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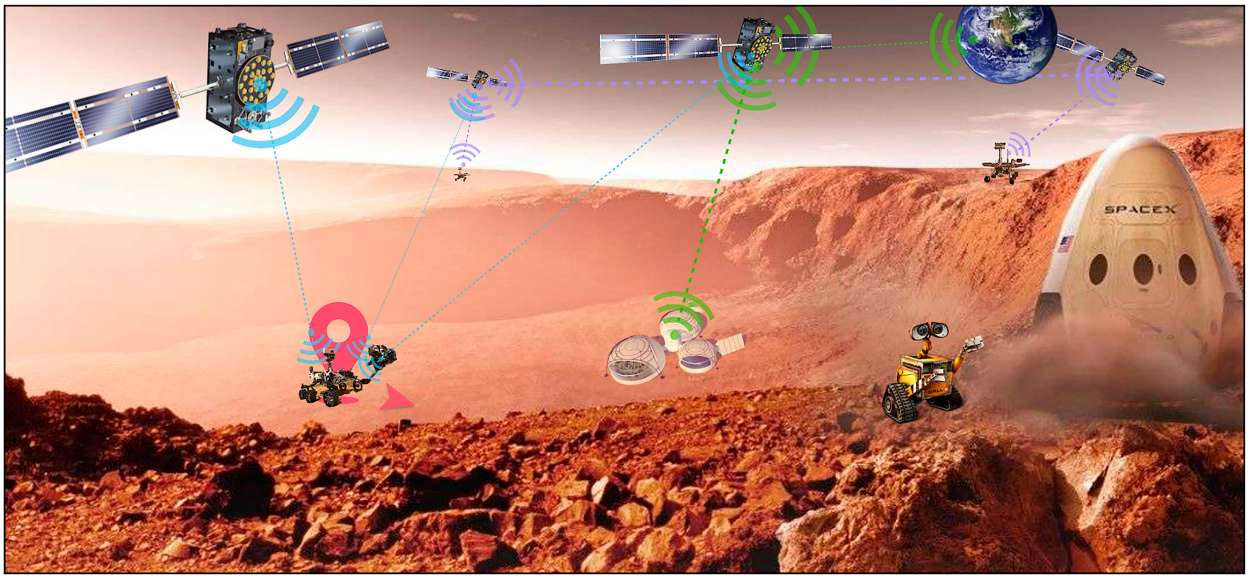
Musknav

Introduction

This is the final report for the project in spacecraft design and engineering. The project is dubbed Musknav. It sounds Russian but it's not. It's called so in the name of the recent achievements of SpaceX and their race towards the colonization of Mars. Musknav hopes to be an enabling technology to that process. Hopefully a real project, similar to the one idealized in this class project will soon see the light of day.



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0. Terminology

Mars Lander: *a person that has set foot on Mars*

Musknav: *constellation of satellites providing navigation and communication means on Mars*
Melonsat: *satellite of the Musknav constellation*

ME: *mechanical structure subsystem*
EPS: *electrical power subsystem*
CDH: *command and data handling subsystem*
TCS: *thermal control subsystem*
COM: telecommunications subsystem
ADCS: *attitude determination and control subsystem*
THR: *thrusters of the ADCS*
GNSS: *global navigation satellite system, also the acronym used for navigation subsystem*

Galileo: *global navigation satellite system created by European Space Agency*
GPS: *global positioning system created by the United States Department of Defense*
GLONASS: *global navigation satellite system created by Russian Roscosmos*

LV: *launch vehicle / rocket*

1. Mission Definition

1.1. Mission Objectives

The primary goal of this mission is to provide reliable location data and interplanetary communication means to future Martian expeditions and Mars landers. This will ease future missions' requirements for data transmission and allow for greater robot autonomy[1].

A secondary objective is to bring people together around this great endeavour which is to colonise Mars, spark interest in further missions, and become an interplanetary species.

Just as for the navigation and telecom satellites orbiting Earth, a similar all-in-one constellation will be set up around Mars to do just that.

The mission will encourage technically challenging ideas such as ballistic capture, betavoltaic power cells, simultaneous bidirectional communications through a single antenna and/or full system autonomy, over long periods of time.

1.2. Stakeholders

There are various stakeholders to such a project, they have been categorized in Figure 1.

