# POLITECNICO DI TORINO

**Master Degree in Aerospace Engineering**


Master Thesis

# Concurrent Engineering Methodologies applied to Mars-Sample Return Orbiter, with the focus on System and Sub-System budgets and their correlation with Mission Analysis


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March 2019

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# *Abstract*


Alla fine del mio percorso universitario, ho deciso di toccare con mano lo studio di una missione interplanetaria, nell'ambiente stimolante di Thales Alenia Space a Torino. La missione in oggetto è Mars Sample Return ed il lavoro di questi sei mesi consiste nel coadiuvare lo sviluppo del progetto dell'orbiter attraverso un approccio multidisciplinare. Il focus è indirizzato allo studio ed allo sviluppo dei vari sistemi e sottosistemi, tenendo conto dell'obbligo del soddisfacimento dei requisiti imposti dall'agenzia spaziale europea, e dei vincoli di progetto derivanti da simili parametri. Durante questo studio, si susseguono frequenti meeting, teleconferenze e scambio di dati ed email con altre aziende collaboratrici, con l'ESA e la NASA ed altri rami aziendali interni in Thales. L'obiettivo ultimo, è creare un database di informazioni utili allo sviluppo della missione, senza privilegiare una branca ingegneristica per trascurarne un'altra, e quindi avere una visione sistemistica globale di insieme. Come si evince dal titolo della tesi, il design avviene in un ambiente collaborativo in cui ogni specialista e membro del team multidisciplinare conosce il minimo indispensabile del lavoro altrui; le informazioni derivanti dalle diverse branche ingegneristiche vengono raccolte in modo che possano essere costruiti i budget tecnici di missione, in grado di definire la fattibilità della stessa, e validare l'analisi di missione, ossia il modello geometrico della missione. Il lavoro inizia con la costruzione del budget di massa e di potenza, e continua con il calcolo delle proprietà inerziali mediante la costruzione del modello geometrico con il software IDM-CIC; successivamente, viene creato un modello di simulazione di missione su STK con lo scopo di validare i dati dell'analisi di missione e di costruire il pointing budget. Tutte le informazioni ed i modelli creati, vengono continuamente aggiornati secondo un ciclo di ottimizzazione ciclico.

I risultati del mio lavoro hanno permesso non solo di creare un ponte tra i vari rami aziendali e tra gli stessi membri del team, ma anche di determinare pregi e difetti di una determinata soluzione ingegneristica in fase di progetto dei quali si è tenuto conto in fase di trade-off. Inoltre, è stato possibile scoprire e correggere alcuni errori in fase di progetto, ed è stato possibile trovare una strategia di mitigazione di alcune inaccuratezze modellistiche dei software utilizzati.

## *Definitions and Acronyms*

| ACRONYMS | DEFINITION |
|---|---|
| AGI | Analytical Graphics Incorporated |
| AOCS | Attitude and Orbital Control System |
| BC | Baseball Card |
| CAD | Computer aided design |
| CCM | Capture and Containment Module |
| CCRS | Capture Contain Return System |
| CDF | Concurrent Design Facilities |
| CE | Concurrent Engineering |
| COG | Center of gravity |
| CP | Chemical Propulsion |
| EAM | Earth Avoiding Manoeveur |
| ECSS | European Cooperation for Space Standardization |
| EEV | Earth Entry Vehicle |
| EP | Electric Propulsion |
| ERM | Earth Return Module |
| ERO | Earth Return Orbiter |
| ESA | European Space Agency |
| ESTEC | European Space Research and Technology Centre |
| ETM | Earth Targeting Manoeveur |
| FPA | Flight Path Angle |
| HB | Hybrid Propulsion |
| HGA | High Gain Antenna |
| GMV | Gmv innovation solution company |
| GNC | Guidance Navigation and Control System |
| IDM | Integrated Design Model |
| INIT | Init Mode |
| J2000 | Modified Julian Day 2000 |
| LEOP | Launch and Early Orbit Phase |
| LGA | Low Gain Antenna |
| LMO | Low Mars Orbit |
| LOS | Line of sight |
| M2020 | NASA's Mars 2020 Rover |
| MAG | Mission Analisys Guideline |
| MAV | Mars Ascent Vehicle |
| MCI | Mass Centre of gravity Inertia |
| ME | Main Engine |
| MMOD | Micrometeoroids and Orbital Debris |
| MMI | Mono-methyl-hydrazine |
| MOI | Mars Orbit Insertion |
| MON | Mixed Oxides of Nitrogen |
| MSR | Mars Sample Return |
| N2H4 | Hydrazine |
| NASA | National Aeronautics and Space Administration |

| | |
|---|---|
| NOM | Nominal Mode |
| OCM-C | Orbital control mode critical |
| OCM-N | Orbital Control Mode Nominal |
| OS | Orbiting Sample |
| PP | Planetary Protecton |
| PPU | Power Processor Unit |
| PRR | Preliminary Requirement Review |
| RAAN | Right Ascension of the Ascending Node |
| RCS | Reaction Control System |
| RWL | Reaction Wheels |
| RDV | Rendez-Vous |
| REL | Realy Mode |
| RF | Radio Frequency |
| RVA | Rendez-Vous Approach System |
| RVC | Rendez-Vous and Capture Mode |
| SAFE-1 | Safe 1 Mode |
| SAFE-2 | Safe 2 Mode |
| SAFE-P | Safe Proximity Mode |
| SC | Soccer Card |
| SHS | Sample Handling System |
| SFR | Sample Fetch Rover |
| SRL | Sample Return Lander |
| STK | Systems Tool Kit |
| TAS | Thales Alenia Space |
| TAS-F | Thales Alenia Space France |
| TAS-I | Thales Alenia Space Italy |
| TAS-UK | Thales Alenia Space United Kingdom |
| TCM | Trajectory Correction Manoeuvre |
| TOA | Target Orbit Acquisition |
| TRL | Technology Readiness Level |

*Table A - Acronyms*

# *Contents*

# Part I – Introduction

# Chapter 1

# Mars-Sample Return Mission

The red planet has been the subject of study and exploration since the 1960s. Over the decades, various missions have contributed to spread information about the soil and atmosphere. Despite the technological progress allowed the use of increasingly sophisticated technologies, no mission could ever be comparable to a study of the ground and the Martian rocks in a laboratory or in any case in an independent manner. A study of this type would obtain more detailed and independent information than the study that could offer a probe in orbit around Mars. MRS is a huge campaign of space missions with very important implications in the study of Mars. The various missions, constituting the entire campaign, consist in the collection of samples of rocks and soil dust and Martian underground, in order to return them to Earth and to analyze them in terrestrial laboratories. Analysis of this type are very powerful and efficient: being carried out on the Earth they would be independent of temporal, budget and space constraints. According to the Executive Director of The Planetary Society, Louis Friedman, any of Earth's laboratories could study a sample so the MSR campaign has an high expected scientific return on investment. Due to this, for the planetary science community, any Mars Sample Return mission is one of the most important robotic space missions.

The project and the development of a campaign of such missions is not at all simple. In fact, most of the projects did not pass the feasibility phase and they remained as only study cases. A MSR mission has never gone beyond phases A and B until today due to technical and economic reasons.

*Figure 1.1 - MSR Campaign*

## 1.1 Description of the MSR Campaign

There is currently a collaboration between NASA and ESA for the MRS campaign. This joint venture explores mission concepts for an international MSR campaign between 2020 and 2030: it is composed by three launches, in order to land on Mars surface, to find and store samples and deliver them to Earth.

Returning to Earth a set of Mars rocks, soil and atmospheric samples before 2031, is the goal to be achieved by the MSR campaign, that is composed of three missions.

1. The first launch is scheduled for 2020 and concerns NASA's Mars 2020 mission. A rover will explore and rigorously document the surface of strategic areas of the red planet. It will have a container for 31 rock and soil samples taken from the rover's mechanical arm. The samples will be sealed and stored for a future taking in other MRS phases: they will be retrieved later for flight to Earth.
2. The second mission is Sample Return Lander (SRL) and it will be in 2026: NASA will launch to Mars a surface platform, the Sample Fetch Rover (SFR) provided by ESA and a Mars Ascent Vehicle (MAV). At this point the ESA comes into play with the Sample Fetch Rover: it will land with the lander designed by NASA and will go to retrieve the samples of Martian rocks collected by the M2020 rover. Subsequently the soil samples will be delivered from the SFR to the Mars Ascent Vehicle (MAV), ready to lift off, with the precious content, from the Martian surface to get into a parking orbit.
3. In the final phase of the campaign, in the third mission, ESA provide Mars-Sample Return Orbiter which will launch in 2026. At the beginning, ERO will provide monitoring, data relay and tracking of the Mars Ascent Vehicle launch. Once in Martian orbit, the MAV releases to ERO a container containing the samples of Martian soil, called Orbiting Sample (OS). ERO, which sent from Earth, will capture the OS. The samples will be sealed in a biocontainment system before being inserted into an Earth entry capsule: this aspect is necessary to prevent contaminating Earth with unsterilized material. The ERO will return back home with samples inside a capsule or return vehicle called Earth Entry Vehicle (EEV), in full compliance with the Planetary Protection requirements . Once the Earth is reached, the ERO will release the EEV with the precious scientific payload that will land safely in the USA, in order to end up in a specialized handling facility. At the end, the ERO will perform an Earth avoidance maneuver, thereby ending its mission.

The following figure summarizes the entire MSR mission campaign. As it can be seen, with the Sample Return Lander mission, NASA will send from Earth and land a platform near Mars 2020 site. From here, the Sample Fetch Rover, a small rover launched by ESA, will collect the catched samples. Once it has retrieved them, SFR will take the samples to the SFL platform. Here, the SFR will load the samples into a single basketball-size metallic container on a launcher which will perform the lift off from Mars and it will carry the canister into Mars orbit. This vehicle is called Mars Ascent Vehicle (MAV). ESA's Earth Return Orbiter will search and capture the football-size sample container orbiting Mars. ERO will take the samples to Earth. It is reiterated that ESA and NASA are exploring the concepts for these missions, with ESA assessing the Sample Fetch Rover and Earth Return Orbiter.

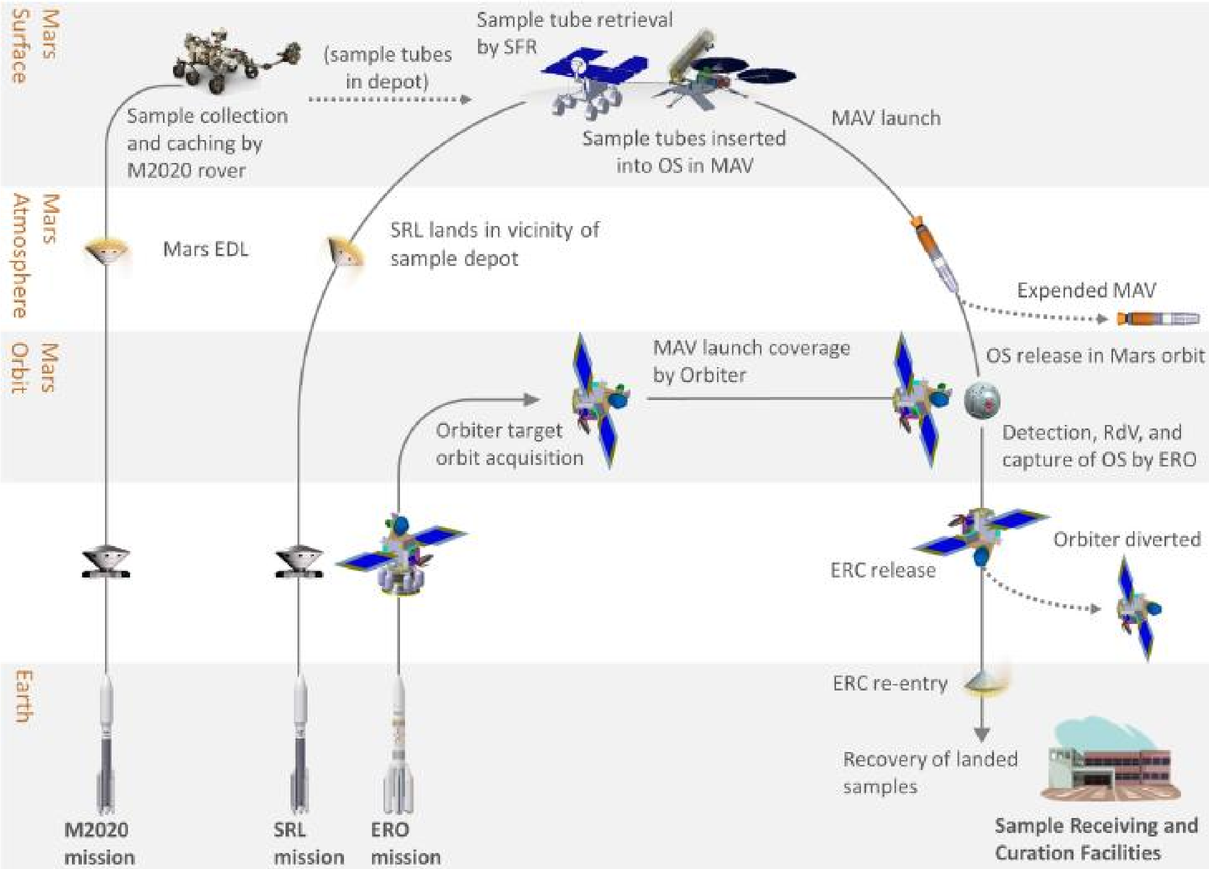



*Figure 1.1.1 - Campaign Concept (courtesy of ESA)*

## 1.1.1 Risk of biological contamination

The difficulty and complexity of the implementation of an MRS mission is increased by the need to avoid terrestrial bacterial contamination on the Martian samples, and above all by the need to avoid the reverse path: the contamination by Martian organisms potentially dangerous for humans. To all this, there is the clear opposition of international organizations on the realization of a mission of this kind in general. An example can be the International Committee Against Mars Sample Return.

This organization aims to avoid the risk of contamination on the Earth and therefore opposes the delivery of samples of Martian rocks until they have been declared safe for humanity and uncontaminated by unknown organisms. The investigations, always according to this organization, should be followed on Mars or on the International Space Station but always in a quarantine regime.

## 1.1.2 Planetary Protection

Two main aspects lead this preliminary mission analysis of planetary protection, corresponding with the two most critical phases:

a) Forward contamination, concerning the orbit stability around Mars.

b) Backward contamination, concerning the Earth potential contamination.

The forward contamination aspect is regulated by ECSS requirement, one of the following conditions shall be met:

a) The probability of impact on Mars by any part of a spacecraft assembled and maintained in ISO level 8 cleanrooms, or better, is ≤ 1x10-2 for the first 20 years after launch, and ≤ 5x10-2 for the time period from 20 to 50 years after launch.

b) The total bioburden of the spacecraft, including surface, mated, and encapsulated bioburden, is ≤ 5x10-5 bacterial spores.

Therefore, once the LMO will have been defined, its stability will be analyzed for 20 and 50 years. In case the selected orbit did not meet the requirement, an alternative stable orbit would be proposed, with the twofold goal of fulfilling the ECSS requirements while minimizing the $\Delta V$ for its acquisition.

On the other hand the backward contamination requirement imposes that "the orbiter does not hit the Earth for at least the following 100 years after Earth avoidance maneuver". The effectiveness of the Earth avoidance maneuver is strictly dependent on its execution time: the sooner the engines firing is completed the better. Nevertheless an early EAM also causes an early EEV release, increasing the capsule dispersion at the entry point. Considering the mission requirement ("The EEV shall be released in the vicinity of Earth 1-4 days before Earth arrival.") and 50 m/s of initial allocation for the EAM, a preliminary analysis of the ERO orbit stability after EEV release has been performed (considering the perturbation of the Sun, Mercury, Venus, Mars and Jupiter). If the maneuver is performed 1 day before the Earth, the satellite will be already within the Earth sphere of influence, and a first close encounter with the Earth is expected in year 2066 (if the EAM is instead anticipated at 4 days, the first close encounter with earth would be in year 2082).

Once the inbound leg will have been fully defined and the requirements boundaries will have been specified with more detail, a full Monte-Carlo analysis will be performed to properly size the EAM.

# 1.3 Mars-Sample return Orbiter Mission

Within the MSR campaign, the last mission is described in detail, which according to the baseline will start in 2026 and will end by 2030-2031, but a postponement through 2027 and 2028 back-up missions that will end will be provided by 2035. In this paragraph, there is an overview of MSR-O scenario with its mission phases, addressed with details and its relevant timelines.

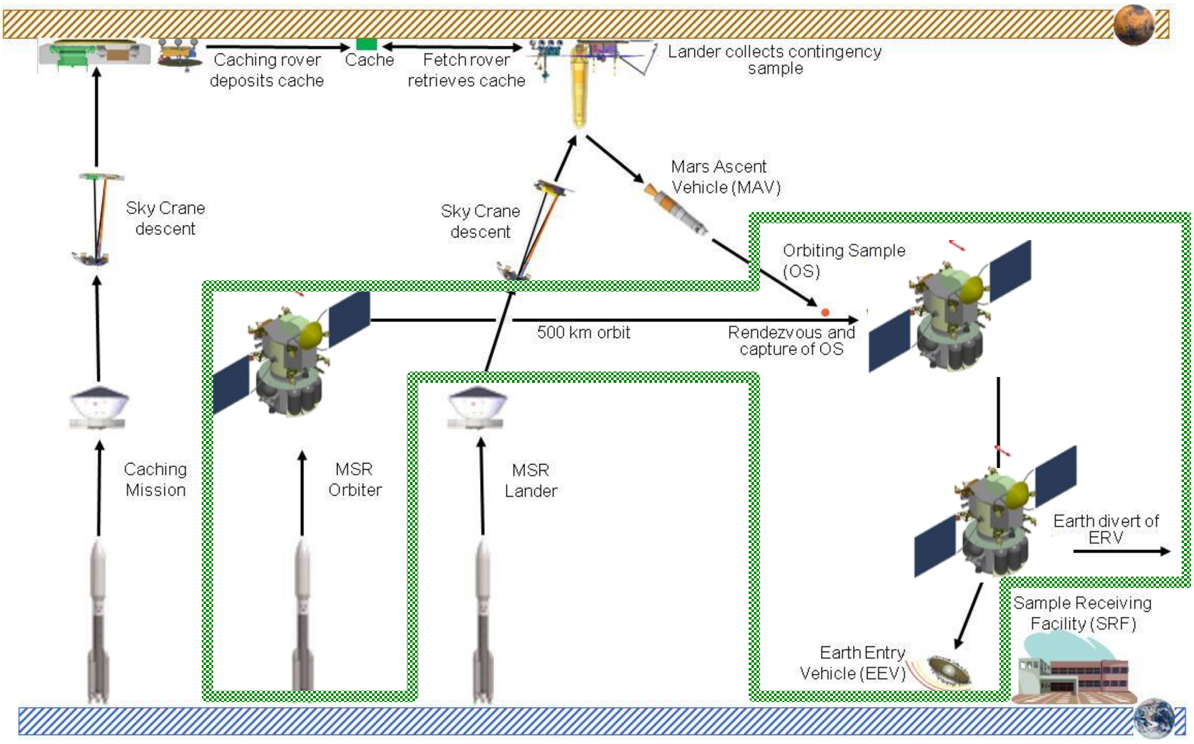



*Figure 1.3.1 - MSR Orbiter Mission Architecture (courtesy of ESA)*

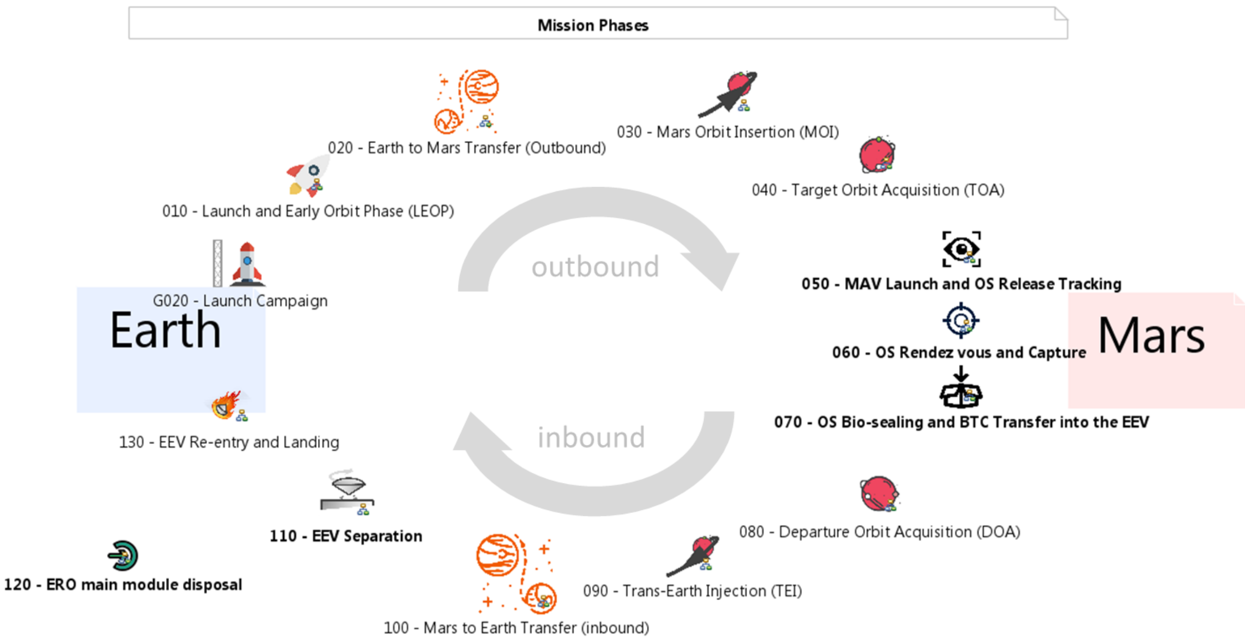



*Figure 1.3.1.1 – MSR-O Mission Phases (in bold the payload critical)*

### 1.3.1 Earth Departure Phase

The Earth departure and the injection into the Mars transfer trajectory is performed directly by the final stage of Ariane 64. The performances of the Ariane 64 launcher for direct launching depend highly on the escape velocity and infinite declination that are given by Earth-Mars relative positions.

The architectures that are selected for the MBR show the V∞ and DLA characteristics reported in table below.

| **Propulsion Solution** | **Earth escape $V_\infty$** | **Mars arrival $V_\infty$** | **Earth $V_{entry}$** |
|---|---|---|---|
| Electric | 2.92 km/s | 0.61 km/s | 13.0 km/s |
| Hybrid | 2.50 km/s | 1.35 km/s | 12.9 km/s |
| Hybrid | 2.65 km/s | 1.57 km/s | 12.8 km/s |
| Chemical | 3.21 km/s | 2.98 km/s | 12.3 km/s |

*Table 1.1 - Launch Characteristics*

The Orbiter is separated by the upper stage. In order to ensure the Telemetry acquisition after separation, the ejection attitude is such to point the spacecraft HGA toward the Earth. The Cruise phase starts after the ground recovers control of the spacecraft and lasts until the start of the Mars Orbit Insertion manoeuvre. In the early period of the cruise the Orbiter undergoes a series of checks and in-flight tests to guarantee its functionality.

### 1.3.2 Earth-Mars Cruise Phase

The Earth Mars Cruise starts at the end of the launcher upper stage when the S/C is separated onto the transfer trajectory to Mars. The Cruise is different for the three mission architectures identified depending of the propulsion source.

Shortly, in the EP-EP and HB-EP options the transfer is performed by implementing long continuous thrust arches using the electric motors, in the CP-CP option the transfer is based on mid-course impulsive manoeuvres to achieve the right declination for Mars orbit insertion.

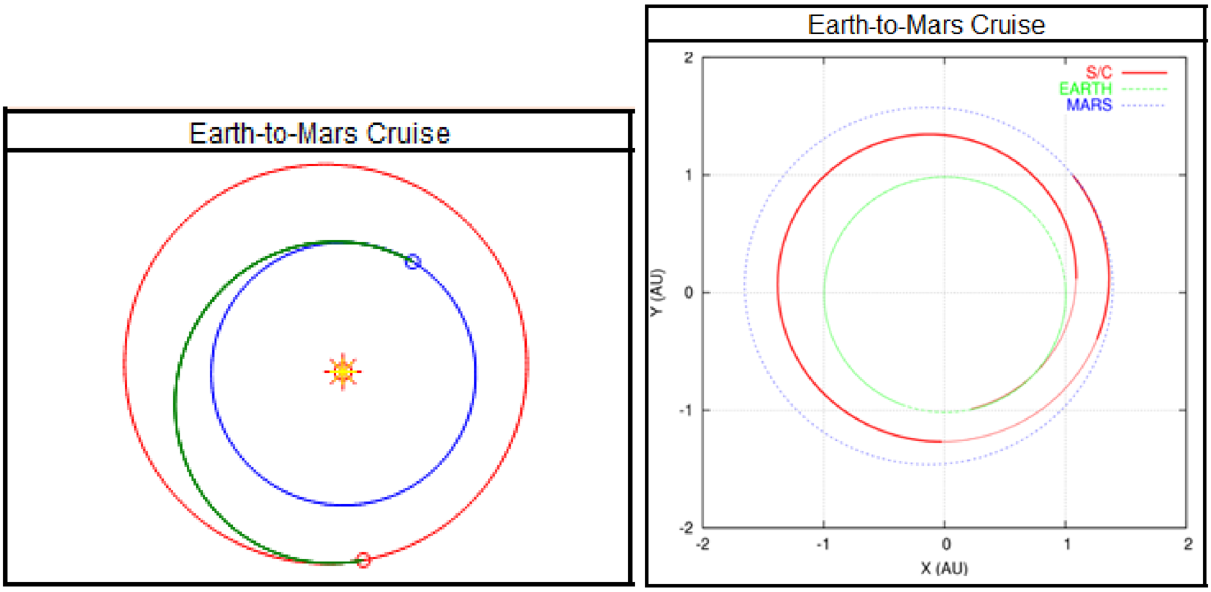



*Figure 1.3.2.1 - Examples of outbound cruise*

### 1.3.3 Martian Phase

The Martian phase covers all the operations performed in Mars proximity. This phase is actually divided into Mars Orbit Insertion, Target Orbit Acquisition and Low Mars Orbit.

The first two sub-phases are different for the three mission architectures identified: in the EP-EP option there isn't a proper MOI but the orbiter is gently brought into the target orbit with a continuous burn of the electric thrusters so that the trajectory takes the form of a spiral (spiral-in or spiral-down). In the Hb-EP option the MOI is performed by an impulsive manoeuvre with the chemical high-thrust engine, followed by a spiral-down TOA based on electric thrusters.

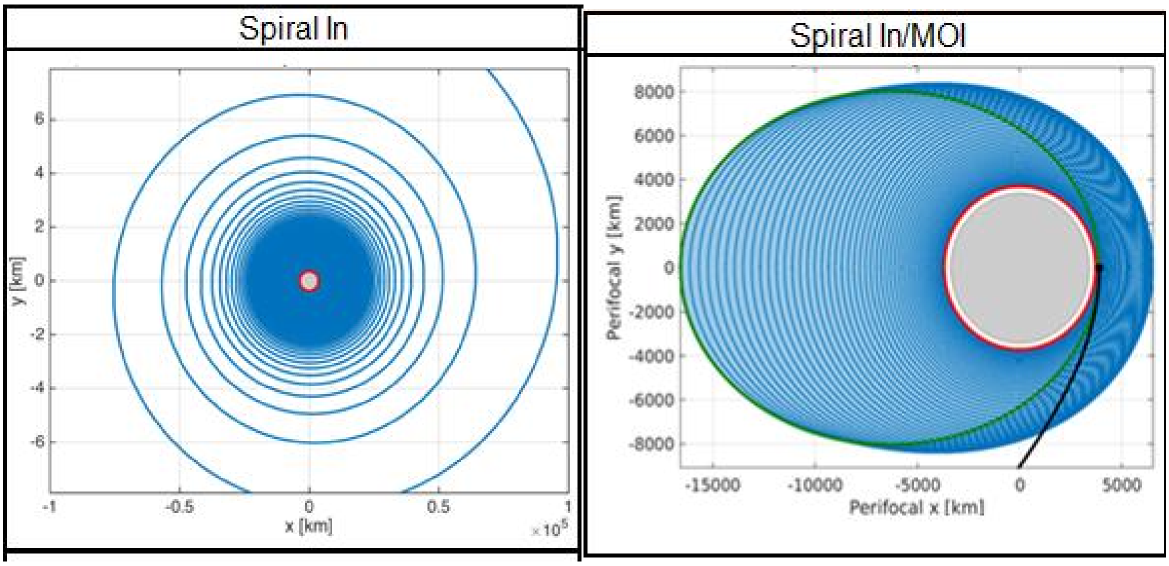



*Figure 1.3.3.1 - Spiral in solutions*

Finally, in the CP-CP option there is an impulsive MOI (however less Δ-V demanding than in the Hb-EP option) followed by  an Aerobraking phase.

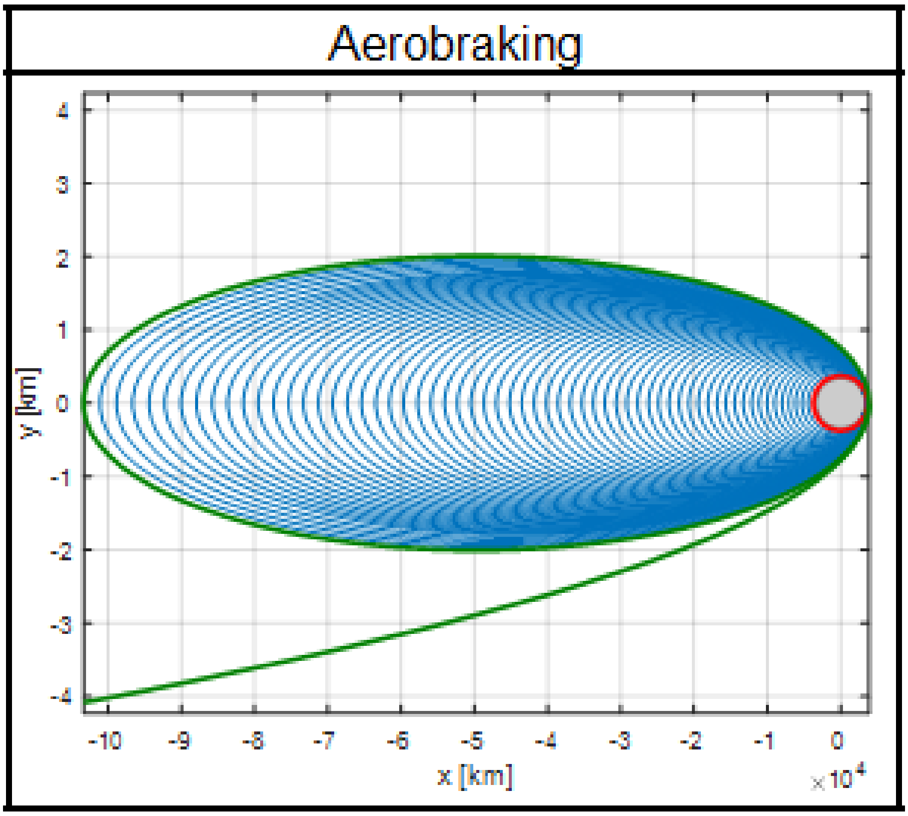



*Figure 1.3.3.2 - Aerobraking solution*

The Mars proximity operations are affected by a Solar conjunction event. The details of the impacts on each one of the proposed architectures are described separately in the following paragraphs. Once the Low Mars Orbit is acquired the Orbiter may be requested to perform data relay of Mars assets data to Earth.

The MAV coverage consists of monitoring the MAV launch preparation and launch, by acquiring the associated data and transmitting them back to the Earth when in visibility with the Ground station.

The MSR rendezvous and capture operations begin when the OS is released in orbit by the MAV launched from the Mars surface. The MAV reaches, with a certain accuracy, the orbit from where it releases the OS with a given release velocity. This phase determines completely the target orbital parameters.

## 1.3.4 MAV launch and OS release tracking

The MAV launch and OS release tracking phase starts when the ERO is placed in the Target Orbit, at least 10 days prior to MAV launch. Such phase is composed by the following sub-phases:

- MAV Monitoring Launch Preparation: this phase includes the pre-placement of the ERO in the Target Reference Orbit and the test of MAV-ERO commands, the MAV-ERO transmission and data relay functions. The nominal duration is 10-14 days depending of the launch window.
- MAV launch and OS release tracking: from a small time prior to launch the MAV will start sending its signals to the ERO. In parallel with such transmission, once the OS is released, an optional beacon (trade-off still open on NASA side) is transmitted for open-loop recording by the ERO. OS beacon relay could be performed in a subsequent moment. The nominal duration will be about 2h.

This phase ends with the MAV disposal and its nominal duration shall be considered 11 to 25 days.

### 1.3.5 OS search, Rendez-Vous, Capture

The OS search, Rendez-Vous and Capture phase is composed by four main subphases from system point of view:

- OS search: determining the actual orbit of the OS after release; the search phase during which the Orbiter detects the OS from its search orbit (can be higher or lower than OS orbit, depending on system constraints and visibility windows limitations due to the Mars limb exclusion angle of the sensors), and performs OS orbit determination. Depending on the search phase, orbital manoeuvres could be needed to take the orbiter at the beginning of the orbit synchronization phase. The Search phase has the objective to detect and track the OS after its orbit injection. In general this phase will be done on-ground through batch filtering. The reference orbit is a circular 375 km altitude orbit (higher than the OS circular orbit – 343 km). The orbit consolidation will be performed during the activity in order to take into account updated mission requirements and the constraints from all the subsystems.
- OS Orbit Synchronization: to reach a co-planar orbit with the OS.
- OS Intermediate/Short Range RDV: to reach a stable position at few km to the OS.
- OS Close Range (Forced Motion and Capture): to capture the OS.

### 1.3.6 Earth Return Phase

In the Earth return phase we have the Mars escape, Mars to Earth cruise and the Earth approach. The Mars escape starts at the end of the rendezvous phase once the OS has been captured and transferred to the EEV. The goal of the phase is to place the S/C on the right trajectory to reach the Earth within the timing constraints of the mission. The escape phase is different for the three mission architectures identified: actually the EP-EP and HB-EP options show a quite similar escape that is performed by a continuous burn of the electric thrusters so that the trajectory takes the form of a spiral (spiral-out or spiral-up) until the orbiter leaves definitely the Mars gravity field, flying to the Earth only under the Sun gravitational effects.

In the CP-CP option the chemical high thrust engine provide an impulsive ΔV that puts the orbiter onto the correct trajectory that intersects the Earth one at the right time.

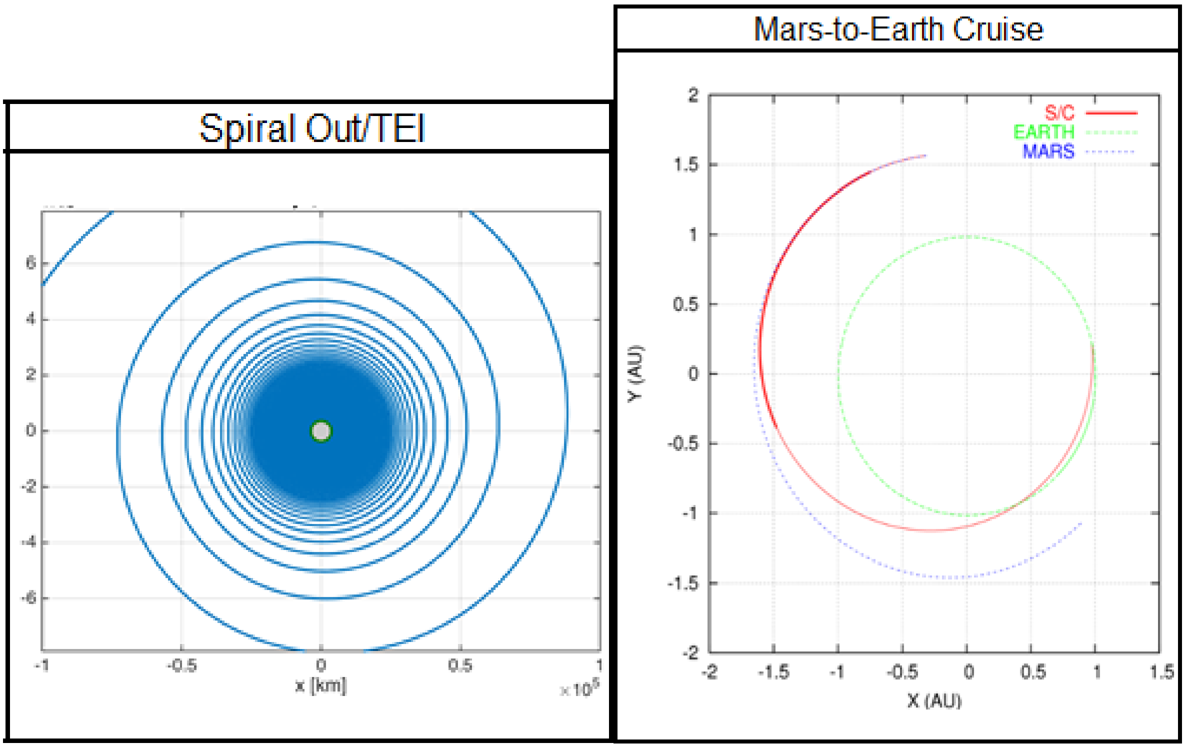



*Figure 1.3.6.1 - Inbound phase*

During the Mars to Earth cruise, also known as inbound leg, the S/C approaches the Earth preparing the re-entry phase and performing trajectory trimmings if necessary. In the Earth approach the final adjustment of the trajectory, to achieve the desired landing conditions, is done. For propulsion reasons the orbiter trajectory during cruise is such to “miss” the Earth RDV and fly away from its gravitational field; therefore an Earth targeting Trajectory Correction Manoeuvre (TCM) is performed in the proximity of the Earth (still out of the Earth sphere of influence) a few days before the arrival. An intensive orbit determination coupled to a stable satellite attitude allows a fast and accurate convergence of ground navigation filters. Based on this trajectory determination, a final targeting is accomplished through another TCM to achieve the required landing location.

Once the ground control segment has checked that all the critical parameters are nominal, the EEV is released on operator decision by a dedicated sequence, providing it the proper kinematics conditions, re-entry velocity and Flight Path Angle (FPA), for its safe re-entry into the Earth atmosphere. Finally, once the EEV is separated from the Orbiter by a sufficient distance, an Earth avoidance TCM is performed by the Orbiter to fly by the Earth at a safe distance. A failure between the targeting and avoidance TCMs that would prevent from doing the avoidance manoeuvre can have dramatic planetary protection consequences, such as backward contamination of the Earth by Martian dust since the Orbiter could have been contaminated during rendezvous and capture phase. The duration between both TCM should thus be reduced to a minimum, in consistency with the reliability of the Orbiter and with the feasible Delta-V, in order to reach the required probability of failure over this period.

### 1.3.7 EEV release and ERO disposal

A preliminary reference scenario for the EEV release and ERO disposal is described in this section. In the next phases of the project, it will be detailed and refined according to the backward planetary protection requirements and the mission risk evaluations.

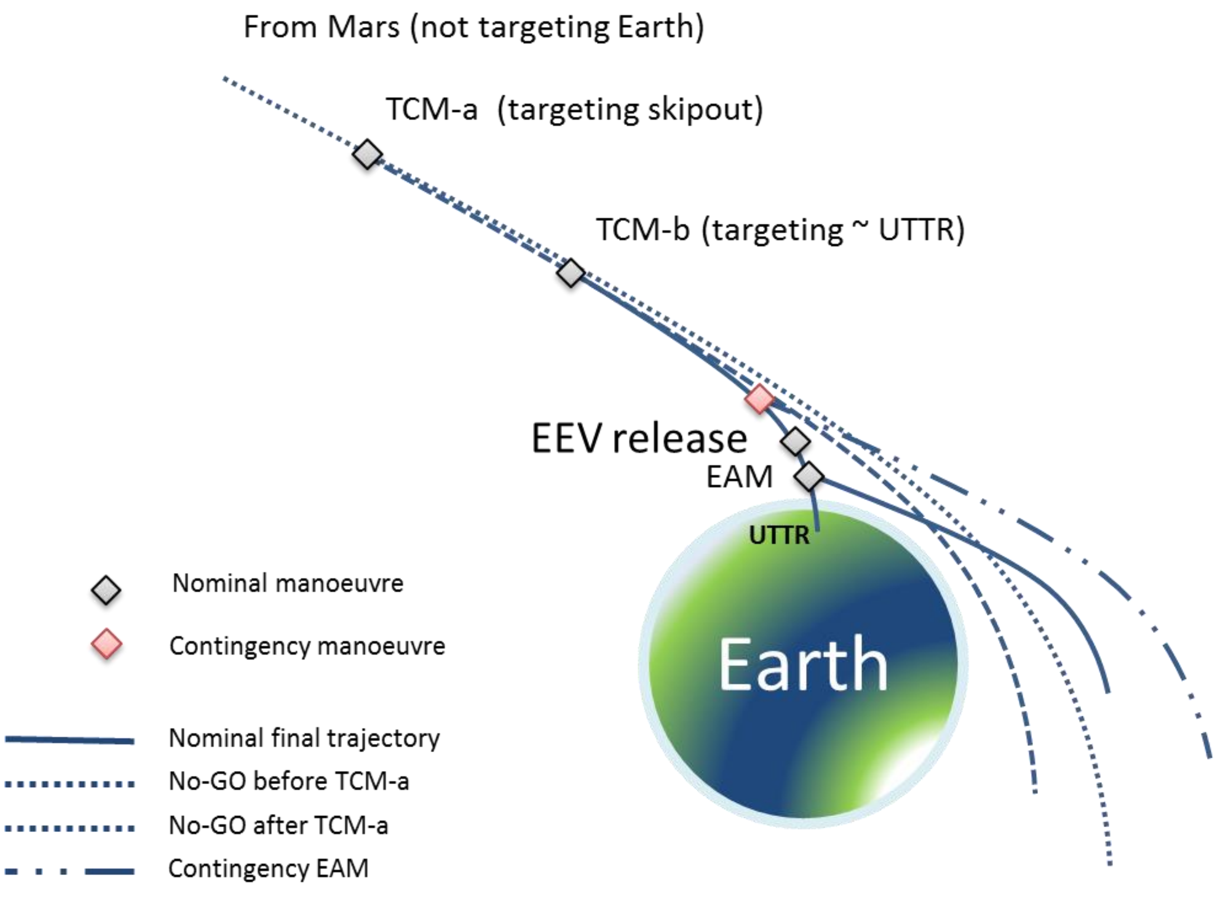



*Figure 1.3.7.1 - Illustrative view of Earth approach strategy*

The ERO shall be verified to be at least single failure tolerant when engaging on a trajectory potentially allowing for an entry into Earth atmosphere. The ERO shall be re-oriented to avoid entry into Earth atmosphere as soon as any function on board required to ensure nominal injection of the ERC into its entry trajectory or required to re-direct the ERO to avoid Earth entry is zero failure tolerant.

Hence, the ERO is injected into a Mars-to-Earth trajectory with low probability of impact, so that the overall probability of backward contamination is below the required $10^{-6}$ probability. A number of trajectory correction manoeuvres (TCM) will be performed to adjust the targeting, up to the moment where the targeting to Earth provides a threat to the backward contamination. From this moment on, the ERO will have pre-loaded Earth Avoidance Manoeuvres to be performed in case there is not a “go-ahead” from ground and/or there is an on-board evaluation of the status of the ERO and the EEV which provides evidence of impossibility to perform the manoeuvre respecting the required level of risk (in absence of ground command or in proximity of Earth).

# 1.4 Mars Sample Return – Earth Return Orbiter

The Orbiter configuration is driven by the need to accommodate the large payload and by the staging concept necessary to do the mission within the launchable mass provided by AR64.

The S/C is made of two principal stages:

- Main Module (MM): portion of the ERO which is returning to Earth, excluding parts part of the Payload. The Main Module hosts the Capture Containment Return Module that is partially separated after the Orbiting Sample has been encapsulated in the Earth Entry Vehicle, part of the Earth Return Module. Finally the EEV is separated after Earth arrival to enter the Earth atmosphere and land in the Utah desert.
- Propulsion Module (PM): portion of the ERO which is dropped at Mars prior to the RDV phase. The PM is separated after the arrival in Low Mars Orbit and before starting the OS search/synchronization phases, at an altitude compatible with the Mars PP.
- CCRS: Customer furnished Payload, including the SHS, the EEV (released on Earth vicinity) and all the related structure/mechanisms/interfaces which will remain attached to the ERO up to the disposal phase, needed to support the SHS and the EEV.

The assembly of those modules is sometimes referred to as the Composite S/C or simply the Composite.

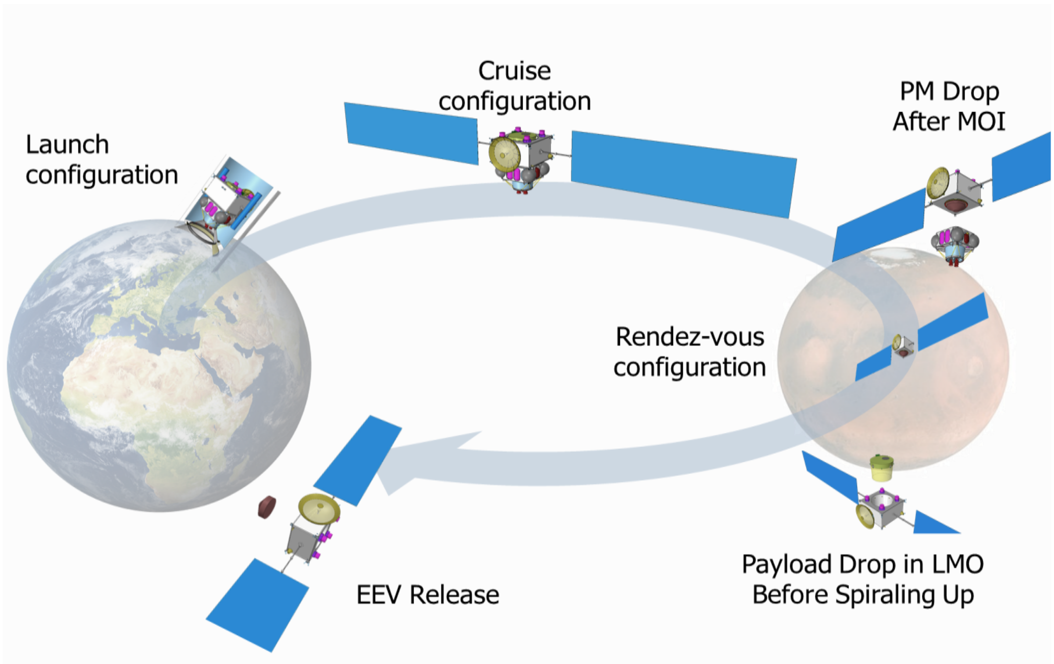



*Figure 1.4.1 ERO mission scenario*

Depending on the various system and mission architectures, this thesis refers to "Baseball Cards" and "Soccer Cards" appropriately numbered, as agreed between the various companies in the contract and NASA.

| Configuration | MM | PM | EEV | OS |
|---|---|---|---|---|
| Launch Configuration (mechanisms stowed) | X | X | X | |
| Outbound Configuration (mechanisms deployed) | X | X | X | |
| Rendez-Vous Configuration | X | | X | |
| OS Processing Configuration | X | | X | X |
| Return Configuration | X | | X | X |
| Disposal Configuration | X | | | |

*Table 1.2 - Configuration and ERO modules*

### 1.4.1 Physical Configuration for Hybrid Solution

The PM is designed to host the propulsion for the Mars orbit Insertion Manoeuvre; this subsystem is made of  a main engine installed at the bottom of the module, one big MON tank inside the central tube, four MMH tanks at the corners of the module and two large He tanks to pressurize the whole system. In addition the PM also carries the electric propulsion subsystem for the outbound leg and spiralling down manoeuvres; this subsystem is made of four electric thrusters with their own PPU and four tanks containing the Xe propellant.

The MM is designed to accommodate the CCRS and the electric propulsion subsystem; this subsystem is made four electric thrusters mounted on top of the MM supplied by four PPU, fed from two Xe tanks, slightly larger than the ones mounted inside the PM. In addition the MM hosts the sensors  used for the attitude and position control during the RDV and capture of the OS; this subsystem is made by N2H4 monopropellant mini-thrusters and two tanks. The MM also hosts the RF, EPS, DH and GNC subsystems. The EPS has a Solar Array  made of  2 flexible deployable wings mounted on the lateral sides of the parallelepiped. The TT&C subsystem is fitted with a HGA mounted on one of the front faces of the parallelepiped.

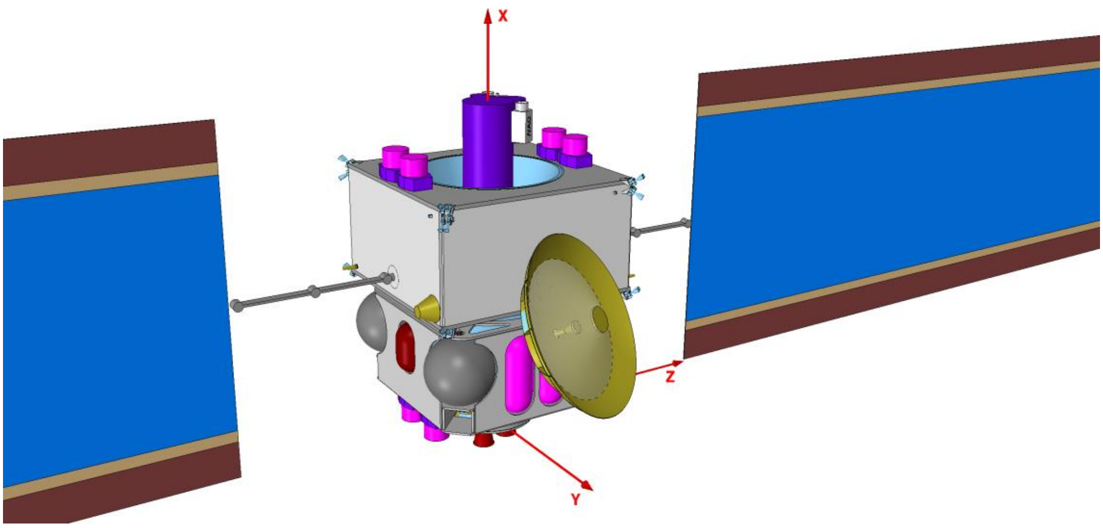



*Figure 1.4.1.1 - S/C architecture*

# *Chapter 2*

# Concurrent Engineering

Concurrent engineering, using an integrated product team approach is a work methodology emphasizing the parallelization of tasks: also called simultaneous or collaborative engineering or integrated product development, it refers to an approach used in product development in which functions of manufacturing engineering, design engineering, and other engineering functions are integrated to reduce time and cost required to bring a new product to market.

In system engineering, engineers modify design parameters, according to the imposed constraints, using the same documents shared on the company network: so the entire team works at the same time, and each component of it has its own main task.

Concurrent engineering develops through two main cornerstones:

- All phases and elements of the product development and production process (entire life cycle) are taken into consideration and therefore studied from the early phases of design: modeling, production, assembly, testing, maintenance, disposal and recycling are studied from the beginning.
- All design activities are performed simultaneously (and therefore concurrently): in this way, the concurrent nature of the activities increases the quality and productivity of the project phases. By collaborating different engineering branches together, design errors are discovered and located in advance of traditional engineering strategies: in this way the design changes are made earlier reducing costs as the project is still flexible and modifiable because the model is not yet complicated computationally and the physical construction of the product's hardware is not still happened.

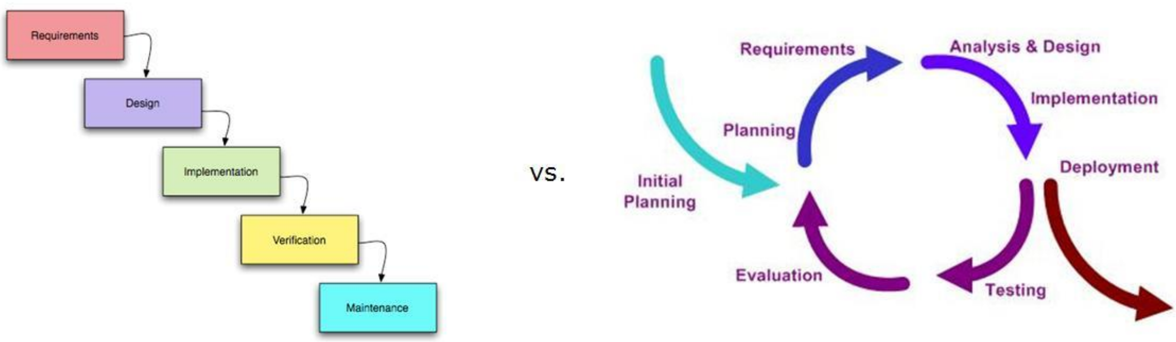



*Figure 2.1 - Sequential Development Method vs. Iterative Development Method in CE*

# 2.1 Strategies for new product development

In the aerospace industry, various engineering methods have been used, some of which will be immediately described.

## 2.1.1 Sequential new product development

The old way of proceeding with the engineering approach is called Over The Wall Engineering or Waterfall model. This type of engineering design approach consists in the execution of tasks by a member of the team. Once he has completed it, hands over the task to the next team member. In most engineering areas, this engineering design approach is sequential and straightforward:  the waterfall model, in software and hardware development, is a non-flexible and non-iterative designing mode, as the tasks just completed and performed are not modified and repeated. This way of thinking and proceeding is called "Waterfall approach", since the flow of actions is directed roughly in one direction during the design phases (conception, initiation, analysis, research, design, development, construction, testing, delivery, deployment, maintenance and disposal. Through these phases, this process moves downwards like a waterfall.

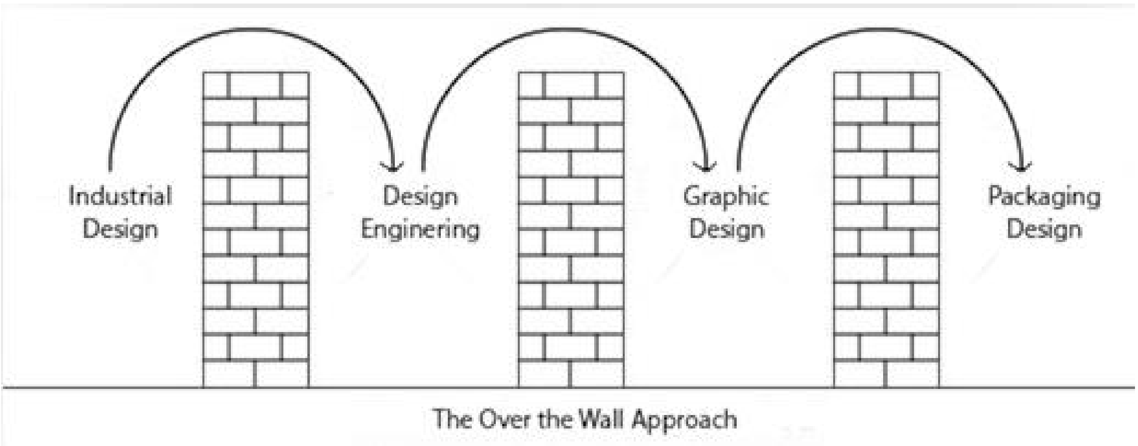



*Figure 2.1.1.1 Traditional approach*

In the manufacturing and construction engineering industries, the changes in the design phase are prohibitive economically from the beginning of the product’s development, as the environmental and physical context of the product is structured and almost fixed: the waterfall development model originated and developed in these engineering fields. In the past, the success of the companies was achieved with the development, the design and the manufacture of high quality products which can satisfy real needs at competitive prices; in this way, when there weren’t acknowledged and applied alternatives in the business know-how, the Waterfall model was preferred.

Planning and execution of a project have traditionally been marked by the definition of objectives and milestones. The objectives defined by these milestones are met through execution, some of which must be performed in sequence, others of which can be conducted in parallel on the corporate network. To support the product development process, planning techniques were performed such as evaluation and review of the program: evaluation techniques based on graphic review and critical path method, for example, are two frequently used approaches. However, until the beginning of the 1990s the reduction of the duration of the design phase and therefore the temporal compression and timing were not a major problem in the process phases of research and development of an engineering product. In planning and scheduling activities and tasks, time compression problems were implicitly present, but not binding. At the beginning of the 90s, with the growth of consumerism, the criteria of business development began to change radically to adapt to world change; the marketing criteria followed the same process. Marketing studies have shown that the launch of a product on the market, delayed few months late, has negative effects on the company far worse than a financial cost overrun of 50%. This happens because nowadays the technology evolves rapidly and a product launched in the late market becomes practically obsolete and less palatable in the eyes of the consumer: in other words, one of the most important keys to a company's success is time.

### 2.1.2 Centralized Team Working

Centralized communication consists of storing all the documentation, communications and information necessary for the project phases in one place: all the interested parties (team members or company hardware and software) are involved through the connection to a single server or design central authority, which has a global view of the whole process and stores the entire wealth of knowledge transmitted.

Centralized scientific organizations have a single scientific data manager within the company. These structured teams allow the participation and collaboration of team members with their colleagues on several projects at the same time, improving their professional growth and speeding up the technical mentorship and tutoring phase. Thanks to this approach, communication, programming and all the documentation can be subdivided into subsections, allowing projects to be consistently updated and projects divided up. In this way, every pièce of information is efficiently traced and maintained.

From a structural point of view, the centric approach reduces the creation of knowledge silos; it allows the creation of teams that take specific analytical tasks and simplifies recruitment and therefore the recruitment of useful staff. On the other hand, sector experts working in a centralized team, follow the priorities of their business partners; often these priorities could be far from the general ones of the project or the context of prioritization might not be effective. In some cases, an unhealthy project dynamic can be established, in which priority is given to satisfying the requests of individual product managers rather than reasoning as a team partner and carrying out tasks in a correct sharing of project data and objectives: in this way, company know-how and, more generally, data science, instead of being actively and profitably considered helping the other members of the team, almost takes on a support function, rather than being the beating heart of the design philosophy.

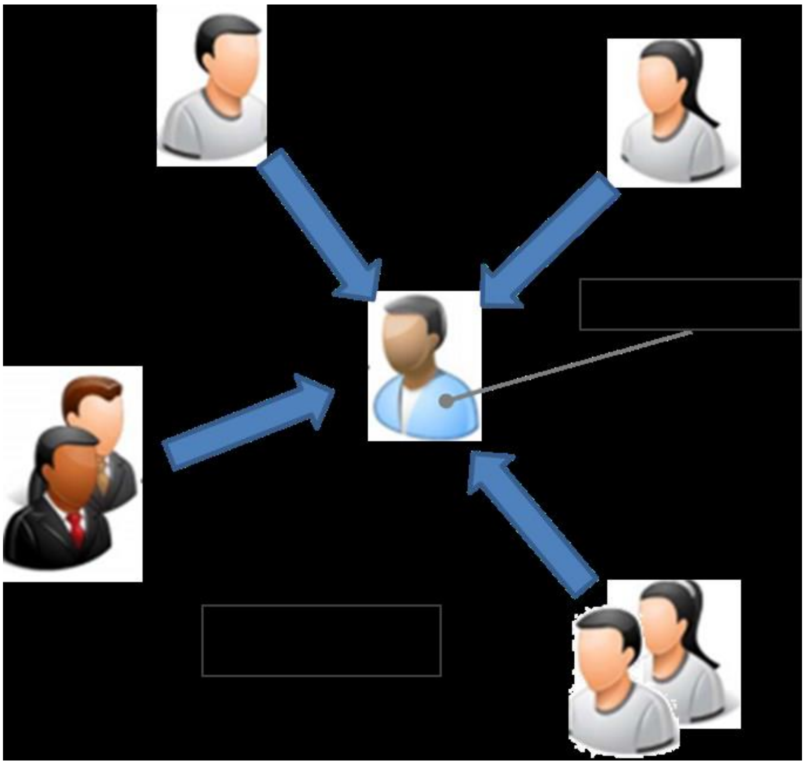


*Figure 2.1.2 - Centralized Team Work*

### 2.1.3 Concurrent Engineering Team Working

ESA defines the methodology using these words: “Concurrent Engineering is a systematic approach to integrate product development that emphasizes the response to customer expectations. It embodies team values of co-operation, trust and sharing in such a manner that decision making is by consensus, involving all perspectives in parallel, from the beginning of the product life cycle”.

This innovative approach is based on controlled and shared data between sector experts and system engineers who have an overview: the development of a product is therefore not a linear process. The project development team is composed of a team leader assisting a system engineer who has a coordinating role. These two figures direct the various expert engineers who are specialized in different disciplines, constituting most of the aspects of the system. All team members work together and simultaneously on the same project. During the entire life cycle of the project, the communication and exchange processes of ideas and information must necessarily be carried out collaboratively and efficiently; in addition, resources must therefore be optimized as the same people can work side by side in other business projects.

Whereas the traditional engineering approach consists of organizing meetings at the whole team level to assign inputs and tasks, and then let everyone work on their own assignment, the collaborative approach follows the logic and will spread throughout the team, often mediated by interdisciplinary compromises resulting from conflicting needs.

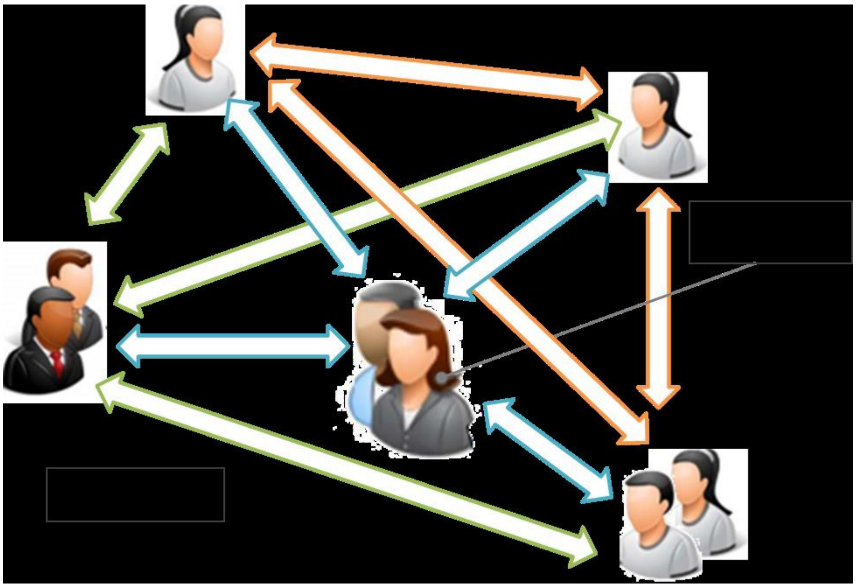


*Figure 2.1.3.1 - Concurrent team work*

With concurrent engineering, information is easily shared between the various engineering disciplines, optimizing the time (and therefore the economic resources) used by the experts of the team as the activities can be overlapped. The process is therefore more efficient and allows a reduction in costs.

Depending on the progress of a project phase, it is decided which engineering is entitled to participate in a team meeting. The organization of the same also depends on what the purpose is: brainstorming, expert advice, sharing ideas, new scenarios, a technical definition phase, a new conceptual or technological option, a mission analysis or more. The team leader optimizes and organizes the meetings, which are in turn influenced by the criteria previously exposed.

*Figure 2.1.3.2 - CE Network*

## 2.2 Peculiarities of CE

In this paragraph the key features will be summarized.

Concurrent engineering requires that the engineering processes traditionally taken into consideration in the more advanced phases of the project life cycle, are no longer ignored in the initial phases and are therefore started and studied in a contemporary context. In order to be successful with this method, it is necessary that all the engineering components of the company are included in the same way as the problems related to the formulation and the selection of the design options. Engineers must necessarily communicate with other designers, experts in technical languages not familiar to others and usually isolated in their design process. It is therefore of fundamental importance to manage all the information and contributions of the various participants to the process towards a common project goal at the team level.

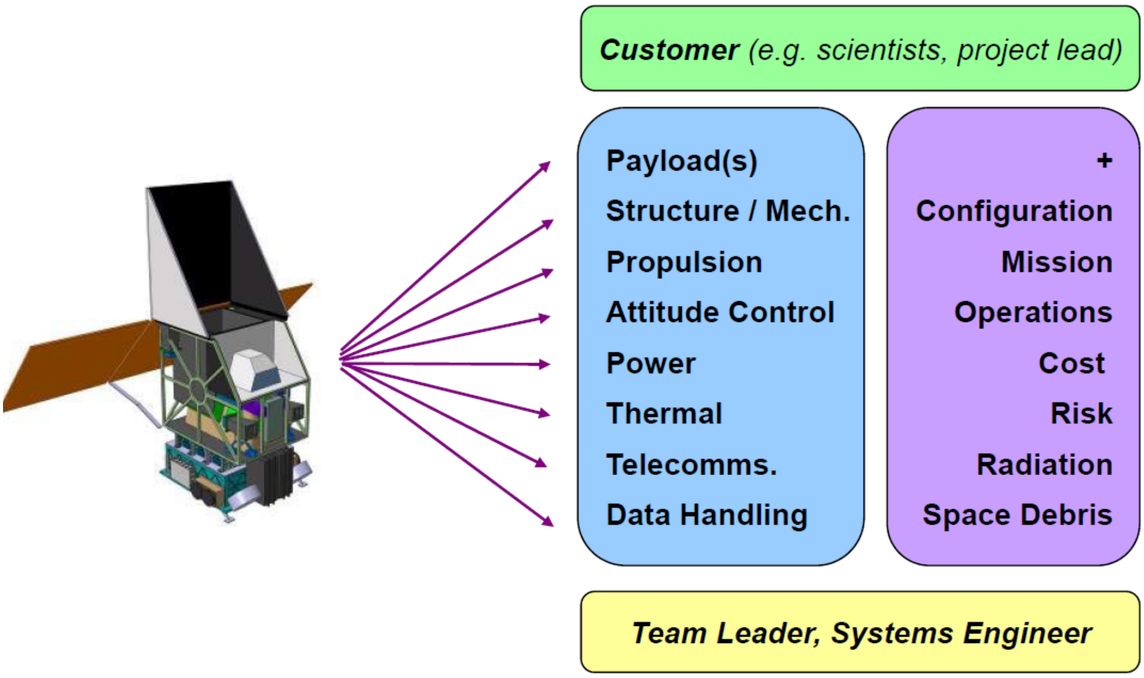



*Figure 2.2.1 - Multidisciplinary team*

A guideline for concurrent engineering to be effective over the long term is the presence of a fully integrated computer-aided design and production environment. In an automated engineering design environment, engineers could model their own task guidelines (instead of creating them from scratch) to achieve the same design goals at the team level.

- Concurrent engineering (CE) is a design method that perceives, supports and anticipates changes in design, manufacturing and product distribution processes. This discipline therefore emerges to achieve the objectives of improving quality, reducing costs and improving delivery performance.
- The concurrent design is a management and engineering philosophy that has the task of reducing time and costs from the conception of the product to the development of

the aforesaid and consequently to its modifications, continuously improving its performance and quality.

- CE implies that all the resources and components both physical and soft and mental are managed in parallel and at the same time (as an example we can remember the equipment, production processes, tools, repair processes, design processes and product development) .
- The idea of concurrent engineering clashes with the current methodologies of sequential processes in the sector, in which the product is initially designed and developed, and only afterwards the production criteria are chosen and established.

In practice, the application of Concurrent Engineering methods means:

- Focus on the Entire Product Life.
- Encouraging the evaluation and the generation of multiple Concept of design.
- To communicate the right information to the right people at the right time.
- Addressing and solving potential problems during the design phase, causing the engineering team to break down any cultural and organizational barriers between the various engineering sectors in all the design, production and product support processes.
- Involving in the team all the disciplines by integration of systems.
- To be careful to design quality during the entire design process.

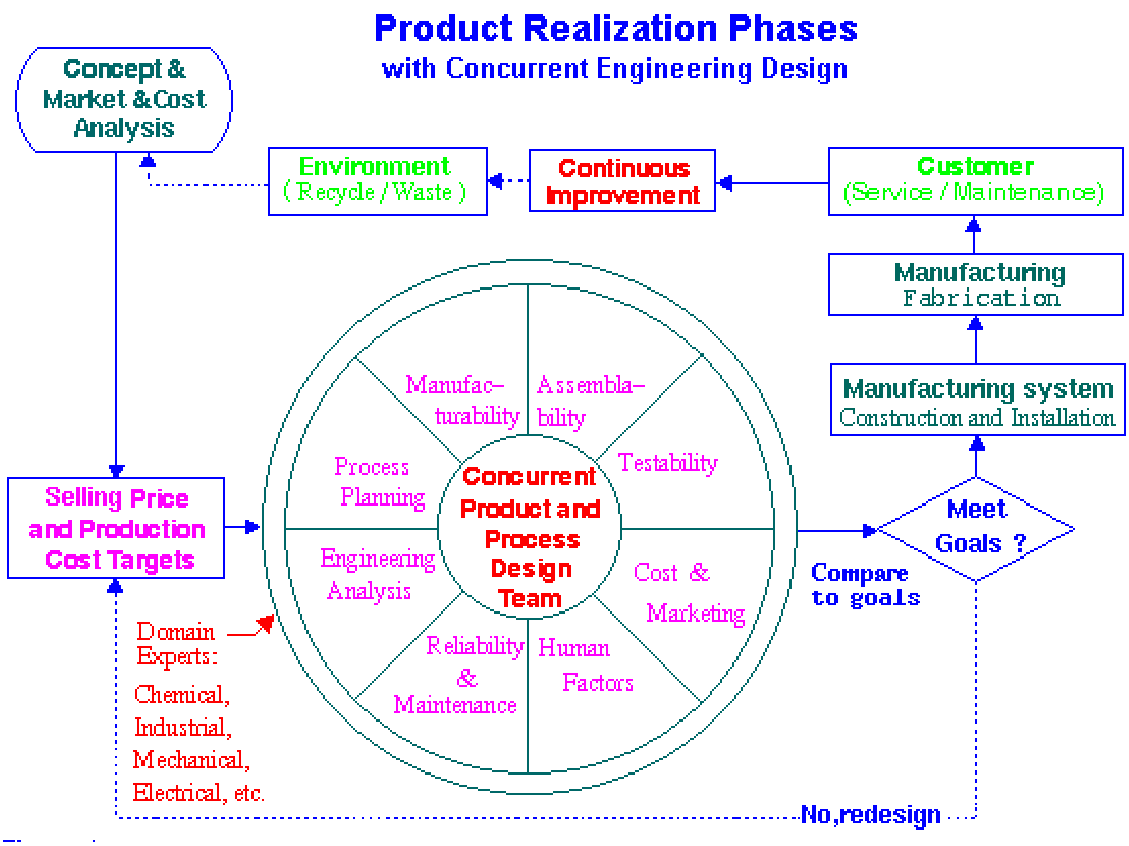



*Figure 2.2.2 CE Working Strategy*

As already mentioned before, a key element of the CE model is that the entire product life cycle is taken into consideration: everything is included, such as the development of the project, conceptual, the definition of the requirements, the execution of computational models, the creation of physical prototypes, product production, maintenance forecasting, complete project financing, workforce capacity and time requirements. Many companies have adopted concurrent engineering for design because it has been shown that the correct implementation of this method allows a cost reduction. With the Waterfall Method, an engineering team has no way of realizing what has happened before and what will happen later in the design phases, so anticipating inevitable problems becomes impossible and error correction becomes more expensive. The linear cascade method therefore starts from the needs and the needs of the possible customers and passes sequentially to the design and subsequent implementation in the finished product: replacement with an iterative and integrated approach becomes convenient. As can be seen, while in the sequential method in the event that something goes wrong, the design is usually difficult to modify and therefore is discarded or strongly altered. The concurrent or iterative design process, on the other hand, taking into account all the product life cycle processes from the beginning, encourages rapid design changes, allowing a more flexible approach to design and more easily evolving.

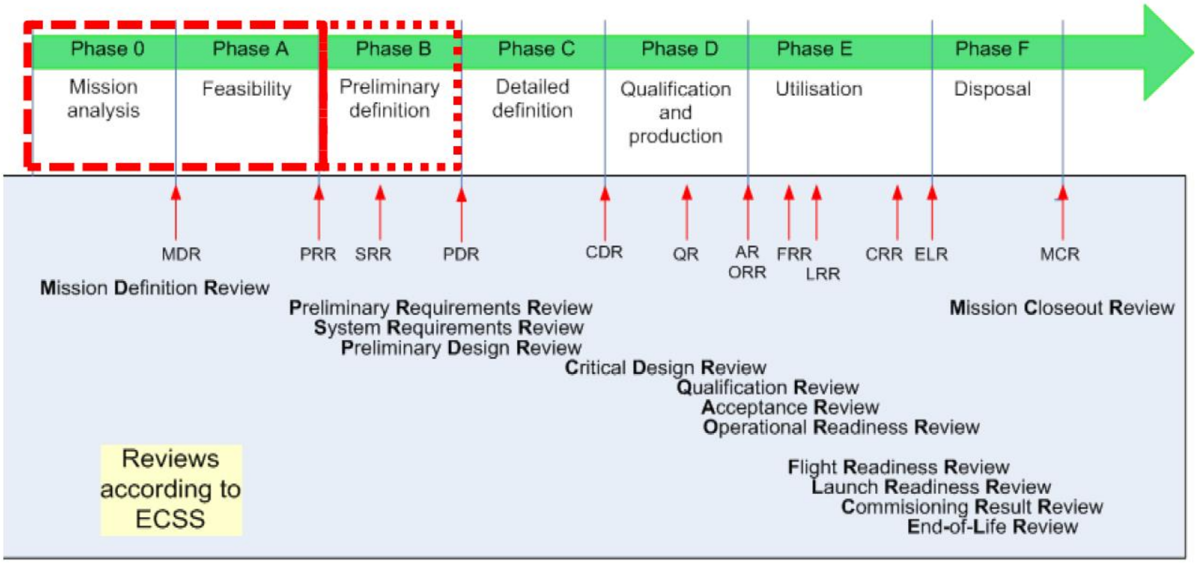



*Figure 2.2.3 - CE during design phases for Space Missions*

## 2.3 Traditional Engineering vs Concurrent Engineering

The main difference between concurrent engineering and sequential design is the approach to design: at the beginning of a project, with a CE methodology, the design strategy and product characteristics are presented and presented to the EC team. In this way, during the design phase, the whole team is involved; obviously being the team composed in a heterogeneous way, the advantage consists in the union and in the simultaneous implementation of the various sector knowledge: the domain experts of various fields of engineering, production, marketing, sales, packaging, inspection, assembly and environment will improve product design.

The graph below compares the development time of each approach as it relates to the number of design changes. As mentioned earlier, the concurrent engineering approach is intended to identify and solve issues early on. It can be seen this in the graph, where concurrent engineering undergoes many more design changes at the early stages of development than sequential engineering.

In contrast, sequential engineering undergoes the most number of design changes pretty late in the game. These late stage design changes tend to have the greatest effect on a project's timeline.

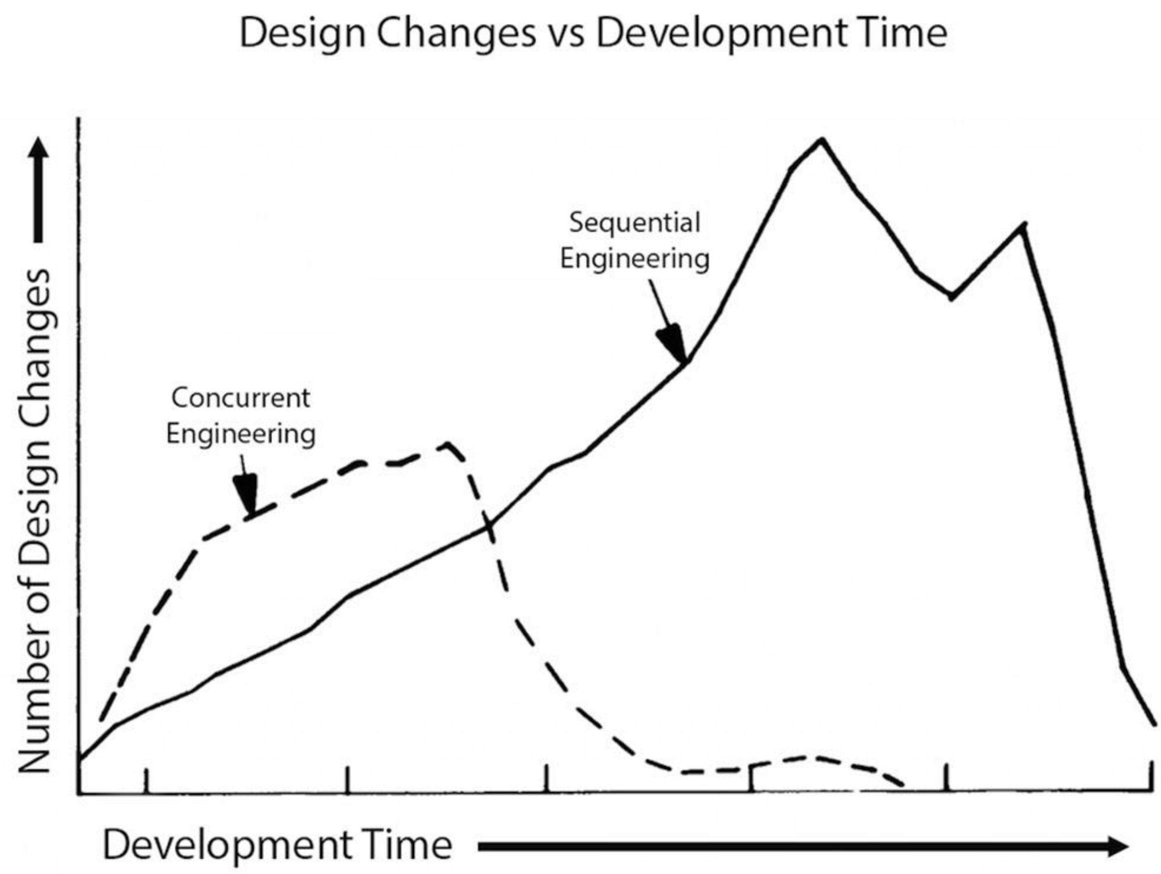



*Figure 2.3.1 - Design changes*

As it can be seen in the figure 2.3.1, a collaborative and simultaneous approach reduces design changes.

Teams that use concurrent engineering concurrently tend to make changes to the project first. As can be seen from the graph, between 24 months and 18 months before the launch of a hypothetical product, indicated as zero month on the horizontal axis, there are many more design changes compared to teams that apply traditional approaches. On the other hand, the same teams that apply the CE, make fewer design changes in the 12 months prior to the launch of the product compared to the Over the Wall team, which instead have a huge number of changes in the six months previous product launch.

This has important consequences also from an economic point of view:

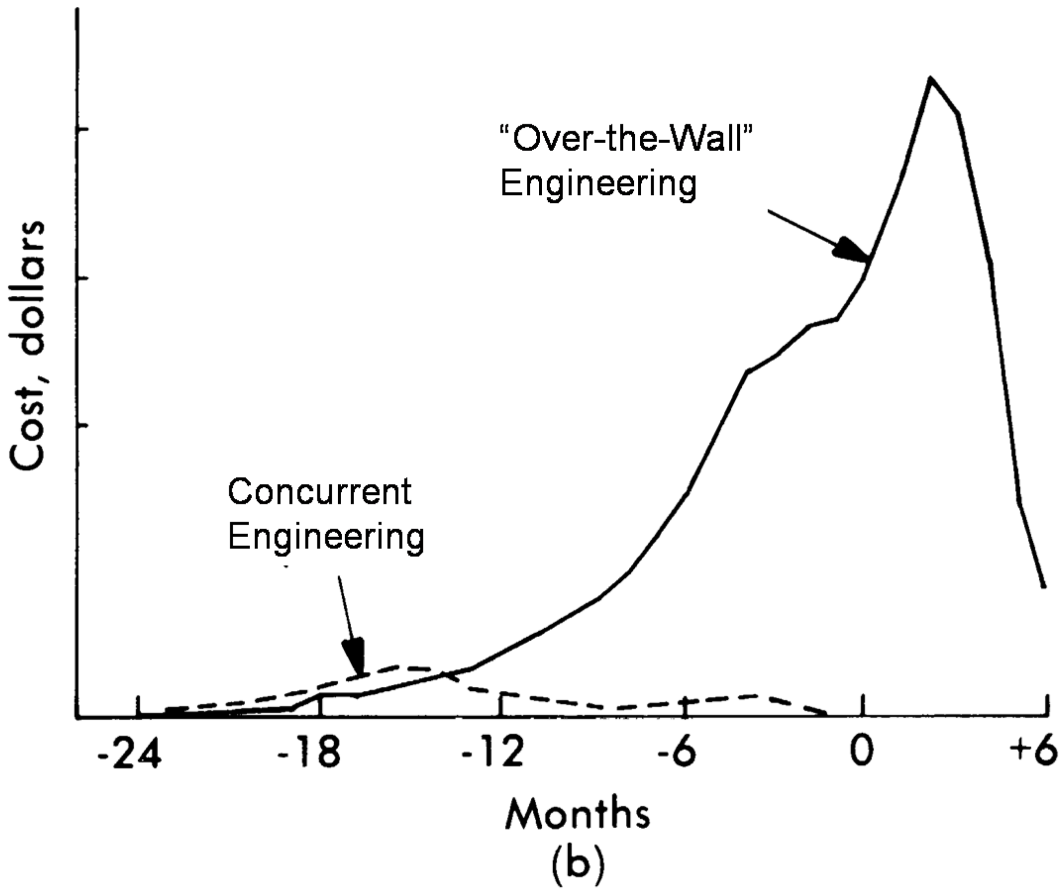



*Figure 2.3.2 - CE cost saving*

Figure 2.3.2 shows the product development costs versus time for both the concurrent engineering strategy and the over-the-wall strategy. In the beginning the concurrent engineering strategy costs more because of the cost paying representatives of all of the stakeholders to participate on the design team. The over-the-wall strategy is expensive near launch because many people are added to the design team correct design issues that were not detected and dealt with earlier in the process.

A good feature of this CE phase is that by designing the product the CE team also designs the process for the manufacturing maintenance and disposal of the product. The team decides of what kind of equipment, process and treatment is going to be used unlike instead of a team that applies a sequential philosophy, and that then allow the important decisions only to the designers, without involving the entire team of experts.

The following table summarizes the advantages and disadvantages of the various engineering approaches.

| | **Centralized Method** | **Sequential Method** | **Concurrent Method** |
|---|---|---|---|
| ADVANTAGES | - General awareness of  the project<br>- More efficient than Sequential Method<br>- Faster than Sequential Method | -Simple to apply | - Very efficient method<br>- Speed increases<br>- Increased system awareness<br>- Better communication<br>-Reduces product cycle time and cost<br>- Increases productivity by stopping mistakes in their tracks<br>- Increases quality by supporting the entire project cycle<br>- It encourages multi-disciplinary collaboration |
| DISADVANTAGES | - One person is responsible for everything | - Poor data exchange poor communication<br>- Slow speed of work<br>continue changes<br>- Not compliance with all requirements | - Complex to manage<br>- Relies on everyone working together hence communication is critical<br>- Room for mistakes are small as it impacts all the departments or discipline ie electrical, mechanical or software |

*Table 1.1 - Different Methods*

# 2.4 Tools of CE

The European Space Agency  has a main assessment center located in its technical center in Noordwijk (Netherlands). The Concurrent Design Facility (CDF) is operational since 2000 for future space missions and industrial review.  CDF is an innovative structure with a centralized computer network and a series of multimedia devices, software and hardware tools that are always connected to each other. This allows a scientific and engineering team and other experts from different disciplines to apply the design method to the design of future space missions, facilitating the interaction between the various disciplines and making the exchange of consistent and effective information. The results are of high quality and are obtained in a very short time.

Concurrent design facility (CDF) is an environment in which engineers from different sectors and expert specialists from various scientific fields meet to perform system engineering studies for a space project. The design process is facilitated by the presence of various experts with heterogeneous knowledge in a room, and all can access all the information and data of the project, through software and hardware tools that allows the instantaneous exchange of data; nowadays, these environments are also present in the research centers ESA, NASA and various agencies and companies in the same sector.

The main development of the CDF is present in the quality of the training of the team members. In the CDF environment, a concurrent design methodology is applied in order to carry out a preliminary study of space missions quickly, effectively and economically, taking into account revision proposals, estimating costs and considering compromises.

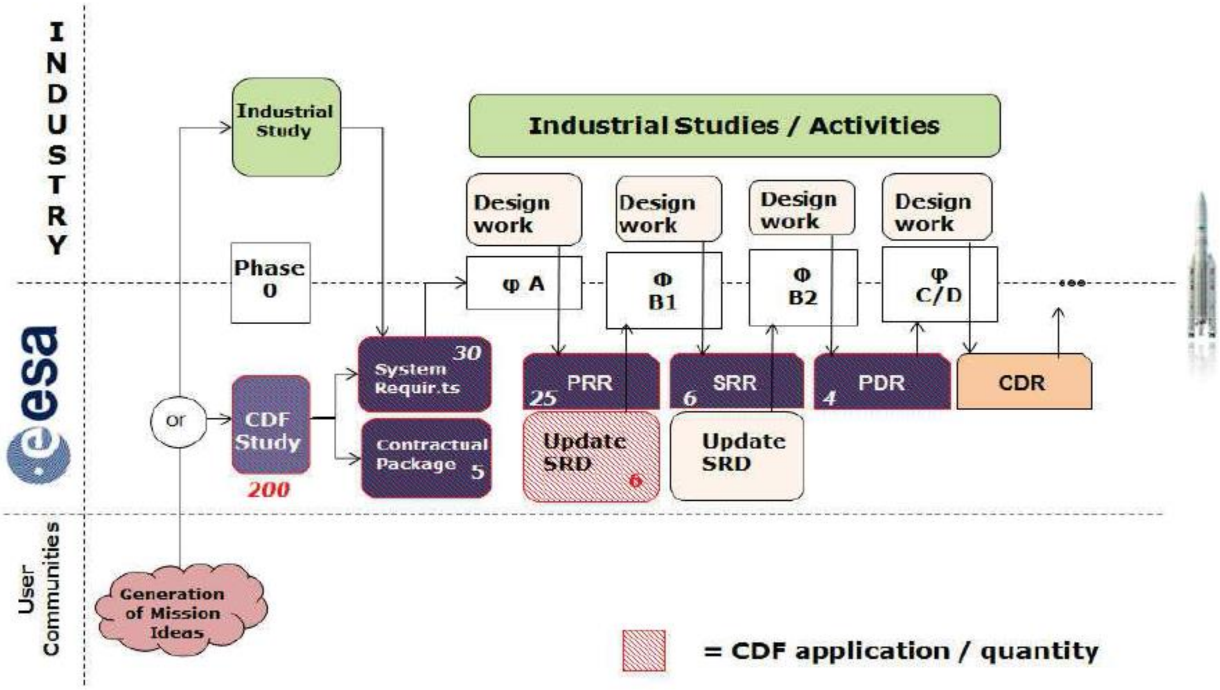



*Figure 2.2.1  - CDF usage during Design Phases*

### 2.4.1 CE Facilities

The CDF is a structure composed of design rooms and various support or auxiliary rooms, all grouped around a central space. The main design room is used for general studies of missions or for important technological tools and has many computer stations inside it; instead, other rooms, such as the project room, or the MICRA room (Mission Concepts and Requirements Assessments) are identical design rooms, separated by a glass wall, which are mainly used for less important and sectorial studies or revisions, as well as for meetings for sector studies.

As already said then, the CDF is a set of chambers that create a multidisciplinary design environment and provide efficient communication, an efficient exchange of data, a database of information through hardware and software tools provided to all team members working at the same time.

*Figure 2.4.1.1 - CE Room*

Effective communication are obtained by means of lay-out, large screens, smartboards, visualizers and microphones; effective rendering are obtained by means of models linked to graphical representations, 3D computer aided design (CAD), simulations, brainstorming, stereo projection, rapid prototyping; it must be remembered that each workstation also has a camera and microphone to enable more inclusive communication for remote study participants.

The design room of support is often used as a conventional meeting room, but can easily be converted into a project room by including all the services of the other rooms. In this way there is a connection between the various sale through complete video conferencing facilities and an internal audio and video network, in order to allow the exchange of data and the display of the same from any screen or workstation on one or all the screens in the other rooms. Users of these rooms can use their own laptop or computers and both can be selected and projected on preview screens when selected. Often the different workstations are identical, but sometimes there are computer stations, specific and dedicated configurations.

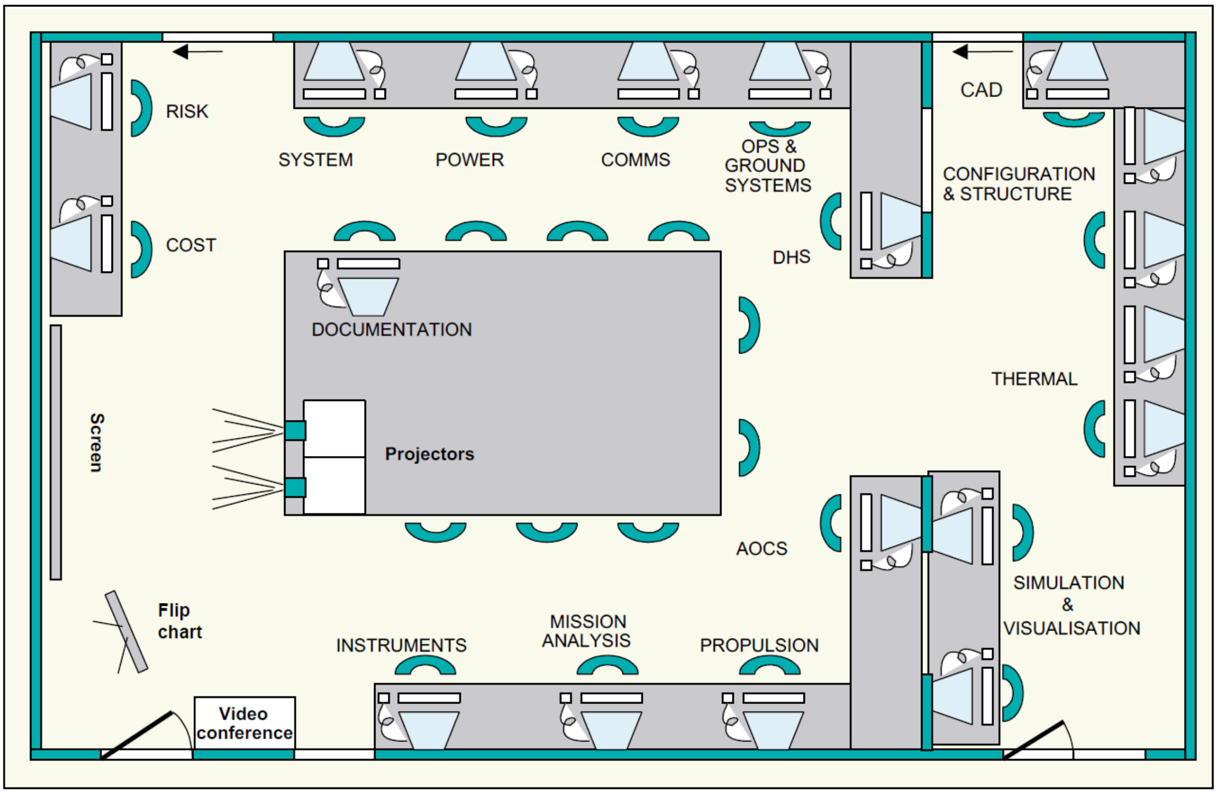



*Figure 2.4.1.2 - Layout of a Concurrent Design Facility*

Simultaneous design based on the CE method, allows information redundancy as team members are involved in multiple aspects of the project during each process of the entire product development life cycle, rather than having only knowledge of their spacial design fields; this redundancy reduces the risk of data loss and increased costs and delays for the project, in the event that a member of the team suddenly can no longer continue the study of the project or leave the company or the project unexpectedly.

## 2.4.2 CE Software

In the engineering area, several spreadsheets have been implemented in the company network for product development in the EC environment. Excel and Matlab calculation tools are often used, as well as for example CAD programs like CATIA, SolidWorks and structural analysis programs such as Abacus, Patran & Nastram.

Any software can be used on the network at the same time by different computers. The goddess remains that of modifying the same file and verifying the consequences in multidisciplinary fields.

ESA uses a system engineering software called Concorde. For example, European companies use IDM software. These two software are among the most important, as they link aspects of different disciplines in a single file, using a CAD interface combined with the tabular one used on Excel.

Serapis,  Osyris 3D, AKA, Vivace, LEAPS, KAOS are efficient centralised tools to prepare integrated design:

-Well suited for large trade-off rapid assessment.

-Enables rapid interaction with expert.

-Enables to work with a limited team.

| Tool | Function | Interface format | Integration |
|---|---|---|---|
| *Technical Database* | A repository to store the values and the parameters associated with the various technical options and required to verify the requirements and justify the design | Xls, csv and xml files | Partial |
| *Equipment Database* | A repository of the various standard equipment data bases. This repository is required to introduced validated values in the Technical Database | csv files | Partial |
| *Simplified trade-off* | A tool helping to preliminary assess trade-offs to determine the most promising options | Excel files | None |
| *Mission Scenario Simulation* | A tool to determine mission scenarios to perform consistent end-to-end simulations for early validation of design choices | Excel files, matlab files | None |
| *3D visualisation* | A tool to visualise the spacecraft in orbit wit its proper attitude to ease the mission understanding | xyz, pqr, 3ds or cmod, ssc and q files | Partial |
| *CAD Tool* | A tool to verify configuration of the spacecraft consistently with choices made and stored in the technical database | Step, Csv or API | Partial |
| *Power Simulation* | A tool to perform EPS simulations consistently with mission scenario | Excel files | Partial |
| *Thermal Control Simulation* | A tool to perform TCS simulation consistently with mission scenario | Excel files | Partial |
| *Orbit determination* | A tool to determine best orbit consistent with mission requirement | Txt or xyz and pqr files | Partial |
| *Functional Description and Modelling representation* | A tool to implement Modelling Appraoch | None | None |
| *User Front End* | An ergonomic user front is required to help the user to visualise and to retrieve data from the various database and launch the tools | xml files | Partial |
| *Shared Repository* | A storage volume for users to store and easily retrieve information related to the study in object (any kind of file) | None | None |
| *Requirements Management* | For any project it is necessary to have a tool to store the documents of the project, required by the client or higher level contractor or necessary for lower level contractors | None | None |
| *Documents Management* | For any project it is necessary to have a tool to store requirement, to generate requirement compliancy from data and document tracing | None | None |
| *Efficient e-mail system* | To manage file exchange through project partners | None | None |

*Figure 2.4.2.1 - Tools required for proper Engineering in Phases 0/A and preparation for Phase B1.*

For this thesis, carried out in Thales Alenia Space, the IDM-CIC software is used. The following chapter will offer a description of this tool.

