

MegaSat: feasibility of a modular and expandable geostationary platform for optimizing GEO-slot allocations

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Abstract

The increasing congestion in geostationary orbit, driven by the growing demand for satellite-based services, presents significant challenges for efficient slot allocation. Addressing this issue, this paper presents a feasibility study of a modular and expandable geostationary platform designed to optimize orbital slot allocation. The proposed MegaSat platform offers a scalable solution by allowing multiple payloads to be launched and serviced over time, making efficient use of allocated GEO slots. Key features include an architecture for gradual expansion and integration of new payloads, and advanced propulsion systems for optimal positioning. The study explores the economic and operational benefits, demonstrating its potential to reduce costs and improve service lifetimes for satellite operators. Results indicate that MegaSat can significantly enhance GEO slot utilization, providing a viable solution to the challenges posed by increasing congestion in geostationary orbit.

Keywords: Infrastructure, Modularity, Geostationary Orbit, Structural Analysis, In-orbit Assembly

1. Introduction

The market for GEO satellites is estimated to grow by over \$3 billion in the 5 year period 2024-2029 [1]. However, as demand increases, so does the threat of orbit saturation in this space-limited environment. As a result, the industry continues to strive for a sustainable solution to increasing GEO capability while ensuring space debris and end-of-life disposal operations remain at the forefront of thought.

The proposed design is a modular, scalable infrastructure, with the capability to host commercial communications satellites in GEO, accessible by multiple operators. This concept has the potential to facilitate easier access to the sector by increasing the density of satellites in GEO, driving growth and innovation in the industry. To ensure an extended lifespan for the infrastructure, the ability to routinely replace components must be built into the design, being applied to both scheduled maintenance and emergency replacements.

Deploying a satellite to GEO is often associated with high costs, long lead times and higher risks due their complexity, therefore, designing a large space infrastructure to be deployed into GEO must be carefully considered to ensure economic viability. As the mass and volume of what can be launched is constrained by the launch vehicle, a large space structure therefore requires either in-orbit fabrication or some form of modularity, launched using multiple vehicles and assembled in-orbit[2]. Tradition-

ally, in-space assembly has been associated with very high costs due to the requirements of in-situ human operations. Due to the very strict safety margins seen with human space flight, particularly with EVAs and human habitation modules, robotic automation shows enormous potential to revolutionise this field [3]. The industry continues to make progress developing free-flying ground-breaking robotic arms, such as MOSAR, CANADARM and MIR-ROR's MAR, that are well-suited for in-orbit assembly and autonomous maintenance.[4][5]

A final focus of the MegaSat design is flexibility. By designing the MegaSat to be modular and to use universal connectors, the structure can be expanded and adapted, depending on the role it needs to fulfil. Any customer can dock to any available connector, allowing MegaSat to meet any specific customer location preferences. In addition, the electric propulsion system can also be docked to any connector, allowing for adaptability during emergencies and end-of-life operations. Universal connectors, such as SIROM and iBOSS iSSI [6], are currently being studied and developed. Making use of this research, MegaSat aims to make use of a proprietary design to meet power and data requirements for this project.

Through this paper, the following concepts will be explained, starting with the mission definition and its main requirements, and the advantages of this new concept, followed by the structural design and its operative configurations. The concepts of operations outlines the schedule for

the satellite to be operative throughout its lifetime. After reviewing all the subsystems to verify the feasibility of the infrastructure, a financial study is conducted to assess the profitability of this new satellite concept.

2. Mission Definition

The ultimate aim of the MegaSat project is to provide services to customers in Geostationary Orbit. The problem-statement is formalised as follows: **“The MegaSat shall demonstrate the provision of long-term services to third-party communication satellites in GEO, supported by in-orbit assembly”**. The problem-statement was interpreted to require the physical hosting of customer satellites, and existing satellites were taken as examples of satellites that could be hosted.

A number of requirements immediately follow on from the problem-statement:

Size: The platform should host multiple satellites to be successful as a concept. The current architecture hosts 13 satellites at the end of phase 1. It follows that the platform itself should be able to host at a reasonable number of satellites - 13 satellites number of satellites.

Modularity: Given the dimensions required to host 13 satellites and the constraints of current GEO launchers, the platform must be modular - i.e., it must be possible to launch it in constituent parts and re-assemble in orbit. Modularity should extend as far as possible - for example, the connectors that attach the satellites are also compatible with the thrusters that provide station keeping and in-orbit manoeuvres. This feature allows the infrastructure to adapt to the market and to be extendable in the future, following the request of more slots or maintaining the minimum service.

Service Provision: One of the complexities of designing a satellite to stay in GEO is the number of subsystems required to make it functional. By providing a number of these, the MegaSat project not only lowers the resource cost to the customer in the design and deployment process, but takes responsibility for the ongoing provision of these services (Services-as-a-Service). This allows the customer to focus on the development of their payload. The architecture provides the following services: power, thermal management and full transfer of the customer satellite from orbital injection to docking on the MegaSat infrastructure.

Longevity: MegaSat aims to achieve a lifespan of 45 years.

Replaceability: Any satellite in orbit for an extended period of time attracts risks of damage resulting from debris and meteoroid collisions. A replaceability requirement was set following analysis with ESA's Meteoroid and Space Debris Terrestrial Environment Reference (MASTER) model, version 8.0.3[7]. Specifically, the solar panel

sections, batteries, Hall effect thrusters and thermal management components should be replaceable.