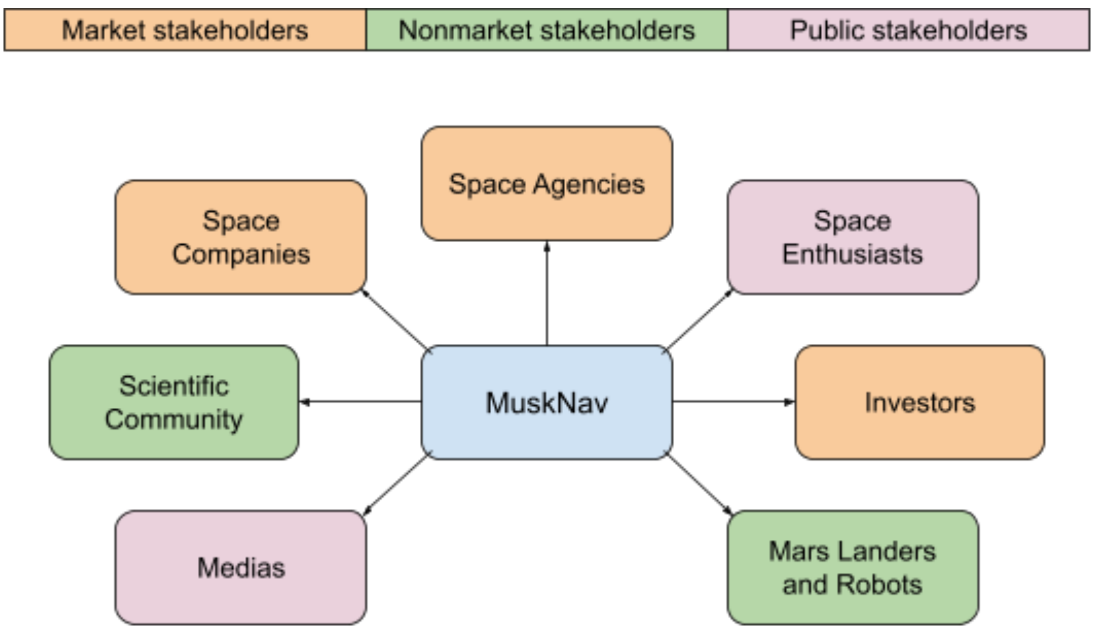

Figure 1: Hub and Spoke model of stakeholders.

Space Companies: The private sector's expertise in the space domain will be needed for this mission to succeed and some of the companies will then benefit from it by making use of the constellation in their future projects.

[1] Navigation is currently a limitation https://mars.nasa.gov/mer/mission/timeline/surfaceops/navigation/

Space Agencies: The exploration of Mars has been a center of interest for a long time for them and this enabling technology is just as much an enthusiastic project as it is an enabler for their future missions.

Space Enthusiasts: Hopefully it will inspire people to help with space exploration or at least spark their curiosity, and unite them in this great endeavor.

Scientific Community: The project will be testing new technologies and ideas, and provide a platform for future experiments.

Investors: These provide funds to the project for other reasons than those cited above, they will generally be secondary market stakeholders, not directly involved in the project development.

Medias: Engage public interest and report on the mission progress. It would be a step towards making Mars feel more like a possible home to humans.

Mars Landers and Robots: Humans on Mars will have a way to communicate through satellite phones and know where they are at all times using the provided GPS functionalities, even when far from base, as they would on Earth. The robots will be able to send results directly back to Earth using the constellation as a relay, communicate between each other directly and navigate without the need for human intervention. This gain in autonomy would allow the robots to build bases, explore, operate without much supervision.

1.3. Heritage and Challenges

There are now 14 satellites (6 active) orbiting Mars[2]. Just as for those missions, the Melonsats will be monitored from ground stations on Earth. However, this monitoring will suffer from delays in communication, lack of visibility due to planetary motion and others; to compensate for that, the Melonsats will have some autonomous operational capability similar to the one GPS satellites have per military requirement.

The telecommunications technology will be of great interest. Although its workings can be inspired from the existing tracking and data relay satellites, this project will seek to use miniaturized and multipurpose antennas that have been in development in the recent years.

For energy generation, the newly developed betavoltaic power cells will be considered, at least for an eventual future generation of satellites.

Ballistic capture has already proved effective for lunar missions but an attempt at ballistic capture is yet to be made with Mars and will definitely be a first in its kind.

The remaining parts envisioned so far for this project may reuse standard technology. For example, the atomic clocks needed for a GNSS constellation around Mars have no special, additional requirement to those used in satellites around Earth so they can be reused. If by any chance, one of the above doesn't work out the possibility to default to existing technology still exists (and is actually the one mostly considered in this report).

[2] https://en.wikipedia.org/wiki/List_of_Mars_orbiters

1.4. Timeline Proposition

The constellation's existence would be of very little use at the moment as there are not enough users on Mars. Therefore, the start of the project is set to 2024 when SpaceX hopes to have Starships flying to Mars. It is expected this project could be built, up and running in about 7 years. Now, these were also the expectations for the European Galileo project that eventually took 16 years to complete so the timeline in Figure 2 is dilated by a fair amount. This gives a decent amount of time for the satellites to pass flight readiness review and be ready to launch when colonization time comes. The hardest part is to convince the right people that this mission can in fact be very beneficial to them.

Delays are to be expected throughout the project, at the beginning they will likely be due to a lack of funding and time spent coordinating with partners, while at the end they will mostly be caused by logistics. Hopefully, this is accounted for in the dilated timeline.

In addition, the satellites won't be sent all at once. The first batch will be tested a little before sending in the others to minimise failure costs. That's why the production phase overlaps with the actual mission operations and why it will take some time before the constellation reaches full operational capability.

A satellite is set to have an operational lifetime of 15 years, after which it will be disposed of (destroyed/repurposed) and replaced if desired.

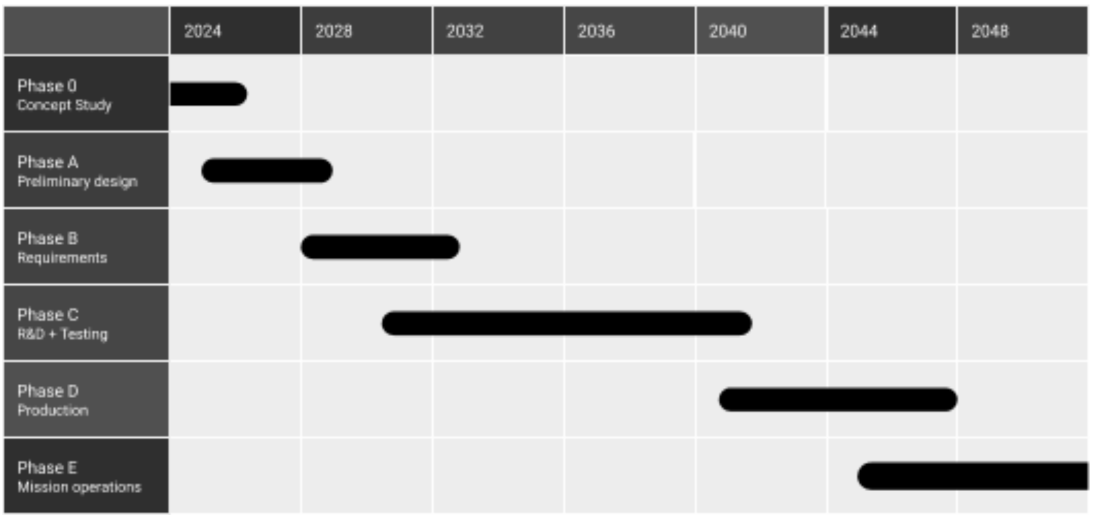

Figure 2: Project timeline. The first launch is estimated to be in the fall of 2044 but production and launch could be delayed if the purpose for Musknav is unclear at that time.

