EXECUTIVE SUMMARY OF THE THESIS

Parametric Design Tool for a GEO Mission Architecture

LAUREA MAGISTRALE IN SPACE ENGINEERING - INGEGNERIA SPAZIALE

Author: ANGELO ROBERTO LANNUTTI

Advisor: PROF. MICHÈLE ROBERTA LAVAGNA

Co-advisor: SALVATORE ANDREA BELLA

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1. Introduction

The expansion of the New Space Economy has increased the demand for satellites, including those for In Orbit Servicing (IOS), in Geostationary orbit (GEO). These satellites, differing in dimensions and power consumption from traditional telecommunication satellites in GEO, face a lack of literature for accurate estimation of subsystems' mass and power, hindering innovation in the private sector and acting as a growth barrier for space industry companies. Consequently, the thesis aims to provide Systems Engineers with a practical tool for determining preliminary mass and power budgets in the design of satellites in GEO.

Existing methods for preliminary design of GEO satellites typically rely on statistical approaches. This thesis introduces an analytical approach for crucial subsystems (EPS, PS) due to their sensitivity to final architecture budgets, while statistical methods are employed for subsystems conceptually similar to telecommunication satellites. Current statistical regressions from GEO satellite datasets alone are insufficiently accurate for novel mission concepts, such as IOS refueling missions, where powerless payloads lead to inaccurate relations.

The proposed iterative method incorporates payload mass, power, and a combination of statistical regressions in the initial iteration. Subsequent steps refine the budget with EPS and PS sizing, allowing customization to specific needs. Unlike multidisciplinary optimization or AI-generated solutions, this approach offers flexibility and maintains validity with limited payload information. The tool aims for slightly higher accuracy than existing statistical relations, offering a trade-off with increased input demands.

2. Literature Review

The main focus of the literature review is towards publications enabling statistical preliminary design of GEO satellite budgets. Two notable works, "FADSat: A system engineering tool for the conceptual design of geostationary Earth orbit satellites platform"[5] and "System Analysis and Design of the Geostationary Earth Orbit All-Electric Communication Satellites"[6], are highlighted. These works provide valuable insights into statistical relations crucial for algorithm functioning and handling non-analytically modeled subsystems.

The first work, FADSat, is detailed as a system engineering tool capable of designing GEO satellite platforms efficiently. It employs a statistical

design model for rough estimations, followed by a parametric design model for more precise subsystem design. Linear regressions based on a database of GEO communication satellites are utilized, and the statistical model serves as a reference for validating the tool.
The second work analyzes a dataset of 70 GEO communication satellites, focusing on all-electric satellites. Statistical relations for estimating mass, power, and cost are derived, and the approach is validated using Space Mission Analysis and Design techniques. The study provides insights into trade-offs and is compared with the developed GEOdesign Tool.
A dataset comparison is presented, revealing that the first statistical model is better suited for chemical and hybrid propulsion satellites, while the second model is more suitable for all-electric satellites, as visible from the Figures 1 and 2. This distinction emphasizes the necessity of separating the applications of the two statistical models in the developed tool.

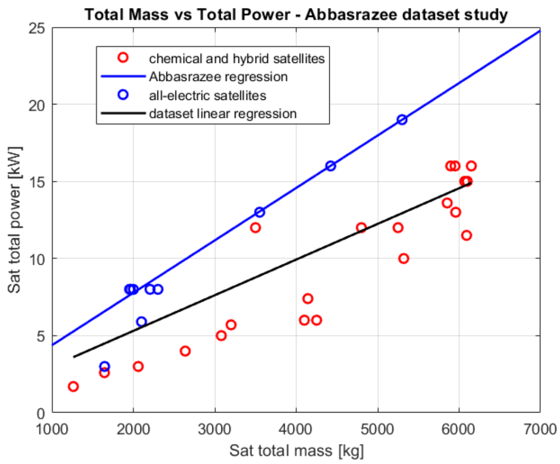

Figure 1: [6] dataset comparison with all-electric satellites.