3. Structural organisation and configurations

The aim of this section is to present the different configurations that MegaSat will go through during its life in orbit, and the different parts that make it up.

3.1. Key components

To be fully assembled, the MegaSat has to go through 3 configurations. Each new one being an evolution of the previous one, to which certain elements have been added. The 3 components of the structure are as follows:

The central structure: Its position in the MegaSat is shown in 2. It houses the energy sources, a large part of the AOCS systems, a data management system and the equipment needed to keep the main payload running. It consists of a cube measuring 3.3 m on each side and 4 beams 5.8 m long, connected to the previous part by a pivot system. On the side of the cube facing the Earth, a large customer satellite is positioned as a space measuring 2.9 m by 2.9 m by 0.8 m, which houses the main payload equipment. On the other side is a cylinder 2 m in diameter and 2.1 m deep. In this space will be placed all the electrical and payload equipment needed for the MegaSat to operate correctly. The CAD is shown in Figure 2. To fit this part of the structure into the payload fairing, the beams rotate around the pivot that connects them to the cube. The rest of the MegaSat is built around this part.

The square: This is the first structural element mainly dedicated to connecting client modules. It is made up of two identical parts that fit on the central structure. Its integration into the structure is shown in 2. Dedicated mechanisms are used to assemble the square in orbit and keep it in position. It can accommodate 4 customer satellites and contains electrical, AOCS and payload components. The client units are not docked directly on the square but to the interface presented into section 3.1. Once deployed in orbit, the square forms a square torus measuring 15m on each side and 1.5m thick.

The extension: It is the third and final structural part of the platform. As its name suggests, it is the element that allows the MegaSat to scale from one configuration to another. Each extension enables 4 client satellites to be added by the same principle as for the square, using the docking interface. This part of the MegaSat is always assembled in pairs in order to maintain as much symmetry as possible in the structure and thus guarantee to avoid over-consumption of propellant, one on the East side and one on the West. The final configuration presented in this paper is formed using 4 extensions, bringing the total number of client satellites to 21.

These elements form the skeleton of the MegaSat, but in order to guarantee a certain degree of agility in the