1.5. Cost Estimation

The following cost estimation is based on the Galileo project. Its costs haven't been very transparent, the best estimation stands at about €10 billion [7], of which nearly €6 billion went towards ground infrastructure cost alone while the final cost to build one satellite, with a lifetime of at least 12 years, stands close to €35 million, omitting the launch costs. In 2010 it was estimated that by 2030 the project will have cost around €22 billion, far from its original estimate of €7.7 billion in 2000. This just shows how volatile such estimations can be.

Assuming space agencies will be interested in collaborating on the development of Musknav, most of the technology and existing facilities could be reused. In addition, with the recent privatization of the space industry, big name companies have a vested interest in the mission's success. Some of these players are known for making very bold moves, not always possible under government owned agencies. This inherent competition should substantially drive down mission cost.

However, the challenges faced are not minor and critical to the mission, they will eventually delay the project. The risk to undertake is also considerably higher than for a constellation setup around Earth. Thorough planning and elaborate testing will be required.

Altogether, a pleasing cost estimate seems to be under the $15 billion mark all included, for the 20 years of project development suggested by the timeline in Figure 2. In that regard, the satellites' production, launch and operational costs, estimated at around $150 million for a 15 year lifetime are negligible and costs not related to mass won't be considered a factor in component choices, unless other factors prove indecisive.

The detailed project cost breakdown won't be made here due to lack of easily accessible data but an attempt is made for the Melonsat in Annex SWaP-DC Budget. Ultimately, divided up into the final number of 21 satellites the cost would be at $715 million per satellite (max), which makes this a top tier mission.

Overall, this project assumes all partners agree to cooperate as needed and any refusal to do so and the resulting consequences won't be discussed in this report.

2. Mission Design

2.1. Mission ConOps

The baseline mission ConOps picturing the mission at a high level is presented in Figure 3.

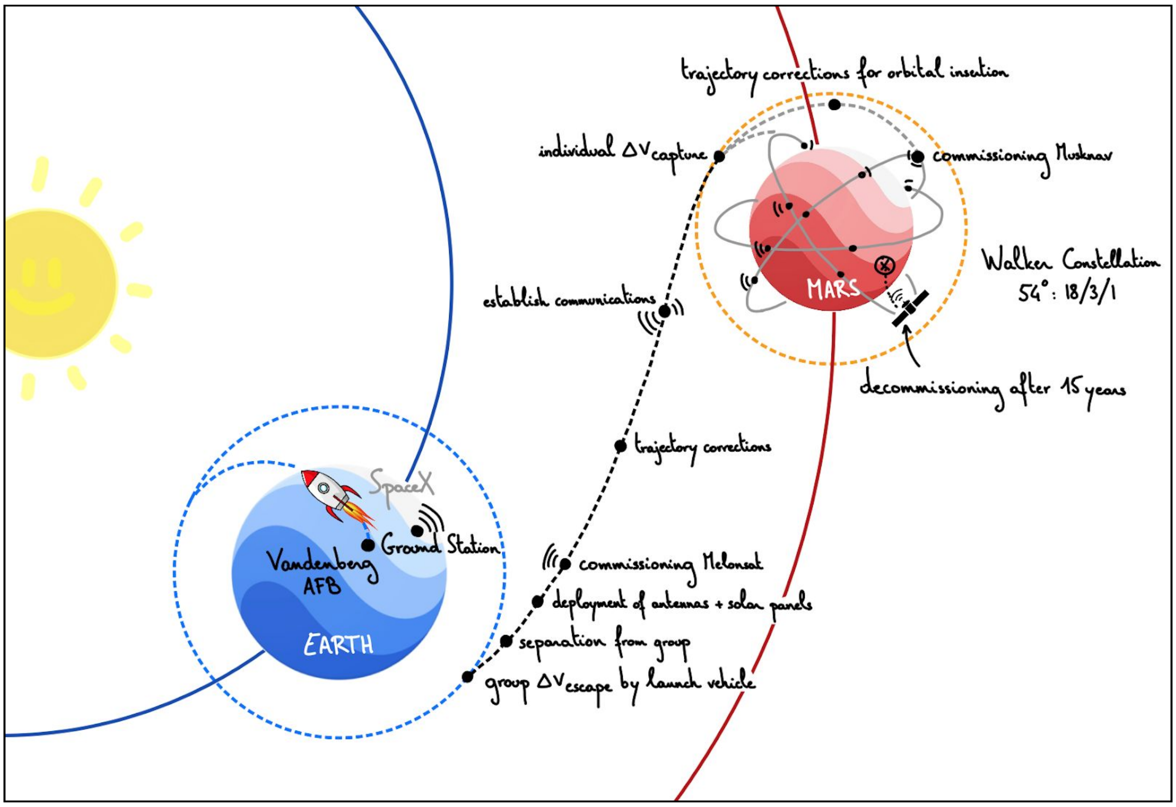

Figure 3: Simplified drawing of the mission ConOps from launch at Vandenberg Air Force Base to ballistic capture of the satellite by Mars and constellation setup.