3. Methodology

In order to ensure a rapid and dependable design process, with the ability to monitor potential sources of uncertainties and make adjustments to key assumptions easily, an iterative approach has been employed for the algorithm.

3.1. Algorithm Overview

The algorithm takes inputs such as payload mass and power, total ΔV, propulsion type, propellant characteristics, thrust level (for electric

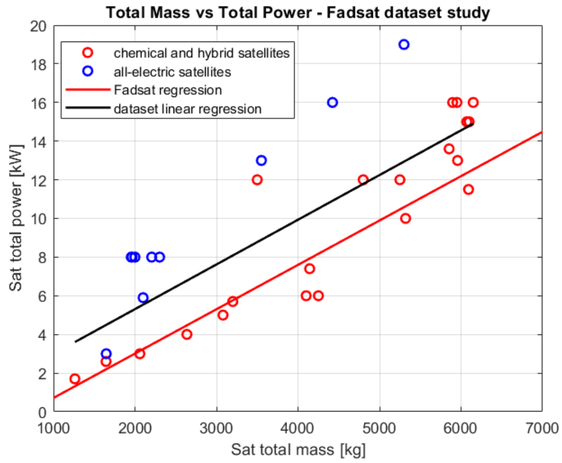

Figure 2: [5] dataset comparison with chemical and hybrid satellites.

propulsion only), specific impulse, and expected lifetime of the satellite. These inputs are utilized for estimating the initial satellite mass and power budgets, as well as sizing the Propulsion and EPS subsystems.
Once initial parameters are estimated, an iterative process begins. The calculated dry mass is used as input for the Propulsion Subsystem sizing, determining the peak power by comparing payload power with the propulsion subsystem power, in case of electric propulsion. The peak power, along with the satellite's expected lifetime, serves as input for the EPS sizing.
The dry mass of the satellite and the bus power are used to evaluate the power and mass of the remaining subsystems, updating the total budget values. This iterative process ends when the relative differences of the total budgets of 2 subsequent iterates are below 1%. The entire process, ensures a reliable design while allowing flexibility for adjustments based on changing assumptions.

3.2. Subsystem Models

The initial estimation of the total budget, uses the statistical relations for communication satellites referenced in the works discussed in the section 2, with assumptions regarding the estimation of the power budget. This one is retrieved with a statistical relation linked to the payload mass, but then only the 25% of the total power extrapolated with this relation, is considered to be the bus power of the spacecraft [9]. The payload power in input is then summed to the bus power to obtain the peak power, if the satellite has chemical propulsion. Otherwise, the peak power can be obtained by adding the electric power consumption of the thrusters to the bus power, if the satellite has electric propulsion and the consumption of these require more power than the payload. The subsystems are categorized into those modeled using statistical sizing (PS and EPS) and those using analytical sizing (ADCS, OBDH, TCS, TTMTC, Charging and Regulation power, harness mass and the Structure mass).

3.3. Main Assumptions

The main assumptions of the model are summarized as follows:

- **SMAD Reference Sizings:** SMAD book reference sizings [10] are considered accurate estimates for this design phase, for the PS and EPS subsystems.
- **Different Relations for Propulsion Systems:** All-electric satellites and chemical/hybrid propulsion satellites exhibit different relationships between payload and total parameters.
- **GEO Orbit Period:** The period of the GEO is assumed to be exactly 24 hours.
- **Eclipse Duration:** There are 2 periods of the year in which GEO spacecraft are in shadow, and the eclipse lasts 72 minutes per day.
- **Total Power Estimation:** Communication payload power is initially estimated to be 75 % of the total power based on a communication satellite database found in literature [9].
- **Separation of Subsystems:** Telecom subsystem is considered separate from the payload in communication satellites.
- **Payload Utilization:** The input payload is not utilized during the transfer phases. This hypothesis is inserted to establish two main power modes to be evaluated in case electric propulsion is used. The solar array power is then extracted, considering the line losses and the peak power mode between these two.
- **Technological Advancements:** Weight and power evolution of hardware due to technological advancements is not considered.
- **3-Axis Stabilization:** Satellites are assumed to be 3-axis stabilized. This hypothesis is in line with all the communication satellites present in GEO, as seen from literature data of the most common spacecraft buses [4] [8].
- **Subsystem Features Consistency:** Features of the non-modelled subsystems remain relatively consistent across satellites with different propulsion systems, and the following proportional relations are extrapolated from GEO communication satellites datasets [5] [9] [10]:
  - Structure subsystem mass is considered proportional to the dry mass of the satellite.
  - ADCS mass and power are proportional to dry mass and total power.
  - OBDH subsystem is proportional to dry mass and total power.
  - Harness mass is proportional to the dry mass of the spacecraft.
  - Charging and Regulation power is proportional to total power, and its mass is included in the harness mass.