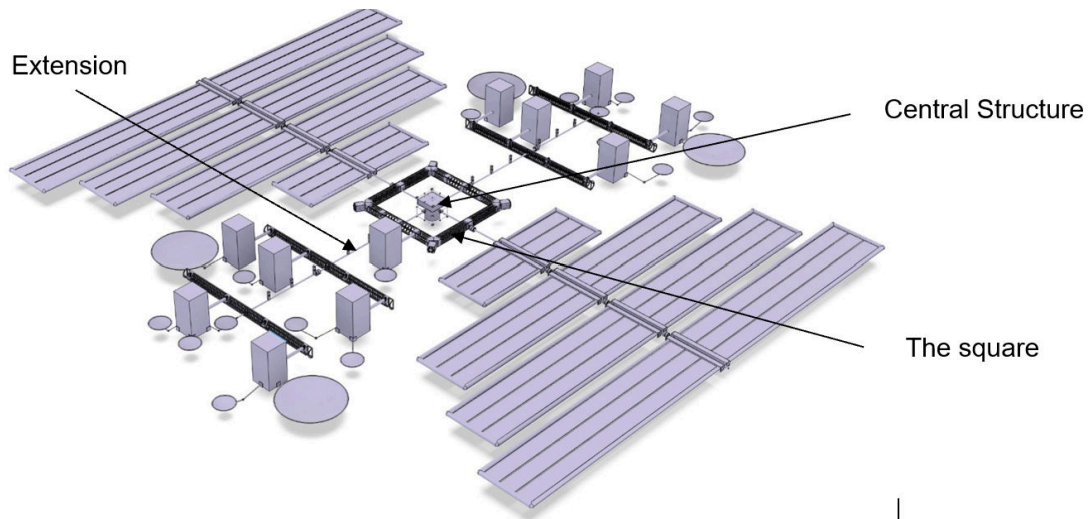


Figure 1: Last configuration of MIDAS in orbit

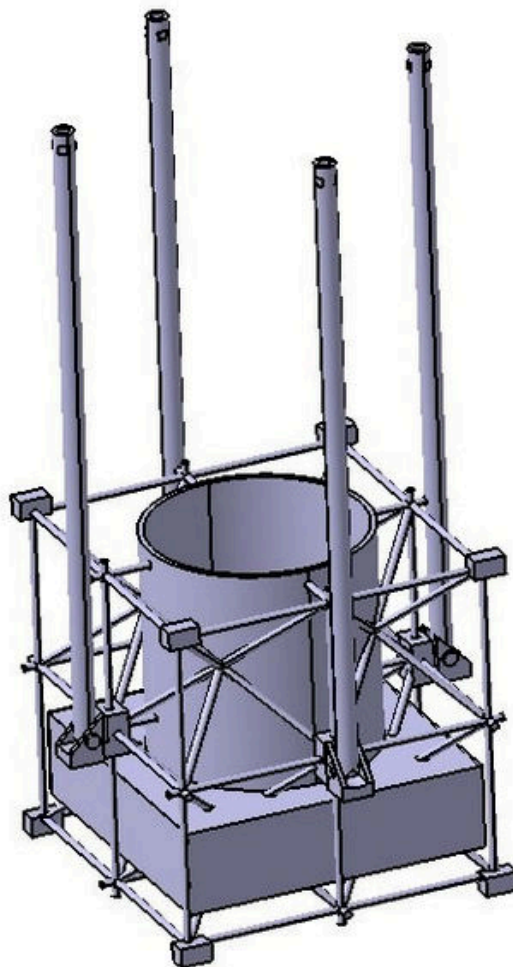


Figure 2: CAD of the central structure in the launch configuration

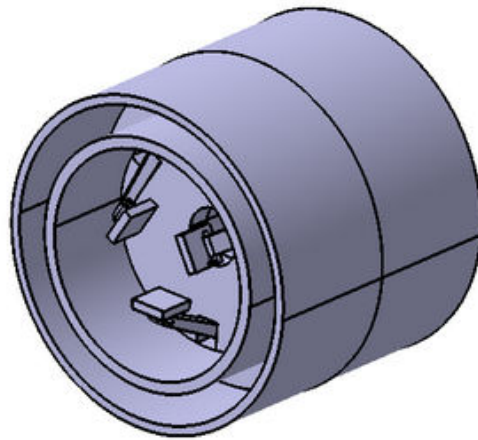


Figure 3: Last configuration of MIDAS in orbit

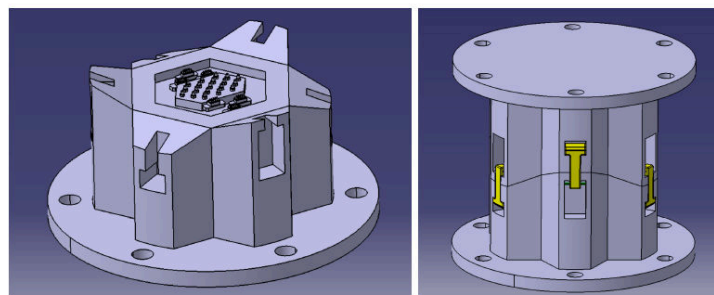


Figure 4: CAD model of the docking interface

assembly of the megastructure it is necessary to use two mechanisms to act as articulations for the satellite. One of them, the universal connector, is used to connect the beams of the different parts presented earlier together. The other one is the docking interface allowing the docking of customer satellites to the MegaSat.

The connector: It consists of a cylinder that connects two beams of any diameter as long as it is smaller than the maximum permissible one 3. It is therefore used to connect the extensions and solar panels to the structure already in orbit. To perform that, it uses a mechanism that are grabbing each of the beam, each of these is mounted on a bearing allowing the rotation of each part independently of the other. This allows the connector to act as a solar array drive mechanism, or to participate in the MegaSat safety system.

Docking Interface Two of the structural parts introduced earlier are designed to accommodate customer satellites. For this purpose, a universal docking system has been designed. The docking interface mechanical interface designed is similar to SIROM latching system [8] Mechanical validation and simulations confirmed the interface's durability as it could withstand mission loads. Spring-loaded pins were chosen for their reliability and simplicity. Six Spacewire connectors are chosen to ensure a data rate of 1000 Mbps. The final docking interface has a mass of 41.7 kg. The design ensures that any satellite or module can dock to any slot. Figure 4 present the final docking interface designed.

3.2. MegaSat operational configurations

First configuration: The first MegaSat configuration consists of the central structure and the square, plus two solar panels on each side. This allows us to have the main payload as well as 4 others in orbit.

Second configuration: For the second step, an extension is added on each side, along with a solar panel on each side. This allowed the addition of 8 customer satellites, bringing the total to 13.

Third configuration: Finally, the same step as above is repeated to add another 8 customer units. This brings the MegaSat to a size of more than 80m by 100m and accommodates 21 customers.

4. Concept of Operations

This section outlines the comprehensive plan for the deployment, assembly, and operational phases of the MegaSat satellite infrastructure
MegaSat ConOps is divided into three main phases.

4.1. Phase 0

An initial set of components will be launched using a Falcon Heavy rocket, executed over three sequential launches. The launch times are assumed to be ideal, with a maximum difference of 3 days between each launch. This is currently achieved by Falcon 9, and it is expected that Falcon Heavy will achieve the same in the future [9]. The chosen rocket was this model from SpaceX since the main challenge to address in the case of this infrastructure is the size and weight. The main infrastructure comprises three components: two deployable, lateral and a central module. The mass of the lateral parts is 15.9 tons, and the one of the main infrastructure is 6 tons. The 3 components deployed into a GTO+ (with a perigee of approximately 14,000 km to minimize risks).

The launch sequence play a key role in the mission since the first part is the main module and is the one that has the thrusters in it. Following, the one "Boomerang" or modular extension is inserted in GTO+. The "boomerang" refer to the two deployable lateral parts that join together to conform the central infrastructure. Then, these parts autonomously rendezvous and dock with the central structure to form an initial satellite configuration. Then, the same procedure happens with the other extension.

The in-orbit assembly process initiates with the Canadarm3 robotic arm, which precisely grabs the first boomerang when it is positioned approximately 5 meters from the central structure. This operation ensures that the boomerang maintains a stable attitude while being securely attached to the central structure. Once the first boomerang is successfully berthed, the robotic arm repeats the same procedure for the second boomerang. This sequential assembly completes the main infrastructure, setting the foundation for subsequent robotic operations, such as solar array deployment and then orbit-raising maneuvers, leading to the full operational capacity of the system.