Launch date and time will be decided in collaboration with SpaceX, providing the launch vehicle, see section 2.2. The details of the launch will likely be left at their discretion if a Hohmann transfer is used. If the attempt at a ballistic capture is made, collaboration with Boeing, developing the model will be necessary.

The Melonsats will be launched in groups. Once deployed from the launch vehicle they will be separated to allow for the solar panels and antennas to deploy for the first commissioning. At this stage, they still follow the same trajectory. It is only near Mars that individualised trajectory differentiations will be made for orbital insertion. If they happen to be secondary payloads to a Starship inbound to Mars this will probably be easier, a quick commissioning check will have to be made through the Starship once in space.

If the launch vehicle doesn't provide the escape Δv, the making of a group container providing that speed should be considered to simplify the satellites. That container would then separate from the group and engage the commissioning sequence.

During the orbit transfer, the Melonsat will perform commissioning to ensure everything is still working fine after the violent launch. If something is wrong it should give the operators enough time to decide what to do (several failure scenarios will be prepared for). Trajectory correction maneuvers will then be performed, as necessary.

Once the Melonsats approach Mars they will start to coordinate with Musknav and the ground station to position themselves into orbit (this also implies potential repositioning of the previous Melonsats) effectively creating a networked system. Once in orbit they will perform another commissioning check within the constellation to ensure all communication systems work as expected and inform the ground station of the result.

After an estimated 15 years of operations, the Melonsats will be crashed into a safe spot on Mars so that if some parts survive, the materials could potentially be reused. This shall be arranged so as to be compliant with planetary protection guidelines. Their limited components do not really allow for a better second life and keeping the Melonsats in orbit has no added value. If a better idea comes up for this, such as testing the components to their limit in outer space, it will be very welcomed as well.

Some redundancy for this ConOps has been considered in Annex Risk Analysis.

2.2. Launch Vehicle

First off, note that by the time this mission launches, newer and better rockets will probably be available so the specifications below will need to be adapted. The currently selected launch vehicle is the Falcon 9, operated by SpaceX. This is not only because of the competitive price of the launch and capabilities of the rocket but also because SpaceX has a vested interest in Mars missions. In addition, SpaceX expects to be flying Starships to Mars frequently so the satellites could become secondary payloads to one of those missions.

The Falcon 9 can carry a payload of 4,020 kg to Mars [2]. Galileo satellites measure 2.91 x 1.7 x 1.4 meters and weigh 732.8 kg [5]. Given the fairing in Figure 4 and assuming the Melonsats will measure and weigh 20% more, three to four satellites could be deployed in one launch at a cost of roughly $60 million.

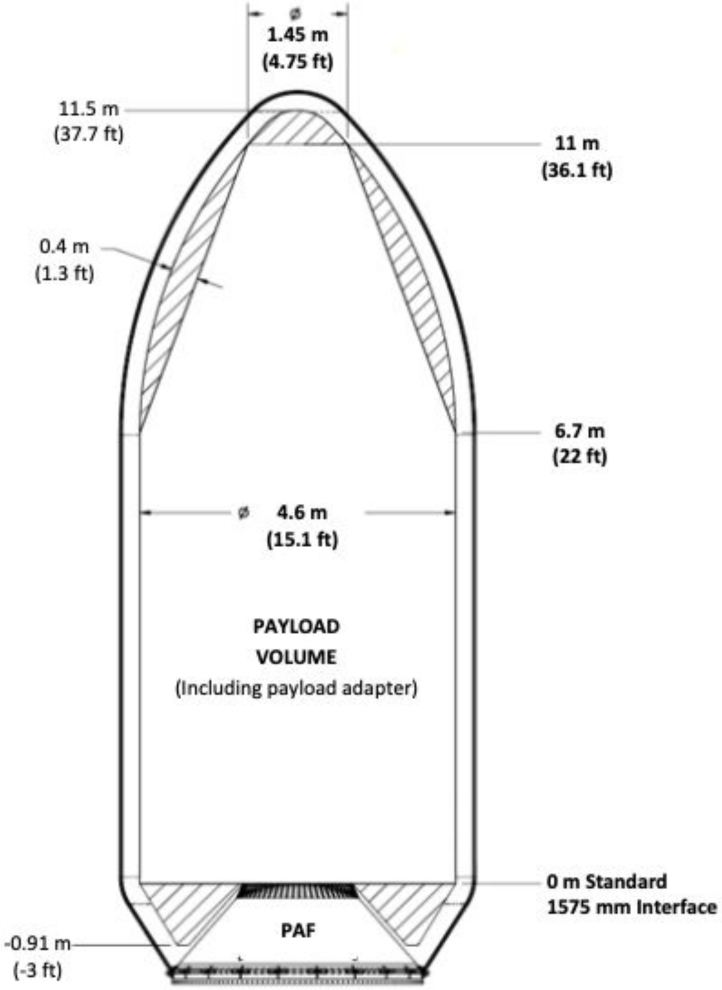

Figure 4: Falcon fairing dimensions, copied from Figure 5-1 of the Falcon 9 user guide [2].

According to the user manual of the Falcon 9 [3], for a mission to Mars, the launch will likely take place from the Vandenberg Air Force Base.

Although planning is useful, many breakthroughs are expected for launch vehicles and by the time this mission launches most mission plans will likely be outdated. Therefore, plans made today mainly serve for baseline estimations and determining feasibility.

2.3. Orbit Selection

2.3.1. Orbit Properties

For the orbital properties, various factors have been judged interesting, notably: altitude, angle of coverage, period, time in eclipse and velocity. These are all interdependent. The angle of coverage θ_d has been chosen as the free parameter and set to 76deg [11].

The altitude $h = R\,(\frac{\sin\theta_d}{\tan\eta} + \cos\theta_d - 1)$ is determined through the use of Figure 5 and the result is shown in Table 2.