A deeper justification of this last assumption is reported in the main work of the thesis. However, the ADCS mass is based upon the mass and not on the inertial properties, to avoid introducing a further source of error by supposing a certain shape and mass distribution of the satellite. As the mass grows, contextually also the volume of the spacecraft grows, modifying partially the inertial properties. The solar panels' growth is also partially taken into account by the mass growth, because it is linked to the installation of more antennas and more transponders, resulting in more power. Therefore, it is conservative to suppose that the modification of the inertial properties due to volume growth and due to the solar arrays' dimension growth, is partially taken into account by a direct relation with the dry mass. An acceptable error is introduced due to the large amount of satellites present in the dataset (462 [5]) from which the relations are taken. This could lead to an overestimation of the ADCS subsystem for non-communication satellites, due to the bus power hypothesis for which the actual solar panels area can be lower than the solar panels area to which the subsystem is linked by the statistical relation, if the payload power is much lower than communication satellites typical power or it is zero. However, this effect is mitigated by the iterative process and by the uncertainty related to the relation itself.

3.4. System First Estimate

For the first estimate of the total budget, different relations are implemented depending on the type of propulsion system chosen by the user. Given the payload mass and power in input, statistical relations from [5] are used for chemical and hybrid satellites, while the relations from [6] are used for electrical satellites.

3.5. Model Limitations

Even though the model incorporates statistical sizing for various subsystems, there are certain limitations in the payload mass range. The tool is designed for payload masses between 130 kg and 650 kg for chemical and hybrid satellites [5] and between 140 kg and 1500 kg for all-electric satellites [1]. These limitations reflect also in the type of payload that can be used for the sizing of IOS satellite, for example a single tether mission cannot be sized due to the too low payload mass. Also, a refueling satellite which carries all the propellant needed to refuel a high number of spacecrafts cannot be sized due to the high payload mass. In addition, the assumptions on the subsystems characteristics and the dataset utilized, do not permit to size peculiar spacecrafts like fuel depots that lack of Propulsion Subsystem (PS) or have passive ADCS.

3.6. PS and EPS Design

The sizing equations are the classical methods for preliminary sizing referenced in [10]. Regarding the PS, Monopropellant or bipropellant can be chosen for the chemical propulsion. The chosen propellant for electric propulsion is Xenon, due to its widespread presence in the reference literature. It should be highlighted that the hybrid propulsion is distinguished in two types: in the first one, the main thrusters that perform the orbit raising and therefore must carry also the propellant for the station keeping are the chemical ones, in the second one the situation is opposite.

For EPS, GaAs solar panels and Li-Ion batteries are chosen due to their massive presence in the reference literature [4][8], with the sizing based on peak power requirements, either in nominal mode or transfer mode.

3.7. Statistical Sizing

Remaining subsystems are modeled using constant statistical values or linear regressions. Subsystems like TTMTC and TCS are modeled using constant statistical values extracted from [9], while others are modeled as a statistical percentage of the dry mass and power of the spacecraft, with relations retrieved from [5].

4. Validation

The tool underwent validation using two distinct datasets comprising communication satellites, as accurate information regarding IOS satellites in GEO was unavailable. Two separate validations were conducted: one for chemical and hybrid design, and another for all-electric satellite design. A comparison, which is not reported in this text, was also performed with the statistical relations presented in [6] for all-electric satellites and with the SDM in [5] for chemical and hybrid propulsion satellites.