4.2. Phase 1: Initial Configuration and Expansion

Following the successful docking of the Boomerangs, the second phase focuses on the initial configuration and expansion. MegaSat will undergo a series of diagnostic tests to ensure all systems are operational. After a period of 3 months, additional docking and solar extensions will be launched and attached, increasing the capacity to accommodate up to 13 customer satellites. The station will then enter a monitoring phase to ensure stability and functionality before further expansion, this configuration will last 1.5 years and then Phase 2 begins.

4.3. Phase 2: Extended Configuration and Life Extension

The third phase is the extended configuration and life extension. MegaSat will continue to expand to support up to 21 satellites, with provisions for future extensions beyond 30 satellites. The infrastructure will be maintained through scheduled replacements of solar panels, batteries, and thrusters, ensuring a projected operational lifetime of 45 years. At the end of its mission, MegaSat will be decommissioned, and the individual modules will be safely disposed of to minimize space debris. This is done by undocking the client's satellites and moving them to the corresponding graveyard and then, do a similar maneuver with the main structure, both scenarios using its own propulsion system.

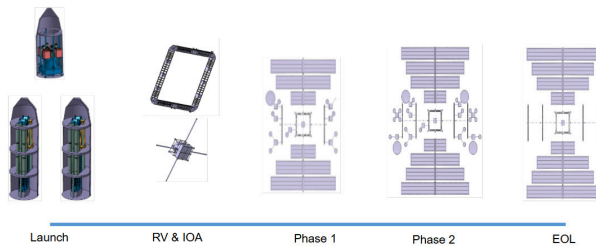


Figure 5: Configurations

As it can be seen in Figure 5, there are several configurations of the infrastructure. The initial configuration can accommodate 5 customer satellites, and diagnostics and testing of the front payload are performed every 3 months. The station will remain in this configuration for 1.5 years to allow for diagnostics and system monitoring before transitioning to the next phase. After 3.5 years of successful operation in orbit, it will scale up to 21 satellites.

4.4. Station-Keeping and End Of Life

Attitude control is a key aspect when dealing with a infrastructure of this dimensions, not only because its main objective is communication and so it will have to keep pointing accuracy within some ranges but also since the dimensions of it makes it a challenge to correct all the possible perturbations[10].

As previously mentioned, the spacecraft will be placed at GEO. In this orbit, forces will perturb the spacecraft's position, causing it to drift within its assigned slot. Significant perturbative forces include the Earth's non-sphericity, solar radiation pressure, and gravitational influences from other celestial bodies like the Moon.

To counteract these perturbations and maintain the position within the limits, an electric propulsion system used. The satellite has to be kept with 0° eccentricity (+0.03), and above 0°N Latitude and 12.5°E Longitude to have full coverage in the desired area (+0.1°).

Station-keeping manoeuvres are performed to keep the

satellite within the expected slot. Numerical simulations shows that the ΔV required to perform East-West manoeuvres is 2m/s and 44 m/s per year for North-South manoeuvres, values that are in accordance with existing literature [10]

On the other hand, the End of life sets the end of the mission and moves the infrastructure to the graveyard orbit. This process, passivation, ensures that the satellite will stay in a safe orbit, and the possibility of collision with active satellites will be reduced, while at the same time decreasing the possibility of an explosion due to residual propellant or battery issues. The first step consists on undocking the client's satellites and start the orbit raise towards the corresponding graveyard orbit. The increment in height is computed as follows [10].

$$\Delta h = 235 + 1000 \cdot \left(1000 \cdot \frac{C_R}{m} \right) \quad (1)$$

As it can be seen, the final graveyard will depend on the area (A), mass (m) and Coefficient of reflectivity C_R of the spacecraft. Resulting in an increase of 241.3050 km and so using Hohmann transfer a DV of 8.722 m/s and requiring 12.07 hours. These values are for the worst case scenario, this is, the case in which 21 satellites are docked to the structure. So, the need Dv is 8.6046 m/s and is achieved using Hall Thrusters in 4 days by elliptic raising and then circularization. Once the spacecrafts arrived to the desired orbit, they empty their batteries and fuel tanks in order to avoid explosions [11].

5. Communication and Payloads

MegaSat is a versatile telecommunications satellite which shall enhance telecommunications in four domains: maritime broadband, inflight broadband, LEO data relay, and ground broadband services. The platform supports high-speed internet, real-time data relay, multi-satellite coordination, and secure data transmission from remote facilities. With its central antenna, it shall achieve an overall data rate of 275 Gbps while maintaining a high carrier-to-noise ratio of over 80 dB-Hz.

The payload system was configured to meet the varied requirements of customers' satellites and to offset the high cost of the initial launch. The final satellite configuration includes one large antenna on top of the central square of MegaSat and of 21 user satellites which can be equipped with their own antenna, docked on the external supporting beams and extensions. The large central antenna, along with the central structure, are launched first to justify the economic viability of the initial launch.

5.1. Communications

The Telemetry, Tracking, and Command (TT/TC) antenna subsystem is vital for communication between

MegaSat and ground stations. The design includes a primary high-gain antenna, a backup high-gain antenna for redundancy, and two omnidirectional antennas for broader coverage. Link budget analyses have been performed to ensure reliable data transfer and command reception, utilizing existing off-the-shelf components to minimize risks and ensure compatibility.