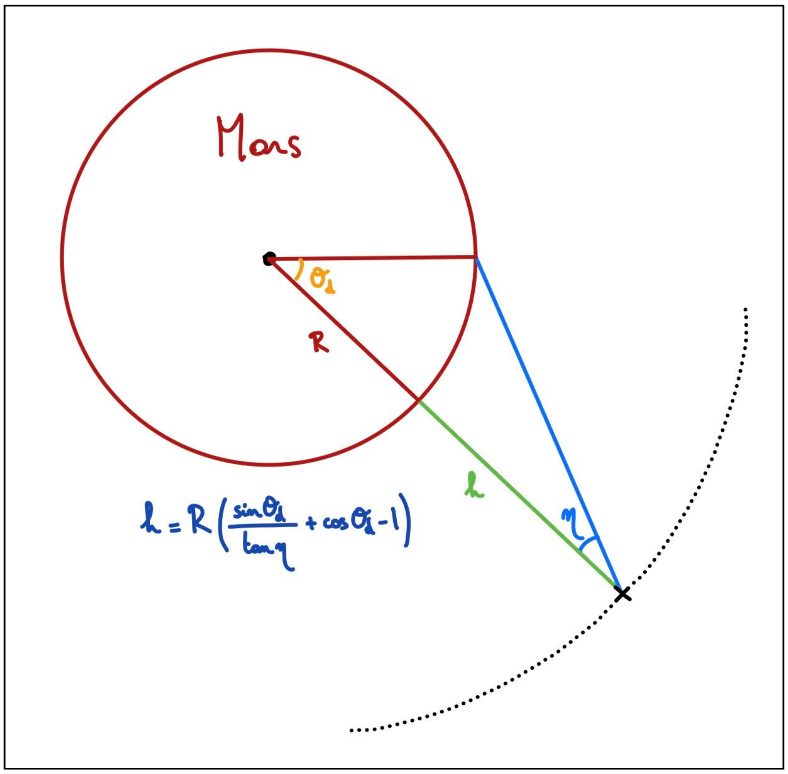

Figure 5: Orbit altitude determination in order to achieve a desired angle of coverage (in orange) setting the field of view of the satellite to 76deg (value for GLONASS [11]) (in blue).

The period is then computed as $T = 2\pi(R+h)/v$ and the time in eclipse as $T_e = 2R/v$, where $v = \sqrt{GM/(R+h)}$ is the orbital velocity, with R and M being the radius and mass of Mars. The approximation for T_e is justified in Figure 6. Results are shown in Table 1.

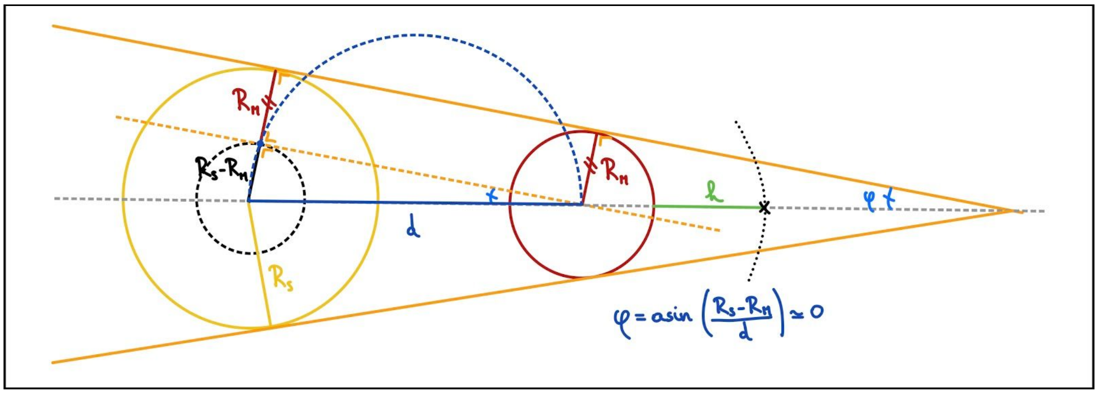

Figure 6: Eclipse time determination yields that Mars is sufficiently far from the Sun to approximate the distance travelled in eclipse as being the diameter of Mars.

orbital velocity	2,803	m/s
orbital period	12,222	s
=	3.39	h
eclipse duration	2,419	s
=	0.67	h

Table 1: Chosen orbit properties. For comparison, a day on Mars lasts 24h37min, so a Melonsat circles the planet six times a day.

These results are relevant because the time in eclipse will affect energy needs and the communication window with Earth. Speed will likely deteriorate the intra-satellite communication. Altitude will affect the localization precision. Indeed, the greater the time needed for the signal to reach the GNSS receptor, the greater the time difference and the easier the deduction of a correct position. That is why this altitude would be considered pretty low, (15x) compared to the current system in use around the Earth.

This trade-off would need to be explored further but it is hard to evaluate the link between the altitude and actual precision as this requires advanced techniques, and many corrections are often possible so this is left as is for this project. In any case, the spreadsheets with technical data are made for this to be easily modifiable.

The main difference would be that a Melonsat being further would increase precision and planet coverage while adding delay to the communication time, which would be critical when used by autonomous robots, as well as increase the energy needs. It is supposed here that the shorter communication delay dominates the need for precise location. Most robots will be able to rely on their maps and the communication system to offset this inaccuracy on the local scale while being well aware of their global position provided by Musknav.

Other factors derived from these results such as inter-satellite distance will be discussed in the other sections, where relevant.

2.3.2. Walker Constellation

Choosing the right type of constellation is key to the mission's reason for existence. Musknav has to reliably cover at the very least the main areas of interest and at best the whole planet. In a nutshell: "cover most of the space, most of the time". For this, the Walker Delta constellation configuration is chosen, inspired from the Galileo project.