4.1. Chemical and hybrid comm satellites

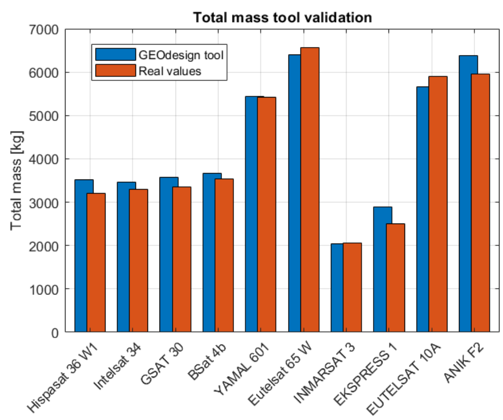

Figure 3: Total mass comparison for communication chemical and hybrid satellites.

Figures 3 and 4 demonstrate the tool's validation, with values close to real ones. However, there are slightly lower errors for total mass bud-

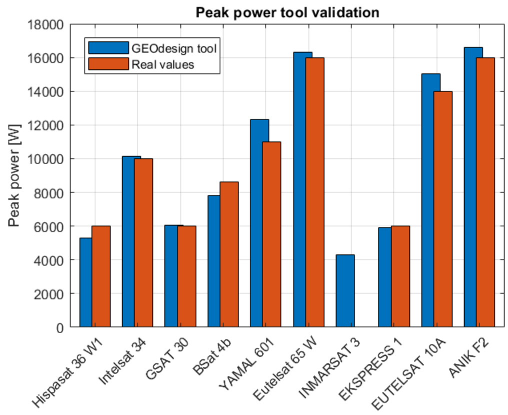

Figure 4: Total power comparison for communication chemical and hybrid satellites.

geting compared to solar array power budgeting. The average relative error is 3% for the mass budget and 3.3% for the power budget, with standard deviations of 4.3% and 4.5%, respectively. Precision is attributed to the choice of communication satellites datasets. The discrepancy arises from uncertainty related to payload power consumption, a major factor in total power. The highest mass relative error (15%) occurs for the Ekspress AM1 satellite due to an input payload mass outside dataset limitations. The highest power errors are obtained for the satellites Hispasat 36 W1 and YAMAL 601 whose relative errors are around 10%, due to the uncertainty in the electric thrusters used as secondary propulsion. Inmarsat 3 is an interesting case for robust validation, lacking information on solar array power but contributing to correct sizing despite it is the only one directly inserted in GEO.

4.2. Chemical and hybrid non-comm satellites

Here the tool is compared with several statistical relations, commonly used for the sizing of Earth orbiting satellites and referenced in [7], [3], and [10]. As previously noted, the estimations are more accurate for the mass budget than for the power budget. This is likely due to uncertainties in both the power of the payload and the real total power of the satellites. The slightly higher average error is a result of the statistical relations used being ill-suited for satellites with a different purpose, even if they share the same orbit. However, the results obtained are notably superior for total mass sizing when compared to Zandbergen's statistical relation and marginally better than Brown's relations and SMAD relation for power. This reaffirms the tool's utility in comparison to the use of a common statistical relation. The average relative error of the tool lies around 15 % for the mass budget and 43 % for the power budget, with respective standard deviations of 9% and 15%.

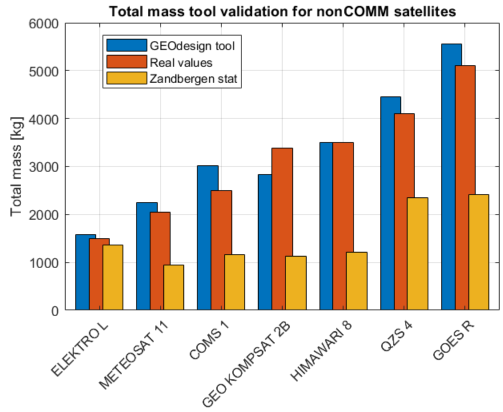

Figure 5: Total mass comparison for out of the database chemical and hybrid satellites.