# *Chapter 3*

# IDM-CIC

An iterative development study of a product requires an engineering model capable of connecting the various subsystems, updating the information and managing the relationships between them. This is realized by an Integrated Design Model (IDM) containing an interdisciplinary data structure and based on the application software MS Excel, The integrated design model (IDM) used by ESA for feasibility studies of space missions is based on Excel. The software collects input from different disciplinary fields during phase A and inserts them for review by the agency. The goal is to evaluate the various alternative options in an iterative way. There was an issue of the multi-domain approach to smoothly evolve from phase 0/A to complete life cycle model taking into account Virtual Spacecraft initiatives, so the first step into modelling approach was to use the Integrated Design Model (a meta-model) provided by ESA. An IDM brings gain in efficiency, but also, unfortunately, leads to some difficulties related to the compatibility between the new model and practices and tools of the company. Hence, companies and agencies performed evolutions of the data model to improve suitability to multi-domain representation.

There is an enormous and critical data exchange coordination through various sources: each specialist participates to the design with their domain and tools, which are not always developed to fit within concurrent engineering environment and related formalised data flow.

At the dawn of the use of IDM, the model used in CDF was built on a spreadsheet and data storage basis and each calculation and analysis had targets for the subsystem level and the study guides were just the demands of the system engineers; in order to involve the various disciplines, the system budgets have been formalized and the various IDM tools with a determined data flow. For over two years, in Thales Alenia Space the tool used to design and represent aerospace vehicles comply with ECSS standards and is common to various international space agencies: this model is adapted and organized in an effective manner with the calculation methods and organization internal company.

*Figure 3.1 - IDM-CIC Logo*

## 3.1 What is it IDM-CIC

The name of the tool implementing the Concurrent engineering data model is IDM-CIC, standing for Integrated Design Model – Centre d'Ingénierie Concourante, the French translation for Concurrent Engineering Centre. IDM-CIC is a model based on Microsoft Excel, but extends the functionality of the Office package software: it is both a hierarchical model and a distributed model implementation strategy in Excel. It has also visualization tools like Sketchup and IDM View.

### 3.1.1 Hierarchical Model

For each study a version of the model is created, consisting of several elements (satellite, launch vehicle, control center, etc.), in turn made up of the various systems (TT & C, DHS, Hybrid Propulsion System, etc.) and subsystems (System Chemical Propulsion, Electric Propulsion System for example) up to the level of equipment (filters, cables, connectors). Each element therefore has general information at a general level and is also associated with information related to the different subsystems, divided into units . Finally, each unit is described by different parameters, such as for example weights, dimensions, mass properties, optical, thermal, energetic properties, etc. The following figure explains the reasoning above.

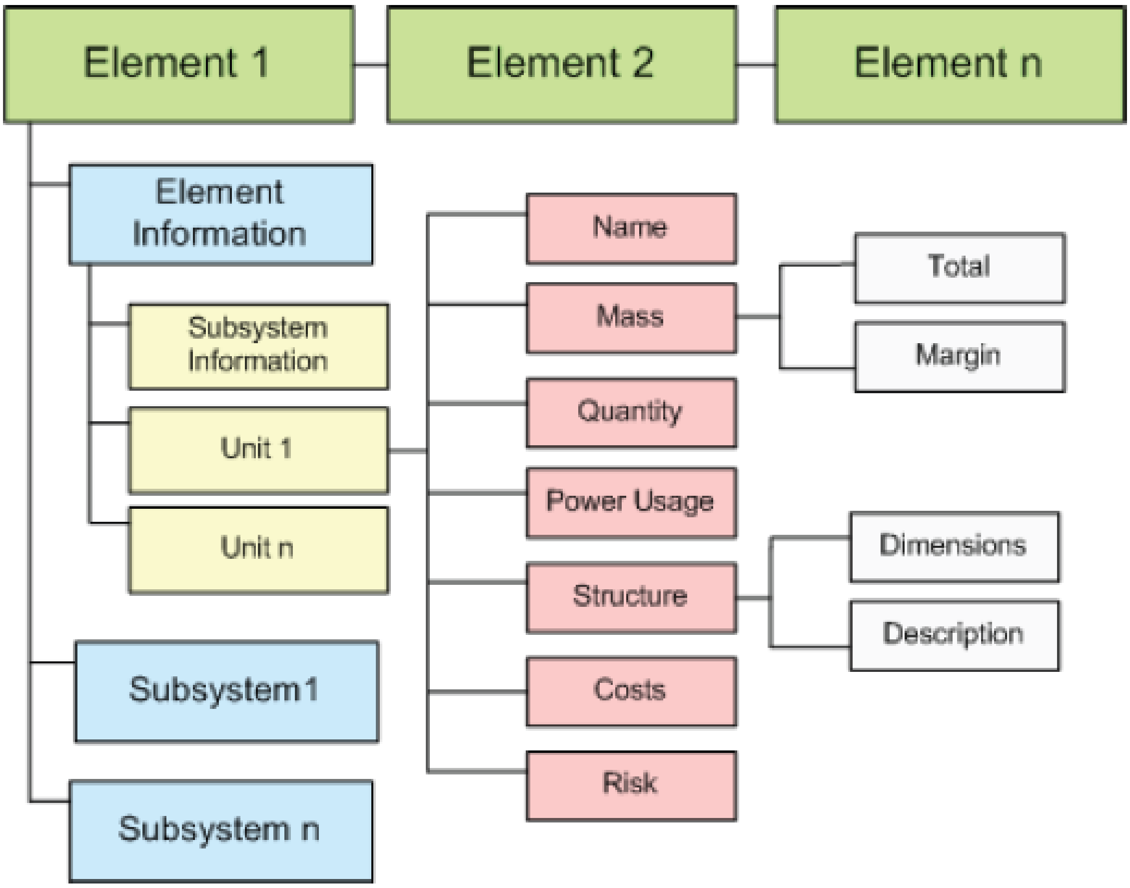



*Figure3.1.1.1 Hierarchical view of the Integrated Design Model*

## 3.1.2 Distribuited Excel Implementation

In practice, models built using IDM-CIC are divided into different Excel workbooks to allow simultaneous changes to the system by multiple members of the engineering team within the CE context. Each internal workbook therefore represents a specific engineering branch or a subsystem or a discipline related to a system: all the walls inside the single folder are made up of a set of parameters appropriate to the system: it is based on Excel Workbooks, but it use an application with XML files.

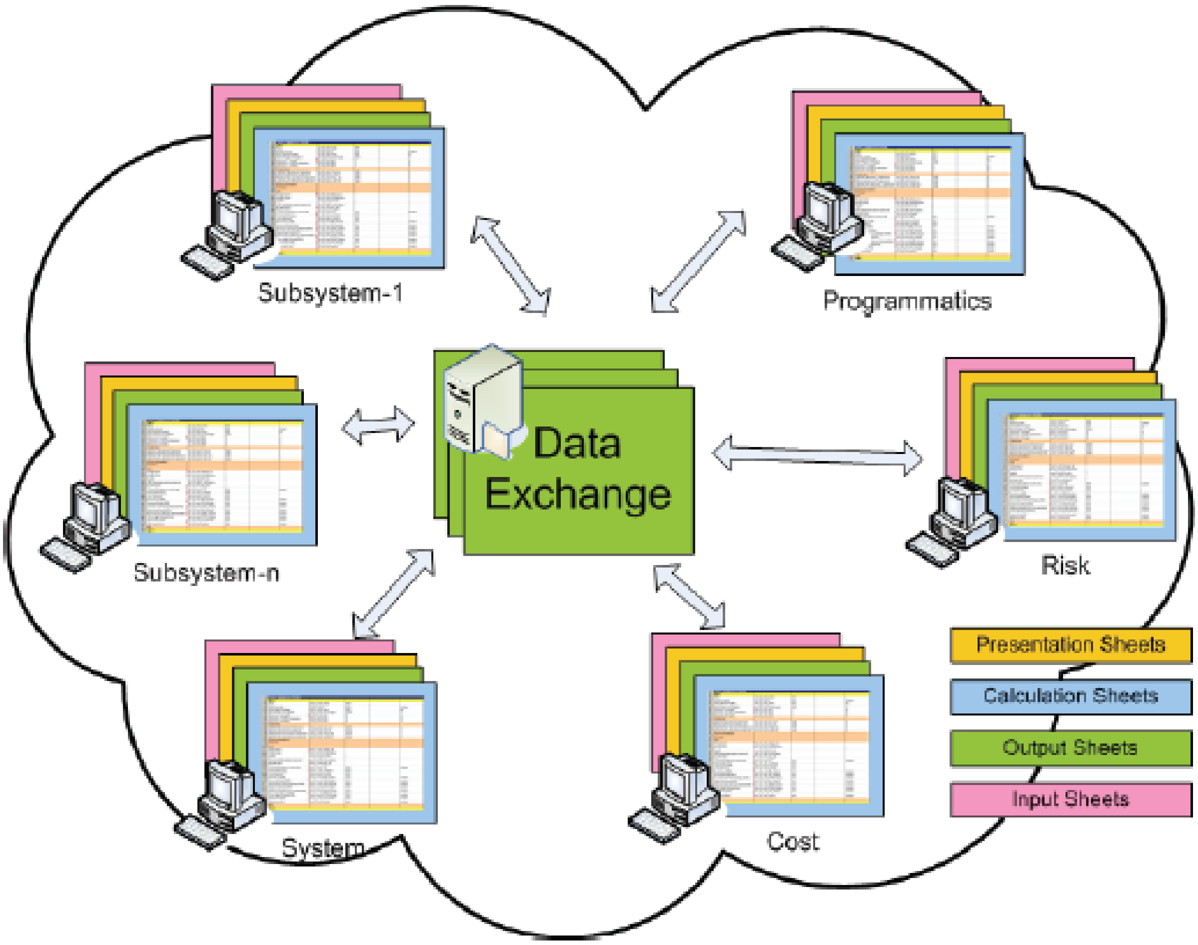



*Figure 3.1.2.1 - Structural Concept of IDM-CIC*

## 3.2 User management

The System defines the architecture and the roles; the user takes the functions coming with their roles (it connects with the defined role). After getting the approval from the system responsible it is necessary to commit in CDF section. Once all commit is received, the system export as a new XML to start new iteration, in order to maintain the workbook, for example to keep using new calculation sheets introduced.

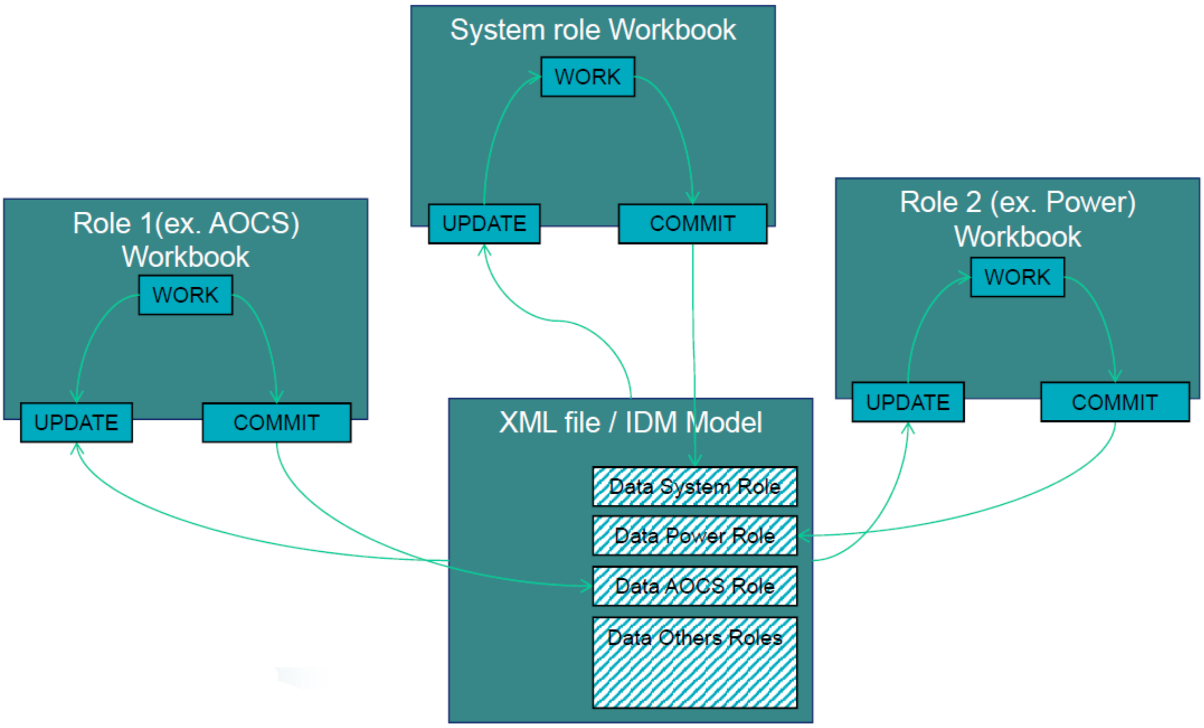



*Figure 3.3.1 - System functions*

### 3.2.1 Roles and rights

Each member of the team assumes roles connected to the tools integrated in the model. Roles are connected to the tools integrated and have different right to modify the workbook. Each specialist user can modify a folder like System structure, User management, Additional properties definitions, Mass Budget, Power Budget, Propellant Budget (Propulsion), Dissipation Budget, Configuration, Saved Configuration and Coordinate systems, Centring and Inertia Budget, Mission Phases, DV budget, Equipment data. The system responsible List of system roles controls all the assignments of all the users. Choosing the role of competence it can be changed the corresponding workbook.

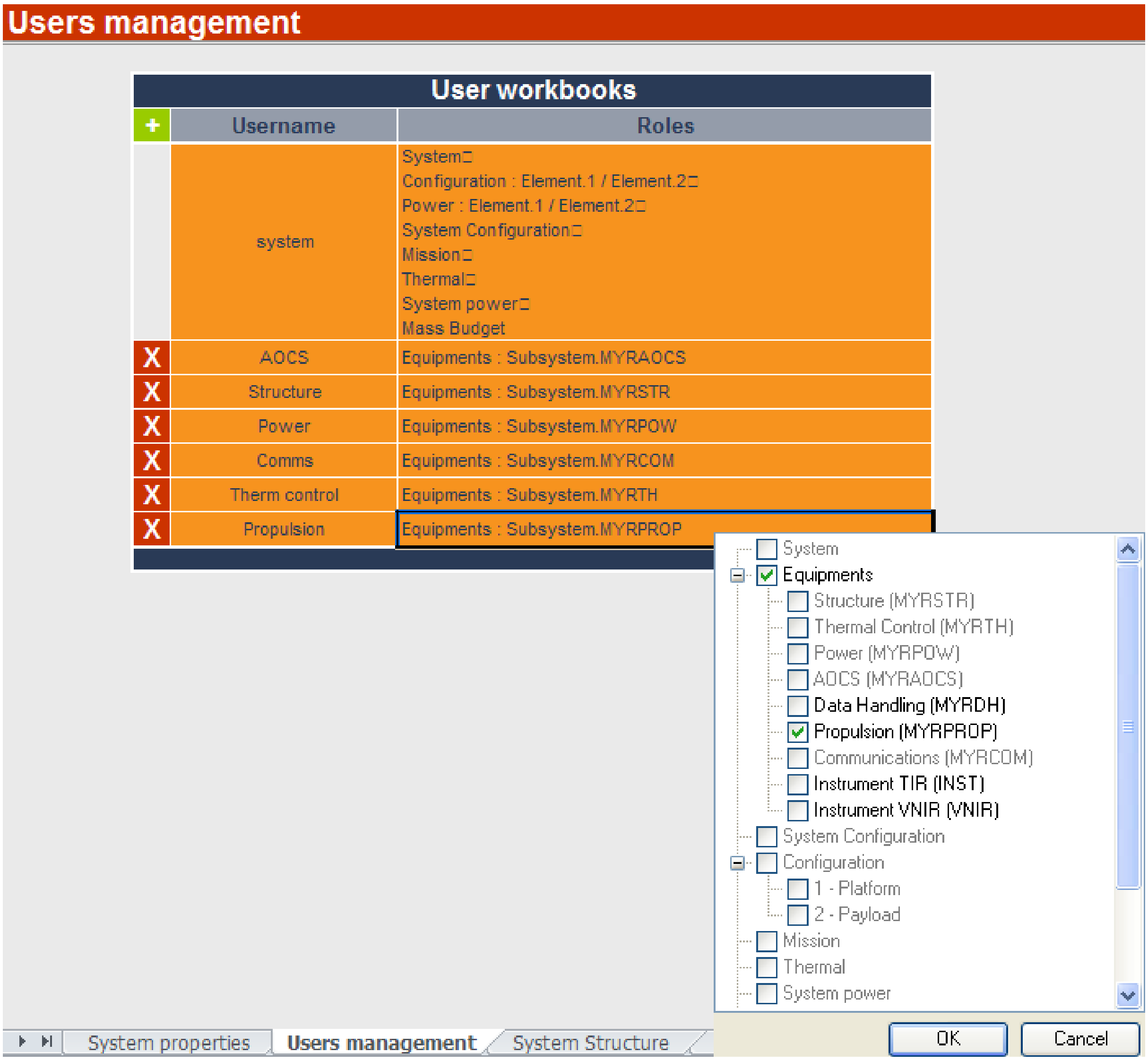



*Figure 3.2.1.1 - User management*

### 3.2.2 Workbook Functions

This sub-section is made explicit by way of example some workbooks, usually divided among the various specialist users.

1. User management : it selects the access of each user (it is better to rewrite workbook after having selected the new roles).
2. System Structure : it selects the structural subsystem and elements.
3. System properties : in this folder there are the main system parameters (lifetime, orbital parameters, launcher capacity, exc.).
4. Additional properties definitions : used to create new parameters at element, system, subsystem, equipment level.
5. Additional properties : visualisation of all parameters you are allowed to modify.
6. Single system with geometry configured to compute budgets, to visualise things on SketchUp, to convert geometry in step file format,  to store and load configurations.

7. Coordinate systems : used to define articulations and additional reference frames in term of positioning (x, y, z coordinates) with respect the system reference frame and orientation (rotations order and angles). It is useful to remember that Reference frames can also be referred to other reference frames.
8. Configuration : used to control the configuration of each equipment (reference frame, position and rotations) / min and max of articulations / Elements Custom properties
9. Saved Configuration : used to select the configurations (articulations values and tank value) and compute MCI for every configurations.
10. Mass Budget : it allows the possibility to put target mass for each element and to force mass values and margin for each subsystem, propellant mass and system margin.
11. Element power budget : used to create element power mode selected for each element mode once defined the associated equipment operative mode (with element power margin included).
12. System power budget : used to create system power mode using power budget elements.
13. Thermal configuration: it defines Thermal modules for dissipation purposes. There is a chose for each equipment (thermal module associated).
14. Dissipation Budget : Filled automatically on the basis of the System Power, Budget and Thermal Module defined.
15. Mission: it allows to introduce manoeuvers and mission phases, to select thrusters and to compute effective thrust and Isp for each manoeuvre.
16. Propellant Budget Top Down: it computes the propellant budget for the max allocated launch mass. It requires the definition of the max launch mass in the Elements Manager, the mission phases and manoeuvres in the mission workbook and any information of the thrusters in any workbook.
17. Propellant Budget Bottom Up: it computes the propellant budget for the current dry mass allocation, by requiring the definition of the mass of each equipment in all the workbooks, all mission phases and manoeuvres in the mission workbook and any information linked to the thrusters in any workbook.

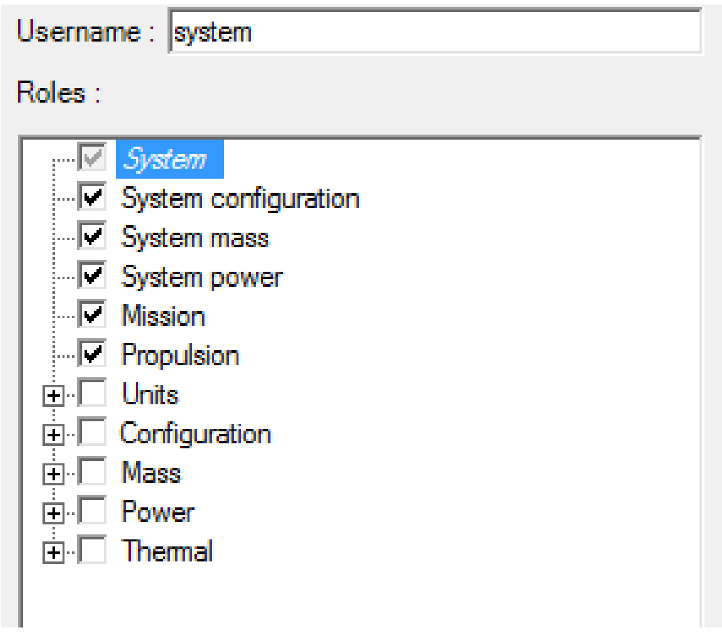



*Figure 3.2.2.1 - Workbooks*

## 3.3 How does IDM-CIC work

Once the project of interest is open with the own role of competence, it is possible to modify the project.

### 3.3.1 IDM-CIC Menù

At the top there is a menu screen, as it can be seen in the following figure.

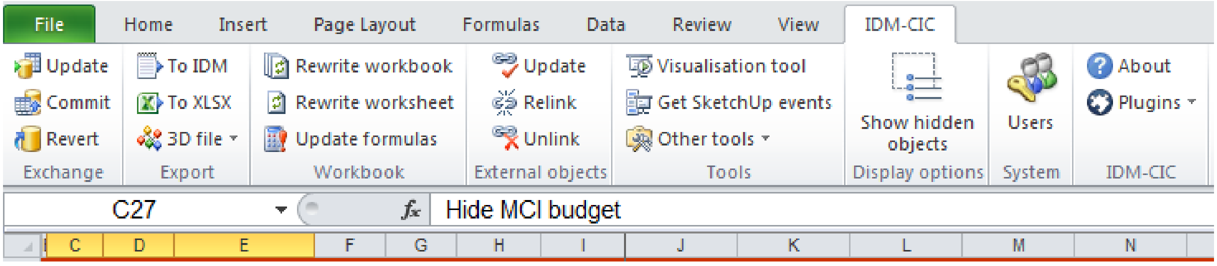



*Figure 3.3.1 - Top Menù*

In the IDM-CIC menu is possible to:

- Rewrite workbook: the entire workbook, important when changes in the architecture (addition/removal elements, modes, equipment).
- Update formulas: to update the computations, important when changing values.
- Data explorer : access to all parameters names in IDM, important when searching to retrieve parameters for insertion of ad-hoc computations.
- Visualisation tool : use to visualise on Sketchup or IDM View.
- Read-only reports or read-only additional properties.
- Update : update information from the system while keeping the work done.
- Commit : send work to the system / XML file.
- Revert : use to cancel modification and to rebuild the system.
- To XML : export the current system to XML file.

### 3.3.2 Equipment data and functions

It is very useful to include and exclude various sub-systems or equipment, or to change mass properties in the various configurations. Each subsystem and elements is green if activated, red if not.

There are five Equipment Functions:

- Order : used to order the equipment.
- Import : to import equipment from other XML file.
- Visu : to visualize equipment in SketchUp with all shapes.
- \+ : to add new equipment.
- X : to delete an equipment.

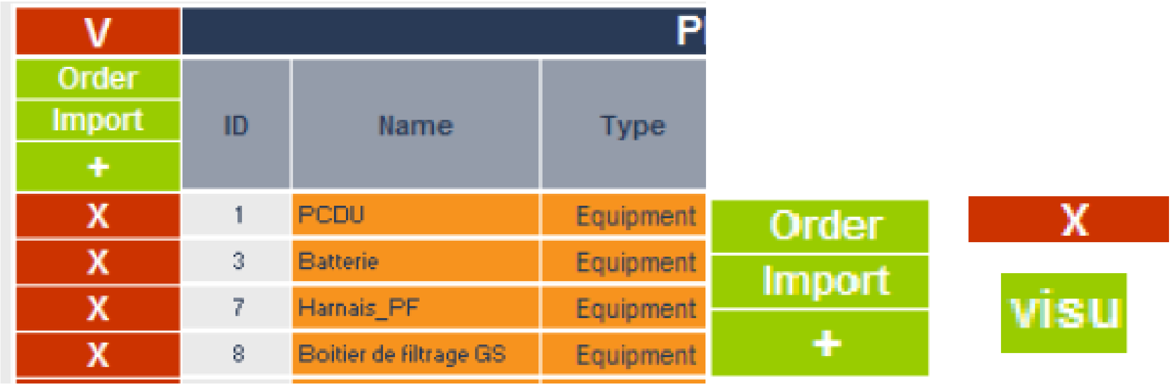



*Figure 3.3.2.1 - Equipment Functions*

The menu that allows changes in custom properties is used daily: it adds parameters for each equipment (Shapes and geometrical definition , Power modes, Thruster modes, Mass, COG, Inertia matrix, Temperatures requirements, Risk characterisation, Tank data).

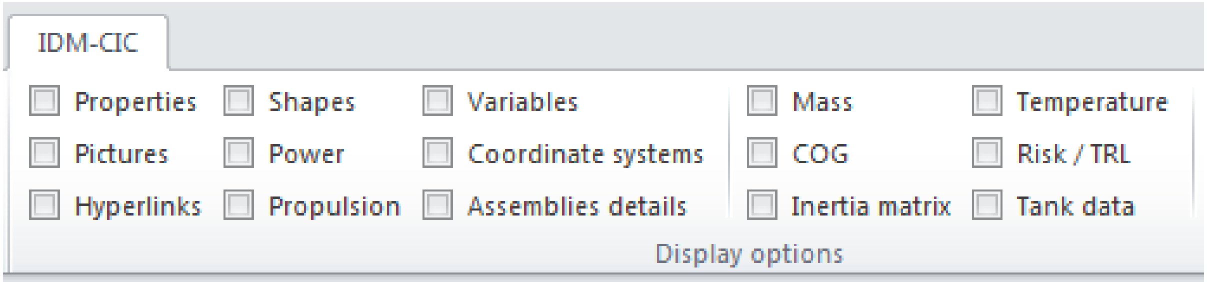



*Figure 3.3.2.2 - Custom Properties*

### 3.3.3 Reference Systems

In the construction of objects and their mutual positioning it is necessary to define appropriate reference systems at the level of a complete object and at the level of a single component, for the correct assembly.

- Satellite reference frame is the base reference system.
- Mounting reference frame is the reference introduced to help the mounting of equipments.
- Equipment reference frame is the reference system of any equipment.
- Subshape reference frame is the reference system of any subshape. Every subshape has its own standard reference frame.

It is necessary to define the link between the various reference systems by means of an appropriate sequence of translations and rotations. Obviously these transformations are the result of the cheaper choice of the partnership between the reference systems.

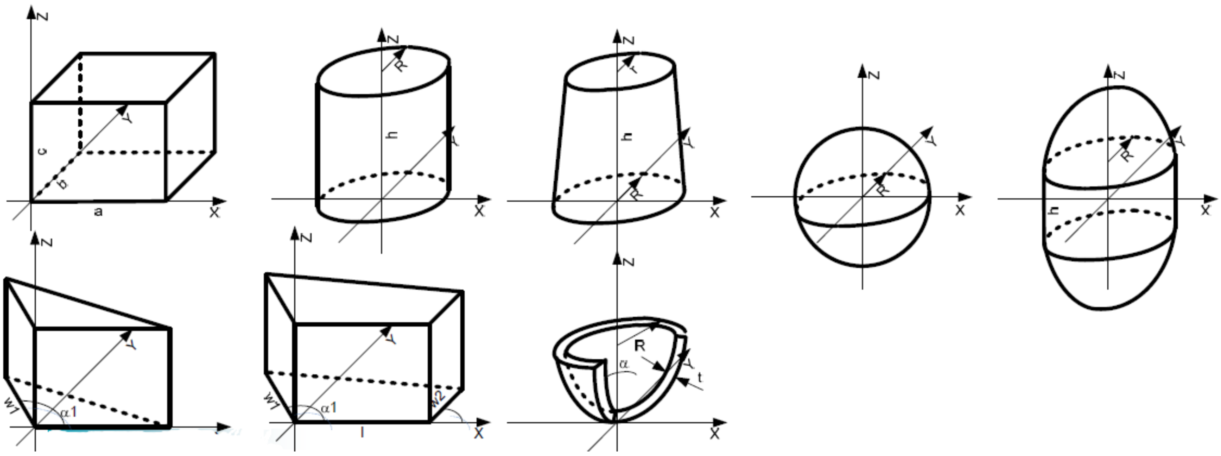


*Figure 3.3.3.1 - Reference systems*

### 3.3.4 Mounting of Shapes

The construction procedure of the individual components is briefly listed. It is mandatory to:

- Decide where the centre of reference of an equipment and directions of its axes.
- Mount the sub-shapes on the equipment reference frame (Position of the centre of the sub-shape frame in the equipment reference frame, rotations to align the equipment reference frame to the sub-shape frame).
- Decide where the system reference frame is.
- Decide which additional reference systems are and mount them on the system reference system (Position of the centre of the additional reference frame in the system reference frame, rotations to align the system reference system frame to the additional reference frame).
- Decide in which reference frame to mount each of the equipment (system or additional).
- Mount the equipment on selected reference frame (Position of the centre of the equipment frame in the selected reference frame, rotations to align the selected reference frame to the equipment frame).

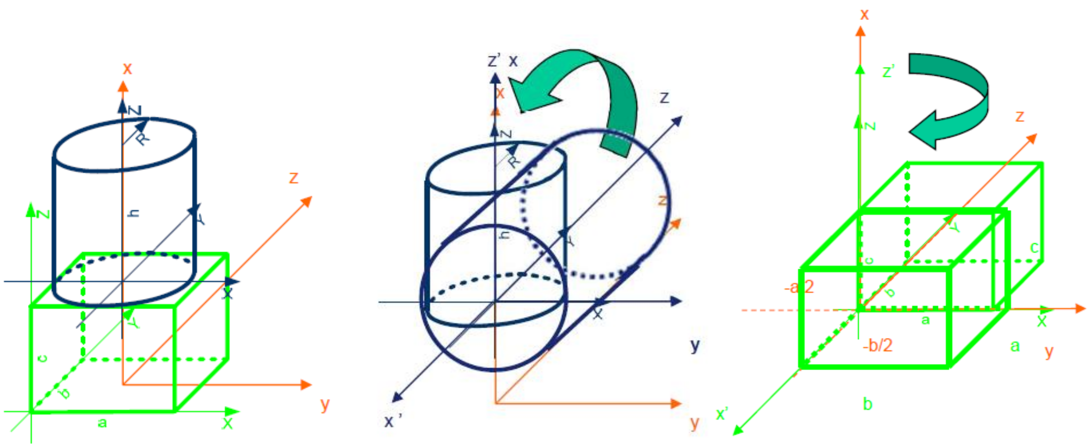


*Figure 3.3.4.1 - Examples of mounting shapes*

# 3.4 Budgets

One of the strengths of this exceptional tool is the ability to estimate the various mission budgets quickly and with good approximation in different configurations varying from time to time the chosen parameters. Each budget is defined in all the various washed out configurations.

## 3.4.1 Mass Budget

In the work folder called Mass Budget you have an overview of the masses constituting the main system and the whole S/C. Through various drop-down menus it is possible to visualize the mass of the single component (with or without margin) and the relative contribution within the system. This process proceeds to know the value of the mass of the whole S / C, including the mass of propellant with relative margins and percentages. The final results are precisely the dry mass and the wet mass of the system.

**Mass Budget**

**Configuration :** Baseline

| PLM | Target wet mass [Kg] : | 1100 | Without margin [Kg] | Margin [%] | Margin [Kg] | Including margin [Kg] | % of total |
|---|---|---|---|---|---|---|---|
| Total dry mass without system margin | | | 715,00 | 20,00% | 143,00 | 858,00 | |
| System margin | | | | 20,00% | 171,60 | 1029,60 | |
| Total wet mass including all margins | | | | | | 1029,60 | |

| SVM | Target wet mass [Kg] : | 685 | Without margin [Kg] | Margin [%] | Margin [Kg] | Including margin [Kg] | % of total |
|---|---|---|---|---|---|---|---|
| Total dry mass without system margin | | | 375,64 | 16,79% | 63,08 | 438,72 | |
| System margin | | | | 20,00% | 87,74 | 526,46 | |
| Propellant mass | 87,058824 | 2,00% | 87,06 | 2,00% | 1,74 | 88,80 | |
| Total wet mass including all margins | | | | | | 615,26 | |

| SSH | Target wet mass [Kg] : | 310 | Without margin [Kg] | Margin [%] | Margin [Kg] | Including margin [Kg] | % of total |
|---|---|---|---|---|---|---|---|
| Total dry mass without system margin | | | 227,71 | 11,92% | 27,14 | 254,85 | |
| System margin | | | | 20,00% | 50,97 | 305,82 | |
| Total wet mass including all margins | | | | | | 305,82 | |

| Losses&Miscellanea | | Target wet mass [Kg] : | | | | 0 | | Without margin [Kg] | Margin [%] | Margin [Kg] | Including margin [Kg] | % of total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| + - | Subsystem | Unit | | | | Forced values | | | | | | |
| | | Name | Quantity | Mass [Kg] | Margin [%] | Mass [Kg] | Margin [%] | | | | | |
| ▼ | Subsystem STR | | | | | | | 5,00 | 0,00% | 0,00 | 5,00 | 0,30% |
| | | Balancing Mass | 1 | 5,00 | 0,00% | | | 5,00 | 0,00% | 0,00 | 5,00 | |
| ▼ | Subsystem Harness | | | | | | | 108,61 | 0,00% | 0,00 | 108,61 | 6,52% |
| | | PCDU Losses | 1 | 0,00 | 20,00% | | | 0,00 | 20,00% | 0,00 | 0,00 | |
| | | Harness | 1 | 0,00 | 20,00% | | | 0,00 | 20,00% | 0,00 | 0,00 | |
| | | Harness PLM | 1 | 60,06 | 0,00% | | | 60,06 | 0,00% | 0,00 | 60,06 | |
| | | Harness SVM | 1 | 30,71 | 0,00% | | | 30,71 | 0,00% | 0,00 | 30,71 | |
| | | Harness Sunshield | 1 | 17,84 | 0,00% | | | 17,84 | 0,00% | 0,00 | 17,84 | |
| Total dry mass without system margin | | | | | | | | 113,61 | 0,00% | 0,00 | 113,61 | |
| System margin | | | | | | | | | 0,00% | 0,00 | 113,61 | |
| Total wet mass including all margins | | | | | | | | | | | 113,61 | |

| System | Without margin [Kg] | | Margin [Kg] | Including margin [Kg] | |
|---|---|---|---|---|---|
| Total dry mass without system margins | 1431,96 | | 233,22 | 1665,18 | |
| Total dry mass including system margins | | | | 1975,49 | |
| Total propellant mass | 87,06 | | 1,74 | 88,80 | |
| Total wet mass including all margins | | | | 2064,29 | |

*Figure 3.4.1.1 - Mass Budget Example*

The information comes partly from the individual components making up the subsystems (mass and mass margin depending on the TRL), partly from indications at the system level (system margin for example).

## 3.4.2 MCI Budget

This folder displays the mass properties of each individual object at the equipment, subsystem, system, and S/C level. Each calculation of center of gravity and moment of inertia can be performed by excluding or inserting margins and referring to multiple reference systems.

**Configuration details**

Configuration : Reference

| SVM-TAS-F | Mass [kg] | COG x [mm] | COG y [mm] | COG z [mm] | Mass with margins | COG including mass margins x [mm] | y [mm] | z [mm] |
|---|---|---|---|---|---|---|---|---|
| Total | 233,71 | 160,7657 | -196,8181 | 974,6445 | 269,417 | 160,7657 | -173,7321 | 963,7834 |

| SVM-OHB | Mass [kg] | COG x [mm] | COG y [mm] | COG z [mm] | Mass with margins | COG including mass margins x [mm] | y [mm] | z [mm] |
|---|---|---|---|---|---|---|---|---|
| Dry | 186,24 | 54,55058 | -40,07127 | 517,4582 | 219,6045 | 55,51526 | -40,77989 | 515,9671 |
| Propellant | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Total | 186,24 | 54,55058 | -40,07127 | 517,4582 | 219,6045 | 54,55058 | -40,77989 | 515,9671 |

| SVM-TAS-I | Mass [kg] | COG x [mm] | COG y [mm] | COG z [mm] | Mass with margins | COG including mass margins x [mm] | y [mm] | z [mm] |
|---|---|---|---|---|---|---|---|---|
| Total | 24,376 | -352,7182 | 402,4976 | 340,4824 | 27,6462 | -352,7182 | 375,9864 | 328,1616 |

**PAYLOAD**

| Subsystem | Unit | Instance | MCI data row > | Mass [kg] | COG x [mm] | COG y [mm] | COG z [mm] | Mass with margins [kg] | COG including mass margins x [mm] | y [mm] | z [mm] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| STRUCTURE SUBSYSTEM | | | Total | 113 | 0 | 0 | 2995,59174 | 135,6 | 0 | 0 | 2995,59174 |
| | Structural Tube | | | | | | | | | | |
| | | 1 | Total | 77 | 0 | 0 | 3458,90604 | 92,4 | 0 | 0 | 3458,90604 |
| | SVM I/F Ring | | | | | | | | | | |
| | Equipm. Brackets | | | | | | | | | | |
| | Sun Shield FPA | | | | | | | | | | |
| | Instrument I/F Ring | | | | | | | | | | |
| | Mirror Support Assembly | | | | | | | | | | |
| THERMAL CONTROL SUBSYSTEM | | | Total | 16,5 | 0 | 0 | 0 | 19,8 | 0 | 0 | 0 |
| PAYLOAD - Mirror Assembly | | | Total | 176,828 | 0 | 0 | 1570,59771 | 212,1936 | 0 | 0 | 1570,59771 |
| PAYLOAD - Focal Plan Assembly | | | Total | 62,633 | 13,756103 | 0 | 5329,89756 | 76,38492 | 13,756103 | 0 | 5333,01144 |
| Total | | | | 368,961 | 2,335168 | 0 | 2574,947 | 443,97852 | 2,335168 | 0 | 2583,086 |

*Figure 3.4.2.1 - MCI Budget Example part A*

**SVM-OHB** — Inertia matrix at system origin including mass margins

| Subsystem | Unit | Instance | MCI data row > | Ixx [kg.m²] | Ixy [kg.m²] | Ixz [kg.m²] | Iyy [kg.m²] | Iyz [kg.m²] | Izz [kg.m²] |
|---|---|---|---|---|---|---|---|---|---|
| STRUCTURE SUBSYSTEM | | | Total | 135,325466 | 6,70527 | -18,043272 | 143,480276 | 14,587208 | 62,213785 |
| THERMAL CONTROL SUBSYSTEM | | | Total | 0 | 0 | 0 | 0 | 0 | 0 |
| CHEMICAL PROPULSION SUBSYSTEM (controlled) | | | Dry | 15,54105 | 0 | 0 | 32,76105 | 0 | 17,22 |
| | | | Propellant | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | Total | 15,54105 | 0 | 0 | 32,76105 | 0 | 17,22 |
| | Tubing | | | | | | | | |
| | Fill&Drain Valve | | | | | | | | |
| | Pressure Transducer | | | | | | | | |
| | Propellant Latch Valve | | | | | | | | |
| | Bracketry | | | | | | | | |
| | Harness & Thermal | | | | | | | | |
| | 22 N Thruster | | | | | | | | |
| | Propellant Filter | | | | | | | | |
| | Hydrazine Line Tank (PTD-96 lt.) | | | | | | | | |
| | | 1 | Dry | 7,770525 | 0 | -8,1795 | 16,380525 | 0 | 8,61 |
| | | | Propellant | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | Total | 7,770525 | 0 | -8,1795 | 16,380525 | 0 | 8,61 |
| | | 2 | Dry | 7,770525 | 0 | 8,1795 | 16,380525 | 0 | 8,61 |
| | | | Propellant | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | Total | 7,770525 | 0 | 8,1795 | 16,380525 | 0 | 8,61 |
| | 1 N Thruster | | | | | | | | |
| Dry | | | | 150,8665 | 6,70527 | -18,04327 | 176,2413 | 14,58721 | 79,43379 |
| Propellant | | | | 0 | 0 | 0 | 0 | 0 | 0 |
| Total | | | | 150,8665 | 6,70527 | -18,04327 | 176,2413 | 14,58721 | 79,43379 |

*Figure 3.4.2.2 - MCI Budget Example part B*

| System | Inertia matrix at system origin including mass margins: Ixx [kg.m²] | Ixy [kg.m²] | Ixz [kg.m²] | Iyy [kg.m²] | Iyz [kg.m²] | Izz [kg.m²] | Inertia matrix at COG including mass margins: Ixx [kg.m²] | Ixy [kg.m²] | Ixz [kg.m²] | Iyy [kg.m²] | Iyz [kg.m²] | Izz [kg.m²] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Dry | 5389,647 | 0,061642 | -50,57605 | 5335,879 | 10,66948 | 543,6428 | 2954,288 | -2,085067 | 21,76805 | 2900,512 | -61,53279 | 539,3494 |
| Propellant | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Total | 5389,647 | 0,061642 | -50,57605 | 5335,879 | 10,66948 | 543,6428 | 2954,288 | -2,085067 | 21,76805 | 2900,512 | -61,53279 | 539,3494 |

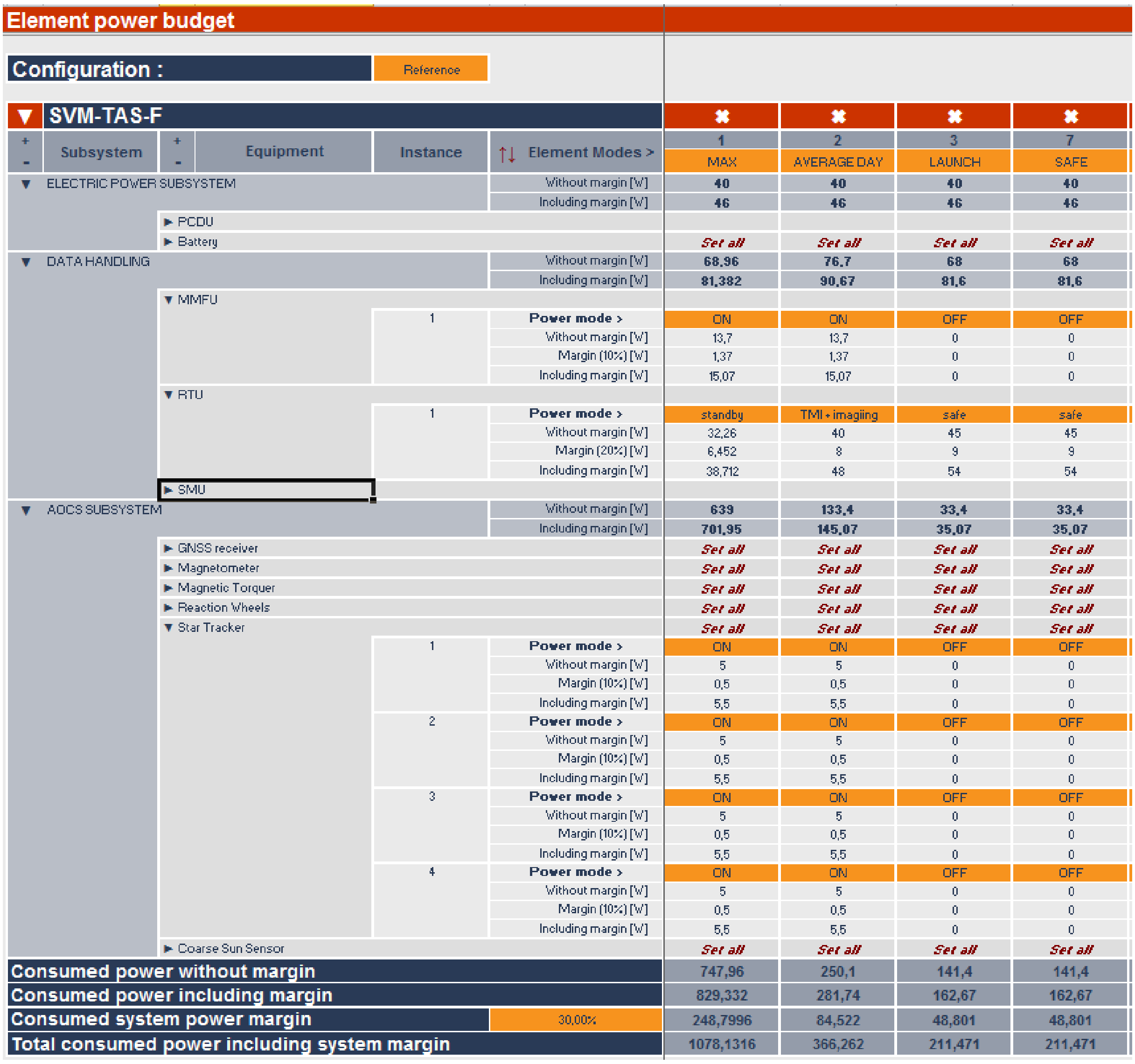
*Figure 3.4.2.3 - MCI Budget Example part C*

### 3.4.3 Element Power Budget

The power budget is initially defined at the individual component level, entering information about its nominal consumption in various ways (on, off and others).

It is easy to assign to each instance of each equipment its operative mode in the element mode. Visualization is simplified by the possibility of expanding the elements and subsystems instances by arrows.

The element power budget manages system-level information and not the main S/C level. The following figure explains this concept.



Element power budget

Configuration : Reference

▼ SVM-TAS-F

| Subsystem | Equipment | Instance | Element Modes > | 1 MAX | 2 AVERAGE DAY | 3 LAUNCH | 7 SAFE |
|---|---|---|---|---|---|---|---|
| ▼ ELECTRIC POWER SUBSYSTEM | | | Without margin [W] | 40 | 40 | 40 | 40 |
| | | | Including margin [W] | 46 | 46 | 46 | 46 |
| | ► PCDU | | | | | | |
| | ► Battery | | | Set all | Set all | Set all | Set all |
| ▼ DATA HANDLING | | | Without margin [W] | 68,96 | 76,7 | 68 | 68 |
| | | | Including margin [W] | 81,382 | 90,67 | 81,6 | 81,6 |
| | ▼ MMFU | | | | | | |
| | | 1 | Power mode > | ON | ON | OFF | OFF |
| | | | Without margin [W] | 13,7 | 13,7 | 0 | 0 |
| | | | Margin (10%) [W] | 1,37 | 1,37 | 0 | 0 |
| | | | Including margin [W] | 15,07 | 15,07 | 0 | 0 |
| | ▼ RTU | | | | | | |
| | | 1 | Power mode > | standby | TMI + imagiing | safe | safe |
| | | | Without margin [W] | 32,26 | 40 | 45 | 45 |
| | | | Margin (20%) [W] | 6,452 | 8 | 9 | 9 |
| | | | Including margin [W] | 38,712 | 48 | 54 | 54 |
| | ► SMU | | | | | | |
| ▼ AOCS SUBSYSTEM | | | Without margin [W] | 639 | 133,4 | 33,4 | 33,4 |
| | | | Including margin [W] | 701,95 | 145,07 | 35,07 | 35,07 |
| | ► GNSS receiver | | | Set all | Set all | Set all | Set all |
| | ► Magnetometer | | | Set all | Set all | Set all | Set all |
| | ► Magnetic Torquer | | | Set all | Set all | Set all | Set all |
| | ► Reaction Wheels | | | Set all | Set all | Set all | Set all |
| | ▼ Star Tracker | | | Set all | Set all | Set all | Set all |
| | | 1 | Power mode > | ON | ON | OFF | OFF |
| | | | Without margin [W] | 5 | 5 | 0 | 0 |
| | | | Margin (10%) [W] | 0,5 | 0,5 | 0 | 0 |
| | | | Including margin [W] | 5,5 | 5,5 | 0 | 0 |
| | | 2 | Power mode > | ON | ON | OFF | OFF |
| | | | Without margin [W] | 5 | 5 | 0 | 0 |
| | | | Margin (10%) [W] | 0,5 | 0,5 | 0 | 0 |
| | | | Including margin [W] | 5,5 | 5,5 | 0 | 0 |
| | | 3 | Power mode > | ON | ON | OFF | OFF |
| | | | Without margin [W] | 5 | 5 | 0 | 0 |
| | | | Margin (10%) [W] | 0,5 | 0,5 | 0 | 0 |
| | | | Including margin [W] | 5,5 | 5,5 | 0 | 0 |
| | | 4 | Power mode > | ON | ON | OFF | OFF |
| | | | Without margin [W] | 5 | 5 | 0 | 0 |
| | | | Margin (10%) [W] | 0,5 | 0,5 | 0 | 0 |
| | | | Including margin [W] | 5,5 | 5,5 | 0 | 0 |
| | ► Coarse Sun Sensor | | | Set all | Set all | Set all | Set all |
| Consumed power without margin | | | | 747,96 | 250,1 | 141,4 | 141,4 |
| Consumed power including margin | | | | 829,332 | 281,74 | 162,67 | 162,67 |
| Consumed system power margin | | | 30,00% | 248,7996 | 84,522 | 48,801 | 48,801 |
| Total consumed power including system margin | | | | 1078,1316 | 366,262 | 211,471 | 211,471 |

*Figure 3.4.3.1 Element power budget*

### 3.4.4 System Power Budget

In the system power budget, on the other hand, there is an overview of the powers at stake. It is also possible to define and manage the operating modes of the system. It is simple: the only operation to be performed is to assign to each element its operative mode in the system mode.

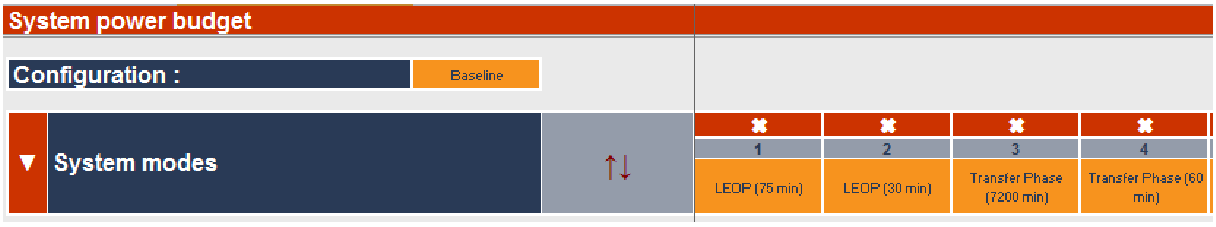



*Figure 3.4.4.1 - System modes*

Subsequently the power margins are inserted for each subsystem, subsequently at system level and finally at S/C level.

| SVM | | | | | | | |
|---|---|---|---|---|---|---|---|
| Subsystem | Equipment | Instance | Element Mode > | Launch | Sun Aquisition | Nominal Mode 1 | Nominal Mode 2 |
| Consumed power without margin | | | | 141,86 | 288,342 | 356,36 | 384,242 |
| Consumed power including margin | | | | 162,032 | 321,6304 | 400,472 | 430,1504 |
| Consumed system power margin | | | 20,00% | 32,4064 | 64,32608 | 80,0944 | 86,03008 |
| Total consumed power including system margin | | | | 194,4384 | 385,95648 | 480,5664 | 516,18048 |
| **Losses&Miscellanea** | | | | | | | |
| Subsystem | Equipment | Instance | Element Mode > | Launch | Sun Acquisition | Nominal mode 1 | Nominal mode 2 |
| Subsystem Harness | | | Without margin [W] | 12,352469 | 22,072011 | 48,388217 | 50,195631 |
| | | | Including margin [W] | 12,352469 | 22,072011 | 48,388217 | 50,195631 |
| | PCDU Losses | | | | | | |
| | | 1 | Power mode > | Launch | Sun Aquisition | Nominal 1 | Nominal 2 |
| | | | Without margin [W] | 6,08496 | 10,872912 | 23,83656 | 24,726912 |
| | | | Margin (0%) [W] | 0 | 0 | 0 | 0 |
| | | | Including margin [W] | 6,08496 | 10,872912 | 23,83656 | 24,726912 |
| | Harness | | | | | | |
| Consumed power without margin | | | | 12,352469 | 22,072011 | 48,388217 | 50,195631 |
| Consumed power including margin | | | | 12,352469 | 22,072011 | 48,388217 | 50,195631 |
| Consumed system power margin | | | 20,00% | 2,4704938 | 4,4144022 | 9,6776434 | 10,0391262 |
| Total consumed power including system margin | | | | 14,822963 | 26,486414 | 58,06586 | 60,234758 |
| Total consumed power without any margin | | | | 188,212469 | 344,414011 | 733,148217 | 762,837631 |
| Total consumed power without system margins | | | | 215,184469 | 384,502411 | 842,940217 | 874,426031 |
| Total consumed system power margin | | | | 43,036894 | 76,900482 | 168,588043 | 174,885206 |
| Total consumed power including system margins | | | | 258,221363 | 461,402894 | 1011,52826 | 1049,311238 |

*Figure 3.4.4.2 - System Power budget Example*

### 3.4.5 Thermal Configuration

The first step is to calculate the dissipation budget is to define the thermal modules for each subsystem defined by the various situations (thermal, environmental, propulsive, etc.) that are configured during the mission phases. Subsequently, specific thermal modes are assigned for each component: the union of thermal modes of each component defines Thermal Modes of the Sub-System. System mode are defined in System Power Budget.

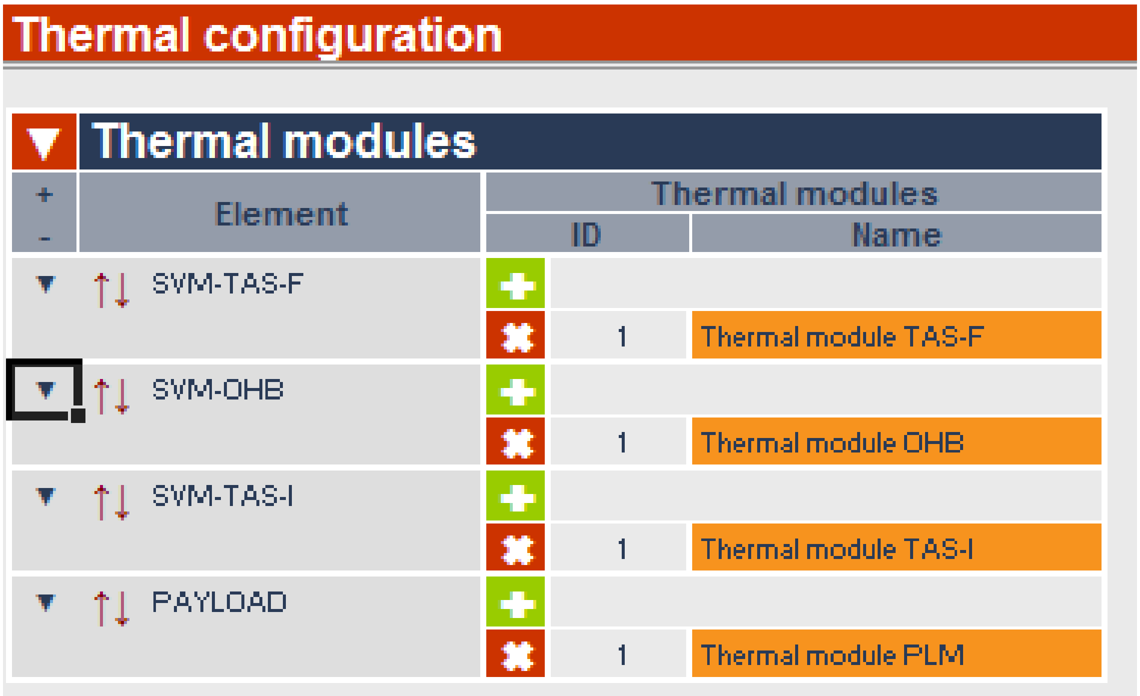



*Figure 3.4.5.1 - Example of Thermal Modules*

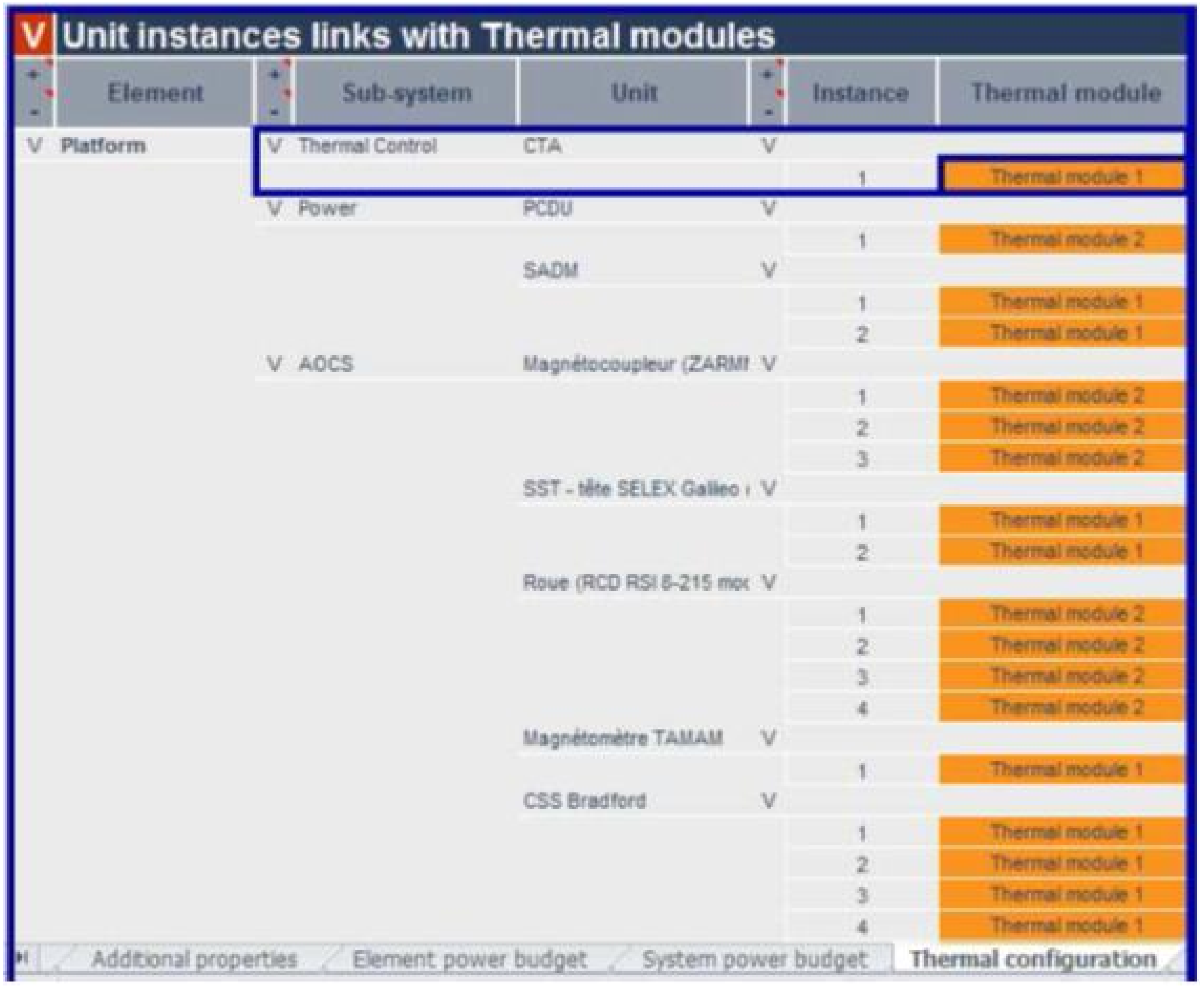



*Figure 3.4.5.2 - Equipments thermal modes*

## 3.4.6 Dissipation Budget

The dissipation budget is divided in turn at the level of a single subsystem and at the S/C level. The information reported is the same: thermal mdi of the single components, subsystems and systems and calculated dissipated powers. The dissipation of the S/C is equal to the sum of the dissipations of the various components, less than the addition or subtraction of dissipative margins.

| SVM-TAS-F | | | | 1 | 2 |
|---|---|---|---|---|---|
| Thermal module | Equipment | Instance | Element Mode > | MAX | AVERAGE DAY |
| Thermal module TAS-F | | | Without margin [W] | 811 | 265,4 |
| | | | Including margin [W] | 893,75 | 296,87 |
| | PCDU | 1 | Power mode > | ON | ON |
| | Battery | 1 | Power mode > | ON | OFF |
| | | | Without margin [W] | 20 | 0 |
| | | | Margin (0%) [W] | 0 | 0 |
| | | | Including margin [W] | 20 | 0 |
| | Battery | 2 | Power mode > | ON | OFF |
| | GNSS receiver | 1 | Power mode > | ON | ON |
| | GNSS receiver | 2 | Power mode > | STANDBY | STANDBY |
| | Magnetometer | 1 | Power mode > | ON | ON |
| | Magnetometer | 2 | Power mode > | OFF | OFF |
| | Magnetic Torquer | 1 | Power mode > | Not mapped | ON |
| | Magnetic Torquer | 2 | Power mode > | Not mapped | ON |
| | Magnetic Torquer | 3 | Power mode > | Not mapped | ON |
| | | | Without margin [W] | 0 | 4,8 |
| | | | Margin (5%) [W] | 0 | 0,24 |
| | | | Including margin [W] | 0 | 5,04 |
| | Reaction Wheels | 1 | Power mode > | PEAK | ON |
| | | | Without margin [W] | 150 | 20 |
| | | | Margin (10%) [W] | 15 | 2 |
| | | | Including margin [W] | 165 | 22 |
| | Reaction Wheels | 2 | Power mode > | PEAK | ON |
| | Reaction Wheels | 3 | Power mode > | PEAK | ON |
| | | | Without margin [W] | 150 | 20 |
| | | | Margin (10%) [W] | 15 | 2 |
| | | | Including margin [W] | 165 | 22 |
| | Reaction Wheels | 4 | Power mode > | PEAK | ON |
| | Star Tracker | 1 | Power mode > | ON | ON |
| | | | Without margin [W] | 5 | 5 |
| | | | Margin (10%) [W] | 0,5 | 0,5 |
| | | | Including margin [W] | 5,5 | 5,5 |
| | Star Tracker | 2 | Power mode > | ON | ON |
| | Star Tracker | 3 | Power mode > | ON | ON |
| | Star Tracker | 4 | Power mode > | ON | ON |
| | Coarse Sun Sensor | 1 | Power mode > | ON | ON |
| | Coarse Sun Sensor | 2 | Power mode > | ON | ON |
| | | | Without margin [W] | 0 | 0 |
| | | | Margin (5%) [W] | 0 | 0 |
| | | | Including margin [W] | 0 | 0 |
| **Dissipated power without margin** | | | | 811 | 265,4 |
| **Dissipated power including margin** | | | | 893,75 | 296,87 |
| **Dissipated system power margin** | | | 30,00% | 268,125 | 89,061 |
| **Total dissipated power including system margin** | | | | 1161,875 | 385,931 |

| | | |
|---|---|---|
| Total consumed power margin | 195,6 | 247,6 |
| Total consumed power without system margin | 232,26 | 284,76 |
| Total consumed power margin | 23,226 | 28,476 |
| Total consumed power including system margin | 255,486 | 313,236 |

Additional properties / Element power budget / System power budget / Thermal configuration / Dissipation budget

*Figure 3.4.6.1 – Dissipation Budget*

## 3.4.7 Propellant Budget Bottom-up

The Propellant Mass Budget Bottom-Up starts from the current dry mass and computes the Wet mass. It gives an indication of the margins in the current implementation (the max dry mass, the launcher capacity, the capacity of selected tanks). The effective starting Mass derives from the Mass Budget. If the cell is green, Launcher and or tank capacities are enough (red if not).

## 3.4.8 Propellant Budget Top-Down

The Propellant Mass Budget Top-Down starts from the launcher capacity and it gives the max dry mass, the max propellant to size tanks: the Mass target for the system is put in the Mass Budget.

The function creates two tabs, on the basis of the information coming from Mission workbook, the information entered in the Elements Manager tab (Launcher capacity, Elements Mass targets) and the overall Mass Budgets.

| Configuration : | FLIGHT |
|---|---|

**System launch**

| | |
|---|---|
| Launchable mass [Kg] | 2000,00 |
| Wet mass delta [Kg] | 812,00 |
| Launch mass [Kg] | 1188,00 |
| Adapter mass [Kg] | 78,00 |
| System propellant margin | 2,00% |

**Mass evolution**

| Mission phase | Maneuver | Thrusting element | Involved elements | Mass before [Kg] | DV without margin [m/s] | DV margin [%] |
|---|---|---|---|---|---|---|
| Operational | | | | 1110,00 | | |
| | CAM | SVM-OHB | SVM-TAS-F SVM-OHB SVM-TAS-I PAYLOAD | 1110,00 | 1,00 | 1,00 |
| | SK | SVM-OHB | SVM-TAS-F SVM-OHB SVM-TAS-I PAYLOAD | 1108,49 | 23,80 | 0,05 |
| | Re-entry | SVM-OHB | SVM-TAS-F SVM-OHB SVM-TAS-I PAYLOAD | 1089,82 | 184,00 | 0,05 |

**Budgets [Kg]**

| Object | Consumed propellant mass | Consumed propellant mass incl. margin | Tanks capacity | Tanks delta | Max dry mass allocation | Max dry mass allocation delta |
|---|---|---|---|---|---|---|
| System | 154,32 | 157,40 | 192,00 | 34,60 | 952,60 | -200,18 |
| SVM-TAS-F | 0,00 | 0,00 | 0,00 | 0,00 | | |
| SVM-OHB | 154,32 | 157,40 | 192,00 | 34,60 | | |
| SVM-TAS-I | 0,00 | 0,00 | 0,00 | 0,00 | | |
| PAYLOAD | 0,00 | 0,00 | 0,00 | 0,00 | | |

*Figure 3.4.7.1 - Propellant Margin*

Ultimately, the Propellant Top-Down that gives the mass allocation per each element for the current launcher and the Propellant Bottom-Up that gives the launch mass for the current implementation.

### 3.4.9 Delta V Budget

In the Delta V budget, for each mission phase, all the manoeuvers to be performed are listed, specifying all the propulsion elements involved. The propulsion parameters of the thrusters (such as the specific impulse) are then taken, to which the thruster efficiencies and the relative delta V margins will be added during each single maneuver.

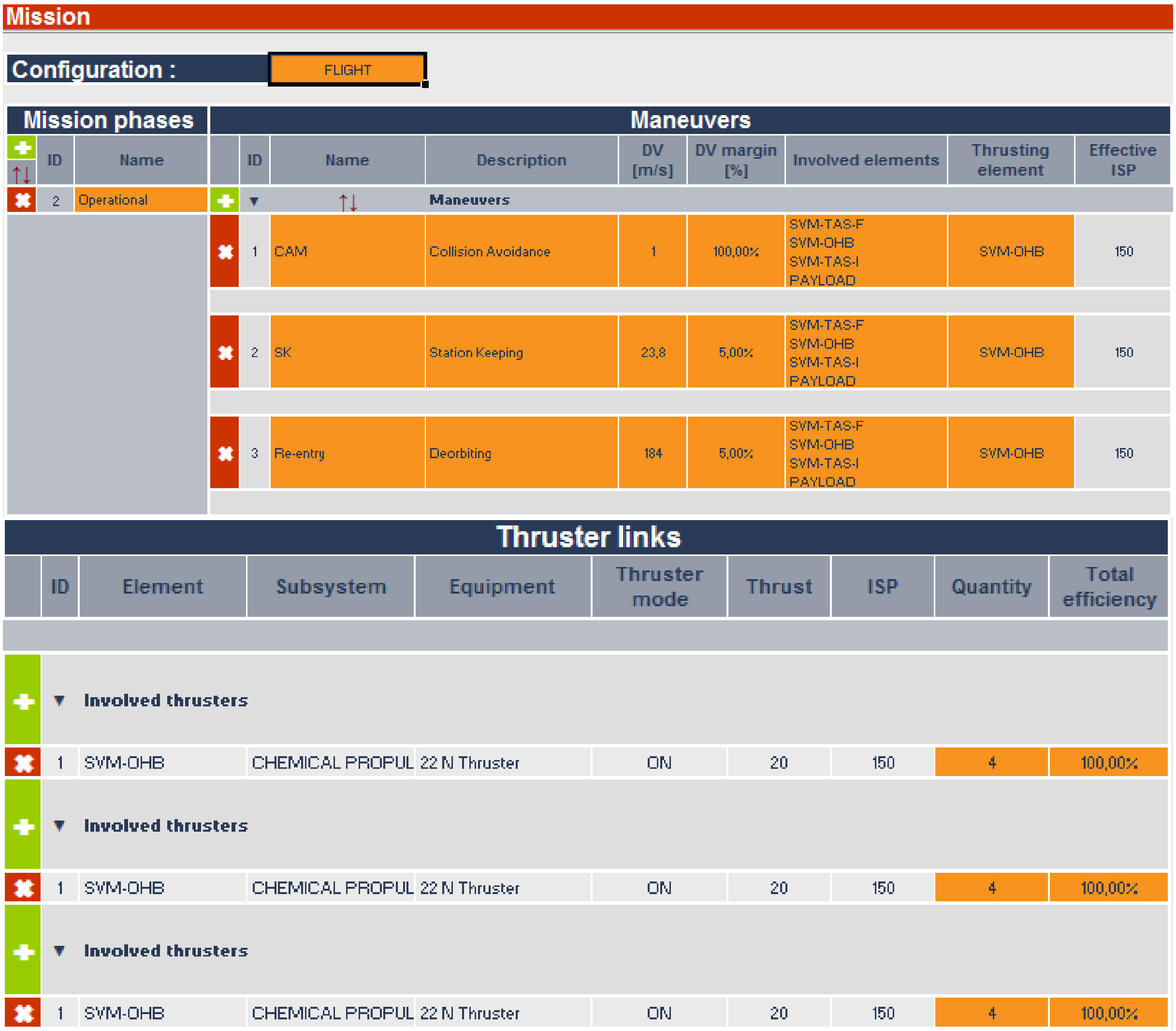



*Figure 3.4.9.1 - Delta V budget Example*

The result consists of balancing the total delta V with the margin, depending on the propellers used.

## 3.5 Additional Functions

What has been said up to this point is only the tip of the iceberg of the functionality of this powerful tool.

### 3.5.1 IDM View and Google Sketchup

Useful to visualise only one equipment use the "visu" cell in the shapes definition unless the various equipments are assembled with the right reference frame. It is better to assemble the various equipments in the configuration workbook rather than in Subsystem level, except for several shapes equipment. All the positioning modifications in IDM model (equipment or configuration level) are automatically transfert to the Sketchup visualization. The positioning of equipments (or shapes) can be modified using translate and rotate functions.

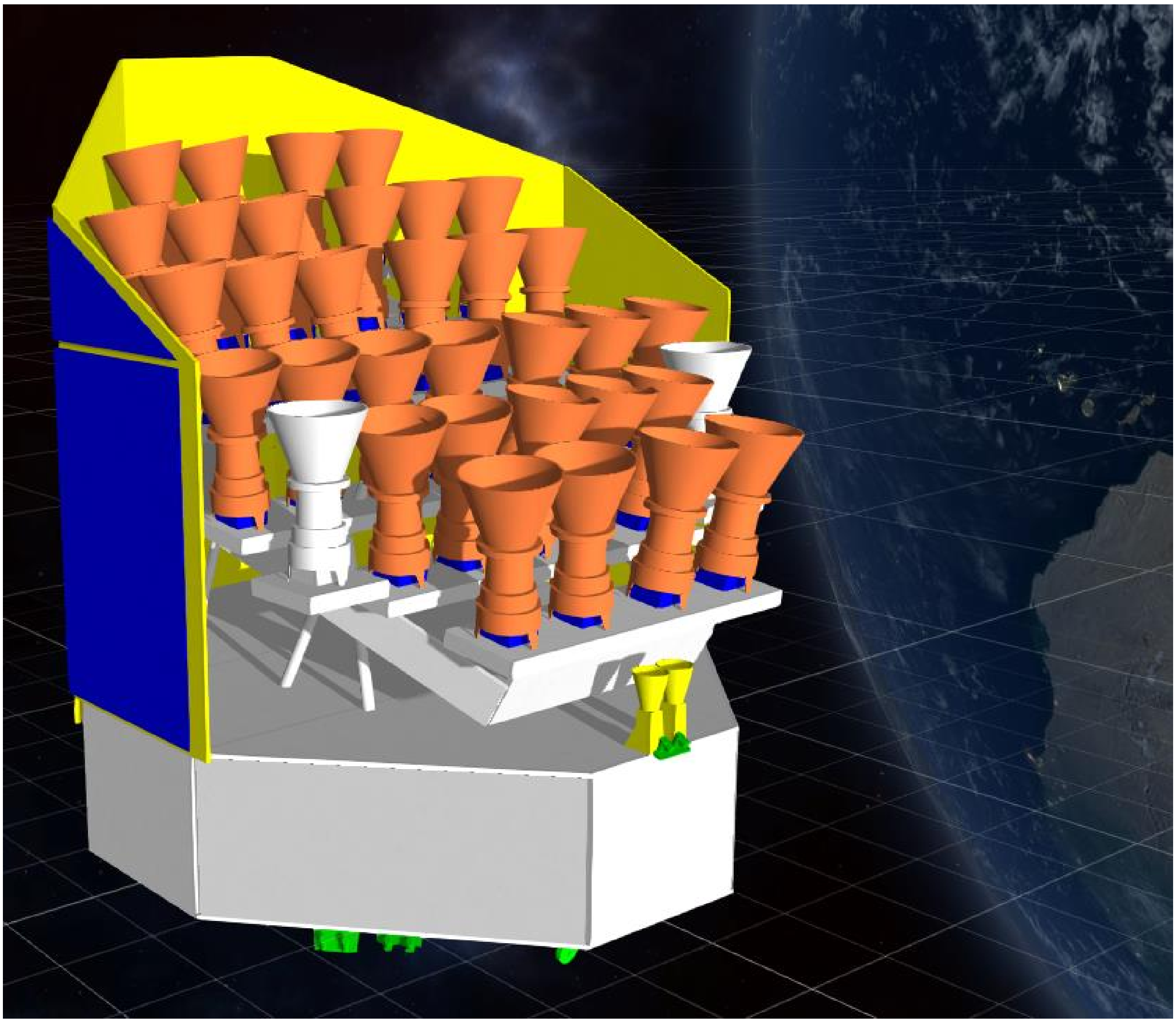


*Figure 3.5.1.1 - Example of IDM View*

### 3.5.2 Import and export of objects from other projects

The function import is very useful to use former project, a tool available in the Version 3 of IDM. Equipments (in SubSystem Workbooks) or elements (in System Structure Workbook) from other projects with the XML file can be imported: the idea is to have a list of platforms – payloads elements and import the one needed; so, when a new project is created, it is necessary only to create at least one element for platform and one for payload, so this tool is very useful to work faster and build new projects.

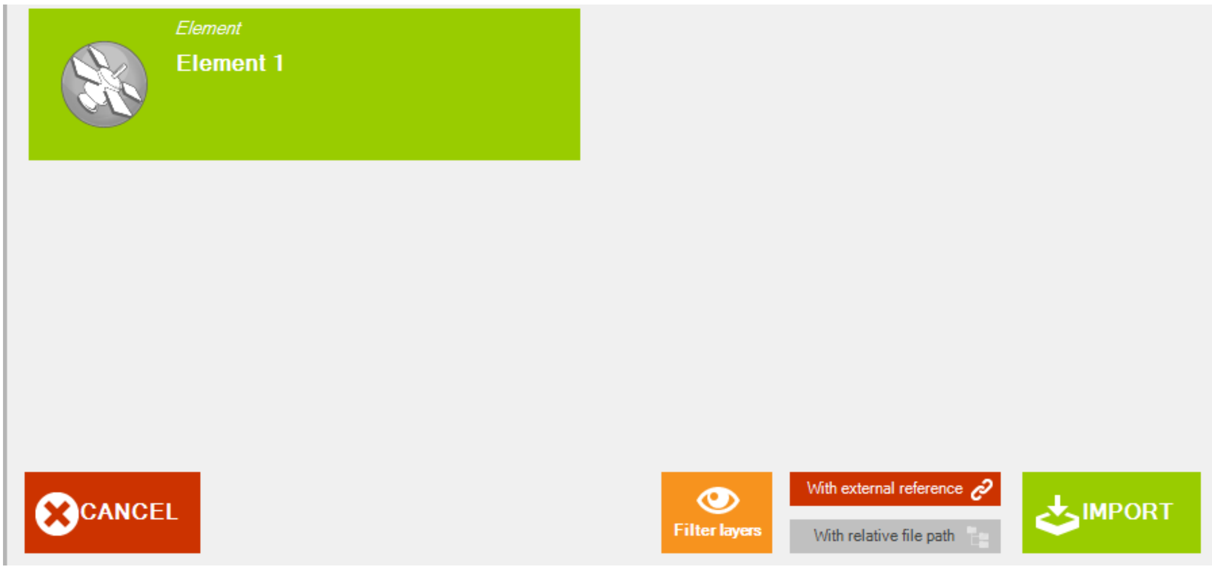



*Figure 3.5.2.1 - Import function*

### 3.5.3 Export of data

IDM-CIC can communicate with other programs: in the menu you have a choice of data export formats:

- To IDM: save an executable copy on IDM-CIC.
- To XLSX: save all folders as an Excel file divided in row and columns.
- To 3D file: the geometrical model can be used in other software like STK.

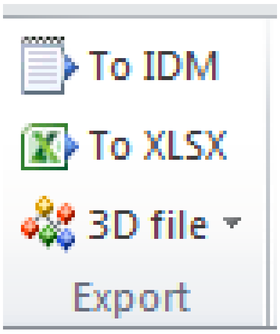



*Figure 3.5.3.1 - Export*

# Chapter 4

# STK

Analytical Graphics, Inc. has built a physical model on which Systems Tool Kit has been programmed, better known by the abbreviation STK (previously the Satellite Tool Kit). STK is a software that performs complex analyzes, by scientists and engineers, of terrestrial, maritime, aeronautical and space objects and provides all the results in a single integrated solution. The software, through geometric and physical information, determines the position, the dynamics and the properties of objects over time, the relative spatial relations between them depending on complex simultaneous constraint conditions. STK has been developed as a commercial solver since 1989 by the AGI. It was originally created to solve problems involving satellites orbiting the Earth and with subsequent versions it is now used in the aerospace and defense scientific communities and for many other applications. Since STK's launch, this software application, developed by AGI, helps engineers to map space and time and make better and faster decisions. The eleventh version of Systems Tool Kit (STK), using a four-dimensional interacting globe, models within it various complex systems such as terrestrial, maritime, air and space and analyzes their performance in real time or simulated.


*Figure 4.1 - STK Intro Logo*

## 4.1 Application Areas

AGI software applies to a wide range of problems for any land, sea, air and space systems. Thanks to our amazing customers, our technology has helped solve some pretty unique challenges that we never envisioned. The accuracy and flexibility of our 4D software environment coupled with its open API has shown that using our robust commercial technology leads to faster and better decisions for the aerospace industry's most complex problems.

### 4.1.1 Space Design

In STK the engineer can design all aspects of a space mission for any type of orbit around any central body in any phase of the mission. The tool is validated and verified for use in the design, planning and operation of satellite missions or satellite systems. The software binds multidisciplinary aspects such as commercial, civil, defense and intelligence operations, orbit determination, planning and detection of maneuvers and joint analysis technology. Here there are some examples:

- Orbit and constellation design
- Power and fuel budgeting
- Payload performance
- Attitude and orbit modeling
- Communication modeling
- Space weather
- Trade analyses and optimizations
- Maneuver planning
- Rendezvous and proximity operations

### 4.1.2 Space Operations

The mission can be operated by complimentary tools used to design it for better resolution and situational awareness. Hence:

- Orbit determination
- Maneuver planning
- Scheduling
- Space weather effects
- Real-time visualization
- Conjunction avoidance

### 4.1.3 Multi Domain

The software allows multi-domain analysis, operational images by drawing data from any source and in any format; through any unit or any coordinate system entered previously or subsequently allows to determine the impact of all events related to the mission, such as:

- Highly accurate vehicle modeling
- Land, Sea, Air and Space
- RF communications and radar modeling
- Coverage and LOS
- Collection planning
- Real-time data visualization
- Specific analysis
- Supports Model-Based Engineering
- Integration with legacy systems

### 4.1.4 Aircraft and UAV

In the tool is possible to design aircrafts and UAVs at the mission level with constraints:

- Aircraft flight modeling
- Formation flying
- Navigational precision
- Test and evaluation support
- Radar and detection modeling
- Dense traffic safety of flight analysis
- Pre-flight planning
- Real-Time visualization
- Post-flight reconstruction
- Terrain effects
- RF communications

### 4.1.5 Missile Systems

In addition, the possibility of modeling and design end-to-end complex defense and missile systems is also considered.

- Mid-range and theater models
- Intercept analysis
- Radar modeling
- Various sensors
- Flight and reentry modeling, including multiple RDVs and all stages

# 4.2 STK Highlights

As listed on the official website www.agi.com, the resources used on STK are multiple, including:

- Model with accurate Earth and other planet representations in time and space.

- Wide support with cloud and server-based data, flexible development kits and components.

- Streaming imagery, terrain or other maps and data.

- Realistic, idealistic or user-ingested dynamic vehicles.

- Vehicle orientation, pointing, and sensor fields of view.

- Report or define new points, vectors, angles, axes and coordinate systems.

- Run in real time or simulate in past or future time.

- Analyze complex physical relationships between all the vehicles, sensors and environment.

- Report, graph or export the results.

- Visualize the scenario in any way imaginable in a 3D environment.

- Create videos, custom views or images to clearly convey results.

- Integrate, customize or extend capability with file formats.

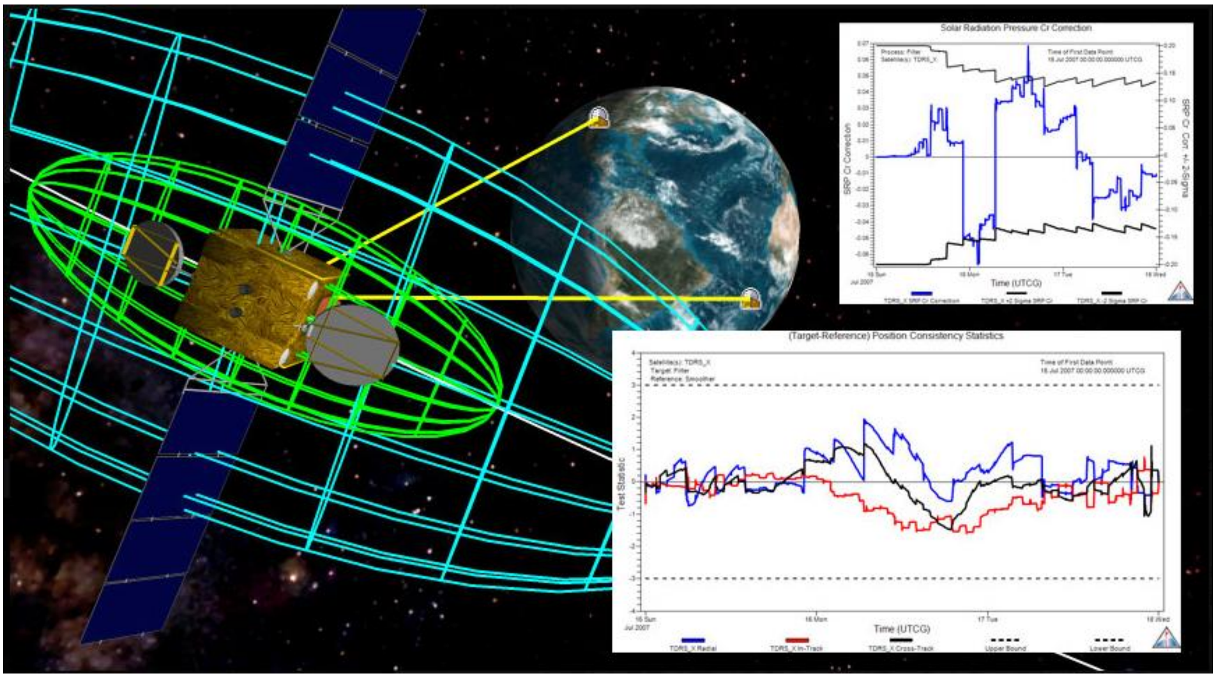



*Figure 4.2.1 - STK Highlights*

## 4.2.1 Interface

The STK interface consists in a standard workspace, flanked by customizable toolbars, maps and 3D windows. All analyzes can be performed through mouse and keyboard interaction or by using a scripting interface called Connect that allows STK to act within a client / server environment.

Every analysis, design space or new project within STK is called a scenario. Within each scenario it is possible to create, insert and modify any number of objects such as satellites, aircraft, targets, ships, communication systems or other. Each scenario defines the predefined time limits for the objects or various mission phases, as well as the selection of the various basic units with the characteristics and properties. The only limitation is that only one scenario can exist at any time, although the data can be exported and reused in subsequent analyzes.

For every aspect of every object within a scenario, various tables, reports and graphs can be created (both static and dynamic). To carry out a more in-depth and accurate analysis, it is also possible to report the relative parameters, between an object and the other, and the effect of the restrictions (constraints) of the real world. Through the use of constellation objects and chains, it is possible to group multiple child objects and to investigate the multi-path interactions between them.

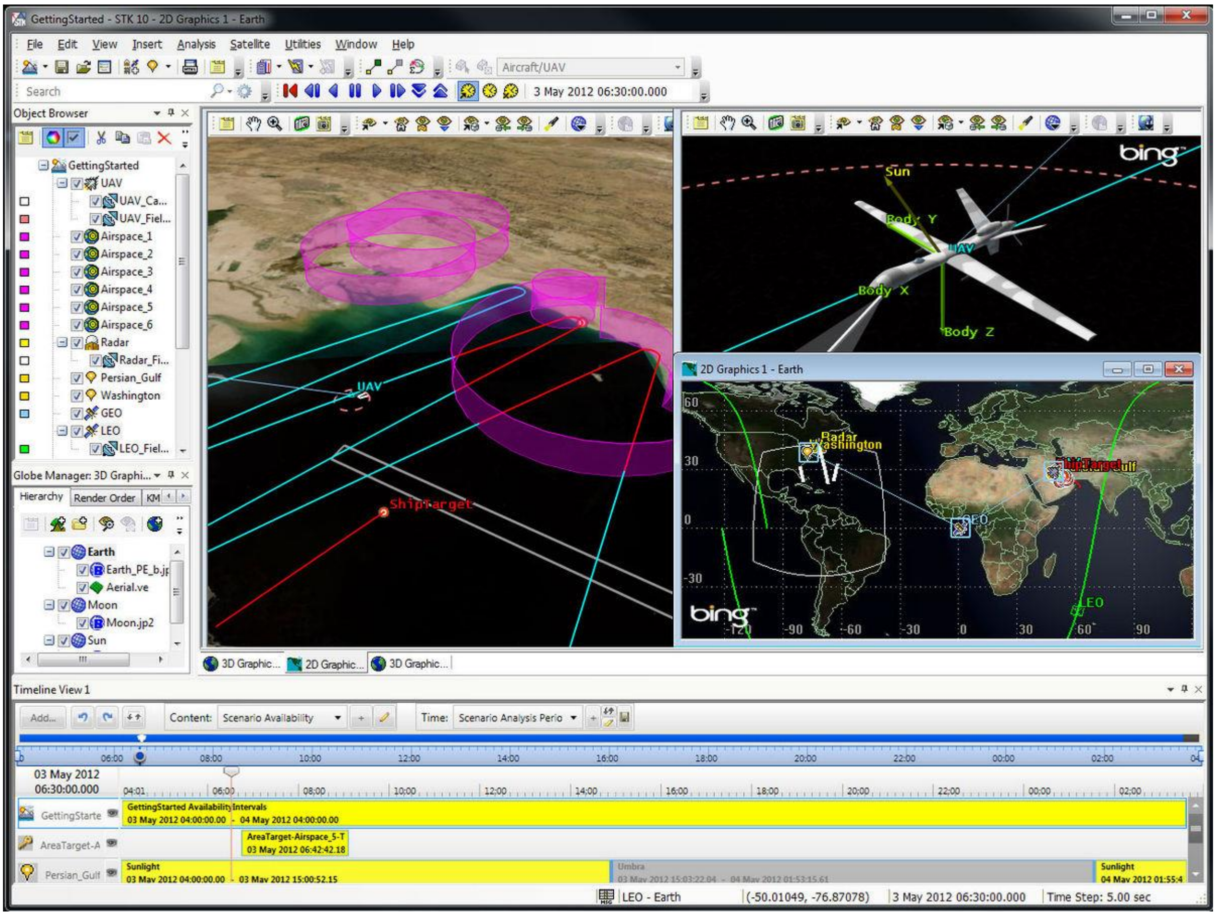



*Figure 4.2.1.1 - STK snapshot*

## 4.2.2 Modules and integration

AGI also offers software development kits to incorporate STK functionality into third-party applications (such as Matlab and Excel) or to create new applications based on AGI technology. STK is a modular product: it allows the addition of modular modules from other software, in the same way as MATLAB and Simulink, and allows users to add modules to the baseline package to enhance specific functions. So, STK can be incorporated into another application or controlled by an external application or incorporate and control other applications. Both integration techniques can use the computer programming language of connection scripting to perform this activity: for this purpose an object model can also be used for multiple programmed integration methodologies. STK can be guided by a script executed by the internal STK Web browser or controlled by an external source.

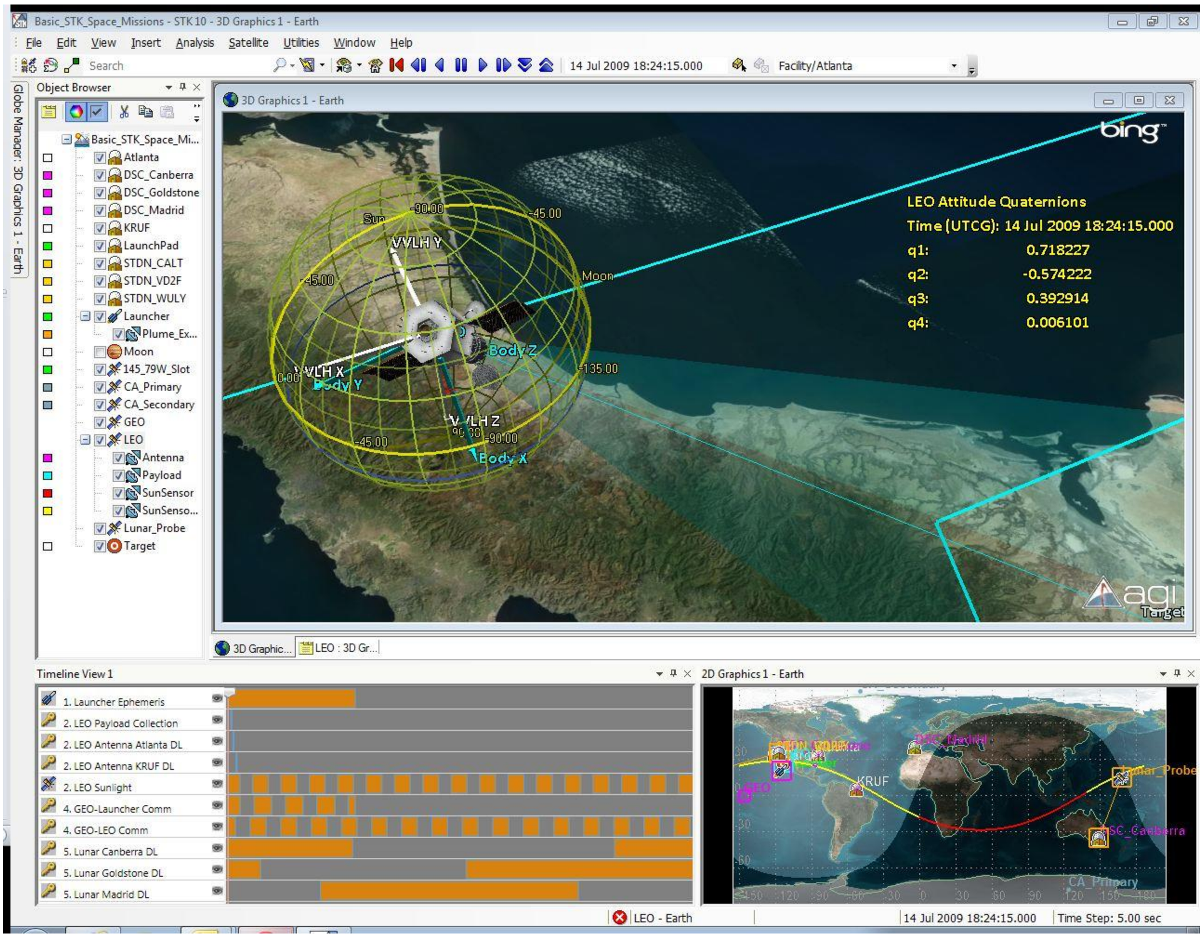



*Figure 4.2.2.1 - STK Modules*

## 4.2.3 Connect

Connect is a messaging format, which allows you to program actions to be performed, program applications and tools in the programming language and the chosen language of the developer. Applications have been developed in C, C ++, C #, Perl, Visual Basic, VBScript, Java, JavaScript and MATLAB.

# Part II – Design in Thales Alenia Space

# Chapter 5

# Estimate of Mass Budget

The mass budget is one of the most important data at the design stage. The mass parameter is constantly updated for any modification and is given by the sum of the individual systems that make up the entire S/C. The total mass estimate was made using the IDM-CIC software and strongly determined the subsystems themselves. The process is therefore iterative as a modification of the masses has repercussions on the individual components and in turn the individual components modify the mass budget. The constraints imposed obviously concern the maximum mass to be loaded on the Ariane 64 launcher, as per the relevant legislation. Among the consequences of a change in mass, one can recall the effect on the propulsive parameters: the higher the dry mass of the S/C, the greater the thrust the propeller has to supply and the greater will be the propellant on board; nonetheless, even the GNC system undergoes variations: a mass variation affects the inertial properties and therefore the attitude control (the inertia wheels, for example, must be sized accordingly). You can also remember the presence of variations in thermal properties, as heating / cooling a larger spacecraft will require more electrical power, and so on. Tied to the mass are certainly the dimensions of the various subsystems, and the structures will then rebuild everything. For these reasons the mass budget will be studied at the single component level, at the subsystem level and at global S/C level in the various mission phases. As can be seen from the introductory chapter on the ERO, the spacecraft is not a single indivisible object for the entire duration of the mission. It was decided to divide it into the main module and a propulsion module useful for the outbound phases and part of the Martian phases. this is due to the fact that it is convenient to get rid of empty tanks and useless weights. Sometimes, during the design phase, space vehicles should be built in a modular way in order to save weight. The fact of being able to get rid of the red planet of the drop stage, saves hundreds of kilograms of propellant for the return phase. the propulsive data have been confirmed by mission analysis, GNV and TAS-F and confirm the goodness of the decision to divide the entire composite. The final result of this work is not only a total estimate of the mass, but also the weight of the single component in the system and the percentage of mass of the single system in the overall S/C. It should be noted that this chapter refers exclusively to the ERO spacecraft in hybrid propulsion configuration, according to the mission schedule SC9 and BC14.