The primary high-gain antenna and the back-up one chosen are 0.6m diameter K-band all-metal reflector antenna developed by BeyondGravity. This antenna provides a frequency range between 25.5 and 27.0 GHz, with return loss superior to 25 dB and with a power handling above 60 W. For enhanced data link redundancy with ground stations, X-band helix data downlink antennas (Generation 2) will be installed on MegaSat's boomerang structures. These helix antennas provide a robust alternative communication path, ensuring continuous connectivity even if the primary antennas fail.

5.2. Payload System Design

5.2.1. Customer Satellite Design

All 21 customer satellites shall have a standardized design and size to fit into their respective spot while fulfilling their own mission objective. MegaSat provides each satellite equal power and data services. The key specifications that the customer satellites shall meet include a maximum mass of 3,000 kg, an average power requirement of 25 kW, and an average antenna diameter of 4.5 m. Different size and location of payload spots exist offering several pointing attitudes and a variety of purposes for the different user payloads. Therefore, some flexibility in design exists for the customers, making MegaSat compatible with a wide range of user satellite missions and configuration.

5.2.2. Customer Satellite interference

Interference between users' antennas on Megasat is minimized through strict frequency coordination and isolation techniques. Thus, precise docking of the customer satellites shall minimise the electromagnetic interferences during integration.

6. Power

MIDAS was designed to accommodate up to 21 client modules which shall be supplied in electricity and shall have access to MIDAS' data storage systems. Producing 580 W in this configuration. The power system for MIDAS and its customer satellites consists of rolled-out solar arrays with triple-junction solar cells, paired with lithium-ion batteries. To be able to establish the size and dimension of the power system, power consumption of equipment of each subsystems were collected. The greatest power con-

sumption comes from the payload as the ability to deliver up to 25kW of electricity per customer module was one of MIDAS' payload and electrical requirement. The distribution of power consumption is presented in Table 1 below. The power system and more precisely, the electrical power system designed shall therefore have as characteristics a total average power of 537.45 kW with a total peak power of 543.05 kW and shall have a minimum lifetime of 15 years.

The triple-junction solar cells used in MIDAS are optimized to capture different photon wavelengths, and therefore increasing the overall efficiency. Nevertheless, the main advantage resides in the fact that, by storing the solar arrays rolled up, therefore, space is saved at launch. The solar panels chosen are IRosa solar panels developed by Redwire Space. Their efficiency is of 0.31. During eclipse season, Li-ion batteries are used. These batteries are the most commonly stored energy solution used on satellites. A trade-off based on specific energy, weight and efficiency was performed and the resulting choice of Li-ion batteries was the MP 174565 xtd Li-Ion battery manufactured by Saft. Their specific energy is of 150 W-h/kg. The lithium-ion batteries were then designed in reference to the satellite's peak power consumption considering the authorised discharge coefficient, discharge efficiency, specific energy and battery density. The final volume and the mass of the batteries system created for 21 customers satellites is of 5 816kg for 15 years of autonomy, or 6 107kg when considering a 0.05 margin. Once the capacity of the batteries known, the area of solar array is computed knowing shall be replaced after 15 years of mission and that the specific power of a solar pannel was of 70 W/kg. Finally, the solar arrays surface area required was of 2 676 m² and the total mass of the solar panels is found to be of 8 265 kg. The Power Management And Distribution (PMAD) subsystem encompasses all blocks connecting the source, storage, and load, along with necessary power conditioning equipment for each component. The project's focus was on estimating the PMAD weight and optimizing the main bus voltage. The PMAD system mass was assumed to be a proportion of the total power system mass and several previous spacecraft sizing investigations have referenced this proportion to be within 0.2 to 0.3. The final estimated mass of the PMAD system was then computed to be of 4 694 Kg. Finally, a 300 V bus voltage was selected, anticipating that suitable off-the-shelf parts will be available within the next five years, aligning with the timeline for MegaSat's development.

7. Thermal control system

Designing an efficient and reliable thermal control system is vital for the structure's success. The thermal analysis involved both hand calculations and validation through a

	Peak Power per unit(kW)	Average power per unit (kW)	Number of units
Customers	25	25	20
Central Dish	25	25	1
Sensors	0.05	0.05	1
Robotic arm	1.3	0.5	1
AOCS (Thusters)	9	9	1
Power losses	2	6	1
Processing data	0.5	0.5	1
Total	541.85	537.05	

Table 1: Power consumption

model in ESATAN software. Due to MIDAS' large size, numerous parts and the different purposes of its structural elements, it was impossible to consider it as one thermally coherent unit. Separating it into 3 different thermally stable and coherent structures was necessary to establish heat balances and efficient thermal control managements. Those 3 thermal units are the central structure, the boomerangs structure only - isolated from the central structure - and the solar arrays, deployed to provide power for up to 13 customers satellites (which corresponds to the configuration without any extension). Those structures each faced 3 different situations: sun illumination, eclipse time and orbital transfer from GTO to GEO. The solar arrays shall be equipped with sensors and actuators allowing them to rotate around their axis to always point towards the Sun to ensure maximum efficiency. Moreover, the beams between the solar arrays and the central structure were assumed to be conductive interfaces and no radiative coupling between the solar array and the body was assumed.

The nominal operating ranges were collected for all equipment used by the others work packages and sorted regarding in which thermal structure studied they are located. The temperature range specifications for each thermal case were established and are summarised in Table 2 below. Moreover, using the power consumption, the efficiency of the energy conversion and the use case of each electric element of MIDAS, the internal heat dissipation by each equipment was calculated and the total sum of heat dissipation flux for each structure is presented in the table below.