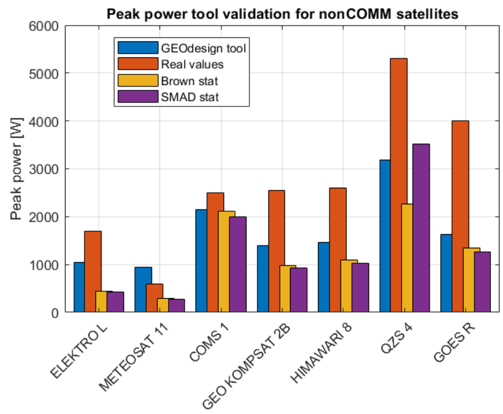

Figure 6: Total power comparison for out of the database chemical and hybrid satellites.

4.3. All-electric comm satellites

No all-electric satellites that are not intended for communication purposes are present today in the geostationary orbit, so the flexibility of the tool for all-electric satellites sizing could not be proved.

In the Figures 7 and 8, it is clear that the sizing of the electric propulsion system leads to slightly different results than before, and the average error is higher for both the budgets. The reason

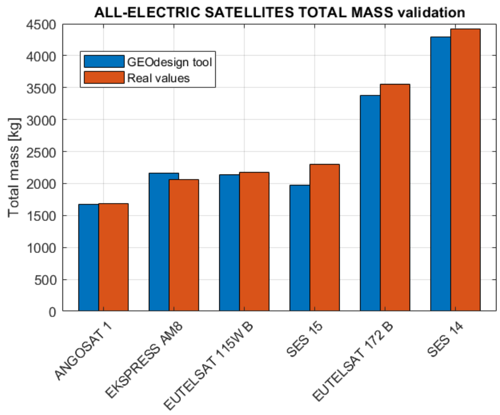

Figure 7: Validation on total mass for communication all-electric satellites.

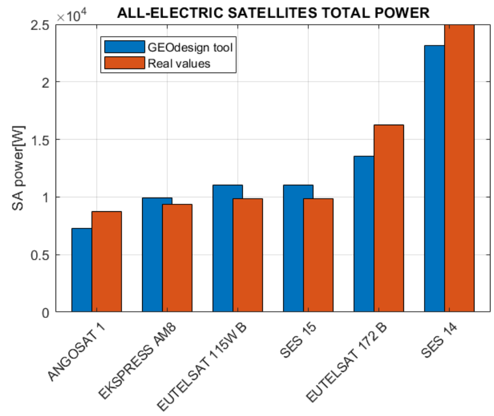

Figure 8: Validation on total power for communication all-electric satellites.

may lie in the presence of a lower number of spacecrafts in the dataset used in [6], with respect to the dataset used in [5], that links obviously to an error increase. However, the tool is validated also for this type of architecture, with relative errors that are lower or comparable to the set of statistical relations developed in [6]. The average relative errors obtained are around 5% for the total mass sizing and 15% for the total power sizing, with standard deviations around 5% and 6%.

5. Study cases

After the validation of the tool, different practical cases of the preliminary sizing of IOS satellites are performed. The tool will be used to perform a trade-off on the type of propulsion selected, once the mission scenario is defined and to look at the variation of the satellite's budgets due to the changes in the mission architecture. The selected mission profiles and scenarios have been studied by National Astronautics and Space Administration (NASA) in [2] and the main features will be briefly exposed.

5.1. De-orbiting mission

The mission focuses on designing a Servicer spacecraft capable of capturing and controlling multiple legacy non-cooperative satellites in nearly co-planar geosynchronous orbits. The objective is to relocate these satellites, such as Solar Dynamics Observatory (SDO) and Geostationary Operational Environmental Satellite (GOES), to a disposal orbit 350 km above the GEO belt. The Customer satellites, assumed to tumble at 0.25 degrees per second per axis, are boosted using supervised Autonomous Rendezvous and Capture (AR&C) techniques. The Servicer is equipped with necessary hardware and fuel and with 4 robotic arms of 157 kg each. It executes sorties to approximately 10 Customer satellites, with about one degree of orbit plane change between each. The mission life spans 5 years, servicing 10 Customers. The payload information, the operations and the Autonomous Rendez-vous and Capture (AR&C) ΔV are retrieved from [2]. In the Table 1 is shown that