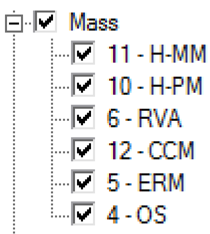



*Figure 5.1 - Mass Budget System Role*

# 5.1 Construction of blocks

The construction of the macroblocks is an iterative process as it follows the various configurations during the project phases and countless changes take place. In this IDM-CIC spreadsheet no information related to the shapes of the elements constituting the set will be added in what will be the object of the chapter related to the mass and inertial properties of the spacecraft. In this chapter, the spreadsheets relating to the configurations of the various internal reference systems, the MCI budget, the calculation of the propellant weights with both top down and bottom-up approaches are therefore ignored. It is useful to also ignore propulsive information, mission analysis, thermal analysis and thermal configurations as not directly related to the mass budget.

The first step is to insert system management data.

**System management**

| System properties | |
|---|---|
| Project name | Mars Sample Return - Earth Return Orbiter (MSR-ERO) - cfg. C, H2 |
| Version | 0,1 |
| Launcher name | Ariane 64 |
| Launcher capacity [Kg] | 0 |
| Launcher margin | 0.00% |
| Launch date | 2026 |
| Lifetime | 8 |
| Propellant margin | 0.00% |
| Adapter mass [Kg] | 110 |
| Perigee | 0 |
| Apogee | 0 |
| Inclination | 0 |
| Insertion | |
| Comment | |

*Figure 6.1.1 - System properties*

Subsequently it is necessary to worry about denouncing the elements constituting the composite. For this purpose the whole S/C is divided into physical macroblocks: Main Module, Propulsion Module, RVA, CCM, ERM, OS. In this way it is possible to foresee the existence of a specific internal system simply by constructing a table in which the desired rows are added according to the number of constituent elements.

**Elements**

| ✖ | ✖ | ✖ | ✖ | ✖ | ✖ |
|---|---|---|---|---|---|
| 11 | 10 | 6 | 12 | 5 | 4 |
| H-MM | H-PM | RVA | CCM | ERM | OS |

*Figure 5.1.2 – Element's division*

In the next subparagraph there is an overview of the table previously seen.

### 5.1.1 System Structure Division

Each element of the composite is in turn made up of the various internal on-board systems. Obviously some elements are decidedly more complex than others and this depends on the fungi performed: in short, each element will have its own subsystems and will never be all. The main module is the element with multiple internal systems: data management, regulation and distribution of energy, the interface with the payload are some of the examples of the functions it must perform. The propulsion module instead is a purely propulsive element and for example it is provided with a chemical engine (which is not true in MM). The other elements, on the other hand, are much simpler: the RVA has a GNC sub-system inside, whereas the rest has specific components for the given purpose.

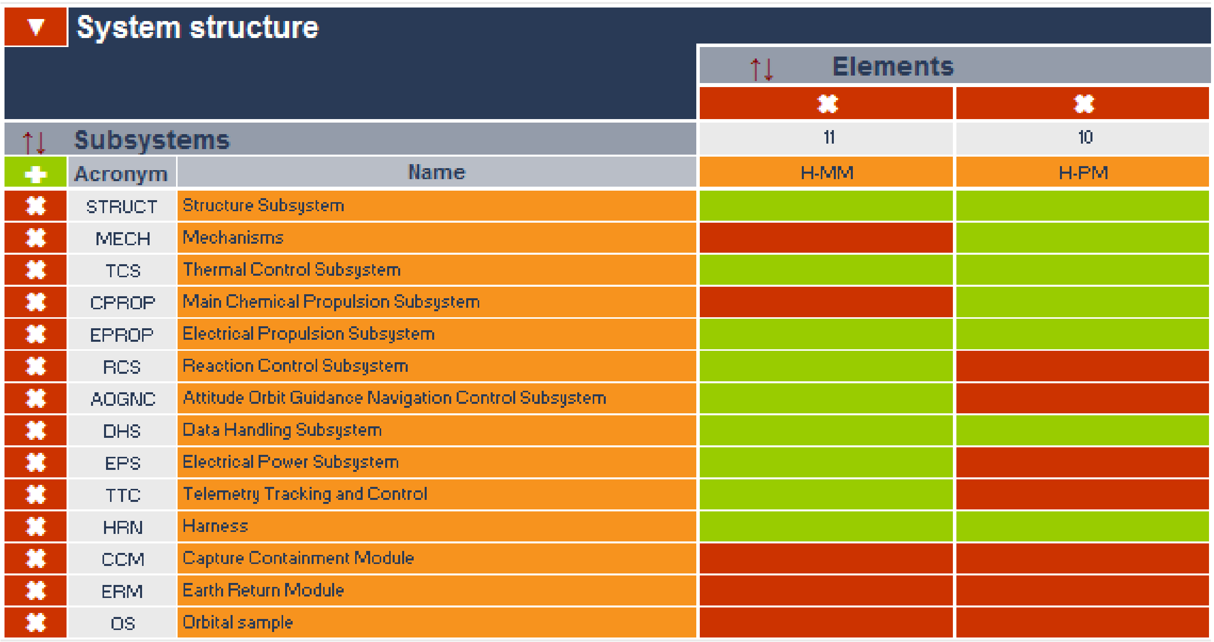



*Figure 5.1.1.1 - Elements of MM e PM*


*Figure 5.1.1.2 - Minor Elements Divison*

### 5.1.2 Different Configurations

Given the modularity of the spacecraft, the mass budget will be strongly affected. Although the calculation of the masses is referred to in this chapter exclusively to the dry mass, it is not constant throughout the entire mission. As already mentioned, various mission phases must be considered:

- Outbound phase configuration: the configuration is called “Hb-EP” and refers to the use of a hybrid propulsion of the Main Module and Propulsion Module, with the included ERM, RVA and CCM devices.
- Inbound phase configuration: it is called “HybRet” and it does not provide for CCM, RVA and PM previously dropped.
- Drop stage configuration: this configuration refers to everything that is unhooked near Mars and it is called “HybDrop”.

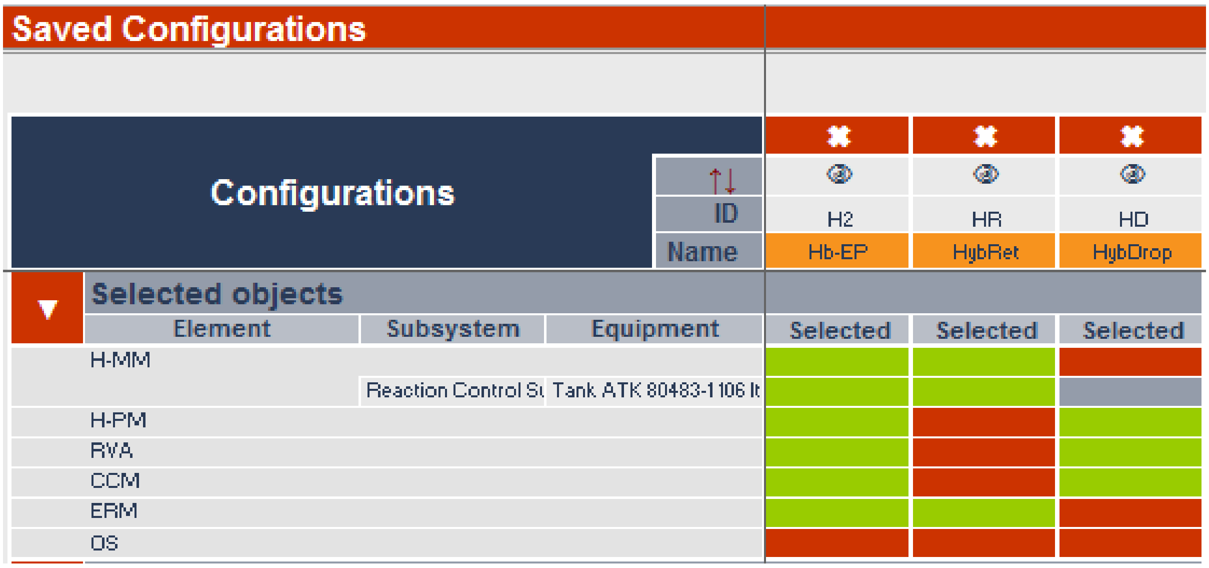



*Figure 5.1.2.1 - Different composite configurations*

The 3 configurations are the most limiting from the design point of view, but in the subsequent phases of the project the various mass budgets will have to be examined in greater depth.

From the previous figure there is the absence of the OS in the various mass calculations. In IDM-CIC it can be taken into account (only for the inbound phase) in the reference configuration in which there is a list of all the internal systems. In any case, the mass value of the OS has a small weight in the accounts and is constant as it does not depend on the various engineering parameters but is an assumption at the level of the mission requirement.

# 5.2 On board subsystems

The next step in the construction of the model is the creation of the various onboard subsystems constituting each macro block. As it can be seen in the System Structure Division sub-paragraph, each built subsystem is unique and refers exclusively to its own module. Each of them is therefore made up of the various internal equipment in which the names and values of masses and mass margins are listed at the level of a single element. It is anticipated that for reasons of privacy policy, most of the technical data is omitted.

## 5.2.1 Structure Subsystem

The structural subsystem has been modeled for the MM and PM.

**H-MM units**

Import

| ID | Name | Hidden | Type | Categories | Qty | Opt | Maturity level | Mass margin [%] |
|---|---|---|---|---|---|---|---|---|
| 1 | Tube assembly | No | Eq | None | 1 | No | To be developed (20%) | 20.00% |
| 2 | Platforms | No | Eq | None | 1 | No | To be developed (20%) | 20.00% |
| 4 | Equipment panel as | No | Eq | None | 1 | No | To be developed (20%) | 20.00% |
| 3 | Others | No | Eq | None | 1 | No | To be developed (20%) | 20.00% |
| 5 | Shear panel asseml | No | Eq | None | 1 | No | To be developed (20%) | 20.00% |

Go to top

**H-PM units**

Import

| ID | Name | Hidden | Type | Categories | Qty | Opt | Maturity level | Mass margin [%] |
|---|---|---|---|---|---|---|---|---|
| 1 | Cone Assembly | No | Eq | None | 1 | No | To be developed (20%) | 20.00% |
| 2 | Platforms | No | Eq | None | 1 | No | To be developed (20%) | 20.00% |
| 3 | Others | No | Eq | None | 1 | No | To be developed (20%) | 20.00% |
| 9 | Later Panels | No | Eq | None | 1 | No | To be developed (20%) | 20.00% |
| 10 | Shear Panel | No | Eq | None | 4 | No | To be developed (20%) | 20.00% |
| 11 | Central Tank Platfc | No | Eq | None | 1 | No | To be developed (20%) | 20.00% |

*Figure 5.2.1.1 - MM & PM Structure Subsystems*

## 5.2.2 Thermal Control Subsystem

The thermal control system is intended as a unit of active and passive elements: only the PM and the MM are provided.

**H-MM units**

| ID | Name | Hidden | Type | Categories | Qty | Opt | Maturity level |
|---|---|---|---|---|---|---|---|
| 1 | MLI | No | Eq | None | 1 | No | To be developed (20%) |
| 6 | Heaters, thermistor | No | Eq | None | 1 | No | To be developed (20%) |
| 2 | Propulsion Therma | No | Eq | None | | No | To be developed (20%) |
| 3 | Paint & Tape | No | Eq | None | | No | To be developed (20%) |
| 9 | Heat Pipes | No | Eq | None | 48 | No | To be developed (20%) |
| 4 | Doublers | No | Eq | None | | No | To be developed (20%) |
| 5 | Thermal Fillers & wa | No | Eq | None | | No | To be developed (20%) |
| 8 | Miscellaneous | No | Eq | None | | No | To be developed (20%) |
| 10 | Miscellanea | No | Ass | None | 1 | | |

Go to top

**H-PM units**

| ID | Name | Hidden | Type | Categories | Qty | Opt | Maturity level |
|---|---|---|---|---|---|---|---|
| 8 | MLI | No | Eq | None | 1 | No | To be developed (20%) |
| 2 | Propulsion Therma | No | Eq | None | 1 | No | To be developed (20%) |
| 3 | Heaters Thermistor | No | Eq | None | 1 | No | To be developed (20%) |
| 4 | Paint & Tape | No | Eq | None | 2 | No | To be developed (20%) |
| 5 | Heat Pipes | No | Eq | None | 60 | No | To be developed (20%) |
| 9 | Doublers | No | Eq | None | 1 | No | To be developed (20%) |
| 10 | Thermal Fillers & wa | No | Eq | None | 1 | No | To be developed (20%) |
| 11 | Miscellaneous | No | Eq | None | 1 | No | To be developed (20%) |

*Figure 5.2.2.1 - TCS Masses*

### 5.2.3 Electrical Propulsion Subsystem

The EP subsystem has been modeled for the MM and PM.

**H-MM units**

| ID | Name | Hidden | Type | Categories | Qty | Opt | Maturity level | Mass margin [%] | MCI data origin | Database Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| 3 | RIT-2X Assy | No | Th | None | 4 | No | To be modified (10%) | 10.00% | Manual | ArianeGroup |
| 23 | PPU RIT | No | Eq | None | 4 | No | To be modified (10%) | 10.00% | Manual | ArianeGroup |
| 26 | TOM | No | Eq | None | 4 | No | To be modified (10%) | 10.00% | Manual | RUAG |
| 6 | Xenon Tank | No | Tk | None | 2 | No | To be modified (10%) | 10.00% | Manual | ATK 133L Xe qualified for SBN |
| 14 | Pyrovalve | No | Eq | None | 2 | No | Fully developed (5%) | 5.00% | Manual | ArianeGroup |
| 16 | Pressure Regulator | No | Eq | None | 1 | No | To be developed (20%) | 20.00% | Manual | SMC |
| 18 | Service Valve | No | Eq | None | 3 | No | Fully developed (5%) | 5.00% | Manual | Moog UK |
| 9 | Latch Valve | No | Eq | None | 4 | No | Fully developed (5%) | 5.00% | Manual | VACCO |
| 8 | Filter | No | Eq | None | 1 | No | Fully developed (5%) | 5.00% | Manual | Sofrance |
| 7 | High Pressure Tras | No | Eq | None | 1 | No | Fully developed (5%) | 5.00% | Manual | ASL |
| 20 | Piping and bracket | No | Eq | None | 1 | No | To be developed (20%) | 20.00% | Manual | |
| 27 | EP harness | No | Eq | None | 1 | No | To be developed (20%) | 20.00% | Manual | As per ESA (TBC) |

Go to top

**H-PM units**

| ID | Name | Hidden | Type | Categories | Qty | Opt | Maturity level | Mass margin [%] | MCI data origin | Database Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| 28 | RIT-2X Assy | No | Th | None | 4 | No | To be modified (10%) | 10.00% | Manual | ArianeGroup |
| 29 | PPU RIT | No | Eq | None | 4 | No | To be modified (10%) | 10.00% | Manual | ArianeGroup |
| 27 | TOM | No | Eq | None | 4 | No | To be modified (10%) | 10.00% | Manual | RUAG |
| 6 | Xenon Tank | No | Tk | None | 4 | No | Fully developed (5%) | 5.00% | Manual | ATK 133L Xe qualified for SBN |
| 8 | Pyrovalve | No | Eq | None | 2 | No | Fully developed (5%) | 5.00% | Manual | ArianeGroup |
| 9 | Pressure Regulator | No | Eq | None | 1 | No | To be developed (20%) | 20.00% | Manual | SMC |
| 12 | Service Valve | No | Eq | None | 3 | No | Fully developed (5%) | 5.00% | Manual | Moog UK |
| 14 | Latch Valve | No | Eq | None | 4 | No | Fully developed (5%) | 5.00% | Manual | VACCO |
| 17 | Filter | No | Eq | None | 1 | No | Fully developed (5%) | 5.00% | Manual | Sofrance |
| 31 | Flow Control Valve | No | Eq | None | 4 | No | To be developed (20%) | 20.00% | Manual | Nammo/Vac co/Bradford |
| 18 | High Pressure Tras | No | Eq | None | 1 | No | Fully developed (5%) | 5.00% | Manual | ASL |
| 20 | Piping and bracket | No | Eq | None | 1 | No | To be developed (20%) | 20.00% | Manual | |

Subsystem STRUCT | Subsystem TCS | **Subsystem EPROP** | Subsystem RCS | Subsystem AO

*Figure 5.2.3.1 - E Propulson Subsystems*

## 5.2.4 Reaction Control Subsystem

This subsystem is modeled only in the MM.

**H-MM units**

| ID | Name | Hidden | Type | Categories | Qty | Opt | Maturity level | Mass margin [%] | MCI data origin | Database Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | N2H4 20N thruster | No | Th | None | 24 | No | Fully developed (5%) | 5.00% | Manual | ArianeGroup |
| 2 | Tank ATK 80483-11 | No | Tk | None | 2 | Yes | To be developed (20%) | 20.00% | Manual | Arianegroup BT 01-0 |
| 3 | Service Valve | No | Eq | None | 5 | No | Fully developed (5%) | 5.00% | Manual | |
| 4 | Latch Valve | No | Eq | None | 2 | No | Fully developed (5%) | 5.00% | Manual | |
| 5 | Filter | No | Eq | None | 1 | No | Fully developed (5%) | 5.00% | Manual | |
| 6 | Pressure Trasduce | No | Eq | None | 3 | No | Fully developed (5%) | 5.00% | Manual | |
| 7 | Piping and Bracket | No | Eq | None | 1 | No | To be developed (20%) | 20.00% | Manual | |

*Figure 5.2.4.1 - MM Reaction control Subsystem*

## 5.2.5 Data Handling system

The DHS has been modeled for the MM and PM.

**H-MM units**

| ID | Name | Hidden | Type | Categories | Qty | Opt | Maturity level | Mass margin [%] | MCI data origin |
|---|---|---|---|---|---|---|---|---|---|
| 1 | SMU | No | Eq | None | 1 | No | To be modified (10%) | 10.00% | Manual |
| 3 | Earth Avoid El. Unit | No | Eq | None | 1 | No | To be developed (20%) | 20.00% | Manual |

Go to top

**H-PM units**

| ID | Name | Hidden | Type | Categories | Qty | Opt | Maturity level | Mass margin [%] | MCI data origin |
|---|---|---|---|---|---|---|---|---|---|
| 1 | RTU/PDU | No | Eq | None | 1 | No | To be developed (20%) | 20.00% | Manual |

*Figure 5.2.5.1 - DHS*

### 5.2.6 Guidance Navigation and Control Subsystem

The GNC Subsystem  has been modeled for the MM and RVA.

**H-MM units**

Import

| ID | Name | Hidden | Type | Categories | Qty | Opt | Maturity level | Mass margin [%] | MCI data origin | Database Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| 2 | Star-Tracker OH | No | Eq | None | 4 | No | To be modified (10%) | 10.00% | Manual | Sodern Hydra |
| 6 | Star Tracker EU | No | Eq | None | 2 | No | Fully developed (5%) | 5.00% | Manual | Sodern Hydra |
| 3 | IMU - ICU | No | Eq | None | 1 | No | To be developed (20%) | 20.00% | Manual | IMU Astrix 120 - Inertial Core Unit |
| 7 | IMU - GEU | No | Eq | None | 1 | No | 15% | 15.00% | Manual | IMU Astrix 120 - Gyro Electrical |
| 4 | Sun Sensors | No | Eq | None | 6 | No | Fully developed (5%) | 5.00% | Manual | Moog Bradford |
| 5 | Reaction Wheels | No | Eq | None | 4 | No | To be modified (10%) | 10.00% | Manual | |

Go to top

**RVA units**

Import

| ID | Name | Hidden | Type | Categories | Qty | Opt | Maturity level | Mass margin [%] | MCI data origin | Database Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| 2 | Wide Angle Camera | No | Eq | None | 2 | No | To be developed (20%) | 20.00% | Manual | |
| 6 | Narrow Angle Cam | No | Eq | None | 2 | No | To be developed (20%) | 20.00% | Manual | |
| 7 | Sun Sensor | No | Eq | None | 2 | No | To be developed (20%) | 20.00% | Manual | additional margin for possible doppler |

*Figure 5.2.6.1 - GNC Subsystems*

### 5.2.7 Electric Power Subsystem

The EP Subsystem has been modeled only for the MM.

**H-MM units**

Import

| ID | Name | Hidden | Type | Categories | Qty | Opt | Maturity level | Mass margin [%] | MCI data origin | Database Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| 2 | PCDU | No | Eq | None | 1 | No | Fully developed (5%) | 5.00% | Manual | |
| 1 | Flexible Solar Array | No | Eq | None | 2 | No | Custom | 10.99% | Manual | 33kW @ 1AU |
| 3 | Battery | No | Eq | None | 1 | No | To be developed (20%) | 20.00% | Manual | |
| 4 | SADM+SADE | No | Eq | None | 2 | No | To be modified (10%) | 10.00% | Manual | one DOF |

*Figure 5.2.7.1 - EP Subsystem*

### 5.2.8 Telemetry Tracking and Control Subsystem

The TT&C Subsystem has been modeled only for the MM.

**H-MM units**

| ID | Name | Hidden | Type | Categories | Qty | Opt | Maturity level | Mass margin [%] | MCI data origin | Database Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| 11 | Transponder Mediu | No | Eq | None | 3 | No | To be modified (10%) | 10.00% | Manual | BEPI heritage |
| 2 | TWTA X-band | No | Eq | None | 2 | No | To be developed (20%) | 20.00% | Manual | SICRAL Heritage |
| 13 | TWTA Hi-band | No | Eq | None | 2 | No | Fully developed (5%) | 5.00% | Manual | |
| 1 | X-RFDN | No | Eq | None | 3 | No | Fully developed (5%) | 5.00% | Manual | |
| 3 | X-Waveguide Path | No | Eq | None | 1 | No | To be developed (20%) | 20.00% | Manual | |
| 4 | LGA + bracket | No | Eq | None | 2 | No | To be modified (10%) | 10.00% | Manual | exomars TGO |
| 19 | MGA + bracket | No | Eq | None | 1 | No | Fully developed (5%) | 5.00% | Manual | |
| 5 | 2.0 m HGA reflecto | No | Eq | None | 1 | No | Fully developed (5%) | 5.00% | Manual | |
| 6 | HGA RF parts | No | Eq | None | 1 | No | To be modified (10%) | 10.00% | Manual | exomars TGO |
| 7 | HGA Ant. Point. M | No | Eq | None | 1 | No | Fully developed (5%) | 5.00% | Manual | exomars TGO |
| 8 | HGA HDRM | No | Eq | None | 1 | No | To be modified (10%) | 10.00% | Manual | exomars TGO |
| 9 | HGA SC I/F parts | No | Eq | None | 1 | No | To be developed (20%) | 20.00% | Manual | |
| 15 | Low Gain-RFDN | No | Eq | None | 2 | No | To be modified (10%) | 10.00% | Manual | |
| 20 | External WG path tc | No | Eq | None | 1 | No | To be developed (20%) | 20.00% | Manual | |
| 18 | UHF Transceiver (E | No | Eq | None | 2 | No | 15% | 15.00% | Manual | ExoMars TGO Electra |
| 16 | UHF antenna | No | Eq | None | 2 | No | To be modified (10%) | 10.00% | Manual | |
| 17 | UHF Cables | No | Eq | None | 1 | No | Fully developed (5%) | 5.00% | Manual | |

*Figure 5.2.8.1 - TT&C Subsystem*

### 5.2.9 OS,CCM and ERM Modules

From a purely conceptual point of view The OS module and the RVA module are considered as one single element. The ERM, on the other hand, includes the EEV and other ERM units.

**ERM units**

| ID | Name | Hidden | Type | Categories | Qty | Opt | Maturity level | Mass margin [%] | MCI data origin |
|---|---|---|---|---|---|---|---|---|---|
| 1 | EEV without OS | No | Eq | None | 1 | No | 0% | 0.00% | Manual |
| 2 | Other ERM units | No | Eq | None | 1 | No | 0% | 0.00% | Manual |

*Figure 5.2.9.1 - Example of ERM unit*

### 5.2.10 Harness and Mechanism Subsystems

Harness was built only in PM, MM and RVA. The mechanisms subsystem is present only in the PM.

| H-PM units | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| ID | Name | Hidden | Type | Categories | Qty | Opt | Maturity level | Mass margin [%] | MCI data origin | Database Ref. |
| 1 | Clamp Band 1666V | No | Eq | None | 1 | No | Fully developed (5%) | 5.00% | Manual | SAAB, GAIA heritage |
| 2 | Clamp Band Retent | No | Eq | None | 1 | No | Fully developed (5%) | 5.00% | Manual | SAAB, GAIA heritage |
| 3 | Pyro Bolt Cutter | No | Eq | None | 2 | No | Fully developed (5%) | 5.00% | Manual | SAAB, GAIA heritage |
| 4 | Separation Springs | No | Eq | None | 1 | No | Fully developed (5%) | 5.00% | Manual | SAAB, GAIA heritage |

*Figure 5.2.10.1 - Mechanism Subsystem*

### 5.2.11 Main Chemical Propulsion Subsystem

The Chemical Propulsion is located only in the PM.

| H-PM units | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| ID | Name | Hidden | Type | Categories | Qty | Opt | Maturity level | Mass margin [%] | MCI data origin | Database Ref. |
| 1 | 1300N thruster | No | Th | None | 1 | No | Fully developed (5%) | 5.00% | Manual | LEROS 1c |
| 4 | N2H4 tank | No | Tk | None | 5 | No | Fully developed (5%) | 5.00% | Manual | ATK 80350 |
| 19 | MON tank | No | Tk | None | 1 | No | Fully developed (5%) | 5.00% | Manual | OST 26/x |
| 21 | Pressurant Tank P | No | Tk | None | 3 | No | To be modified (10%) | 10.00% | Manual | PVG family (67 lt) |
| 22 | Pyrovalve A | No | Eq | None | 6 | No | Fully developed (5%) | 5.00% | Manual | ArianeGroup |
| 18 | Pressure Regulato | No | Eq | None | 3 | No | Fully developed (5%) | 5.00% | Manual | SMC |
| 15 | Check Valve | No | Eq | None | 3 | No | Fully developed (5%) | 5.00% | Manual | Moog UK |
| 13 | Service Valve | No | Eq | None | 11 | No | To be developed (20%) | 20.00% | Manual | Moog UK |
| 11 | Filter | No | Eq | None | 3 | No | Fully developed (5%) | 5.00% | Manual | VACCO |
| 10 | Pressure Transduc | No | Eq | None | 6 | No | To be modified (10%) | 10.00% | Manual | Bradford |
| 8 | Piping and Bracket | No | Eq | None | 2 | No | To be developed (20%) | 20.00% | Manual | |
| 24 | Pressurant (He) | No | Eq | None | 1 | No | Fully developed (5%) | 5.00% | Manual | He |
| 25 | Checker Regulator | No | Eq | None | 1 | No | To be developed (20%) | 20.00% | Manual | |
| 26 | Pyrovalve B | No | Eq | None | 2 | No | Fully developed (5%) | 5.00% | Manual | |
| 27 | No.return pressure | No | Eq | None | 1 | No | To be modified (10%) | 10.00% | Manual | |

*Figure 5.2.11.1 - Main CP Subsystem*

# 5.3 Mass budget Analysis and results

The mass budget consists of the sum of the masses of the various systems in the various mission configurations, inserting appropriate margins for any changes in the design phase and inaccuracies. In this phase the data are summarized for a formal check in order to check again what was done previously.

## 5.3.1 Maturity Margins and System Margins

To set the mass budget analysis it is necessary to define the margins to be inserted on the values to be calculated.

At the individual component level, a mass margin is defined due to the maturity level of the individual component and it depends on the TRL of the object. For this reason this type of margin applies only at a low level and is different between one object and another. The margin varies on average between 0% if the value is univocally defined, and 20% if the item is in prototype phase.

| Maturity level | Mass margin [%] | MCI data origin | Database Ref. | Mass [kg] | Mass incl margin [kg] |
|---|---|---|---|---|---|
| To be modified (10%) | 10.00% | Manual | | 18 | 19.8 |
| To be developed (20%) | 20.00% | Manual | | 3.3 | 3.96 |
| | | | | | |
| | | | | 21.3 | 23.76 |

*Figure 5.3.1.1 - Example of mass margin*

Subsequently at system level the sum of the masses is made (including the margins previously described). To this is added a mass margin defined at system level as a percentage of the total. The value of the system margin depends on the progress of the project and varies between 20% and 30%.

| Target wet mass [Kg] : | | | 12 | | Without margin [Kg] | Margin [%] | Margin [Kg] | Including margin [Kg] | % of total |
|---|---|---|---|---|---|---|---|---|---|
| Unit | | | Forced values | | | | | | |
| Quantity | Mass [Kg] | Margin [%] | Mass [Kg] | Margin [%] | | | | | |
| | | | | | 12.00 | 0.00% | 0.00 | 12.00 | 0.42% |
| 1 | 12.00 | 0.00% | | | 12.00 | 0.00% | 0.00 | 12.00 | |
| | | | | | 12.00 | 0.00% | 0.00 | 12.00 | |
| | | | | | | 30.00% | 3.60 | 15.60 | |
| | | | | | | | | 15.60 | |

*Figure 5.3.1.2 - Example of system margin*

## 5.3.2 Mass budget results

The final result is the sum of the various masses of the subsystems including the system margins, for each planned configuration. At the end of this work, compliance with the launch requirements as maximum mass has been demonstrated and a slight reduction in masses is expected, reducing margins as the project phase progresses.

| Configuration : | Reference |
|---|---|

| H-MM | Target wet mass [Kg] : 0 | Without margin [Kg] | Margin [%] | Margin [Kg] | Including margin [Kg] | % of total |
|---|---|---|---|---|---|---|
| Total dry mass without system margin | | 1218.94 | 13.00% | 158.42 | 1377.36 | |
| System margin | | | 30.00% | 413.21 | 1790.57 | |
| Propellant mass | | 0.00 | 0.00% | 0.00 | 0.00 | |
| Total wet mass including all margins | | | | | 1790.57 | |

| H-PM | | | | Target wet mass [Kg] : | 0 | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Subsystem | Unit | | | | Forced values | | Without margin [Kg] | Margin [%] | Margin [Kg] | Including margin [Kg] | % of total |
| | Name | Quantity | Mass [Kg] | Margin [%] | Mass [Kg] | Margin [%] | | | | | |
| Structure Subsystem | | | | | | | 247.65 | 20.00% | 49.53 | 297.18 | 10.45% |
| Mechanisms | | | | | | | 15.10 | 5.00% | 0.76 | 15.86 | 0.56% |
| | Clamp Band 1666V | 1 | 8.20 | 5.00% | | | 8.20 | 5.00% | 0.41 | 8.61 | |
| | Clamp Band Retention set 16 | 1 | 2.70 | 5.00% | | | 2.70 | 5.00% | 0.14 | 2.84 | |
| | Pyro Bolt Cutter | 2 | 0.60 | 5.00% | | | 1.20 | 5.00% | 0.06 | 1.26 | |
| | Separation Springs Assembly | 1 | 3.00 | 5.00% | | | 3.00 | 5.00% | 0.15 | 3.15 | |
| Thermal Control Subsystem | | | | | | | 67.41 | 20.00% | 13.48 | 80.89 | 2.84% |
| Main Chemical Propulsion Subsystem | | | | | | | 164.86 | 5.66% | 9.32 | 174.18 | 6.12% |
| Electrical Propulsion Subsystem | | | | | | | 290.00 | 9.71% | 28.16 | 318.15 | 11.18% |
| Data Handling Subsystem | | | | | | | 4.00 | 20.00% | 0.80 | 4.80 | 0.17% |
| Harness | | | | | | | 28.65 | 20.00% | 5.73 | 34.37 | 1.21% |
| Total dry mass without system margin | | | | | | | 817.66 | 13.18% | 107.78 | 925.44 | |
| System margin | | | | | | | | 10.00% | 92.54 | 1017.98 | |
| Propellant mass | | | | | | | 0.00 | 0.00% | 0.00 | 0.00 | |
| Total wet mass including all margins | | | | | | | | | | 1017.98 | |

| RVA | Target wet mass [Kg] : 0 | Without margin [Kg] | Margin [%] | Margin [Kg] | Including margin [Kg] | % of total |
|---|---|---|---|---|---|---|
| Total dry mass without system margin | | 25.76 | 17.86% | 4.60 | 30.36 | |
| System margin | | | 20.00% | 6.07 | 36.43 | |
| Total wet mass including all margins | | | | | 36.43 | |

| CCM | Target wet mass [Kg] : 0 | Without margin [Kg] | Margin [%] | Margin [Kg] | Including margin [Kg] | % of total |
|---|---|---|---|---|---|---|
| Total dry mass without system margin | | 212.00 | 0.00% | 0.00 | 212.00 | |
| System margin | | | 0.00% | 0.00 | 212.00 | |
| Total wet mass including all margins | | | | | 212.00 | |

| ERM | Target wet mass [Kg] : 0 | Without margin [Kg] | Margin [%] | Margin [Kg] | Including margin [Kg] | % of total |
|---|---|---|---|---|---|---|
| Total dry mass without system margin | | 288.00 | 0.00% | 0.00 | 288.00 | |
| System margin | | | 20.00% | 57.60 | 345.60 | |
| Total wet mass including all margins | | | | | 345.60 | |

| OS | Target wet mass [Kg] : 12 | Without margin [Kg] | Margin [%] | Margin [Kg] | Including margin [Kg] | % of total |
|---|---|---|---|---|---|---|
| Total dry mass without system margin | | 12.00 | 0.00% | 0.00 | 12.00 | |
| System margin | | | 30.00% | 3.60 | 15.60 | |
| Total wet mass including all margins | | | | | 15.60 | |

| System | Without margin [Kg] | | Margin [Kg] | Including margin [Kg] | |
|---|---|---|---|---|---|
| Total dry mass without system margins | 2574.36 | | 270.80 | 2845.16 | |
| Total dry mass including system margins | | | | 3418.18 | |
| Total propellant mass | 0.00 | | 0.00 | 0.00 | |
| Total wet mass including all margins | | | | 3418.18 | |

*Figure 5.3.2.1 - Mass Budget results*

It should be noted that the IDM-CIC model developed is also useful for carrying out subsequent analyses as will be seen, for example, in the chapter concerning the power budget.

## 5.4 Mass Budget Updates

The PRR has been a watershed in design choices. In agreement with the ESA, some configurational changes were made to be made to the ERO which caused a modification of all the design parameters, including the Mass Budget.

### 5.4.1 Configuration Updates

The new post-PRR configuration consists of a PM smaller than the previous configuration, able to allocate only the chemical propulsion and a larger MM with purely electric propulsion. In essence, the electric propulsion previously present in the PM is translated all in the MM, so that the lines of the propulsion system have less design constraints and that the design complication is reduced.

### 5.4.2 Systems Updates

The new configuration includes various changes in the internal subsystems:

- MM Electric Propulsion System: allocation of all Xenon tanks in the MM with consequent increase in weights and overall dimensions.
- MM Structures and Thermal Control System: increase in weight and size due to the need to allocate a heavier and bulky electric propulsion system.
- PM Full Chemical Propulsion System: removal of electric propulsion with consequent reduction of masses and volumes.
- PM Structures and Thermal Control System: reduction of the masses.
- Propellant masses: increase in total masses because the propulsive efficiency due to the new configuration has decreased.

### 5.4.3 Mass Budget Results Updates

The new configuration has a lower dry mass, because control and control valves for electric propulsion in the PM and for cutting mechanisms of the propellant lines are no longer required. The new configuration presents different tanks allocated in a more congenial way in the new spaces. In general, the dry mass has decreased by about 100 kilos but the propellant mass has increased by 200. In total, the mass budget has a higher mass of 100 kilos but has less constructive complexity and greater reliability.

# Chapter 6

# First Preliminary Estimate of MCI budget

The estimate of the inertial properties of the spacecraft is a problem of fundamental importance in engineering design. In spatial products, these details are necessary to obtain information relative to the angular positioning of a probe or satellite with a reference such as, for example, the Sun. Knowing the inertial properties is fundamental for the attitude control of the S/C and therefore to maintain a correct alignment between the antennas of the spacecraft and those on the Earth, as well as between the solar panels and the Sun: the MCI budget is therefore fundamental for the development of the space mission and has strong implications in the development and sizing of internal sub-systems. Information concerning the MCI show problems to solve and opportunities to be seized. Having a clear idea of the inertial parameters involved saves time and costs for the entire life cycle of the product, as well as to meet the obvious energy, communication, navigation and thermal motivations.

The purpose of this preliminary analysis is to have a general idea about mass and inertial properties: in the worst conditions of maximum weight with the margins of masses and very high powers. The system is built with numerous and important simplifying hypotheses: this allows a rough estimate of the order of magnitude of the quantities involved in a couple of days of work. This strategy is useful in the initial phases of the project, because a detailed analysis would require a lot of calculation time and the results would no longer be correct when changes are made during the design phase.

The IDM-CIC software is used as it allows quick analysis and general considerations related to various engineering disciplines. The geometries are inspired by the CAD drawings developed by the Catia Composer software, while the mass data, configurations, propulsive and propellant quantitative parameters derive from company databases.

The aim is to have an initial reference and then to improve it with the progress of the project phases: as the design phases progress, the level of detail will always be greater. Since an estimate of MCI has never been made before, it is obvious that it mainly affects the order of magnitude of the parameters at stake. The same file will be resumed later to increase the level of detail and possibly update it with the subsequent changes in the design phase. the whole understood will therefore refer exclusively to the first version of the ERO.

The results will depend on the chosen reference system so in this regard, the ECSS normative standards are read for the final choice.

The entire chapter is addressed to the BC14 hybrid propulsion architecture with launch in October 2026.

# 6.1 Construction of macroblocks

The spacecraft is built in simplified macroblocks. The fundamental hypothesis assumed is that each of them consists of extrusion and union of simple figures such as cones, parallelepipeds, spheres and cylinders. The masses include not only the structures but also all the internal subsystems. This means that mass density is considered homogeneous and this is not true. Each object has its own local geometric reference system. The origin is then modified according to reasons of simplicity. To exploit the symmetries, the origins are inserted in the symmetry centers.


*Figure 6.1.1 - Construction of blocks*

### *6.1.1 Main module*

The main module is built as a parallelepiped with a cylindrical cavity: the presence of the antenna and the thrusters is ignored. It is hypothesized for simplicity that the axis of the cylindrical cavity coincides with the axis of symmetry of the parallelepiped, but it is necessary to remember that the MM's parallelepiped is not square based.

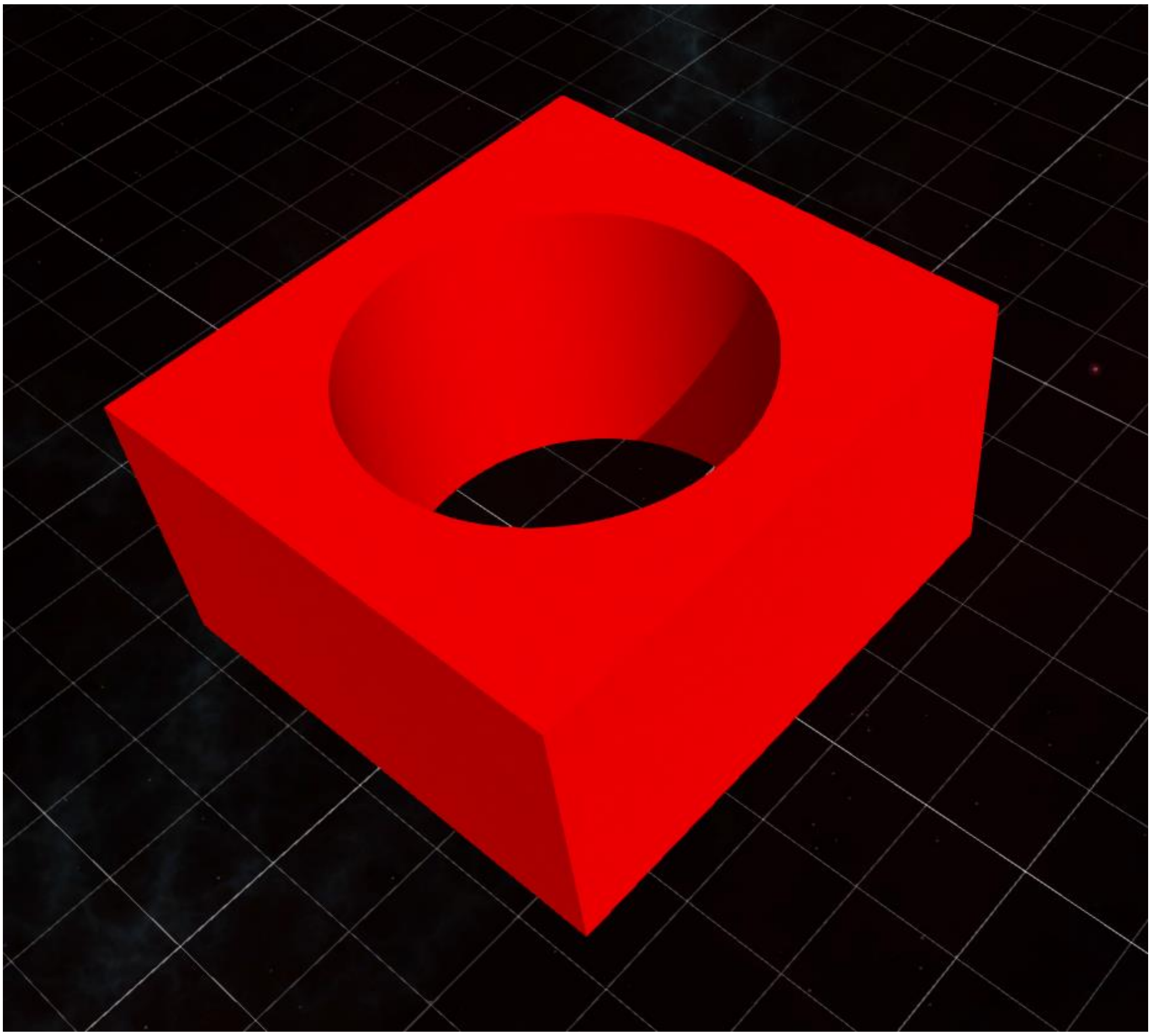


*Figure 6.1.1.1 MM block*

The cavity will receive the payload, but the parallelepiped structure has the dimensions sufficient to house the propellant tanks inside it.

An important simplification concerns the lack of modelling of the main antenna of the orbiter: its mass is considered in the Main Module as uniformly distributed.

For these reasons, the centre of gravity divides the dimensions in half: as it was conceived, the MM module is geometrically symmetrical with its centre of gravity.

### *6.1.2 Solar Array*

The solar arrays were built exclusively in the deployed configuration. They are simply represented by two parallelepipeds, having a thickness of orders of magnitude lower than the other two dimensions.

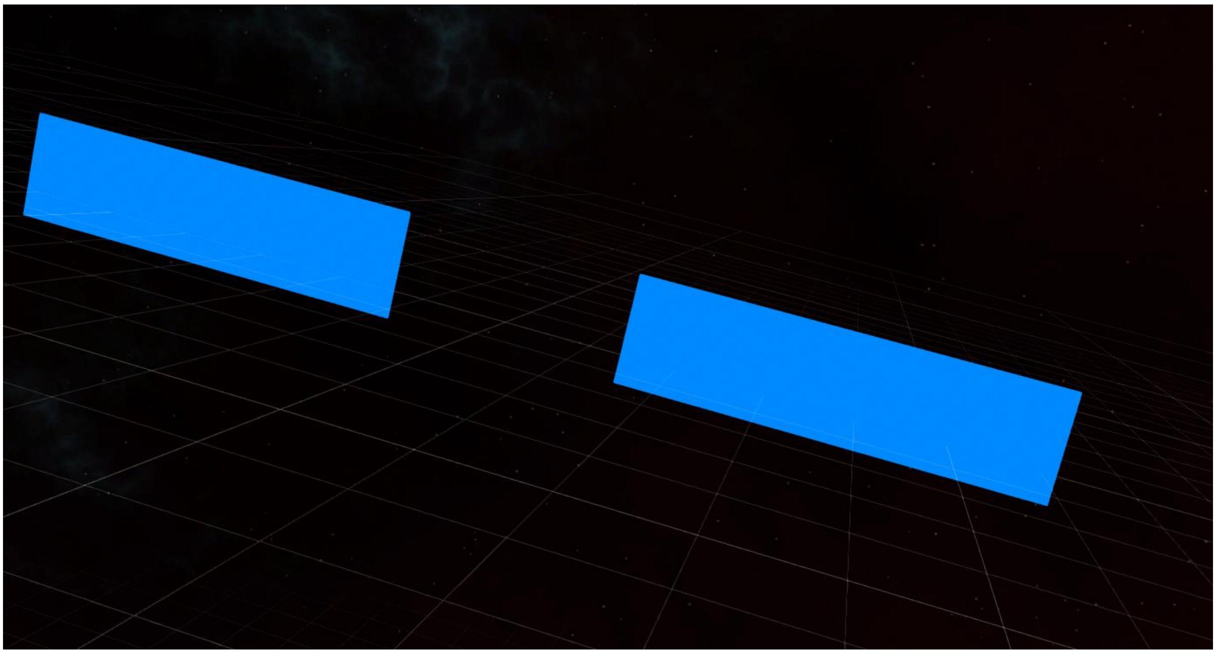


*Figure 6.1.2.1 - Solar Array block*

As can be seen, they are at equal distance from their axis of symmetry.

Once you have drawn the solar arrays, there are articulation properties added, to allow the rotation of the Solar Arrays on the longitudinal symmetry axis. As is known, the solar panels rotate to have the best alignment with the sun's rays, so the center of gravity and moments of inertia of the whole system vary accordingly: the MCI analysis must be allowed according to various angles of rotation.

After defining the solar arrays as assembly elements and not equipment elements, the assembly properties are added, that is, the rotating reference system with the origin at the centreline.

| Articulations values | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| ID | Name | Type | Axis | Min. | Max. | Value | Value | Value | Value |
| ▼ MM | | | | | | | | | |
| ▼ Structure and units | | | | | | | | | |
| ▼ SA Wings (1) | | | | | | | | | |
| 2 | SADM axis | Rotation | Y | 0 | 360 | 0 | 0 | 0 | 0 |
| ▼ SA (1) | | | | | | | | | |
| 1 | SA rotation rs 0 | Rotation | Y | 0 | 360 | 0 | 0 | 0 | 0 |

*Figure 6.1.2.2 - Articulation values for MCI*

In all six configurations, the panels can rotate in continuous and non-discrete intervals, according to the whole lap angle.

### *6.1.3 Propulsion Module*

The Propulsion Module is built as union of a parallelepiped with a square base and a hollow cone of constant thickness, that has a height greater than that of the parallelepiped: it comes out from both the lower platform of the parallelepiped and the upper one.

| Unit content | | | | Shapes definition | | | | | | | | | | | | | | Positions | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Id | Name | Hidden | Layers | Color | Texture | Opacity | Type | Topology | 3D | Help | d1 [mm] | d2 [mm] | d3 [mm] | d4 [mm] | End type | A1 [°] | A2 [°] | X [mm] | Y [mm] | Z [mm] | Rot. order | R1 [°] | R2 [°] | R3 [°] |
| Import data | | | | | | 99 | | | | | | | | | | | | | | | | | | |
| Shapes | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | Topology 1 | No | Default | | | | S | | Topo | | | | | | | | | 0 | 0 | 0 | Rxyz | 0 | 0 | 0 |
| | | | | | | | | I | Para | | 2940 | 2940 | 1802 | | | | | -1470 | -1470 | 438 | Rxyz | 0 | 0 | 0 |
| | | | | | | | | I ∪ | HTC | | 590 | 950 | 2378 | 29,5 | Disc | 360 | | 0 | 0 | 0 | Rxyz | 0 | 0 | 180 |
| | | | | | | | | I - | TC | | 560,5 | 920,5 | 2378 | | Disc | 360 | | 0 | 0 | 0 | Rxyz | 0 | 0 | 0 |

*Figure 6.1.3.1 - PM Structure definition*

The object is symmetrical only in plan: so the centre of gravity lies on the intersection of the diagonals of the square.

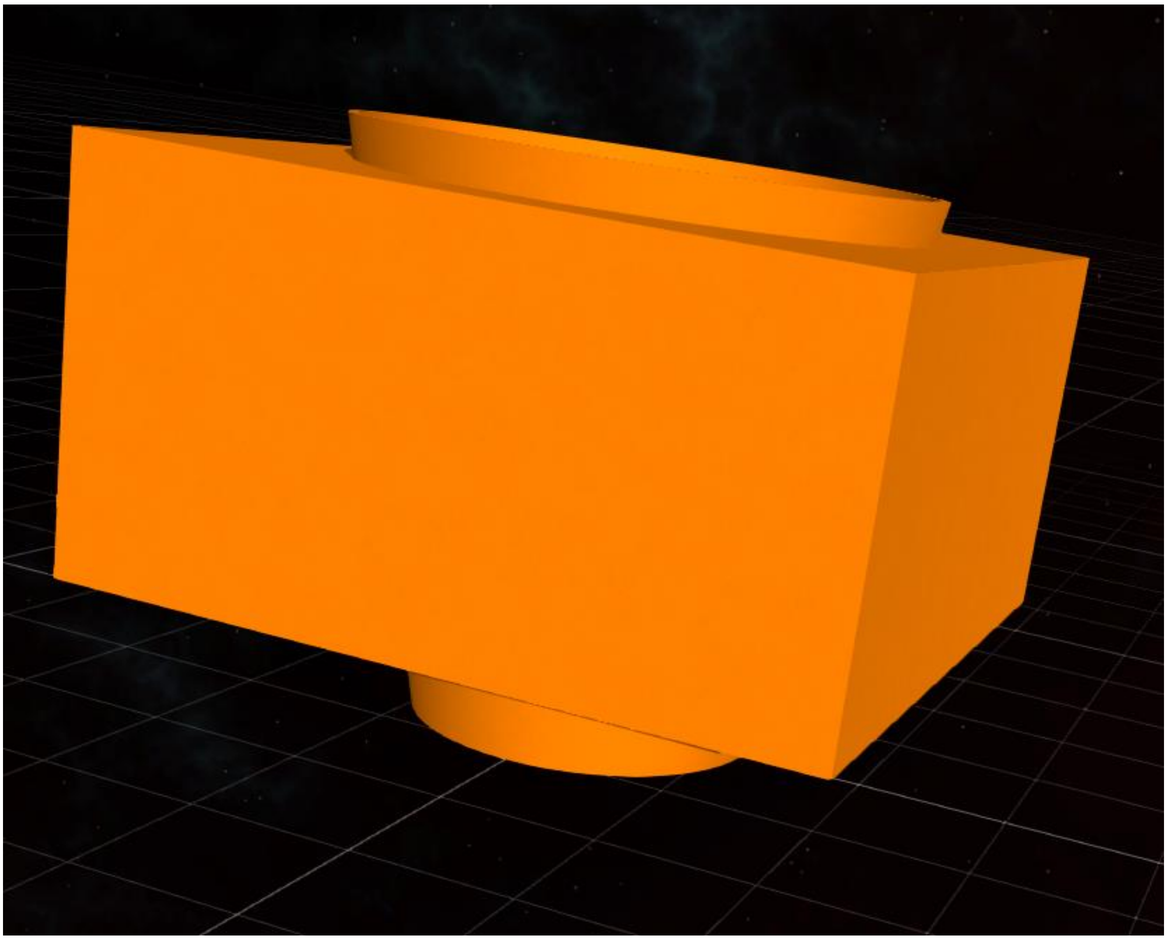


*Figure 6.1.3.2 PM block*

### *6.1.4 CCM + RVA, ERM and OS*

Everything related to the payload is enclosed in the following figure, where:

- CCM + RVA is represented by the turquoise cylinder.
- ERM consists of the most stocky cylinder, and represents the union of EEV and the external structural part of the ERM, which are geometrically indistinguishable with the ERM. In fact, what changes between these objects is mass, which for ERM consists of the sum of EEV and ERM structural unit.
- OS is a sphere contained in the EEV.

In this case, some conical truncated cone objects were approximated to an equivalent cylinder, having a diameter equal to that relative to the major base of the truncated cone.

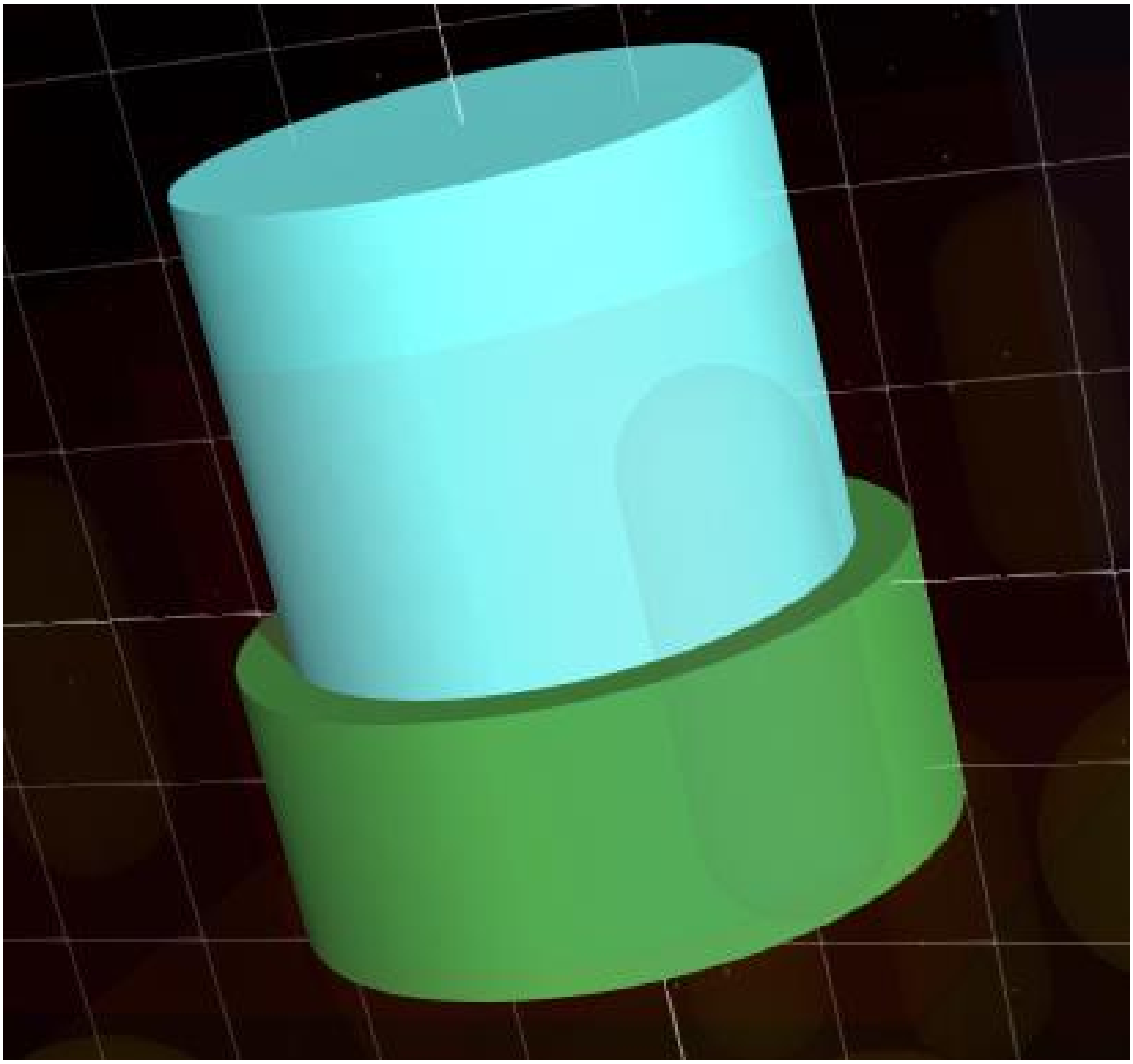


*Figure 6.1.4.1 - Payload module*

Since detailed information are not available for positioning the OS and EEV, it was decided to position them with reasonable local z-axis values. Also in this case, the objects are symmetrical respect to the central axis of the cylinders with homogeneous mass density.

## 6.1.5 Tanks

In the system structure, the tank subsystem is only present in the PM and in the MM. This is because is necessary that the relative mass of propellant not to be separated from the structures that house it. In IDM-CIC, the shape of a tank consists of two identical hemispheres divided by a cylinder of the same radius. In the Main Module, two tanks of Xenon and two tanks of hydrazine have been dimensioned, while in the Propulsion Module there are four Xenon tanks (identical to the previous ones) and five chemical bipropellant spherical tanks: the cylinder height of the tank figure is zero. Four tanks out of five are equal and the last one is larger than all. In reality some real PM's tanks are closer to an ellipsoid rather than a sphere, so the chosen diameter is a weighted average of the semi-major and semi-minor axis. Unlike the previous elements, in this case it is necessary to add information related to the tank capacities and fillings.

**MM units**

| ID | Name | Hidden | Type | Categories | Qty | Opt | Tank: Capacity [Kg] | Tank: Max filling [%] | Maturity level | Mass margin [%] | MCI data origin |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Xe tanks | No | Tk | None | 2 | No | 212 | 100,00% | 0% | 0,00% | Geometry |
| 2 | RCS N2H4 tanks | No | Tk | None | 2 | No | 82,5 | 100,00% | 0% | 0,00% | Geometry |

Go to top

**PM units**

| ID | Name | Hidden | Type | Categories | Qty | Opt | Tank: Capacity [Kg] | Tank: Max filling [%] | Maturity level | Mass margin [%] | MCI data origin |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Xe Tanks | No | Tk | None | 4 | No | 182,75 | 100,00% | 0% | 0,00% | Geometry |
| 2 | Biprop N2H4 tank | No | Tk | None | 4 | No | 125,25 | 100,00% | 0% | 0,00% | Geometry |
| 3 | Biprop MON tank | No | Tk | None | 1 | No | 589 | 100,00% | 0% | 0,00% | Geometry |

*Figure 6.1.5.1 - IDM-CIC units*

In this case the choice of tank thicknesses was derived from the company know-how, as the internal pressure is not yet known. For the sake of simplicity, the plant positioning of all the tanks has been made symmetrically. To all this must be added the difficulty of modelling the position of the centre of gravity of the propellant for tanks not full.

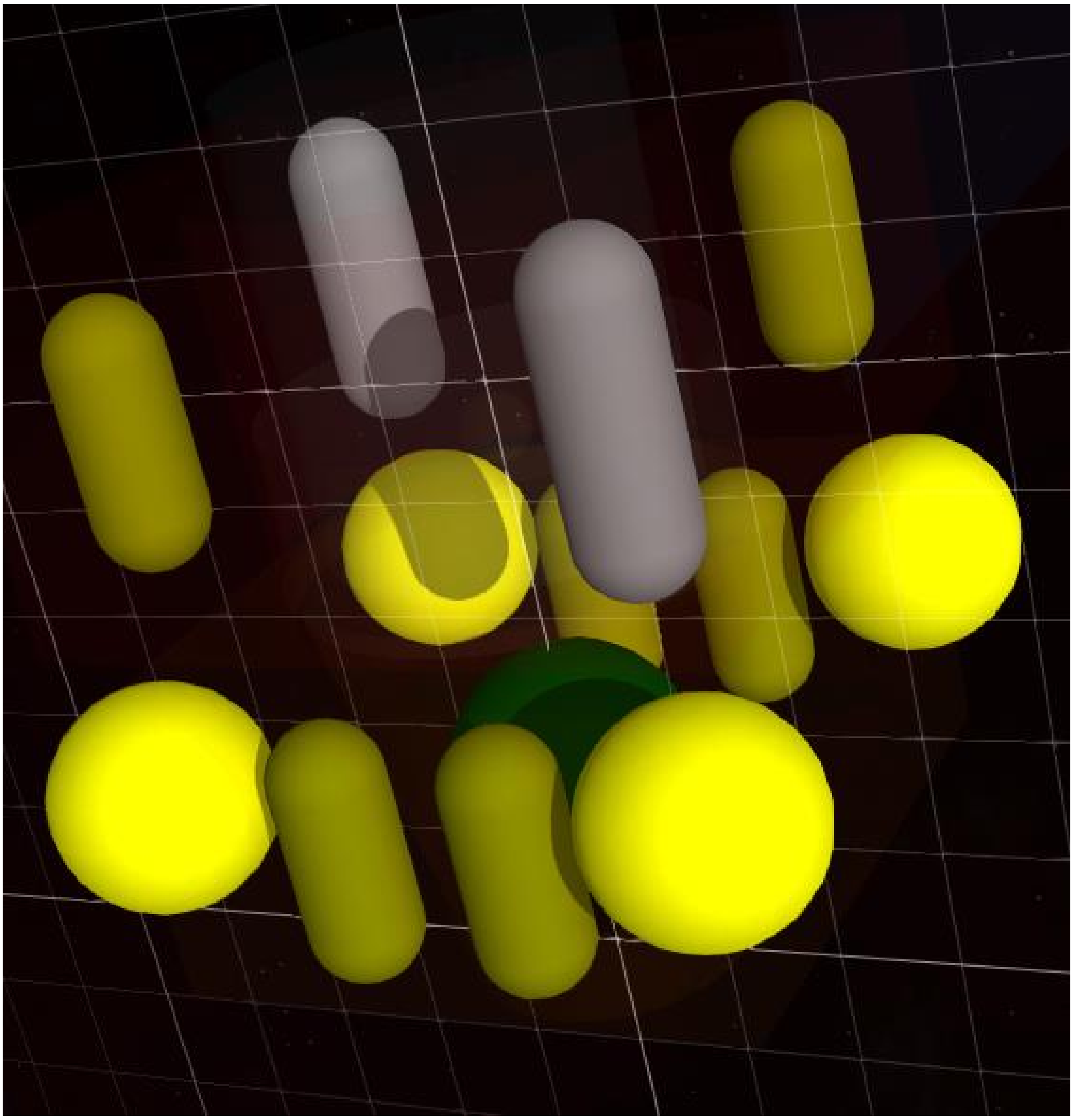


*Figure 6.1.5.2 - Tank modules*

The position along the thrust axis (x axis of the whole system) of the tanks and therefore of the propellant is approximate, very close to the centre line of the structural side panels. In this case the symmetry is only in plan because the tanks do not occupy perfectly symmetrical positions respect to the global centre of gravity of all thirteen. It is opportune to remember that the bipropellent tanks, not being in the reality of a perfectly spherical shape, assume very rough position values along the X axis of the whole system.

It is mandatory to remember, when modelling a tank, whatever the shape, one must choose a geometric modelling as a "tank" otherwise it will present computational problems of insertion of the propellant. Construction of tanks with objects of an unconventional shape must always take place starting from the form of a candy.

# 6.2 Choice of Reference Systems

The reference frame system is defined by ECSS. All reference frames are linked each other by rotations and translations. In this work we have considered only geometric reference systems related to blocks created. Therefore, no reference is made to reference systems that could be used in the GNC, for example.

**Coordinate system definitions**

| + - | ID | Name | Hidden | Parent | Position in parent coordinate system | | | | | | | Articulation | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | x [mm] | y [mm] | z [mm] | Rot. order | R1 [°] | R2 [°] | R3 [°] | Type | Axis | Min. | Max | Value | Auto |
| ▼ | ↑↓ MM | | | | | | | | | | | | | | | | |
| + | 1 | MM | No | PM | 0 | 0 | 1938 | Rxyz | 0 | 0 | 0 | N | | | | | |
| ▼ | ↑↓ PM | | | | | | | | | | | | | | | | |
| + | 1 | PM | No | System | 0 | 0 | 0 | Rxyz | 0 | 90 | -90 | N | | | | | |
| ▼ | ↑↓ CCM+RVA | | | | | | | | | | | | | | | | |
| + | 1 | CCM+RVA | No | MM | 0 | 0 | 0 | Rxyz | 0 | 0 | 0 | N | | | | | |
| ▼ | ↑↓ OS | | | | | | | | | | | | | | | | |
| + | 1 | OS | No | MM | 0 | 0 | 0 | Rxyz | 0 | 0 | 0 | N | | | | | |
| ▼ | ↑↓ ERM | | | | | | | | | | | | | | | | |
| + | 1 | ERM | No | MM | 0 | 0 | 0 | Rxyz | 0 | 0 | 0 | N | | | | | |

*Figure 6.2.1 - Coordinate System Definitons*

## 6.2.1 S/C Reference Frame – MRS-O

This reference system is the most important of the whole chapter: it is imposed by the ECSS legislation and is the reference for the generation of the MCI budget. Any work related to the inertial properties of the S / C, to be shared both internally in the company and externally with the ESA, NASA, partners and external supplier, or other collaborating companies, will be referred to this reference system.
The European Cooperation for Space Standardization (ECSS) defines active Engineering Standards: in the ECSS Coordinate system definition, is stated that the choice of the reference systems used is not arbitrary. The reference system used for the delivery of the results is the one related to the launch phase.

At launch configuration the S/C is so structured (see figure 6.2.1.2)

- MM, with solar panel stowed (not visible) and tanks inside.
- PM with tanks inside.
- CCM+RVA.
- ERM.

The MRS-O S/C Reference Frame is a right-handed, orthogonal coordinate system used for geometrical configuration, design drawings and dimensions and defined as follows:

OSC origin is located on the Spacecraft Composite / Launcher separation plane at the centre of the Spacecraft interface ring;

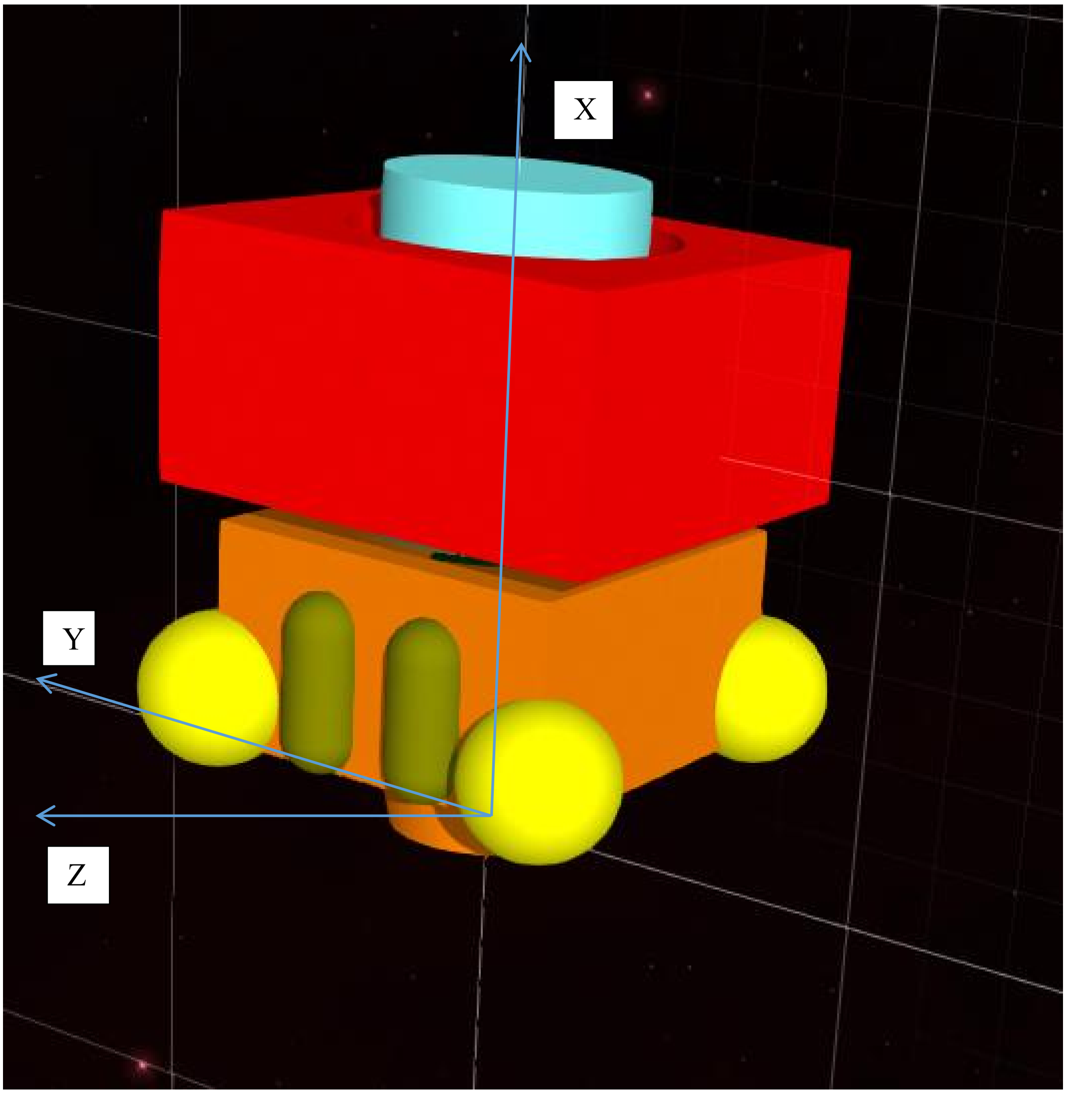



*Figure 6.2.1.2 - S/C launch configuration*

- $X_{SC}$ axis orthogonal to the Spacecraft Composite / Launcher separation plane, pointing positively from the separation plane towards the CCM;
- $Y_{SC}$ axis emanates from the origin and is nominally orthogonal to the Solar Array plane in deployed configuration. The Y direction will point from the RF origin to the lateral antenna.
- $Z_{SC}$ axis is defined using the +X and +Y axes using the right hand rule.

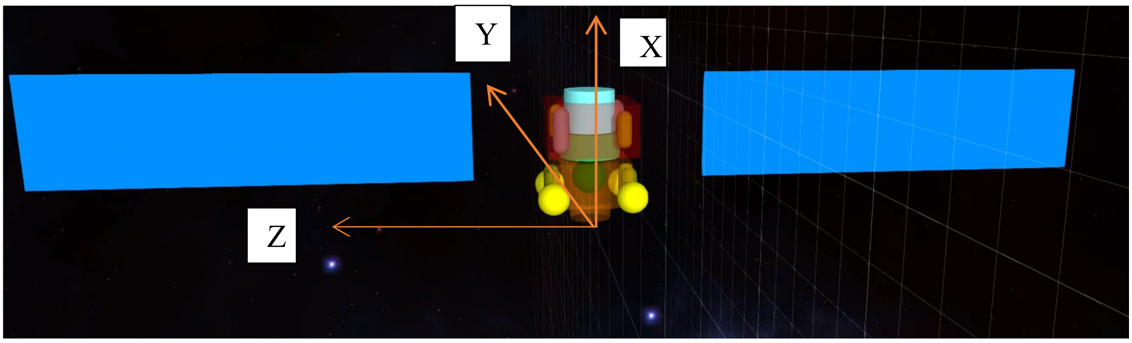



*Figure 6.7.1.2 S/C Reference Frame*

## 6.2.2 Propulsion Module Reference Frame

The Propulsion Module Reference Frame has the origin coinciding with S/C Reference Frame, but it was obtained by two 90-degree rotations between the axes. The two reference systems are linked by rotation matrices containing two angles of Euler.

• ZPM axis orthogonal to the Spacecraft Composite / Launcher separation plane, pointing positively from the separation plane towards the CCM: this axis coincides with the X axis of the S / C reference system in launch condition;

• YPM axis emanates from the origin and is nominally orthogonal to the Solar Array plane in deployed configuration. The Y direction will point from the RF origin to the lateral antenna.

• XPM axis is defined using the +Z and +Y axes using the right hand rule: this axis has the same direction as the Y axis of the S / C reference system at launch but in the opposite direction.

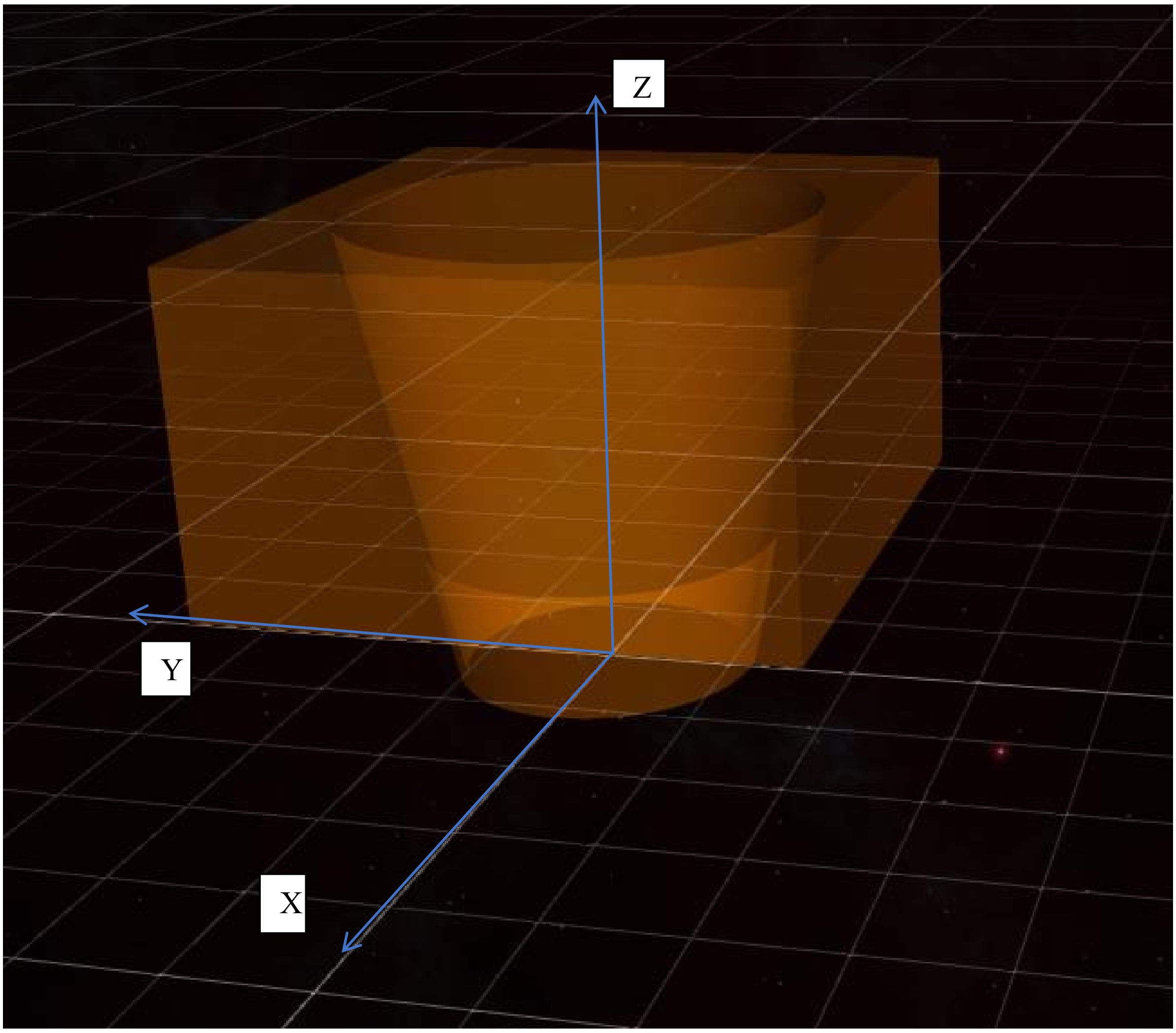



*Figure 6.2.2.1 PM Reference Frame*

### 6.2.3 Main Module Reference System

The Main Module Reference Frame has the origin 200 mm above the upper platform of the PM (above 2030 mm from the S/C origin), so the X and Y coordinates of the origin coinciding with PM Reference Frame.

- ZMM axis orthogonal to the Spacecraft Composite / Launcher separation plane, pointing positively from the separation plane towards the CCM;
- YMM axis emanates from the origin and is nominally orthogonal to the Solar Array plane in deployed configuration. The Y direction will point from the RF origin to the lateral antenna.
- XMM axis is defined using the +Z and +Y axes using the right hand rule.

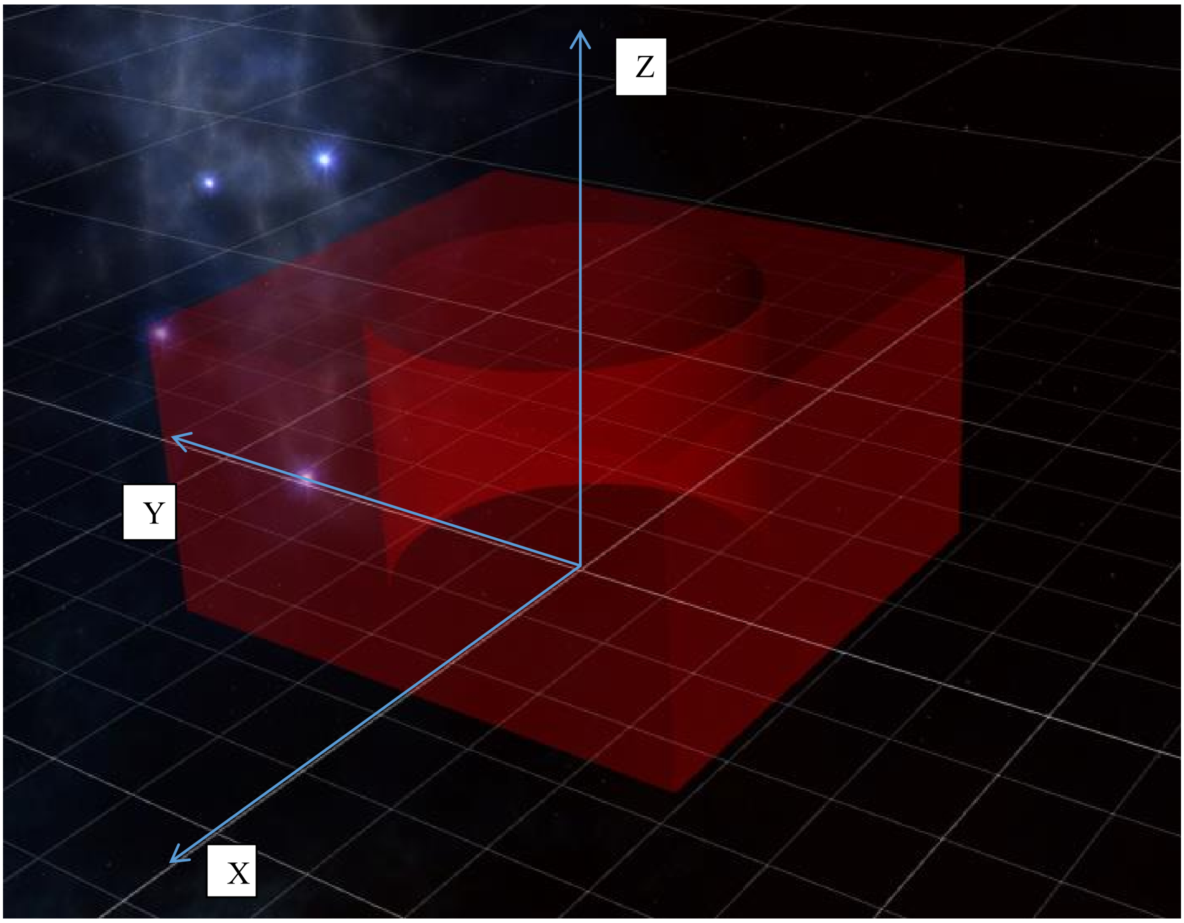



*Figure 6.2.3.1 - MM layout and reference frame*

### 6.2.4 CCM&RVA, ERM, OS Reference Frame

The Reference Frame of CCM&RVA unit, ERM unit and OS unit coincide with the MM Reference Frame System.

# 6.3 Assembly Properties

Once the structural macroblocks and tanks have been constructed, and the various geometric reference systems have been defined, the whole system consisting of all the parts is created. In this phase, we make sure of the constructive coherence with the CAD drawings and the reference systems.

**MM**

| Subsystem | Unit | Inst | Coordinate system | Position in coordinate system | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | x [mm] | y [mm] | z [mm] | Rot. order | R1 [°] | R2 [°] | R3 [°] |
| Structure and units | | | | | | | | | | |
| | MM platform | | | | | | | | | |
| | | 1 | MM | 0 | 0 | 0 | Rxyz | 0 | 0 | 0 |
| | SA Wings | | | | | | | | | |
| | | 1 | MM | 0 | 0 | 750 | Rxyz | 0 | 0 | 0 |
| | | | | | | | | | Articulations | |
| Tanks | | | | | | | | | | |
| | Xe tanks | | | | | | | | | |
| | | 1 | MM | 993,02 | 899,6 | 214 | Rxyz | 0 | 0 | 0 |
| | | 2 | MM | -993,02 | -899,6 | 214 | Rxyz | 0 | 0 | 0 |
| | RCS N2H4 tanks | | | | | | | | | |

**PM**

| Subsystem | Unit | Inst | Coordinate system | Position in coordinate system | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | x [mm] | y [mm] | z [mm] | Rot. order | R1 [°] | R2 [°] | R3 [°] |
| Structure and units | | | | | | | | | | |
| | Equipment 1 | | | | | | | | | |
| | | 1 | PM | 0 | 0 | 0 | Rxyz | 0 | 0 | 0 |
| Tanks | | | | | | | | | | |

**CCM+RVA**

| Subsystem | Unit | Inst | Coordinate system | Position in coordinate system | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | x [mm] | y [mm] | z [mm] | Rot. order | R1 [°] | R2 [°] | R3 [°] |
| Structure and units | | | | | | | | | | |
| | CCM | | | | | | | | | |
| | | 1 | CCM+RVA | 0 | 0 | 0 | Rxyz | 0 | 0 | 0 |

**OS**

| Subsystem | Unit | Inst | Coordinate system | Position in coordinate system | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | x [mm] | y [mm] | z [mm] | Rot. order | R1 [°] | R2 [°] | R3 [°] |
| Structure and units | | | | | | | | | | |
| | OS | | | | | | | | | |
| | | 1 | OS | 0 | 0 | 375 | Rxyz | 0 | 0 | 0 |

**ERM**

| Subsystem | Unit | Inst | Coordinate system | Position in coordinate system | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | x [mm] | y [mm] | z [mm] | Rot. order | R1 [°] | R2 [°] | R3 [°] |
| Structure and units | | | | | | | | | | |
| | EEV => click to disable | | | | | | | | | |
| | | 1 | ERM | 0 | 0 | 0 | Rxyz | 0 | 0 | 0 |
| | ERM structure and avionics | | | | | | | | | |
| | | 1 | ERM | 0 | 0 | 0 | Rxyz | 0 | 0 | 0 |

*Figure 6.4.1 - Assembly of the system*

What it is done  in practice is to define the position and orientation in the space of each object, according to the most convenient reference system. In turn, being the translational and rotational relations between the already defined reference frames, each object will occupy the relative positions desired with the others.

The following figure shows the final result of the system.

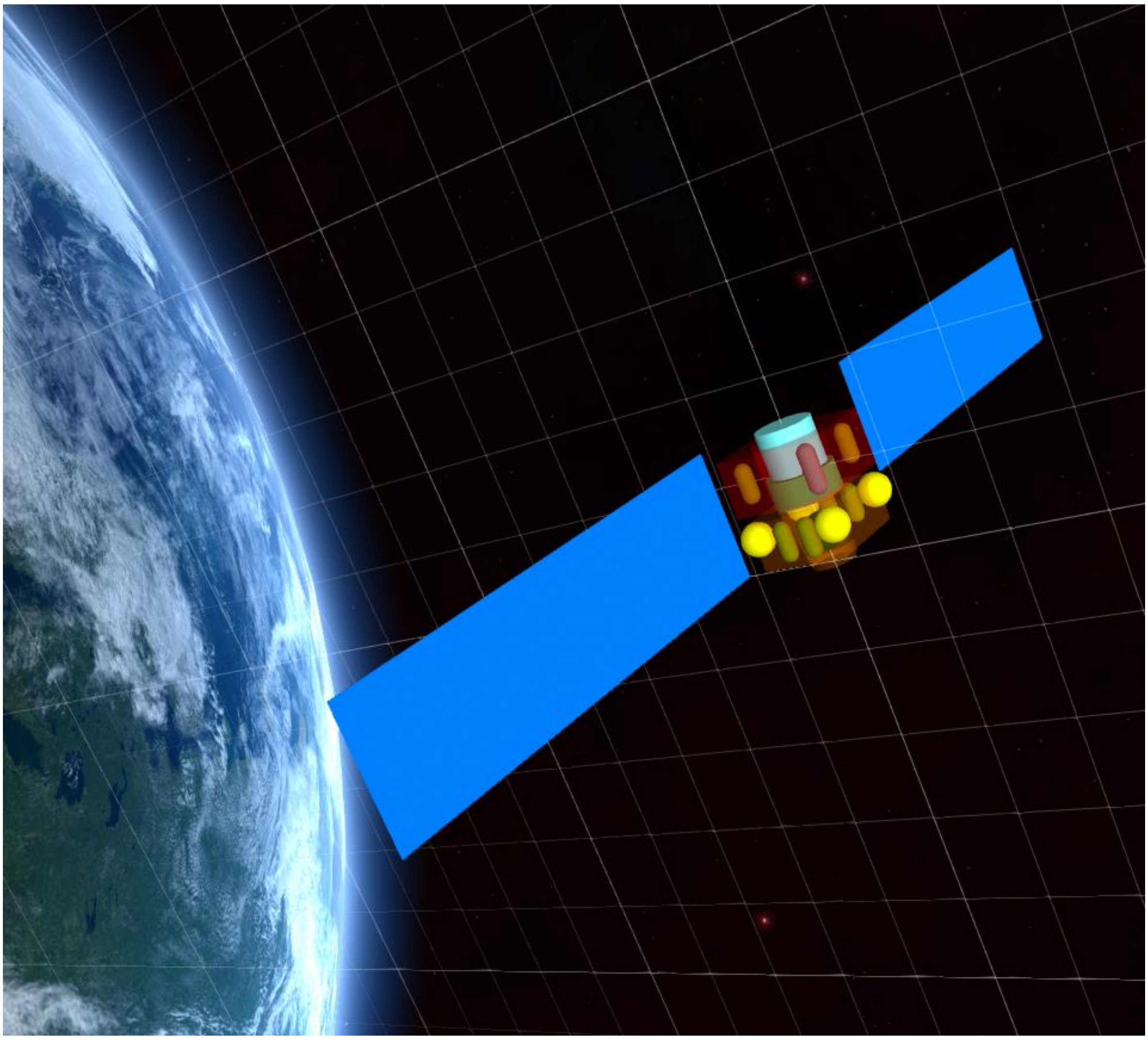


*Figure 6.4.2 - Final result of the system*

## 6.4 Configurations of the model

The configurations of the model roughly coincide with the mission phases, concerning the most important maneuvers. At macroscopic level, the position of the center of gravity of the whole system, and therefore the values of the barycentric moments of inertia, varies according to the consumption of propellant (mass reduction) and the detachment of the various modules according to the various phases.

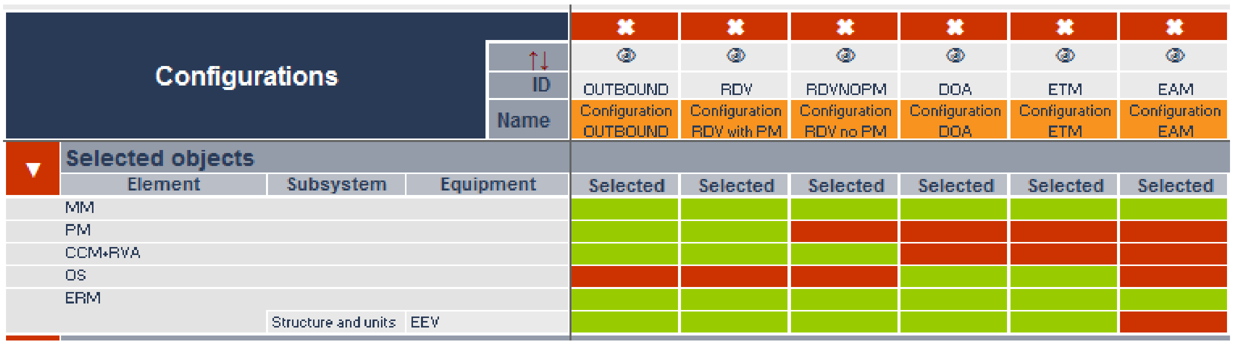



*Figure 6.3.1 - Configuration definitions*

1) Outbound configuration: in this configuration you have Main Module, Propulsion Module, Solar Arrays, CCM + RVA, ERM present and 100% full tanks. Absent of course the OS.
2) RDV with PM: the same as outbound condition but the filling of the PM's tanks is a low percentage of the total.
3) RDV without PM: the same as configuration 2, without the dry mass of the PM and the small amount of fuel left in the PM.
4) DOA: starting from configuration 3 (we only have the MM), we have the OS in the system, but the CCM + RVA has been unhooked. The filling of the Main Module tanks is no longer 100% but slightly lower.
5) ETM: same configuration as DOA, but the Xenon tanks are almost empty.
6) EAM: in the last configuration, the EEV has been released (only the structural masses of the ERM are considered) and all the tanks of the MM are almost completely empty.