The heat dissipated by the batteries during the eclipse, when discharging, being higher than during daytime, when it is charging, might seem counter intuitive, but one must remember that those values refer to the total heat dissipated during each phase and that the eclipse period is very short compared to the charging period. Therefore, the batteries discharge in a very short amount of time, resulting in a high heat dissipation

The heat transfers accomplished between the space-

craft and its space environment happen via thermal radiation at every external surface. Therefore, to maintain operating temperature inside the spacecraft, thermal radiation heat transfer is controlled thanks to wavelength-dependent surface coating. To fulfil their function as radiators, those surfaces shall be located on MIDAS in areas that never see the Sun: which are the external surfaces of the boomerangs that point to the central structure, the central structure's surfaces perpendicular to the solar panels beam and the back of the solar panels. A trade-off on the surface coating used for radiators surface chosen was established and highlighted that the MAP PSBN paint was the most suited one for MIDAS.

A MLI blanket was designed to protect and insulate the spacecraft surfaces from the harsh space environment. The more layers of reflectors the blanket is composed of, the less heat is transmitted and the lower the total emissivity of the blanket is. After trade-offs on MLI materials, MIDAS' MLI blanket was composed of 25 layers, consisting of Dacron netting for the spacers, DAM for the reflectors and for the outer and inner layers. [12]

For all cases, the temperature T inside all 3 structures using the Heat balance equation was computed and if the temperatures computed were outside of the operating temperature ranges, some additional thermal control management was put into place. All temperatures computed for both the central structure and the solar arrays were within operational range during daytime and eclipse. The temperatures of the boomerangs were below the minimum allowed temperature and additional passive thermal device was needed where the radiator area could vary to allow optimal temperature in different situations as 31 m^2 of radiator areas was needed during daytime but only 8 m^2 were required during the eclipse. Therefore, 23 m^2 of Venetian blind louvres which open passively through a spring-actuation mechanism working though conduction were added to the structure. The louvres area is split into 4 to have one louvre on each inner face of the boomerangs. Those 4 identical louvres are constructed with a 3mm thick base plaque and 8 trio of Al-Li 2090 pivoting blades of dimension $2.1 \times$

Thermal unit	Temperature range	Heat dissipation (W)		
		Daytime	Eclipse	Transfer
Central Structure	0 to 40°C	10 632	13 648	54000
Boomerangs	0 to 50°C	neg.	neg.	
Solar Arrays	-100 to 150 °C	39 152	0	20556

Table 2: Nominal operating temperature ranges and heat dissipation

Thermal unit	Radiator area (m^2)	Temperature (°K)	
		Daytime	Eclipse
Central Structure	27.625	306.80	311.7
Boomerangs	23	283.92	-
	0	-	274
Solar Arrays	1629.74	344.36	341.5

Table 3: Temperature of each structure during daytime and eclipse

0.115m and of 5mm thick.

The beams connect solar to pannels and their conductivity is $\kappa = 220W.m^{-2}.K^{-1}$ approximately. During daytime the heat transfer goes from the solar arrays to the central structure during those phases and therefore its sign is positive as it enters the central structure. The internal temperatures of the central structure, considering conduction, are presented in the table 4 below. The final temperatures during the daytime and eclipse phases are within the operational temperature range of the central structure.

8. Structure sizing

8.1. The key elements of sizing

The constraints that MIDAS will encounter during its life can be divided into two parts. The first is the constraints seen by each component as it is carried into orbit by the launcher. To do this, particular configurations are needed to get each part (structural or otherwise) into space. The second is the stresses experienced by the complete structure when assembled in orbit. Details of these phases are given below.

8.1.1. Stress during the launch

SpaceX was chosen as the launch vehicle provider. A manual user is available for Falcon 9 and Heavy, giving a number of constraints that the payloads must meet. <https://www.spacex.com/media/falcon-users-guide-2021-09.pdf>

8.1.2. Stress during orbit phase

The second phase covers the life of MIDAS once in orbit. As in the previous section, it is important to study the eigenfrequency of each configuration. The natural frequencies of a structure this large are low, resulting in the structure being easily excited. In addition to this, three perturbations are imposed on the MegaSat during its lifetime

in space.

- The first is the docking of a customer satellite. During docking, the satellites arrive at a certain speed, which is absorbed by the structure of the MegaSat, applying stress to the components.
- The second is the constraint associated with using thrusters for a manoeuvre. Whether to avoid a piece of debris, correct an orbit or for any other manoeuvre, AOCS equipment applies a force to the structure that needs to be studied.
- The last is the stress within the structure caused by the impact of debris on the solar panel. Debris-avoidance systems are in place on the MegaSat, but in the event of a malfunction it is important to anticipate the potential damage caused by an impact.

All these studies will be carried out independently of each other, as it has been decided that the probability of two of these elements occurring at the same time is too low.

8.2. Response of structures to different stresses

8.2.1. Calculation methodology

All the results given below were determined using finite element software. To do this, each flight configuration and orbit configuration was modelled and then a series of loads were applied. For the stress part during flight, 3 loads have a non-negligible probability of arriving at the same time. To ensure the relevance of the study, a superposition theorem was performed to obtain the maximum stress. All the assumptions (calculation/inertia, etc.) were made with the aim of overestimating the stress determined.

