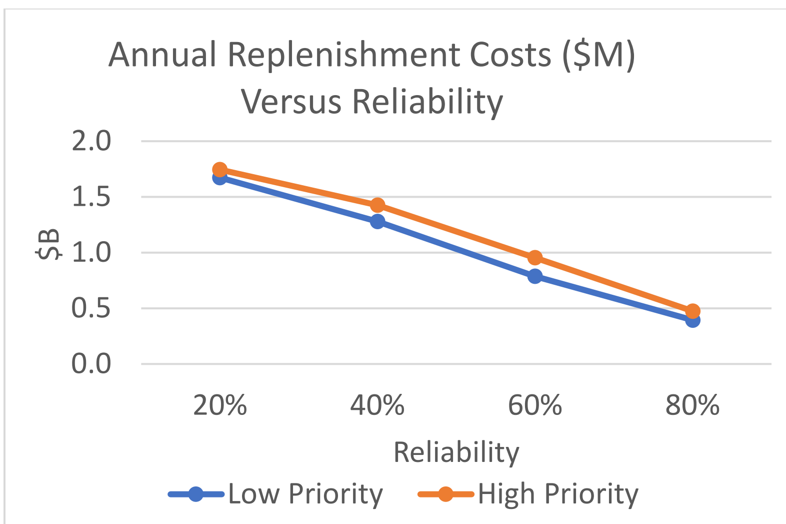

Figure 5. Annual Replenishment Cost as a Function of Reliability

Poor reliability increases replenishment costs if constellation performance is to be maintained.

Planned Constellations Telesat Lightspeed and T1TL

In 2016, Telesat announced it would launch an LEO constellation of 120 (about 800 kg) satellites, at an altitude of about 1,000 km, distributed in six orbital planes. Telesat (n.d.a) launched an experimental LEO satellite in January 2018. The number of satellites has changed over the years as Telesat looks for investors. Currently, Telesat Lightspeed is planning to have 198 satellites (including 10 spares), is estimated to cost $5 billion (but will likely cost 5–10% more; Forrester, 2022), and will be launched in 2025 (9 years from the beginning of development).[2]

Meanwhile, in February 2022, the U.S. Space Force awarded contracts totaling $1.8 billion to three development teams for their T1TL LEO constellation. The first launch is scheduled for October 2024, about 2.7 years after the contracts were awarded. The T1TL constellation comprises 126 (approximately 500 kg) satellites to be deployed at an altitude of 1,000 km into 6 orbital planes.

Both T1TL and Lightspeed provide an exceptional opportunity to test the predictive power of the Constellation CER discussed in this paper. Figure 6 shows our model predictions for the Lightspeed and T1TL constellations superimposed on the training data. Keep in mind there are no actual values for these constellations, so horizontal lines represent the possibilities. It will be interesting to see how these two satellite constellation programs execute.

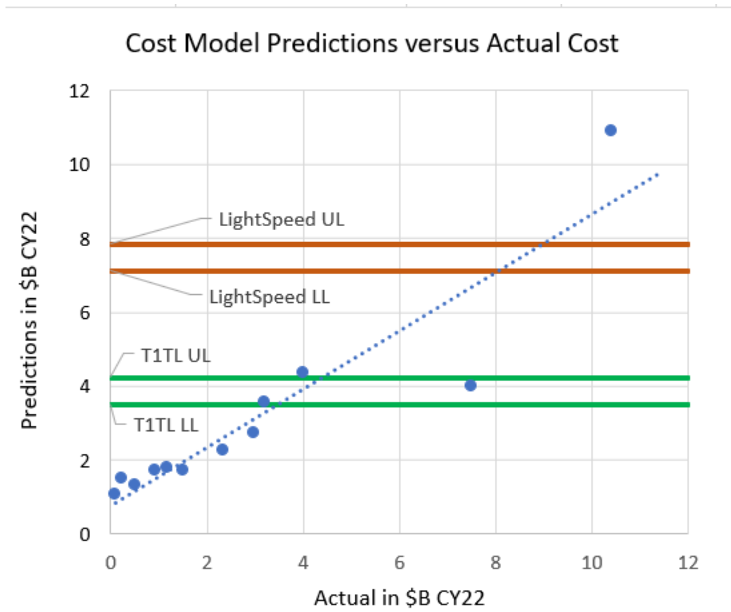

Figure 6. CER Predictions for Lightspeed and T1TL

Summary

Understanding the cost and schedule implications for developing and procuring a LEO-based megaconstellation's ground system and satellites, including initial launch and replenishment costs, is essential for DoD planning purposes. This paper describes robust and simple parametric cost models, with reasonable explanatory and predictive power, that we developed to estimate the costs of these megaconstellations.

The average development time for the 22 LEO, MEO, and HEO constellations identified in this study is 7.4 years, with a +/-1 standard deviation range from 4.3 years to 10.6 years. The average time for the 13 LEO constellations is 7.2 years, with a +/- 1 standard deviation range from 5.3 years to 9.0 years.

[2] $5 billion includes satellites, ground facilities, launch vehicles, and software platforms (Jewett, 2022).

Using regression analysis, we developed a cost estimating relationship (CER) for LEO megaconstellations based on historical cost and schedule data from 12 commercial, military, and research satellite constellations launched over the last 30 years. The CER is based on two independent variables: (1) the development time, and (2) the physics-based, synthetic variable MAN (Mass (kg) * Orbital Altitude * Number of Satellites in the Constellation). This is a measure of the "work" needed to get the constellation into its operational orbit.

A replenishment cost model was developed for LEO constellations placed into six orbital planes based on a function of reliability. It demonstrates how poor reliability leads to high replenishment costs.

This method can provide quick and reasonably accurate cost estimates for megaconstellations.

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