# 6.5 MCI Budget Result

In this phase, before displaying the required results, a check is made of the masses and the relative margins used.

| MM | | | | | COG | | |
|---|---|---|---|---|---|---|---|
| Subsystem | Unit | Instance | MCI data row > | Mass [kg] | x [mm] | y [mm] | z [mm] |
| ▼ Structure and units | | | Total | 1372,184 | 2688 | 0 | 0 |
| | ▼ MM platform | | | | | | |
| | | 1 | Total | 964,896 | 2688 | 0 | 0 |
| | ▼ SA Wings | | | | | | |
| | | | 1 | Total | 407,288 | 2688 | 0 | 0 |
| | ▼ SA | | | | | | |
| | | 1 | Total | 407,288 | 2688 | 0 | 0 |
| ► Tanks | | | Dry | 80,64 | 2688 | 0 | 0 |
| | | | Propellant | 1089 | 2688 | 0 | 0 |
| | | | Total | 1169,64 | 2688 | 0 | 0 |
| **Dry** | | | | **1452,824** | **2688** | **0** | **0** |
| **Propellant** | | | | **1089** | **2688** | **0** | **0** |
| **Total** | | | | **2541,824** | **2688** | **0** | **0** |

| PM | Mass [kg] | COG x [mm] | COG y [mm] | COG z [mm] |
|---|---|---|---|---|
| **Dry** | **852,452** | **1085,903** | **0** | **0** |
| **Propellant** | **1821** | **1064,795** | **0** | **-0,200714** |
| **Total** | **2673,452** | **1006,243** | **0** | **-0,128617** |

| CCM+RVA | Mass [kg] | COG x [mm] | COG y [mm] | COG z [mm] |
|---|---|---|---|---|
| **Total** | **248,31** | **2845,5** | **0** | **0** |

| OS | Mass [kg] | COG x [mm] | COG y [mm] | COG z [mm] |
|---|---|---|---|---|
| **Total** | **12** | **2313** | **0** | **0** |

| ERM | | | | | COG | | |
|---|---|---|---|---|---|---|---|
| Subsystem | Unit | Instance | MCI data row > | Mass [kg] | x [mm] | y [mm] | z [mm] |
| ▼ Structure and units | | | Total | 288 | 2153 | 0 | 0 |
| | ▼ EEV | | | | | | |
| | | 1 | Total | 100 | 2153 | 0 | 0 |
| | ▼ ERM structure and avionics | | | | | | |
| | | 1 | Total | 188 | 2153 | 0 | 0 |
| **Total** | | | | **288** | **2153** | **0** | **0** |

| System | Mass [kg] | COG x [mm] | COG y [mm] | COG z [mm] |
|---|---|---|---|---|
| **Dry** | **2853,586** | **2167,538** | **0** | **0** |
| **Propellant** | **2910** | **1672,242** | **0** | **-0,125601** |
| **Total** | **5763,586** | **1887,185** | **0** | **-0,059659** |

*Figure 6.5.1 - MCI budget A*

As can be seen, except for machine precision errors, the center of gravity lies on the X axis of the system since the positioning of the masses is homogeneous as regards the structures and symmetrical with regard to the tanks. The center of gravity assumes higher X axis values as the Propulsion Module propellant is consumed. It undergoes a sudden increase when the PM is removed from the MM. Subsequently, the center of gravity assumes lower X axis values when the block CCM + RVA is removed (the center of gravity of this block has a large X) and the OS is added. Subsequently there are small variations of position due to the consumption of the propellant of the MM. Finally, the release of the EEV causes a slight increase in the value of the X axis of the position of the center of gravity, since the mass contribution is small compared to the whole MM.

| MM | Inertia matrix at system origin including mass margins | | | | | | Inertia matrix at system COG including mass margins | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Ixx [kg.m²] | Ixy [kg.m²] | Ixz [kg.m²] | Iyy [kg.m²] | Iyz [kg.m²] | Izz [kg.m²] | Ixx [kg.m²] | Ixy [kg.m²] | Ixz [kg.m²] | Iyy [kg.m²] | Iyz [kg.m²] | Izz [kg.m²] |
| Dry | 42643,56 | 0 | 0 | 52705,29 | -26,34628 | 11986,85 | 42643,56 | 0 | -0,06941 | 43139,84 | -26,34628 | 2421,404 |
| Propellant | 1980,379 | 0 | 0 | 8852,416 | -499,3663 | 9044,961 | 1980,379 | 0 | -0,052028 | 1682,398 | -499,3663 | 1874,943 |
| Total | 44623,94 | 0 | 0 | 61557,71 | -525,7126 | 21031,81 | 44623,94 | 0 | -0,121439 | 44822,24 | -525,7126 | 4296,347 |

| PM | | | | Inertia matrix at system origin including mass margins | | | | | | Inertia matrix at system COG including mass margins | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Subsystem | Unit | Instance | MCI data row > | Ixx [kg.m²] | Ixy [kg.m²] | Ixz [kg.m²] | Iyy [kg.m²] | Iyz [kg.m²] | Izz [kg.m²] | Ixx [kg.m²] | Ixy [kg.m²] | Ixz [kg.m²] | Iyy [kg.m²] | Iyz [kg.m²] | Izz [kg.m²] |
| ▼ Structure and units | | | Total | 823,496046 | 0 | 0 | 1208,95459 | 0 | 1208,95459 | 823,496049 | 0 | 0,031644 | 947,877861 | 0 | 947,877859 |
| | ▼ Equipment 1 | | | | | | | | | | | | | | |
| | | 1 | Total | 823,496046 | 0 | 0 | 1208,95459 | 0 | 1208,95459 | 823,496049 | 0 | 0,031644 | 947,877861 | 0 | 947,877859 |
| ▼ Tanks | | | Dry | 545,515401 | 0 | 0 | 604,790188 | 0 | 604,790188 | 545,515402 | 0 | 0,009106 | 407,987321 | 0 | 407,98732 |
| | | | Propellant | 2439,56693 | 0 | 0,397664 | 3863,22584 | 0,133082 | 3020,35325 | 2439,56689 | 0 | -0,202758 | 3030,18481 | 0,133082 | 2187,31226 |
| | | | Total | 2921,83454 | 0 | 0,284771 | 4061,92978 | 0,1252 | 3268,97923 | 2921,83451 | 0 | -0,255278 | 3690,8266 | 0,1252 | 2897,87608 |
| | ► Xe Tanks | | | | | | | | | | | | | | |
| | ► Biprop N2H4 tank | | | | | | | | | | | | | | |
| | ▼ Biprop MON tank | | | | | | | | | | | | | | |
| | | 1 | Dry | 10,696641 | 0 | 0 | 55,040695 | 0 | 55,040695 | 10,696641 | 0 | 0,003878 | 78,525224 | 0 | 78,525223 |
| | | | Propellant | 60,08389 | 0 | 0 | 479,361516 | 0 | 479,361516 | 60,083892 | 0 | 0,036667 | 701,410166 | 0 | 701,410163 |
| | | | Total | 70,780531 | 0 | 0 | 534,402211 | 0 | 534,402211 | 70,780534 | 0 | 0,040545 | 779,935389 | 0 | 779,935387 |
| Dry | | | | 1369,011 | 0 | 0 | 1813,745 | 0 | 1813,745 | 1369,011 | 0 | 0,040751 | 1355,865 | 0 | 1355,865 |
| Propellant | | | | 2439,567 | 0 | 0,397664 | 3863,226 | 0,133082 | 3020,353 | 2439,567 | 0 | -0,202758 | 3030,185 | 0,133082 | 2187,312 |
| Total | | | | 3745,331 | 0 | 0,284771 | 5270,884 | 0,1252 | 4477,934 | 3745,331 | 0 | -0,223634 | 4638,704 | 0,1252 | 3845,754 |

| CCM+RVA | Inertia matrix at system origin including mass margins | | | | | | Inertia matrix at system COG including mass margins | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Ixx [kg.m²] | Ixy [kg.m²] | Ixz [kg.m²] | Iyy [kg.m²] | Iyz [kg.m²] | Izz [kg.m²] | Ixx [kg.m²] | Ixy [kg.m²] | Ixz [kg.m²] | Iyy [kg.m²] | Iyz [kg.m²] | Izz [kg.m²] |
| Total | 69,83719 | 0 | 0 | 2113,618 | 0 | 2113,618 | 69,83719 | 0 | -0,014197 | 331,1244 | 0 | 331,1244 |

| OS | Inertia matrix at system origin including mass margins | | | | | | Inertia matrix at system COG including mass margins | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Ixx [kg.m²] | Ixy [kg.m²] | Ixz [kg.m²] | Iyy [kg.m²] | Iyz [kg.m²] | Izz [kg.m²] | Ixx [kg.m²] | Ixy [kg.m²] | Ixz [kg.m²] | Iyy [kg.m²] | Iyz [kg.m²] | Izz [kg.m²] |
| Total | 0,09408 | 0 | 0 | 64,29371 | 0 | 64,29371 | 0,09408 | 0 | -0,000305 | 2,269905 | 0 | 2,269905 |

| ERM | | | | Inertia matrix at system origin including mass margins | | | | | | Inertia matrix at system COG including mass margins | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Subsystem | Unit | Instance | MCI data row > | Ixx [kg.m²] | Ixy [kg.m²] | Ixz [kg.m²] | Iyy [kg.m²] | Iyz [kg.m²] | Izz [kg.m²] | Ixx [kg.m²] | Ixy [kg.m²] | Ixz [kg.m²] | Iyy [kg.m²] | Iyz [kg.m²] | Izz [kg.m²] |
| ▼ Structure and units | | | Total | 116,64 | 0 | 0 | 1406,81779 | 0 | 1406,81779 | 116,640001 | 0 | -0,004567 | 92,16946 | 0 | 92,169459 |
| | ▼ EEV | | | | | | | | | | | | | | |
| | | 1 | Total | 40,5 | 0 | 0 | 488,4784 | 0 | 488,4784 | 40,5 | 0 | -0,001586 | 32,003285 | 0 | 32,003284 |
| | ▼ ERM structure and avionics | | | | | | | | | | | | | | |
| | | 1 | Total | 76,14 | 0 | 0 | 918,339392 | 0 | 918,339392 | 76,140001 | 0 | -0,002981 | 60,166175 | 0 | 60,166175 |
| Total | | | | 116,64 | 0 | 0 | 1406,818 | 0 | 1406,818 | 116,64 | 0 | -0,004567 | 92,16946 | 0 | 92,16946 |

| System | Inertia matrix at system origin including mass margins | | | | | | Inertia matrix at COG including mass margins | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Ixx [kg.m²] | Ixy [kg.m²] | Ixz [kg.m²] | Iyy [kg.m²] | Iyz [kg.m²] | Izz [kg.m²] | Ixx [kg.m²] | Ixy [kg.m²] | Ixz [kg.m²] | Iyy [kg.m²] | Iyz [kg.m²] | Izz [kg.m²] |
| Dry | 44199,14 | 0 | 0 | 58103,76 | -26,34628 | 17385,33 | 44199,14 | 0 | -0,047728 | 44921,27 | -26,34628 | 4202,833 |
| Propellant | 4419,946 | 0 | 0,397664 | 12715,64 | -499,2332 | 12065,31 | 4419,946 | 0 | -0,254786 | 4712,583 | -499,2332 | 4062,255 |
| Total | 48555,84 | 0 | 0,284771 | 70413,32 | -525,5874 | 29094,48 | 48555,84 | 0 | -0,364141 | 49886,51 | -525,5874 | 8567,665 |

*Figure 6.5.2 - MCI budget B*

The moments of inertia are calculated both with respect to the center of gravity and with respect to the origin of the reference system. In turn by including or omitting the mass margins. Obviously, being the center of gravity lying on the X axis of the S/C, the values of moments of inertia with respect to this axis will not vary significantly in the two cases.

## 6.5.1 Recommended future development for the MCI budget

The steps to be taken in order to refine the analysis certainly include the union of the various IDM-CIC models present in the company, as each one has unique information and is missing in the other models. It is therefore necessary to start building the various internal sub-systems to make mass properties less uniform and to build more complicated forms. It would be advisable to start modelling the most massive subsystems such as batteries and inertia wheels, as they would have information about the position of the center of gravity in the Y-Z plane. A more accurate design of the tanks would help the improvement of everything. The construction of the thrusters and the lateral antenna is necessary, as they cause an important contribution of the mass properties variation. In the subsequent phases of the project the propellant must be modelled more precisely, for this reason the following paragraph is a study to clarify some aspects.

# 6.6 IDM-CIC Propellant Exercise

A new IDM-CIC model has been created so that the propellant management in the software can be tested.

## 6.6.1 Scope and purpose of the Tank exercise

This paragraph clarifies some aspects related to the calculation of masses and inertias in the IDM-CIC software. The goal is to understand how tank filling management affects inertial and mass properties.

## 6.6.2 Tank Exercise Model Creation

A single element called "COMPOSITE" has been created, which in turn is made up of two subsystems: Full Tank and Half Filed Tank.

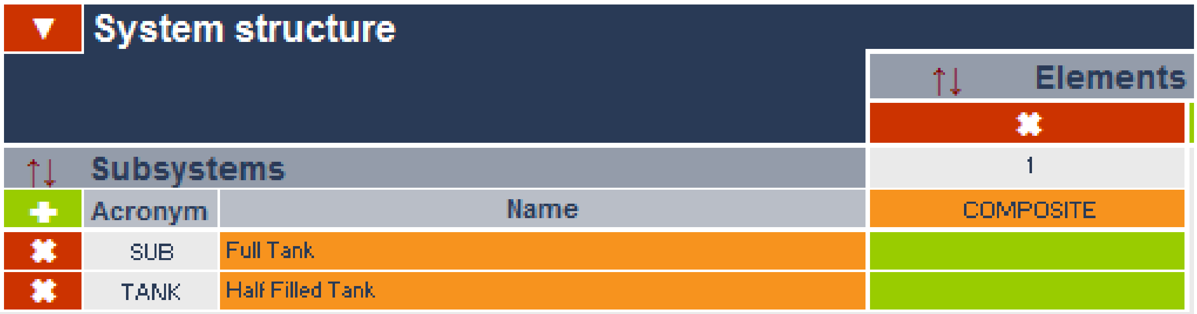



*Figure 6.6.2.8 – Tank Exercise Subsystems*

## 6.6.3 Tank Exercise Element Creation

The Full Tank subsystem consists of a single tank element. The body reference system originates in the geometric center of the tank (half height and in the center of the circumference). Hence, in this way the origin of the axes coincides with the center of gravity. The full tank has a zero structural weight and it can contain 100 kg of propellant with a maximum 100% volumetric filling.

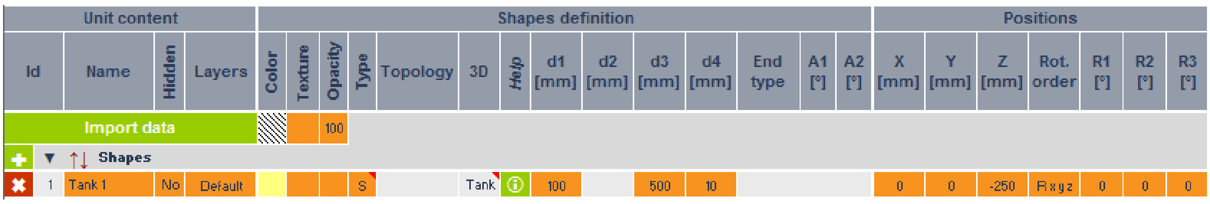



*Figure 6.6.3.1 - Full Tank Shape*

**COMPOSITE units**

Import

| ID | Name | Hidden | Type | Categories | Qty | Opt | Tank Capacity [Kg] | Tank Max filling [%] |
|---|---|---|---|---|---|---|---|---|
| 1 | Tank Full | No | Tk | None | 1 | No | 100 | 100.00% |

*Figure 6.6.3.1 - Full Tank data*

The Half Filled Tank is modeled identically in terms of shapes and body reference system. The only difference is a max 50% volumetric filling.

**COMPOSITE units**

Import

| ID | Name | Hidden | Type | Categories | Qty | Opt | Tank Capacity [Kg] | Tank Max filling [%] | Unit content |
|---|---|---|---|---|---|---|---|---|---|
| 1 | reference half tank | No | Tk | None | 1 | No | 100 | 50.00% | Import data |

Shapes

| Id | Name | Hidden | Layers |
|---|---|---|---|
| 1 | Tank 1 | No | Default |

*Figure 6.6.3.2 - Half Filled Data*

The following figure shows the geometry of both tanks (they coincide in a single shape from a geometric point of view).

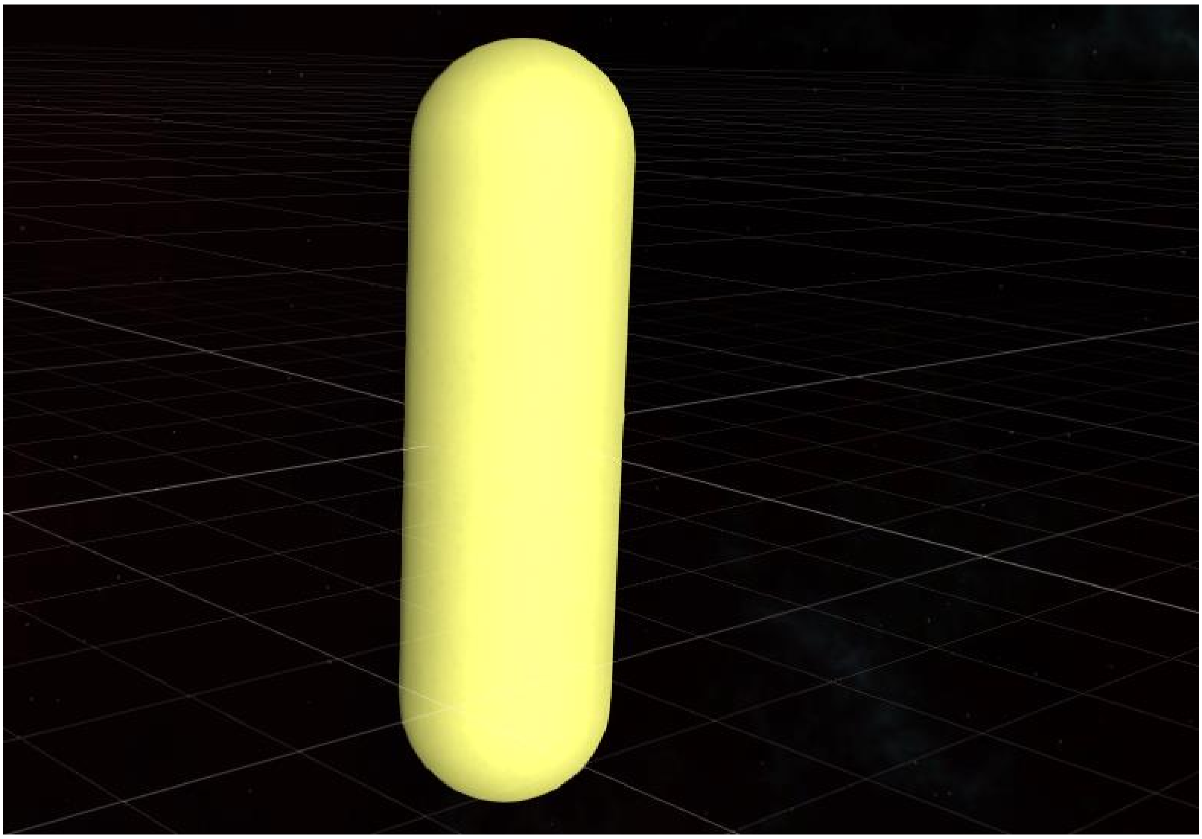


*Figure 6.6.3.3 - View of the tank*

## 6.6.4 Coordinate reference frame definition in the Tank Exercise

The reference frame system of each tank coincides with that of the main system: any translation or rotation is absent.

**Coordinate system definitions**

| + / - | ID | Name | Hidden | Parent | Position in parent coordinate system x [mm] | y [mm] | z [mm] | Rot. order | R1 [°] | R2 [°] | R3 [°] | Type |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ↑↓ | COMPOSITE | | | | | | | | | | | |
| + | 1 | COMPOSITE | No | System | 0 | 0 | 0 | Rxyz | 0 | 0 | 0 | N |
| ✖ | 5 | Full | No | COMPOSITE | 0 | 0 | 0 | Rxyz | 0 | 0 | 0 | N |
| ✖ | 6 | Half filled | No | COMPOSITE | 0 | 0 | 0 | Rxyz | 0 | 0 | 0 | N |

*Figure 9.6.4.1 - Reference Frames*

## 6.6.5 Configurations in the tank exercise

In the model there are 3 configurations in which both tanks are always present: FULL, HALF, LIMITED. It is necessary to remember that the only masses present for the purpose of the calculations concern exclusively the presence of the propellant and not the structures of the tanks.

1. FULL: Full Tank with 100% filling and empty Half Filled Tank.
2. HALF: Full Tank with 50% filling and empty Half Filled Tank.
3. LIMITED: Empty Full Tank and Half Filled Tank with 100% filling.

**Configurations**

| | | | | | | FULL | HALF | LIMITED |
|---|---|---|---|---|---|---|---|---|
| | | | | | ID | FULL | HALF | LIMITED |
| | | | | | Name | Configuration FULL | Configuration HALF | Configuration LIMITED |
| **Selected objects** | | | | | | | | |
| Element | | Subsystem | | Equipment | | Selected | Selected | Selected |
| COMPOSITE | | | | | | | | |
| **Articulations values** | | | | | | | | |
| ID | Name | Type | Axis | Min. | Max. | Value | Value | Value |
| **Variables value** | | | | | | | | |
| ID | Name | | | Type | | Value | Value | Value |
| **Tanks filling percentages** | | | | | | | | |
| Model object | | | | Instance | | Filling | Filling | Filling |
| ▼ COMPOSITE | | | | | | | | |
| ▼ Full Tank | | | | | | | | |
| ▼ Tank Full | | | | | | | | |
| | | | | 1 | | 100.00% | 50.00% | 0.00% |
| ▼ Half Filled Tank | | | | | | | | |
| ▼ reference half tank | | | | | | | | |
| | | | | 1 | | 0.00% | 0.00% | 100.00% |

*Figure 6.6.5.1 - Configurations*

### 6.6.6 Mass Budget of the tank exercise

At this point the mass budget is executed by setting null margins. The forced masses and propellant masses are not inserted manually, but the considerations made above are valid.

**Configuration :** Configuration FULL

| COMPOSITE | | | | Target wet mass [Kg] : | 0 | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Subsystem | Unit | | | Forced values | | Without margin [Kg] | Margin [%] | Margin [Kg] | Including margin [Kg] |
| | Name | Quantity | Mass [Kg] | Margin [%] | Mass [Kg] | Margin [%] | | | | |
| Full Tank | | | | | | 0.00 | 0.00% | 0.00 | 0.00 |
| | Tank Full | 1 | 0.00 | 0.00% | | 0.00 | 0.00% | 0.00 | 0.00 |
| Half Filled Tank | | | | | | 0.00 | 0.00% | 0.00 | 0.00 |
| | reference half tank | 1 | 0.00 | 0.00% | | 0.00 | 0.00% | 0.00 | 0.00 |
| Total dry mass without system margin | | | | | | 0.00 | 0.00% | 0.00 | 0.00 |
| System margin | | | | | | | 0.00% | 0.00 | 0.00 |
| Propellant mass | | | | | | 100.00 | 0.00% | 0.00 | 100.00 |
| Total wet mass including all margins | | | | | | | | | 100.00 |

| System | Without margin [Kg] | | Margin [Kg] | Including margin [Kg] |
|---|---|---|---|---|
| Total dry mass without system margins | 0.00 | | 0.00 | 0.00 |
| Total dry mass including system margins | | | | 0.00 |
| Total propellant mass | 100.00 | | 0.00 | 100.00 |
| Total wet mass including all margins | | | | 100.00 |

*Figure 6.6.6.1 - FULL Mass Budget*

In the FULL configuration, as you can expect, you have 100 kilos of fuel (100% of filling on 100 kilos distributed in 100% of the volume).

**Configuration :** Configuration HALF

| COMPOSITE | | | | Target wet mass [Kg] : | 0 | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Subsystem | Unit | | | Forced values | | Without margin [Kg] | Margin [%] | Margin [Kg] | Including margin [Kg] |
| | Name | Quantity | Mass [Kg] | Margin [%] | Mass [Kg] | Margin [%] | | | | |
| Full Tank | | | | | | 0.00 | 0.00% | 0.00 | 0.00 |
| | Tank Full | 1 | 0.00 | 0.00% | | 0.00 | 0.00% | 0.00 | 0.00 |
| Half Filled Tank | | | | | | 0.00 | 0.00% | 0.00 | 0.00 |
| | reference half tank | 1 | 0.00 | 0.00% | | 0.00 | 0.00% | 0.00 | 0.00 |
| Total dry mass without system margin | | | | | | 0.00 | 0.00% | 0.00 | 0.00 |
| System margin | | | | | | | 0.00% | 0.00 | 0.00 |
| Propellant mass | | | | | | 50.00 | 0.00% | 0.00 | 50.00 |
| Total wet mass including all margins | | | | | | | | | 50.00 |

| System | Without margin [Kg] | | Margin [Kg] | Including margin [Kg] |
|---|---|---|---|---|
| Total dry mass without system margins | 0.00 | | 0.00 | 0.00 |
| Total dry mass including system margins | | | | 0.00 |
| Total propellant mass | 50.00 | | 0.00 | 50.00 |
| Total wet mass including all margins | | | | 50.00 |

*Figure 6.6.6.2 - HALF Mass Budget*

In the HALF configuration, you have 50 kilos of fuel (50% of filling on 100 kilos distributed in 100% of the volume).

| Configuration : | Configuration LIMITED |
|---|---|

| COMPOSITE | | Target wet mass [Kg] : | | | 0 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Subsystem | Unit | | | | Forced values | | Without margin [Kg] | Margin [%] | Margin [Kg] | Including margin [Kg] |
| | Name | Quantity | Mass [Kg] | Margin [%] | Mass [Kg] | Margin [%] | | | | |
| Full Tank | | | | | | | 0.00 | 0.00% | 0.00 | 0.00 |
| | Tank Full | 1 | 0.00 | 0.00% | | | 0.00 | 0.00% | 0.00 | 0.00 |
| Half Filled Tank | | | | | | | 0.00 | 0.00% | 0.00 | 0.00 |
| | reference half tank | 1 | 0.00 | 0.00% | | | 0.00 | 0.00% | 0.00 | 0.00 |
| Total dry mass without system margin | | | | | | | 0.00 | 0.00% | 0.00 | 0.00 |
| System margin | | | | | | | | 0.00% | 0.00 | 0.00 |
| Propellant mass | | | | | | | 100.00 | 0.00% | 0.00 | 100.00 |
| Total wet mass including all margins | | | | | | | | | | 100.00 |

| System | Without margin [Kg] | | Margin [Kg] | Including margin [Kg] |
|---|---|---|---|---|
| Total dry mass without system margins | 0.00 | | 0.00 | 0.00 |
| Total dry mass including system margins | | | | 0.00 |
| Total propellant mass | 100.00 | | 0.00 | 100.00 |
| Total wet mass including all margins | | | | 100.00 |

*Figure 6.6.6.3 - LIMITED Mass Budget*

In the LIMITED configuration, you have 100 kilos of fuel (100% of filling on 100 kilos distributed in 50% of the volume).

## 6.6.7 MCI Budget of the tank exercise

The final step consists in performing the calculation of the inertial properties of the system in order to deduce information on the filling of the tanks.

| Configuration : | Configuration FULL |
|---|---|

| COMPOSITE | | | | COG | | |
|---|---|---|---|---|---|---|
| Subsystem | Unit | Instance | MCI data row > | x [mm] | y [mm] | z [mm] |
| Full Tank | | | Dry | 0 | 0 | 0 |
| | | | Propellant | 0 | 0 | 0 |
| | | | Total | 0 | 0 | 0 |
| | Tank Full | | | | | |
| | | 1 | Dry | 0 | 0 | 0 |
| | | | Propellant | 0 | 0 | 0 |
| | | | Total | 0 | 0 | 0 |
| Half Filled Tank | | | Dry | 0 | 0 | 0 |
| | | | Propellant | 0 | 0 | 0 |
| | | | Total | 0 | 0 | 0 |
| | reference half tank | | | | | |
| | | 1 | Dry | 0 | 0 | 0 |
| | | | Propellant | 0 | 0 | 0 |
| | | | Total | 0 | 0 | 0 |
| Dry | | | | 0 | 0 | 0 |
| Propellant | | | | 0 | 0 | 0 |
| Total | | | | 0 | 0 | 0 |

| System | COG x [mm] | COG y [mm] | COG z [mm] |
|---|---|---|---|
| Dry | 0 | 0 | 0 |
| Propellant | 0 | 0 | 0 |
| Total | 0 | 0 | 0 |

*Figure 6.6.7.1 - FULL MCI Budget A*

| + - | Unit | Instance | MCI data row > | Inertia matrix at system COG Ixx [kg.m²] | Ixy [kg.m²] | Ixz [kg.m²] | Iyy [kg.m²] | Iyz [kg.m²] | Izz [kg.m²] |
|---|---|---|---|---|---|---|---|---|---|
| | | | Dry | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | Propellant | 3.442414 | 0 | 0 | 3.442414 | 0 | 0.389323 |
| | | | Total | 3.442414 | 0 | 0 | 3.442414 | 0 | 0.389323 |
| | ▼ Tank Full | | | | | | | | |
| | | 1 | Dry | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | Propellant | 3.442414 | 0 | 0 | 3.442414 | 0 | 0.389323 |
| | | | Total | 3.442414 | 0 | 0 | 3.442414 | 0 | 0.389323 |
| | | | Dry | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | Propellant | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | Total | 0 | 0 | 0 | 0 | 0 | 0 |
| | ▼ reference half tank | | | | | | | | |
| | | 1 | Dry | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | Propellant | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | Total | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | | **0** | **0** | **0** | **0** | **0** | **0** |
| | | | | **3.442414** | **0** | **0** | **3.442414** | **0** | **0.389323** |
| | | | | **3.442414** | **0** | **0** | **3.442414** | **0** | **0.389323** |

| | Inertia matrix at COG Ixx [kg.m²] | Ixy [kg.m²] | Ixz [kg.m²] | Iyy [kg.m²] | Iyz [kg.m²] | Izz [kg.m²] |
|---|---|---|---|---|---|---|
| | **0** | **0** | **0** | **0** | **0** | **0** |
| | **3.442414** | **0** | **0** | **3.442414** | **0** | **0.389323** |
| | **3.442414** | **0** | **0** | **3.442414** | **0** | **0.389323** |

*Figure 6.6.7.2 - FULL MCI Budget B*

The center of gravity of the propellant lies at the origin of the system's reference system; given the symmetry of the propellant distribution, the inertia tensor matrix is diagonal and has identical components.

**Configuration :** Configuration HALF

| ▼ COMPOSITE | | | | | | COG x [mm] | y [mm] | z [mm] |
|---|---|---|---|---|---|---|---|---|
| + - | Subsystem | + - | Unit | Instance | MCI data row > | | | |
| ▼ | Full Tank | | | | Dry | 0 | 0 | 0 |
| | | | | | Propellant | 0 | 0 | 0 |
| | | | | | Total | 0 | 0 | 0 |
| | | ▼ | Tank Full | | | | | |
| | | | | 1 | Dry | 0 | 0 | 0 |
| | | | | | Propellant | 0 | 0 | 0 |
| | | | | | Total | 0 | 0 | 0 |
| ▼ | Half Filled Tank | | | | Dry | 0 | 0 | 0 |
| | | | | | Propellant | 0 | 0 | 0 |
| | | | | | Total | 0 | 0 | 0 |
| | | ▼ | reference half tank | | | | | |
| | | | | 1 | Dry | 0 | 0 | 0 |
| | | | | | Propellant | 0 | 0 | 0 |
| | | | | | Total | 0 | 0 | 0 |
| **Dry** | | | | | | **0** | **0** | **0** |
| **Propellant** | | | | | | **0** | **0** | **0** |
| **Total** | | | | | | **0** | **0** | **0** |

| **System** | COG x [mm] | y [mm] | z [mm] |
|---|---|---|---|
| **Dry** | **0** | **0** | **0** |
| **Propellant** | **0** | **0** | **0** |
| **Total** | **0** | **0** | **0** |

*Figure 6.6.7.3 - HALF MCI Budget A*

| + - | Unit | Instance | MCI data row > | Ixx [kg.m²] | Ixy [kg.m²] | Ixz [kg.m²] | Iyy [kg.m²] | Iyz [kg.m²] | Izz [kg.m²] |
|---|---|---|---|---|---|---|---|---|---|
| | | | | **Inertia matrix at system COG** | | | | | |
| | | | Dry | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | Propellant | 1.942147 | 0 | 0 | 1.942147 | 0 | 0.28559 |
| | | | Total | 1.942147 | 0 | 0 | 1.942147 | 0 | 0.28559 |
| ▼ | Tank Full | | | | | | | | |
| | | 1 | Dry | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | Propellant | 1.942147 | 0 | 0 | 1.942147 | 0 | 0.28559 |
| | | | Total | 1.942147 | 0 | 0 | 1.942147 | 0 | 0.28559 |
| | | | Dry | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | Propellant | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | Total | 0 | 0 | 0 | 0 | 0 | 0 |
| ▼ | reference half tank | | | | | | | | |
| | | 1 | Dry | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | Propellant | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | Total | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | | **0** | **0** | **0** | **0** | **0** | **0** |
| | | | | **1.942147** | **0** | **0** | **1.942147** | **0** | **0.28559** |
| | | | | **1.942147** | **0** | **0** | **1.942147** | **0** | **0.28559** |

| | Inertia matrix at COG | | | | | |
|---|---|---|---|---|---|---|
| | Ixx [kg.m²] | Ixy [kg.m²] | Ixz [kg.m²] | Iyy [kg.m²] | Iyz [kg.m²] | Izz [kg.m²] |
| | **0** | **0** | **0** | **0** | **0** | **0** |
| | **1.942147** | **0** | **0** | **1.942147** | **0** | **0.28559** |
| | **1.942147** | **0** | **0** | **1.942147** | **0** | **0.28559** |

*Figure 6.6.7.4 - HALF MCI Budget B*

In the HALF configuration, the above considerations are valid, but since the mass is halved compared to the previous case, the moments of inertia take on smaller values.

**Configuration :** Configuration LIMITED

| + - | Subsystem | + - | Unit | Instance | MCI data row > | x [mm] | y [mm] | z [mm] |
|---|---|---|---|---|---|---|---|---|
| ▼ | **COMPOSITE** | | | | | **COG** | | |
| ▼ | Full Tank | | | | Dry | 0 | 0 | 0 |
| | | | | | Propellant | 0 | 0 | 0 |
| | | | | | Total | 0 | 0 | 0 |
| | | ▼ | Tank Full | | | | | |
| | | | | 1 | Dry | 0 | 0 | 0 |
| | | | | | Propellant | 0 | 0 | 0 |
| | | | | | Total | 0 | 0 | 0 |
| ▼ | Half Filled Tank | | | | Dry | 0 | 0 | 0 |
| | | | | | Propellant | 0 | 0 | 0 |
| | | | | | Total | 0 | 0 | 0 |
| | | ▼ | reference half tank | | | | | |
| | | | | 1 | Dry | 0 | 0 | 0 |
| | | | | | Propellant | 0 | 0 | 0 |
| | | | | | Total | 0 | 0 | 0 |
| **Dry** | | | | | | **0** | **0** | **0** |
| **Propellant** | | | | | | **0** | **0** | **0** |
| **Total** | | | | | | **0** | **0** | **0** |

| **System** | COG | | |
|---|---|---|---|
| | x [mm] | y [mm] | z [mm] |
| **Dry** | **0** | **0** | **0** |
| **Propellant** | **0** | **0** | **0** |
| **Total** | **0** | **0** | **0** |

*Figure 6.6.7.5 - LIMITED MCI Budget A*

| + - | Unit | Instance | MCI data row > | Inertia matrix at system COG Ixx [kg.m²] | Ixy [kg.m²] | Ixz [kg.m²] | Iyy [kg.m²] | Iyz [kg.m²] | Izz [kg.m²] |
|---|---|---|---|---|---|---|---|---|---|
| | | | Dry | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | Propellant | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | Total | 0 | 0 | 0 | 0 | 0 | 0 |
| ▼ Tank Full | | | | | | | | | |
| | | 1 | Dry | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | Propellant | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | Total | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | Dry | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | Propellant | 1.942147 | 0 | 0 | 1.942147 | 0 | 0.28559 |
| | | | Total | 1.942147 | 0 | 0 | 1.942147 | 0 | 0.28559 |
| ▼ reference half tank | | | | | | | | | |
| | | 1 | Dry | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | Propellant | 1.942147 | 0 | 0 | 1.942147 | 0 | 0.28559 |
| | | | Total | 1.942147 | 0 | 0 | 1.942147 | 0 | 0.28559 |
| | | | | **0** | **0** | **0** | **0** | **0** | **0** |
| | | | | **1.942147** | **0** | **0** | **1.942147** | **0** | **0.28559** |
| | | | | **1.942147** | **0** | **0** | **1.942147** | **0** | **0.28559** |

| | Inertia matrix at COG Ixx [kg.m²] | Ixy [kg.m²] | Ixz [kg.m²] | Iyy [kg.m²] | Iyz [kg.m²] | Izz [kg.m²] |
|---|---|---|---|---|---|---|
| | **0** | **0** | **0** | **0** | **0** | **0** |
| | **1.942147** | **0** | **0** | **1.942147** | **0** | **0.28559** |
| | **1.942147** | **0** | **0** | **1.942147** | **0** | **0.28559** |

*Figure 6.6.7.6 - LIMITED MCI Budget B*

In the LIMITED configuration, the moments of inertia of the Full Tank seen in the HALF configuration are shifted to the Half Tank. In calculating the moments of inertia of the entire system, values identical to the previous case are obtained. Although the last two configurations have different masses, moments of inertia are identical. The position of the center of gravity never changes.

## 6.6.8 Conclusions of the tank exercise

1. From a geometric point of view, in IDM-CIC the propellant is always distributed symmetrically in the tank: the center of gravity in the various cases is always the same whether the tank is full or half full.
2. If the maximum filling is 100%, the propellant is distributed in the entire volume in a homogeneous manner regardless of the propellant consumed. In the FULL and HALF configurations, the center of gravity is the same, so varying only the filling in the configurations, what changes is only the total amount of propellant, not its distribution: halving the mass halves the density.
3. Varying only the max filling does not change the amount of mass or the position of the center of gravity, but only moments of inertia. By halving the max filling, it doubles the density and the propellant is allocated in a reduced volume. Since the HALF and LIMITED configurations have different masses but identical moments of inertia, it is concluded that the Max Filling is modelled as an insertion of symmetrical empty space inside the tank, or it is as if its thickness had increased. The volume reduction is symmetrical with respect to the center of mass.

# 6.7 MCI Model Updates

After the PRR updates were made on the configuration of the ERO. As already written in the chapter on the Mass Budget, the PM will be purely chemical and the electric propulsion will be present entirely in the MM, so the MCI model was then updated with the new geometries and masses.

## 6.7.1 New modules shapes

Starting from the previous configuration, the OS, the ERM and the CCM remain identical. The MM is a parallelepiped of greater dimensions than the previous case, with a cylindrical cavity and protrusion of contact with the PM in the shape of a truncated hollow cone.

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Topo | | | | | | | 0 | 0 | 0 | Rxyz | 0 | 0 | 0 |
| | Para | 2800 | 2600 | 2100 | | | | -1400 | -1300 | 60 | Rxyz | 0 | 0 | 0 |
| - | Cyl | 985 | | 2100 | | | 360 | 0 | 0 | 60 | Rxyz | 0 | 0 | 0 |
| ∪ | HTC | 985 | 985 | 2160 | 20 | Disc | 360 | 0 | 0 | 0 | Rxyz | 0 | 0 | 0 |

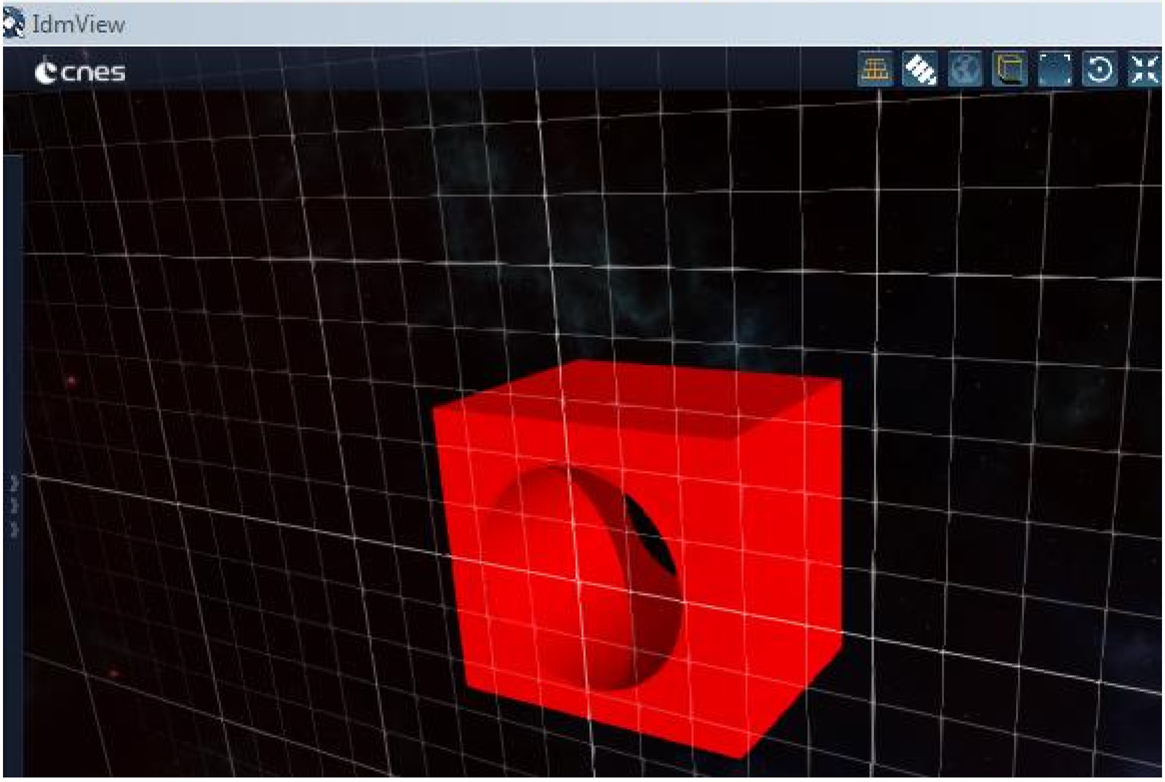



*Figure 6.7.1.1 - MM updates*

The PM loses the form of a parallelepiped. Its envelope is a hollow cone trunk delimited by two hollow truncated cone platforms with a very stocky shape (high radius and small height). The lower platform exits from the cone of a small thickness and allows to visualize the space inside. In this way the object is hollow inside and the allocation of the tanks will not be superimposed on the equally distributed structural mass: this approach allows a better approximation, which is not possible in the MM given the geometric complexity.

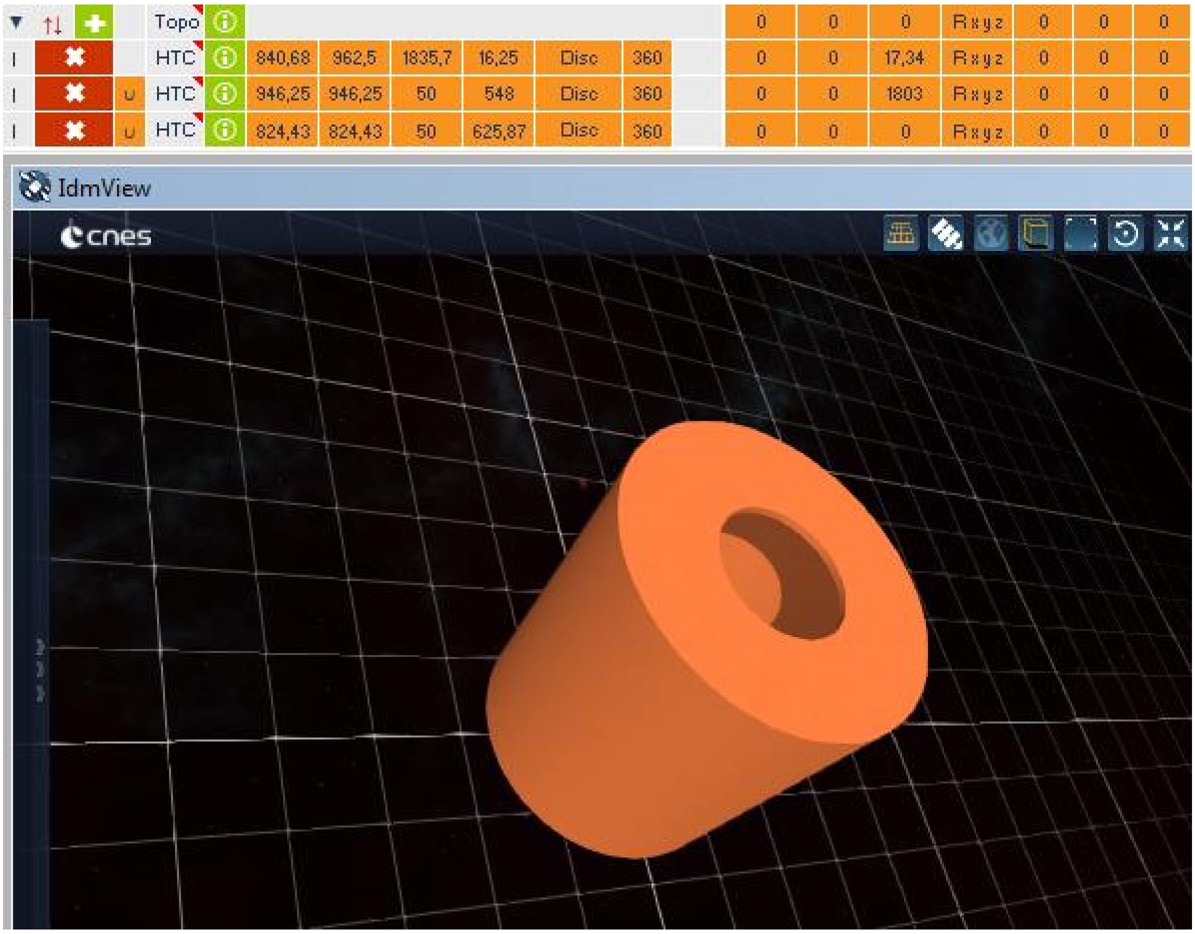



*Figure 6.7.1.2 - PM shapes updates*

## 6.7.2 Tank accommodation updates


*Figure 6.7.2.1 - Tank Model Updates*

The new configuration presents in PM 4 new bipropellant tanks (identical to each other) and 4 identical spherical pressurizing tanks. The MM has 2 levels of accommodation of the tanks: in the lower level there are 2 pressurizing tanks identical to each other, 4 tanks of Xenon 120 liters; in the upper line there are 4 x 90 liters tanks.

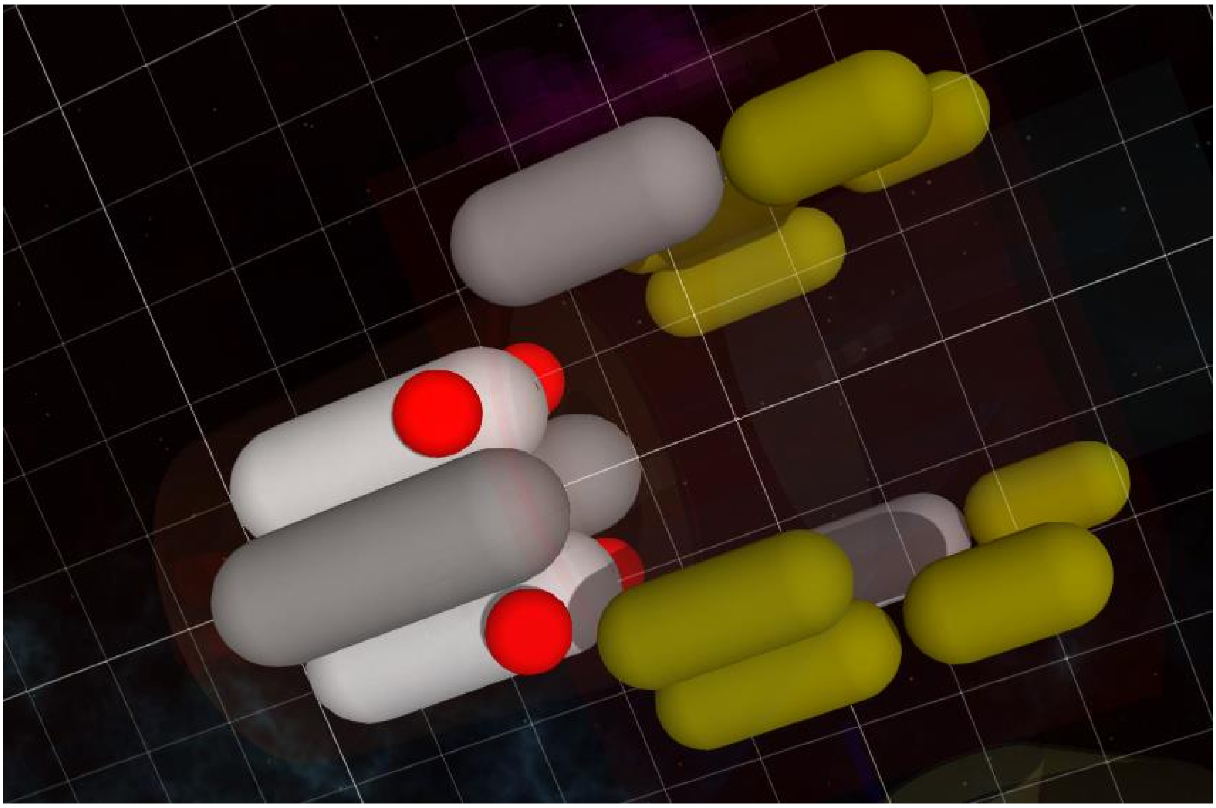


*Figure 6.7.2.2 - Tank Accomodation Updates*

HGA, Solar Arrays, electric thrusters and chemical thrusters were built as separate systems.

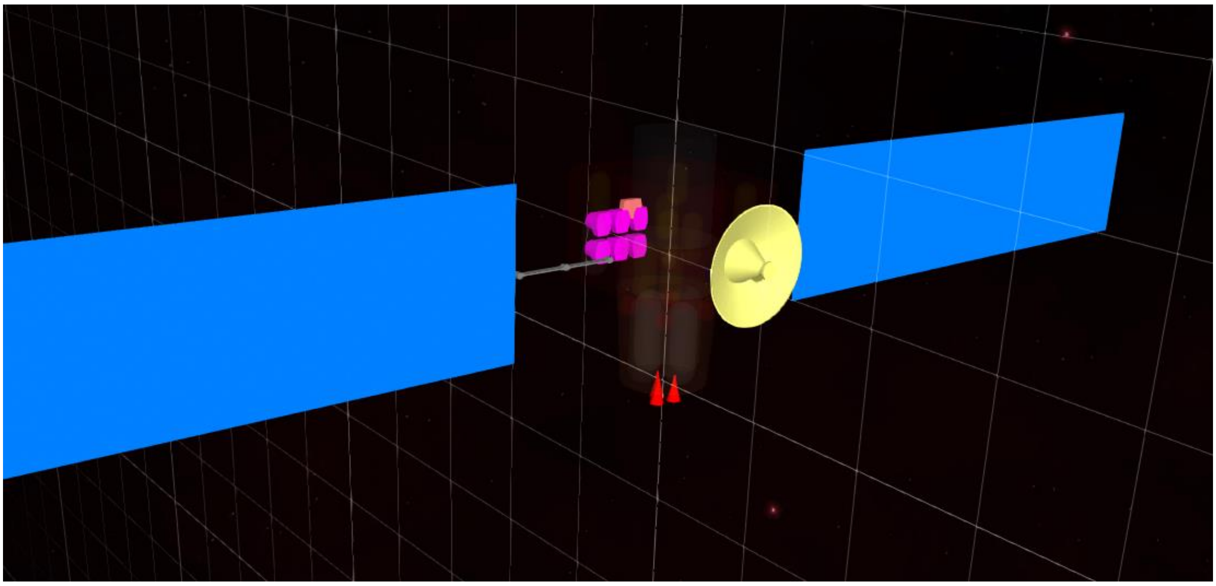


*Figure 6.7.2.3 – Update of other elements*

The position of these elements is provisional and falls within the eligible simplification hypotheses. It is also useful to note that solar panels are provided with yokes.

### 6.7.3 Assembly updates

At this point, all the relative positions between the various internal reference systems and the positions of the individual objects change.

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| MM | | | | | | | | | | |
| 1 | MM | No | PM | 0 | 0 | 1861,7 | Rxyz | 0 | 0 | 0 |
| PM | | | | | | | | | | |
| 1 | PM | No | System | 0 | 0 | 0 | Rxyz | 0 | 90 | -90 |

*Figure 6.7.3.1 - MM reference frame update*

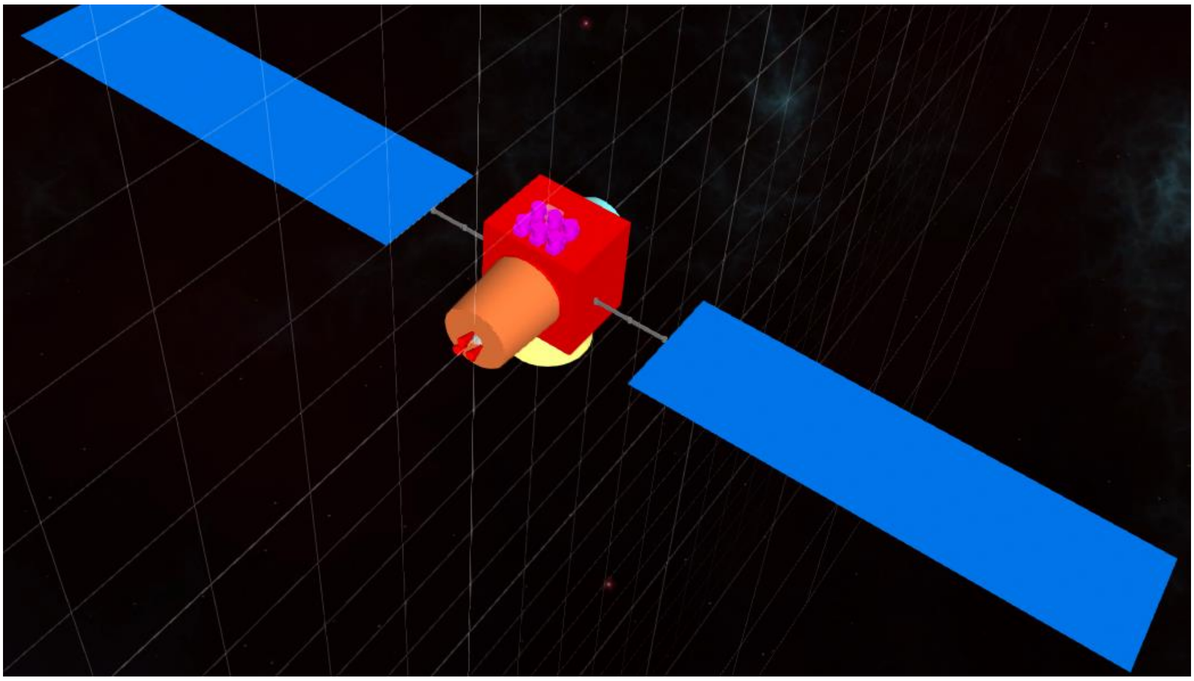


*Figure 6.7.3.1 - Final Configuration Update*

### 6.7.4 Configuration Updates

In the new model more configurations have been inserted, and for each configuration two different types of tank emptying are assumed for the Xenon tanks. The first case is a symmetric emptying and equal in percentage value in all the tanks, instead, the second case involves starting to empty first the Xenon tanks that have the largest X coordinate and then the lower tanks. The COGs of the individual modules have been inserted in an Excel sheet.

| Configurations | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | ID | OUTBOUND | BEFOREMOI | SPIRALINSTAR | PMJETTISONE | RDVNOPM | DOA | MARS-SOI | ETM | EAM |
| | | Name | OUTBOUND | BEFOREMOI | AFTER MOI | PM JETTISONED | Before RDV | LMO depart | MARS-SOI | Configuration ETM | Configuration EAM |
| **Selected objects** | | | | | | | | | | | |
| Element | Subsystem | Equipment | Selected | Selected | Selected | Selected | Selected | Selected | Selected | Selected | Selected |
| MM | | | | | | | | | | | |
| PM | | | | | | | | | | | |
| CCM+RVA | | | | | | | | | | | |
| OS | | | | | | | | | | | |
| ERM | | | | | | | | | | | |
| | Structure and units | EEV | | | | | | | | | |

*Figure 6.7.4.1 - Configuration Updates*

## 6.7.5 COG Results Updates

At the end, the excursion of the barycentre was calculated with Excel in the two cases:

| | Mass | xCoG |
|---|---|---|
| CCM | 249 | 3706,9 |
| MM dry | 1880,7 | 2837,8 |
| ERM dry | 277 | 2342,5 |
| PM dry | 451,3 | 975,2 |
| OS | 12 | 2333,8 |
| Xe UP | 599,21 | 3550,2 |
| Xe DOWN | 699,97 | 2325,33 |
| RCS | 225 | 2588,5 |
| MON | 755 | 904,1 |
| MMH | 805 | 835,25 |

AS

| | OUTBOUND | BEFORE MOI | AFTER MOI | PM JETTISONED | Before RDV | LMO depart | MARS-SOI | ETM | EAM |
|---|---|---|---|---|---|---|---|---|---|
| CCM | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| MM dry | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| ERM dry | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| PM dry | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| OS | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 |
| % Xe UP | 100,00% | 53,43% | 51,19% | 49,88% | 3,00% | 3,00% | 3,00% | 3,00% | 3,00% |
| % Xe DOWN | 100,00% | 100,00% | 100,00% | 100,00% | 75,90% | 70,00% | 50,00% | 12,00% | 10,00% |
| %RCS | 100,00% | 100,00% | 100,00% | 100,00% | 100,00% | 65,00% | 60,00% | 60,00% | 2,60% |
| %BIPROP | 100,00% | 100,00% | 5,00% | 0,00% | 0,00% | 0,00% | 0,00% | 0,00% | 0,00% |
| %BIPROP | 100,00% | 100,00% | 3,00% | 0,00% | 0,00% | 0,00% | 0,00% | 0,00% | 0,00% |
| Dry Mass | 2858 | 2858 | 2858 | 2406,7 | 2406,7 | 2169,7 | 2169,7 | 2169,7 | 2169,7 |
| Propellant | 3084,18 | 2805,13 | 1293,61 | 1223,86 | 774,254 | 654,205 | 502,961 | 236,973 | 93,8233 |
| TOT MASS | 5942,18 | 5663,13 | 4151,61 | 3630,56 | 3180,95 | 2823,91 | 2672,66 | 2406,67 | 2263,52 |
| XCoG | 2194,718 | 2127,93 | 2577,89 | 2804,01 | 2763,5 | 2689,78 | 2709,29 | 2751,73 | 2763,68 |

| | |
|---|---|
| MAX | 2804,0112 |
| MED | 2709,2943 |
| MIN | 2127,9263 |
| excursion | 676,08493 |

SYMM

| | OUTBOUND | BEFORE MOI | AFTER MOI | PM JETTISONED | Before RDV | LMO depart | MARS-SOI | ETM | EAM |
|---|---|---|---|---|---|---|---|---|---|
| CCM | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| MM dry | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| ERM dry | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| PM dry | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| OS | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 |
| % Xe UP | 100,00% | 79,78% | 78,13% | 77,00% | 42,00% | 35,00% | 25,00% | 8,00% | 6,30% |
| % Xe DOWN | 100,00% | 79,78% | 78,13% | 77,00% | 42,00% | 35,00% | 25,00% | 8,00% | 6,30% |
| %RCS | 100,00% | 100,00% | 100,00% | 100,00% | 100,00% | 69,00% | 67,00% | 66,00% | 2,60% |
| %BIPROP | 100,00% | 100,00% | 5,00% | 0,00% | 0,00% | 0,00% | 0,00% | 0,00% | 0,00% |
| %BIPROP | 100,00% | 100,00% | 3,00% | 0,00% | 0,00% | 0,00% | 0,00% | 0,00% | 0,00% |
| Dry Mass | 2858 | 2858 | 2858 | 2406,7 | 2406,7 | 2169,7 | 2169,7 | 2169,7 | 2169,7 |
| Propellant | 3084,18 | 2821,49 | 1301,95 | 1225,37 | 770,6556 | 609,963 | 475,545 | 252,434 | 87,6983 |
| TOT MASS | 5942,18 | 5679,49 | 4159,95 | 3632,07 | 3177,356 | 2779,663 | 2645,25 | 2422,13 | 2257,4 |
| XCoG | 2194,718 | 2162,55 | 2624,92 | 2858,61 | 2854,085 | 2780,925238 | 2775,88 | 2765,63 | 2775,6 |

| | |
|---|---|
| MAX | 2858,615 |
| MED | 2775,600 |
| MIN | 2162,547 |
| excursion | 696,068 |

*Figure 6.7.5.1 - COG Update*

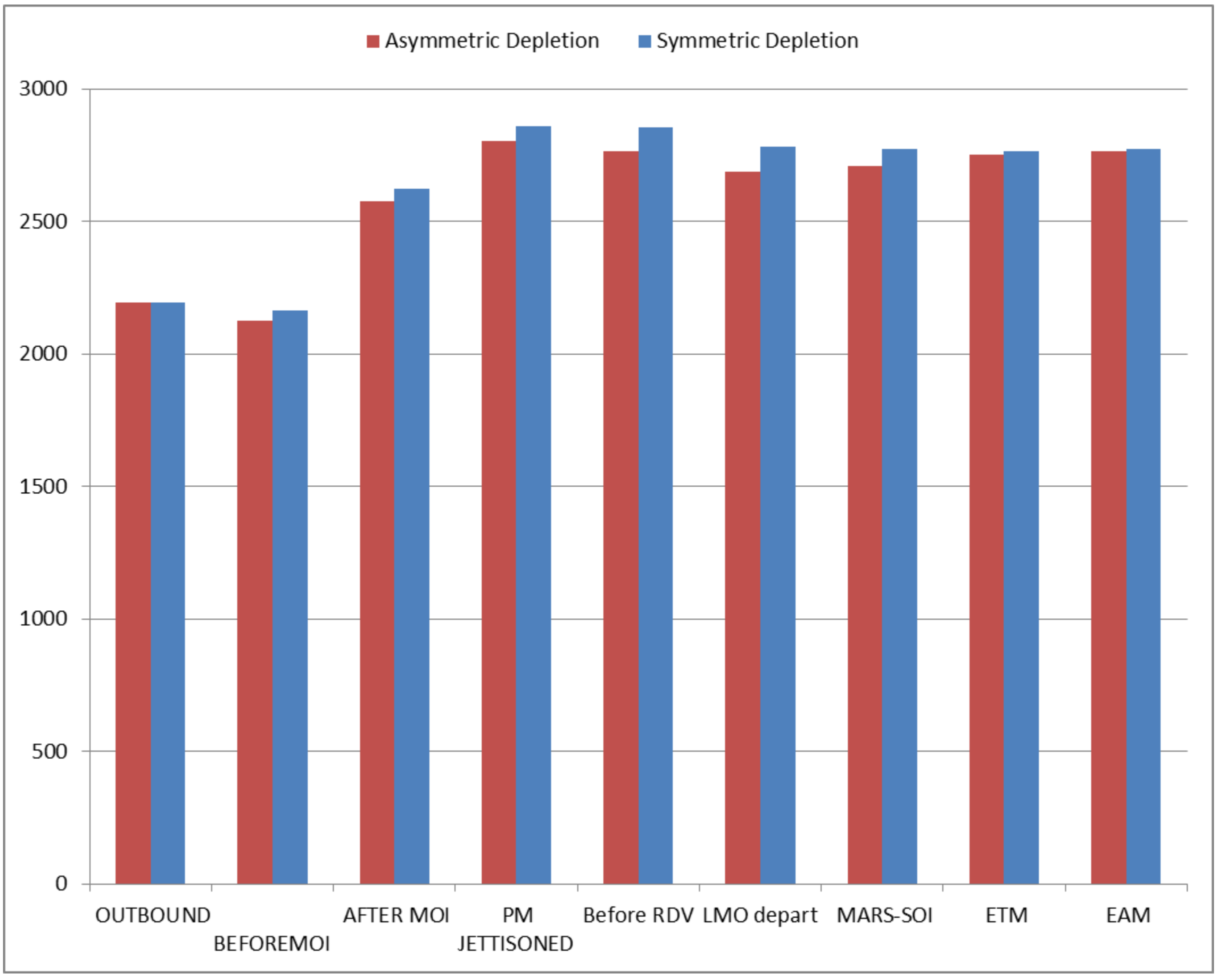



*Figure 6.7.5.2 - COG Excursion*

# Chapter 7

# Power Budget

In this chapter, a preliminary calculation is made of the power budget for the hybrid solution. the chosen scenario is relative to mission dates that make the estimate of conservative calculations and which may allow the possibility of being able to change, for example, the launch date. in any case, if the power budget for the purely chemical or purely electric propulsion solution were to be implemented, the results would be completely different. For these reasons, this paragraph refers exclusively to SC9 and BC14, as the hybrid propulsion system architecture is analysed with the launch scheduled for October 2026.

The power budget is one of the most binding design aspects of the entire mission. The electric power on board is necessary for the operation of all the internal subsystems and its correct regulation depends on the mission's resounding or its failure. The fact that electric propulsion on board is also present determines the necessity of the production and storage of electric energy in considerable quantities, appropriately providing the demand and the power delivered net of light and shadow cycles between the various planets.

From a conceptual point of view the power budget consists in the study of the required electric power; after obtaining the results of what ERO needs to be able to operate correctly, a study will be carried out that can in some way predict how much electricity can be stored in the Outbound and Inbound phases. The estimate of the available electric power is coarse, this because the purpose of this calculation is not so much to provide precise and punctual values but rather to estimate an order of magnitude relatively quickly. It is obvious that more accurate analyses will be carried out in the subsequent phases of the project and in any case at the stage A2 / B1 level the responsibility is not TAS Italy but ESA, TAS-UK and TAS-F. Hence, the aim of this chapter is to demonstrate is the fulfillment of the requirements of energy requirements, such as that the demand is lower than what is produced and the power available for electric propulsion is sufficient.

The data used and produced undergo cyclical revisions as the design changes continue, so data and results will not be the final mission values, but data that drive the project and cause changes, which in turn will cause significant changes and repercussions in the sheets calculation related to the power budget.

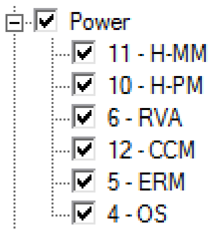



*Figure 7.1 - Power Budget System Role*

# 7.1 Power needed

In this paragraph the calculation of the proper power budget is carried out, that is the estimate of the electric power required by the various components during the various mission phases. The estimate is made with the IDM-CIC software because the parameterization of the data is convenient and there are the worksheet related to the power budget.

## 7.1.1 IDM-CIC source file

The source file of use is the IDM-CIC file built to make the mass budget, of which it has already been widely discussed. The objects of each single subsystem and the various internal subsystems with the data relating to the masses are then confirmed, such as the big blocks (MM, PM, RVA, CCM, OS, ERM).

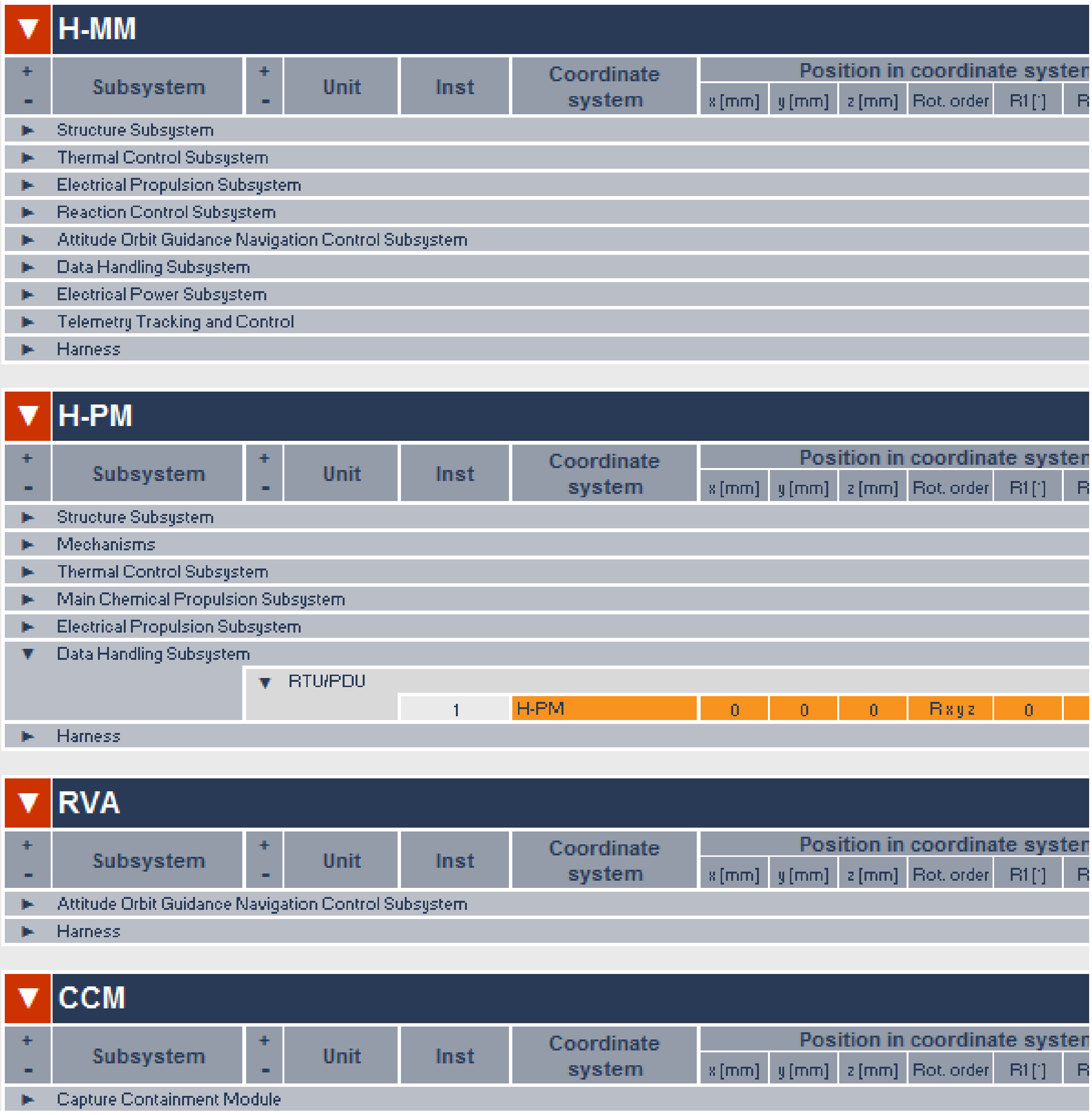



*Figure 7.1.1.1 - Power Budget Modules*

## 7.1.2 Item estimated consumption

The first step for the new analysis is the insertion of the nominal values of consumption of electric power for all those elements that need it (unlike the mass properties, present for all the objects of the model). You then enter the various worksheets and enter the consumption values object by object, subsystem by subsystem.

H-MM units

| ID | Name | Hidden | Type | Categories | Qty | Opt | Custom power | Power margin [%] | Unit content Id | Unit content Name | Unit content Hidden | Unit content Layers | Power [W] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | MLI | No | Eq | None | 1 | No | No | 0.00% | Import data | | | | |
| 6 | Heaters, thermistor | No | Eq | None | 1 | No | No | 20.00% | Import data | | | | |
| | | | | | | | | | Power modes | | | | |
| | | | | | | | | | 2 | Cold TBC 80% | | | 320 |
| | | | | | | | | | 9 | Average TBC | | | 200 |
| | | | | | | | | | 3 | Hot TBC | | | 100 |
| 2 | Propulsion Therma | No | Eq | None | | No | No | 0.00% | Import data | | | | |
| 3 | Paint & Tape | No | Eq | None | | No | No | 0.00% | Import data | | | | |
| 9 | Heat Pipes | No | Eq | None | 48 | No | No | 0.00% | Import data | | | | |
| 4 | Doublers | No | Eq | None | | No | No | 0.00% | Import data | | | | |
| 5 | Thermal Fillers & w | No | Eq | None | | No | No | 0.00% | Import data | | | | |
| 8 | Miscellaneous | No | Eq | None | | No | No | 0.00% | Import data | | | | |
| 10 | Miscellanea | No | Ass | None | 1 | | | | Import data | | | | |

Go to top

H-PM units

| ID | Name | Hidden | Type | Categories | Qty | Opt | Custom power | Power margin [%] | Unit content Id | Unit content Name | Unit content Hidden | Unit content Layers | Power [W] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 8 | MLI | No | Eq | None | 1 | No | No | 0.00% | Import data | | | | |
| 2 | Propulsion Therma | No | Eq | None | 1 | No | No | 0.00% | Import data | | | | |
| 3 | Heaters Thermistor | No | Eq | None | 1 | No | No | 20.00% | Import data | | | | |
| | | | | | | | | | Power modes | | | | |
| | | | | | | | | | 1 | Cold TBC | | | 320 |
| | | | | | | | | | 2 | Average TBC | | | 200 |
| | | | | | | | | | 3 | Hot TBC | | | 100 |
| 4 | Paint & Tape | No | Eq | None | 2 | No | No | 0.00% | Import data | | | | |
| 5 | Heat Pipes | No | Eq | None | 60 | No | No | 0.00% | Import data | | | | |
| 9 | Doublers | No | Eq | None | 1 | No | No | 0.00% | Import data | | | | |
| 10 | Thermal Fillers & w | No | Eq | None | 1 | No | No | 0.00% | Import data | | | | |
| 11 | Miscellaneous | No | Eq | None | 1 | No | No | 0.00% | Import data | | | | |

*Figure 7.1.2.1 - TCS Power datas*

The input of the data obviously was not as trivial as it may appear, as some values are not constant throughout the entire mission, but go according to various parameters. A very important example is the PCDU, which has the task of regulating the electric power of the buses. This regulation and control element dissipates energy approximately in proportion to the regulated power as a percentage of the total. This means that for example if the solar arrays generate more power, the dissipation will be greater and the total consumption will be greater. If this is accompanied by the presence of a minimum constant value to be added, and a filter on the maximum value of the power that can be supplied, there is a complication of the calculations.

### 7.1.3 Power maturity margins

The second step to be taken is the insertion of the power margins at the level of each element, as the level of maturity of the same is a function of the stage of advancement of the design of the item itself. The power margins applied vary between 0% and 20%, according to the theorized assumption. Here there is an example: the TT&C Power Budget Margins.

H-MM units

| ID | Name | Hidden | Type | Categories | Qty | Opt | Custom power | Power margin [%] | Unit content | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Id | Name | Hidden | Layers |
| 11 | Transponder Mediu | No | Eq | None | 3 | No | No | 15.00% | Import data | | | |
| 2 | TWTA X-band | No | Eq | None | 2 | No | No | 5.00% | Import data | | | |
| 13 | TWTA Hi-band | No | Eq | None | 2 | No | No | 20.00% | Import data | | | |
| 1 | X-RFDN | No | Eq | None | 3 | No | No | 5.00% | Import data | | | |
| 3 | X-Waveguide Path | No | Eq | None | 1 | No | No | 10.00% | Import data | | | |
| 4 | LGA + bracket | No | Eq | None | 2 | No | No | 5.00% | Import data | | | |
| 19 | MGA + bracket | No | Eq | None | 1 | No | No | 0.00% | Import data | | | |
| 5 | 2.0 m HGA reflecto | No | Eq | None | 1 | No | No | 5.00% | Import data | | | |
| 6 | HGA RF parts | No | Eq | None | 1 | No | No | 0.00% | Import data | | | |
| 7 | HGA Ant. Point. M | No | Eq | None | 1 | No | No | 5.00% | Import data | | | |
| 8 | HGA HDRM | No | Eq | None | 1 | No | No | 10.00% | Import data | | | |
| 9 | HGA SC I/F parts | No | Eq | None | 1 | No | No | 20.00% | Import data | | | |
| 15 | Low Gain-RFDN | No | Eq | None | 2 | No | No | 5.00% | Import data | | | |
| 20 | External WG path tc | No | Eq | None | 1 | No | No | 0.00% | Import data | | | |
| 18 | UHF Transceiver (E | No | Eq | None | 2 | No | No | 5.00% | Import data | | | |
| 16 | UHF antenna | No | Eq | None | 2 | No | No | 10.00% | Import data | | | |
| 17 | UHF Cables | No | Eq | None | 1 | No | No | 15.00% | Import data | | | |

*Figure 7.1.3.1 - TT&C Item Power Margins*

### 7.1.4 Element power modes

Within the IDM-CIC world it is possible to provide different power modes for each object. This is necessary because a single object can have different modes of operation and peak power values can vary greatly due to mission modes/phases. As an example, the heaters and resistors of the thermal control system can absorb different electrical power values, depending on the heating needs: in this way it is possible to avoid having to choose only the ON-OFF mode of the single object.

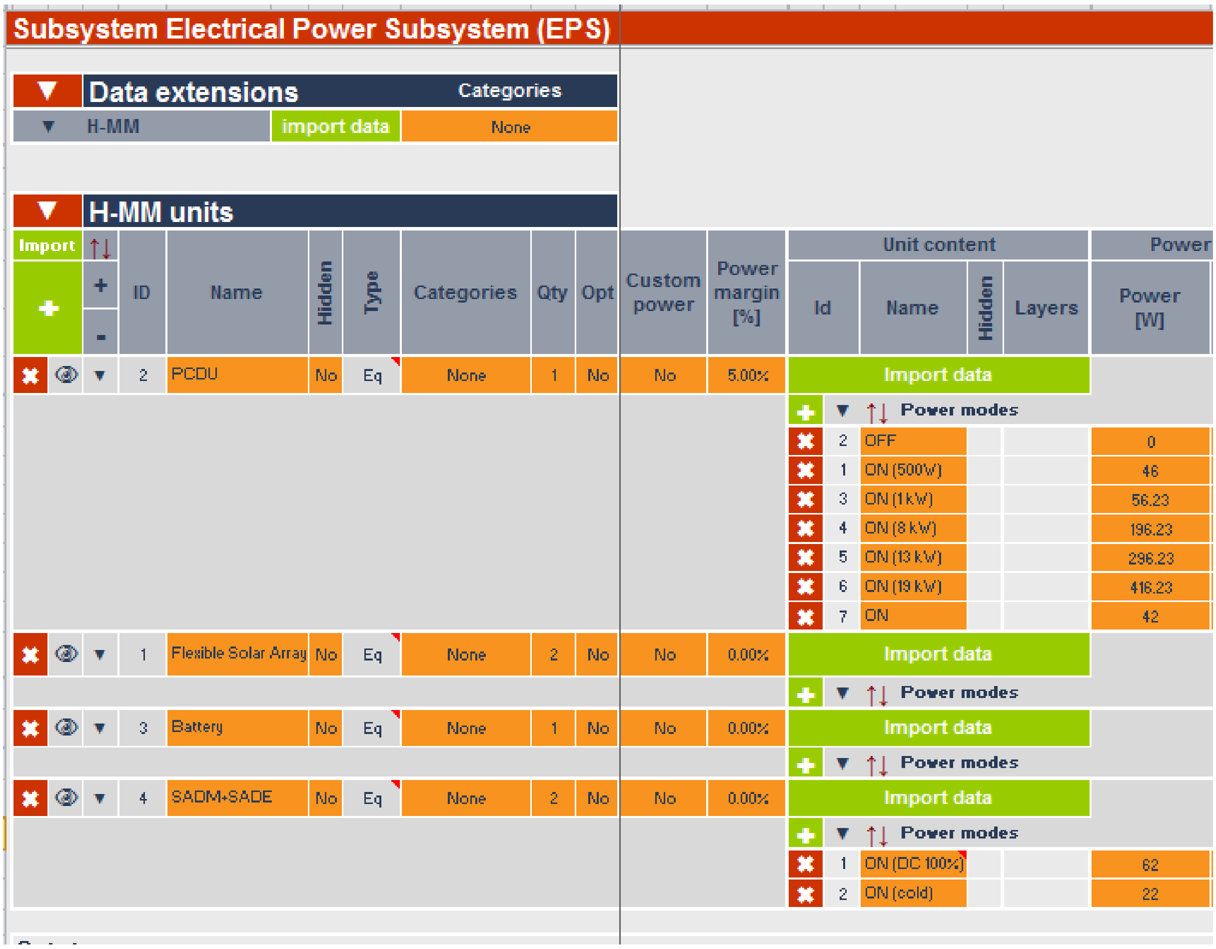



*Figure 7.1.4.1 - PCDU Power modes*

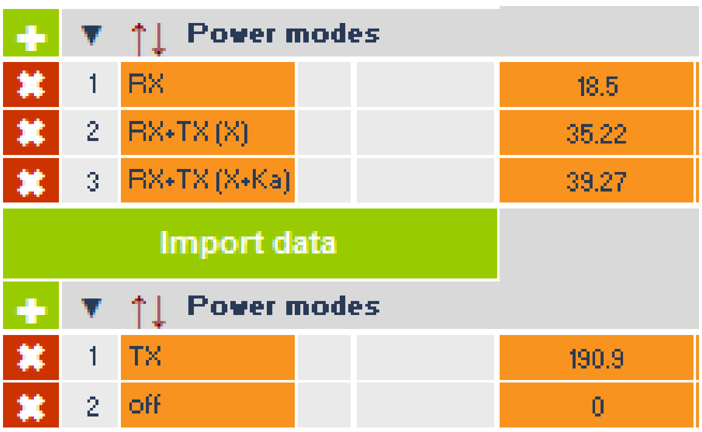



*Figure 7.1.4.2 - Transreceiver Power Modes*

### 7.1.5 Block Configurations

As already done for the calculation of the Mass Budget, 3 main configurations were modeled in the IDM-CIC file: the following figure aims to make this aspect clear.

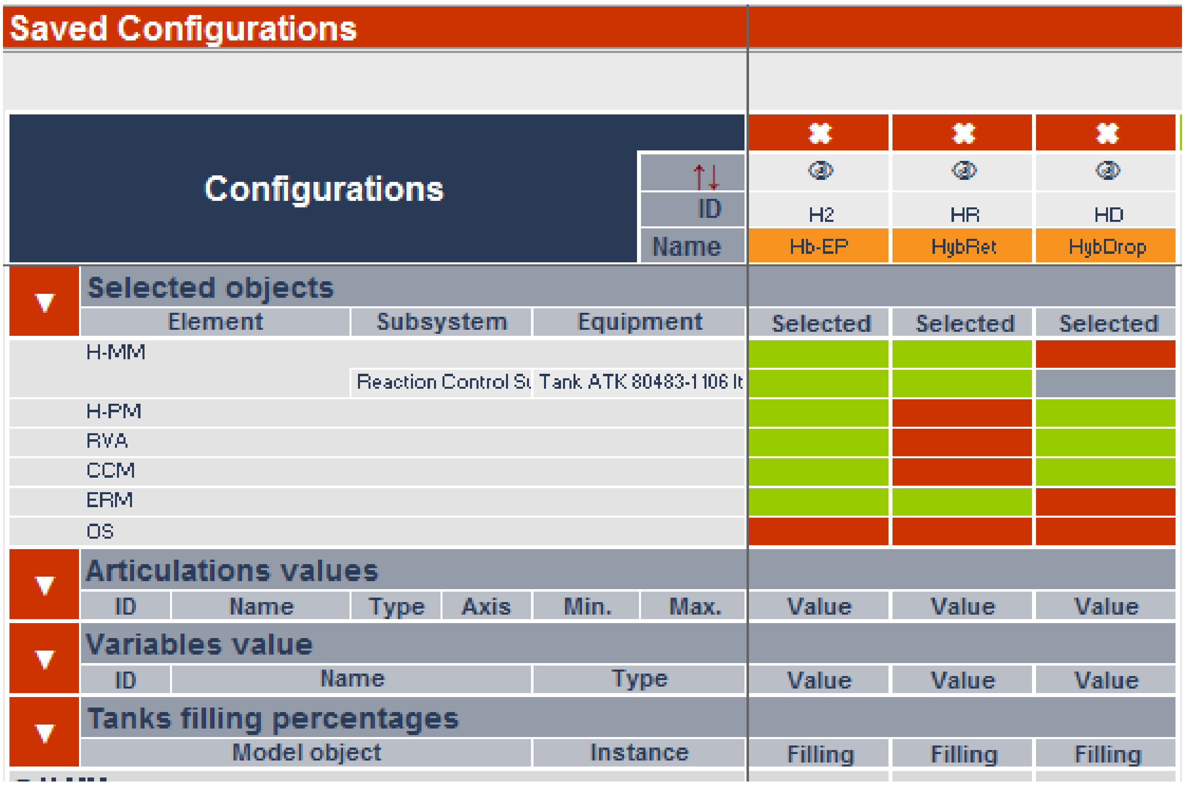



*Figure 7.1.5.1 - S/C configurations for power Modes*

The results of the power budget will be different for each configuration and will be calculated in parallel.

### 7.1.6 ERO Operational Modes

The following picture reports the S/C operational modes and all the allowed mode transitions. The red lines represent automatic transitions triggered by FDIR events, the blue ones the transitions triggered by ground telecommands and the grey ones the transitions performed autonomously on board. Some requirements to be met regarding power modes are listed here:

1)ERO-OPS-010 : The ERO system operational modes shall include:

- modes associated to the ground and flight operations before separation from the launcher: Test and Launch modes
- Fail-Operational modes for Launch, LEOP, and maneuvers
- Fail-Safe modes and Safe Modes.

2)ERO-OPS-020: in case of a major system failure (or a non-recoverable single failure) the ERO shall be able to survive in Safe Mode without the need for Ground contact for some days (to be confirmed).

3)ERO-OPS-030: the ERO operating modes shall include a system-level Safe Mode that ensures the following properties are fulfilled:

• Uninterrupted power supply

• Safe thermal conditions

• Continuous communication with ground

• Predictable configuration minimizing the on-board power demand and data traffic

4)ERO-OPS-040: the ERO in Safe Mode shall ensure a TM bit rate of TBD to the ground segment.

5)ERO-OPS-050: the ERO shall be able to change mode upon receipt of a telecommand at all times and in all spacecraft modes.

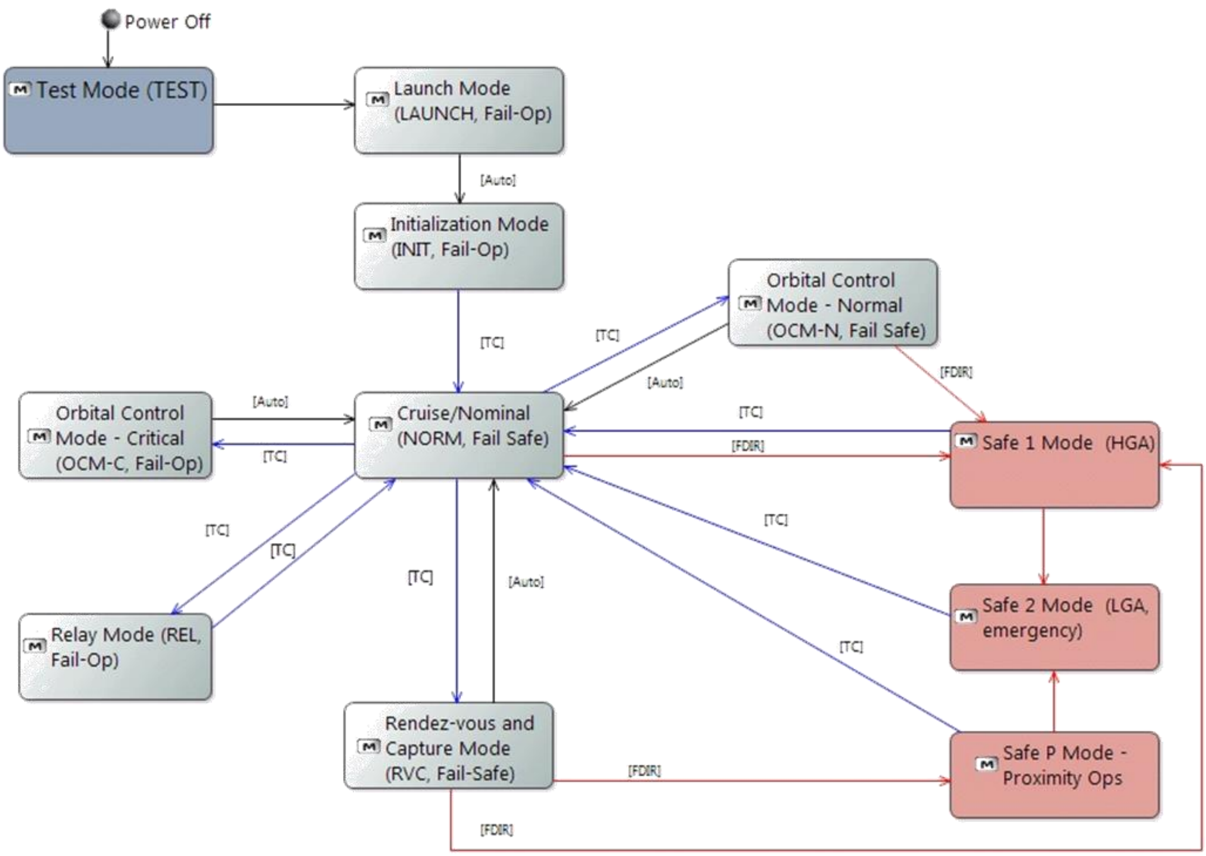



*Figure 7.1.6.1 - Operational Modes transitions*

The system mode logic is implemented in the on board software executing within the SMU. The software contains all general system services and a range of applications for functions (such as for example thermal control, attitude control, etc.).

1. Test Mode (TEST): it is a ground only mode, designed specifically for testing purposes. Only a subset of the avionic units is ON. The S/C is ready to receive tasks s and it generates telemetry packets as soon as the software is up and running. The mode entries automatically when the S/C is powered through the umbilical connector. The mode ends when the S/C powers off.
2. Launch Mode (LAUNCH): this mode is triggered by the software when the umbilical connector is removed, after the final configuration for the flight. The S/C is configured in internal power, i.e. it is powered by its batteries. Launch mode is a pre-separation idle sub-mode maintaining the spacecraft passive on the launcher. When the separation is detected, the system mode manager switches automatically to the INIT Mode. The mode entries when there is the removal of umbilical connector and the Transition to INIT mode starts upon separation detection (separation straps status read-out).
3. Init Mode (INIT): at launcher separation the INIT spacecraft mode is triggered. In this mode the spacecraft performs autonomously the reconfiguration sequence that prepares the S/C to acquire a safe sun pointed attitude. In INIT Mode the S/C performs autonomously the operation sequence that configures the Propulsion Subsystem (venting and priming), allows the acquisition of the Sun Pointing Attitude through the activation of the GNC Software and it enables the communication with ground. The Solar Array deployment is autonomously initiated, once the satellite is in steady state sun pointing. The Propulsion configuration does not include the Pressurization. Pressurization is commanded by the ground in a later phase. Fail-Op strategy is applied with PM in cold redundancy to ensure the execution of this sequence even in case of anomaly. The mode entries during the separation detection (separation straps status read-out). The exit from this mode is performed by Ground after the completion of the automatic activation sequence with a transition to Nominal mode.
4. Nominal mode (NOM): operational mode to be used during the cruise, for nominal operations. Attitude control can be performed either through Reaction Control System or Reaction Wheels. A specific GNC mode is defined for each one of the attitude control methods. The Mode Entry is due to Ground commands and the Mode Exit can be performed by Ground commands (transition to OCM-N, OCM-C, REL, RVC) or by automatic transition: SAFE1.
5. Orbital control mode nominal (OCM-N): in this mode the S/C performs the non-critical manoeuvers (either with the ME, with the RCS thrusters or with Reaction Ion Thrusters). It is implemented with a Fail-Safe strategy.
6. Orbital control mode critical (OCM-C): in this mode the S/C performs the critical manoeuvers (either with the ME, with the RCS thrusters or with Reaction Ion Thrusters). It is implemented with a Fail-Op strategy.
7. Rendez-Vous and Capture Mode (RVC) : this mode is dedicated to the rendezvous operations and the OS capture. The RVC mode implements a Fail Safe approach, with a dedicated safe mode to force the SC to perform a predefined OS avoidance manoeuver. RVC mode foresees the use of the dedicated RVC sensors (WAC and NAC).
8. Relay Mode (REL): this mode is dedicated to the UHF data transfer performed by MSR-ERO Electra UHF radio with other assets. The use of the Electra is foreseen during the SRL descent phase, during the MAV ascent and the release of the OS, and for Mars2020 data relay. It is implemented as a Fail-Safe mode.

9. Safe 1 mode (SAFE-1): The safe modes must be as much independent as possible from the previous spacecraft history to ensure the isolation against potential transmission of previous failure cases. SAFE-1 mode will allow to transmit to Earth at high data rate through a 3-axis controlled HGA pointing. The Safe Mode attitude is driven by thermal, electrical and communication constraints. When a SAFE-1 Mode transition is triggered by a level 2, 3 or 4 alarm, the S/C shall reset the software queue, switch off all the non-permanently powered units, point the Sun in order to generate power, be able to communicate to Ground via HGA and keep the radiators in shadow to reject the excess of heat, while ensuring uninterrupted power supply and safe thermal conditions. Two kinds of guidance laws are defined on-board, one loaded in PM for nominal modes, and one stored in MM to be used in case of SAFE1/NOM-P and NOM-R. These two guidance laws are regularly uploaded on-board by the Ground station.
10. Safe 2 mode (SAFE-2): A second level of safe mode is the ultimate safe mode to maintain a stable Sun pointing and to transmit to Earth at low data rate via LGA. GNC is used to maintain through RCS the Sun pointing attitude, in case the SAFE-1 reconfiguration is not successful.
11. Safe Proximity Mode (SAFE-P): Specific Safe Mode designed for the RDV phase which replaces SAFE-1. In case of a Safe Mode triggered during the proximity Ops, an OS avoidance manoeuver is performed autonomously to prevent a possible uncontrolled collision with the OS. After the successful completion of the diversion manoeuver through the RCS thrusters, the S/C is brought back in NOM-R and controlled through the RWLs.

### 7.1.7 Systems Power Modes

Estimate the power budget does not mean adding up all the maximum power consumption values but estimating the cases of greater use of the same and this does not mean that all the elements reach the peak at the same time. In the model on IDM-CIC, the operational modes of the ERO were not faithfully followed, since the majority of them do not directly specify a precise energy consumption. The power budget is heavily influenced by the mission phases, as well as by the operating modes.
For these reasons, the model will present, under the heading "operating modes",  the electric operating modes, which are nothing more than a series of operating modes in certain phases of the mission. In this phase of the project, for each system (MM, PM, etc.) various power modes are defined, which are connected to the power modes of the individual elements constituting the various subsystems.


*Figure 7.1.7.1 - MM power modes*

In this way of proceeding, however, it is necessary to avoid a misunderstanding: on IDM-CIC the blocks constituting the complete S/C were built under the heading system, and the various internal systems were modelled as subsystems.

In other words, in this paragraph when it comes to system modes, the reference is made to the modules and not of the single system, as it depends on the block or module and is formed by the union of the modes of the single elements.

| RVA | | | | ✖ | ✖ |
|---|---|---|---|---|---|
| Subsystem | Equipment | Instance | Element Modes > | STAND-BY | RDV |
| | | | | STAND-BY | RDV |
| ▼ Attitude Orbit Guidance Navigation Control Subsystem | | | Without margin [W] | 0 | 14 |
| | | | Including margin [W] | 0 | 14 |
| | ► Wide Angle Camera | | | *Set all* | *Set all* |
| | ▼ Narrow Angle Camera | | | *Set all* | *Set all* |
| | | 1 | Power mode > | OFF | ON |
| | | | Without margin [W] | 0 | 4 |
| | | | Margin (0%) [W] | 0 | 0 |
| | | | Including margin [W] | 0 | 4 |
| | | 2 | Power mode > | OFF | ON |
| | | | Without margin [W] | 0 | 4 |
| | | | Margin (0%) [W] | 0 | 0 |
| | | | Including margin [W] | 0 | 4 |
| Consumed power without margin | | | | 0 | 14 |
| Consumed power including margin | | | | 0 | 14 |
| Consumed system power margin | | | 30.00% | 0 | 4.2 |
| Total consumed power including system margin | | | | 0 | 18.2 |

*Figure 7.1.7.2 - RVA power modes*

In the same worksheet the system power margin are entered, which will be calculated from time to time for each module.