The choice has been made to have three planes of equally spaced satellites in a circular orbit. The number of satellites per plane to fully cover the planet includes a safety margin of 20% but for navigation to work, three to four satellites must be visible at all times. That is why this number has been brought up to six Melonsats per plane[3] (without backup). Results

[3] This still needs to be verified. The preliminary 2D drawings seem to guarantee Musknav works with six Melonsats per plane thanks to the desired north pole visibility angle parameter but a 3D modelisation would be a safer test.

from the calculations are shown in Table 2. Following the standard notation [8], the Walker Delta constellation for Musknav is denoted 58°:18/3/1.

satellite mass	1,476.97	kg	number of satellites	3.75	per plane w/o backup + 20% margin for area overlap
satellite field of view	76.00	deg	satellite altitude	2.06E+06	m
desired planet coverage	120.00	deg	semi-major axis	5.45E+06	m
desired north pole visibility angle	16	deg	eccentricity	0	#
number of planes	3	# cst	inter-plane inclination	54	deg
relative spacing between satellites	1	// cst			

Table 2: Walker constellation parameters in red. Technological parameters in blue. Desired parameters in green. Choices in black. Other relevant results in orange.

To provide some operational capability before the whole constellation is deployed, the first Melonsats will be deployed so as to cover the area of greatest interest first (likely human base or robotic mission area coverage), i.e. the equator, for the temperatures in the area are more favorable to our missions. This minimal operational capability can take many forms but will likely evolve from providing only communication means to then, as the constellation grows, adding the navigation functionality. This way, the Melonsats won't need much reorganisation once deployed and their fuel will be preserved to maximise lifetime.

An extra Melonsat will also be added in each orbit for redundancy or improved performance, as deemed necessary as the project evolves. This effectively brings to 7 the number of satellites per orbit, as previously promised in section 1.5. This shouldn't be a problem as the cost of the satellites is negligible compared to the mission budget and the timeline overlap of phases D and E allows for it without causing a mess. Also, extra Melonsats will be produced and kept as backup in case something goes wrong with the ones previously sent to space.

2.3.3. Transfer Orbits

Using Hohmann transfers, relating to Figure 7 and Figure 3, we can determine the optimal trajectory for our spacecraft and the Δv to escape the Earth and the Δv for capture at Mars.

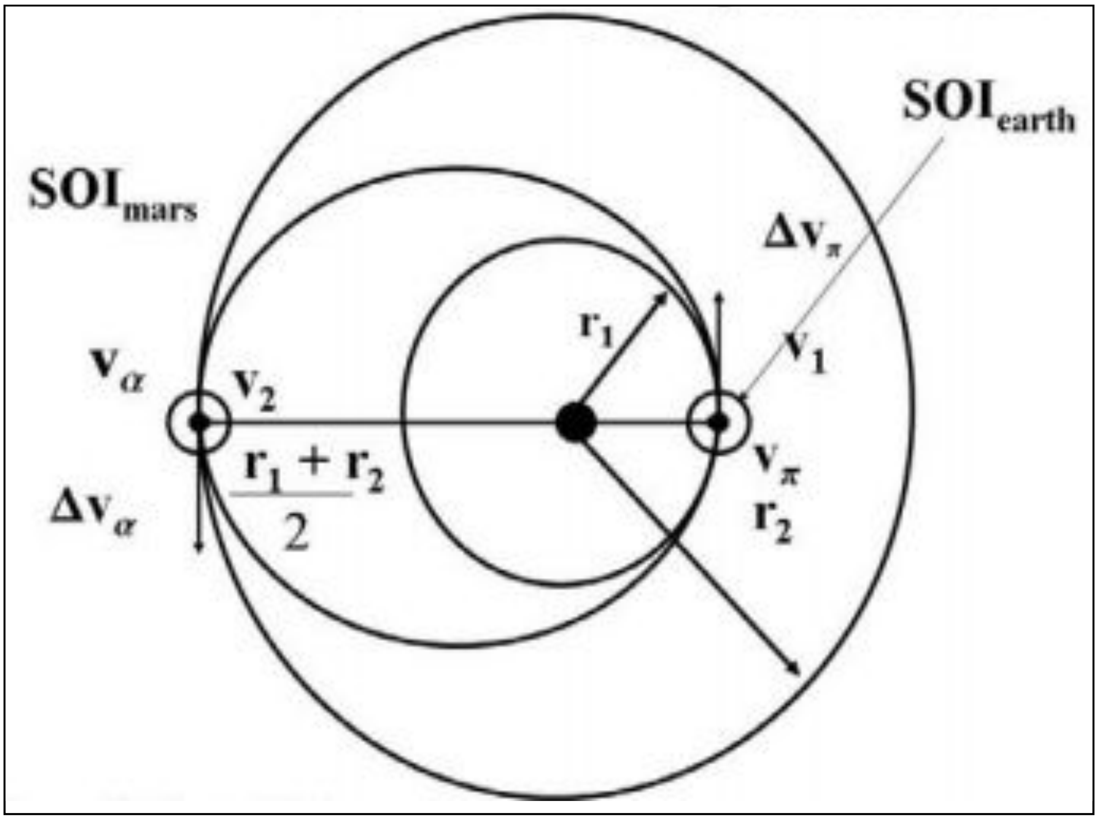

Figure 7: Image representing the Hohmann transfer between Earth and Mars representing all major spheres of influence. Copied from MIT OpenCourseWare [9].