	Dry mass	**Total mass**
NASA	2350 kg	3700 kg
GEOdesign	2374 kg	3718 kg

Table 1: GEOdesign tool result compared to NASA [2]

the results obtained by the tool, are very similar to the results obtained by a team of NASA experts. After this further validation, a possible enhancement of the mission to make it less expensive has been proposed. The new satellite is a hybrid satellite, that is able to perform a GTO to GEO orbit raising with electric propulsion and uses a bipropellant system for the servicing maneuvers. After a trade-off between different electric thrusters and launchers, it has been found that by using Falcon 9 for the insertion in GTO orbit and by mounting 2 XIPS 25 gridded ion thrusters as primary propulsion system, **the launch cost can be decreased by approximately 40 M€**, with respect to a direct insertion in GEO with Ariane 64. **The resulting hybrid satellite has a dry mass of 3280**

kg, a total mass of 4485 kg and a solar array power of 11kW. Despite the accuracy of this solution with respect to the actual real value, the trade-off has been done faster than with the employment of the classical mission design methodology.

5.2. Refueling mission

The refueling mission is referenced in the NASA study[2], but the parking and reference orbits are slightly different than before. In the mission proposed, 2 vehicles are presented: one Refueler, equipped with two robotic arms and with monopropellant based PS, and one Depot, without PS and TTMTCsubsystems. The aim is to refuel 25 clients satellites of 20 kg of hydrazine in 10 years. Due to the peculiar characteristics of the Depot, only the refueler could be sized with the tool. Here, due to the focus of the mission in delivering hydrazine and because of the considerable mass of the Depot spacecraft, a trade off with the use of electric thrusters to enable the orbit raising from GTO loses validity. The output of the tool comparison with the known data of the mission [2] is shown in the Table 2, resulting in a stronger validation.

	Dry mass	**SA area**
NASA	1894 kg	7.2 m^2
GEOdesign	1898 kg	8.8 m^2

Table 2: GEOdesgin tool results compared to NASA [2]

6. Conclusion and future developments

Despite relying on statistical relations from communication satellites, the tool proves effective and superior to existing relations for non-communication satellites. It excels in providing faster preliminary design, demonstrating acceptable accuracy, aiding maneuvering strategy definition, and facilitating high-level trade-offs. However, limitations include constraints on payload mass, spacecraft type restrictions, and lack of validated subsystem budgets. For future developments, the tool could be expanded to cover more orbits and spacecraft types, undergo a more in-depth statistical analysis of subsystems, integrate with a mission analysis tool, and incorporate a cost model for optimal mission architecture evaluation. Academic enhancements might involve expanding payload limitations, offering a choice between different payload characteristics, and incorporating specific relations to evaluate the shielding mass needed for the electrical orbit raising, using SPENVIS. Overall, the tool provides a significant advantage for companies exploring in-orbit servicing satellite concepts, granting flexibility in evaluating mission operations and delivering precise responses on system architectures.

Acronyms

ADCS Attitude Determination and Control Subsystem. 3, 4

AR&C Autonomous Rendez-vous and Capture. 6

EPS Electric Power Subsystem. 1–3

GEO Geostationary orbit. 1, 3–6

GOES Geostationary Operational Environmental Satellite. 6

GTO Geosynchronous Transfer Orbit. 6, 7

IOS In Orbit Servicing. 1, 4, 6

NASA National Astronautics and Space Administration. 6, 7

OBDH On Board Data Handling. 3

PS Propulsion Subsystem. 1, 3, 4, 7

SDM Statistical Design Model. 4

SDO Solar Dynamics Observatory. 6

SMAD Space Mission Analysis and Design. 3, 5

TCS Thermal Control Subsystem. 3, 4

TTMTC Tracking, Telemetry and Telecommand Subsystem. 3, 4, 7

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