## 7.1.8 Element Power Budget Results

The element power budget is a worksheet that performs the power budget at the module level in our case, applying different margins from time to time depending on the various power modes defined before.

| ERM | | | | ✖ | ✖ |
|---|---|---|---|---|---|
| Subsystem | Equipment | Instance | Element Modes > | STAND-BY | OPERATIONAL |
| | | | | STAND-BY | OPERATIONAL |
| ▼ Earth Return Module | | | Without margin [W] | 30 | 100 |
| | | | Including margin [W] | 30 | 100 |
| | ▼ EEV without OS | | | | |
| | | 1 | Power mode > | Standby | Operational |
| | | | Without margin [W] | 30 | 100 |
| | | | Margin (0%) [W] | 0 | 0 |
| | | | Including margin [W] | 30 | 100 |
| Consumed power without margin | | | | 30 | 100 |
| Consumed power including margin | | | | 30 | 100 |
| Consumed system power margin | | | 7.00% | 2.1 | 7 |
| Total consumed power including system margin | | | | 32.1 | 107 |

*Figure 7.1.8.2 - ERM Power Budget*

The various operating modes of the single module are different in number from another module and are conceptually different. They are then disconnected from each other, and the joining element will be the power budget at the entire composite level. In this paragraph two clarifying examples are illustrated.

| H-MM | | | | ✖ | ✖ | ✖ |
|---|---|---|---|---|---|---|
| Subsystem | Equipment | Instance | Element Modes > | CRUISE-NOEP | OCM-C | CRUISE-PM |
| | | | | CRUISE OUTBOUND | MOI | THRUST-DATA RELAY |
| ▶ Thermal Control Subsystem | | | Without margin [W] | 200 | 320 | 200 |
| | | | Including margin [W] | 240 | 384 | 240 |
| ▼ Electrical Propulsion Subsystem | | | Without margin [W] | 30.3 | 0.3 | 30.3 |
| | | | Including margin [W] | 33.315 | 0.315 | 33.315 |
| | ▼ RIT-2X Assy | | | Set all | Set all | Set all |
| | | 1 | Power mode > | OFF | OFF | OFF |
| | | | Without margin [W] | 0 | 0 | 0 |
| | | | Margin (0%) [W] | 0 | 0 | 0 |
| | | | Including margin [W] | 0 | 0 | 0 |
| | | 2 | Power mode > | OFF | OFF | OFF |
| | | | Without margin [W] | 0 | 0 | 0 |
| | | | Margin (0%) [W] | 0 | 0 | 0 |
| | | | Including margin [W] | 0 | 0 | 0 |
| | | 3 | Power mode > | OFF | OFF | OFF |
| | | | Without margin [W] | 0 | 0 | 0 |
| | | | Margin (0%) [W] | 0 | 0 | 0 |
| | | | Including margin [W] | 0 | 0 | 0 |
| | | 4 | Power mode > | OFF | OFF | OFF |
| | | | Without margin [W] | 0 | 0 | 0 |
| | | | Margin (0%) [W] | 0 | 0 | 0 |
| | | | Including margin [W] | 0 | 0 | 0 |
| | ▶ TOM | | | Set all | Set all | Set all |
| | ▶ High Pressure Trasducer | | | | | |
| ▶ Reaction Control Subsystem | | | Without margin [W] | 0.9 | 0.9 | 0.9 |
| | | | Including margin [W] | 0.9 | 0.9 | 0.9 |
| ▶ Attitude Orbit Guidance Navigation Control Subsystem | | | Without margin [W] | 276.5 | 330 | 89.5 |
| | | | Including margin [W] | 290.025 | 346.2 | 93.675 |
| ▶ Data Handling Subsystem | | | Without margin [W] | 65.825 | 65.825 | 65.825 |
| | | | Including margin [W] | 69.075 | 69.075 | 69.075 |
| ▶ Electrical Power Subsystem | | | Without margin [W] | 126 | 86 | 86 |
| | | | Including margin [W] | 128.1 | 88.1 | 88.1 |
| ▶ Telemetry Tracking and Control | | | Without margin [W] | 49.3 | 283.12 | 442.97 |
| | | | Including margin [W] | 51.15 | 295.351 | 455.4035 |
| **Consumed power without margin** | | | | 748.825 | 1086.145 | 915.495 |
| **Consumed power including margin** | | | | 812.565 | 1183.941 | 980.4685 |
| **Consumed system power margin** | | | 10.00% | 81.2565 | 118.3941 | 98.04685 |
| **Total consumed power including system margin** | | | | 893.8215 | 1302.3351 | 1078.51535 |

*Figure 7.1.8.1 - MM Power Budget*

## 7.1.9 S/C Power Modes

The power modes are however defined at the full S / C level, and for this reason the considerations concerning the power modes of the previous paragraph are valid. As a last step before reading the power budget, you must associate each power module of each module with each power mode of the OR.

| ✖ | ✖ | ✖ | ✖ | ✖ | ✖ | ✖ | ✖ | ✖ | ✖ |
|---|---|---|---|---|---|---|---|---|---|
| CRUISE | MOI | TH-RELAY | DATA-RELAY | RDV | LMO-ECLIPSE | BRAZING | CRUISE2 | ORBC | SAFE2 |
| CRUISE OUTBOUND | MOI | THRUST-DATA RELAY | DATA-RELAY | RENDEZVOUS AND CAPTURE | LMO-ECLIPSE | BRAZING | CRUISE INBOUND | ETAM | SAFE |

*Figure 7.1.9.1 - S/C Power modes model*

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| CRUISE | MOI | CRUISE | Not mapped | Not mapped | Not mapped | Not mapped | Not mapped | Not mapped | STANDBY |

*Figure 7.1.9.2 - PM Power Modes Model*

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| CRUISE OUTBOUND | MOI | THRUST-DATA RELAY | DATA-RELAY | RENDEZVOUS AND CAPTURE | LMO-ECLIPSE | BRAZING | CRUISE INBOUND | MOI | SAFE |

*Figure 7.1.9.3 - MM Power Modes Model*

### 7.1.10 System Power Budget Results

After having appropriately mapped the power modes at the level of the composite with those of the modules, the complete power budget is viewable and it cannot be modified as a worksheet. To make any changes, intervene at the module, system, component level.

| System modes | | | | | CRUISE<br>CRUISE OUTBOUND | MOI<br>MOI | TH-RELAY<br>THRUST-DATA RELAY |
|---|---|---|---|---|---|---|---|
| **RVA** | | | | | | | |
| Subsystem | Equipment | Instance | | Element Mode > | STAND-BY | STAND-BY | STAND-BY |
| Consumed power without margin | | | | | 0 | 0 | 0 |
| Consumed power including margin | | | | | 0 | 0 | 0 |
| Consumed system power margin | | | | 30.00% | 0 | 0 | 0 |
| Total consumed power including system margin | | | | | 0 | 0 | 0 |
| **CCM** | | | | | | | |
| Subsystem | Equipment | Instance | | Element Mode > | NO-BRAZING | NO-BRAZING | NO-BRAZING |
| Consumed power without margin | | | | | 0 | 0 | 0 |
| Consumed power including margin | | | | | 0 | 0 | 0 |
| Consumed system power margin | | | | 0.00% | 0 | 0 | 0 |
| Total consumed power including system margin | | | | | 0 | 0 | 0 |
| **ERM** | | | | | | | |
| Subsystem | Equipment | Instance | | Element Mode > | STAND-BY | STAND-BY | STAND-BY |
| Earth Return Module | | | | Without margin [W] | 30 | 30 | 30 |
| | | | | Including margin [W] | 30 | 30 | 30 |
| | EEV without OS | | | | | | |
| | | 1 | | Power mode > | Standby | Standby | Standby |
| | | | | Without margin [W] | 30 | 30 | 30 |
| | | | | Margin (0%) [W] | 0 | 0 | 0 |
| | | | | Including margin [W] | 30 | 30 | 30 |
| Consumed power without margin | | | | | 30 | 30 | 30 |
| Consumed power including margin | | | | | 30 | 30 | 30 |
| Consumed system power margin | | | | 0.00% | 0 | 0 | 0 |
| Total consumed power including system margin | | | | | 30 | 30 | 30 |
| Total consumed power without any margin | | | | | 177.9 | 1417.595 | 1127.345 |
| Total consumed power without system margins | | | | | 201.53 | 1555.6585 | 1236.746 |
| Total consumed system power margin | | | | | 51.459 | 457.69755 | 362.0238 |
| Total consumed power including system margins | | | | | 252.989 | 2013.35605 | 1598.7698 |

*Figure 7.1.10.1 - Example of System Power Budget*

From the analysis it turns out that phases of missions that are decidedly expensive from the point of view of energy for the BUS only (thus excluding the propulsion) are the data-relay since the TT&C system applies the maximum powers, and the SAFE-2 as the control system thermal must heat the composite because of the lack of dissipation due to systems no longer working. If the propulsion is taken into account it is obvious that the operation of thrusters would be the most important item of energy expenditure. The choice to exclude the propulsion from the accounts is due to the fact that the power required by thrusters is not a fixed data, but a value that depends on the remaining available power after considering the bus load: the value of the power budget therefore determines the engine operation and not the other way around.

## 7.2 Power available

After having calculated the energy costs of the buses, we want to balance the electric power produced in order to provide a rough estimate of the power available for the propulsion alone. The trajectories computed are translated into available power from the Solar arrays and the results are compared with the energy requests. The calculations were performed on Microsoft Excel by manipulating various matrix equations with hundreds of thousands of data.

| | Earth departure 20 Oct 2026 | MOI 1 oct 2027 | LMO Arrive 1 Dec. 2027 | LMO depart 20 Mar. 2028 | Mars SOI 30 Aug 2028 | Earth SOI 17 Sept 2029 |
|---|---|---|---|---|---|---|
| Solar Flux @ Earth ($W/m^2$) | 1379 | | | | | 1353 |
| Solar Flux @ Mars ($W/m^2$) | | 618 | 680 | 706 | 552 | |

*Table 7.1 - Solar Flux Examples*

### 7.2.1 ERO-Sun Distances during operations

Input data are the distances sent from Deimos between the composite and the Sun during operations (except during the Mars operations: it assumed that the distance is equal to Mars-Sun Distance).

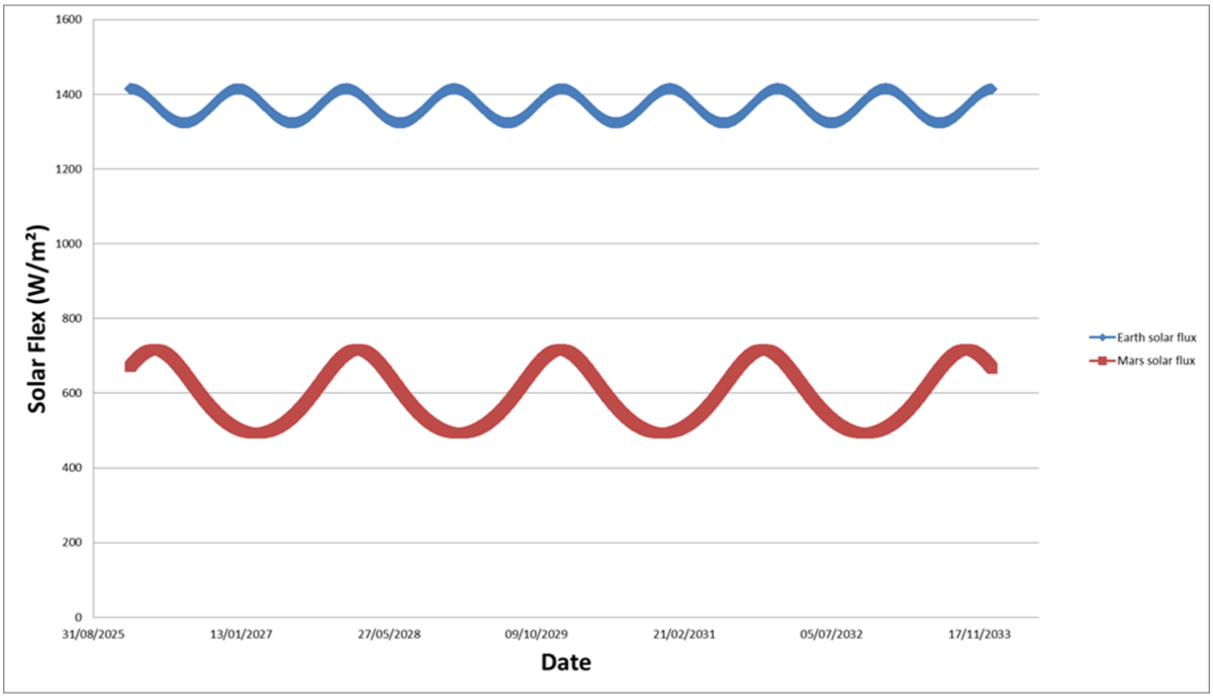



*Figure 7.2.1.1 Mars and Earth Solar Flex*

What it has been done initially is to estimate the solar flow irradiated on the S/C simply by varying the distance and reasonably assuming constant thermal and optical parameters. The data received by Deimos consists of the vector components of the ERO-Sun junction in a heliocentric reference system.

The absolute distance “d” is calculated starting from the 3 vector components, and it is defined as the square root of the sum of the squares of the components. The ERO-Sun distance is:

$$d = \sqrt{{d_x}^2 + {d_y}^2 + {d_z}^2}$$

Where $d_x$, $d_y$ and $d_z$ are the distance component of the ERO to the Sun in the J2000 reference frame (see Mean Earth Equator Reference Frame on literature) with the Sun as central body.

In order to do is to calculate the distance ratio $r_d$ defined as the ratio between the Earth-Sun distance and the ERO-Sun distance or the inverse of the distance between the ERO and the Sun in astronomical units. This means that as the S/C moves away from the sun $r_d$ decreases as the incident radiative flow.

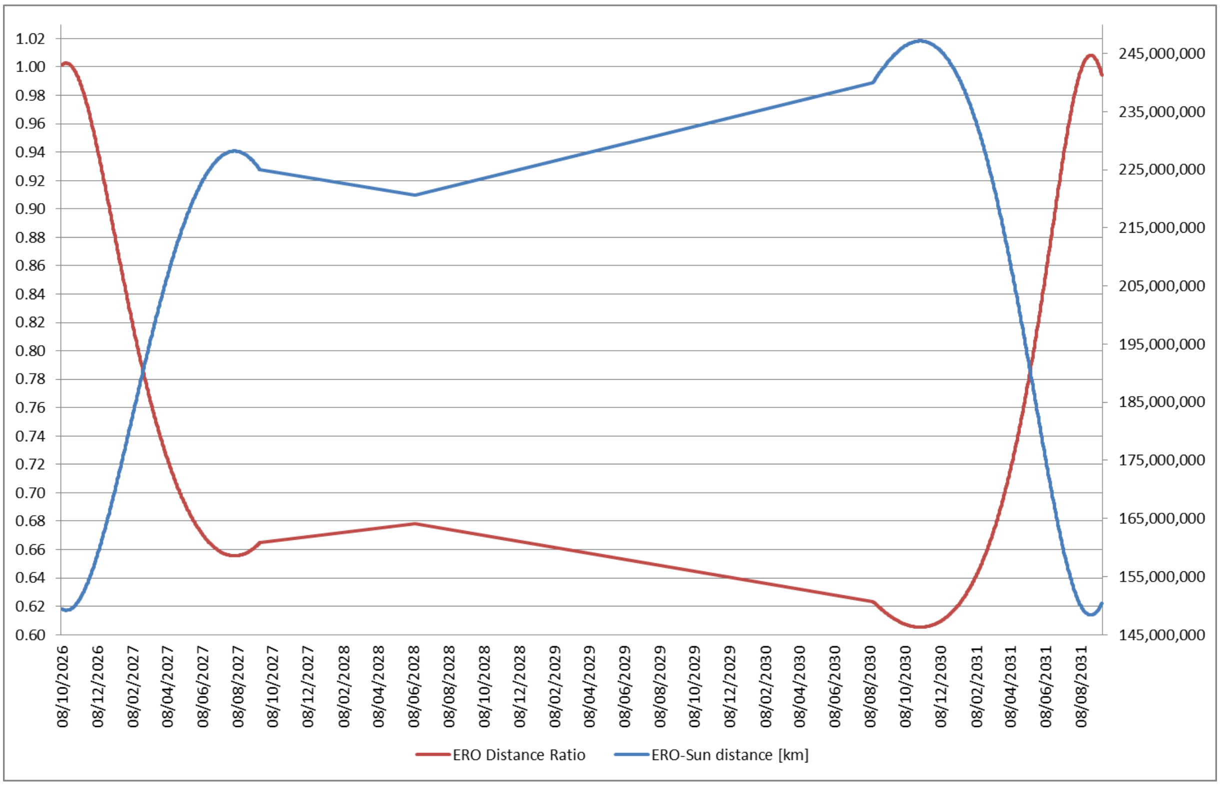



*Figure 7.2.1.1 – ERO-Sun Distance*

The chart shows the trend for the mission with a nominal schedule. The left vertical axis shows $r_d$ values, whereas the right axis represents distances. As it can be noted, the two antibodies are the same but overturned in the same graph. Obviously the back-up mission that provides for delayed launch provides different data, this is because in that solution the planets are not aligned in the same way and therefore a fly-by of the Earth is necessary with a consequent variation of the travel times and types of maneuvers.

### 7.2.2 ERO Solar Flux

The distance ratio is:

$$r_d = {}^{1AU}/_{d}$$

where 1AU is the mean distance between the Earth and the Sun (149600000 km) and d is the distance of the ERO from the Sun during the mission, as Deimos propagated it.

The solar flux is calculated as inversely proportional to the square of the distance from the Sun, so that at 1 AU it is equal to the solar constant: C=1367 W/m$^2$:

$$\phi = C \cdot (r_d)^2$$

The solar flux decreases during the Outbound phase, grows during the Inbound phase and has a sinusoidal trend during the Martian phases. Since the solar flux is equal to the product of a constant and the square of distance ratio, the trend of the latter is similar to the incident radiation from a qualitative point of view: what changes is the order of magnitude.

It is necessary to pay attention in the graph to the extreme similarity between the two trends that seem equal, but this is due to the distance ratio that takes a value very close to unity and for this reason the square of this value is not very different: differences increase as the ERO moves away from the Earth.

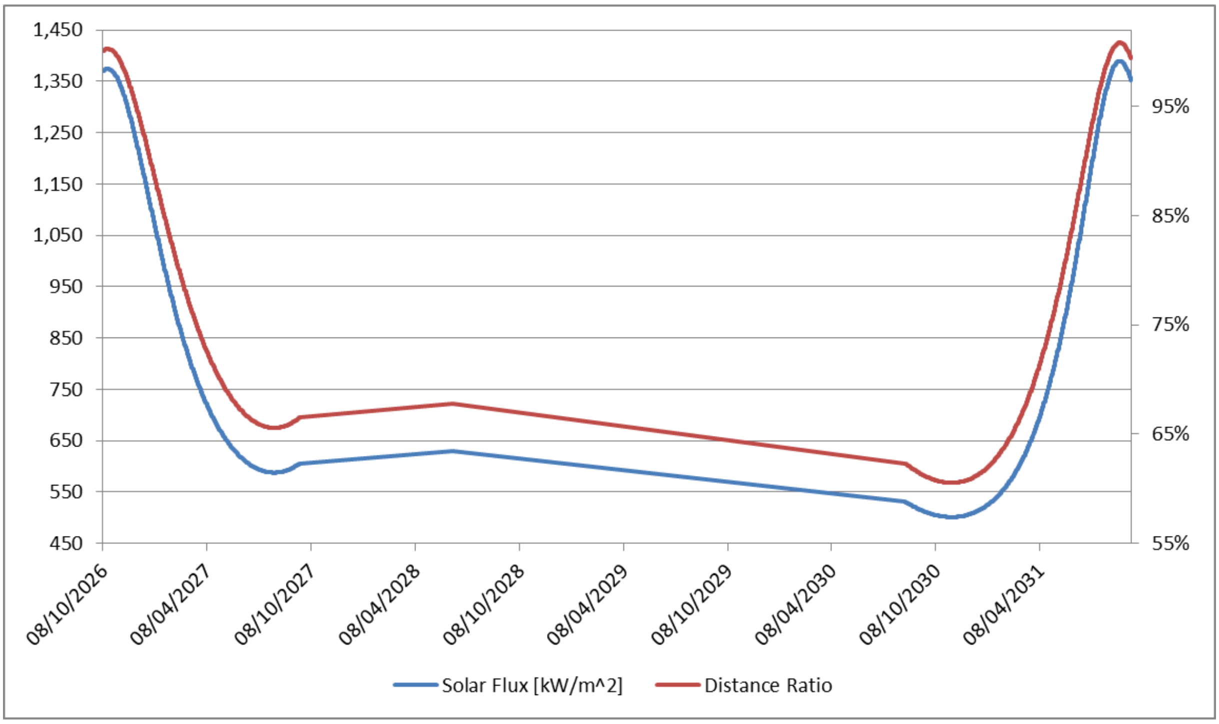



*Figure 7.2.2.1 ERO Solar Flex*

Also in this case, it must be remembered that the back-up mission will have different results both from a qualitative and quantitative point of view.

### 7.2.3 Electric power generated by the Solar Arrays

For reasons of confidentiality, the paragraph is purely illustrative but no technical data will be mentioned. Once having obtained the data and the trends relative to the solar flux incident on the ERO, it is possible to estimate the value of the electric energy produced by the solar arrays assuming the simplification hypothesis:

1. Solar Flux perpendicular to the panel;
2. Decay of solar panels constant and not exponential;
3. Constant efficiency.

At the calculated electrical power, the decay percentage of the solar panels is subtracted and the result is the available power.

The electric power that the solar arrays would generate if there were no decay of the same would be obtained from the following relation:

$$P_T = \phi \cdot \cos\alpha \cdot \eta \cdot S$$

Where $P_T$ is the theoretically producible power output without performance decay, $\alpha$ is the Solar Aspect Angle, $\eta$ is the efficiency of the Solar Arrays and S is the active surface of the panels. In the chapter on the alignment budget, we will try to estimate the Solar Aspect Angle, to obtain more representative data of these estimates. The value of $P_T$ is imposed by international agreements with the space agencies and therefore is a non-negotiable constraint.

Assuming a perfectly right Solar Aspect Angle in every moment of the mission (a very simplifying but reasonable assumption to obtain results in a short time), we obtain a trend of $P_T$ directly proportional to the solar flux.

At this point the performance decay is calculated over time. The decay has a value assumed constant with the variation of the time, therefore in Excel a percentage value of loss has been calculated to be subtracted from $P_T$.

So that this loss can be calculated, the temporal data refer to the beginning of the mission. The percentage of power loss $P_L$ is:

$$\%P_L = k_L \cdot \Delta T$$

Where $k_L$ is the coefficient of annual loss of performance power and is measured in percentage per year (Solar array conservative degradation rate per year accounted from beginning of phase), and $\Delta T$ is the time elapsed since the launch date measured in years.

The loss coefficient is the complement to 100% of $\%P_L$:

$$\%L_L = 100 - \%P_L$$

Once the loss percentage has been calculated, this value is multiplied by $P_T$, and in this way the electrical power generated is obtained:

$$P_G = P_T \cdot \%L_L$$

### 7.2.4 Bus consumption assumptions

For the calculation of the power supplied by the Solar Array, the decay of the solar panels over time and the power losses due to the PCDU were taken into consideration. Subsequently the consumption of the buses according to the various mission modes are taken into account: in this case, for simplicity, we chose to use 1.5 kW buses as consumption (conservative value).

First of all, the power loss due to the PCDU is estimated as $L_{PCDU}$; it consists of the sum of two addends: the first is a constant value due to the ignition of the object and it does not depend on its operation ($ON_{PCDU}$). The second addend is a power value ($F_{PCDU}$) proportional to the $P_T$.

$$L_{PCDU} = ON_{PCDU} + F_{PCDU}$$

The PCDU, however, is not able to control and distribute any value of electric power, but it can manage a maximum value of $P_G$, which will assume maximum values of about 60% of the maximum nominal: in other words it is as if there was a filter low management pass:

$$F_{PCDU} = K_{PCDU} \cdot P_G$$

Where $K_{PCDU}$ is a percentage constant value and $P_G$ is limited to a maximum value. After that, the losses due to the PCDU and the consumption of the bus according to the various mission modes are subtracted from $P_G$: in this case, for simplicity, we chose to use 1.5 kW buses as consumption. The final result of the analysis is the power available for electric propulsion in the various phases of mission $P_A$, taking into account the maximum values of the propulsive parameters.

$$P_A = P_G - L_{PCDU} - L_{bus}$$

Where $L_{bus}$ is the bus power consumption due to mission modes.

$P_A$ is the value of electric power available for propulsion; from a design point of view there is a maximum value of electrical power required, close to 70% of the maximum nominal value that can be supplied. Also in this case, the use is limited to a maximum value.

### 7.2.5 Power Available for EP

The final result of the analysis is the power available for electric propulsion in the various phases of mission, taking into account the maximum values of the propulsive parameters. The following graphs are dimensionless compared to the nominal maximum values of the project, to have a clear perception of the qualitative trends. The analysis is conservative also because it will not always be required the maximum propulsive thrust possible in all the mission phases, but only a part of them and in any case there will also be a duty cycle of use of the propulsors in addition to non-propulsive phases.

As it can be seen, during the Outbound phase, ERO moves away from the Sun and therefore the power available for propulsion initially assumes its maximum value and then decreases.

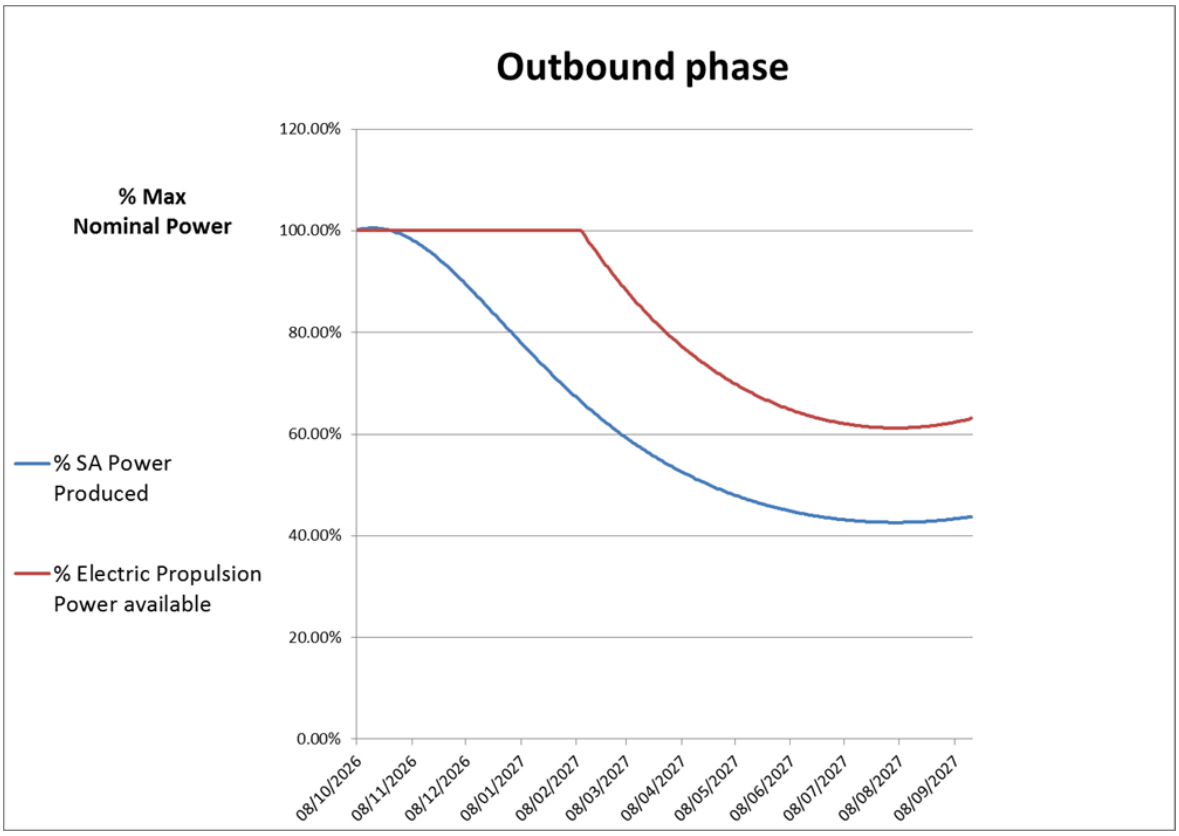



*Figure 7.2.5.1 - Outbound Powers*

When the ERO will be near Mars, it will not need great propulsive powers, so the mission requirements are met.

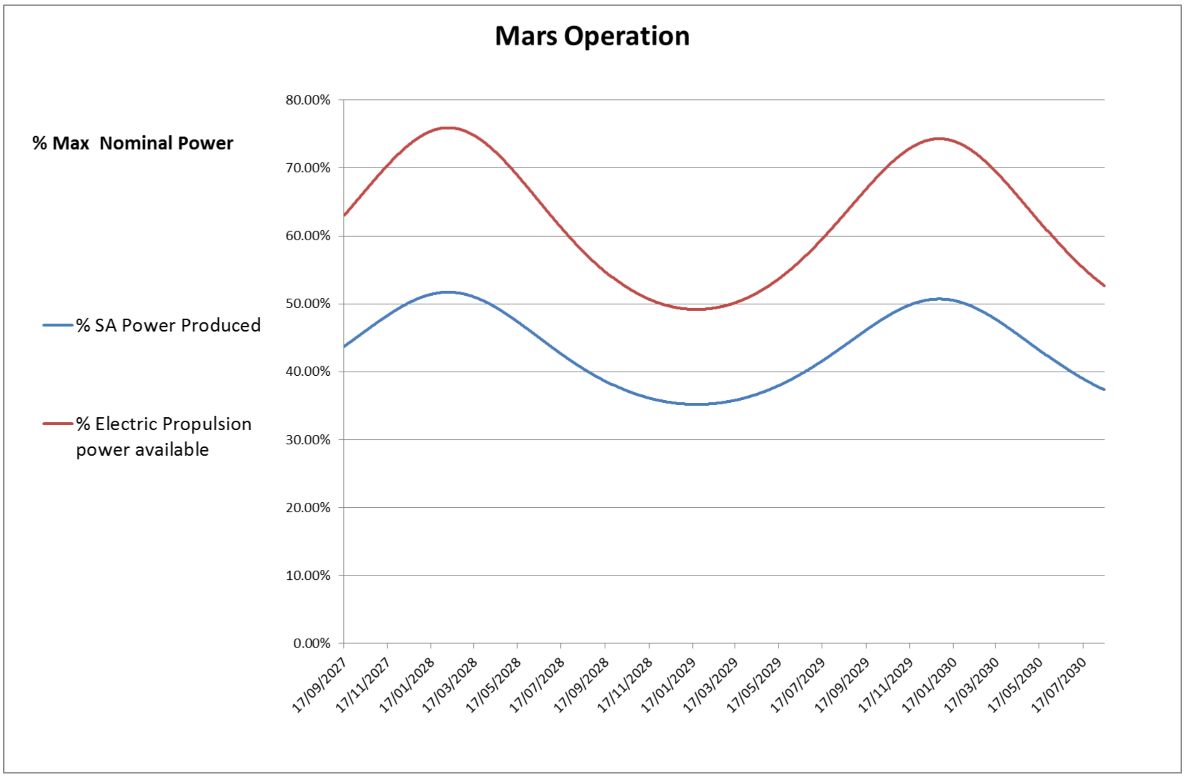



*Figure 7.2.5.1 - Mars Operations Power*

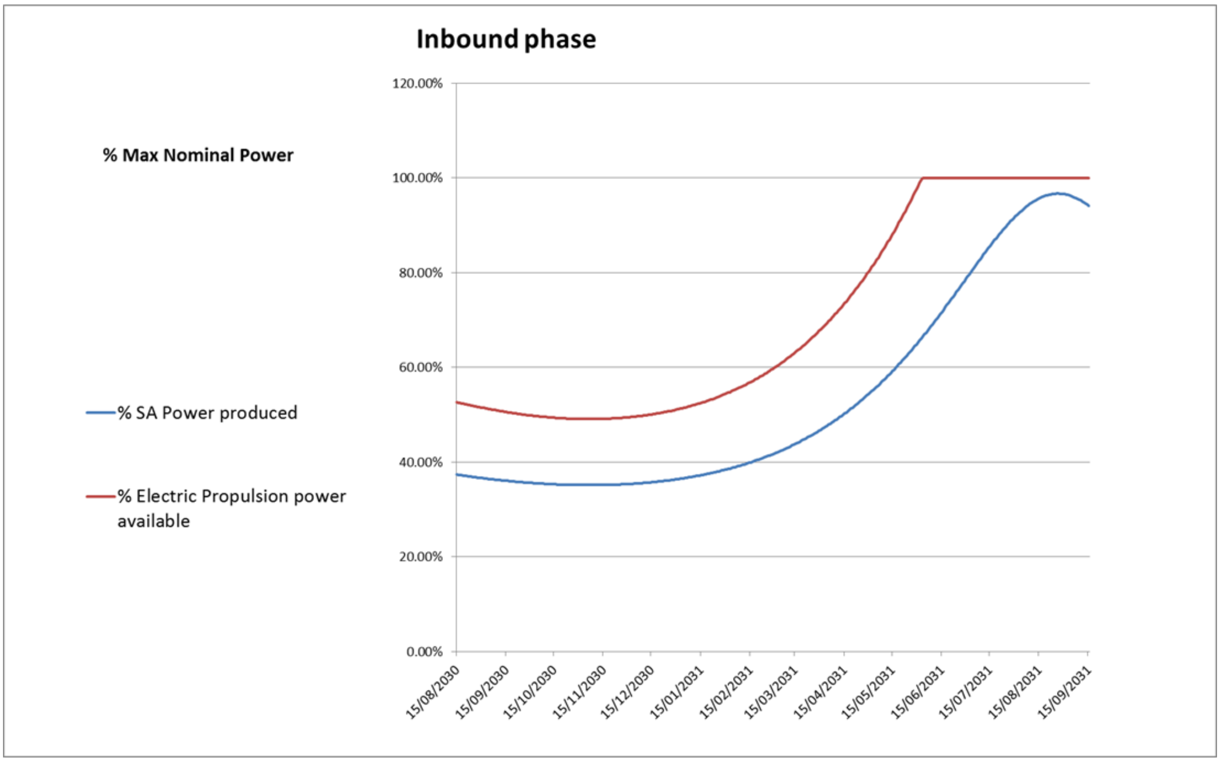



*Figure 7.2.5.3 - Inbound Phase power*

The diagrams show a conservative approach for the Mission Analysis in the inbound trajectory, despite the decay of performance, the available power will always exceed that required by propulsion.

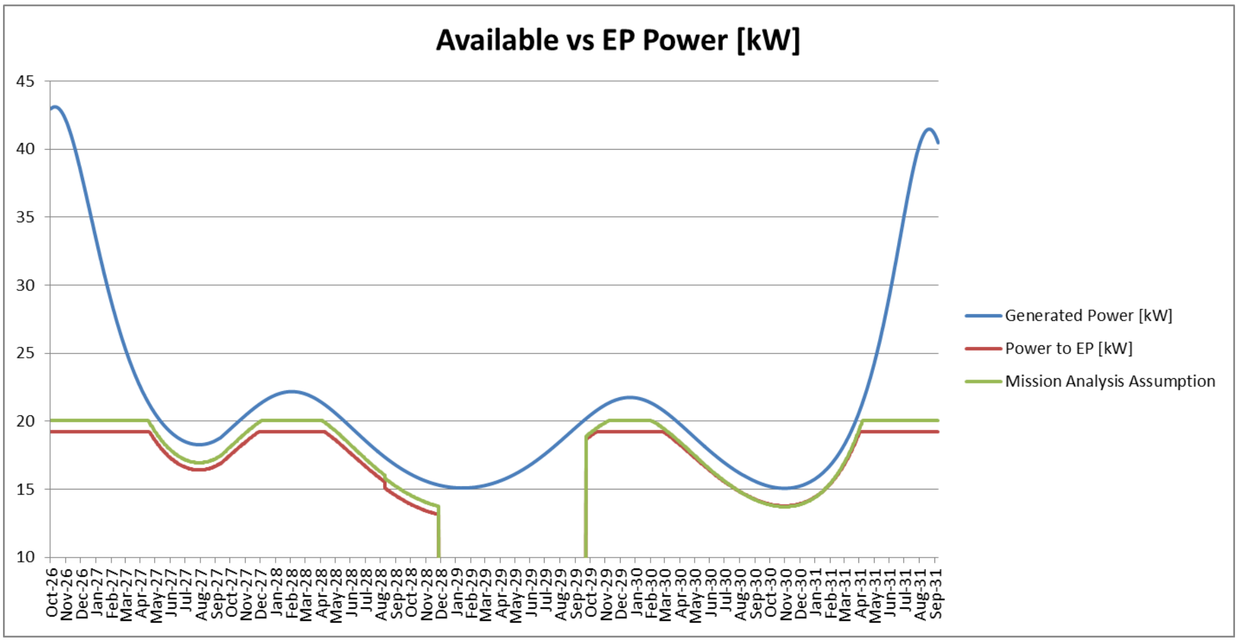



*Figure 7.2.5.4 - Power available vs assumption*

However, the current power consumption estimation provides some conservative aspects (e.g. using the max heating power) which could be counterbalance such difference. Therefore such difference is currently accepted and such phase shall be analysed after PRR, within a more detailed mission, EP, TT&C and Electric Power System analysis.

# Chapter 8

# STK Pointing budget

Among the various mission budgets is important to consider the alignment budget, which is useful for supporting the study of system design and mission analysis. On STK a scenario model of maximum strategic importance is created for the management of the ERO articulations through a mission model based on the geometry of the planets and the S/C immersed inside. The purpose of this study is therefore to estimate the maximum and minimum values and their trends over time of the angles of the S/C joints.

The structure of the ERO presents propulsive and thermal constraints, therefore the solar arrays have an articulation around the z axis of the spacecraft (the reference system is explained in the chapter related to the budget of inertia) that is around the axis relative to the length of the panels themselves: the relative position of the ERO and the Sun does not always allow the correct alignment of the solar rays with the panels and for this reason their rotation must be allowed around the longitudinal axis of the same. The HGA can instead rotate around the thrust axis (x axis of the ERO) and then in azimuth, and can rotate in elevation (around the z axis of the ERO), this because it must point towards the Earth in order to communicate with the ground station.

The data used to calculate the angles of the joints are the trajectories of the ERO in the solar system during the mission phases and the thrust directions, as well as the position of the Sun, Earth, and Mars. These information must be known in the same way as the exact time date: if different times and dates are considered, the positions of the planets will in turn be different. For these reasons, the accuracy required for the data sent by Deimos is maximum.

The STK model's construction strategy is divided into steps: initially a very conservative model is built, ignoring the existence of the joints and studying the values of the angles of the joints by choosing the most advantageous attitude trim; subsequently, geometric degrees of freedom are inserted on the HGA and the Solar Arrays to obtain a less conservative and more accurate view of the situation. The data provide important information on the possibility of moving the HGA and the Solar Arrays on the MM or not and changing configuration and interfaces if necessary.

## 8.1 Creation of STK Scenario Model

The creation of the scenario presupposes the insertion of the representative dates of the entire mission. It is fundamental from the beginning to choose what to model and in what quantities. What is chosen at the beginning are the dates of the scenario, choice of the number and type of the objects, 3D models to be used, display screens and customization of the same.

### 8.1.1 Mission data creation

For the sake of simplicity, the period of calculation chosen will be from October 2026 to November 2034. This choice is not random because we must also provide for the hypothetical back-up missions. The data of the land used remain the standard data or downloaded from the AGI Terrain Server.

### 8.1.2 Choice of satellite object

In the scenario it was decided to create a number of satellites equal to the mission segments studied and analysed by Deimos. This strategy is more convenient than creating a single satellite in which to insert all orbital data, as there are considerable time spaces without data. Four satellites are chosen to create both the BC14 nominal and the BC16 back-up schedules: two for the Outbound phase and two for the Inbound phase. Subsequently, three satellites were created for Spiral In, Spiral Out and Mars Operation for BC14. The total is therefore 7 satellites and this strategy allows a simple and quick manipulation of the received vector and orbital data.

The 3D models of the HERO are derived from IDM-CIC and have been exported as a collada (.dae format) file. They are only 2:

- Complete composite: complete model used for everything that precedes the Martian phases. It is used also for Spiral Down phase.
- Return Model: model without PM and CCM used for everything that follows the RDV phases.

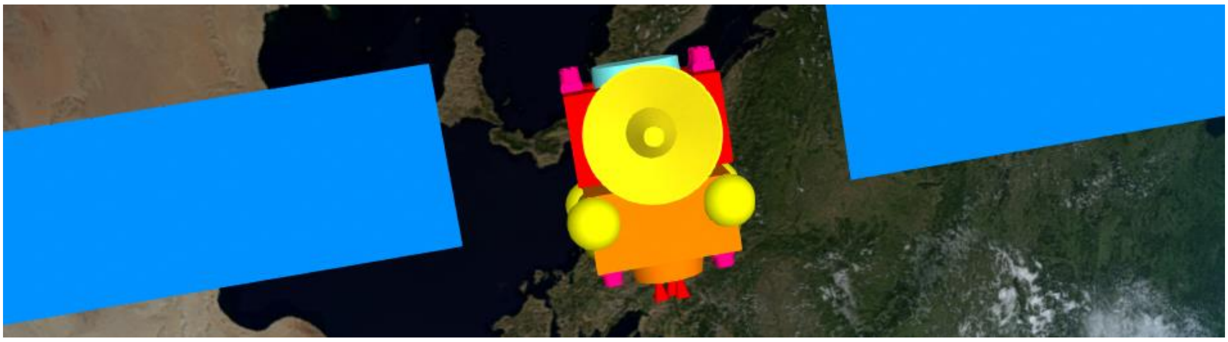


*Figure 8.1.2.1 - Outbound 3D Model*

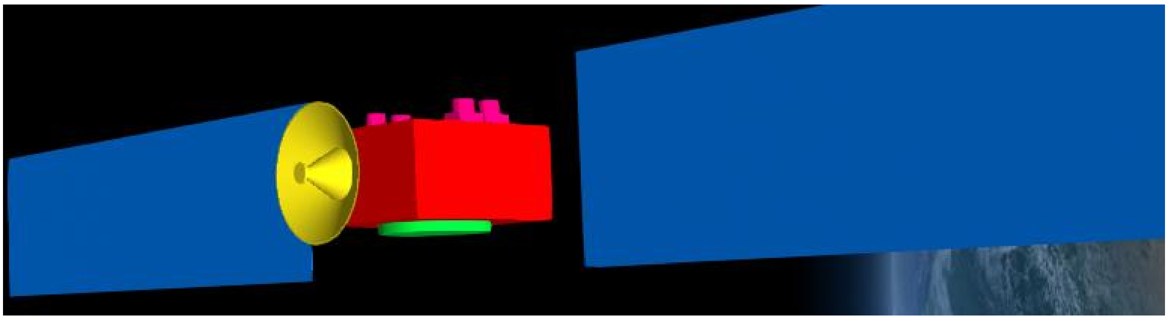


*Figure 8.1.2.2 - EAM 3D Model*

Each inserted satellite will have its own specific properties and its existence dates in the scenario and in the visualizations, according to the ephemeris data received by Deimos, which confirm the SC and the BC sent by NASA and ESA.

### 8.1.3 Globe Manager, Timeline view, graphics and animations

For the study in object the timeline views are created relative to each satellite created in the time intervals defined by the orbital data. For the various animations the 2D screens have been eliminated because the operations do not refer to a single celestial body and the trace on the ground of the satellite is of no interest. Two 3D screens will be created: the first has the Sun as the central body and the second has Mars as the central body. In the Globe Manager, however, Earth is included in the various views, but the gaseous giants are completely useless for analysis purposes. Both the orbits of the planets and the satellites are inserted in both views when they are present and vectors, grids, axes and planes can be added from time to time to improve the understanding of the events. Within the STK model various views have been saved to change the displayed object and the zoom scale. The home view represents the internal solar system in its entirety at the beginning of the mission, while some personalized stored views have been created that display the satellite on its natural scale by zooming on the object at the beginning time of the satellite ephemeris data.

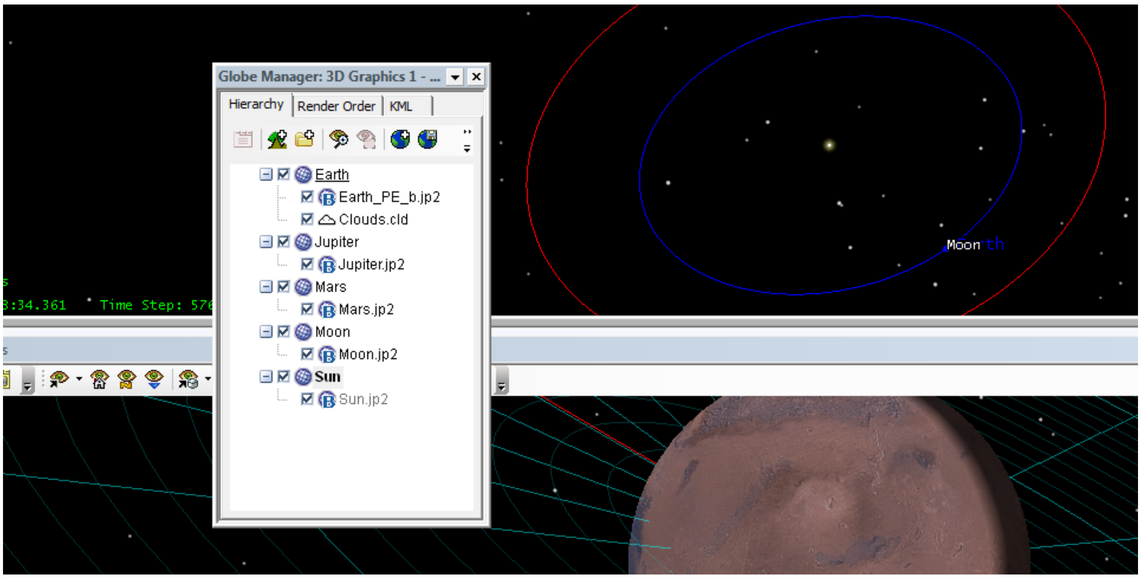



*Figure 8.1.3 - Animation view of the scenario*

## 8.2 Mission analysis input Data

The orbital data arriving from mission analysis are continuously updated as design changes are applied. For this reason various strategies have been developed and the data has been delivered as a different format file. As already mentioned, the data relating to the various mission phases were sent in separate files (Matlab format file .m, Unicode text .txt, file bsd, ext). All files contain, for each time analysed, position and speed of the ERO, components of thrust direction and mass.

| Time MJD2000 | X km | Y km | Z km | Vx km/s | Vy km/s | Vz km/s | Mass kg | Thrust_x N | Thrust_y N | Thrust_z N |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.9777898540E+04 | 0.144202612593E+09 | 0.360686052510E+08 | 0.156342878213E+08 | -0.91330639E+01 | 0.28503640E+02 | 0.11599319E+02 | 0.58600000E+04 | 0.00000000E+00 | 0.00000000E+00 | 0.00000000E+00 |
| 0.9777905422E+04 | 0.144197180884E+09 | 0.360855538095E+08 | 0.156411848895E+08 | -0.91364719E+01 | 0.28502787E+02 | 0.11598950E+02 | 0.58600000E+04 | 0.00000000E+00 | 0.00000000E+00 | 0.00000000E+00 |
| 0.9777912304E+04 | 0.144191747149E+09 | 0.361025018608E+08 | 0.156480817379E+08 | -0.91398798E+01 | 0.28501934E+02 | 0.11598580E+02 | 0.58600000E+04 | 0.00000000E+00 | 0.00000000E+00 | 0.00000000E+00 |
| 0.9777919186E+04 | 0.144186311388E+09 | 0.361194494048E+08 | 0.156549783663E+08 | -0.91432876E+01 | 0.28501081E+02 | 0.11598210E+02 | 0.58600000E+04 | 0.00000000E+00 | 0.00000000E+00 | 0.00000000E+00 |
| 0.9777926069E+04 | 0.144180873600E+09 | 0.361363964412E+08 | 0.156618747748E+08 | -0.91466953E+01 | 0.28500227E+02 | 0.11597840E+02 | 0.58600000E+04 | 0.00000000E+00 | 0.00000000E+00 | 0.00000000E+00 |
| 0.9777932951E+04 | 0.144175433787E+09 | 0.361533429697E+08 | 0.156687709632E+08 | -0.91501029E+01 | 0.28499373E+02 | 0.11597470E+02 | 0.58600000E+04 | 0.00000000E+00 | 0.00000000E+00 | 0.00000000E+00 |
| 0.9777939833E+04 | 0.144169991946E+09 | 0.361702889901E+08 | 0.156756669313E+08 | -0.91535104E+01 | 0.28498518E+02 | 0.11597099E+02 | 0.58600000E+04 | 0.00000000E+00 | 0.00000000E+00 | 0.00000000E+00 |
| 0.9777946715E+04 | 0.144164548080E+09 | 0.361872345022E+08 | 0.156825626792E+08 | -0.91569178E+01 | 0.28497663E+02 | 0.11596729E+02 | 0.58600000E+04 | 0.00000000E+00 | 0.00000000E+00 | 0.00000000E+00 |
| 0.9777953597E+04 | 0.144159102188E+09 | 0.362041795058E+08 | 0.156894582067E+08 | -0.91603251E+01 | 0.28496807E+02 | 0.11596358E+02 | 0.58600000E+04 | 0.00000000E+00 | 0.00000000E+00 | 0.00000000E+00 |
| 0.9777960479E+04 | 0.144153654270E+09 | 0.362211240005E+08 | 0.156963535136E+08 | -0.91637323E+01 | 0.28495951E+02 | 0.11595987E+02 | 0.58600000E+04 | 0.00000000E+00 | 0.00000000E+00 | 0.00000000E+00 |
| 0.9777967362E+04 | 0.144148204325E+09 | 0.362380679862E+08 | 0.157032486000E+08 | -0.91671394E+01 | 0.28495095E+02 | 0.11595616E+02 | 0.58600000E+04 | 0.00000000E+00 | 0.00000000E+00 | 0.00000000E+00 |
| 0.9777974244E+04 | 0.144142752355E+09 | 0.362550114625E+08 | 0.157101434656E+08 | -0.91705464E+01 | 0.28494238E+02 | 0.11595245E+02 | 0.58600000E+04 | 0.00000000E+00 | 0.00000000E+00 | 0.00000000E+00 |
| 0.9777981126E+04 | 0.144137298359E+09 | 0.362719544294E+08 | 0.157170381105E+08 | -0.91739533E+01 | 0.28493381E+02 | 0.11594873E+02 | 0.58600000E+04 | 0.00000000E+00 | 0.00000000E+00 | 0.00000000E+00 |
| 0.9777988008E+04 | 0.144131842337E+09 | 0.362888968864E+08 | 0.157239325345E+08 | -0.91773601E+01 | 0.28492524E+02 | 0.11594502E+02 | 0.58600000E+04 | 0.00000000E+00 | 0.00000000E+00 | 0.00000000E+00 |
| 0.9777994890E+04 | 0.144126384290E+09 | 0.363058388334E+08 | 0.157308267375E+08 | -0.91807668E+01 | 0.28491666E+02 | 0.11594130E+02 | 0.58600000E+04 | 0.00000000E+00 | 0.00000000E+00 | 0.00000000E+00 |
| 0.9778001772E+04 | 0.144120924217E+09 | 0.363227802701E+08 | 0.157377207193E+08 | -0.91841734E+01 | 0.28490807E+02 | 0.11593758E+02 | 0.58600000E+04 | 0.00000000E+00 | 0.00000000E+00 | 0.00000000E+00 |
| 0.9778008655E+04 | 0.144115462118E+09 | 0.363397211964E+08 | 0.157446144800E+08 | -0.91875799E+01 | 0.28489949E+02 | 0.11593386E+02 | 0.58600000E+04 | 0.00000000E+00 | 0.00000000E+00 | 0.00000000E+00 |
| 0.9778015537E+04 | 0.144109997993E+09 | 0.363566616118E+08 | 0.157515080194E+08 | -0.91909863E+01 | 0.28489089E+02 | 0.11593014E+02 | 0.58600000E+04 | 0.00000000E+00 | 0.00000000E+00 | 0.00000000E+00 |
| 0.9778022419E+04 | 0.144104531844E+09 | 0.363736015163E+08 | 0.157584013375E+08 | -0.91943926E+01 | 0.28488230E+02 | 0.11592641E+02 | 0.58600000E+04 | 0.00000000E+00 | 0.00000000E+00 | 0.00000000E+00 |

*Figure 8.2.1 – Mission analysis Input Example*

### 8.2.1 Modified Julian Day 2000

The slow movement of the celestial north pole describes an imaginary circle (precession and nutation motion). As a result, the vernal point is moved over time. This movement added to the motion of the stars determines the need to know the moment in relation to which the coordinates of a celestial body are expressed: this moment is called "epoch". In astronomy, the term J2000 identifies the UT noon of 1 January 2000 relative to the Gregorian calendar or the 2.451.545th Julian day. Hence, all temporal information refers to the J2000 and not to the Gregorian calendar.

### 8.2.2 Mean Earth Equator Reference Frame

The data reference system sent by mission analysis are heliocentric in all mission phases except for the spiral and the Martian phases since the central body considered is Mars. The direction of the axes is that of the axes of the equatorial geocentric system (X axis pointing the constellation of the ram and Z axis towards the north celestial pole) at the time J2000. The same reference frame can have the origin located in the center of different main bodies, respecting the directions of the J2000. This means that in this period the reference system J2000 and the equatorial geocentric coincide as directions. As you can imagine, if the main body is the Earth, equatorial plane and Z axis will be practically coinciding (ignoring the millenarian motions). The axes of the J2000 system, are oriented differently than the aerocentric axes, and this can be seen in the figure.

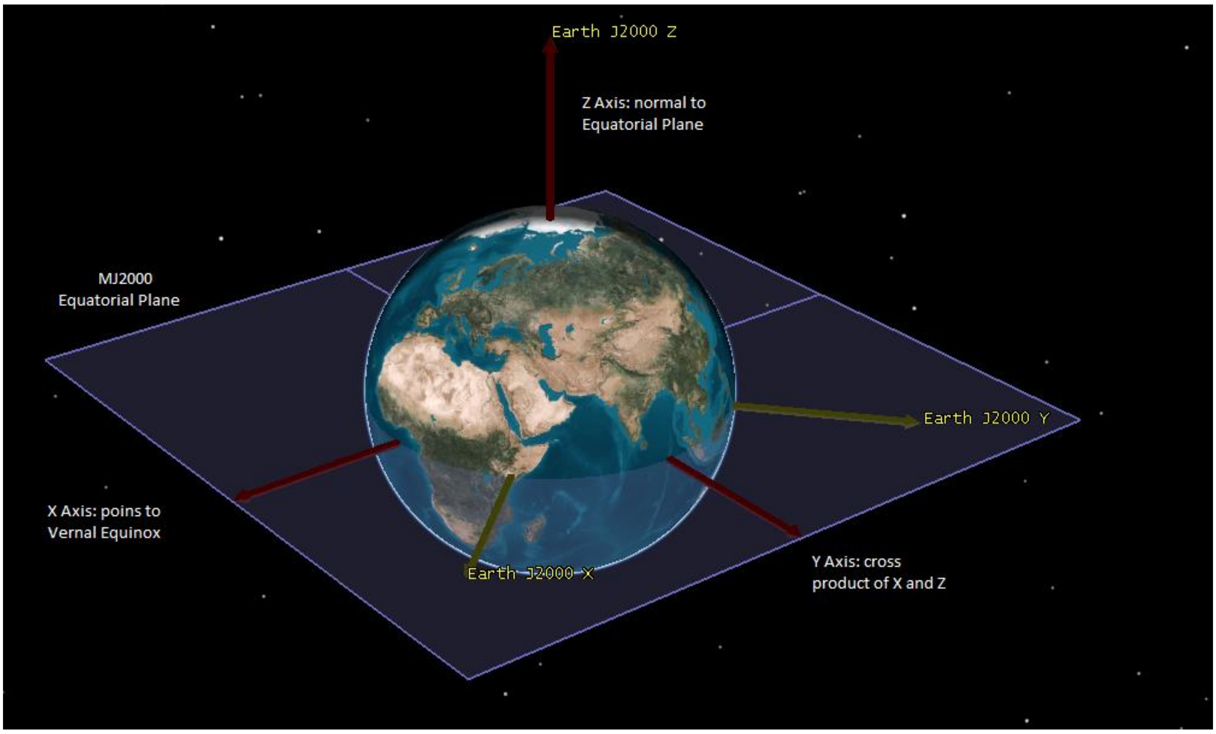



*Figure 8.2.2.1 - J2000 Reference Frame on Earth*

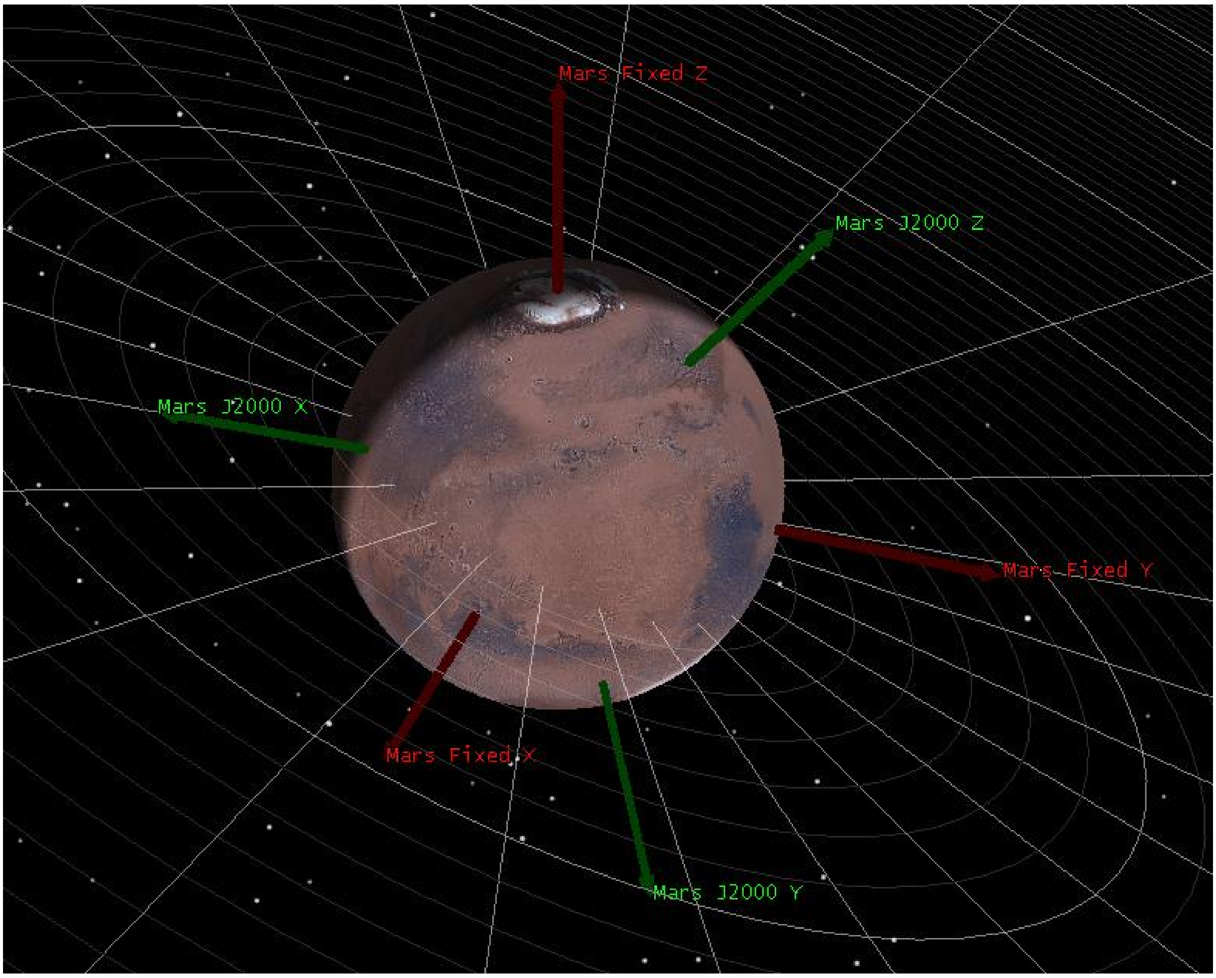



*Figure 8.2.2.2 - J2000 Reference Frame on Mars*

# 8.3 ERO Orbit Definition

For the insertion of the various trajectories of the ERO in the STK model it is necessary to know positions and velocities in the 3 spatial directions of a reference frame system defined before, in a precise astronomical epoch. The data sent by mission analysis must be manipulated as STK can work only with some reference frame systems and only with some units of measurement. In addition to this, it is added that the data must be entered in files with a file format and must be organized according to a precise conventional scheme.

## 8.3.1 Ephemeris and attitude Worksheets

The manipulation of orbital data was performed on Microsoft Excel, Matlab, Notepad and Notepad ++ and it is useful for creating data files for the thrust vector and orbit both. The following list summarizes the steps necessary for this manipulation:

1. The mission analysis data in .txt format are copied into an Excel spreadsheet by importing data; the data instead in Matlab format are copied column by column manually (to do this a transposition between rows and columns has been necessary for each row of data): this is because the data are not structured in a list but in the "structure" mode.
2. The column containing the time instants are converted from J2000 into seconds (the STK ephemeris use only the second as a unit of measurement).
3. A column has been created containing the vector module thrust, note the components. The form is calculated as $|T| = \sqrt{T_x + T_y + T_z}$ , where $T_x$, $T_y$ and $T_z$ are the components in the J2000 reference Frame.
4. It is taken note in strategic cells of the temporal intervals in which the total thrust is null and when not.
5. An orbit worksheet is created consisting of seven columns arranged in: epoch in seconds, three components of the position of the ERO, three components of velocity in space.
6. Creation of a work style related to thrust: it consists of four columns in which the first three represent the spatial components of the push vector and the last one represents the temporal instants in seconds.
7. Export of the Orbit and Thrust worksheets into external text files by means of the save mode "save as .txt file".
8. Manual change of file format (.e for ephemeris, .vd for vector data).

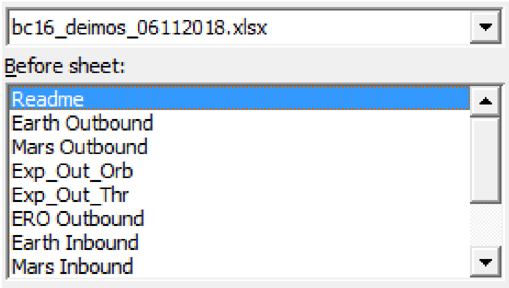



*Figure 8.3.1.1 - BC16 Worksheets*

### 8.3.2 Ephemeris STK file creation

An ephemeris file is an ASCII text file formatted conform to and STK and has an extension .e. Ephemeris data is organized into a table and imported into STK using the StkExternal propagator. This software generates the orbit of the S/C (position and velocity) just using ephemeris data; when necessary, such as when the step size is too big, STK can interpolate between two data points, in the same coordinate frame that the data are supplied in.

In the file the data must be organized in a tabular way. first of all the version of STK used is inserted; then follows the era of the scenario (the epoch through which the times are referred), the central body, the reference frame system, the units of measurement, the interpolation method, the order of interpolation, the number of points of the ephemeris, the beginning and the ending of the ephemeris points. The table below was taken from the AGI manual and it simplifies these aspects.

| KEYWORD | DESCRIPTION |
|---|---|
| stk.v.<major release number>.<minor release number><br>Example: stk.v.11.4 | This information must be the first row of the ephemeris file. It consists of the version of STK software for which the file is formatted to be used. Ephemeris files can be created in and imported to STK software versions consistent with the file version or higher. |
| BEGIN Ephemeris<br>END Ephemeris | It sets off the beginning and end of the ephemeris table lines of data |
| Scenario Epoch<br>Example:<br>ScenarioEpoch<br>15 Feb 2008 04:15:20.0 | It is the reference epoch time for the first timing point value of the ephemeris data. It is specified using Gregorian UTC time (dd mmm yyyy hh:mm:ss.s) but there is no relationship between the scenario epoch specified in the ephemeris table and the actual scenario epoch in the STK scenario. If this keyword is omitted, the default scenario epoch is the actual scenario epoch in the STK scenario. In this case, a time of 10.3 for a particular ephemeris point would correspond to a time of 15 Feb 2008 04:15:30.3. |
| Central Body<br>Example:<br>CentralBody Pluto | The central body to which the ephemeris data points are relative. If this keyword is omitted, the default central body for the S/C is the Earth. |
| Coordinate System<br>Examples:<br>CoordinateSystem TrueOfEpoch | The coordinate system in which the ephemeris points reside. If this keyword is omitted, the default coordinate system is Fixed. |

| | |
|---|---|
| Distance Unit<br>Example:<br>DistanceUnit Kilometers | It sets the distance unit to be used for all distance measurements in the ephemeris table. By default, STK assumes that all distance measurements in an ephemeris table are in meters and velocities are in meters/second. This may be overridden by setting the distance unit to be any valid STK distance unit. |
| Blocking Factor<br>Example<br>Blockingfactor 100000 | It specifies how many ephemeris points will be read at a time. While using large files, this can speed up the loading process by avoiding re-allocating big parts of memory . |
| Interpolation Method<br>Examples:<br>InterpolationMethod Hermite | It is the method by which STK interpolates between ephemeris points. By default, if omitted, STK assumes the Lagrange method. |
| Interpolation Order<br>*Example:*<br>InterpolationOrder 7 | One less than the number of points used in the interpolation. If omitted, the default value is 5. |
| Number Of Ephemeris Points<br>Example:<br>NumberOfEphemerisPoints 23561 | It indicates the maximum number of ephemeris points to read from the file. When not specified, all ephemeris points in the file will be used. |

*Table 8.1 - Orbit Keywords*

In the text file is also compulsory to specify the format for entering the ephemeris data chosen: in this case, the "EphemerisTimePosVel" format has been chosen. Each row contains values of only one data point, separated by at least one space. It is not possible to have more points for the same temporal instant, but it is possible to insert different time intervals between the various points.

BC14_Out.e - Notepad

File Edit Format View Help

```
stk.v.11.0
BEGIN Ephemeris
NumberOfEphemerisPoints 50002
ScenarioEpoch 1 JAN 2000 12:00:00.000
InterpolationMethod Lagrange
InterpolationOrder 7
CentralBody Sun
CoordinateSystem J2000
DistanceUnit Kilometers
EphemerisTimePosVel
```

*Figure 8.3.2.1 - Ephemeris intro file example*

```
8.7452652931200E+08    -8.1740990703200E+07    -1.9138681197000E+08    -8.5589212580100E+07    2.1523900000000E+01    -5.9790347000000E+00    -2.7435310000000E+00
8.7452712374400E+08    -8.1728191999200E+07    -1.9139036681800E+08    -8.5590843759500E+07    2.1524504000000E+01    -5.9776836000000E+00    -2.7429363000000E+00
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8.7452950233600E+08    -8.1676993592000E+07    -1.9140457817200E+08    -8.5597364941000E+07    2.1526919000000E+01    -5.9722788000000E+00    -2.7405573000000E+00
8.7453009676800E+08    -8.1664193092700E+07    -1.9140812900200E+08    -8.5598994352200E+07    2.1527523000000E+01    -5.9709275000000E+00    -2.7399625000000E+00
8.7453069120000E+08    -8.1651392234500E+07    -1.9141167902900E+08    -8.5600623409700E+07    2.1528126000000E+01    -5.9695762000000E+00    -2.7393677000000E+00
8.7453128649600E+08    -8.1638591017400E+07    -1.9141522825200E+08    -8.5602252113600E+07    2.1528730000000E+01    -5.9682248000000E+00    -2.7387729000000E+00
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8.7453366422400E+08    -8.1587382561600E+07    -1.9142941710700E+08    -8.5608763391600E+07    2.1531143000000E+01    -5.9628186000000E+00    -2.7363932000000E+00
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8.7453782697600E+08    -8.1497753959700E+07    -1.9145421666100E+08    -8.5620144507000E+07    2.1535362000000E+01    -5.9533561000000E+00    -2.7322278000000E+00
8.7453842140800E+08    -8.1484948440300E+07    -1.9145775623900E+08    -8.5621768965200E+07    2.1535965000000E+01    -5.9520041000000E+00    -2.7316327000000E+00
8.7453901584000E+08    -8.1472142562700E+07    -1.9146129501300E+08    -8.5623393069500E+07    2.1536567000000E+01    -5.9506521000000E+00    -2.7310375000000E+00
8.7453961113600E+08    -8.1459336327000E+07    -1.9146483298300E+08    -8.5625016819900E+07    2.1537169000000E+01    -5.9493000000000E+00    -2.7304423000000E+00
8.7454020556800E+08    -8.1446529733200E+07    -1.9146837014900E+08    -8.5626640216400E+07    2.1537772000000E+01    -5.9479479000000E+00    -2.7298470000000E+00
8.7454080000000E+08    -8.1433722781300E+07    -1.9147190651100E+08    -8.5628263258900E+07    2.1538374000000E+01    -5.9465957000000E+00    -2.7292518000000E+00

END Ephemeris
```

*Figure 8.3.2.2 - Ephemeris example file ending*

Each line has individual data points following the EphemerisTimePosVel format. The keywords look like this: <TimeInSeconds> <X> <Y> <Z> <xDot> <yDot> <zDot> , where:

| | |
|---|---|
| <TimeInSeconds> | The time value of the point relative to the epoch as defined by the ScenarioEpoch keyword. |
| <X> <Y> <Z> | ERO position components. |
| <xDot> <yDot> <zDot> | ERO velocity components. |

*Table 8.2 - Ephemeris format*

### 8.3.3 Orbit views and verification

After preparing the files, entering in the STK scenario,  the ephemeris data are imported using the properties of the satellite, in the orbit tab. The orbit propagator is an STK external source (or SPICE propagator in same cases), which asks for the location of the correct file. All the data in the figure are automatically loaded and there is no need to insert them, unless there is a need of insertion of additional overwriting and changes in certain time intervals.

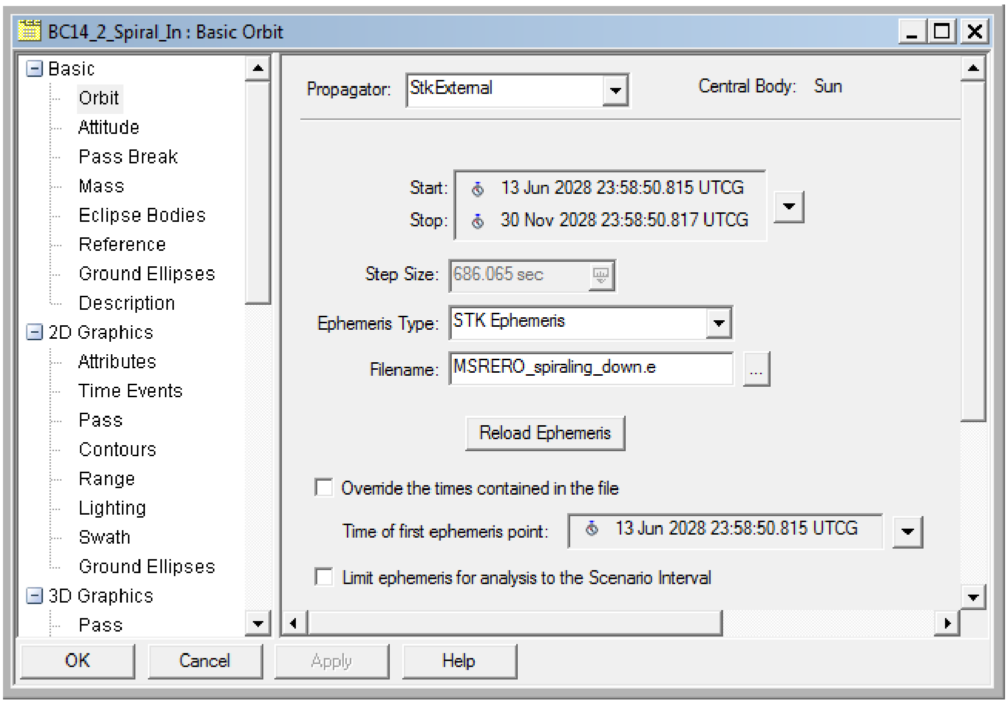



*Figure 8.3.3.1 - Orbit insertion example 1*

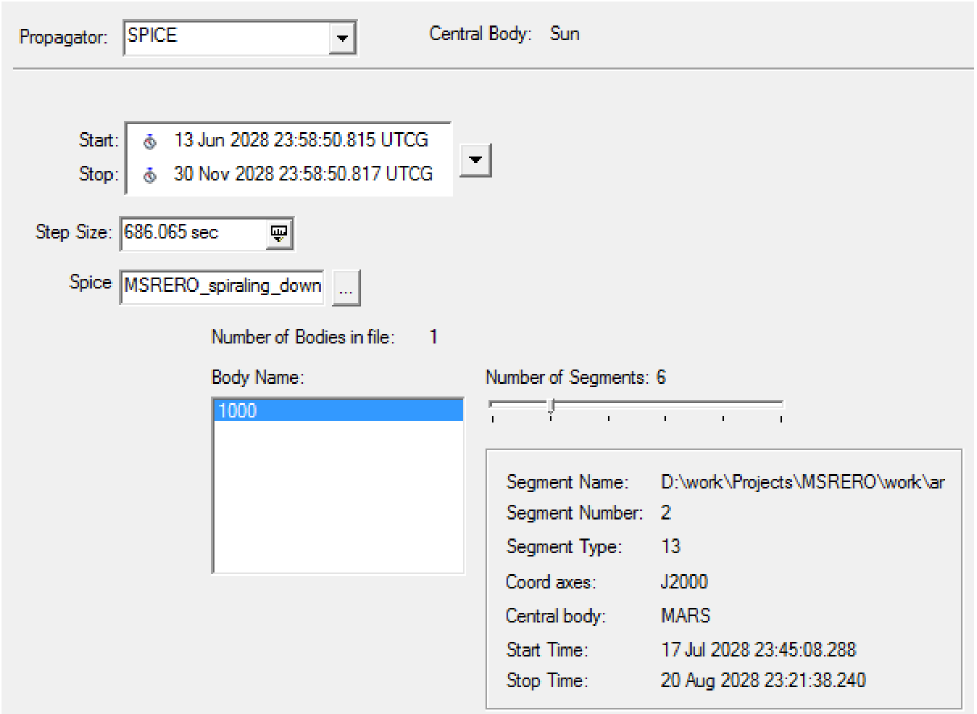



*Figure 8.3.3.2 - SPICE orbit insertion*

In 3D graphics windows  the trajectory can be appreciated and confirmed, as per BC14 and BC16. Here there are some illustrative examples.

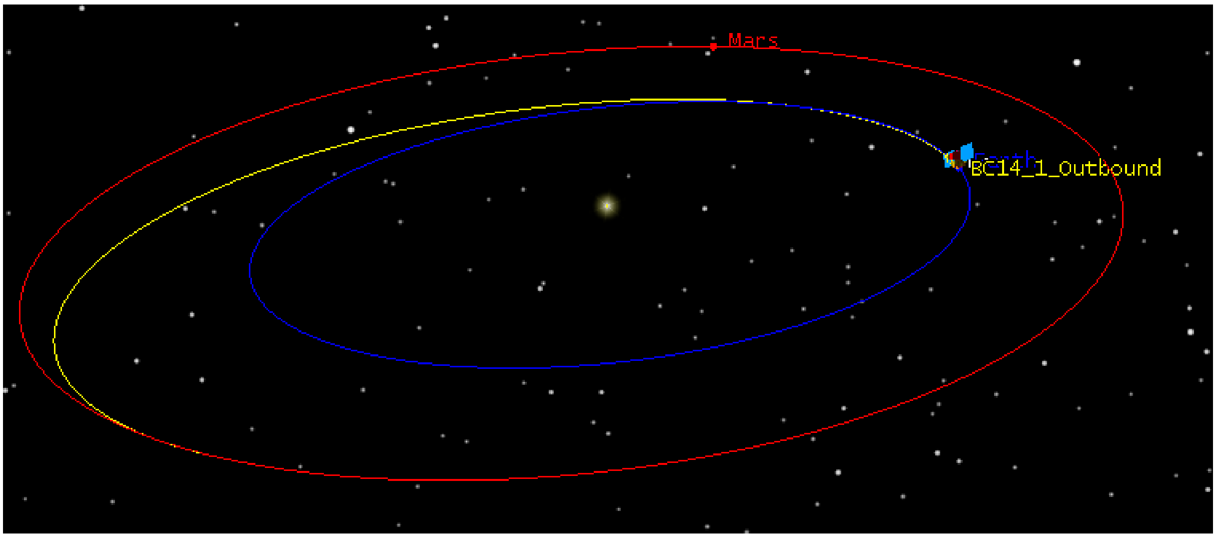



*Figure 8.3.3.3 - BC14 Outbound trajectory*

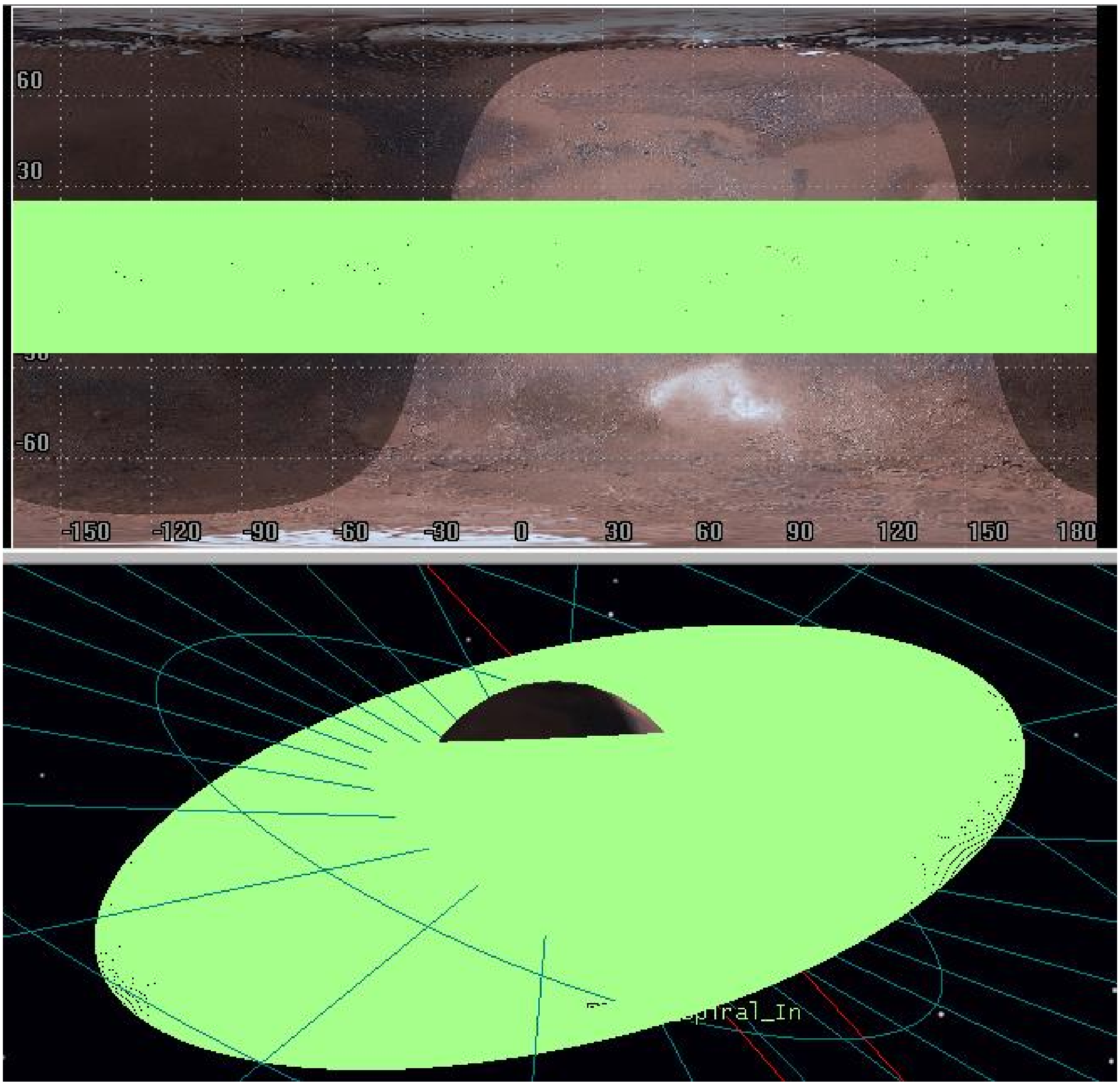



*Figure 8.3.3.4 - BC14 Spiral In trajectory*

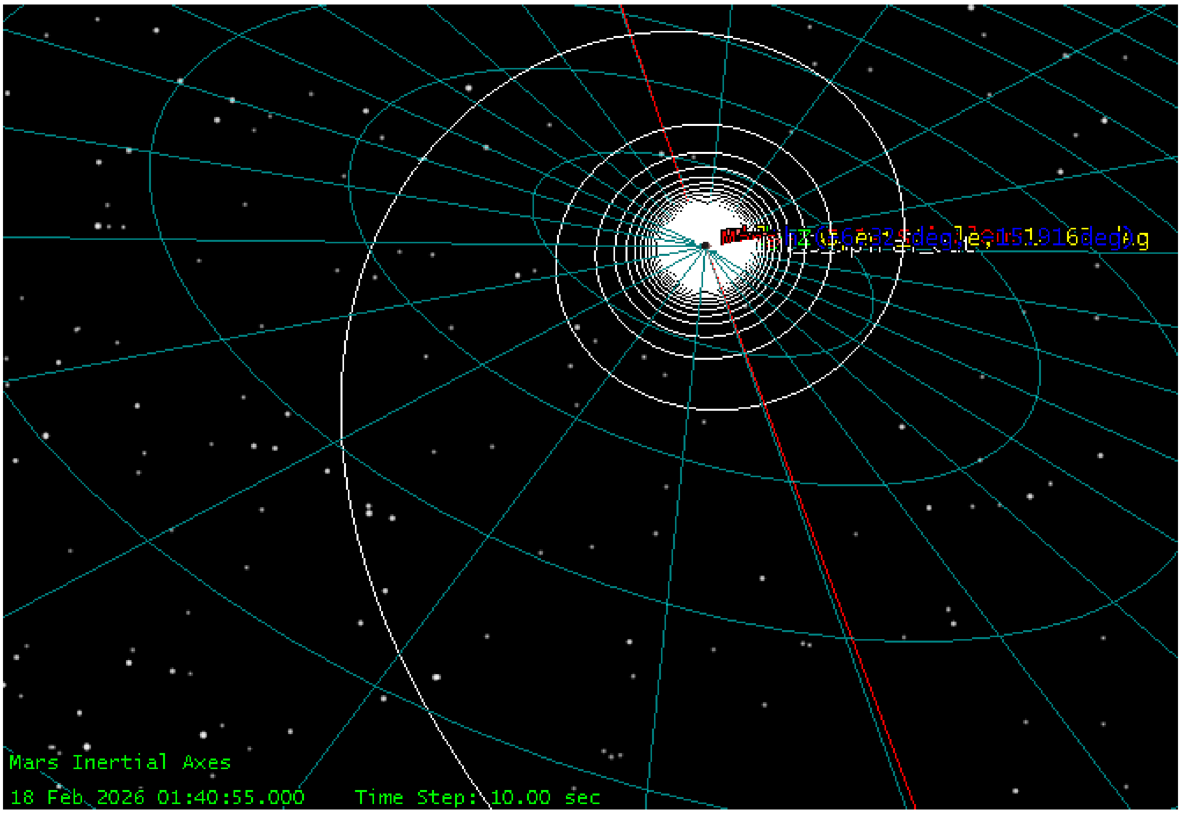



*Figure 8.3.3.5 - BC14 Spiral Up trajectory*

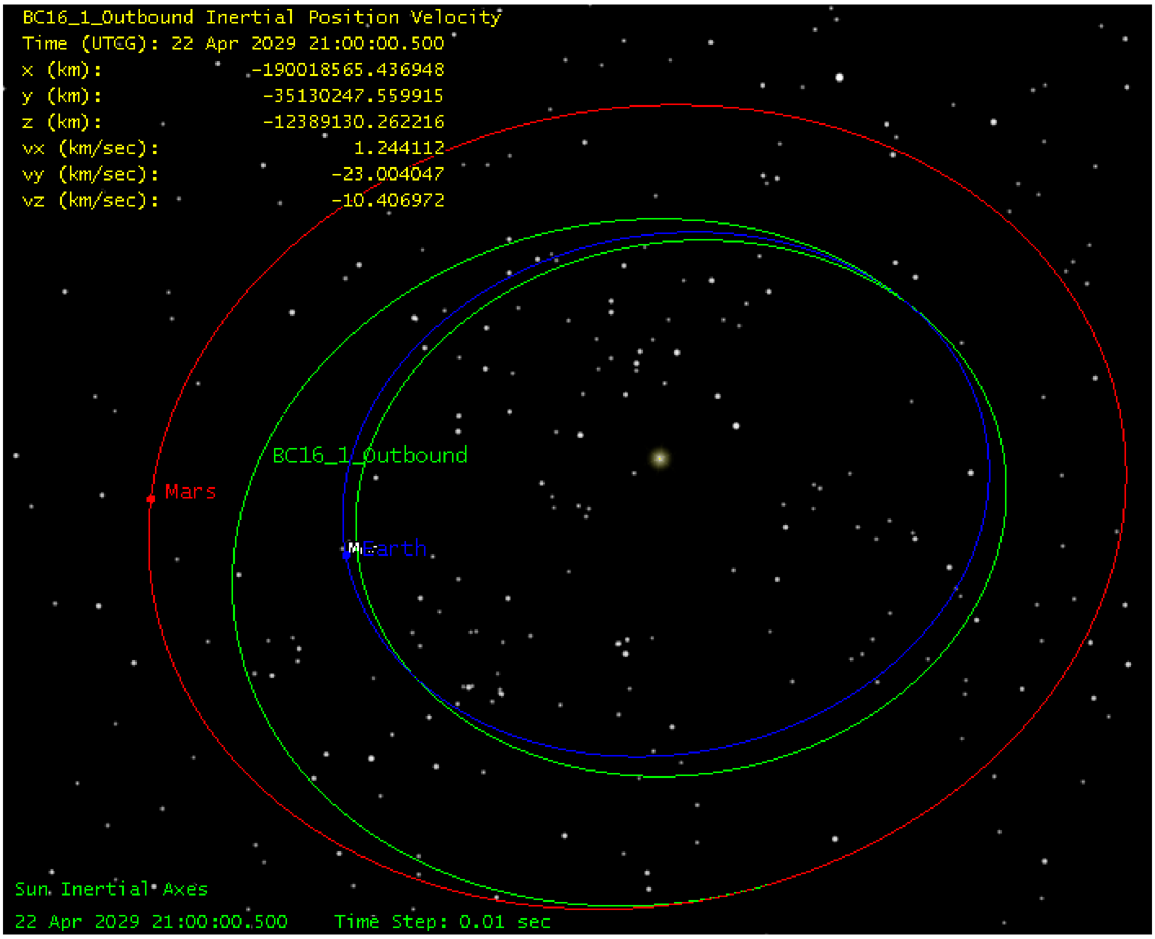



*Figure 8.3.3.6 - BC16 Outbound trajectory*

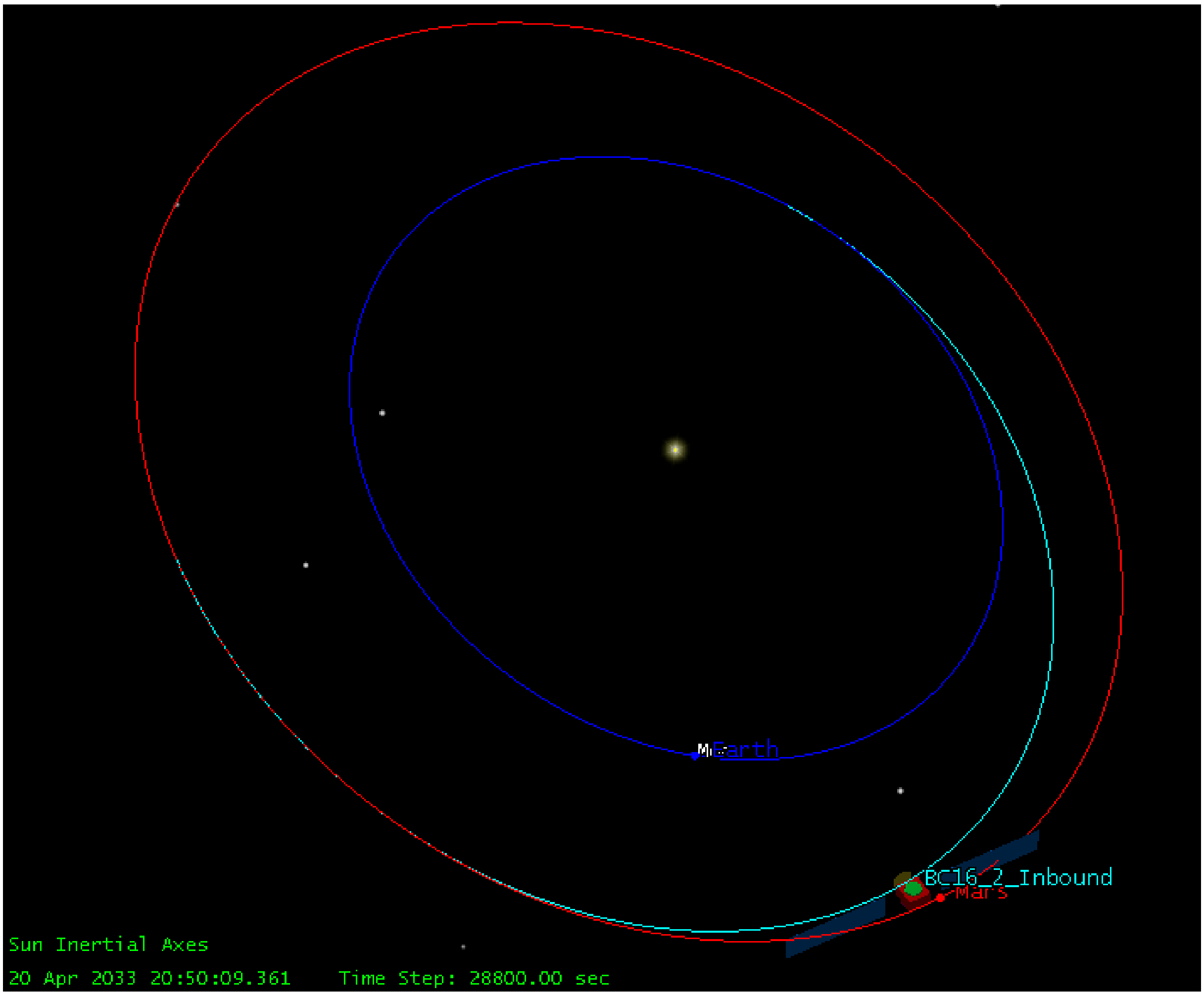



*Figure 8.3.3.7 - BC16 Inbound trajectory*

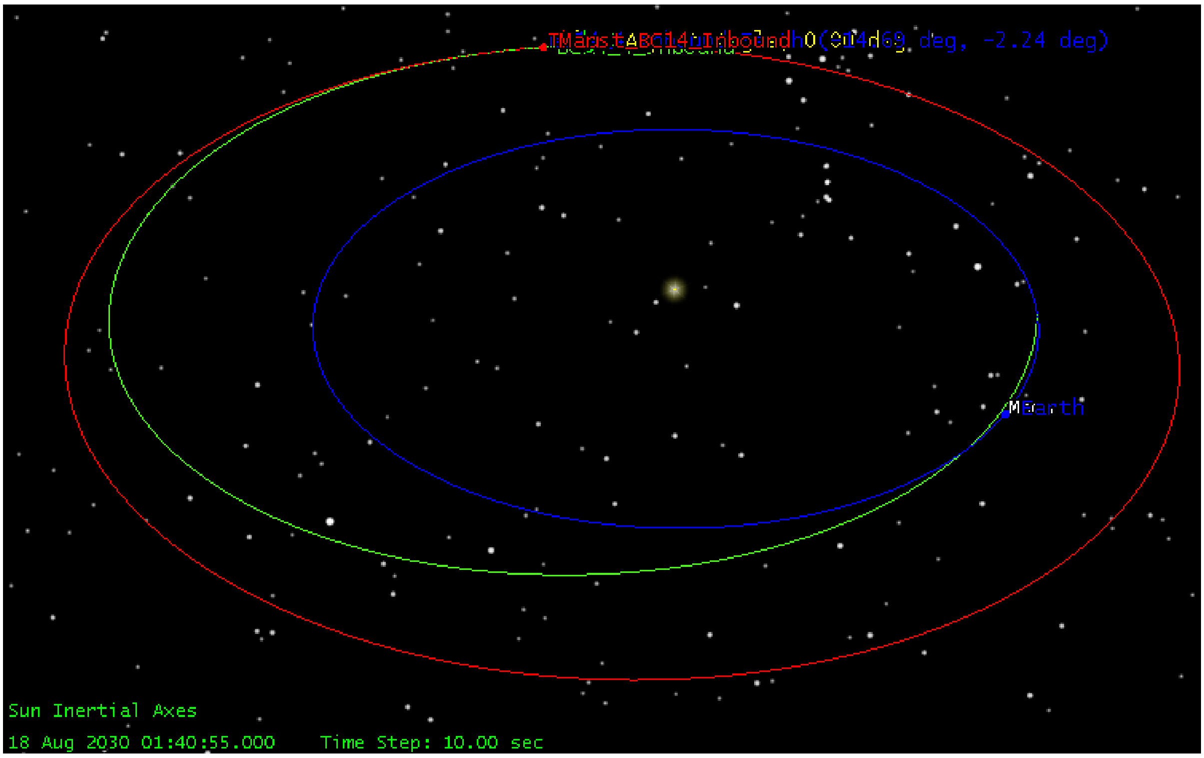



*Figure 8.3.3.8 - BC14 Inbound trajectory*

## 8.3.4 Mars operations Target Orbit

Currently the ephemeris data are not known during the RDV phase, for this reason the ephemeris data are inserted according to the most updated MAG. With the purpose described before, the nominal orbit considered to the OS at the release from the MAV is defined as:

| Orbital Parameter | Symbol | Value | Unit of measure |
|---|---|---|---|
| Pericenter | rp | 3392.33 + 343 | Kilometer [km] |
| Apocenter | ra | 3392.33 + 343 | Kilometer [km] |
| Inclination | i | 18 | Degree [°] |
| Eccentricity | e | 0 | Dimensionless |
| RAAN | Ω | free | Degree [°] |
| Argument of Perigee | ω | free | Degree [°] |
| True anomaly | υ | free | Degree [°] |

*Table 8.3 – MAG Mars Orbital parameters*

For the purpose of the analysis, the unconstrained orbital parameters are entered randomly as they do not alter the results. The insertion of the data is then carried out through the propagation of the problem of the two bodies, hence ignoring orbital perturbations and corrections. The satellite's existence interval is therefore included between the end of the Spiral In phase and the beginning of the Spiral Out phase, and the data entered are the classical orbital parameters in a fixed equatorial reference frame system.

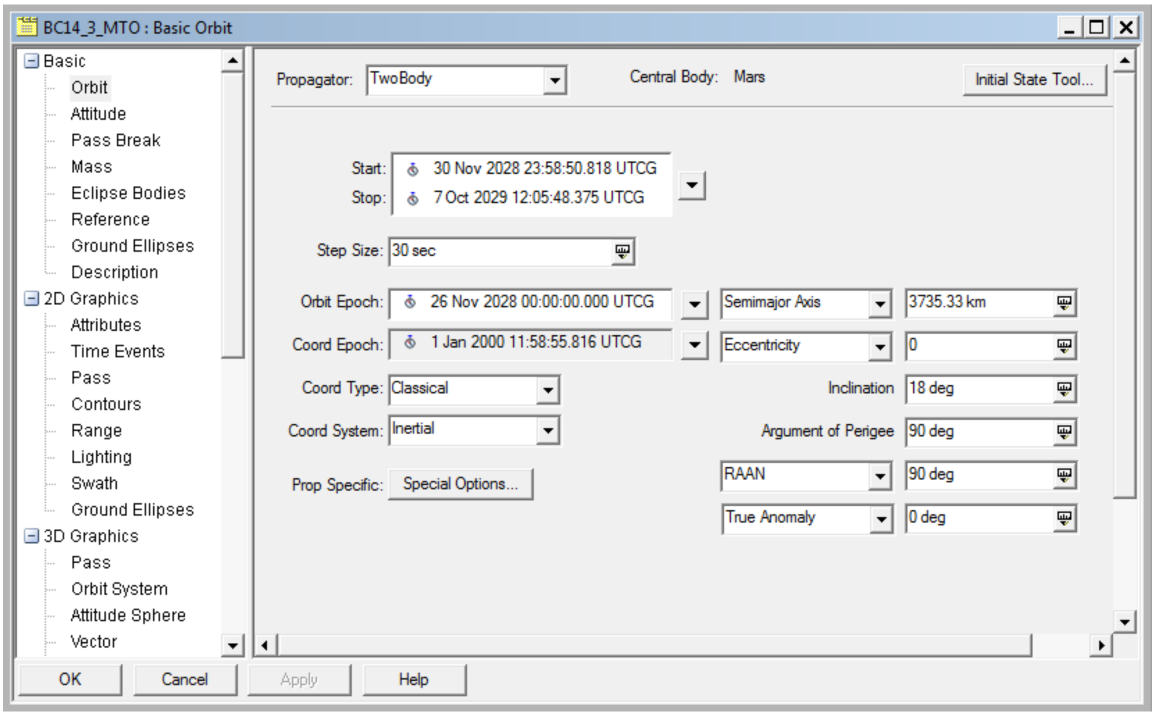



*Figure 810.3.4.1 - Mars Operation Basic Orbit model*

In more in-depth analysis, if the data of any orbital corrections were known, an orbital perturbation could be added due to the presence of a third third body through the HPOP or J2 propagators and other minor perturbations such as the contribution due to the non-sphericity of Mars through the perturbator J4.