The calculations were done in three steps: from Earth's geostationary orbit to the end of its SOI (sphere of influence), from there to the beginning of Mars' SOI, and from there to the desired orbit on Mars; using the equations from [10]. The intermediary steps to stabilize at the SOIs were neglected. For the inclination maneuver $\Delta v = 2v\, sin(\Delta i/2)$ where v is the orbital velocity and Δi the inclination of the orbit plane [16]. Results are shown in Table 3.

Δv escape	3,825	m/s
Δv capture	3,552	m/s
Δv inclination maneuver	2,545	m/s
Δv station keeping	45	m/s per year
total Δv	10,596	m/s
with 10% margin	11,656	m/s

Table 3: Velocity changes required for a Hohmann transfer from Earth to Mars. Estimates for orbit maintenance Δv come from Valispace [16].

Ideally, the launch vehicle will provide the Δv needed to escape the SOI of the Earth thus saving some more fuel for the Melonsats' operations. Alternatively, if it does, the propulsion system could be rescaled to a significantly smaller total Δv.

The time required to reach Mars with a modern rocket is about six months but it seems like a company has recently found a way to cut that time down to three months [4]. This is mostly relevant for the selection of the launch dates and commissioning of the Melonsats as their insertion into Martian orbit will likely require a communication window with Earth.

2.3.4. Ballistic Capture

This mission will attempt a ballistic capture of the Melonsats and default to the Hohmann transfers if necessary. The technique has so far only been used for lunar missions but a renewed model for this technique that would make it applicable for Mars missions has recently been developed by Boeing [1].

This would be mostly out of pure scientific curiosity [6] but would also save fuel and allow launches to take place at nearly anytime as the technique doesn't require a launch window.

2.4. Space Environment

The environment on Mars and its orbit is harsher than on Earth due to the lack of a magnetosphere that deflects radiations. As a result the atmosphere has been stripped away by solar wind. For this reason we will suppose there is no atmospheric drag at Musknav's altitude and no resulting loss affecting inter-satellite communications. When it comes to radiation, it is expected that the Melonsats will endure levels of radiation similar to the ones measured by the Martian Radiation Experiment (MARIE). This means solar events that amount to $8\ rads \approx 0.08\ Gy$ [4] per year on average and a few peaks where the spacecraft would have to endure $2\ rads \approx 0.02\ Gy$ in a single day, every 9 months approximately [23]. This results, over 15 years of lifetime, in a total radiation dose of $120\ rads \approx 1.2\ Gy$, including the occasional, and sometimes extreme, radiation bursts.

With the next solar radiation peak expected around 2024, the launch date set to 2044 is unfortunately situated around the very next peak, occurring every 22 years more or less, as shown in Figure 8. Taking into account further radiation studies yet to be made, it might be smart to delay the launch of the first batch of satellites to operate when the radiations are at their lowest. However, with a lifetime of 15 years and satellites to be replaced over time, operations during this peak period are inevitable at some point and it could be a good thing to test the first batch of satellites in extreme conditions and risk early failure instead of sending in the others and having them all fail at the same time at a later stage.

The thermal aspects related to the environment are discussed in section 11 dedicated to thermal management.

[4] Gy: SI unit for absorbed radiation dose "1 joule of energy deposited in 1 kilogram of mass" ~ 0.01rad

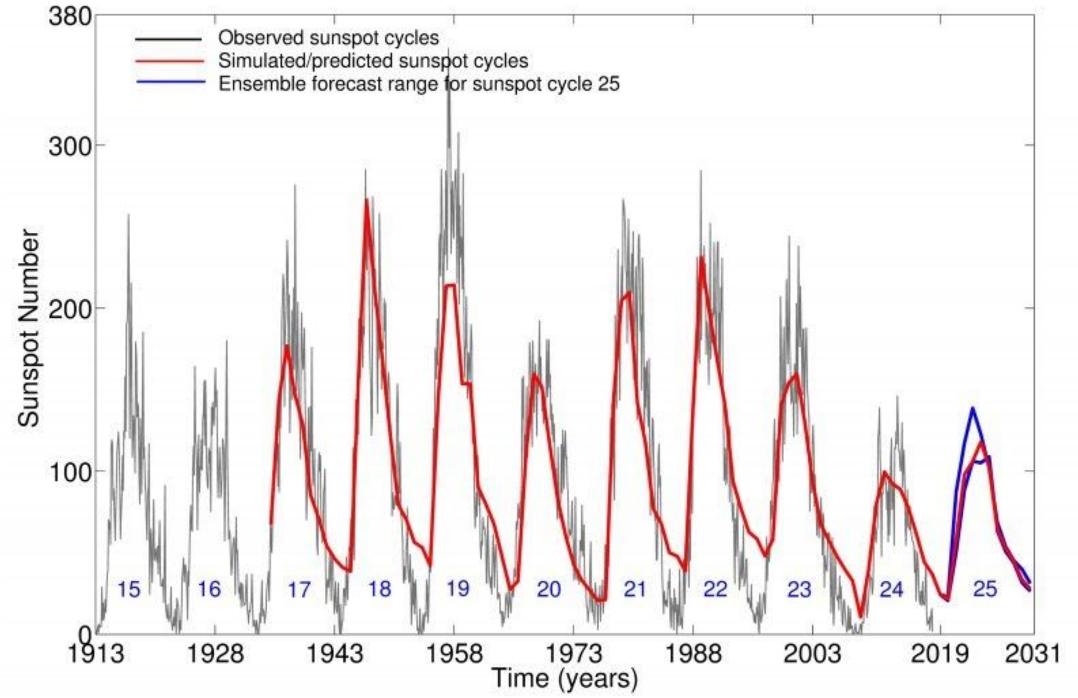

Figure 8: Solar cycles and predictions over time indicating a period of 22 years. Graph reused from EarthSky [24].