8.2.2. Results for the launch

The results of all the studies introduced above can be found in this section. -Natural frequencies:
The table 5 shows the first 3 natural frequencies of each

Thermal unit	Radiator area (m^2)	Temperature ($^{\circ}K$)	
		Daytime	Eclipse
Central Structure	27.625	286.89	310.65

Table 4: Temperatures of the central structure taking into account conduction along the solar panels supporting beams

Bending mode	Central structure frequency (Hz)	Boomerang frequency (Hz)	Extension frequency(Hz)	Interface frequency (Hz)
First mode	50.1	11.8	12.9	1457.9
Second mode	50.2	12.4	25.6	1512.2
Third mode	50.9	14.5	28.7	2833.6

Table 5: First 3 natural frequencies of each component

flight configuration. These 3 modes are bending modes that fall into the ‘lateral frequency’ category. The axial frequencies comply with the conditions requested by SpaceX. -Flight constraint:

The maximum stress undergone by a payload on its journey from Earth to orbit is 155.7 MPa.

-Payload release:

The maximum stress undergone by a payload at the release by the launcher is 151.5 MPa.

It is interesting to note that these values are not obtained for the same payload, as each of the phases stresses the structures differently.

8.3. Conclusion on the feasibility

The two materials chosen have a Yield strength of 520 MPa for the Aluminium alloy and 740 MPa for the Carbon composite (as this material is anisotropic, this is the lowest yield strength.) The stresses undergone by the structures are more than 3 times lower than the yield strength of the materials used (3 being a safety coefficient granted to the design). In addition, all the assumptions were made in order to overestimate the value of these stresses. The conclusion is that MIDAS is structurally viable.

9. Financial Feasibility

The MegaSat is a project which pushes boundaries in terms of size, low TRLs and modularities. This all comes with a cost. However, the project has been fully costed and a business plan put together to ensure it is profitable for the operator. In order for a project to survive in the space industry, it must be profitable and have a solid business case to pitch to customers.

9.1. Savings

Market Research into existing GEO communications satellites (Echostar 24, SES-17 and Eutelsat Konnect VHTS) validated the use of CER tables [10] for subsystem cost estimation. As MegaSat provides multiple subsystems for the customer, reductions in development and test costs resulted in an average saving of 42.65%. For an average GEO satellite on a 15 year mission, this would reduce the estimated end-to-end costs from \$505 Million to \$290 Million. In addition, placing any satellite into GEO through GTO [13] requires a powerful launch vehicle. By reducing the volume and mass of a GEO satellite, satellites which previously required their own launch to GEO can rideshare, significantly cutting launch costs.

8.2.3. Results for the life in orbit

-Natural Frequencies:

As for the launch section, the natural frequencies of the 3 MIDAS configurations were recovered. The first 3 are shown in table 6. Frequencies are indicated in Hz. Values below $1e-5$ are indicated as such as Abaqus cannot give the exact value. Unlike the previous section, the results will be given by configuration and not by component.

-Thrust manoeuvre: Von Mises constraint (Pa) = 0.1.

This value was so low compared with what the structure could withstand that no further study was carried out, as it did not appear to be a dimensional parameter.

-Docking manoeuvre:

Each new configuration brings new docking zones, and the further this docking point is from the MIDAS centre of mass, the greater the stress. The study is therefore carried out at a different point for each configuration. The values are summarized in 7. This operation mainly concerns the docking interface. A study was therefore also carried out to determine the maximum stress seen by this mechanism. The value is 107.4 MPa. These simulations represent the docking of an 8000 kg module arriving at a speed of 0.06m/s.

Midas configuration	Configuration 1	Configuration 2	Configuration 3
Mode 1	2.71e-4	<1e-5	1e-5
Mode 2	3.70e-4	1.62e-4	1e-5
Mode 3	6.35e-4	1e-5	1e-5

Table 6: Natural frequencies of the 3 MIDAS configurations

Midas configuration	Configuration 1	Configuration 2	Configuration 3
Von Mises stress (Pa)	5900	50200	300

Table 7: Von Mises stress of the 3 MIDAS configurations

9.2. Payment Plan - Example

The amount the operator charges the customer would need to be a balance between providing the customer the savings to compensate the additional risk and ensuring profitability to the operator. An example of how this could work would be if the customer agreed to pay \$11 Million per year for a fifteen year mission, a total contract value of \$165 Million. This would provide the customer an overall saving versus a conventional mission of 18%. This would be broken down into a 20% deposit and first payment, totalling \$41.8 Million, then yearly payments of \$8.8 Million paid to the operator for the remainder of the mission. The exact price paid by each customer would likely vary based on a number of additional factors such as: – Company maturity, as newer companies may present more risk and thus be may be charged more as additional insurance. – Slot allocation, as some slots offer more versatility than others on the station by offering a larger area to deploy antennae into. – Lease duration, longer leases can often come with discounts to the customer as they provide security to the operator.

9.3. MegaSat Costings

The steps taken to establish the financial feasibility of MIDAS were as follows:

1. Estimate, through use of SMAD's USCM8 CERs (9.3.1) and open source data and cost reduction techniques, the cost of MIDAS in it's current design state. This includes all individually designed components, industry supplied solar panels, propellant and wrapping cost such as IA&T and through-life operations.
2. In order to determine if MIDAS can compete with the market, conduct market research to estimate the current total cost to a customer of launching a high-throughput GEO communications satellite.
3. From this market research and through use of SMAD, break down the component masses and costs a customer expects to budget for each sub-system. Use this data to determine what the saving

would be to the customer to join MIDAS minus sub-systems MIDAS can provide and compare this to the standard mission cost.