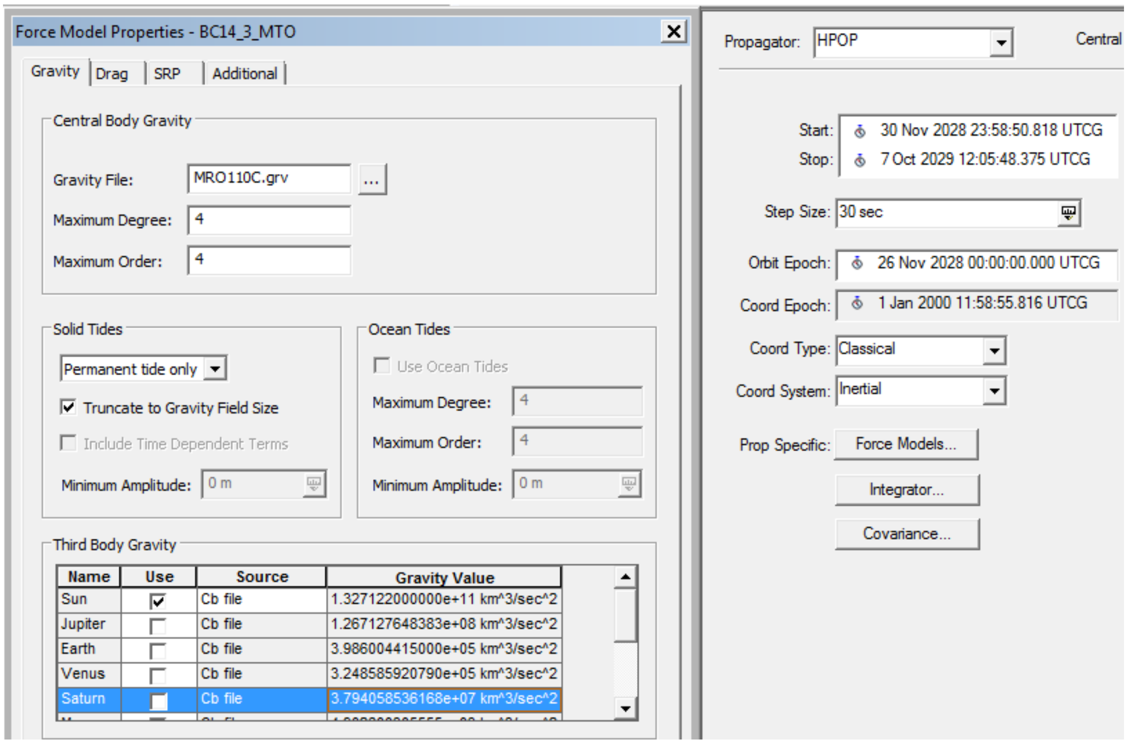



*Figure 8.4.3.2 - HPOP definition*

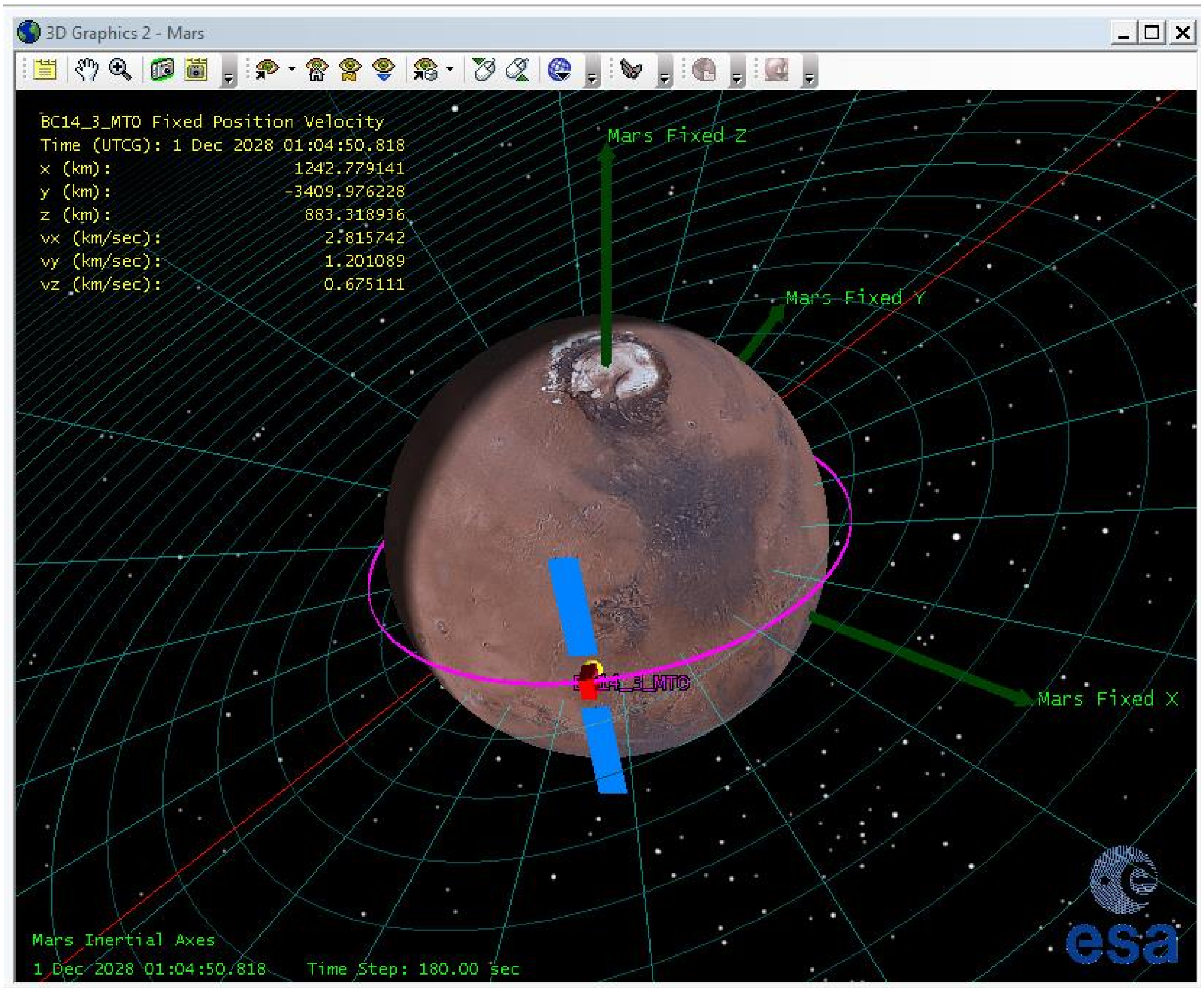



*Figure 8.3.4.3 - Mars Operation Orbit View*

# 8.4 Fixed Geometry Construction

The next step for creating the model is the definition of geometric elements necessary for the analysis to be carried out. For every single satellite created in the STK scenario, all the elements referred to in this paragraph are inserted. In order to bring these elements and to validate them, it is necessary that the ERO 3D models were entered and that each satellite has already ephemeris data. Hence, accessing the properties of the satellite and more precisely in the 3D graphics panel, the procedure consists of opening the "vector" tab.

## 8.4.1 ERO Modelled Axes

The first geometric elements to be inserted are the reference body axes for each satellite created.

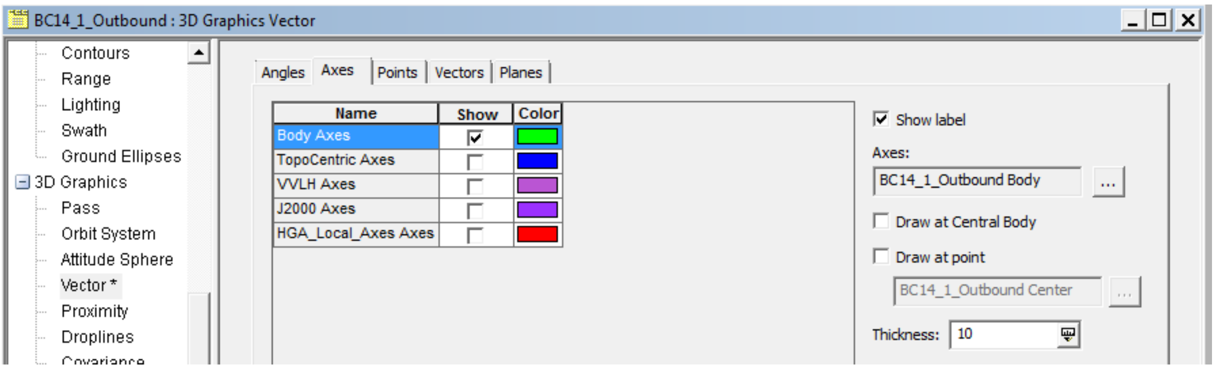



*Figure 8.4.1.1 – Modelled Axes tab*

The first triad coincides with the body axes that have already been discussed in the chapter concerning the inertial budget. This reference system is preloaded in the model by importing the collada model.

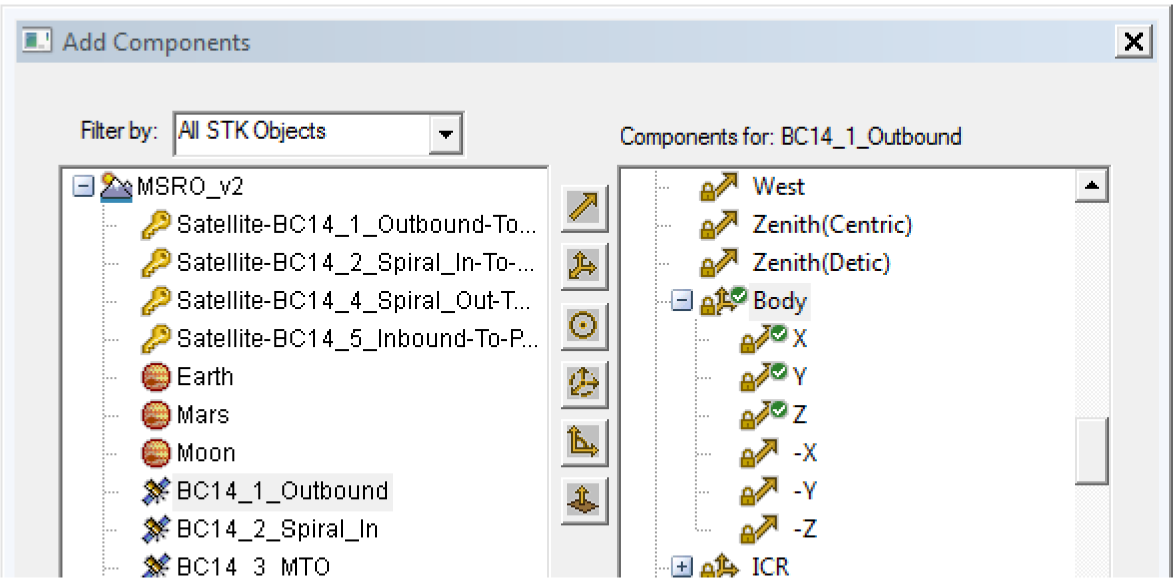



*Figure 8.4.1.2 - Body Axes tab*

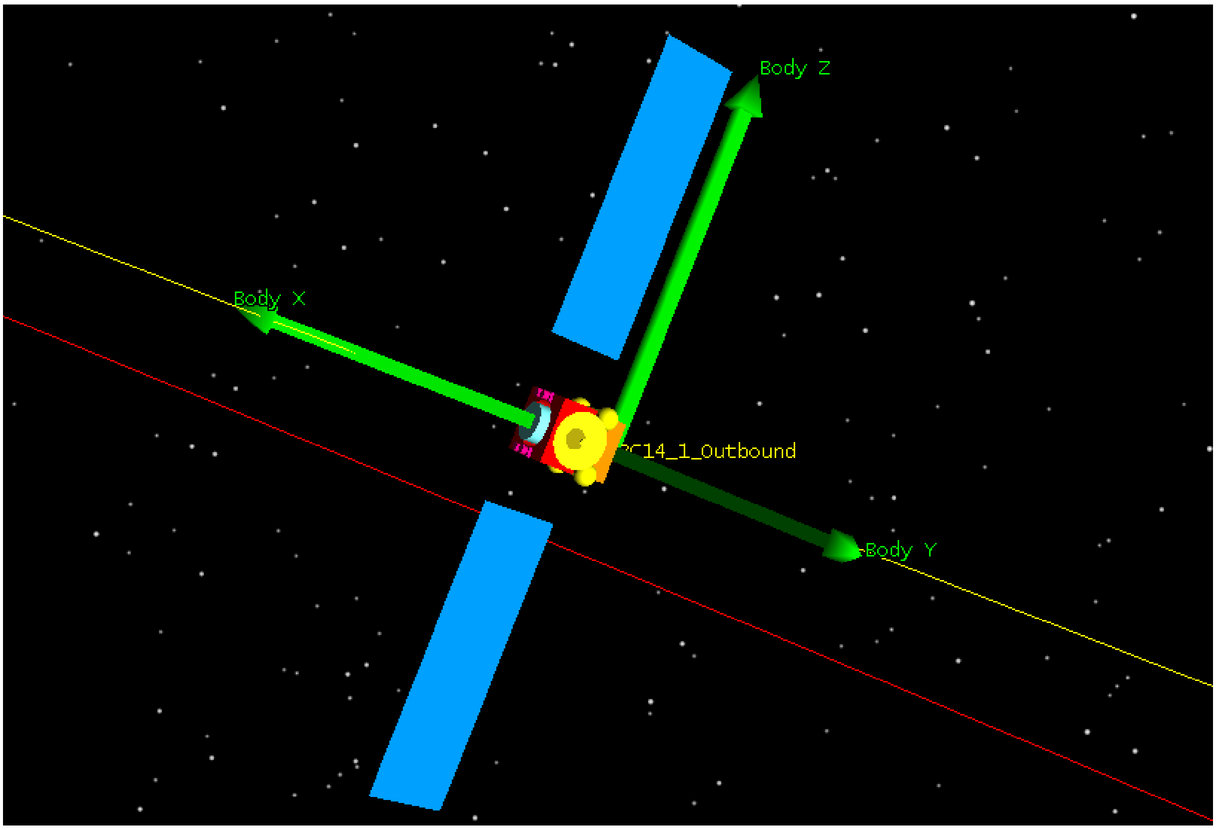



*Figure 8.4.1.3 - Body Axes view*

The second triad of axes is the HGA Local Axes: it is a triplet obtained starting from the body axes and imposing two rotations. The notable angles of the antenna that interest are planar angles in spherical coordinates with respect to the HGA, hence the need to match the nominal pointing of the HGA (semi-positive axis Y body) with the Local X axis. In order to obtain correct elevation information and Azimuth it is necessary to create an ad hoc levorotatory system. The rotations through two angles of Euler imply that the X axis of the HGA coincides with the Y axis body, that the Z axis of the HGA coincides with the X body and that the Y axis of the HGA coincides with the Z body.

To do this, new axes were created by selecting the aligned and constrained mode. The equality between the body Y axis and the HGA Local X axis is imposed, and then a 90 degree elevation is imposed on the Z HGA Local axis. The second axis has not been defined imposing Cartesian coordinates conditions, this because the third axis would have had the wrong direction since the default STK software applies only right-handed triplets.

As can be seen in the following figures, the representation of the HGA Local axes is very similar to that of the Body axes, since the origin coincides and two axes on 3 are parallel. The decision to create these axes and not rely exclusively on those body is essentially due to the fact of wanting to give practical information on the orientation of the antenna. Elevation and Azimuth on the body axes would be difficult to interpret physically, instead on the HGA Local axes would immediately give the value of the angle that the HGA articulation is called to create.

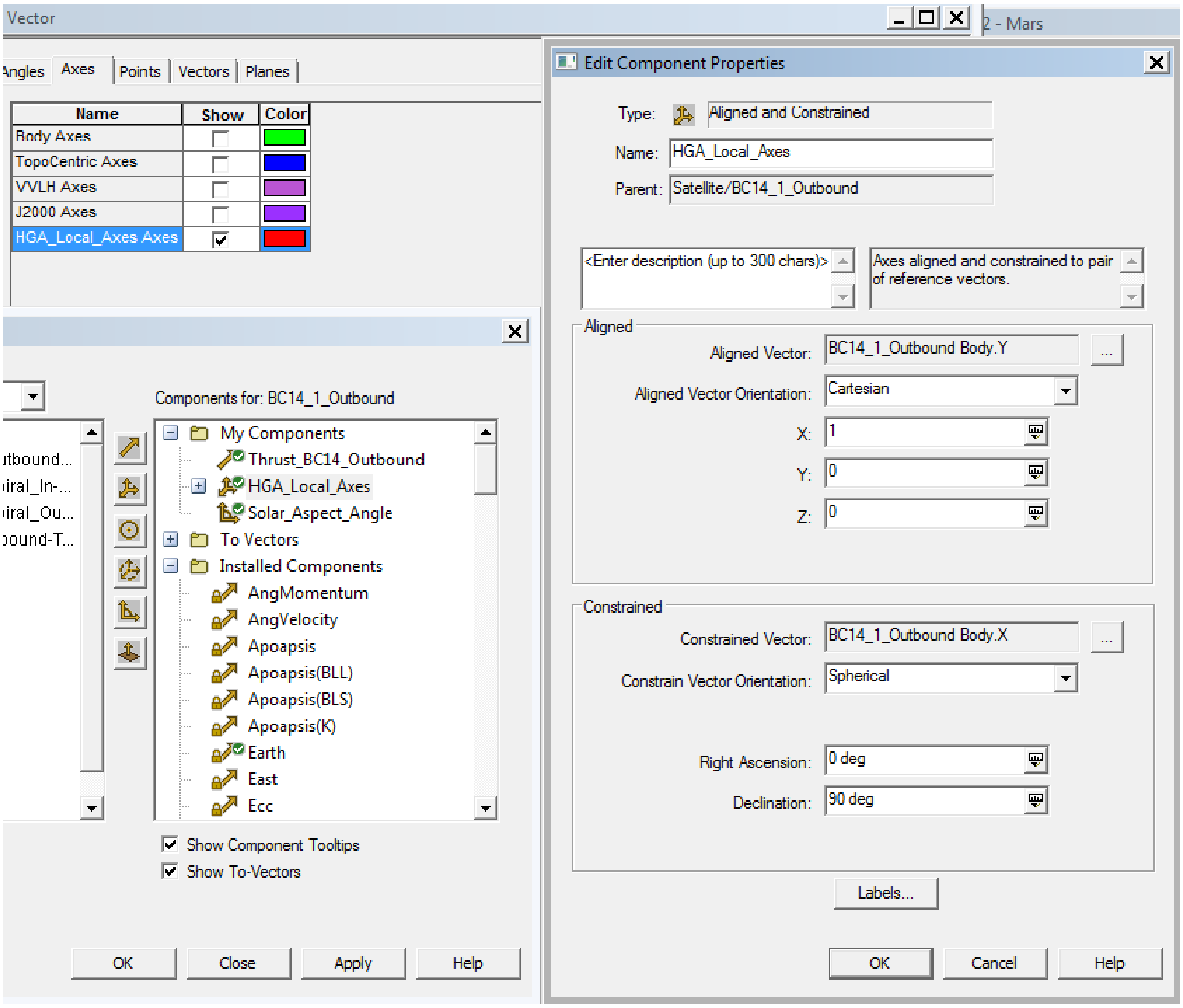



*Figure 8.4.1.4 - HGA Local Axes Creation*

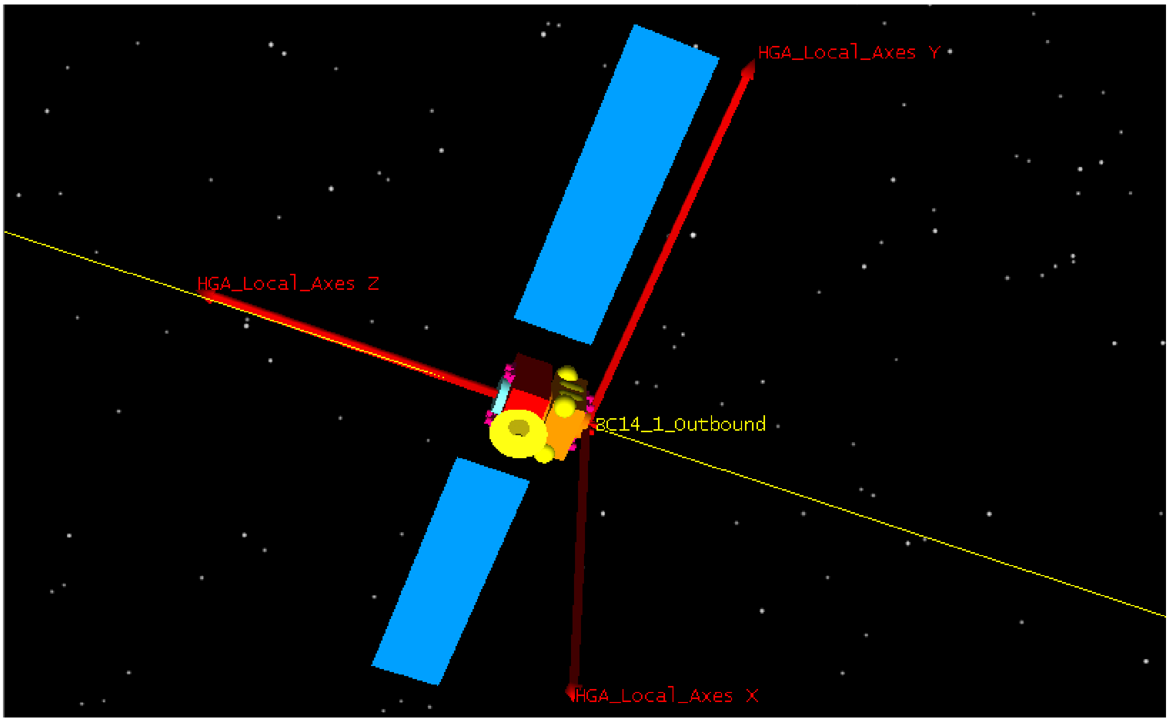



*Figure 8.4.1.5 - HGA Local Axes View*

## 8.4.2 ERO Vectors

The vectors are very important geometrical elements for the STK model. You insert all those that will serve in the calculation of angles and perverify if the various configurations and the attitude has been modeled correctly. Since for each of them it is possible to perform analyzes and calculations of the trends, a specific reference system must be defined for each vector created. For all the vectors the choice falls on the body axes of the ERO, with the exception of the Earth position vector which is defined with the HGA Local.

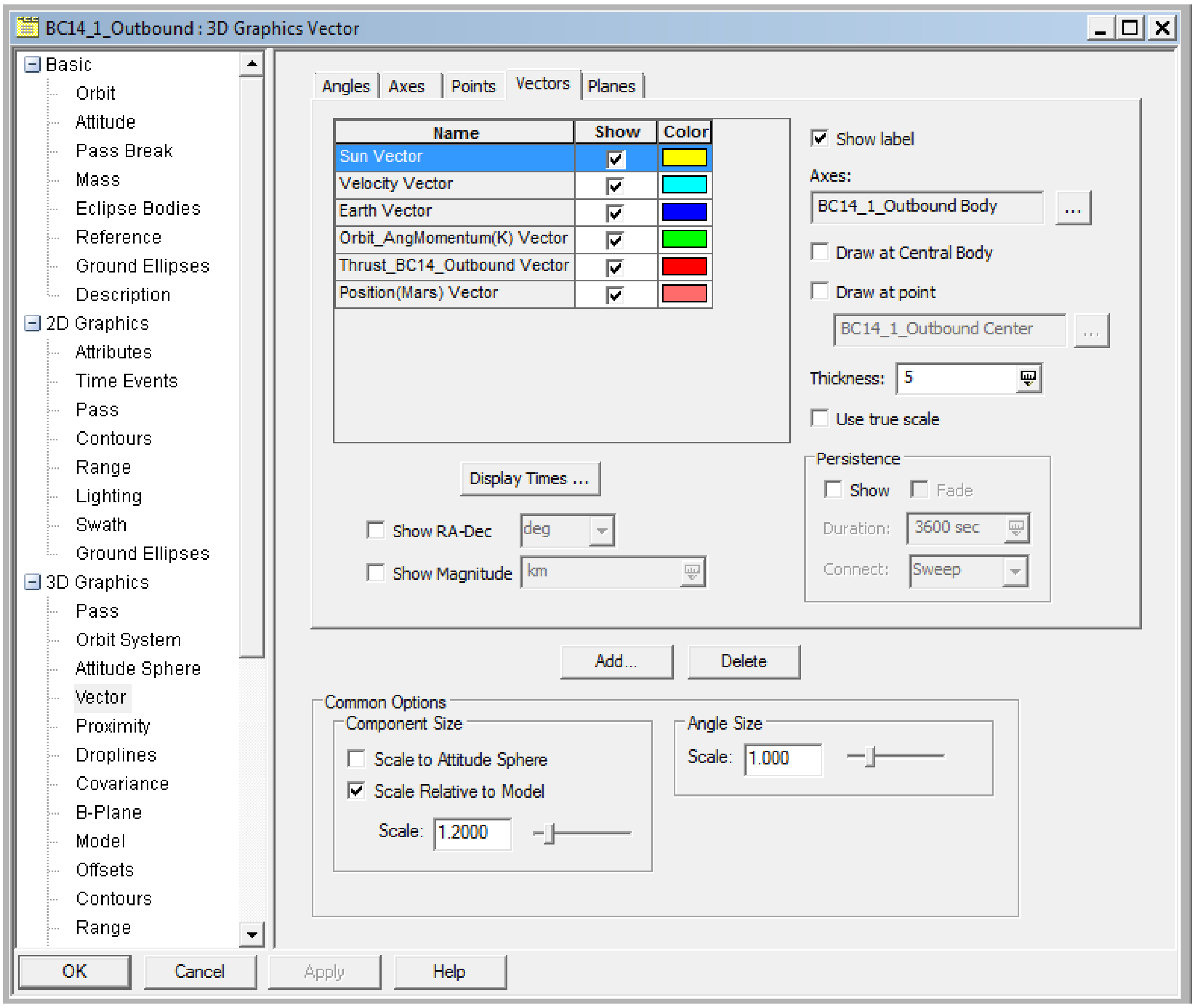



*Figure 8.4.2.1 - 3D Vectors Model Tab*

The first vector entered is the Total Thrust, which will be discussed in the following paragraph. Visualization makes the idea of correct data entry. The next two vectors can be created from the first inserted ephemeris. The velocity vector is created from the mission analysis data and the angular momentum vector K is orthogonal to the orbital plane. The velocity vector identifies the direction that the ERO takes during the simulation, while the angular momentum vector helps to identify all the force components that exist outside the orbital plane. Subsequently, displacement vectors Sun, Earth and possibly Mars were inserted, as they identify the vector which, starting from the origin of the body axes, points towards the center of the bodies listed above. Each vector can then be visualized and can possibly show the magnitude and angular direction with respect to the selected axes of the ERO.

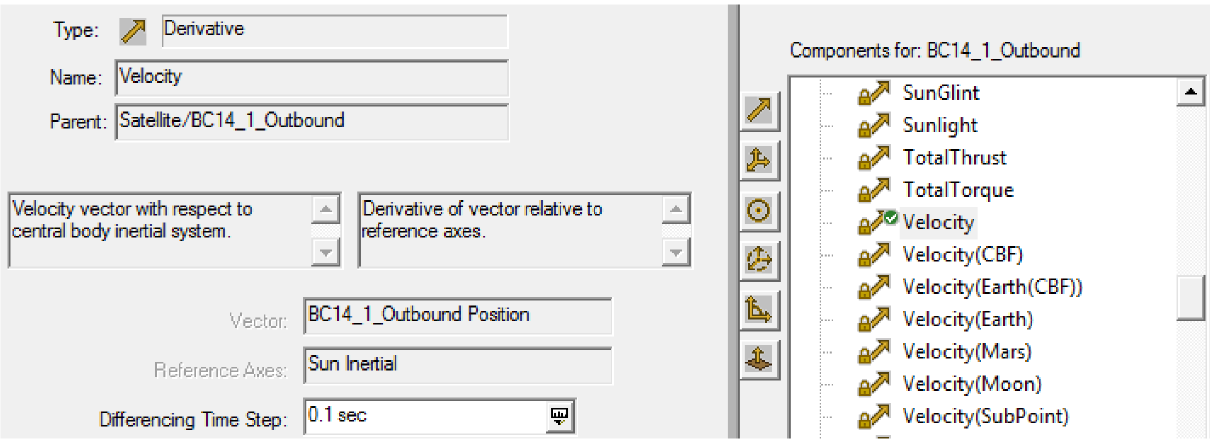


*Figure 8.4.2.3 - Velocity 3D Vector*

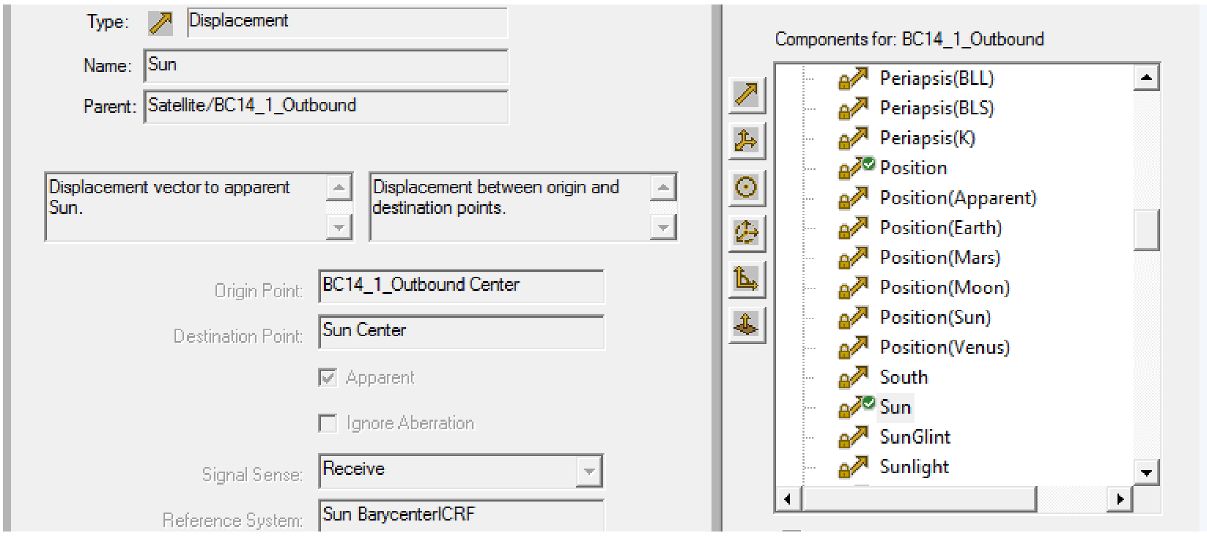


*Figure 8.4.2.4- Sun 3D Vector*

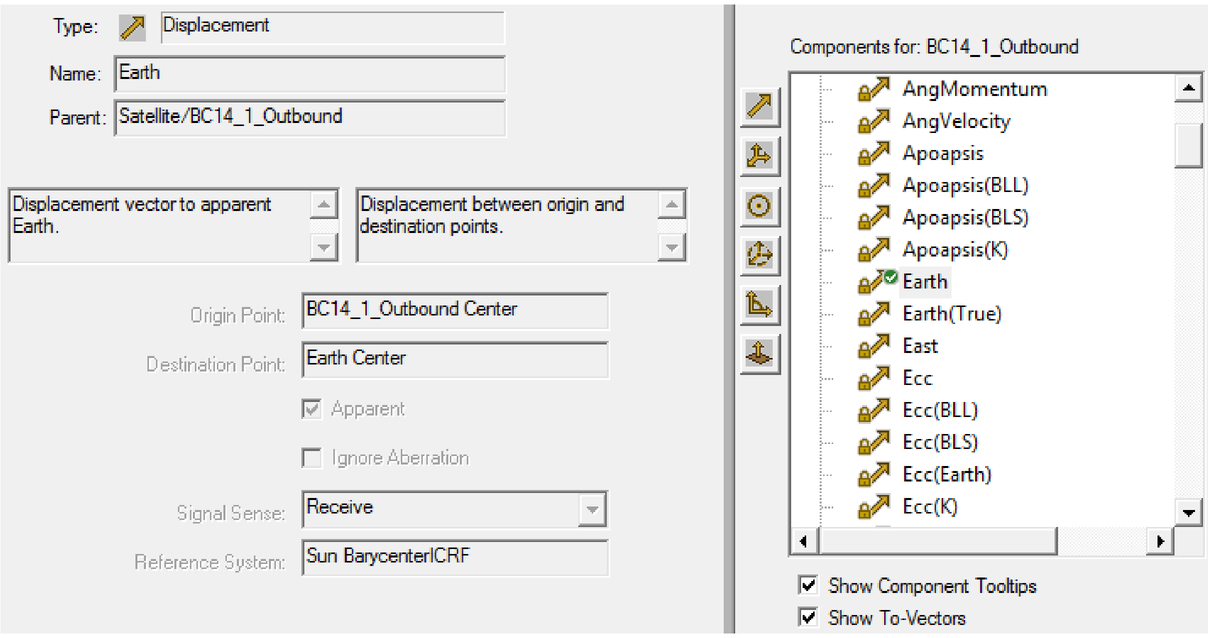


*Figure 8.4.2.5 - Earth 3D Vector*

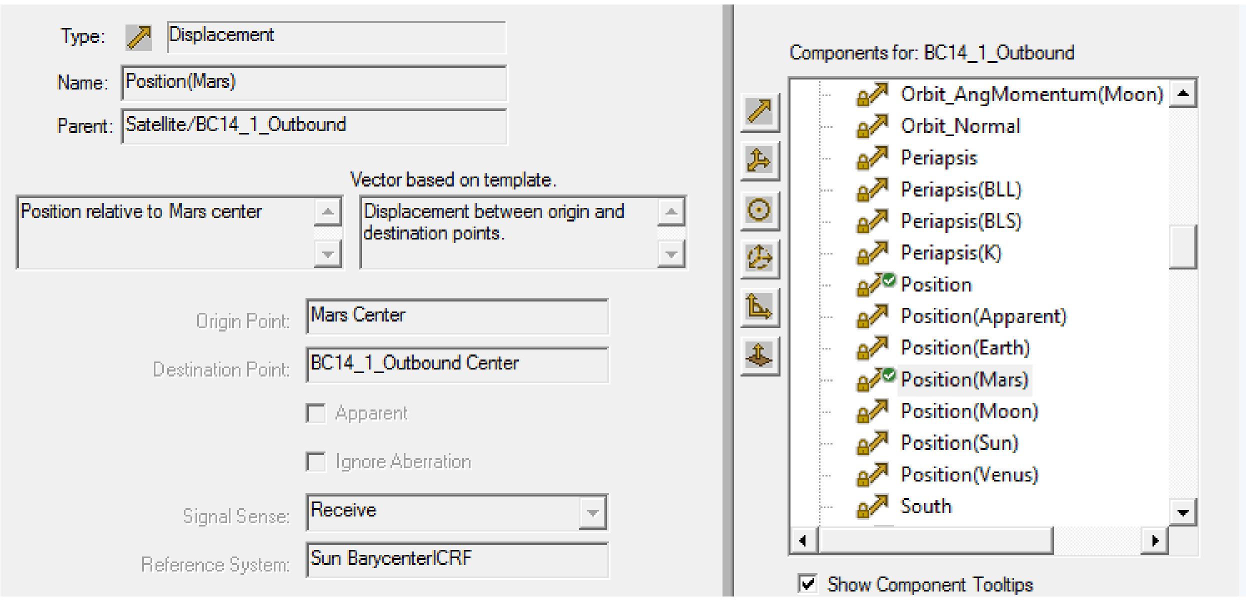



*Figure 8.4.2.6 - Mars 3D Vector*

Finally, a graphic display of the vectors is attached.

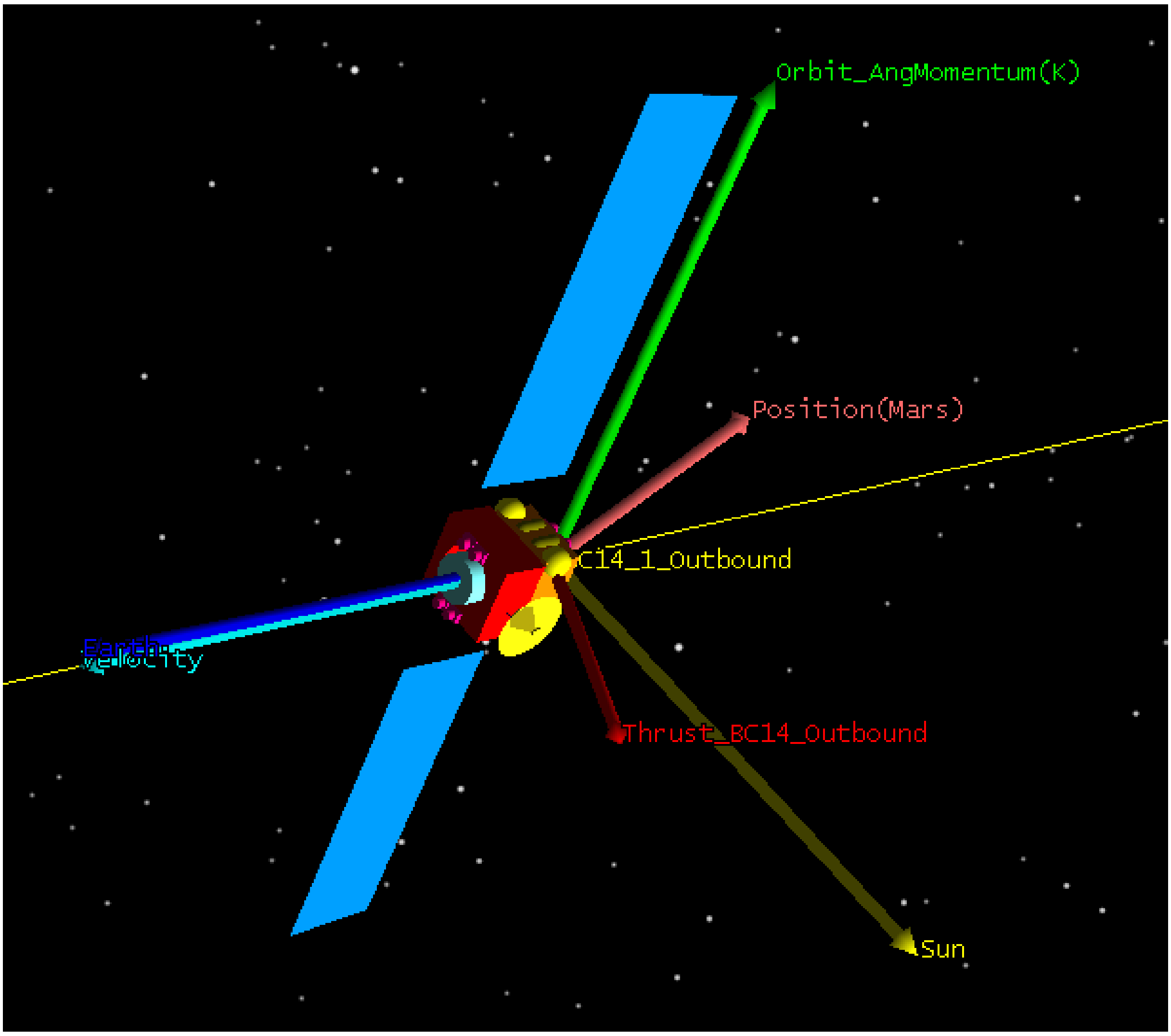



*Figure 8.4.2.7 - 3D Vectors View*

## 8.4.3 ERO Planes

Creating plans in the model is useful for understanding how to calculate certain flat corners. The presence of the planes referred to the body axes is necessary because the angular measurements can't be referred to solid angles. Orbital plane, plans containing the thrust vector and much more can be useful for the 3D view.

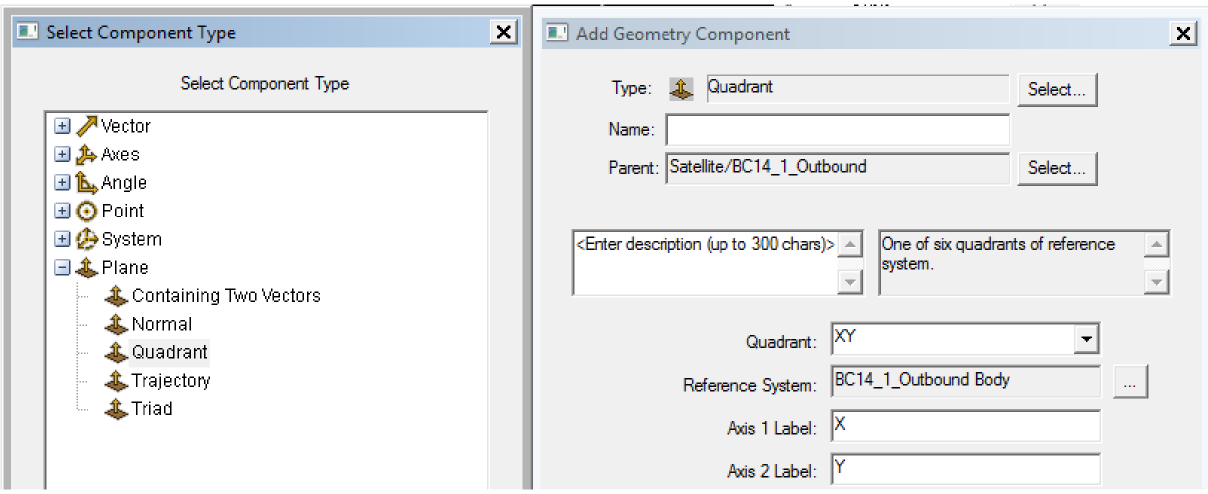



*Figure 8.4.3.1 - model Plane Creation*

## 8.4.4 ERO Angles

The angles relative to the HGA are omitted from this discussion because they are already calculated in polar coordinates through information relative to the Earth vector. The only angle we are interested in is the Solar Aspect Angle. It represents the angle that the articulation must be able to cover to align the Solar Arrays with the sun's rays: it is defined as the plane angle between the Sun vector and the Y-Z plane. From a conceptual point of view it would have been spontaneous to insert the body Y axis for the calculation but in this case the measured angle would have been solid and not plane.

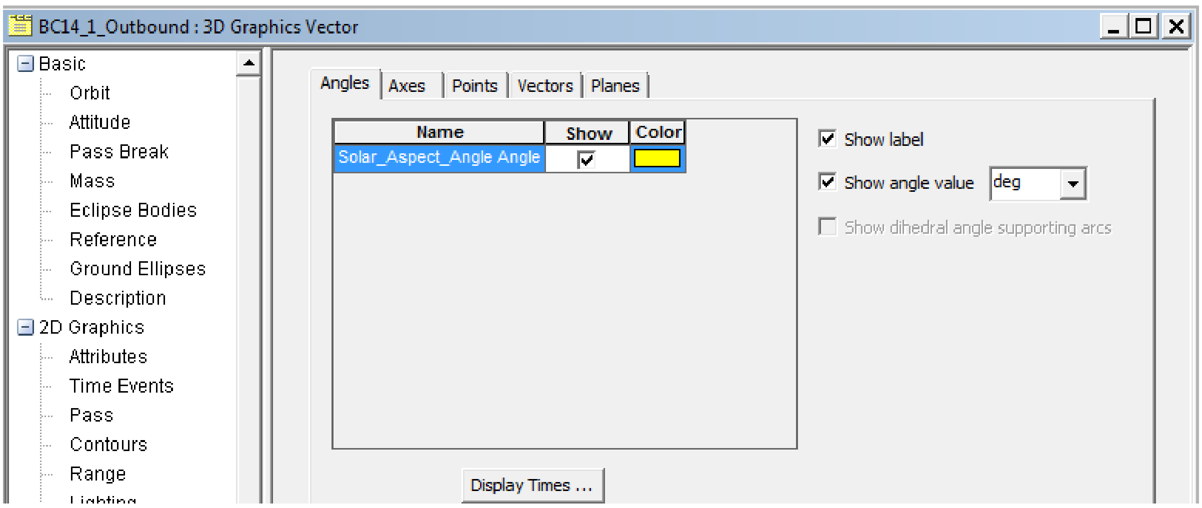



*Figure 8.4.4.1 - SAA tab*

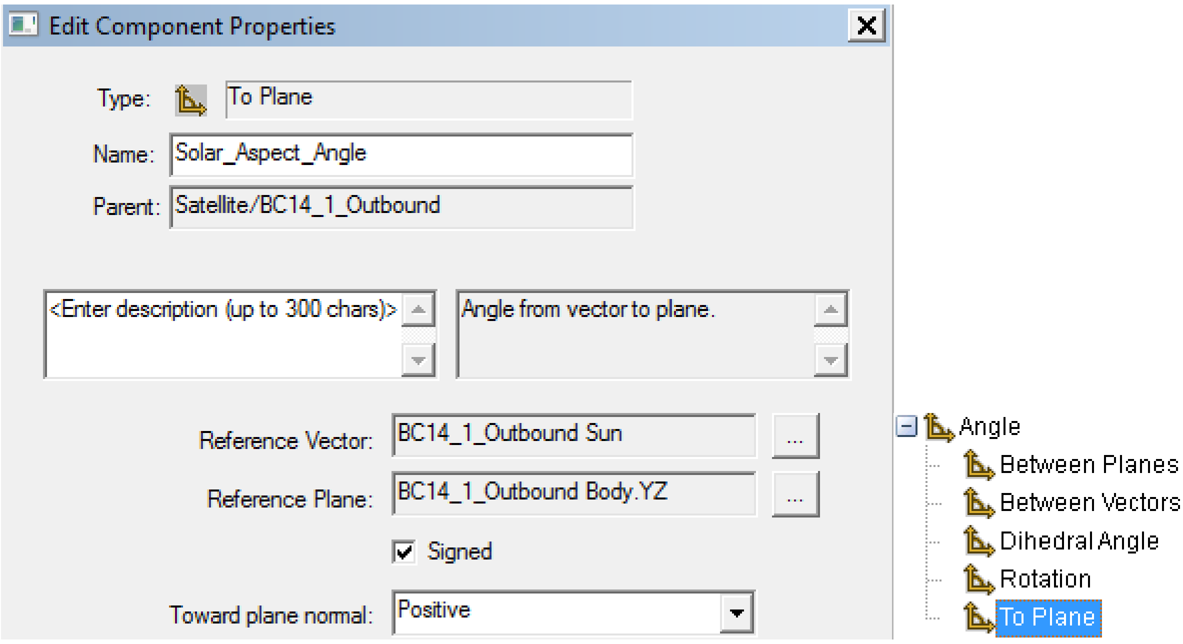



*Figure 8.4.4.2 - SAA Creation*

This angle will not be the incidence of sunlight on the panels, as the articulation will be able to ensure an optimal value for the duration of the mission. In this first analysis we try to understand rather the limit values of rotation. The display of the aforesaid angle is a tile to understand if there are any conceptual errors in the model or if the analysis can move to a next step.

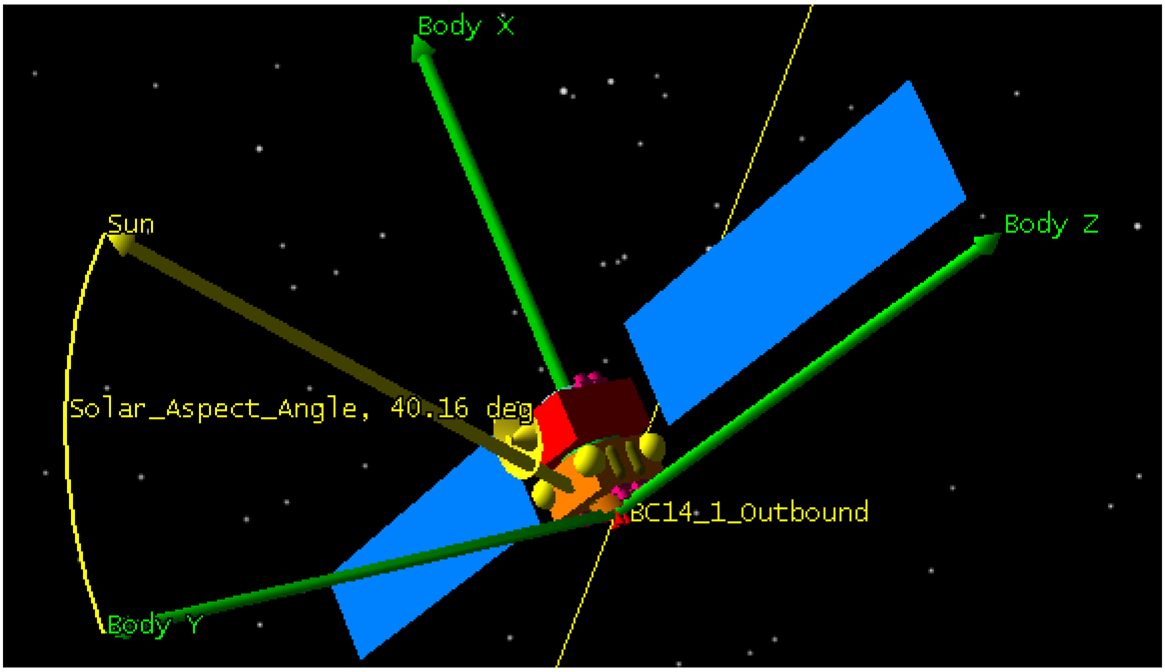



*Figure 8.4.4.3 - SAA 3D view*

This parameter is of considerable importance and the choice of the best attitude has the purpose of minimizing this angle, according to the propulsive parameters.

## 8.5 ERO Attitude Definition

The orbital data of the ERO alone are not sufficient to obtain information on the joints on board. It is necessary to define the attitude of the S/C through its constraints during the motion. There is no doubt that choosing different attitudes will have different results in different degrees of geometric freedom.

### 8.5.1 Attitude Constraint

1. Propulsive phases: the attitude has not inconsiderable design constraints. The main constraint on which is not possible to compromise is that relating to the thrust direction. Excluding side thrusters that affect attitude control, the main chemical and electrical thrusters are able to provide thrust for primary propulsion only in the X body direction: whatever the position of the ERO in the solar system, whenever the primary propulsion is required, the X axis body will be oriented in the desired thrust direction; this means that the only possibility to change attitude with respect to the X axis will be only and exclusively in the non-propulsive phases (it will be possible to rotate the S/C around the thrust axis for other reasons since the thrust constraint would be satisfied anyway). For the insertion of the constraint it must be remembered that the ERO in the launch configuration will have the thrust direction coinciding with the positive semi-axis of the X body; instead, once the drop stage has been unhooked, the thrust direction coincides with the negative semi-axes of the X body. After aligning the body X axis with the desired thrust direction, the S/C could rotate around that axis freely. In this case, the second constraint defines the angular positioning of the ERO and it is due to thermal constraints. For assembly reasons, antenna positioning and propulsive constraints, the housing of the thermal control system allows a better cooling on the side of the HGA (positive body y), and a worse heat dispersion on the opposite side (negative body y). Therefore, it is necessary that the positive body Y axis (and therefore the X-Z body plane with positive normal) is oriented as much as possible towards the Sun and not the contrary, especially when one is closer to the Sun, scilicet during the initial phases of the Outbound and the final stages of the Inbound.
2. No thrust transfer phases: during interplanetary transfers, in the absence of the thrust constraint, the semi-positive Y body axis points the Sun, but the semi-positive X body axis will try to be as aligned as possible to the next thrust direction (negative X axis if the drop module has already been unhooked). ): the alignment coincides with the local speed. From a logical point of view the priority is therefore thermal, but in practice this configuration is very similar to the structure during the propulsive phases.
3. Mars operations (RDV): during the RDV phase, when there isn't any thrust constraint, the semi-positive X axis of the S/C points to the velocity vector due to the cameras inside it and the semi-negative Y axis instead points to Mars because of UHF. The Martian phases obviously include temporal intervals in which the propulsion is used but they are small and limited: in this case one returns to point 1.

### 8.5.2 Propulsive Phase and No Thrust phase periods

In the previous paragraph the creation of the thrust worksheet for each single phase has been described and it consists of tabulated data containing as many rows as the time measurements and four columns (the three thrust directions in a given system of reference and the time point in J2000).

In the general spreadsheet, the result of the thrust forces was calculated: it is appropriate to calculate the period in which the thrusters are switched on and off and take note of them. When the form of the resultant of the forces becomes different from zero (or becomes null), it is useful to take the reference time in J2000 and convert it to the date of the Gregorian calendar; these data are saved in appropriate cells. The following figure shows the columns related to thrust components and a column with the resultant force module.

| | | | | |
|---|---|---|---|---|
| 0.000000000000 | 0.000000000000 | 0.000000000000 | | 0.000000000000 |
| 0.000000000000 | 0.000000000000 | 0.000000000000 | 02/11/2032 h17:59:42.720 | 0.000000000000 |
| 0.000000000000 | 0.000000000000 | 0.000000000000 | | 0.000000000000 |
| 0.000000000000 | 0.000000000000 | 0.000000000000 | 1st Thrust time | 0.000000000000 |
| 0.163233550000 | 0.285309760000 | -0.102021040000 | 11995.000200000000 | 0.344173130270 |
| 0.163219160000 | 0.285330590000 | -0.101986490000 | 32.841222071272 | 0.344173334126 |
| 0.163201350000 | 0.285356360000 | -0.101943720000 | 0.841222071272 | 0.344173582487 |
| 0.163183540000 | 0.285382130000 | -0.101900950000 | 307.249799999999 | 0.344173839013 |
| 0.163165720000 | 0.285407890000 | -0.101858180000 | 2.249799999999 | 0.344174090673 |
| 0.163147890000 | 0.285433640000 | -0.101815410000 | 2.749799999999 | 0.344174337464 |
| 0.163130060000 | 0.285459390000 | -0.101772640000 | 0.749799999999 | 0.344174592420 |
| 0.163112220000 | 0.285485130000 | -0.101729880000 | 17.995199999981 | 0.344174845463 |
| 0.163094380000 | 0.285510870000 | -0.101687110000 | 0.995199999981 | 0.344175103713 |
| 0.163076540000 | 0.285536590000 | -0.101644340000 | 59.711999998845 | 0.344175353535 |
| 0.163058690000 | 0.285562310000 | -0.101601570000 | 0.711999998844 | 0.344175606782 |
| 0.163040830000 | 0.285588030000 | -0.101558800000 | 42.719999930669 | 0.344175863453 |
| 0.163022970000 | 0.285613740000 | -0.101516030000 | | 0.344176119990 |

*Figure 8.5.2.1 - Gregorian epoch of attitude segment*

### 8.5.3 Thrust Vector STK file creation

After taking note of such epochs, entering the worksheet created for the export of the thrust vector, it is saved as a text file .txt in a separate file if it has not already been done previously. So a vector data file is an ASCII text file formatted for compatibility with STK.

The file containing the thrust information must be saved as Vector File Format (* .vd) simply by manually changing the format in the file properties. At this point, as written in the AGI manual, in the file it is compulsory to insert lines of text that contain information on how the file should be read. The following table, taken from the AGI manual, lists the most important keywords for the header of data files.

| KEYWORD | DESCRIPTION |
|---|---|
| stk.v.<major release number>.<minor release number><br>Example: stk.v.10.2 | In the first line of the file, it consists of the minimum version of STK software for which the file is formatted to be used. |
| BEGIN VectorData<br>END VectorData | The beginning and the ending of data lines |
| Number Of Vector Data Points<br><br>*Example:* NumberOfVectorDataPoints 69023 | If specified, it indicates the maximum number of vector data points to read from the file. By default, STK uses all vector data points in the file. In this example, up to 69023 vector data points would be read. |
| Scenario Epoch | It consists of the reference epoch time for the time values of the Vector data in the table. Specify the scenario epoch using Gregorian UTC time (`dd mmm yyyy hh:mm:ss.s`). There is no relationship between the scenario epoch specified in the vector table and the actual scenario epoch in your STK scenario. Default is the actual scenario epoch in the STK scenario. |
| Interpolation Method<br>Example:<br>InterpolationMethod Hermite | It is the method by which STK interpolates the vector points. By default STK uses Lagrange's method. |
| Central Body<br>*Example:* CentralBody Earth | The central body to which the vector points are relative. By default the central body is Earth. |
| Coordinate Axes<br>*Examples:* CoordinateAxes TrueOfEpoch | The reference axes in which the vector data components are expressed. If omitted, the default coordinate axes are Inertial. |
| Coordinate Axes Epoch<br>*Example:*<br>CoordinateAxesEpoch 1 Jun 2003 12:00:00. | It sets the epoch time for the coordinate axes in Gregorian UTC time and it is required with coordinate axes that reference an Epoch. |
| Dimension Name<br>*Example:*<br>DimensionName Distance | It is the type of the dimension (Distance, Time, Angle, etc.) |
| Dimension Unit<br>*Example:*<br>DimensionUnit Meters | It defines the units of measure (Degrees, Radians, Arc Minutes, Pounds etc.) |
| Time Format<br>Examples:<br>TimeFormat DD/MM/YYYY | It defines the date format of time tags in the beginning of the each line data. |

*Table 8.4 - Thrust vector keywords*

The format used is composed by four columns: three components of the thrust vector in Cartesian Format represented in the axes defined using the CoordinateAxes keyword and one for time epoch.

| | |
|---|---|
| VectorDataTimeCartRate | Data consists of X/Y/Z components of vector and rate. |
| VectorDataTimeCart | Data consists of X/Y/Z components of vector. |

*Table 8.5 - Vector Data format*

```
ERO_BC14_Spiral_Out_Thrust.vd - Notepad
File  Edit  Format  View  Help
stk.v.11.0
BEGIN VectorData
NumberOfVectorDataPoints 49999
ScenarioEpoch            01 Gen 2000 12:00:00.000000
CentralBody              Mars
CoordinateAxes           J2000
DimensionName Distance
DimensionUnit Meters

VectorDataTimeCart


-0.2672383400   0.0655550010    0.3467554100        8.172579286656E+08
-0.3233145300   -0.0452769880   0.2989545900        8.172582574176E+08
-0.3501961600   -0.1520178700   0.2240789100        8.172585860832E+08
-0.3454180500   -0.2450242100   0.1288745600        8.172589147488E+08
-0.3093596200   -0.3158714000   0.0219348050        8.172592435008E+08
-0.2452240700   -0.3581118500   -0.0870615190       8.172595721664E+08
-0.1587691600   -0.3678660700   -0.1882140200       8.172599008320E+08
-0.0578069410   -0.3441936100   -0.2722967800       8.172602294976E+08
0.0484923210    -0.2892040600   -0.3316095600       8.172605582496E+08
0.1504366600    -0.2078861700   -0.3607034400       8.172608869152E+08
0.2387134800    -0.1076592700   -0.3569038100       8.172612155808E+08
0.3052639700    0.0023162970    -0.3205691400       8.172615443328E+08
0.3440373300    0.1120002100    -0.2550536600       8.172618729984E+08
0.3515450900    0.2114124600    -0.1663791500       8.172622016640E+08
0.3271632900    0.2915536100    -0.0626571890       8.172625304160E+08
0.2731630100    0.3452156300    0.0466713250        8.172628590816E+08
```

*Figure 8.5.3.1 – beginning of vd file for Spiral Out*

```
-0.0393339580   0.4328740700    0.1903921700        8.336843241408E+08
-0.0393483720   0.4328636500    0.1904074900        8.336846528064E+08
-0.0393627730   0.4328532400    0.1904228000        8.336849815584E+08
-0.0393771610   0.4328428400    0.1904381000        8.336853102240E+08
-0.0393915360   0.4328324400    0.1904533900        8.336856388896E+08
-0.0394058980   0.4328220400    0.1904686700        8.336859675552E+08
-0.0394202470   0.4328116500    0.1904839300        8.336862963072E+08
-0.0394345830   0.4328012600    0.1904991900        8.336866249728E+08
-0.0394489060   0.4327908800    0.1905144400        8.336869536384E+08
-0.0394632170   0.4327805000    0.1905296700        8.336872823904E+08
-0.0394775140   0.4327701300    0.1905449000        8.336876110560E+08
-0.0394917980   0.4327597600    0.1905601100        8.336879397216E+08
-0.0395060700   0.4327493900    0.1905753100        8.336882684736E+08
-0.0395203290   0.4327390300    0.1905905000        8.336885971392E+08
-0.0395345740   0.4327286800    0.1906056900        8.336889258048E+08
-0.0395488070   0.4327183300    0.1906208600        8.336892545568E+08
-0.0395630270   0.4327079800    0.1906360200        8.336895832224E+08
-0.0395772340   0.4326976400    0.1906511600        8.336899118880E+08
-0.0395914290   0.4326873000    0.1906663000        8.336902406400E+08
-0.0396056100   0.4326769700    0.1906814300        8.336905693056E+08
-0.0396197790   0.4326666400    0.1906965500        8.336908979712E+08
-0.0396339340   0.4326563200    0.1907116500        8.336912266368E+08
-0.0396480770   0.4326460000    0.1907267500        8.336915553888E+08
-0.0396622070   0.4326356800    0.1907418400        8.336918840544E+08
0.4573728000    0.1398420500    -0.0329376320       9.413168682240E+08
0.4573578100    0.1399271900    -0.0328810900       9.413181046080E+08
0.4573427900    0.1400123200    -0.0328245420       9.413193418560E+08
0.4573277500    0.1400974600    -0.0327679890       9.413205782400E+08
0.4573126800    0.1401826000    -0.0327114300       9.413218154880E+08
0.4572976000    0.1402677500    -0.0326548660       9.413230527360E+08
0.4572824900    0.1403528900    -0.0325982950       9.413242891200E+08
0.4572673700    0.1404380300    -0.0325417190       9.413255263680E+08
0.4572522200    0.1405231800    -0.0324851380       9.413267627520E+08
0.4572370500    0.1406083300    -0.0324285510       9.413280000000E+08


END VectorData
```

*Figure 8.5.3.2 - Ending of vd file for spiral Out*

### 8.5.4 Thrust Vector model creation

For each range of data received by Mission analysis, a thrust vector is constructed. After entering the Workbench, a new vector is created for each satellite; the chosen creation source is input file.

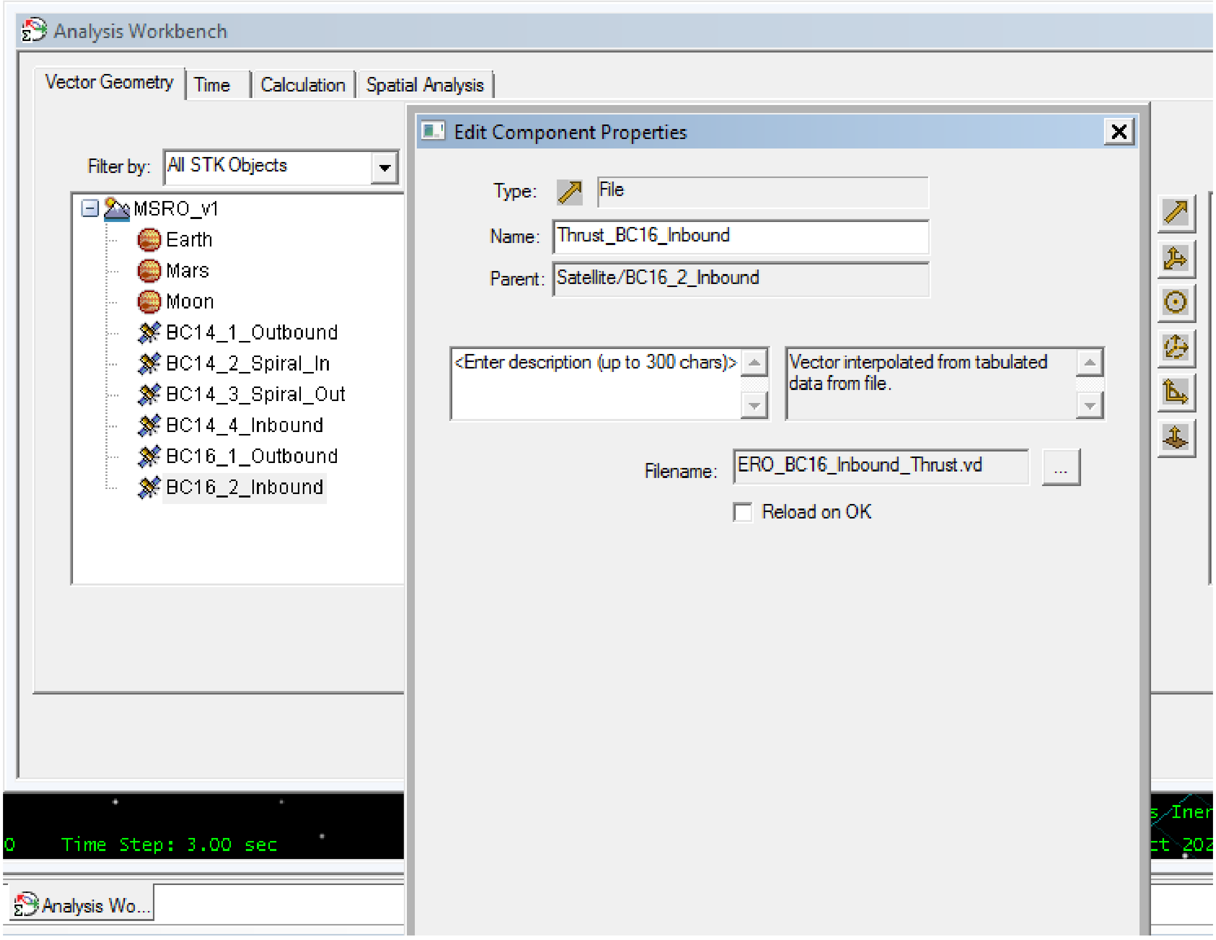



*Figure 8.5.4.1 - Thrust vector model creation*

### 8.5.5 Strategy for entering attitude data

In STK, attitude data can be entered in various ways. The AGI manual recommends inserting the angular orientation of the S/C in the scenario using files containing attitude data. External attitude files must have .a extension and they must be formatted accurately; the insertion of the matrix data of the 3D model consists in the choice of an appropriate reference frame system and data related to the rotation matrices between the body axes and the inertial reference system selected: they may consist of the cosines directors of the rotation angles, the quaternions or Euler's angles. It was not possible to follow this approach because there are no predefined set data, but rather the attitude must defined from scratch by constructing a logical model that can satisfy the two constraints previously described and that improves the performance of the budget allocation. Since the structure is to be constructed in the model and it can't be imported from external sources because they do not exist, the strategy adopted is the one that allows the insertion of the constraints and the preferential alignments in various time intervals. In the properties of the single satellite, by entering the attitude tab, rather than importing external files, the "multi-segment" option is chosen to construct the attitude model; hence, the entire time period of existence of the satellite (generated by ephemeris data) is divided  in time segments. The subdivision is due to the presence or absence of the primary propulsion for interplanetary maneuvers.

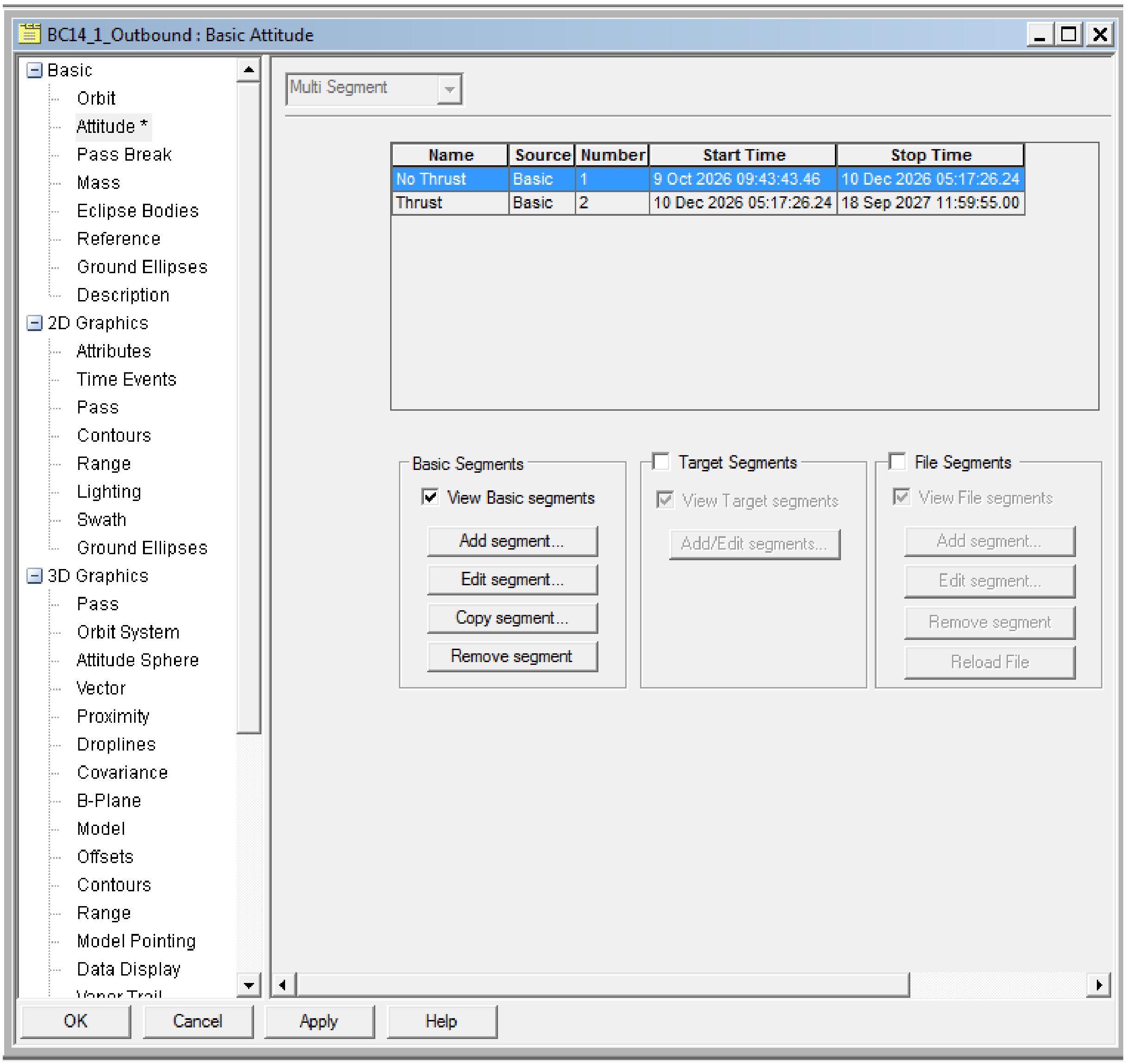



*Figure 8.5.5.1 - Attitude segment division*

The figure above refers to the division of the time segments related to the attitude properties for the ERO during the BC14 Outbound phase. In this approach, however, there is only a rough division of the phases, as in reality there are not long periods of absence of propulsion and long periods of constant presence of the same: what actually happens is that the thrusters operate according to appropriate duty cycle in a way to reduce consumption. Since this is the first analysis and the propulsion data are not definitive, the approach remains simplified to reduce the calculation time and quickly splits all the two simple phases. This approach was performed in all the other mission phases and also in the back-up mission.

The boundary epoch between the two phases must be calculated in the excel worksheets related to the thrust vector simply by looking for the instants in which the thrusters are switched on or off (resultant of the propulsive forces become null or assume values other than zero).

In each individual segment, therefore, the properties of the attitude must be inserted by choosing the "aligned and constrained" model. The choice of properties also involves the 3D model chosen on the basis of propulsive considerations: when the composite is whole in the early phases of the mission it has the direct thrust in the positive direction of the X body, once the drop stage has been dropped, the MM pushes in the negative direction of the X body, so this aspect has been taken into account.

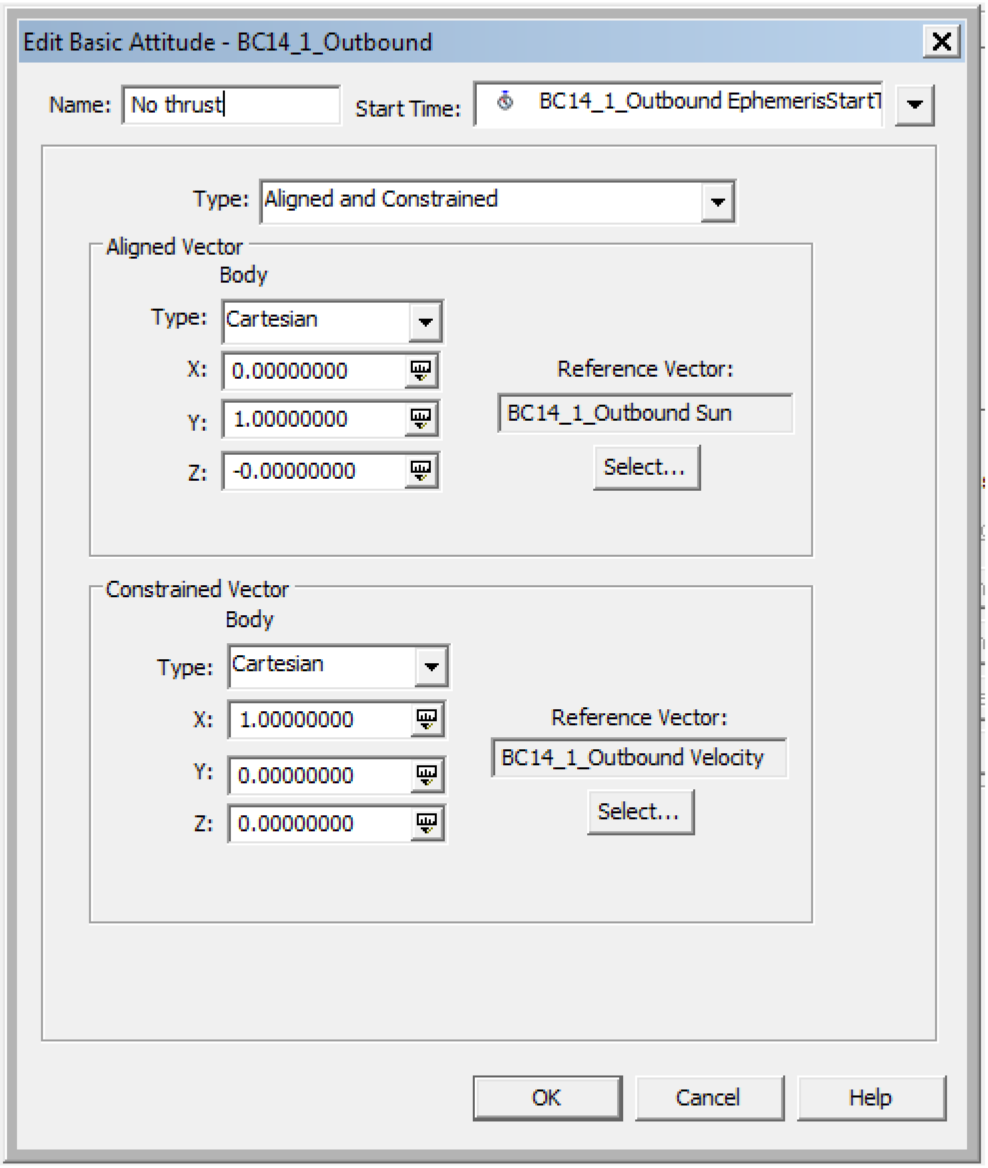



*Figure 11.5.5.2 - Outbound No thrust attitude*

The previous figure shows a time segment in which the ERO has no active thrust. The obligatory alignment is the positive semi-axis of the Y bodies pointing in the direction of the Sun; the X axis body instead points to the velocity vector in order to be as close as possible (it can never be zero) to the next direction of the thrust vector when it will have a module other than 0. In the case of activation of the thrusters, this choice reduces the risk of saturation of the attitude control system to suddenly rotate the S/C. Obviously, in the case of a complete composite, the constraint is referred to the X body semi-positive and in case of only MM it is referred X body semi-negative axes. The starting time is the first ephemeris epoch, while the stopping time is when Thrust module is positive.

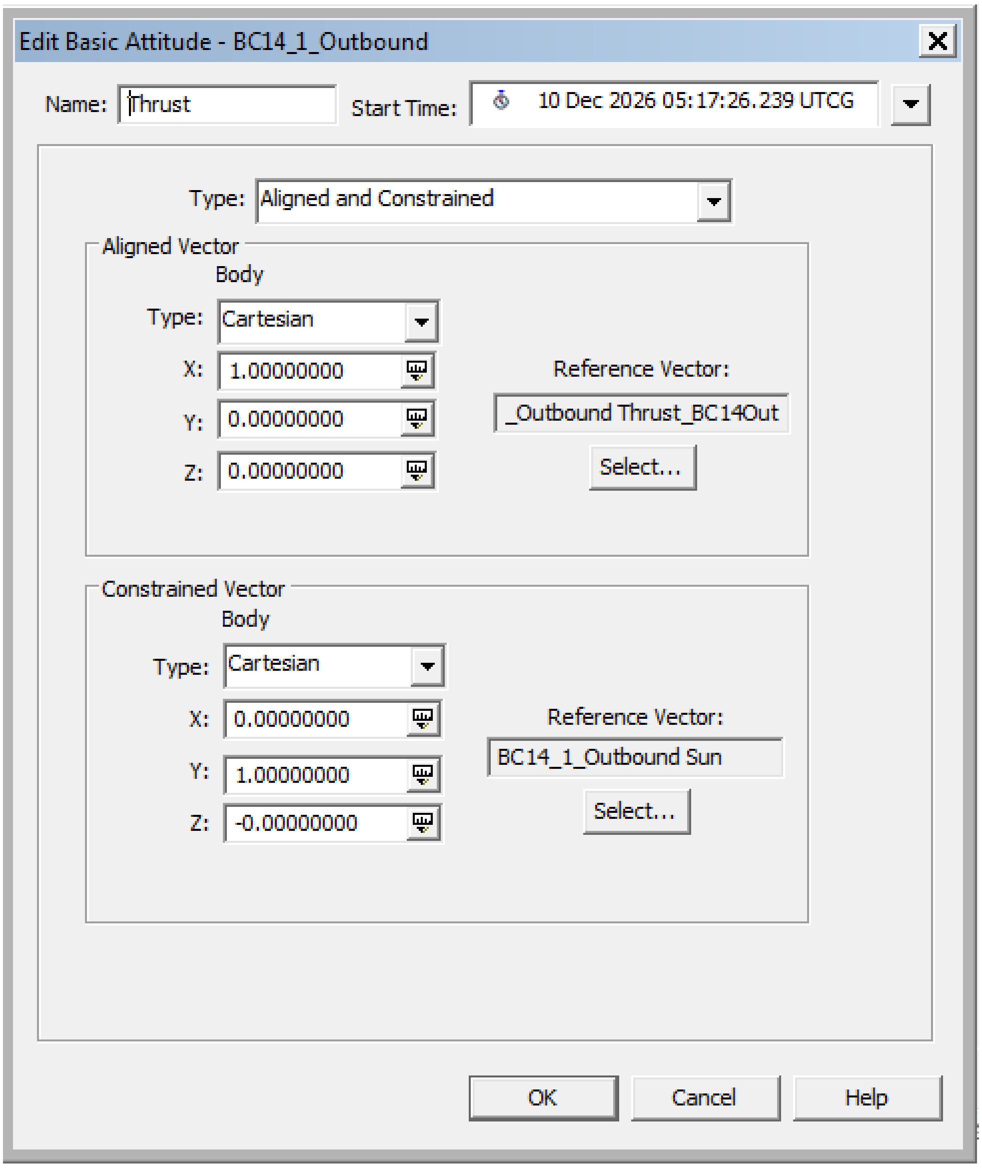



*Figure 8.5.5.3 – Outbound Thrust Attitude*

During propulsion maneuvers, the obligatory constraint concerns the thrust direction: the X body axis must necessarily be aligned with this vector: every failure to satisfy this constraint will produce incorrect results. Obviously, the same considerations made above regarding the positive semi-positive X body axes in case of a complete composite and the negative semi-negative X body axis when the drop stage has been released are valid. Once the thrust axis has been constrained, the preferential direction requires that the semi-positive Y body axis should be as aligned as possible to the direction of the Sun.

This approach is very conservative because it does not require the correct alignment with the Sun; during the non-propelled phases, it will not be necessary to supply the maximum electric power as the buses will be the only ones to need electricity.

### 8.5.6 Attitude verification

In this subparagraph the structure of the ERO is verified during the various mission phases. The verifications concern propulsive considerations and celestial mechanics.

The following figure shows the first phase of the mission, hence the BC14 not propulsive Outbound phase: the thrust vector is absent and for this reason the Y axis is constrained in the direction of the Sun and the semi-positive X body axes is aligned with the velocity. In this first phase the S/C is subject only to the gravitational forces in the model and it can be seen that the solar panels "exit" from the orbital plane. The initial trajectory is not elliptical but it has to do with a hyperbole since with the launch it is evaded from the sphere of terrestrial influence; the gravitational effect introduces a curvature that must subsequently be corrected. For BC14 there is a direct trip to Mars and in this phase there are no fly-bys.

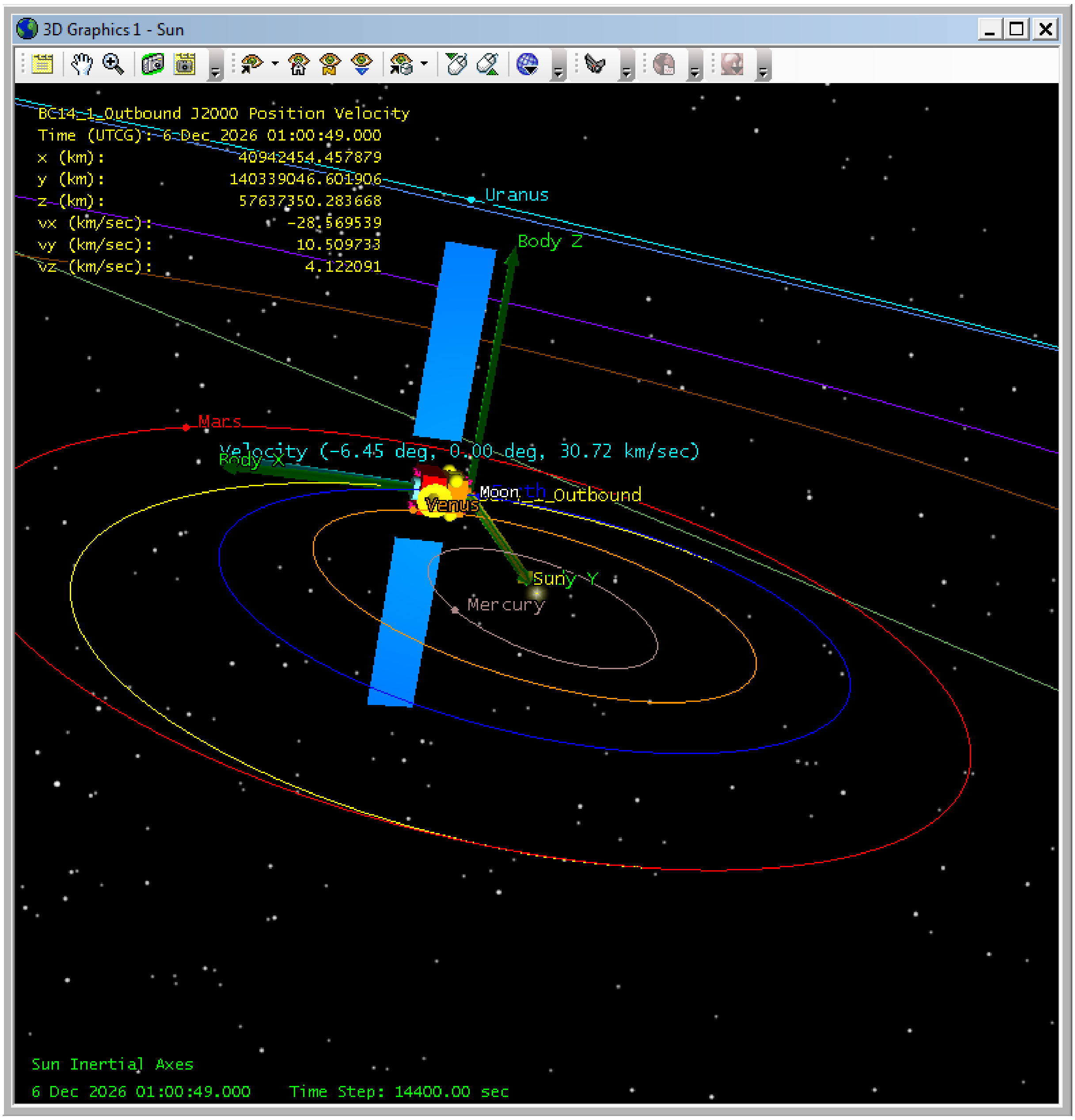



*Figure 8.5.6.1 - BC14 Outbound attitude no thrust phase*

The following image, instead, shows the ERO in propulsive attitude during the BC14 Outbound phase: the X axis coincides with the thrust direction and for this reason the two vectors can’t be distinguished. It is useful to note the preferential alignment of the Sun position vector with the Y axis. The S/C traverses a trajectory around the target planet and for this the vectors in question rotate with the passage of time. In short, the Y axis chases the Sun wherever it is. It is reiterated that this choice of arrangement is still conservative because it presupposes the perennial necessity of having to have the aforementioned attitude. During the Outbound phase, the thrust direction must be towards the outside as the semi-major axis of the ERO must be increased. As time passes, the S/C makes a trajectory arc and the thrust direction rotates so as to bring the ERO closer to Mars. Before the end of the phase there is also a slowing maneuver in order to correct the orbit. In more detail, it is necessary to realize that in the long run a small thrust component out of the plane is necessary because the launch orbit is not on the ecliptic plane and it varies according to the inclination. These considerations can be appreciated in the following figure, but what immediately jumps to the eye is that the non-planar component of thrust is an order of magnitude smaller than the components in the orbital plane.

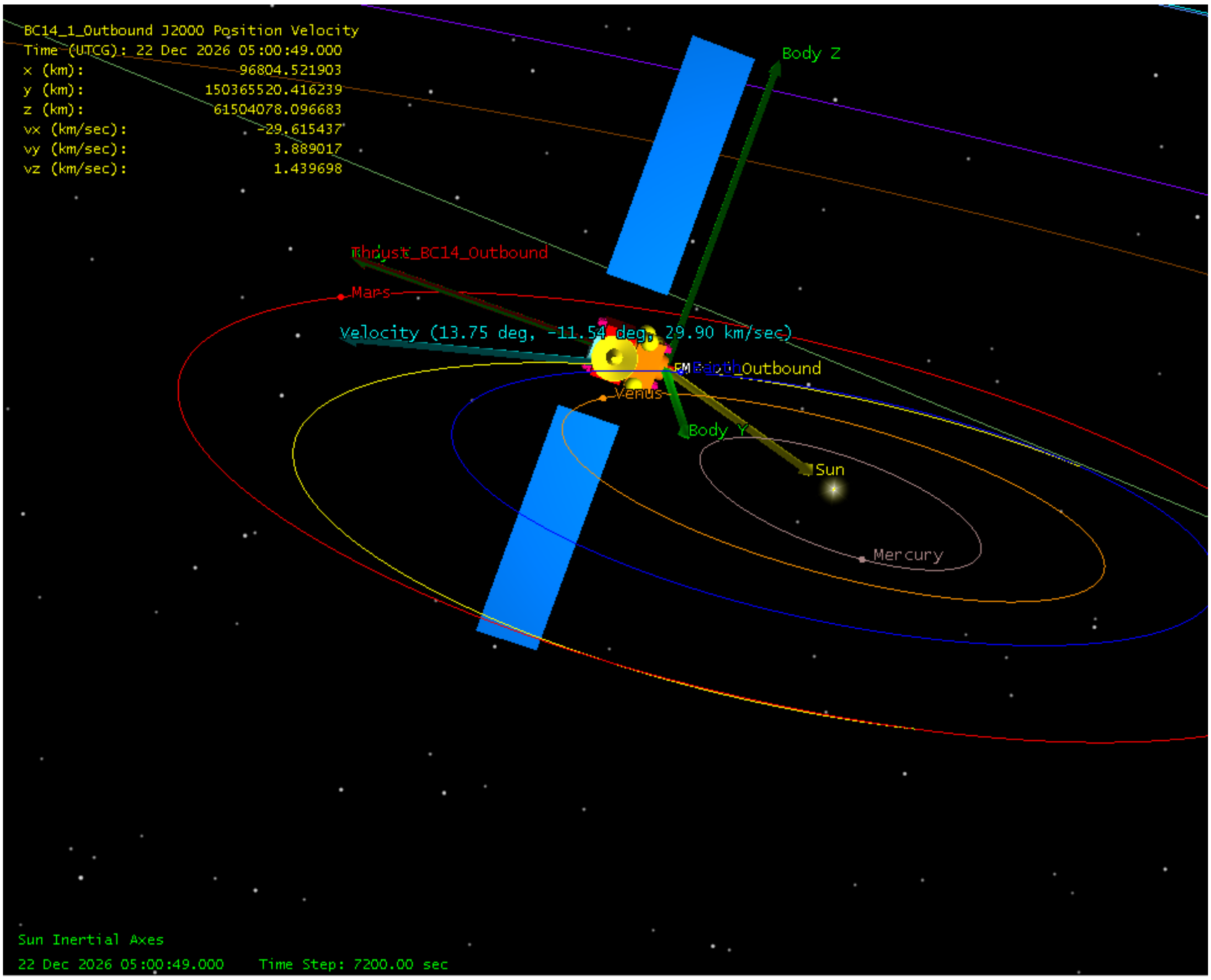



*Figure 8.5.6.2 - BC14 Outbound attitude thrust phase*

For the BC14 Outbound phase there is a continuous correction that brings the ERO into a Martian orbit by aiming the thrust on average in the velocity vector; when the propulsion is activated, unfortunately the attitude can’t be changed and therefore the definitive trend will be that seen in the previous figure.

The following figure shows the BC14 Spiral In phase: since the ERO must reduce the apoares, the thrust is in the opposite direction to the speed, and consequently the ERO is aligned with the thrust direction.

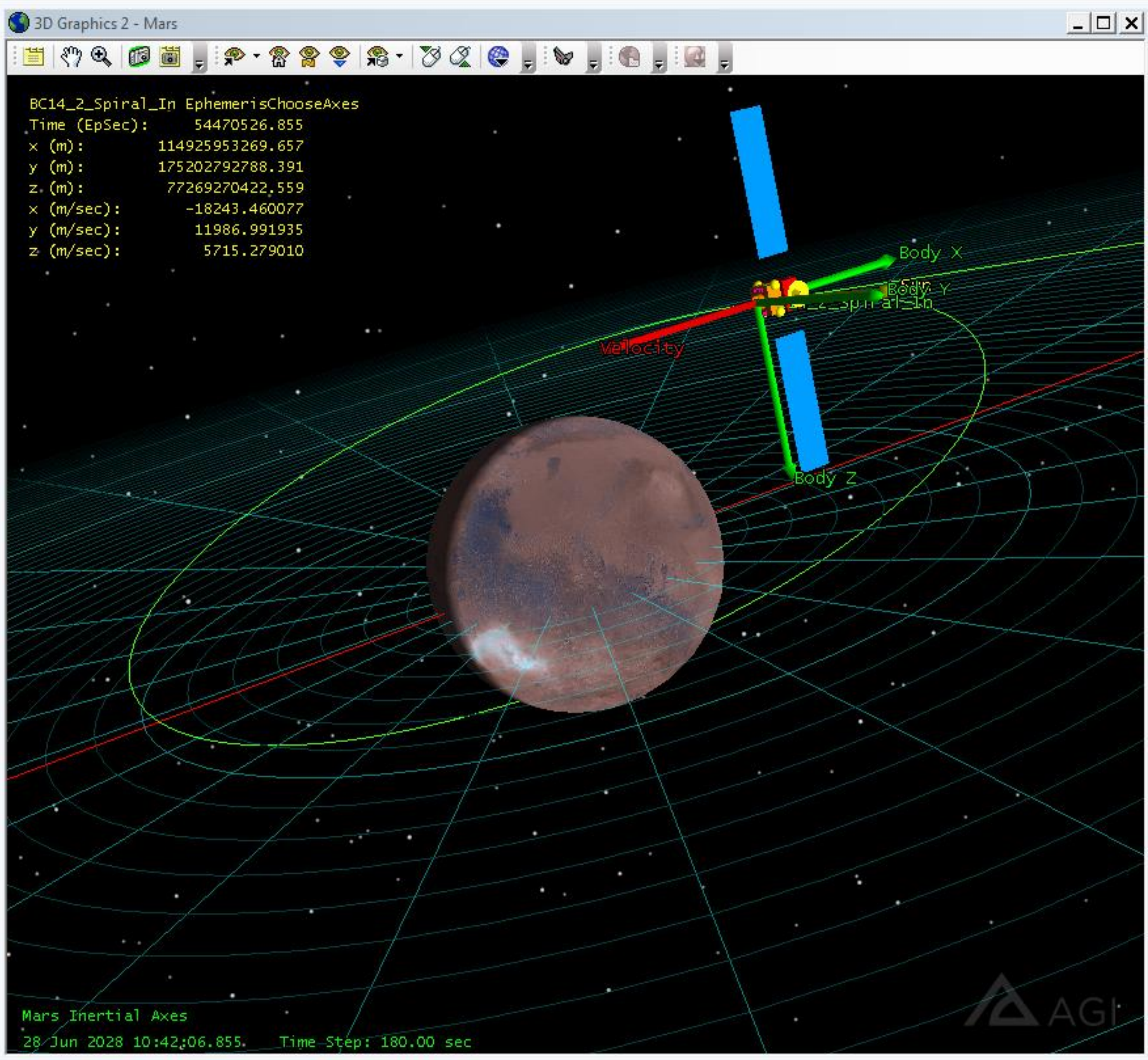



*Figure 8.5.6.3- BC14 Spiral In phase attitude*

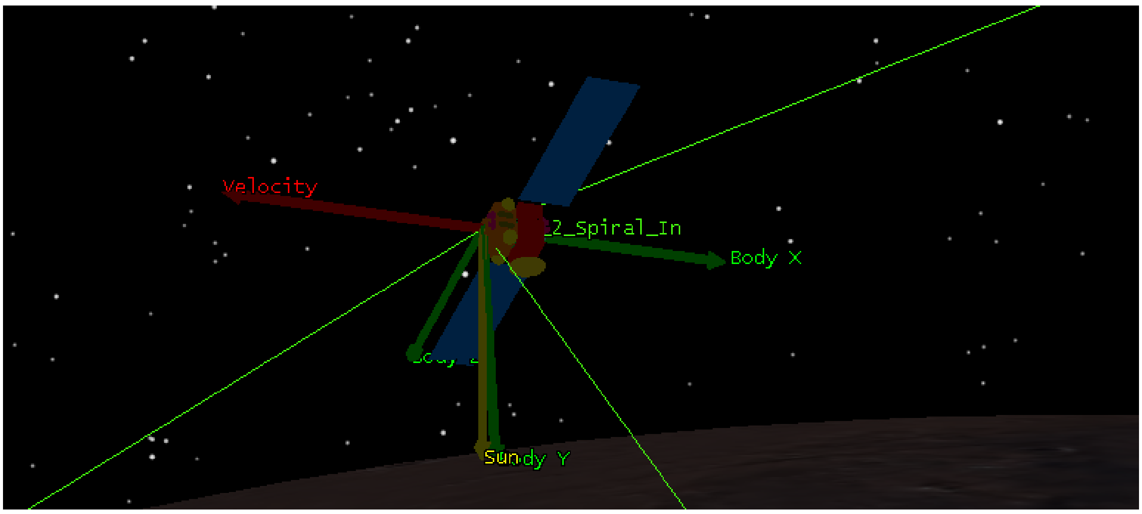



*Figure 8.5.6.4 - BC14 Spiral In final approach*

In the subsequent phases the attitude is reversed because the thrust direction is opposite to the previous cases. The following figures clarify this aspect; moreover, during spiral up, there is no division in temporal arcs of the attitude strategies, since it has been modeled as an entirely propulsive phase. This is a very conservative approach because the duty cycle has not been considered in addition to the omission of the fact that during the eclipse phases there is no primary propulsion and the ERO would reach the orbit tag in more time.