9.3.1. Cost Estimation Techniques and Limitations

Various tools and assumptions were made throughout the estimation process, however, considering the grandiose scale of MIDAS, many of these tools are not entirely accurate.

9.3.2. Cost Estimation Relationship Selection

The CER tables found in SMAD [10] are an industry standard tool in estimating the cost of satellites and offer a classification of both "Recurring" and "Non-Recurring" costs. Analysis of seven GEO satellites showed a closer correlation with "Recurring Costs". For example, Echostar 24, had a dry mass and project cost of 5900 kg and \$480.6 Million (USD2024) respectively [14]. Breaking the mass down into sub-systems and calculating the cost through both the Non-Recurring and Recurring CER tables[10], the values calculated were \$1.43 Billion and \$484 Million respectively. While not all satellite cost estimate that underwent this analysis were so close, the recurring cost model proved far more accurate and was thus used for the remainder of the estimation process. In order to improve the accuracy of estimates, multiplying factors were added to each component to account for TRL. A large majority of this project contains components with TRL below five therefore this has significant effect on the overall cost. Some aspects, such as the development of aluminium trusses required for the CS, Boomerangs and Extensions, would likely cost less than estimated as once the technology is developed for one element, this will translate to the other parts.

9.3.3. Solar Panel Cost Estimation

Using the ISS iROSA panels to estimate costs, a total photovoltaic cell area of 77 m² and the most recent unit cost of \$17.5 Million per panel (\$35 Million for two panels in 2023 [15]) gives \$227,000 per m² of panel area required. MegaSat panels are likely to be cheaper, as there is no requirement for human-rating or retrofitting of ISS deployment equipment.

9.3.4. Final MegaSat Infrastructure Costs

After applying all the above methods and utilising cost reduction strategies, Table 6 presents the final cost of MegaSat to the operator.

T1 Cost- MegaSat	13 Customers	21 Customers
Launch Costs (inc Insurance and LOOS) (\$M2012)	462.94	631.02
Propellant (\$M2012)	6.88	10.04
Central Structure (\$M2012)	568.20	568.20
Boomerangs (\$M2012)	552.07	552.07
Solar Panels (\$M2012)	147.80	207.23
Docking Extensions (\$M2012)	315.79	588.12
Total 2012 T1 Cost (\$M2012)	2053.67	2556.68
Total 2024 Cost (\$M2024)	2640.20	3286.87
Total 2030 Cost (\$M2030) (Initial Investment)	2997.13	3731.22
Replacement Costs - MegaSat	13 Customers	21 Customers
Orbit Control Xenon refills	20.58	29.13
Batteries + OBDH	183.66	408.30
Total Replacement Mission Costs (\$M2024)	204.23	437.43
Total Replacement Mission Costs Inflation Adjusted	355.96	650.00
Total Project Cost Inflation Adjusted (\$B)	3.35	4.38

Figure 6: Total MegaSat Costs

9.4. Final Assumptions and Proposal

This section will explain the final proposal, covering assumptions made, ROI potential and conclude the financial feasibility review of the project. **Assumptions.** It is assumed a continuous 15-year occupancy of each orbital slot. A minimum cost saving for the customer of 20% and a deposit of 50% will be assumed for the first group of missions in order to assist in covering initial investment costs. Missions beyond the first batch could have the option of a lower deposit option with higher recurring payments which may suit smaller enterprises. **Proposal.** Should an operator take the MIDAS project beyond this report, they could see returns of approximately \$17.44 Billion between 2030 and 2075, adjusted for inflation. This equates to \$6.98 Billion of profit in USD2030 over the forty-five year lifespan and comes at an up front investment of \$1.87 Billion, equating to an ROI of 373%. While this project comes with risks, it also brings with it the benefits of developing new large satellite. These include the potential R&D developments that could come out of investing in a project of this scale [10]. Notably, it could advance the technology used in the satellite communications industry

through innovations into solar, battery and AOCS systems.

10. Conclusion

A GEO orbit is a valuable, finite resource, and the MegaSat concept multiplies that resource. The novel features of this concept are as follows:

- Scalable over time - only necessary infrastructure is launched as customers are on-boarded
- Power and Thermal is managed - customer satellites are simpler, faster to develop, and therefore cheaper
- Replacing infrastructure throughout the satellite lifetime ensures an enduring structure
- The MegaSat takes responsibility for the launch, transfer and final docking of each customer satellite, reducing the administration burden on the customer
- The MegaSat is mechanically strong but optimised for mass, minimising the launch costs
- No structural limit on the number of customer units

The concept is financially feasible, providing profit for operators and savings for customers, and allows flexibility for customers in terms of the dimensions of the satellite they can onboard. The size of the structure and the long lifetime, along with the low TRL of some required technologies, does mean that the project comes with some risk. However, that risk is mitigated through the scheduled infrastructure replacement programme, taking advantage of regular commercial launches. This has the additional benefit of the ability to implement the latest and efficient technologies through this replacement scheme, throughout its lifetime.

Furthermore, MegaSat opens up access to the GEO orbit to smaller organisations who might not otherwise be able to afford it, such as universities and other research institutes. Previously only the preserve of large technological companies, this could accelerate research and democratise the GEO space, which can only be a positive thing. MegaSat has the opportunity to change the paradigm, reducing space debris whilst increasing our knowledge of GEO and beyond.

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