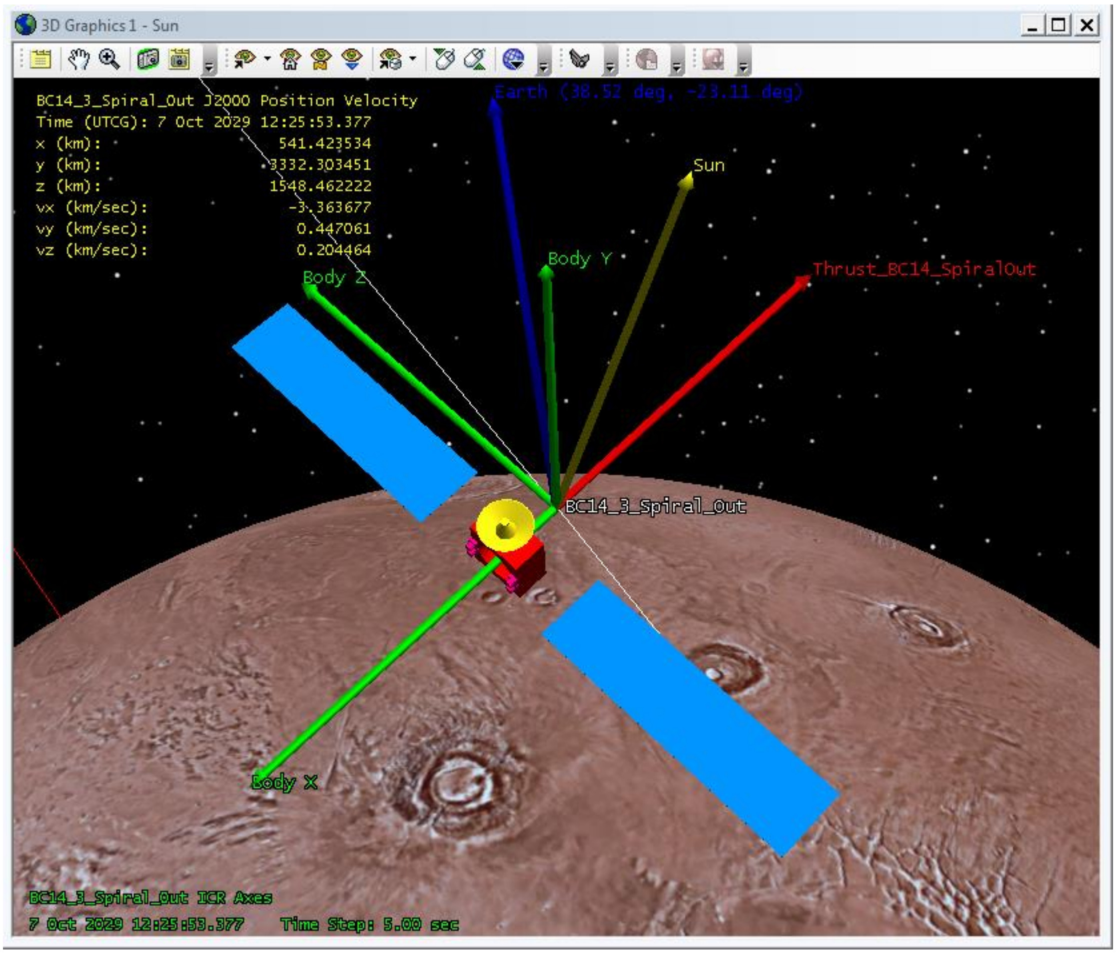



*Figure 8.5.6.5 - BC14 Spiral Out phase attitude A*

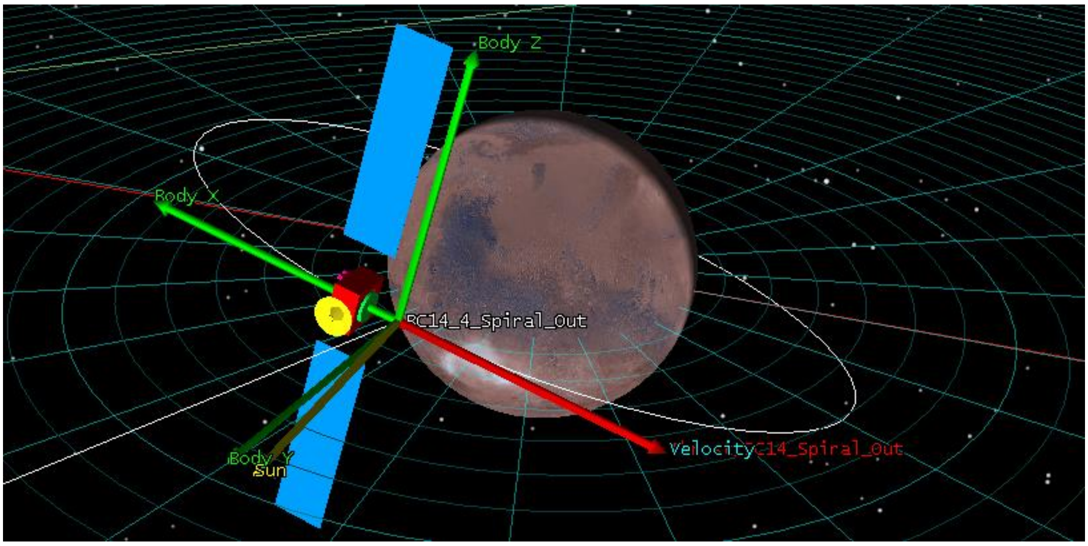



*Figure 8.5.6.6 - BC14 Spiral Up phase attitude B*

During the Spiral Up phase the thrust is aligned with the velocity vector because the upper half-axis of the elliptical orbit must be increased. Small thrust components leave the orbital plane as a change of inclination of the orbit is required.

The following figures concern the BC14 Inbound phase. The non-propulsive phase provides alignment with the speed, the propulsive phase provides alignment with the thrust. During this last time segment there is a thrust component outside the plane as the inbound trajectory is not planar but corrects the strongly inclined orbit of the Spiral Up. For the planar thrust components, there is a direct push towards the Earth in order to slow down the ERO.

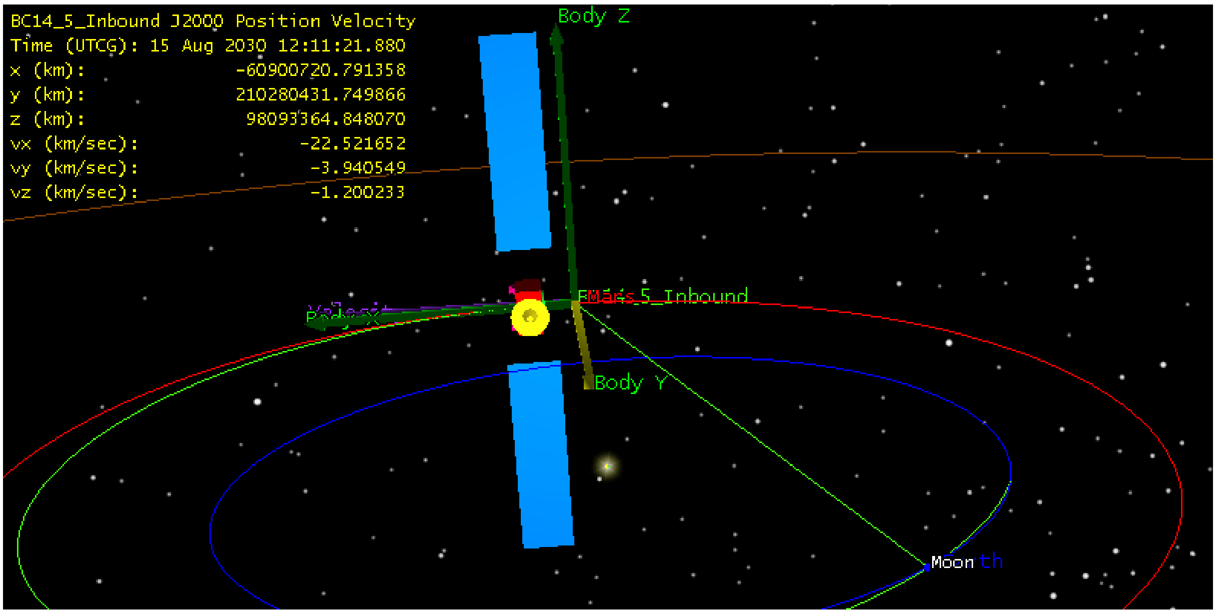



*Figure 8.5.6.7 - BC14 Inbound attitude no thrust phase*

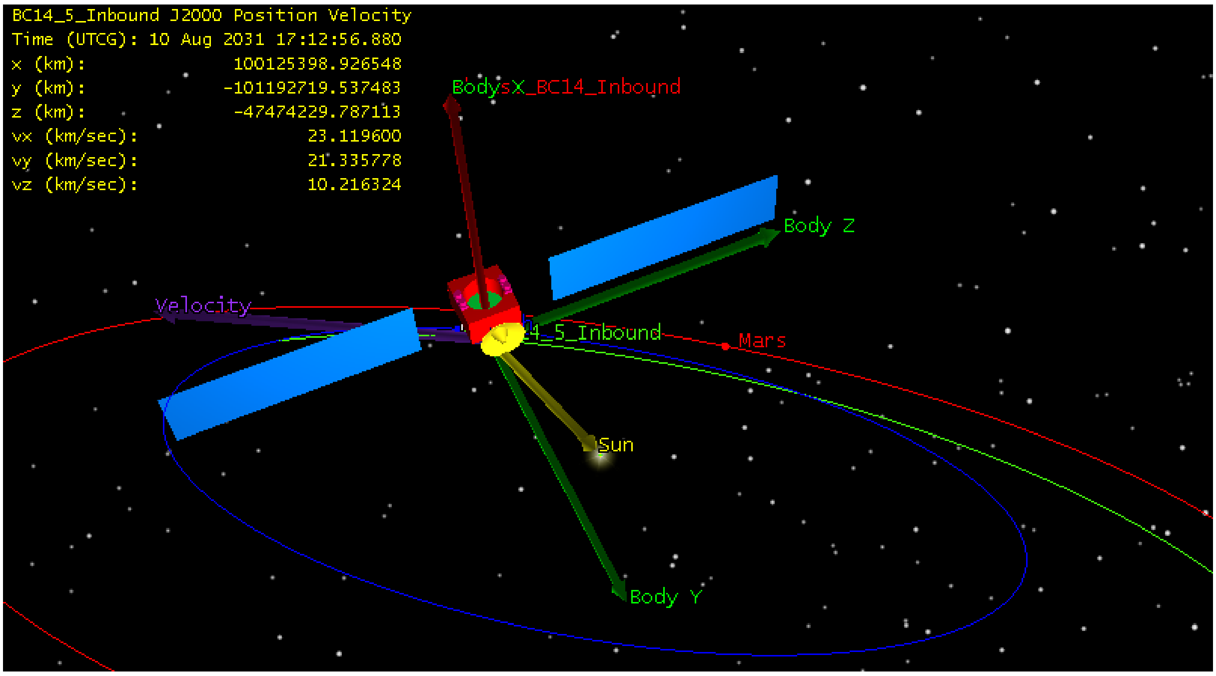



*Figure 8.5.6.8 - BC14 Inbound attitude no thrust phase*

The S/C rotates in order to turn the Solar Arrays towards the Sun. This happens because thrust has the major component direct towards the center of the solar system.

The following figure shows a particular case: Sun and Earth in phase opposition with respect to the ERO: also in this case the attitude does not change: the priority remains the alignment with the direction of the Sun. During the BC16 Outbound phase, there is a large time segment in which there is no active propulsion; this is due to the possibility of carrying out a fly-by of the Earth in order to save fuel. During this time frame the ERO is aligned with the speed. During the propulsive segment, the thrust vector is directed towards the outside as the semi-major axis must be increased.

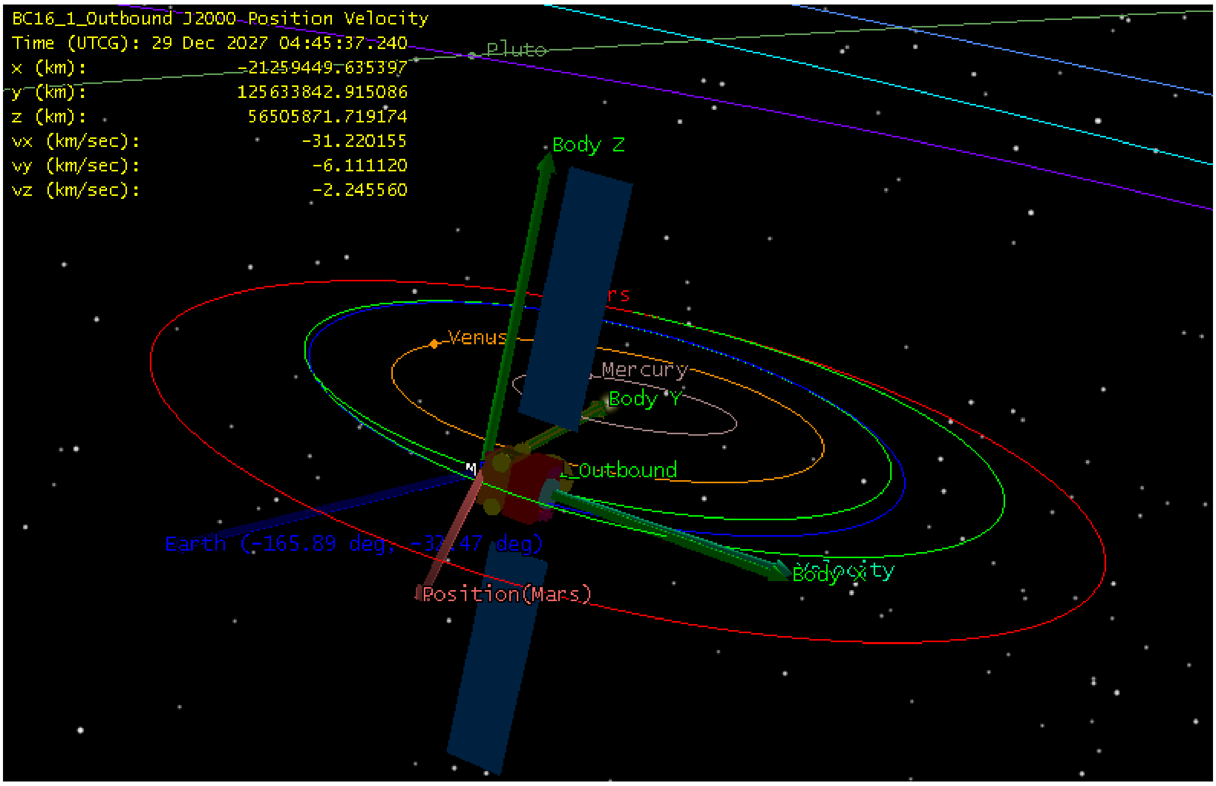



*Figure 8.5.6.9 - BC16 Outbound attitude no thrust phase*

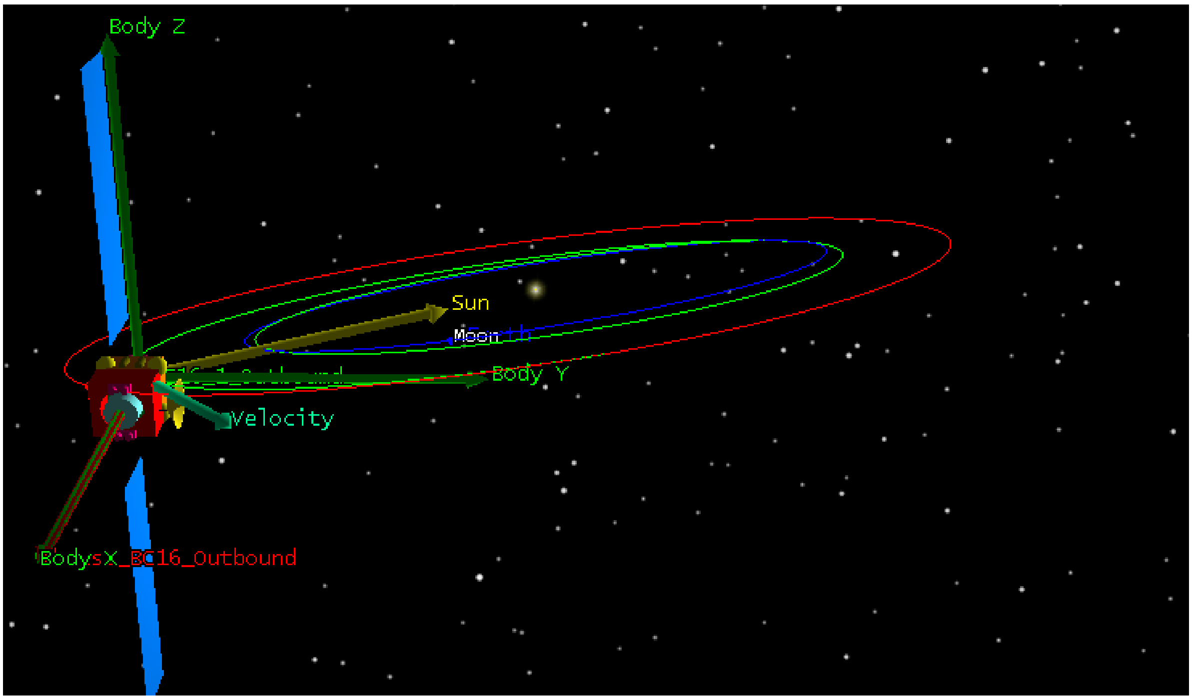



*Figure 8.5.6.10 - BC16 Outbound attitude thrust phase*

The Inbound BC16 phase is divided into a non-propelled segment in which there is alignment with the velocity and a propelled segment in which the ERO is aligned with the thrust. The latter is directed towards the inside of the solar system in order to reduce the semi-major axis. There are small thrust components outside the orbital plane because there are some inclination corrections to be made. The alignment of the Sun with Solar Arrays is always intrinsic in the model.

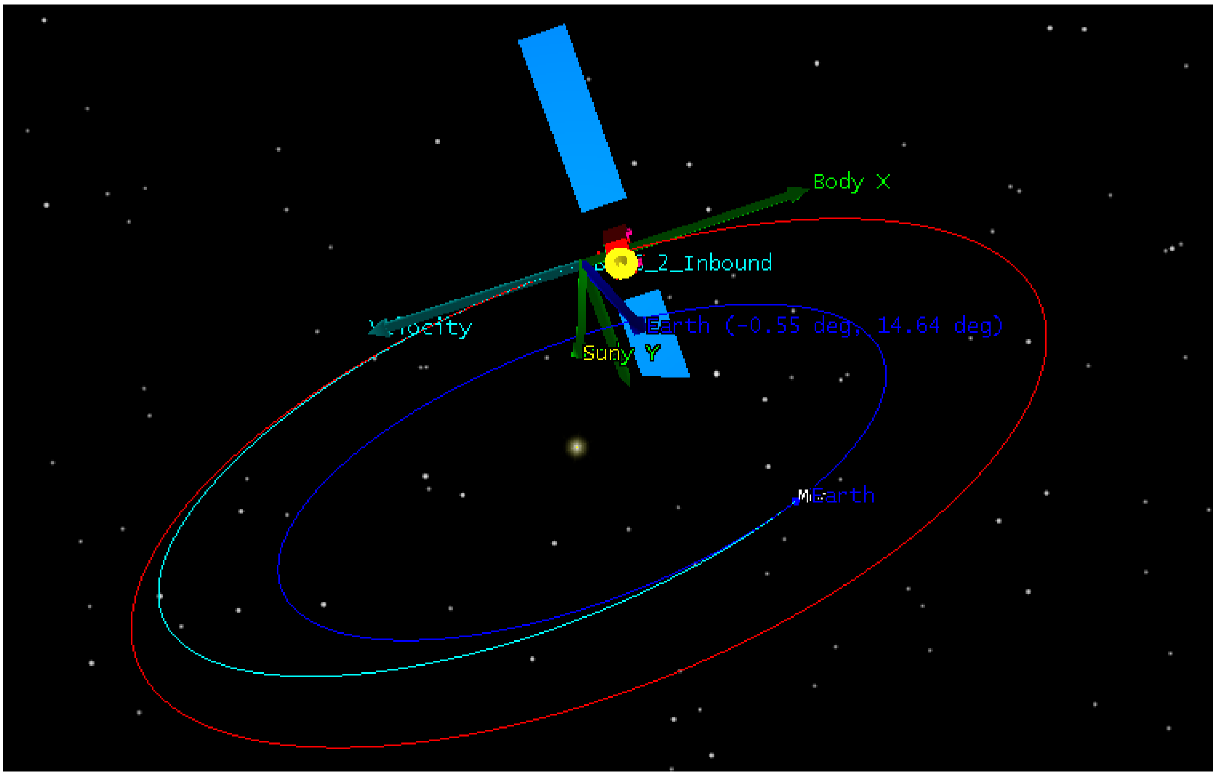



*Figure 8.5.6.11 - BC16 Outbound attitude no thrust phase*

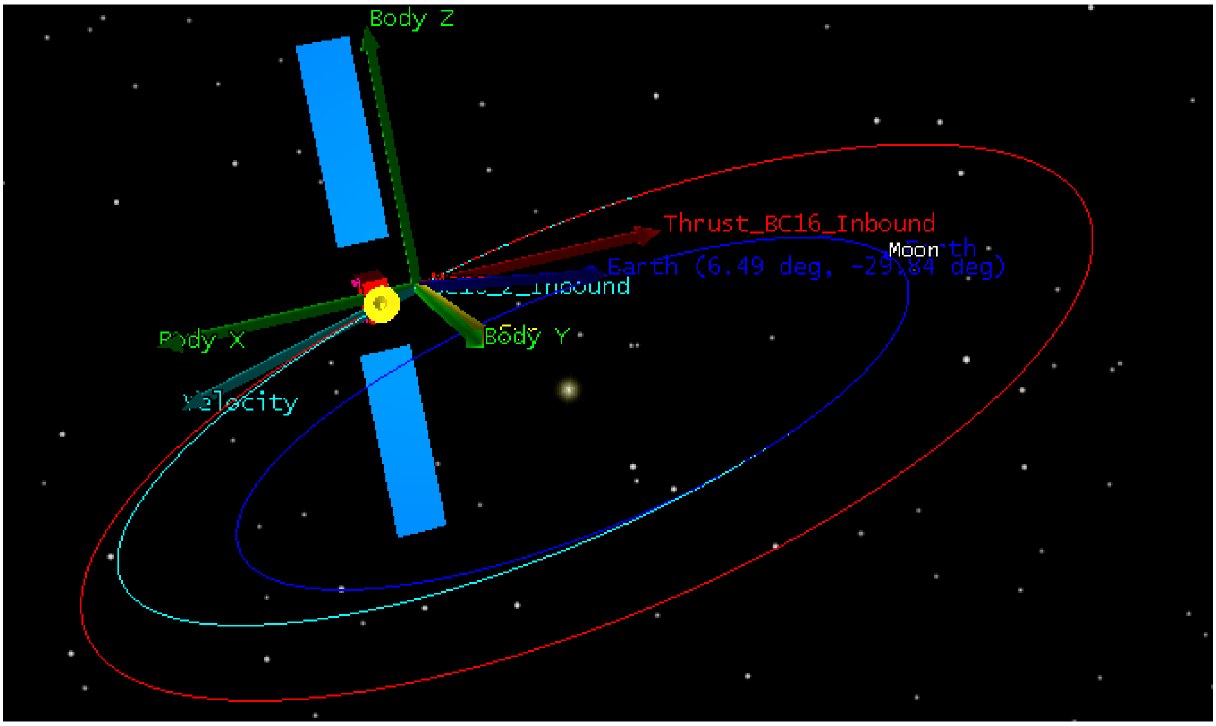



*Figure 8.5.6.12 - BC16 Inbound attitude thrust phase*

## 8.4.7 Mars Operation Attitude

As far as the RDV between the ERO and the OS is concerned, there are no reliable data because the MAV launch site is still unknown: no ephemeris exist in this phase of the project and therefore the orbital construction approach is different. As it has already been said, as a first approximation, the data relative to the nominal target orbit is used and the orbital model is constructed simply by inserting the classical orbital parameters using the "Two bodies" propagator.

Still in the properties of the ERO, in the tab related to the attitude, the "standard" mode (single segment) is chosen by selecting an aligned and constrained insertion. Given the absence of primary propulsion, the attitude is constructed by aiming the positive semi-axis X body in the direction of speed due to the presence of the cameras that have the purpose of starting the search phase. The preferential alignment foresees the negative semi-axis of the Y body directed towards the surface of Mars (nadir), as it is necessary to start in UHF with the MAV. The insertion of this information in the STK model takes place in the properties of the satellite in the "attitude" tab. The selected entry is standard and is represented by the following figure. Then a graphic example of the desired attitude is attached.

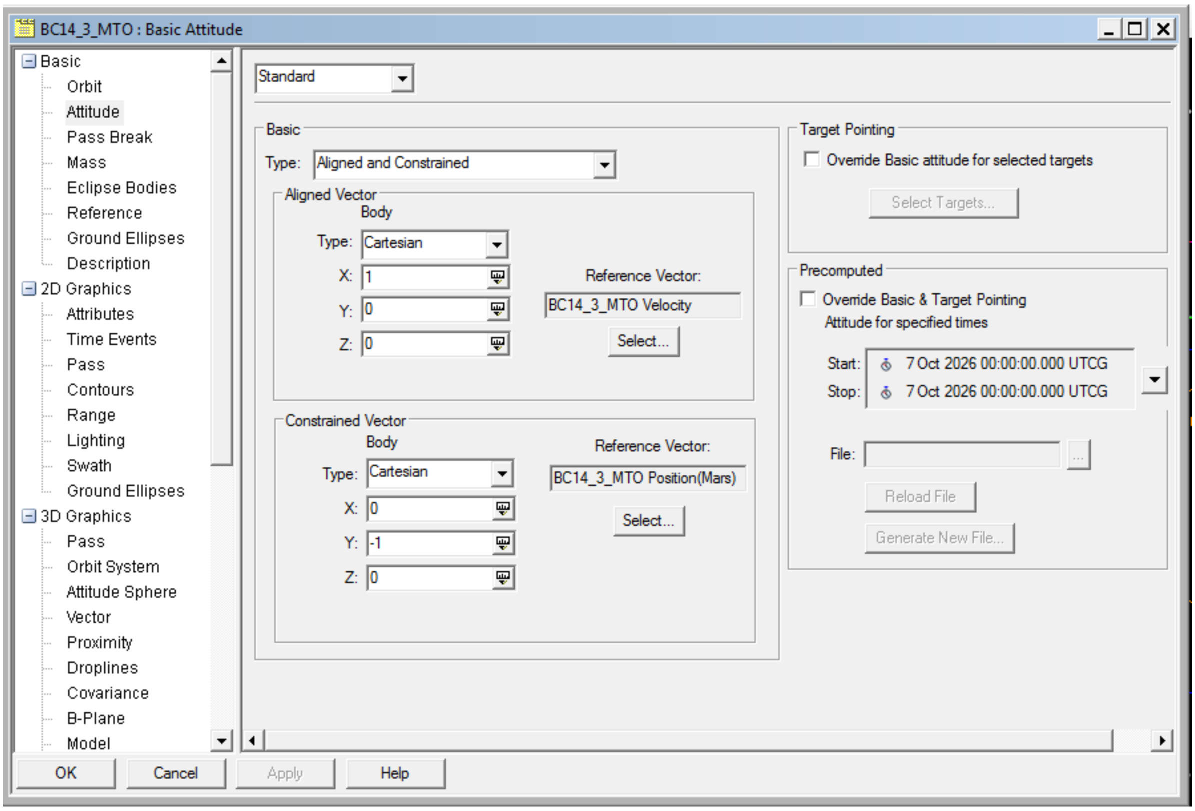



*Figure 8.5.7.1 - Mars Operation Phases Attitude Model*

In the following figures the attitude of the ERO is shown graphically. The S/C follows the trajectory by aligning its X axis with it and during the day, it directs the solar panels directed towards the Sun.

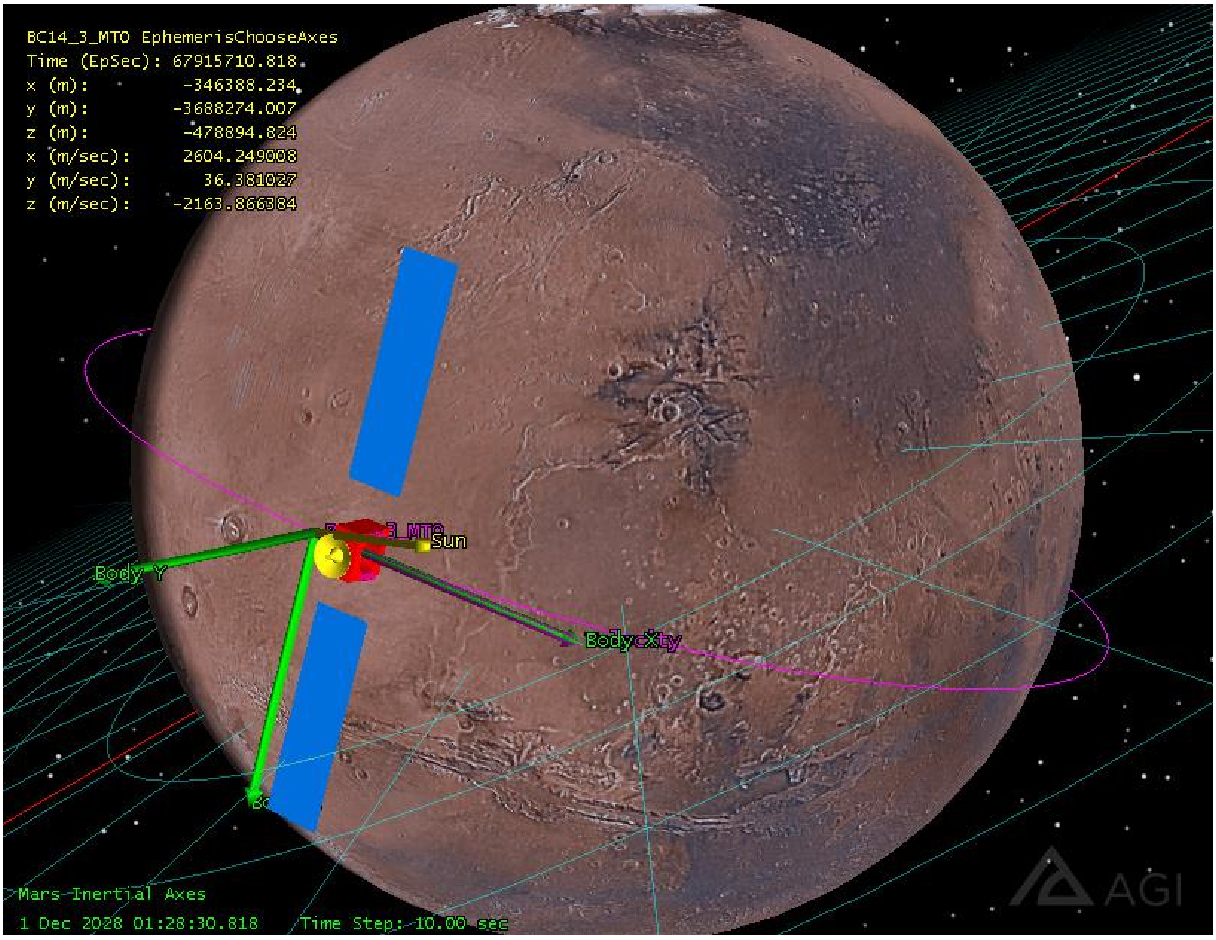



*Figure 8.5.7.2 - Mars Operation Phases Attitude*

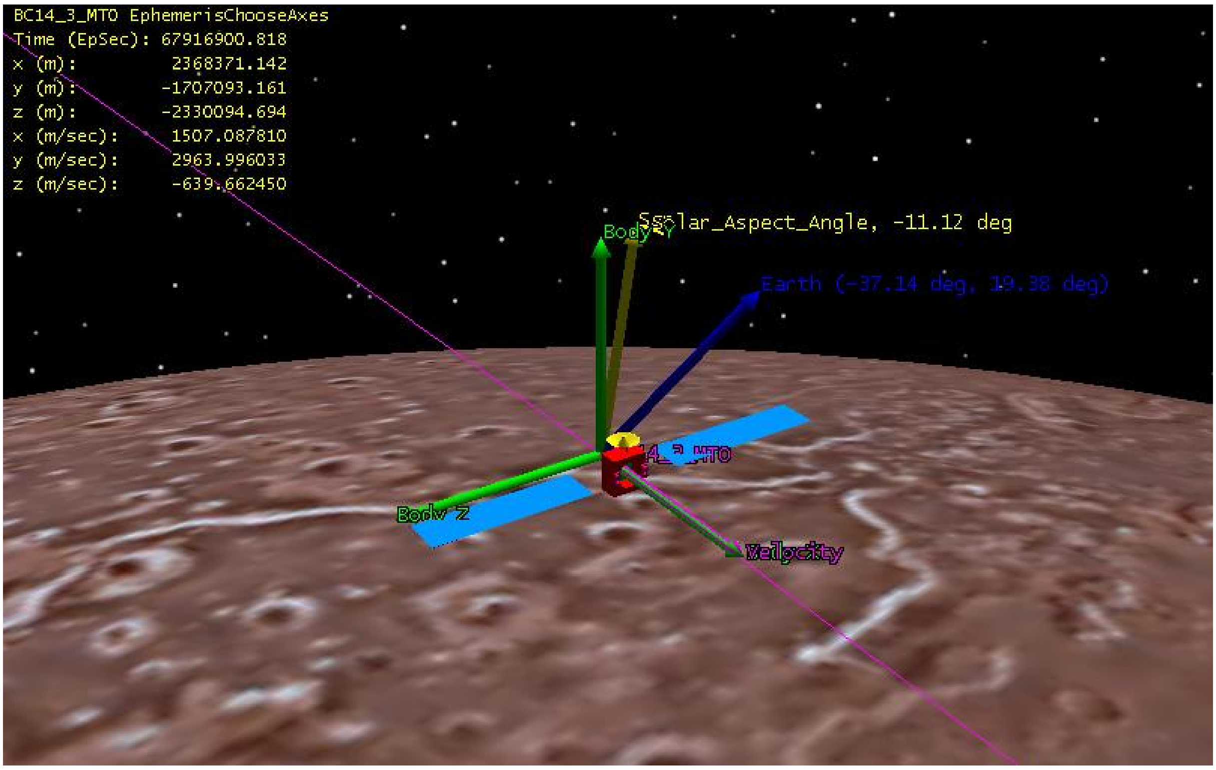



*Figure 8.5.7.3 - Mars Operation Phases Atitude detail*

# 8.6 Access from ERO to Earth

Before starting to set up any analysis concerning HGA Angles and the Solar Arrays Angles, the boundary conditions of these analyses must be defined. Having the information angles is totally useless if the ERO can't communicate with the Earth due to other celestial bodies obstructing the view. Access calculation is a useful and powerful tool that allows the model to have an indication of the possibility of being in line of sight between one object and another. As an example, having small HGA angles is useless if Mars obstructs the view.

## 8.6.1 ERO-Earth Access Definition

The procedure was applied in a mirror-like manner to all the satellites built in the model.

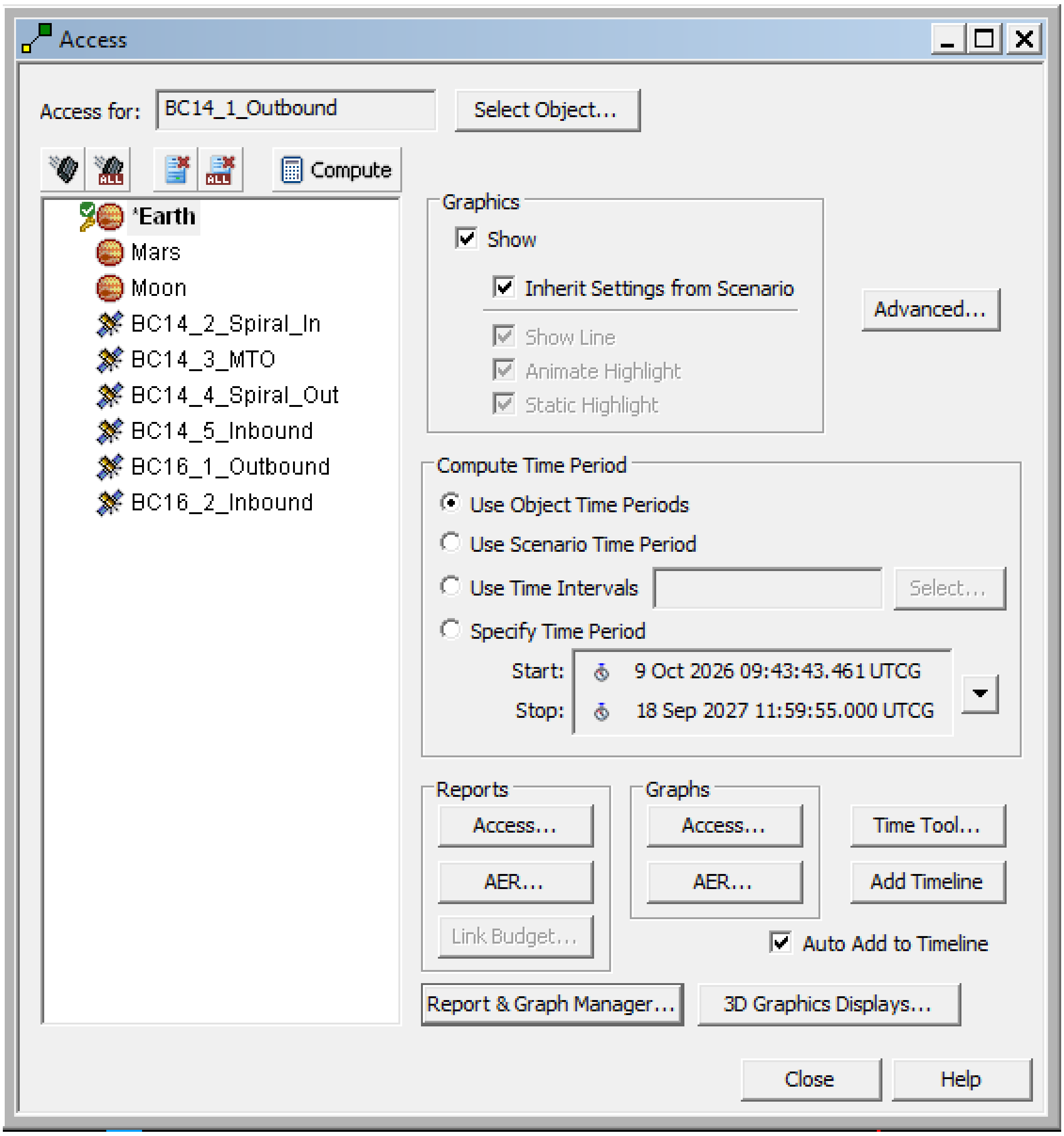



*Figure 8.6.1.1 - Access Creation*

The procedure requires the insertion of the two objects in which access is required. In the scenario the access of the satellite to the Earth is set, hence the moment when the satellite is visible at Earth or vice versa. The setting up of an access can be defined by the specific access toolbar or by the workbench.

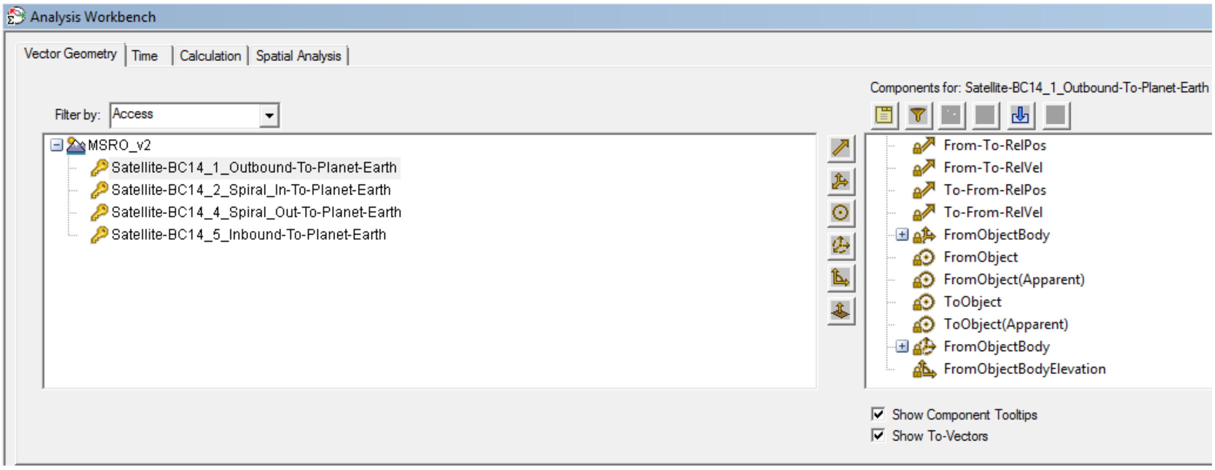



*Figure 8.6.1.2 - Access Workbench*

## 8.6.2 Data representation mode access

After defining the source object of the access and the destination object, the results delivery model and the format type are set through the Report & Graph manager. This tool is useful because it allows the choice of data to be published and the display mode.

In the scenario it was decided to visualize the data related to accesses and time intervals in which one is not in sight with the Earth. For each time frame, the start date and time, end date and time, duration and time segment number are displayed.

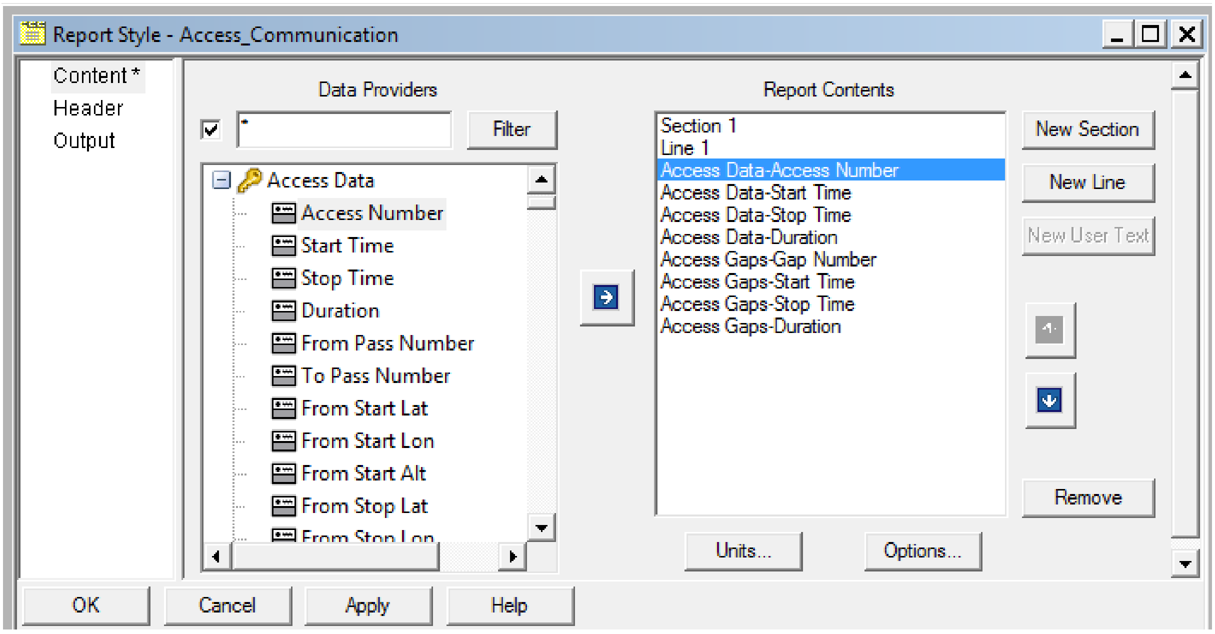



*Figure 8.6.2.1 - Access Report Style*

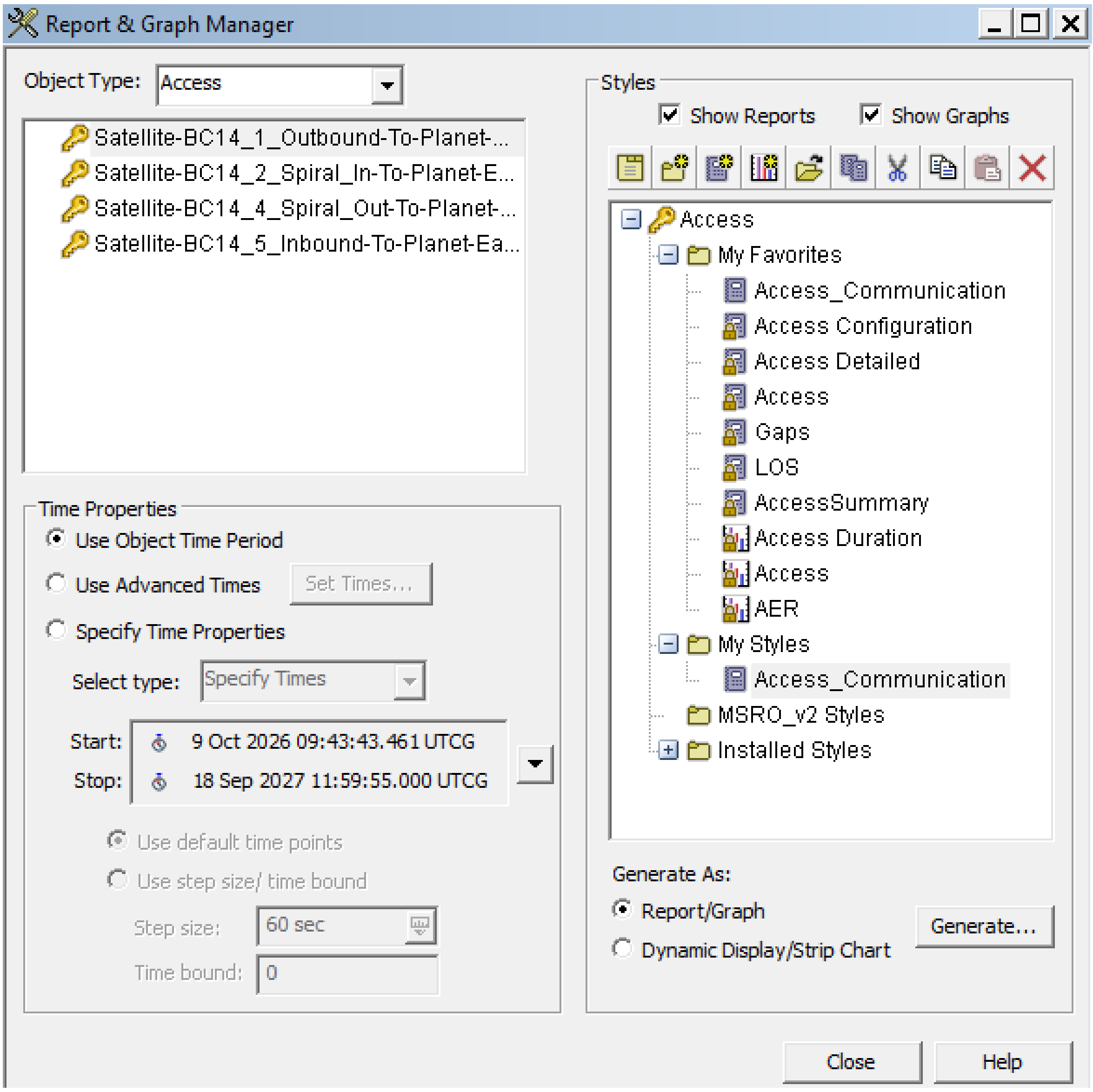



*Figure 8.6.2.2 - Report & Graph Manager for Access*

## 8.6.3 Access Report

After all parameters have been set, the access report can be generated. Each satellite will have its own calculated report and all of them are saved in the "Quick Report" menù.

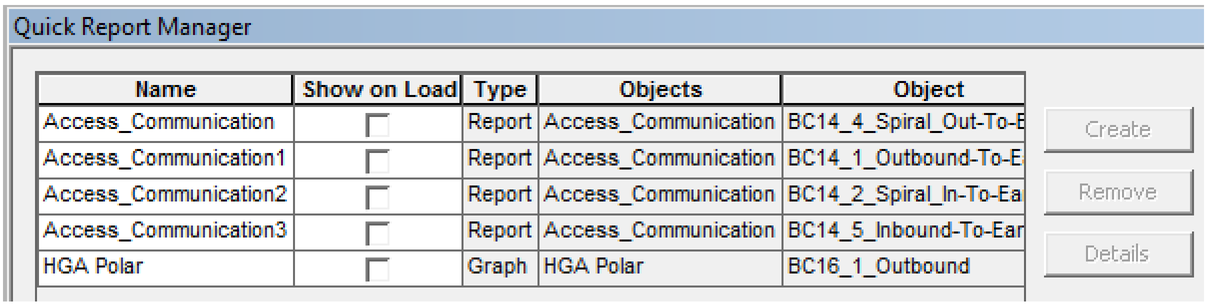



*Figure 8.6.3.1 - Quick Access Report*

Report: Satellite-BC14_4_Spiral_Out-To-Planet-Earth - Access_Communication

Jump To: Top

Start: 7 Oct 2029 12:05:48.376 UTCG
Stop: 29 Apr 2030 22:05:08.920 UTCG

17 Dec 2018 15:31:39

Satellite-BC14_4_Spiral_Out-To-Planet-Earth: Access from ERO to EARTH

| Access | Start Time (UTCG) | Stop Time (UTCG) | Duration (sec) | Gap | Start Time (UTCG) | Stop Time (UTCG) | Duration (sec) |
|---|---|---|---|---|---|---|---|
| 1 | 7 Oct 2029 12:05:48.376 | 7 Oct 2029 12:58:10.655 | 3142.279 | 1 | 7 Oct 2029 12:58:10.655 | 7 Oct 2029 13:40:07.435 | 2516.780 |
| 2 | 7 Oct 2029 13:40:07.435 | 7 Oct 2029 14:52:41.530 | 4354.095 | 2 | 7 Oct 2029 14:52:41.530 | 7 Oct 2029 15:34:38.219 | 2516.689 |
| 3 | 7 Oct 2029 15:34:38.219 | 7 Oct 2029 16:47:17.185 | 4358.966 | 3 | 7 Oct 2029 16:47:17.185 | 7 Oct 2029 17:29:13.441 | 2516.255 |
| 4 | 7 Oct 2029 17:29:13.441 | 7 Oct 2029 18:41:57.438 | 4363.997 | 4 | 7 Oct 2029 18:41:57.438 | 7 Oct 2029 19:23:53.226 | 2515.789 |
| 5 | 7 Oct 2029 19:23:53.226 | 7 Oct 2029 20:36:42.203 | 4368.977 | 5 | 7 Oct 2029 20:36:42.203 | 7 Oct 2029 21:18:37.878 | 2515.675 |
| 6 | 7 Oct 2029 21:18:37.878 | 7 Oct 2029 22:31:32.046 | 4374.169 | 6 | 7 Oct 2029 22:31:32.046 | 7 Oct 2029 23:13:27.363 | 2515.317 |
| 7 | 7 Oct 2029 23:13:27.363 | 8 Oct 2029 00:26:26.865 | 4379.501 | 7 | 8 Oct 2029 00:26:26.865 | 8 Oct 2029 01:08:21.721 | 2514.857 |
| 8 | 8 Oct 2029 01:08:21.721 | 8 Oct 2029 02:21:26.533 | 4384.812 | 8 | 8 Oct 2029 02:21:26.533 | 8 Oct 2029 03:03:20.968 | 2514.434 |
| 9 | 8 Oct 2029 03:03:20.968 | 8 Oct 2029 04:16:31.189 | 4390.221 | 9 | 8 Oct 2029 04:16:31.189 | 8 Oct 2029 04:58:25.091 | 2513.902 |
| 10 | 8 Oct 2029 04:58:25.091 | 8 Oct 2029 06:11:40.739 | 4395.648 | 10 | 8 Oct 2029 06:11:40.739 | 8 Oct 2029 06:53:34.130 | 2513.391 |
| 11 | 8 Oct 2029 06:53:34.130 | 8 Oct 2029 08:06:55.258 | 4401.128 | 11 | 8 Oct 2029 08:06:55.258 | 8 Oct 2029 08:48:48.105 | 2512.848 |
| 12 | 8 Oct 2029 08:48:48.105 | 8 Oct 2029 10:02:14.771 | 4406.666 | 12 | 8 Oct 2029 10:02:14.771 | 8 Oct 2029 10:44:06.937 | 2512.166 |
| 13 | 8 Oct 2029 10:44:06.937 | 8 Oct 2029 11:57:39.212 | 4412.275 | 13 | 8 Oct 2029 11:57:39.212 | 8 Oct 2029 12:39:30.801 | 2511.589 |
| 14 | 8 Oct 2029 12:39:30.801 | 8 Oct 2029 13:53:08.628 | 4417.826 | 14 | 8 Oct 2029 13:53:08.628 | 8 Oct 2029 14:34:59.562 | 2510.934 |
| 15 | 8 Oct 2029 14:34:59.562 | 8 Oct 2029 15:48:43.057 | 4423.495 | 15 | 8 Oct 2029 15:48:43.057 | 8 Oct 2029 16:30:33.294 | 2510.237 |
| 16 | 8 Oct 2029 16:30:33.294 | 8 Oct 2029 17:44:21.267 | 4427.973 | 16 | 8 Oct 2029 17:44:21.267 | 8 Oct 2029 18:26:12.040 | 2510.772 |
| 17 | 8 Oct 2029 18:26:12.040 | 8 Oct 2029 19:40:07.095 | 4435.055 | 17 | 8 Oct 2029 19:40:07.095 | 8 Oct 2029 20:21:55.843 | 2508.748 |
| 18 | 8 Oct 2029 20:21:55.843 | 8 Oct 2029 21:35:56.672 | 4440.829 | 18 | 8 Oct 2029 21:35:56.672 | 8 Oct 2029 22:17:44.634 | 2507.962 |
| 19 | 8 Oct 2029 22:17:44.634 | 8 Oct 2029 23:31:51.443 | 4446.809 | 19 | 8 Oct 2029 23:31:51.443 | 9 Oct 2029 00:13:38.338 | 2506.895 |
| 20 | 9 Oct 2029 00:13:38.338 | 9 Oct 2029 01:27:51.069 | 4452.731 | 20 | 9 Oct 2029 01:27:51.069 | 9 Oct 2029 02:09:37.100 | 2506.030 |
| 21 | 9 Oct 2029 02:09:37.100 | 9 Oct 2029 03:23:55.879 | 4458.780 | 21 | 9 Oct 2029 03:23:55.879 | 9 Oct 2029 04:05:41.020 | 2505.140 |
| 22 | 9 Oct 2029 04:05:41.020 | 9 Oct 2029 05:20:05.768 | 4464.749 | 22 | 9 Oct 2029 05:20:05.768 | 9 Oct 2029 06:01:49.910 | 2504.142 |
| 23 | 9 Oct 2029 06:01:49.910 | 9 Oct 2029 07:16:20.808 | 4470.898 | 23 | 9 Oct 2029 07:16:20.808 | 9 Oct 2029 07:58:03.825 | 2503.017 |
| 24 | 9 Oct 2029 07:58:03.825 | 9 Oct 2029 09:12:40.983 | 4477.158 | 24 | 9 Oct 2029 09:12:40.983 | 9 Oct 2029 09:54:22.729 | 2501.746 |
| 25 | 9 Oct 2029 09:54:22.729 | 9 Oct 2029 11:09:06.270 | 4483.541 | 25 | 9 Oct 2029 11:09:06.270 | 9 Oct 2029 11:50:46.784 | 2500.514 |
| 26 | 9 Oct 2029 11:50:46.784 | 9 Oct 2029 13:05:36.710 | 4489.925 | 26 | 9 Oct 2029 13:05:36.710 | 9 Oct 2029 13:47:16.418 | 2499.708 |
| 27 | 9 Oct 2029 13:47:16.418 | 9 Oct 2029 15:02:12.305 | 4495.887 | 27 | 9 Oct 2029 15:02:12.305 | 9 Oct 2029 15:43:50.799 | 2498.494 |

*Figure 8.6.3.2 - Spiral Out Access report*

Quick reports are tables that show the desired data and can be saved in text, pdf or excel database format.

## 8.6.4 Access Results

The reason why the ERO may not be in sight with the Earth for some period of time is only the presence of a celestial body that obstructs the view. Given the mission geometry and the distances involved, the only celestial body can only be Mars, since it is the only planet present between the ERO and the Earth. Given the distances, the Moon is too small to cause the cessation of communications. The model created in STK asserts that during transfers there is always a direct connection between ERO and Earth. This does not apply during spiral manoeuvers and during the Martian phases. When the ERO rotates around Mars, there will be a succession of accesses and time bows without communication. The period of view is getting smaller as ERO approaches the red planet and it would tend to have 66,5% of the time in sight. For the heights involved, during the Martian phases the ERO will have about 66,5% of the time in sight, but this does not cause problems since the ERO does not have the need to always communicate with the Earth. During the spiral phases instead, the period of time in which ERO can communicate with the Earth is much higher and increases as the S/C moves away from the red planet. The end result is that there are no major problems with communication.

The next diagram shows the percentage of the Access during the Spiral Out phase, which is the phase with a lower percentage, if the Martian phases are excluded (with 32,5 % of gap time).

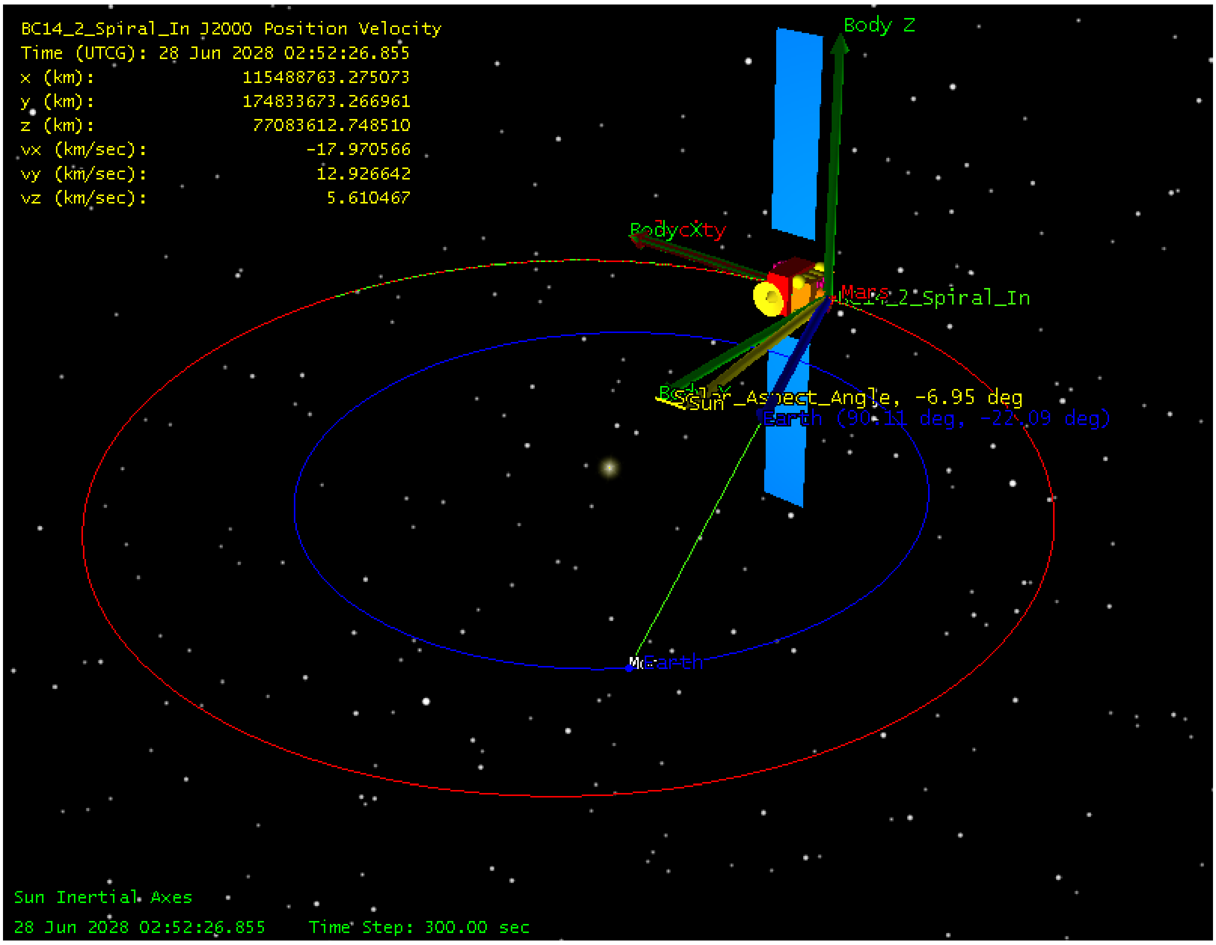



*Figure 8.6.4.1 - Access view*

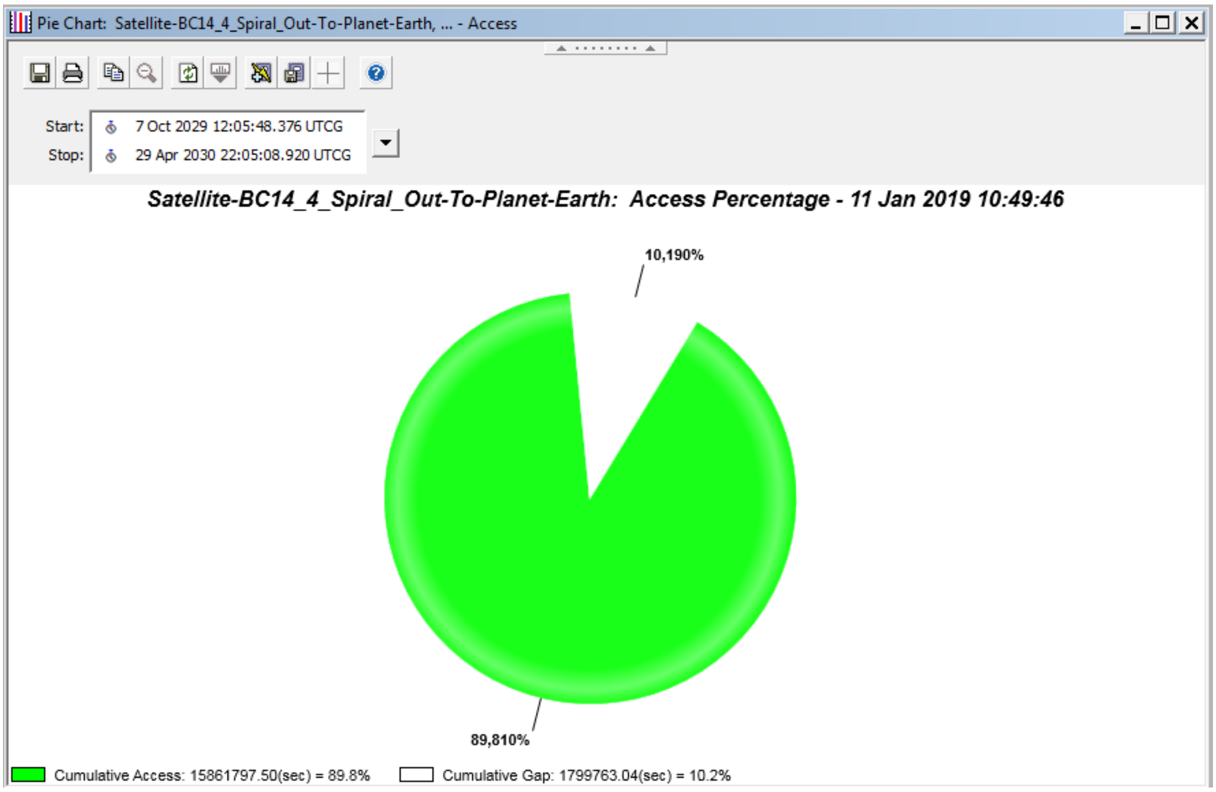



*Figure 8.6.4.2 - Access % during Spiral Out*

# 8.7 Eclipses and light-shadow cycles

The information concerning the eclipses is very important in order to have a precise idea of the cycles of light and shadow that the satellite will see. This information is useful to be able to predict how much electric power the ERO is able to generate.

## 8.7.1 Eclipses in LMO

For a circular orbit around Mars, the duration of the eclipses is determined by the altitude and the solar β angle, defined as the angle between the orbit plane and the direction vector from Mars to the Sun. The following figure shows eclipse fraction with respect to the orbital period as function of the solar β angle for given orbit altitudes. The solar β angle depends on the Sun-Mars geometry, mainly driven by the solar longitude Ls, and the orientation of the orbital plane defined by the orbit inclination and RAAN. For a LMO the evolution of the β angle will be dominated by the J2 RAAN drift of several degrees per day. However, the absolute value of the β angle is bounded by the sum of the inclination and the obliquity of Mars equator to the orbit.

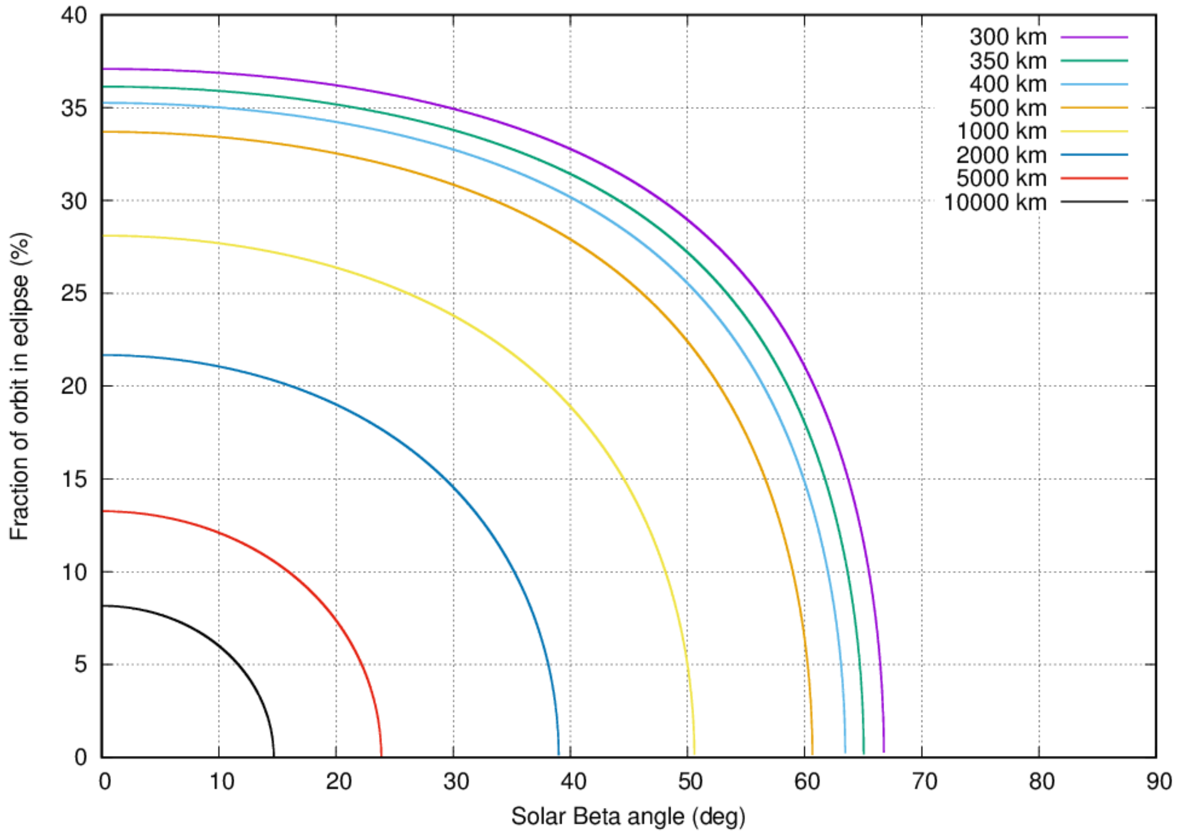



*Figure 8.7.1.1 - Eclipse cycles*

### 8.7.2 Eclipse report Definition

By selecting the report settings, the eclipse data is selected.

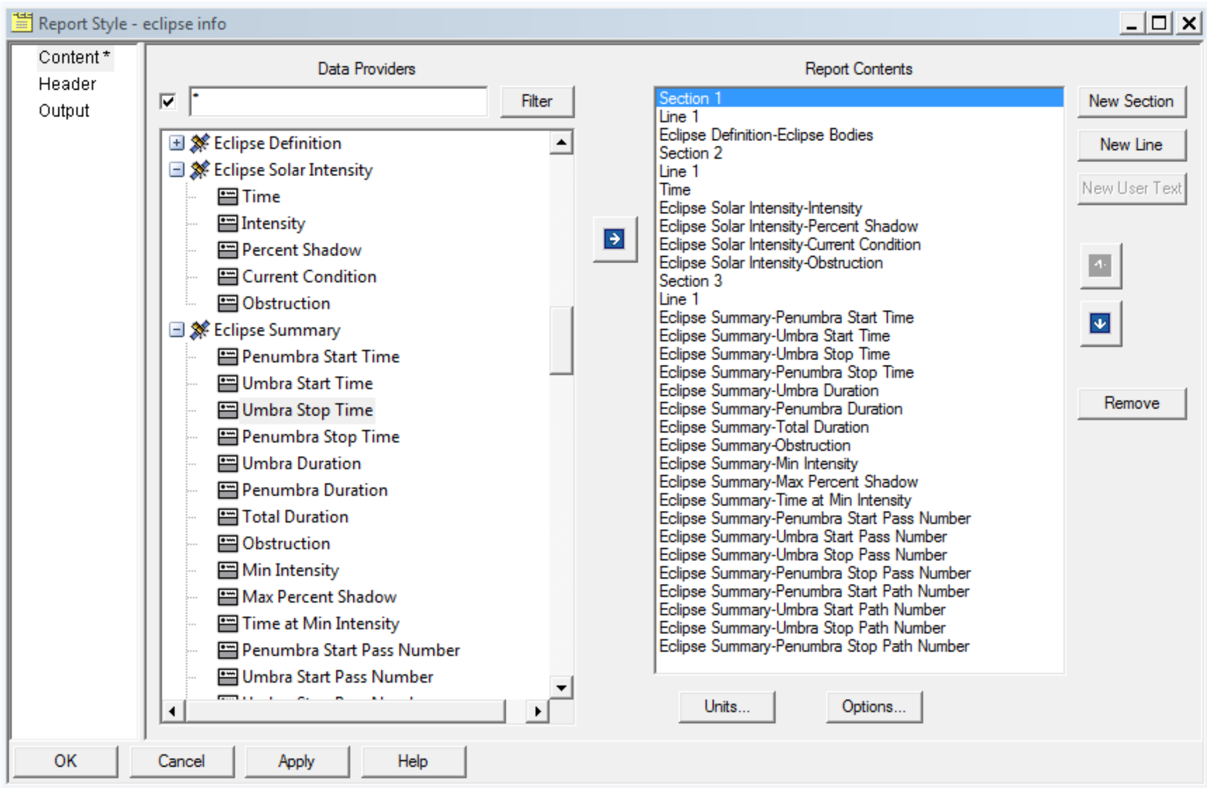
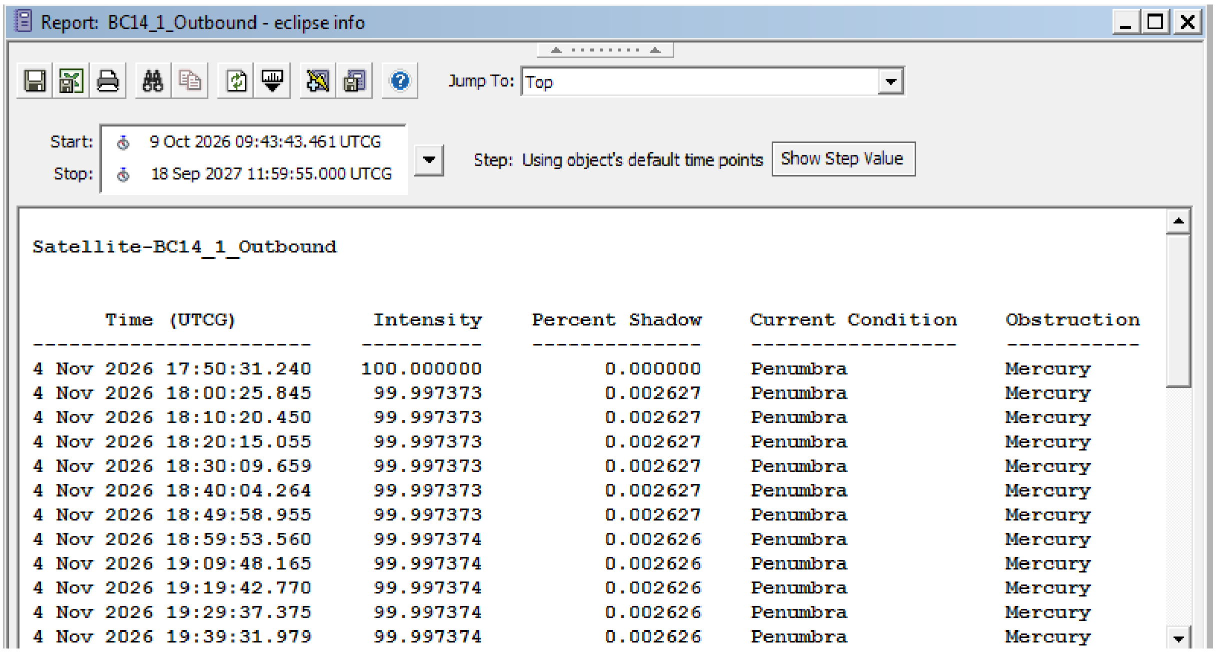



*Figure 8.7.2.1 - Eclipse definition*

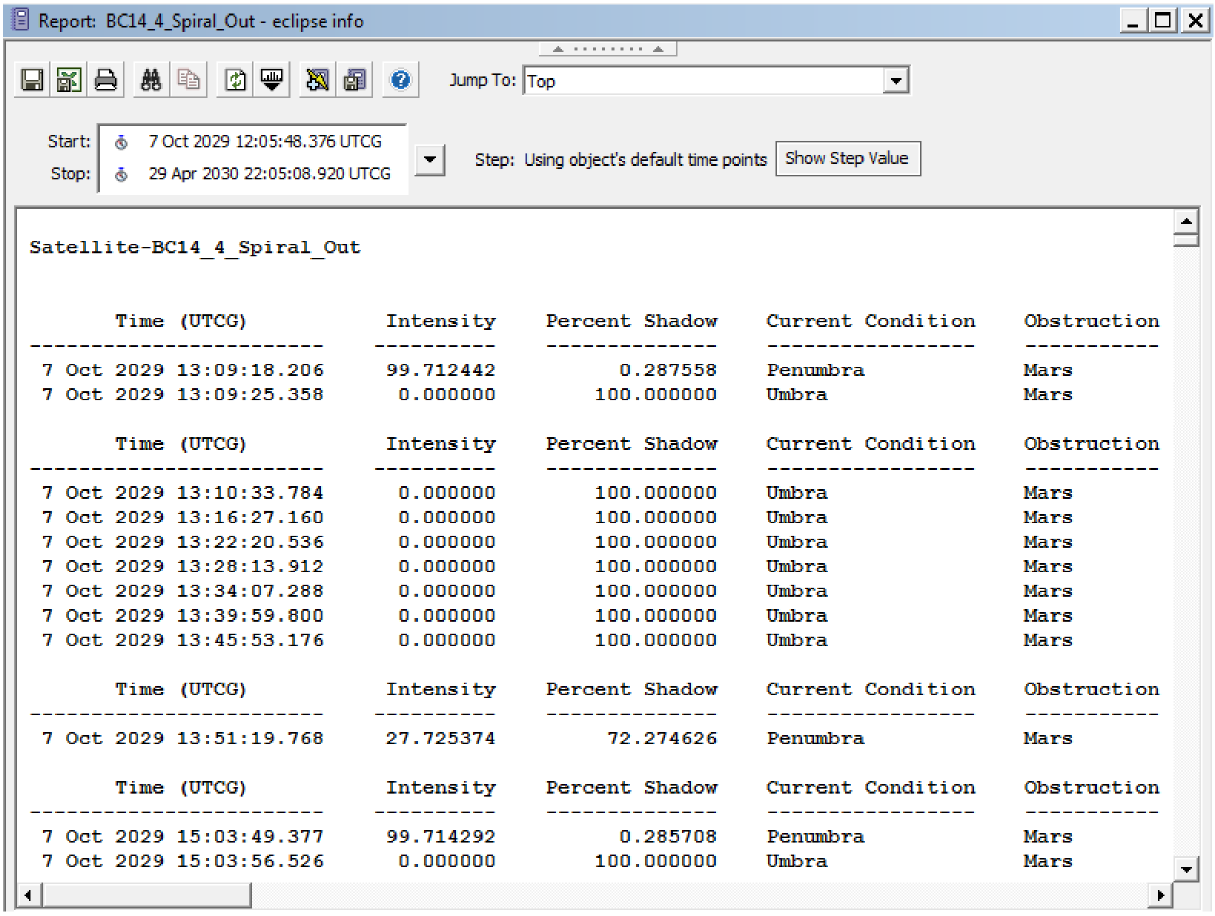
### 8.7.3 Eclipse Results

The calculator provides eclipse data in terms of umbra, penumbra and its percentage at a defined epoch of the scenario. For our purposes, the only elements taken into consideration will be the complete eclipse temporal instants, since Mars is the only celestial body able to shield the sun's rays directed to the ERO. The complete eclipse condition consists in the total overlap of a celestial body aligned with the Sun, while the penumbra condition consists in the partial overlapping; in this case the percentage of penumbra consists in the geometric percentage of the planet in alignment with the Sun: from a physical point of view, when the software declares the penumbra, it does not mean the physical meaning of brightness reduction. However, attention must be paid to the results: a condition of complete eclipse does not automatically translate into a dark condition for ERO. A small asteroid near the Sun would not be noticed by the S/C but the software would classify the phenomenon as an eclipse. In the results there are temporal moments of penumbra due to the presence of Mercury and Venus between the Sun and the S/C, but given the distances involved and the size of the star, the celestial bodies in question do not cause any reduction of electricity produced with the Solar Array. The results consist not only of data in tabular form but also in pie graphs. In them the Gap time is inclusive of the sum of all the temporal arcs of shadow and penumbra, regardless of the percentage of brightness and the aligned celestial body. The three following figures are intended to explain the layout of the results.




| Time (UTCG) | Intensity | Percent Shadow | Current Condition | Obstruction |
|---|---|---|---|---|
| 4 Nov 2026 17:50:31.240 | 100.000000 | 0.000000 | Penumbra | Mercury |
| 4 Nov 2026 18:00:25.845 | 99.997373 | 0.002627 | Penumbra | Mercury |
| 4 Nov 2026 18:10:20.450 | 99.997373 | 0.002627 | Penumbra | Mercury |
| 4 Nov 2026 18:20:15.055 | 99.997373 | 0.002627 | Penumbra | Mercury |
| 4 Nov 2026 18:30:09.659 | 99.997373 | 0.002627 | Penumbra | Mercury |
| 4 Nov 2026 18:40:04.264 | 99.997373 | 0.002627 | Penumbra | Mercury |
| 4 Nov 2026 18:49:58.955 | 99.997373 | 0.002627 | Penumbra | Mercury |
| 4 Nov 2026 18:59:53.560 | 99.997374 | 0.002626 | Penumbra | Mercury |
| 4 Nov 2026 19:09:48.165 | 99.997374 | 0.002626 | Penumbra | Mercury |
| 4 Nov 2026 19:19:42.770 | 99.997374 | 0.002626 | Penumbra | Mercury |
| 4 Nov 2026 19:29:37.375 | 99.997374 | 0.002626 | Penumbra | Mercury |
| 4 Nov 2026 19:39:31.979 | 99.997374 | 0.002626 | Penumbra | Mercury |

*Figure 8.7.3.1 - BC14 Outbound Eclipse Report*




| Time (UTCG) | Intensity | Percent Shadow | Current Condition | Obstruction |
|---|---|---|---|---|
| 7 Oct 2029 13:09:18.206 | 99.712442 | 0.287558 | Penumbra | Mars |
| 7 Oct 2029 13:09:25.358 | 0.000000 | 100.000000 | Umbra | Mars |

| Time (UTCG) | Intensity | Percent Shadow | Current Condition | Obstruction |
|---|---|---|---|---|
| 7 Oct 2029 13:10:33.784 | 0.000000 | 100.000000 | Umbra | Mars |
| 7 Oct 2029 13:16:27.160 | 0.000000 | 100.000000 | Umbra | Mars |
| 7 Oct 2029 13:22:20.536 | 0.000000 | 100.000000 | Umbra | Mars |
| 7 Oct 2029 13:28:13.912 | 0.000000 | 100.000000 | Umbra | Mars |
| 7 Oct 2029 13:34:07.288 | 0.000000 | 100.000000 | Umbra | Mars |
| 7 Oct 2029 13:39:59.800 | 0.000000 | 100.000000 | Umbra | Mars |
| 7 Oct 2029 13:45:53.176 | 0.000000 | 100.000000 | Umbra | Mars |

| Time (UTCG) | Intensity | Percent Shadow | Current Condition | Obstruction |
|---|---|---|---|---|
| 7 Oct 2029 13:51:19.768 | 27.725374 | 72.274626 | Penumbra | Mars |

| Time (UTCG) | Intensity | Percent Shadow | Current Condition | Obstruction |
|---|---|---|---|---|
| 7 Oct 2029 15:03:49.377 | 99.714292 | 0.285708 | Penumbra | Mars |
| 7 Oct 2029 15:03:56.526 | 0.000000 | 100.000000 | Umbra | Mars |

*Figure 8.7.3.2 - BC14 Spiral Out Eclipse Report*

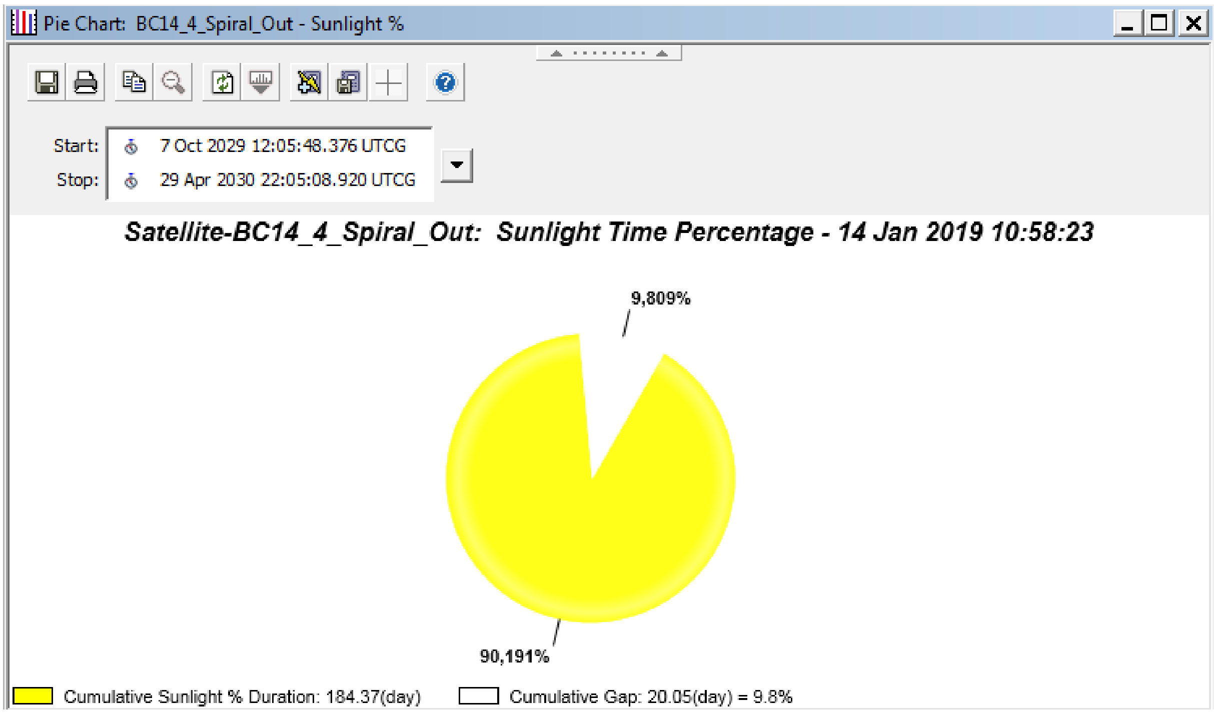



*Figure 8.7.3.3 - BC14 Spiral Out Eclipse Pie Chart*

### 8.7.4 Eclipse Conclusions

The following table summarizes the times of light and shadow during the mission phases. It should be noted that the gap percentage does not coincide with a punctual reduction of electrical power. The actual percentage is calculated taking into account the type of shadow, the celestial body and the distance from the Sun. For example, during the Outbound and Inbound phases of BC14, penumbra is present, but it consists of a few percentage points and refers to celestial bodies that have no impact on performance. Hence, the solar panels will not be affected in any way in terms of energy.

| MISSION PHASE | % LIGHT TIME | % GAP TIME | SHADOW | BODY | EFFECT |
|---|---|---|---|---|---|
| BC14 Outbound | 99,932 % | 0,068 % | Penumbra (Low %) | Mercury | No |
| BC14 Spiral In | 85,498 % | 14,502 % | Mixed (High %) | Mars | 12 % |
| BC14 Mars Phase | 66,066 % | 33,934 % | Umbra (100%) | Mars | 34 % |
| BC14 Spiral Out | 90,191 % | 9,909 % | Mixed (High %) | Mars | 8 % |
| BC14 Inbound | 99,938 % | 0,062 % | Penumbra (Low %) | Venus | No |
| BC16 Outbound | 100,000 % | 0,000 % | Absent | - | No |
| BC16 Inbound | 100,000 % | 0,000 % | Absent | - | No |

*Table 8.6 - Eclipse conclusions*

The study shows the fact that during the transfers there are no appreciable eclipse phenomena. The spiral maneuvers and the Martian phases are the only phases in which it must be taken into account, but with a very high light percentages of time. Taking into account that during the Martian phases a small amount of electricity is required, the mission does not present problems from the lighting point of view.

# 8.8 Solar Aspect Angle Results

Assuming the orientation of the Solar Arrays with the fixed semi-positive Y body axis, the Solar Aspect Angle is calculated: it will be equal to the angle that the articulation must guarantee during the manoeuver. The phases involved exclusively concern those in which the propulsive vector data are known.

## 8.8.1 SAA Reports

The reports consist of the values of the Solar Aspect angle and its rate of change at each moment of time. At the end of the table there is a summary with maximum, minimum and average values. The following figure shows a concluding summary.

```
Solar Aspect Angle
------------------
                          Time (UTCG)           Angle (deg)    AngleRate (deg/day)
                    ------------------------    -----------    -------------------

Global Statistics
-----------------
Min Angle           25 Mar 2027 09:27:44.175        -50.294              -0.000067
Max Angle           18 Sep 2027 11:59:55.000         52.456               1.161093
Mean Angle                                          -19.923
Min AngleRate       10 Dec 2026 13:18:04.893        -14.278              -0.687339
Max AngleRate       18 Sep 2027 11:26:49.071         52.429               1.161301
Mean AngleRate                                                            0.193926
```

*Figure 8.8.1.1 - BC14 SAA Summary Report*

## 8.8.2 SAA Graphs

In the following graphs the red curve represents the SAA (in deg), while the green one represents its instantaneous variation (degs per day) in every time epoch. The graphs are small because it is not important to calculate the precise value: it is important its general trend and the maximum and minimum values already found in the reports.

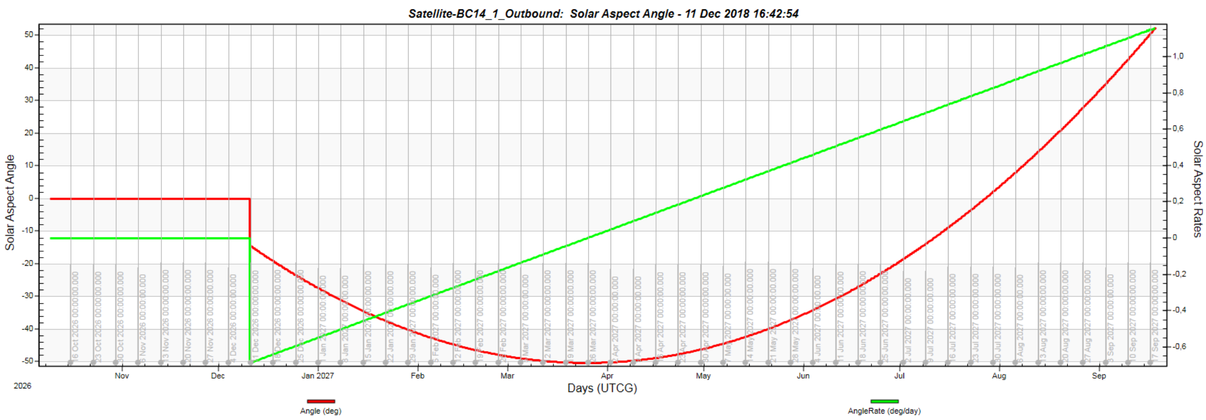



*Figure 8.8.2.1 - BC14 Outbound SAA*

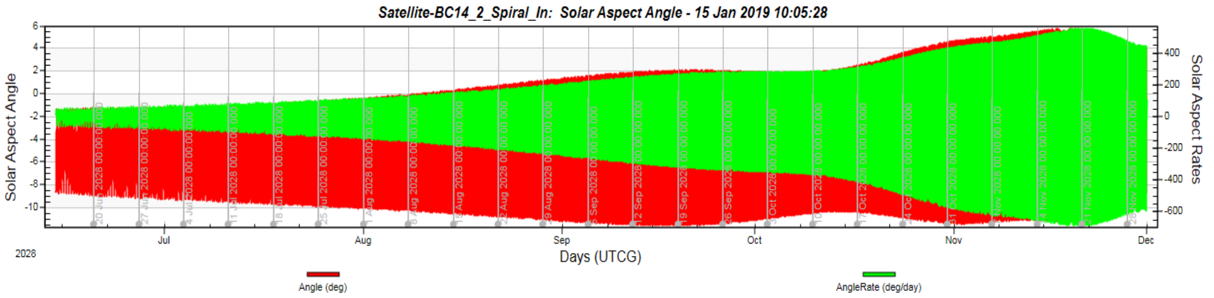



*Figure 8.8.2.2 - BC14 Spiral In SAA*

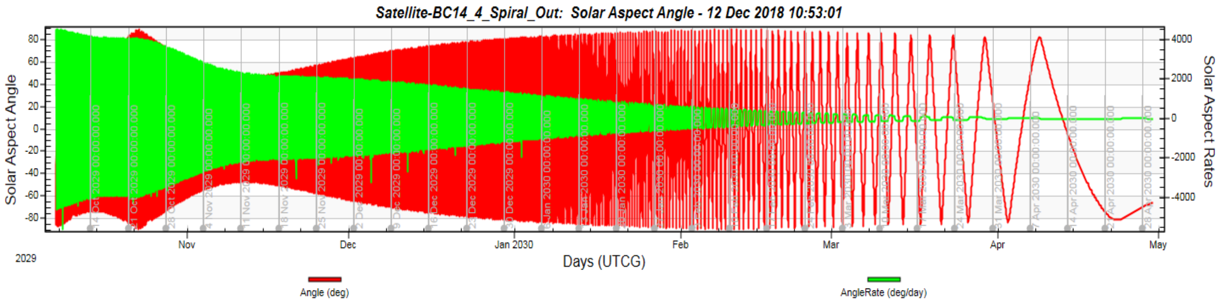



*Figure 8.8.2.3 - BC14 Spiral Out SAA*

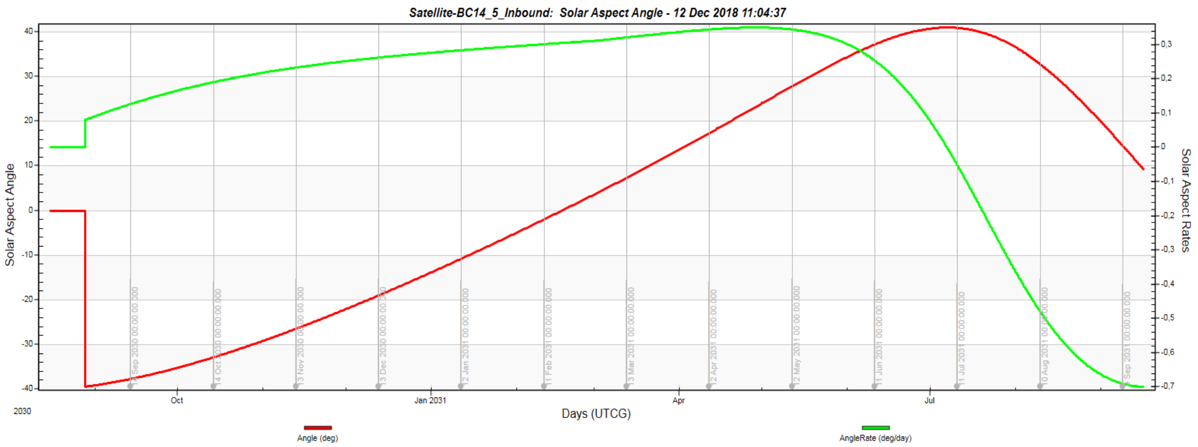



*Figure 8.8.2.4 - BC14 Inbound SAA*

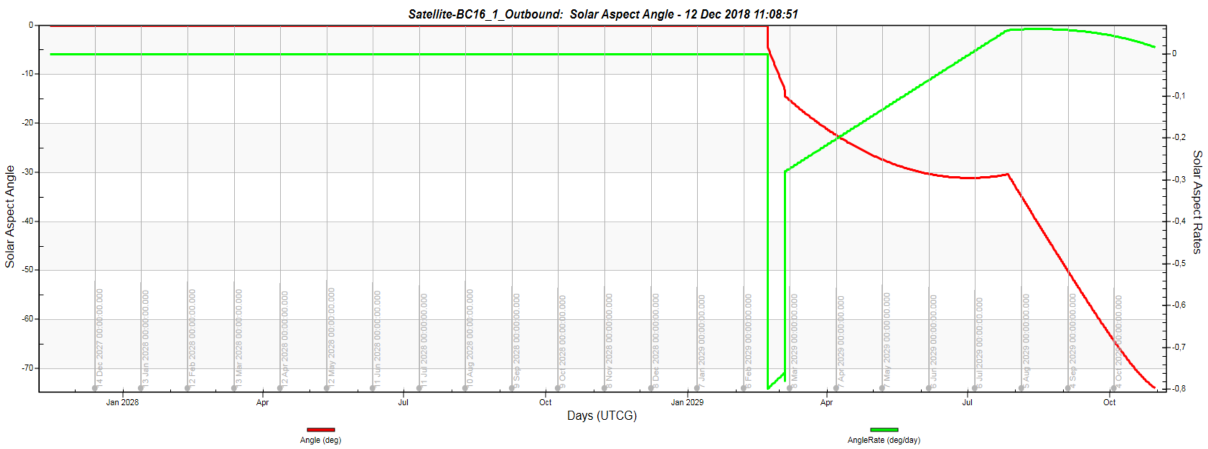



*Figure 8.8.2.5 - BC16 Outbound SAA*

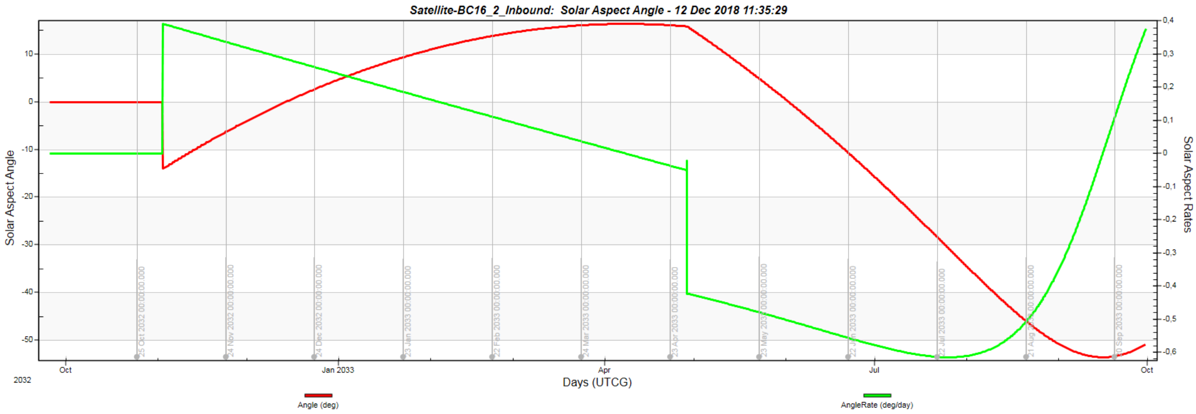



*Figure 8.8.2.6 - BC16 Inbound SAA*

### 8.8.3 SAA Conclusions

The results are summarized in the following table. The angular velocities have been ignored because they take very small values and therefore are not dimensioning for the project.

| MISSION PHASE | MAX SAA | MIN SAA | NOTES |
|---|---|---|---|
| BC14 Outbound | 52,456° | -50,294° | 62 days of No-Thrust Phase |
| BC14 Spiral In | 5,759° | -11,511° | Eclipses |
| BC14 Mars Operations | 89,335° | -89,320° | Eclipses and no primary propulsion |
| BC14 Spiral Out | 89,962° | -89,978° | Eclipses |
| BC14 Inbound | 39,283° | -41,006° | 15 days of No-Trust Phase |
| BC16 Outbound | 0,000° | -74,035° | 465 days of No-Thrust Phase |
| BC16 Inbound | 16,353° | -53,540° | 37 days of No-Thrust Phase |

*Table 8.7 - SAA Results*

The articulation of the Solar Arrays is able to cover the entire angle of rotation, so any result will respect the requirement of generating electricity in an optimal manner. As seen in the section relating to the attitude, no duty cycle of the propulsion has been considered during the whole mission: in reality it is not always necessary a correct alignment between the Solar Panels and the Sun since the primary propulsion is not always active.
-During the transfers there are long periods of time in which the primary propulsion is not active: in this case the values of the SAA have no design restrictions. These periods could be drastically reduced, if it is decided to reduce the thrust levels. The trends are regular and the changes are slow.
-In the schedule the spiral phases should last much longer than the data provided by mission analysis. The Spiral phases can last much longer and therefore the levels of electricity required will be decidedly lower. Mission analysis should consider the fact that when the ERO is in the dark it would not be able to provide primary propulsion. As ERO approaches the planet the trends become irregular and the angular velocities increase: of course, the articulations of the Solar Arrays should only work during the daytime phases.
-During the Martian Phases, the SAA encompasses a wide range of values, but the whole phase sees the absence of the electric primary propulsion combined with the presence of light and shadow cycles so the articulation must not follow this angle.

# 8.9 HGA Articulation Angles Results

Assuming the orientation of the HGA with the fixed semi-positive Y body axis, the HGA Angles are calculated as Azimuth (right ascension: angle on the Y-Z body plane) and Elevation (declination: angle on the X-Y plane): they will be equal to the angles that the articulation must guarantee during the manoeuver. It was not necessary to create the angles of the HGA previously, as they coincide with the right ascension and the declination that the Earth vector assumes with respect to the local HGA reference system. The phases involved exclusively concern those in which the propulsive vector data are known. Below is an example of calculating HGA angle values in Azimuth Elevation coordinates.

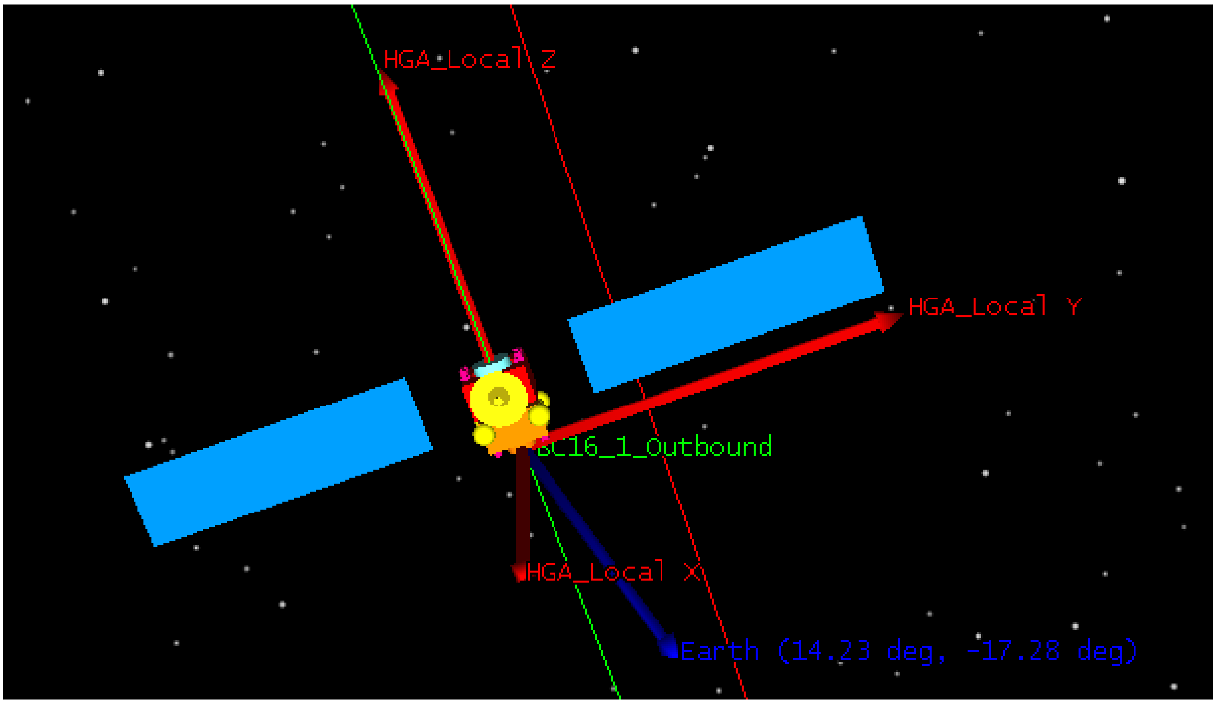



*Figure 8.9.1 - Earth Pointing*

## 8.9.1 HGA Articulation Angles Reports

The reports consist of the values of the HGA Angle and them rate of change at each moment of time. At the end of the table there is a summary with maximum, minimum and average values. The following figure shows a concluding summary.

HGA Angles

| Global Statistics | Time (UTCG) | HGA Azimuth / Right Ascension (deg) | HGA elevation / Declination (deg) |
|---|---|---|---|
| Min HGA Azimuth / Right Ascension | 5 Jan 2027 01:49:21.258 | 8.818 | -15.801 |
| Max HGA Azimuth / Right Ascension | 12 Oct 2026 02:17:10.225 | 91.035 | 76.765 |
| Mean HGA Azimuth / Right Ascension | | 29.705 | |
| Min HGA elevation / Declination | 26 Oct 2026 15:48:53.810 | 51.848 | -58.238 |
| Max HGA elevation / Declination | 9 Oct 2026 09:43:43.461 | 46.525 | 88.267 |
| Mean HGA elevation / Declination | | | -4.156 |

*Figure 8.9.1.1 - HGA Angles Example Report*

## 8.9.2 HGA Articulation Angles Graphs

In the following Azimuth-Elevation graphs the green curve represents the Elevation (in deg), while the black one represents the Azimuth (in deg) in every time epoch. In the following polar graphs the green line represents the orientation of the Earth on the X-Z plane: it is the representation of the sum of all the orientations that the HGA should guarantee throughout the mission phase, regardless of the real need for communication and the time period.
The graphs are small because it is not important to calculate the precise value: it is important its general trend and the maximum and minimum values already found in the reports.

The values represented are the orientations that the HGA must have in order to always aim towards the Earth. From a constructive point of view, the objective of the analysis is to confirm the fact that the antenna will have less Elevation values than the right angle only when it is necessary to communicate with the Earth. With an elevation angle varying between + 90 ° and -90 ° it is possible to point out regardless of the value of Azimuth.

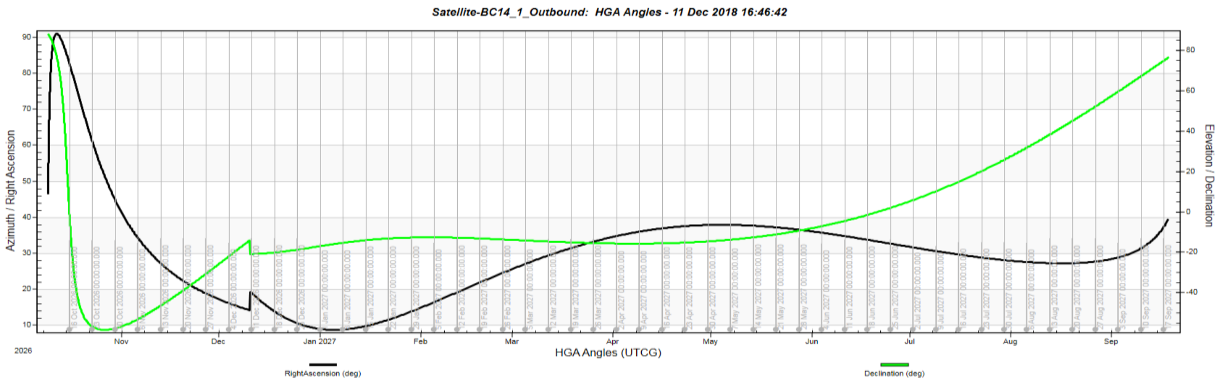



*Figure 8.9.2.1 - BC14 Outbound HGA Angle*

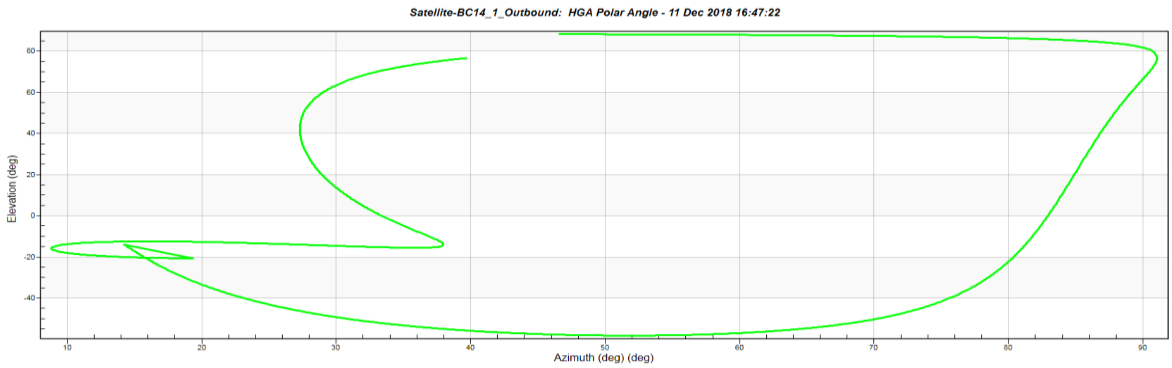



*Figure 8.9.2.2 - BC14 Outbound HGA Polar*

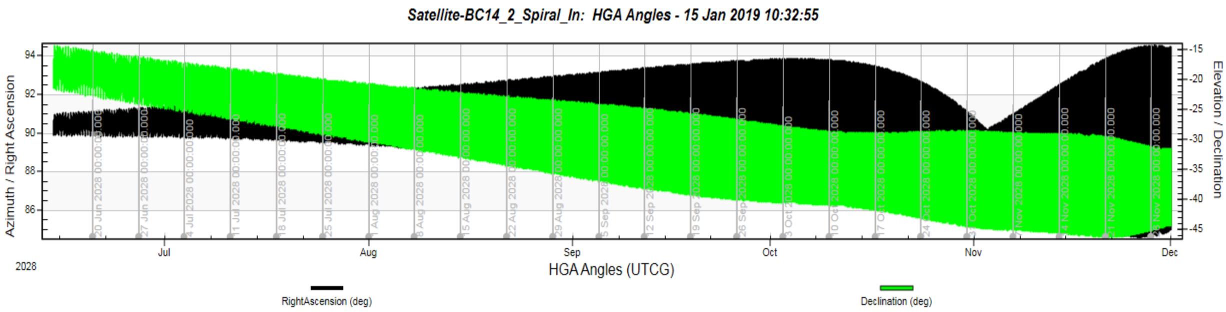



*Figure 8.9.2.3 - BC14 Spiral In HGA angles*

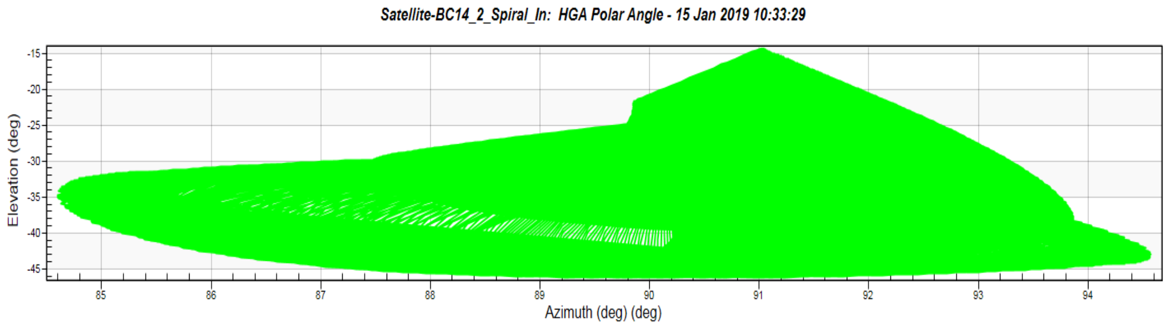



*Figure 8.9.2.4 - BC14 Spiral In Polar*

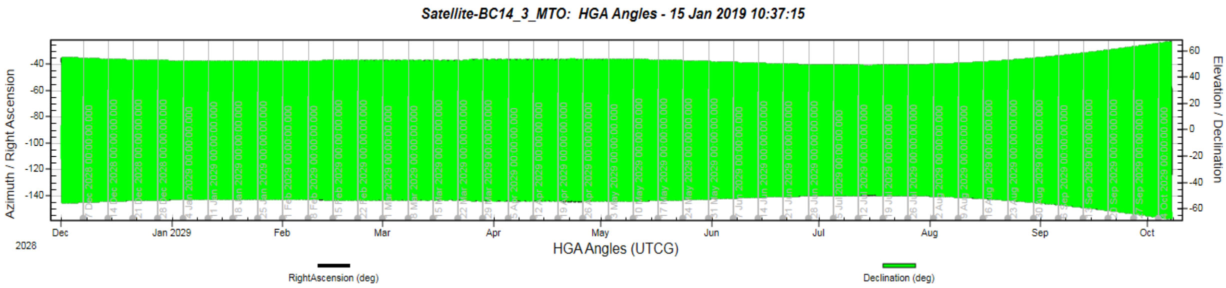



*Figure 8.9.2.5 - BC14 MTO HGA angles*

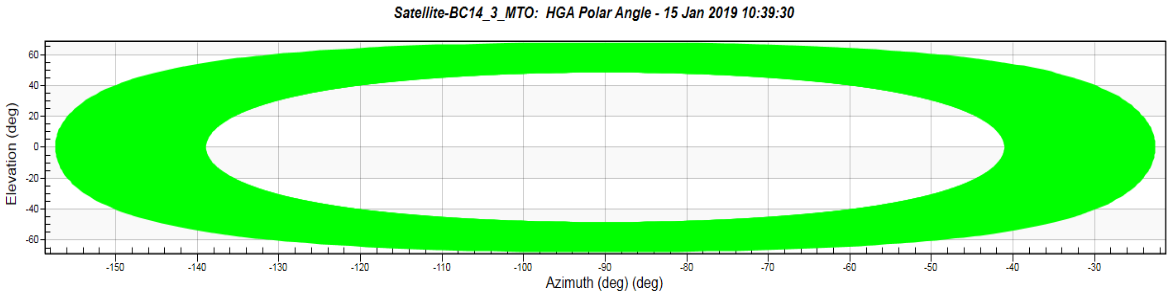



*Figure 8.9.2.6 - BC14 MTO Polar*

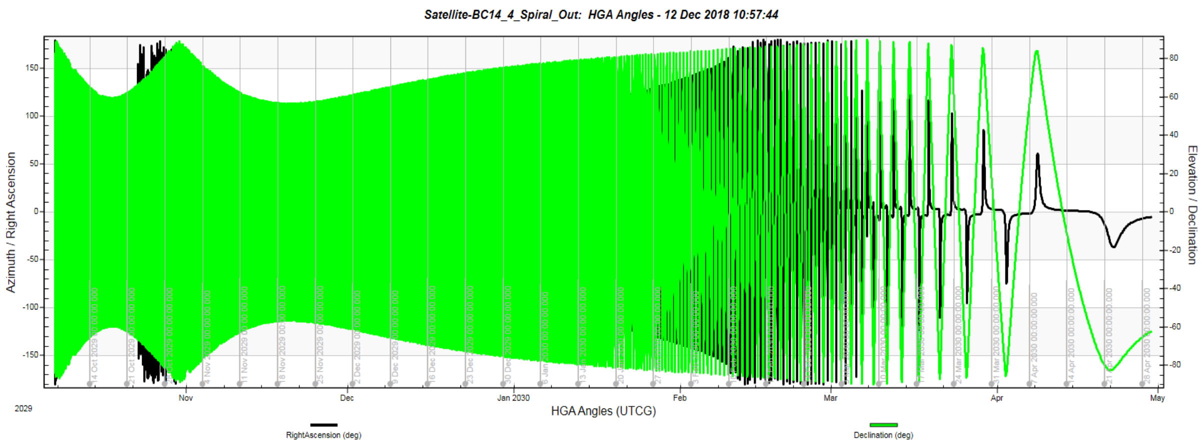



*Figure 8.9.2.7 - BC14 Spiral Out HGA Angle*

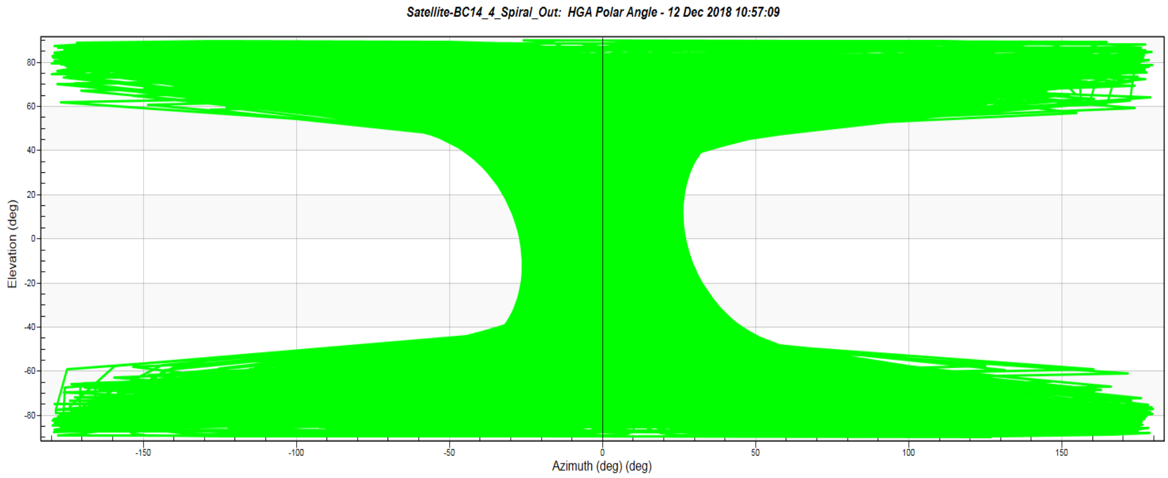



*Figure 8.9.2.8 - BC14 Spiral Out HGA Polar*

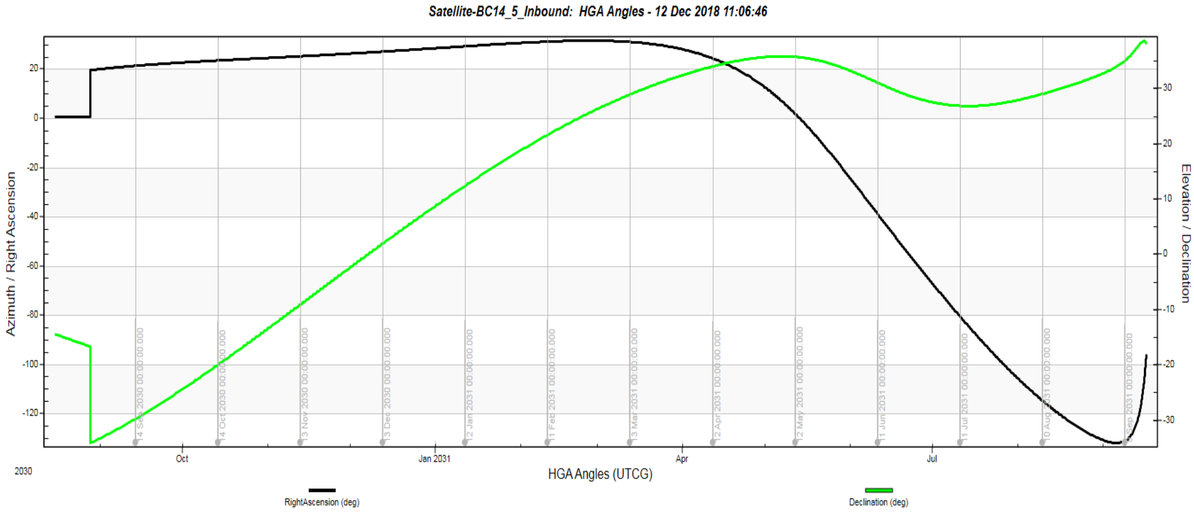



*Figure 8.9.2.9 - BC14 Inbound HGA Angle*

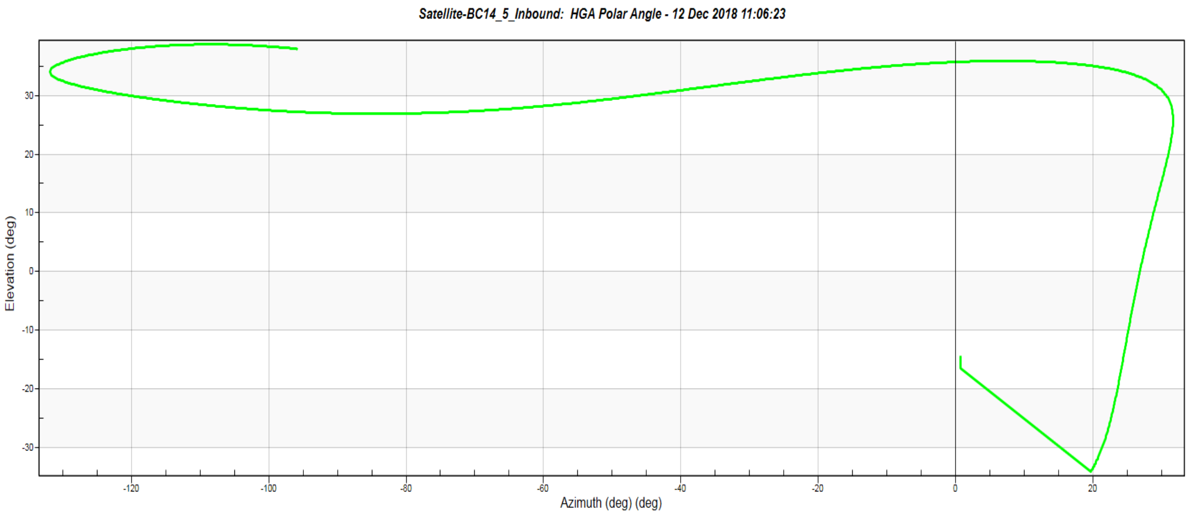



*Figure 8.9.2.10 - BC14 Inbound HGA Polar*

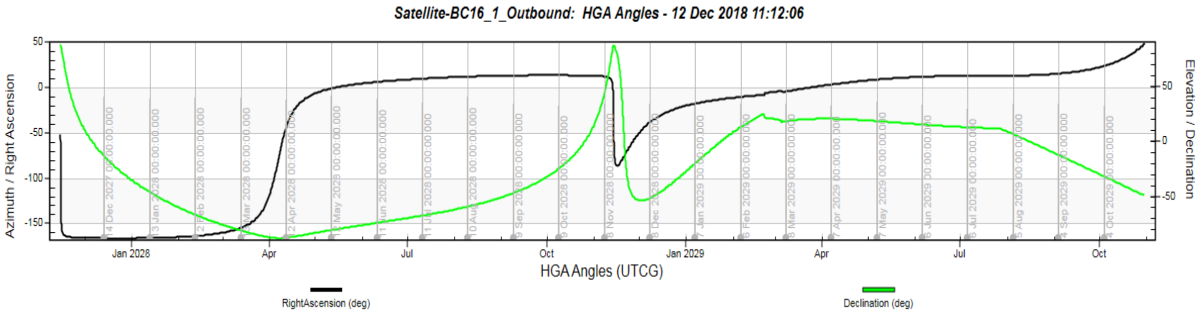



*Figure 8.9.2.11 - BC16 Outbound HGA Angle*

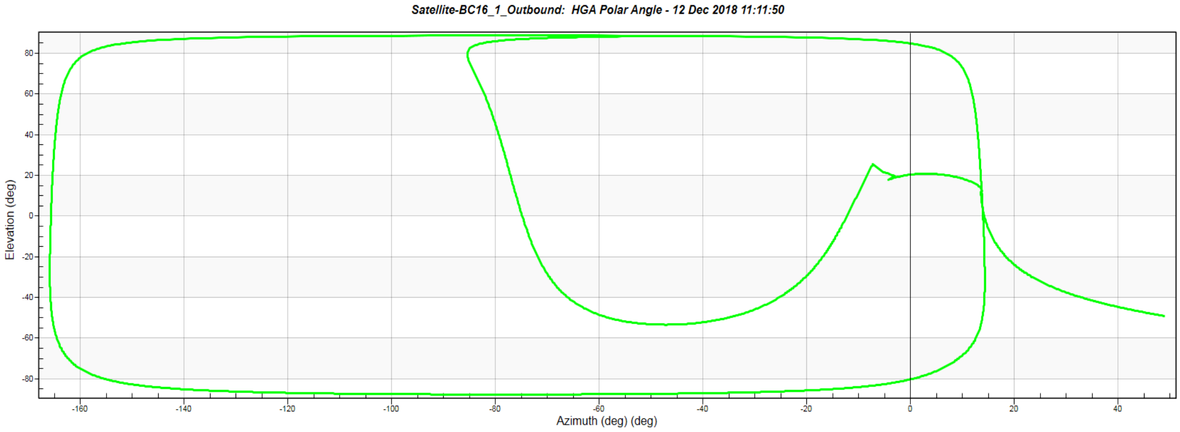



*Figure 8.9.2.12 - BC16 Outbound HGA Polar*

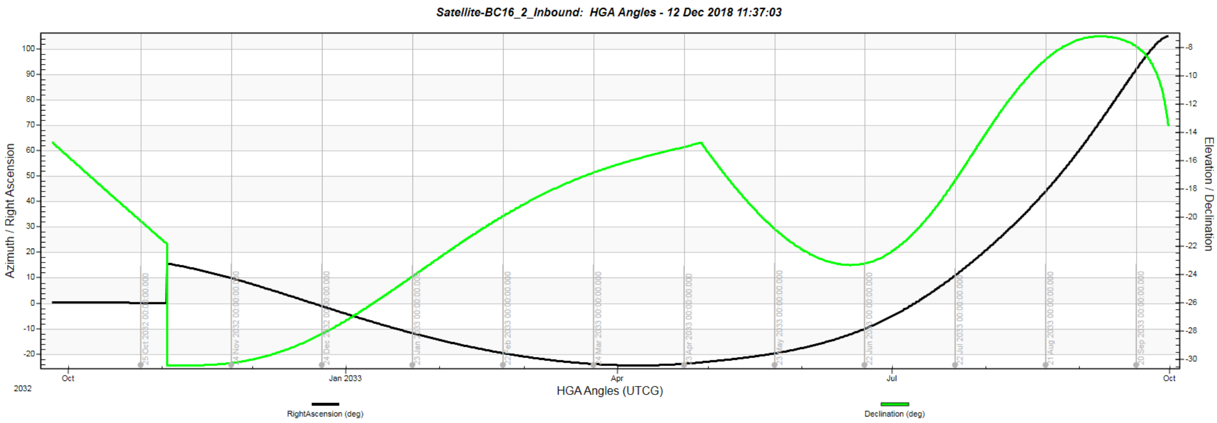



*Figure 8.9.2.13 - BC16 Inbound HGA Angle*

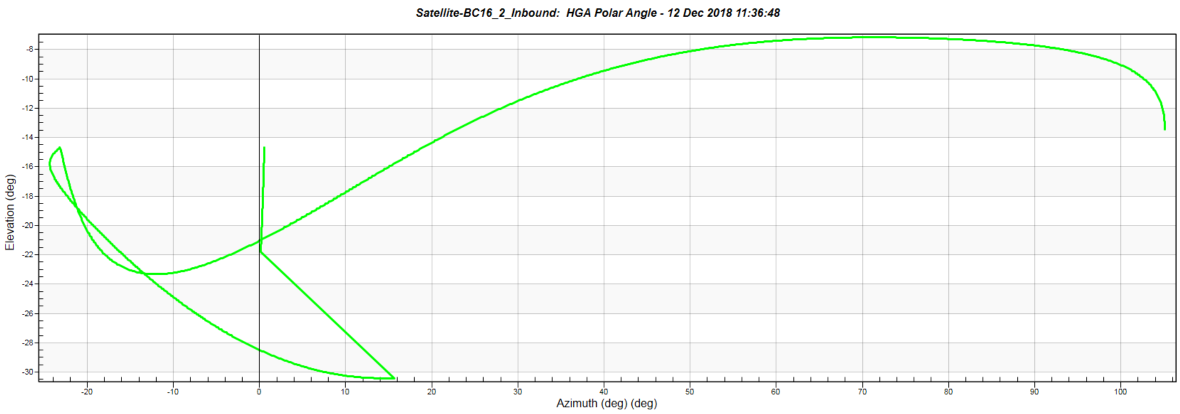



*Figure 8.9.2.14 - BC16 Inbound HGA Polar*

### 8.9.3 HGA Articulation Angles Conclusions

The results are summarized in the following table. The angular velocities have been ignored because they take very small values and therefore are not dimensioning for the project. The "usage" column identifies the need to communicate with the Earth.

| MISSION PHASE | MIN R.A. AZIMUTH | MAX R.A. AZIMUTH | MIN DECL. ELEVATION | MAX DECL. ELEVATION | USAGE |
|---|---|---|---|---|---|
| BC14 Outbound | 8.818° | 91.035° | -58.238° | 88.267° | High |
| BC14 Spiral In | 84.597° | 94.574° | -46.262° | -14.268° | Medium |
| BC14 MTO | -157.337° | -22.647° | -67.361° | 67.345° | Low |
| BC14 Spiral Out | -180,000° | 180,000° | -89.913° | 90,000° | Medium |
| BC14 Inbound | -31.696° | 131.855° | -38.698° | 33.574° | High |
| BC16 Outbound | -165.914° | 48.986° | -87.698° | 88.742° | High |
| BC16 Inbound | -24.356° | 105.098° | -30.417° | 21.865° | High |

*Table 8.8 – HGA Angles Results*

Any result will respect the requirement of pointing the Earth in an optimal manner. As seen in the section relating to the attitude, no duty cycle of the propulsion has been considered during the whole mission: in reality the ERO could change attitude to point the Earth without having to resort to the articulations, since the primary propulsion is not always active.

- During the transfers there are long periods of time in which the primary propulsion is not active: in this case attitude can changes in order to communicate with the Earth. The trends are regular and the changes are slow. In the BC16 Outbound phase, there is a time frame in which the values of the angles approach the design limits, but it is an epoch in which the fly-by of the Earth is being carried out without primary propulsion, so if the ERO needs to communicate it could rotate ERO for the necessary time; in addition during this manoeuver no communication with the Earth is required.
- As ERO approaches the planet the trends become irregular and the angular velocities increase: of course, the articulations of the HGA should only work during the access time phases. Critical values are achieved only during the initial phases of the BC14 Spiral Out manoeuver and especially when the Earth is not in sight. Given the need not to communicate with the Earth and the presence of the red planet that makes communication impossible, this phase does not justify the change in the design of the HGA joints.
- During the Martian Phases, the HGA angles achieve a wide range of values, but the whole phase sees the absence of the communication with the Earth combined with the absence of access with the Earth when critical values are reached, so the articulations must not follow these angles. However, the elevation angle remains controllable.

# 8.10 Articulation data addition

The values of the angles previously found have defined the angles that the joints must be able to cover. The model can specify the articulations components, poitable elements using appropriate ancillary files that communicate with the 3D collada models. The strategy consists of storing ancillary keywords in a separate ancillary file (*.anc). STK associates the ancillary file with the Collada file when both reside in the same directory and share the same base name.

## 8.10.1 Collada 3D Model File

The collada file was generated by IDM-CIC. It contains all the geometric information of the model. Of great interest are the nodes present inside, which consist of parts of the object as they were built in the model. Each node is followed by a 4x4 matrix that identifies position and shape with respect to the "parent" node, silicet the one to which it refers. The nodes of interest, those that refer exclusively to the Solar Array and to the HGA, will be mentioned in the ancillary file.

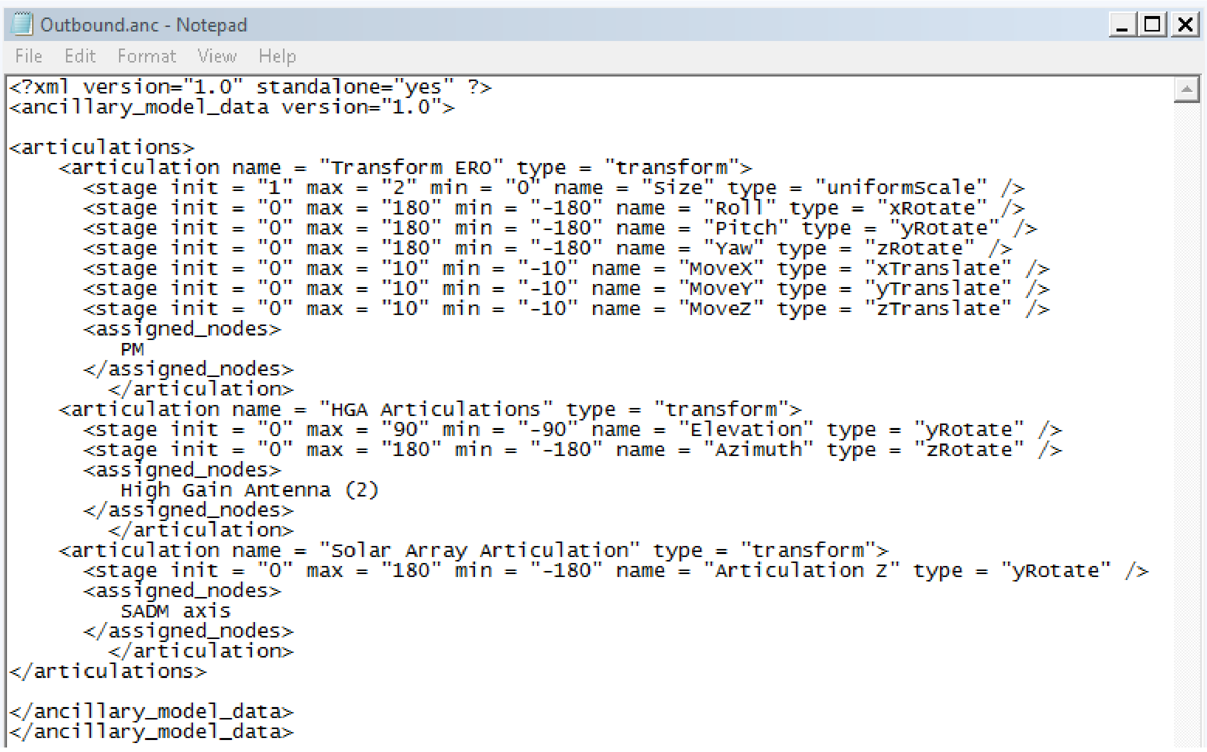
ERO_Outbound.dae

```
<library_visual_scenes>
  <visual_scene id="Root" name="Root">
    <node id="PM" name="PM" type="NODE">
      <matrix>0 0 1 0 -1 0 0 0 0 -1 0 0 0 0 0 1</matrix>
      <node id="MM" name="MM" type="NODE">
        <matrix>1 0 0 0 0 1 0 0 0 0 1 1.937999963760376 0 0 0 1</matrix>
        <node id="CCM+RVA" name="CCM+RVA" type="NODE">
          <matrix>1 0 0 0 0 1 0 0 0 0 1 0 0 0 0 1</matrix>
          <node id="CCM (1)" name="CCM (1)" type="NODE">
            <matrix>1 0 0 0 0 1 0 0 0 0 1 0 0 0 0 1</matrix>
            <node id="Shapes of CCM" name="Shapes of CCM" type="NODE">
              <matrix>1 0 0 0 0 1 0 0 0 0 1 0 0 0 0 1</matrix>
              <node id="Cylinder 1" name="Cylinder 1" type="NODE">
                <matrix>1 0 0 0 0 1 0 0 0 0 1 0 0 0 0 1</matrix>
```

*Figure 8.10.1.1 - Collada Text File*

## 8.10.2 Articulation Ancillary File

The ancillary file is created in the same directory as the collada file. All the geometric transformations allowed are described in it, such as sizing, rotations and translations. The sizing, rotation and translation transformations inserted concern the entire S/C and the Main Module. HGA and Solar Arrays only have the possibility to rotate around the degrees of freedom granted by the joints: Z axis for Solar Array, and X and Z axes for HGA.





```
<?xml version="1.0" standalone="yes" ?>
<ancillary_model_data version="1.0">

<articulations>
    <articulation name = "Transform ERO" type = "transform">
      <stage init = "1" max = "2" min = "0" name = "Size" type = "uniformScale" />
      <stage init = "0" max = "180" min = "-180" name = "Roll" type = "xRotate" />
      <stage init = "0" max = "180" min = "-180" name = "Pitch" type = "yRotate" />
      <stage init = "0" max = "180" min = "-180" name = "Yaw" type = "zRotate" />
      <stage init = "0" max = "10" min = "-10" name = "MoveX" type = "xTranslate" />
      <stage init = "0" max = "10" min = "-10" name = "MoveY" type = "yTranslate" />
      <stage init = "0" max = "10" min = "-10" name = "MoveZ" type = "zTranslate" />
      <assigned_nodes>
         PM
      </assigned_nodes>
        </articulation>
    <articulation name = "HGA Articulations" type = "transform">
      <stage init = "0" max = "90" min = "-90" name = "Elevation" type = "yRotate" />
      <stage init = "0" max = "180" min = "-180" name = "Azimuth" type = "zRotate" />
      <assigned_nodes>
         High Gain Antenna (2)
      </assigned_nodes>
        </articulation>
    <articulation name = "Solar Array Articulation" type = "transform">
      <stage init = "0" max = "180" min = "-180" name = "Articulation Z" type = "yRotate" />
      <assigned_nodes>
         SADM axis
      </assigned_nodes>
        </articulation>
</articulations>

</ancillary_model_data>
</ancillary_model_data>
```

*Figure 8.10.2.1 - Ancillary File*

## 8.10.3 Articulation Definition and View

After completing the insertion of ancillary files, in the 3D properties of the satellite in STK the model can interact with the joints.

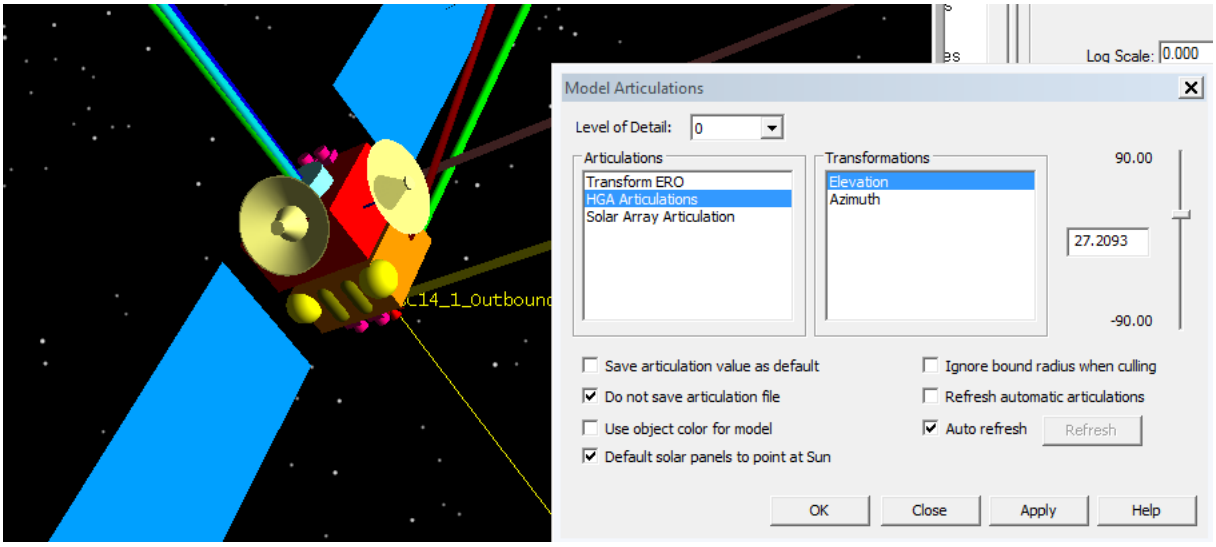




*Figure 8.10.3.1 - HGA Articulations*

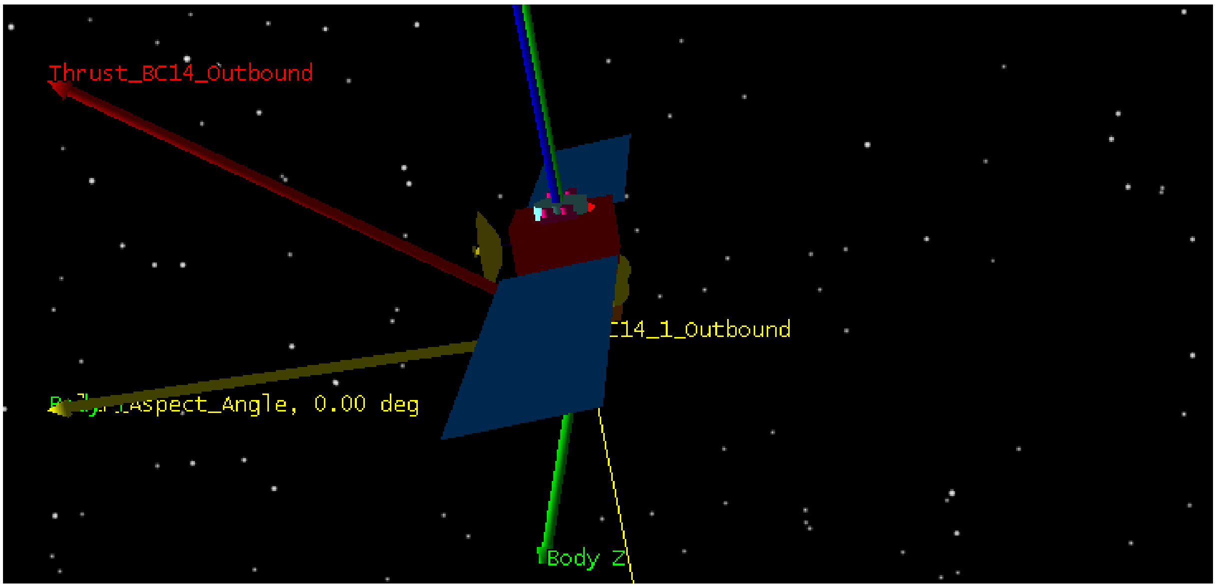



*Figure 8.10.3.2 - Solar Panel Articulation*

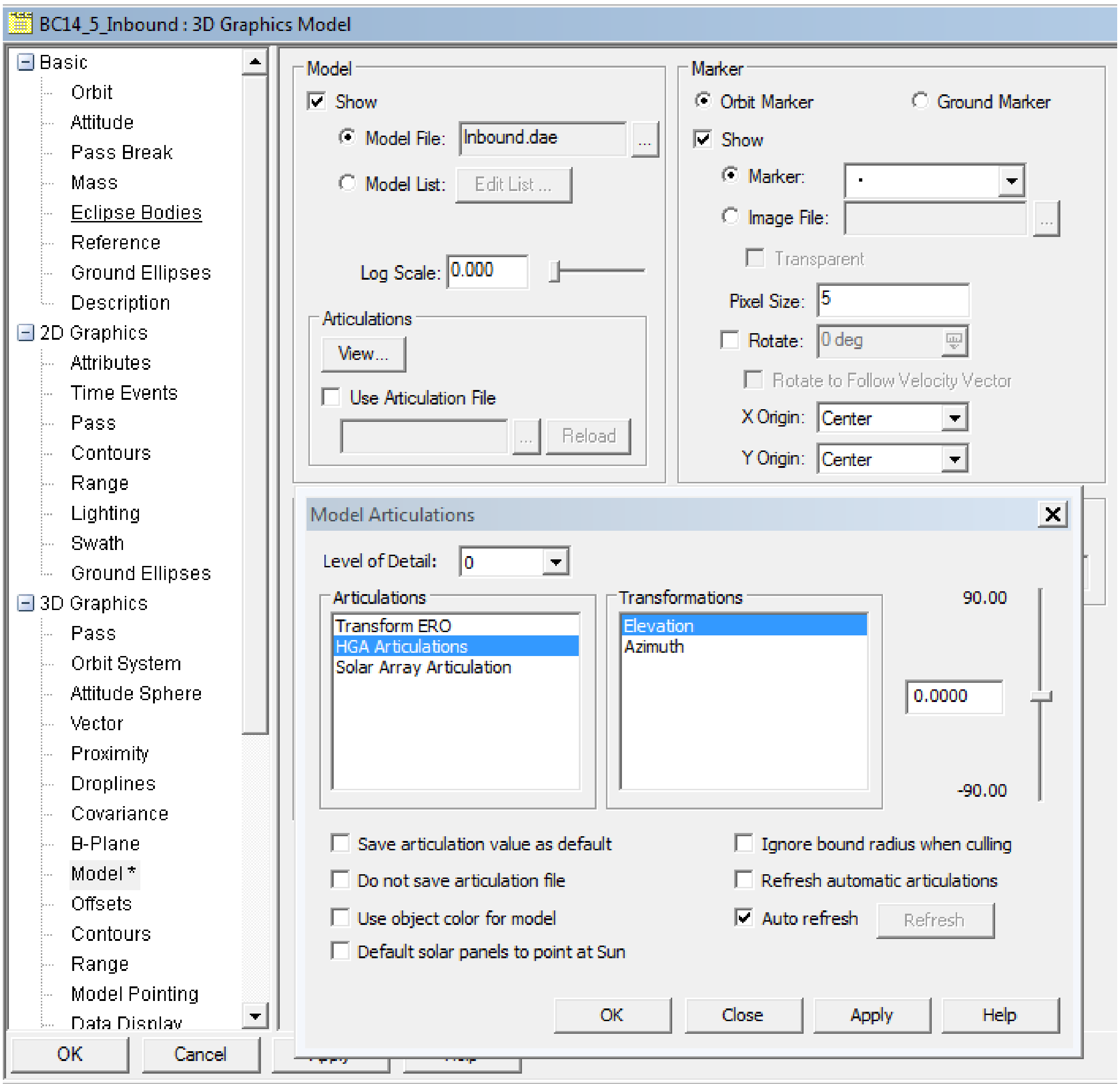



*Figure 8.10.3.3 - Articulation Definition*

# 8.11 Solar Panel Group

In the STK model, the Solar Array elements could be inserted, in order to carry out energy analyses. These analyses will not be performed  because the design of the electrical system has already provided the necessary details. This paragraph is intended to create a graphical display of the results.

## 8.11.1 Solar Panel in Ancillary File

In the Ancillary file previously created, the presence of a group of solar panels was declared, and it is identified by the specific nodes defined in the collada model.

```
<solar_panel_groups>
   <solar_panel_group efficiency = "30" name = "Solar Array">
      <assigned_nodes>
         SADM axis
      </assigned_nodes>
   </solar_panel_group>
</solar_panel_groups>
```

*Figure 8.11.1.1 - Solar Panel Group Declaration*

## 8.11.2 Solar Panel Tool

The Solar Panel Tool is available in the satellite menu. It allows the calculation of the electric power produced and the effective area that is exposed to sunlight, depending on the time instants. In this tool, there is also the Solar Panel view, that is a schematic draw of the object.

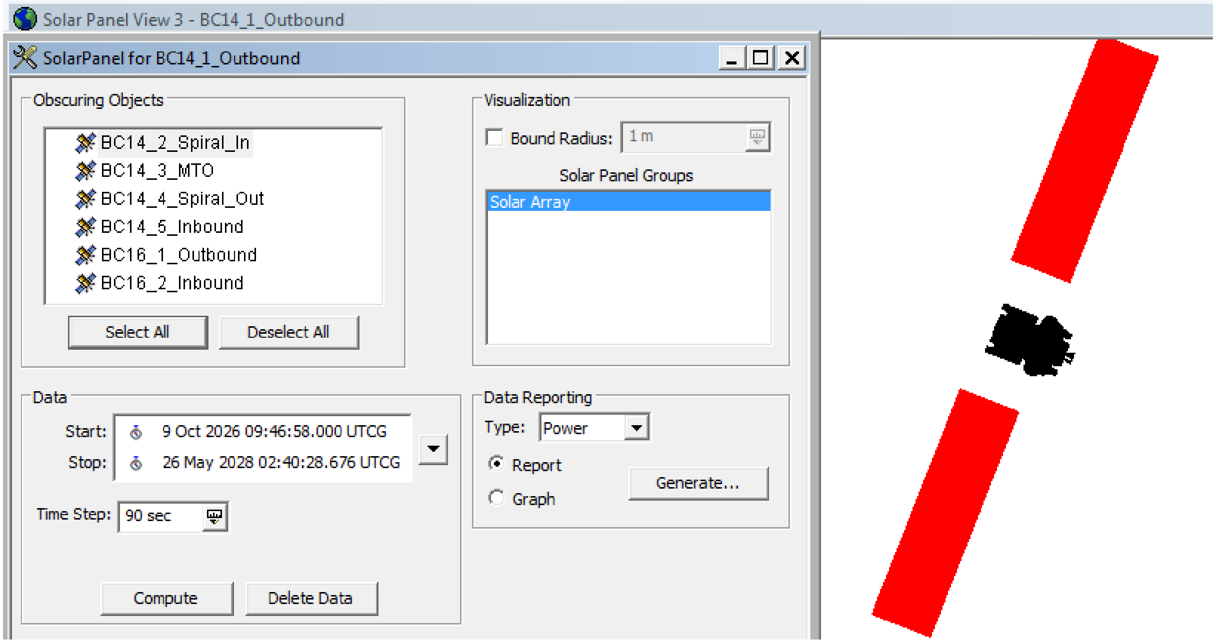



*Figure 8.11.2.1 - Solar panel Tool*

### 8.11.3 Pointable elements

Now the model recognizes the presence of Solar Arrays. In the ancillary file the same node is declared as an pointing element, that is as a portion of S/C able to rotate and change attitude. In the 3D satellite menù, in the "model pointing" tab, the choice was made to point the Sun from the Solar Arrays.

```
<pointing_data>
   <pointing node = "SA2" vector = "0 1 0" />
   <pointing node = "SA (1)" vector = "0 0 1" />
</pointing_data>
```

*Figure 8.11.3.1 - Pointing data*

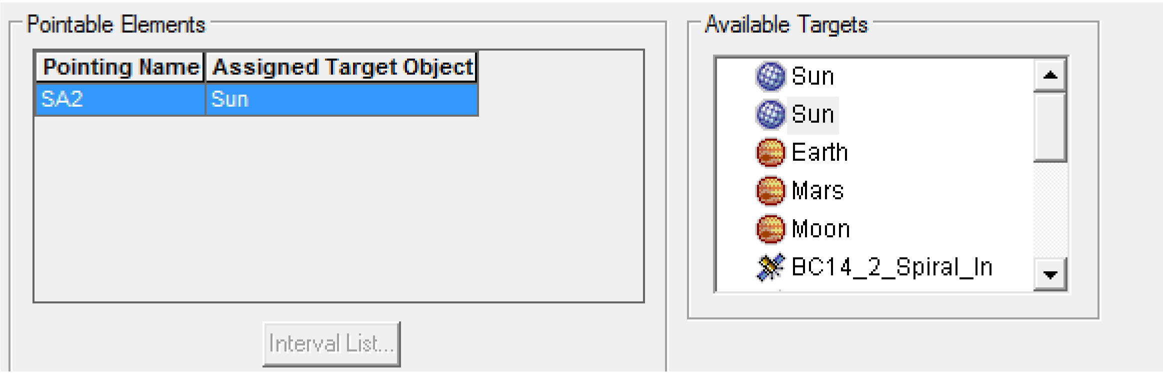



*Figure 8.11.3.2 - Model pointing*

### 8.11.4 Solar Panel Geometry Tool

After inserting a reference node into the model, a point is created in the 3D geometry that is located at the origin of a solar panel.

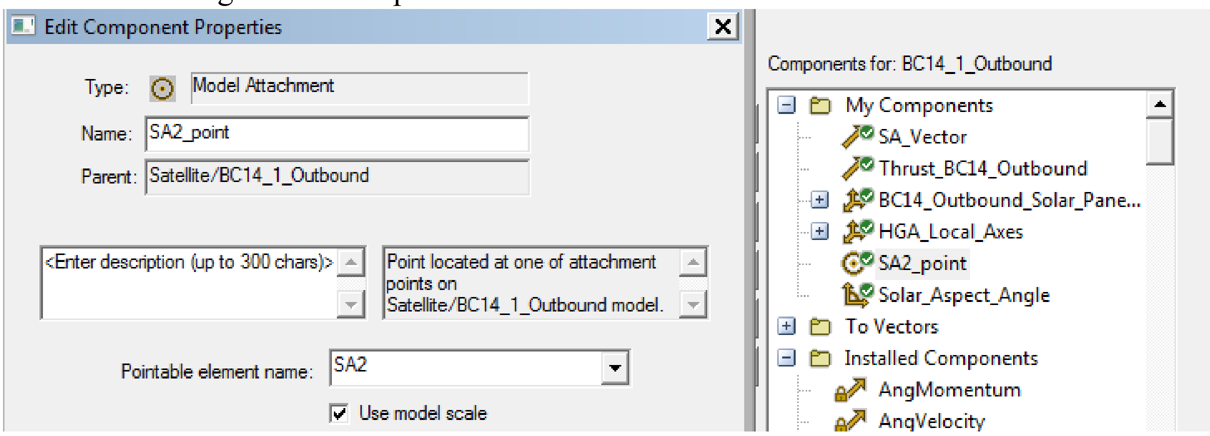



*Figure 8.11.4.1 - Solar Array Point*

In the same point a trio of axes is created, so that the local Y axis is normal to the surface of the panel itself, such that it follows the direction of the Sun.

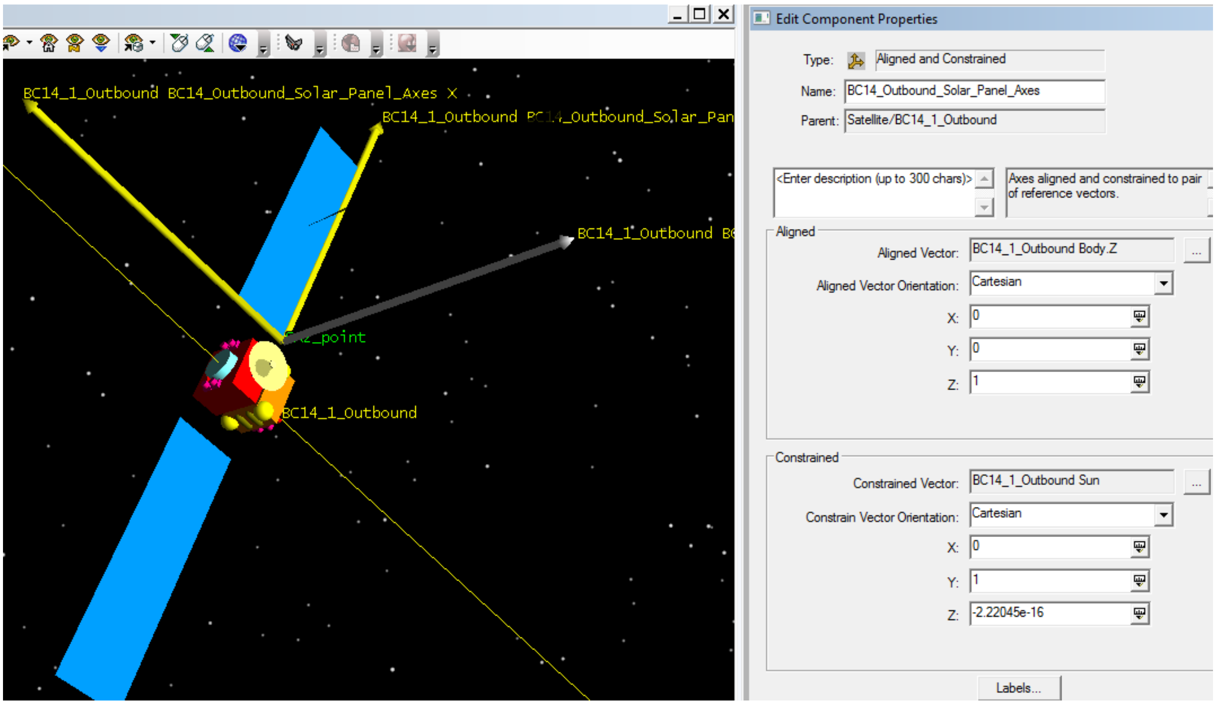



*Figure 8.11.4.2 - Solar Panel Axes*

## 8.11.5 Solar Array Sensor

For a better visualization, a conical sensor with a width of 1° has been created, positioned at the center of a panel and facing the Sun.

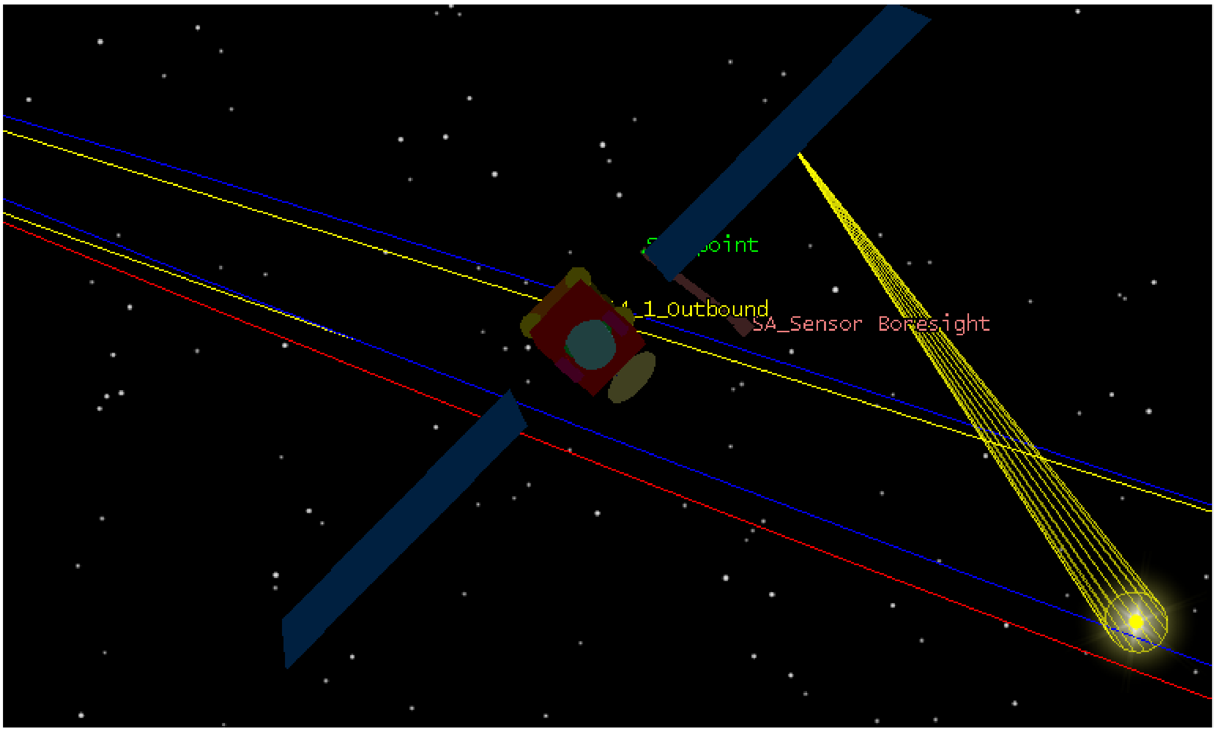



*Figure 8.11.5.1 - Solar Array Sensor*

## 8.12 Model Updates

After the PRR, a higher level of detail is required compared to the previous results. The work that has been done goes in the direction of updating the data and providing less coarse details.

### 8.12.1 Mission Analysis Updates

The main update consists of the new data received from mission analysis, which offer updates in the Spiral and LMO phases.

| NEW PHASE | FORMERLY | NOTES | THRUST |
|---|---|---|---|
| BC14 Spiral In 16600 | BC14 Spiral In | From 16600 to 10600 km of altitude | No data |
| BC14 Spiral In 10600 | BC14 Spiral In | From 10600 to 6600 km of altitude | No data |
| BC14 Spiral In 6600 | BC14 Spiral In | From 6600 to 2000 km of altitude | No data |
| BC14 Spiral In 2000 | BC14 Spiral In | From 2000 to 320 km of altitude | With data |
| BC14 LMO 320 | BC14 MTO | First ephemeris data | No data |
| BC14 Spiral Out | BC14 Spiral Out | General updates | With data |

*Table 8.9 Mission analysis Updates*

In the STK scenario the satellite related to the Spiral In was deleted and replaced with 4 new satellites, each one coinciding with the new time divisions in the table. Since for the first time there are data concerning the orbit during the Martian phases, the LMO satellite is no longer characterized by the propagation of the orbit through the two-body problem, but the ephemeris data are inserted as in all the others.

### 8.12.2 Collada file changes

The file collada, as it has been defined, is not functional because the pointable elements can't be defined in a precise way. To make the Solar Arrays and the HGA independent, unused code strings have been deleted and the rotation matrices of some nodes have been changed. The nodes related to the articulations, have been brought to the first level of the internal hierarchical scale in the collada file, and therefore are univocally determined by simple translation and rotation by the MM reference system and no longer by the root reference system. The goal is to be able to rotate the joints automatically, always pointing them towards the defined targets. The new angles of interest will therefore be the discrepancies between the optimal orientation and the angle that the joint can compensate for.

### 8.12.3 Model Attachments

The modifications of the collada file also have an effect on the ancillary file, since the names of the nodes of interest of the pointing elements must be replaced.

```
<pointing_data>
<pointing node = "SA_Wings" vector = "1 0 0" />
        <pointing node = "SA1" vector = "0 0 1" />
        <pointing node = "SA2" vector = "0 0 1" />
<pointing node = "HGA_Boom" vector = "0 0 1" />
        <pointing node = "HGA_Reflector" vector = "0 0 1" />
</pointing_data>

<solar_panel_groups>
        <solar_panel_group efficiency = "28" name = "SolarPanel">
                <assigned_nodes>
                        SolarArrays
                </assigned_nodes>
        </solar_panel_group>
</solar_panel_groups>

<sensor_origins>
   AntennaPoint
   SA1
   SA2
</sensor_origins>
```

Pointable Elements

| Pointing Name | Assigned Target Object |
|---|---|
| HGA_Boom | Earth |
| HGA_Reflector | Earth |
| SA_Wings | Sun |
| SA2 | Sun |
| SA1 | Sun |

*Figure 8.12.3.1 – Model Attachment update*

After defining the articulations of HGA and Solar Array, the visual result can be appreciated: the joints rotate the two elements in an automatic and controlled manner, according to their defined kinematic limits. During the various mission phases, except during the fly-by of the Earth during the Outbound of BC14, the Earth and Sun position vectors will have roughly similar direction and orientation. This is obvious because the Earth's orbit is within the Martian orbit, and then pointing the antenna to Earth already helps in part to point the Solar Arrays towards the Sun.

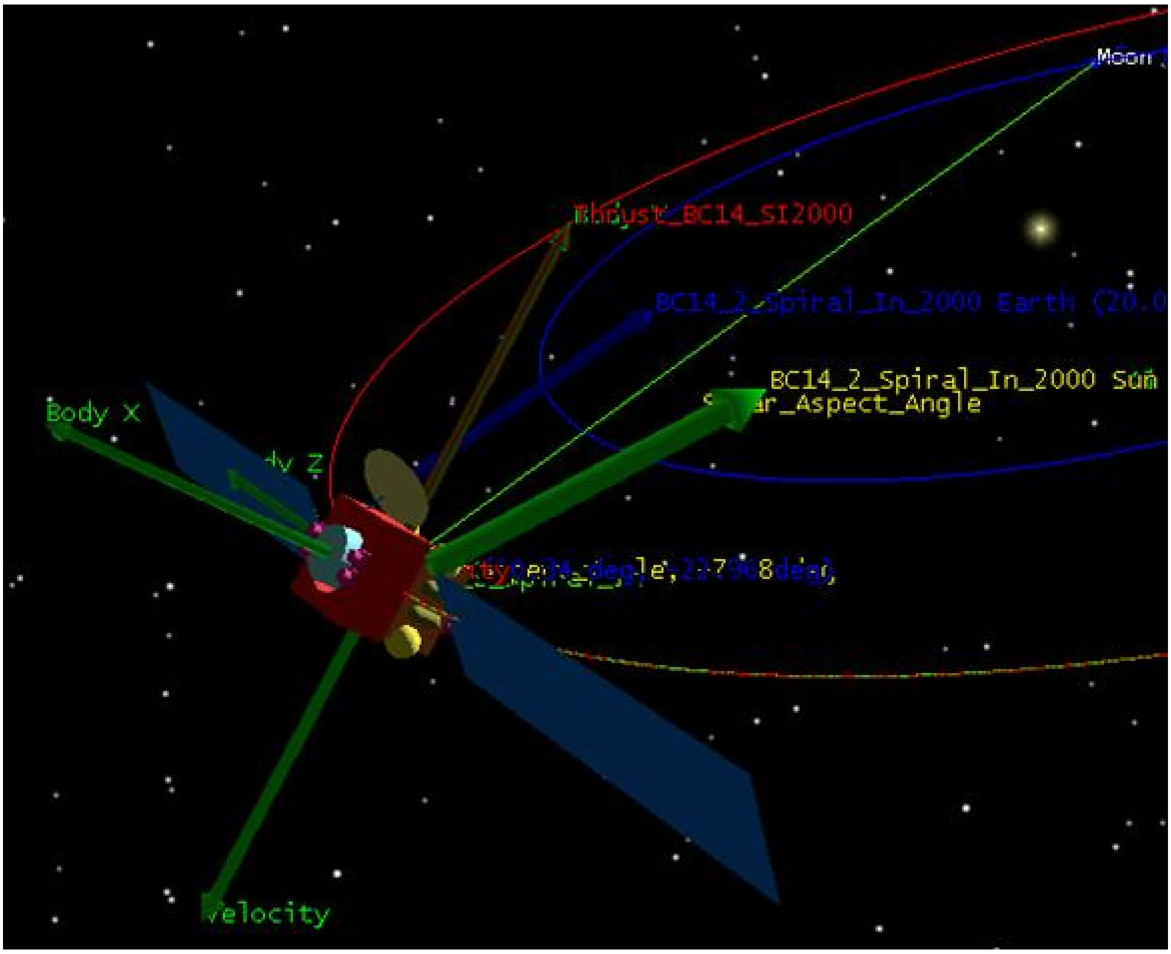



*Figure 8.12.3.2 - Model pointing view update*

At this point it is useful to define the angles of pointing with respect to mobile reference systems of the joints and no longer in body axes.

## 8.12.4 New vector and angle definitions

A point is defined by model attachment on which to draw the new Solar Array vector. The point is the origin of the local reference system of the Solar Panel.

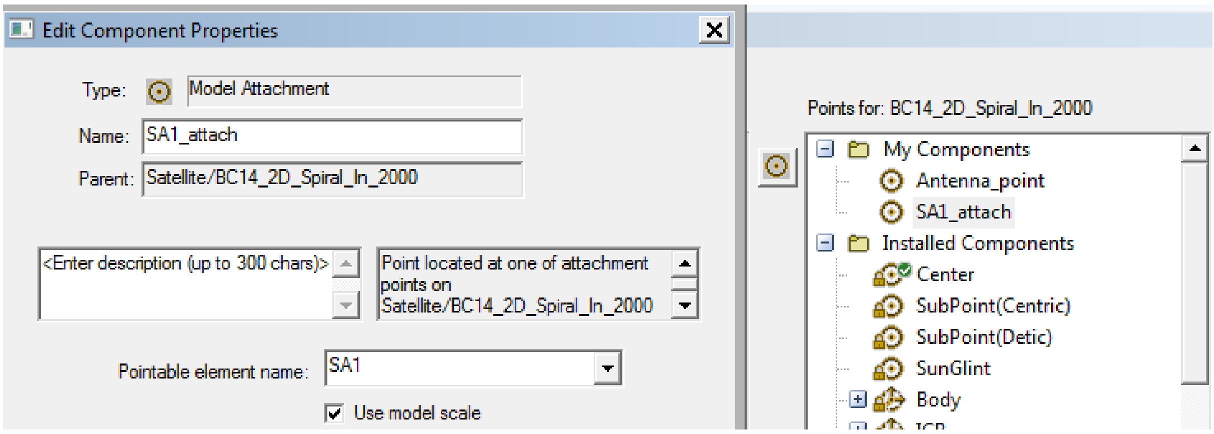



*Figure 8.12.4.1 - Solar Array point*

The Solar Panel vector is then created in the previously point, defined as a pointable element.

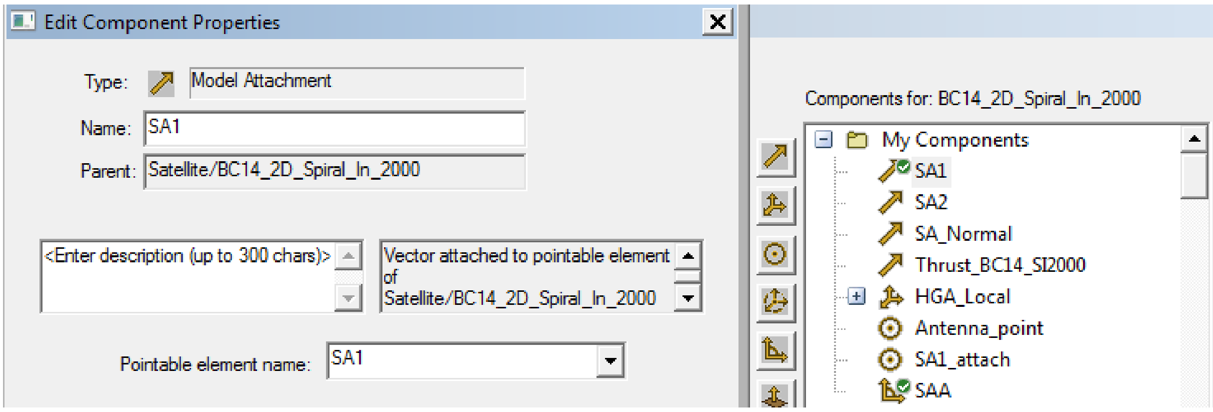



*Figure 8.12.4.2 - Solar Array Vector*

The vector is drawn in the previously created point.


*Figure 8.12.4.3 - Drawing of Solar Array Vector*

The Solar Aspect Angle is defined differently: it is defined as an angle constructed between two vectors, one of which is the vector position of the Sun (as before) and the second is the Solar Array vector built before. This definition allows the calculation of the angle taking into account the articulation and not taking only the angular position of the Sun.

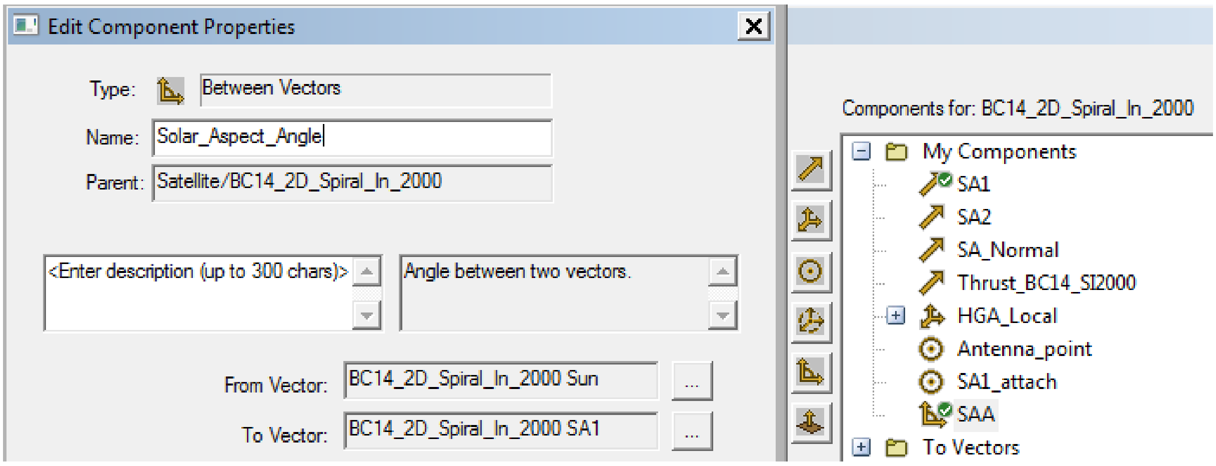



*Figure 8.12.4.4 – Solar Aspect Angle Update*

## 8.12.5 Final results of pointing budget

The graphs of the Solar Aspect Angle are attached during the Spiral In and Outbound BC14 phases only, as LMO, Spiral Up and Inbound phases require updates of the collada model. This angle this time takes into account the angle generated by the yoke of the solar panels. The HGA results are omitted because it would be necessary to have information on the boom.

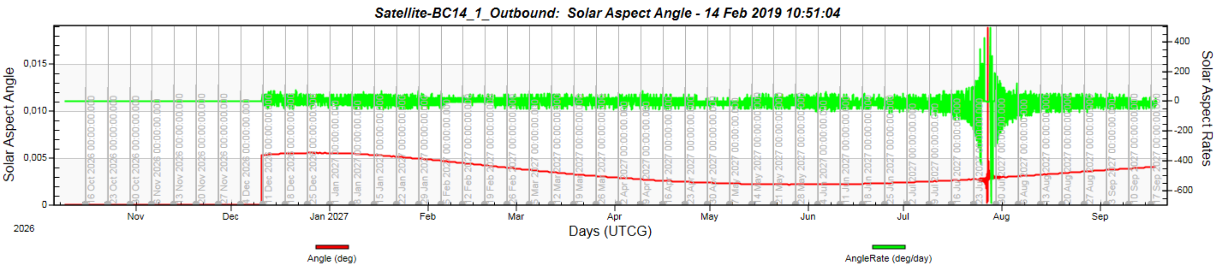



*Figure 8.12.5.1 - BC14 Outbound SAA update*

During the Outbound phase, the articulation of the solar array manages to cancel the Solar Aspect Angle maximizing the production of electric power.

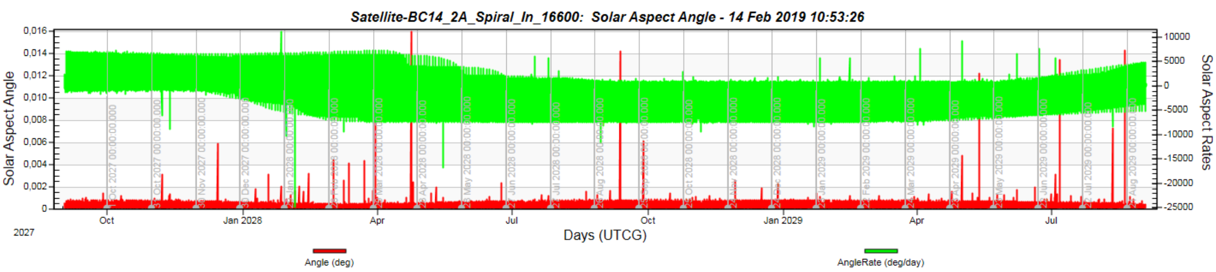



*Figure 8.12.5.2- BC14 Spiral In 16600 SAA*

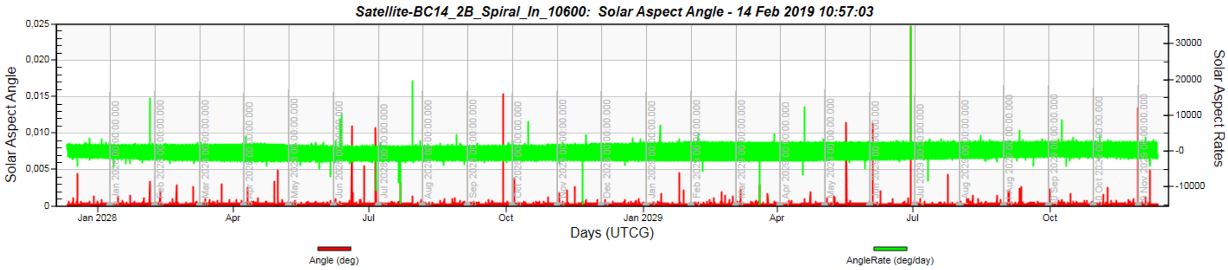



*Figure 8.12.5.3- BC14 Spiral In 10600 SAA*

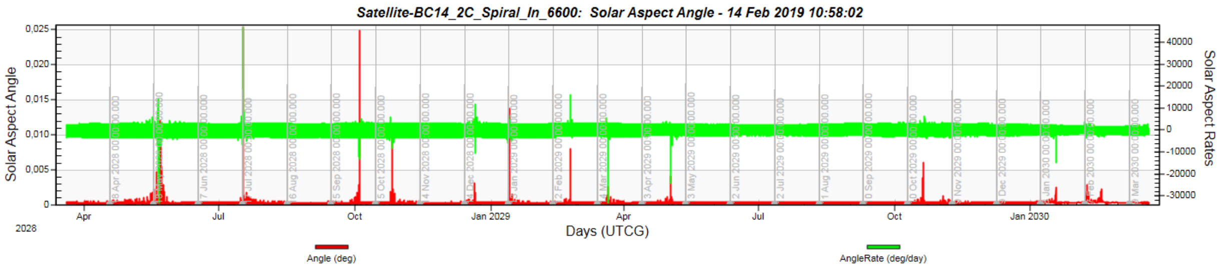



*Figure 8.12.5.4- BC14 Spiral In 6600 SAA*

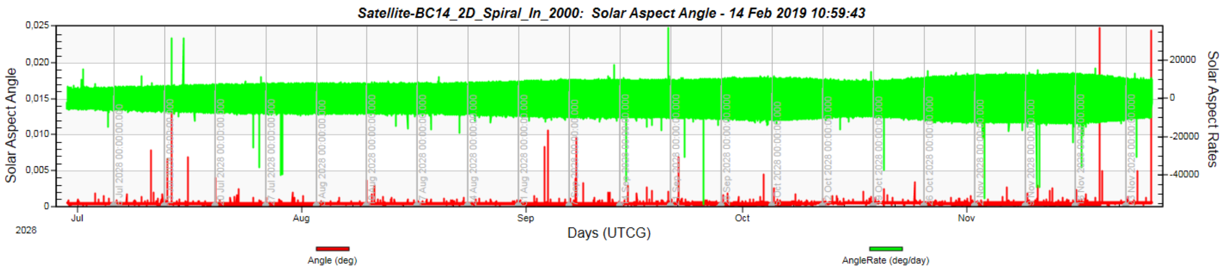



*Figure 8.12.5.5- BC14 Spiral In 2000 SAA*

During the Spiral In phases, the solar panels always point to the Sun. The Solar Aspect Angle values, higher than the Outbound phase, this time oscillate around a single value but they remain contained in the order of cents of degree.

# Chapter 9

# Conclusions

The work carried out in recent months has allowed the creation of a database of information and data useful in the field of systems and mission design. The data belong to different engineering branches, but are linked through concurrent engineering tools.

## 9.1 Results of the work

The thesis work followed the phases of mission design and systems in the final part of phase A2 and the beginning of phase B1. The thesis work has contributed to refine the calculations of the mission budgets and to provide preliminary estimates of technical data useful for providing general indications in the development of the systems.

### 9.1.1 Database and design improvements

The main objective is the creation of a database of technical information useful for the development of systems, which can provide information and be an aid to trade-offs. The technical data come partly from specific physical and engineering analyses (as example structural, propulsive, dynamics, inertial, kinematic, electrical, thermal, etc.) and partly to physical and engineering assessments with first approximation models. These data are shared in excel sheets, in IDM-CIC models and in the technical notes in word format. Specifically, masses and powers of the subsystems, CoG and moments of inertia, assessments of consumption and production of electricity, angles of targeting and so on have been managed.

### 9.1.2 Mission Budgets

An important objective is the creation and subsequent development and updating of the most important mission budgets (masses, powers, inertia, alignment).

| TYPE OF BUDGET | UPDATES | CAUSES OF CHANGES |
|---|---|---|
| Mass Budget | Frequent | System input data, Configurations, Mission Architectures, System Developments, Detail Level. |
| Power Budget | Frequent | System input data, Configurations, Mission Architectures, System Developments, Detail level. |
| Inertial Budget | Periodical | Configurations, Mission Architecture, Detail level. |
| Pointing Budget | Occasional | Mission analysis data, Attitude strategies. |

*Table 9.1 - Mission Budgets Summary*

The table above summarizes the mission budgets created during the months of work in TAS-I. The Link budget, the Thermal budget, the Risk Budget and the Cost budget don't appear as they are object of the study of specialists in the company.

### 9.1.3 Discovery and mitigation of design mistakes

The individual analyses deriving from disparate engineering disciplines make it difficult to see the project as a whole and offers few hint for thought to change approach, but the creation of a single database of data allows to provide hint for thought for any changes and design improvements. The development of data in a concurrent manner allowed the discovery of system configuration problems and, for example, it caused the choice to use a hybrid propulsion. This way of proceeding has anticipated design changes that allow the mitigation of errors.

Thanks to the graphic display of the STK models, it was possible to check the data received from Deimos. The ephemeris and the thrust data were analyzed with simplicity and they were confirmed, although identifying criticalities such as strong simplifying assumptions (absence of the duty cycle). Thanks to the concurrent engineering approach it was possible to identify possible boundary conditions and design constraints.

### 9.1.4 Discovery of inaccuracies in the software used

In the study of the space mission, sometimes the software used have provided results of doubtful validity or lack of precision; this may be due either to inaccuracies and errors to be corrected in the software, or to incorrect interpretation of the results, or to incorrect understanding of the assumptions made in the tools. An engineer collides every day with strange data to check and often errors are caused by the choice of hypotheses in the theories used; occasionally, however, the cause can reside in input with corrections provided by external bodies not dependent on his own work. The following table shows some of these cases, found during the thesis study:

| SOFTWARE | ERROR LEVEL | DESCRIPTION | RESOLUTION |
|---|---|---|---|
| IDM-CIC | Software | Return Module Configuration: removed PM but still taken into account in Mission Budgets | manual calculation on Excel |
| IDM-CIC | Assumption | COG of fuel outside the tank | Utilization only of ellipsoidal shape |
| IDM-CIC | Assumption | MCI computable with maturity margins but no system margins | 20% overestimation of dry masses |
| Matlab | Reading | Ephemeris of the Spiral In with seemingly too small values | Change of origin of the reference system and central body |
| STK | Reading | Direction of thrust outside the orbital plane during transfers | rewriting thrust vector data correctly |

*Table 9.2 - Errors during the thesis*

## 9.1.5 Documents issued and PRR

The thesis work follows the project phases of the A2/B1 mission, assisting the development of systems design. The transition from stage A2 to phase B1 was characterized by the Preliminary Requirements Review, in which there is the release of the preliminary management, engineering and product assurance plan. During this review, the fulfillment of certain objectives has been demonstrated, for example the establishment of the baseline master schedule, the establishment of the baseline cost at completion, the elaboration of the preliminary organizational breakdown structure (OBS), the confirmation of technical solutions for the system and operations concepts and their feasibility and programmatic constraints, the conduction of trade-off studies and selection of the preferred system concept, the establishment of a preliminary design definition for the selected system concept, the determination and the verification program including the model philosophy, the identification and definition of the external interfaces, the preparation of the next level specification and related business agreement documents, the start of the predevelopment work on critical technologies or system design areas, the confirmation of the technical and programmatic feasibility of the system concepts, the selection of system and operations concepts and technical solutions, the preparation of the space debris mitigation plan and the disposal plan, the conduction of the reliability and safety assessment, the finalization of the product tree, the WBS, and the specification tree, the update the risk assessment.

## 9.1.6 Other tasks

In this thesis, second level jobs and studies have been excluded. For information, the Mass Budget, Power Budget and Inertial Budget have been made for the full-chemical version of the ERO. In addition to this, the product tree of the hybrid and chemical configuration were constructed, and studies on configuration and interface changes were made.

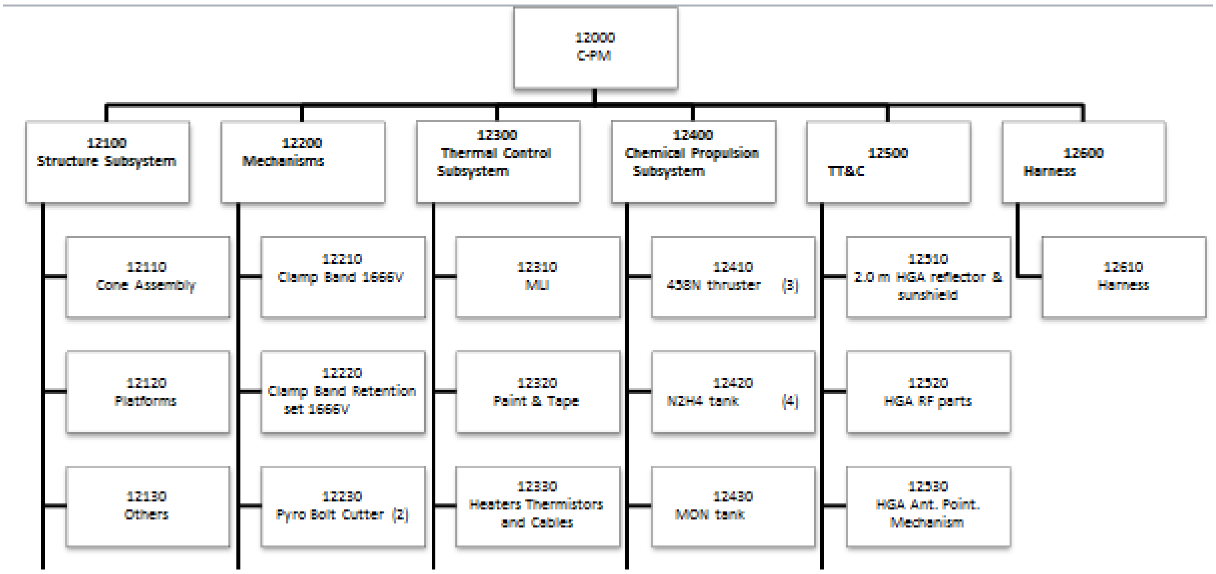



*Figure 9.1.6.1 – Product Tree Extract of chemical version*

## 9.2 Future solutions and ideas

The practical work of developing a space mission has allowed us to highlight some critical areas and to be able to intervene in order to reduce the costs of the engineering area.

### 9.2.1 Cad-IDM communication

Surely it is necessary a meeting point between the CAD model developed with Catia and IDM-CIC to speed up the work. The creation of geometries in IDM-CIC from scratch can be advantageous in the initial phases of the design, but it will not be able to continue beyond phase B as it is possible to create only simple shapes. At this point the solution can be the usage of another software, or making the mission budget directly with Catia. A computationally expensive alternative could be extracting step files from Catia's drawings, but it would be difficult to manage reference frame systems. The advisable solution is to start building on the IDM-CIC the geometries of the individual subsystems, then it is likely to discard the software and perform inertial analysis directly on Catia.

### 9.2.2 One system file

The study of mission budgets is definitely preferable using a single file, building geometry and associating mass parameters in a precise way. This way of proceeding would initially be very onerous from a temporal point of view since the modelling of the individual subsystems is complicated, but after completing the construction of such systems it would save work time and greater precision with a greater ease of identification of errors. Surely this approach will require the creation of various user profiles, so that it is possible to work simultaneously on the single model without overwriting the data and deleting updates from other users. In addition, computational errors on IDM-CIC configurations can be discovered by creating dedicated excel sheets that perform mass property calculations to confirm or not the IDM-CIC results

### 9.2.3 Focus on Hybrid solution

Among the various mission architectures, the choice of primary propulsion is of vital importance. The study of a purely electric or purely chemical propulsion for the type of mission causes non-compliance with some basic requirements such as mass limits at the launch or temporal timing during maneuvers. Although the benefits of a hybrid solution are already known, company resources are still spent on all three solutions. There will come a time when a binding trade-off will put an end to the study of some configurations in order to focus all the attention on the hybrid solution.

### 9.2.4 More accurate STK Scenario

The STK scenario should be updated, inserting a single satellite in which the data of all the ephemerides are united in various time frames. Surely the 3D model of the satellite should be updated and the HGA boom sized to evaluate the angles of the joints in a more precise way. If the design will go towards the direction of lateral electric thrusters it will be necessary to recalculate everything from zero as the results are no longer valid. Furthermore it is necessary to insert the signal envelope in order to have more precise information on the coverage with the Earth. Finally, all the angles of the pointing budget should be calculated according to reference systems in solidarity with the articulation in order to have a precise analysis of the data. Another idea would be to use STK to calculate the electric power produced depending on the situation and the orbital parameters, taking into account eclipses and distances. Working in contact with the business reality, there are then possible points for reflection through the Matlab routines: the creation of functions that check the data entered on STK and confirm that they are sent by mission analysis (example: conversion from calendar Gregorian to julian day and vice versa); it should be created an excel sheet in which there is an automatic extraction of data from Matlab and exported without errors in the text files for the ephemerides.

### 9.2.4 Operative summary of updates

The following table summarizes possible future developments of the mission design.

| TOOL | WHAT | GOAL | USE |
|---|---|---|---|
| IDM-CIC | Single system file | Reduction of analysis times | High |
| IDM-CIC | Creation of subsystem geometries | More accurate mass properties | High |
| IDM-CIC | Catia Step file (complex objects only) | More accurate mass properties | Low |
| IDM-CIC | Creation of User roles | Preventing overwriting errors | Low |
| STK | Single ephemeris files | Better understanding | Low |
| STK | Single thrust vector files | Better understanding | Low |
| STK | Update of 3D model | Attitude correction | High |
| STK | HGA Signal Envelope | Link Budget Validation | Mid |
| STK | Pointing Angles computed on joints | More accurate pointing budget | High |
| STK | Count of electric power generation | More accurate power budget | Low |
| Matlab | Check Routine for STK | Immediate correction of errors | Mid |
| Excel | Automatic extraction of data | Speeding up and fewer errors | High |
| Excel | Mass Properties Worksheet | Validation of IDM-CIC results | Mid |

*Table 9.3 - Future Developments*

# Part III – References and Appendices

# Annex 1

# List of figures

# Annex 2

# List of tables

# *Annex 3*

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