2.5. Phobos and Deimos

A further thing to make sure of during mission design is to make sure our planned orbit does not coincide with one of another celestial body, especially at Mars that has the lowest altitude moons in our solar system. A quick check of this is made in Table 4 and Musknav is indeed midway between Mars and Phobos.

	Distance [km]	Radius [km]
Musknav	5,452	–
Deimos	23,460	13
Phobos	9,377	22

Table 4: No collision check between Musknav and known celestial bodies.

Any effect Phobos or Deimos or any other body such as Earth's Moon might have on Muskanv's operations is ignored throughout the rest of this report. Examples of this could be gravitational pull, restricted communication windows with Earth or even prolonged time in eclipse. Note that all of these are not necessarily bad for the mission.

3. System Engineering

3.1. Requirements

A comprehensive list of requirements is available in the Annex Requirements. They are decomposed into three levels: mission, systems, subsystems, the latter including a mechanical structure, thrusters, an attitude determination and control system, a thermal control system, an electrical power system, command and data handling, telecommunications and a global navigation satellite system that all have a dedicated section in this report.

3.2. Mass Budget

The original mass estimate, based on the mass of a Galileo satellite, 700kg, was 1000kg. Given the Annex-SWaP-DC Budget (Size, Weight and Power - Data, Cost) this now stands at 1472kg so the original plan of launching 4 Melonsats in a Falcon-9 won't stick, it would already be great to have 3. It is very likely this would go down as the Δv budget is huge and considers that the launch vehicle does not provide the initial escape velocity, for example. There is no issue of space in the fairing however so that side is covered.

3.3. System ConOps

A description of the system's nominal concept of operations is depicted in Annex System ConOps, note that it can be overridden at any time by the CDH if necessary. The resulting design structure matrix of interfaces between the different subsystems is in Figure 9 and the budgets involved are available in the Annex SWaP-DC Budget, the data estimates are often based on Annex Requirements.

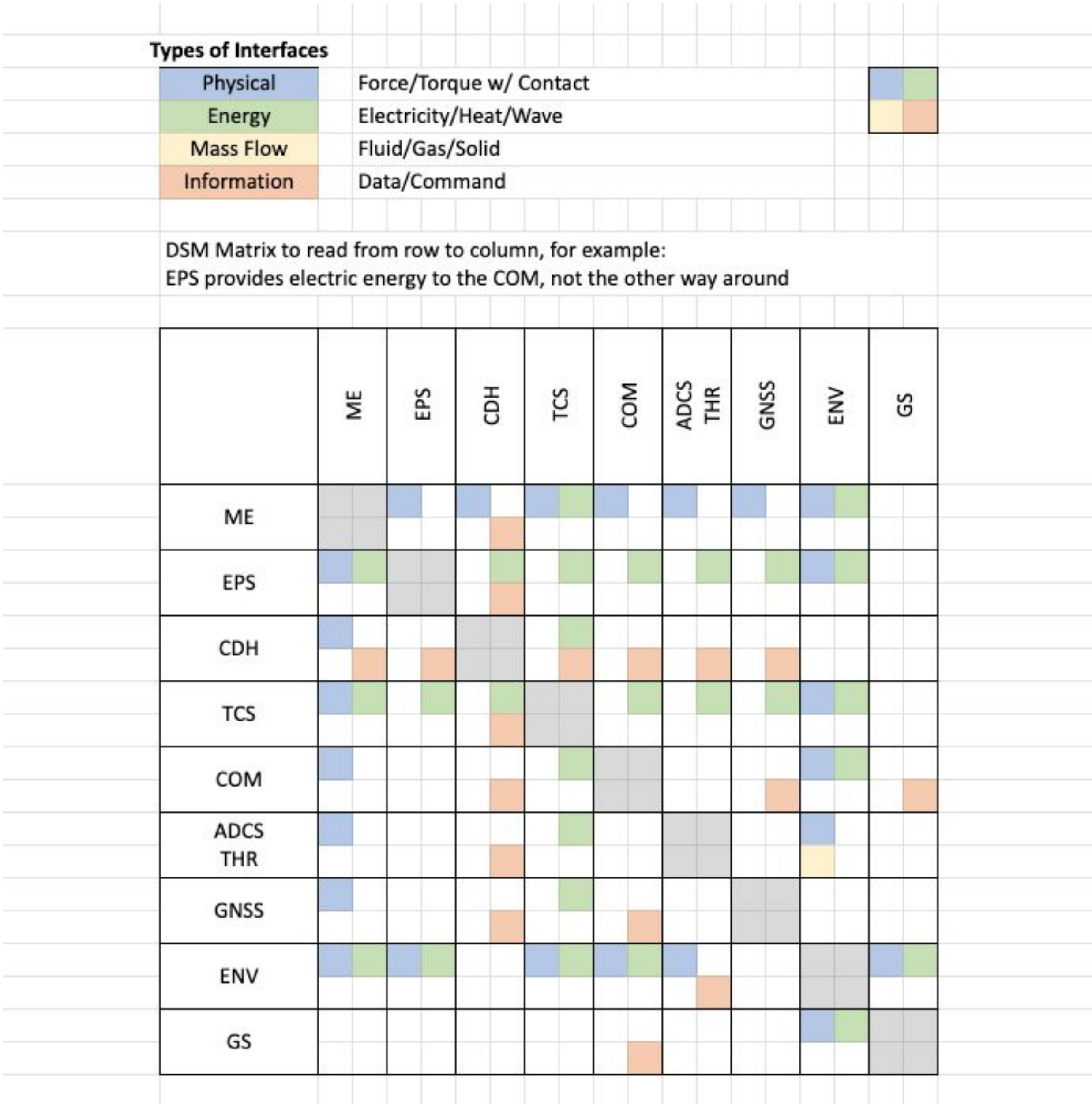

Figure 9: The DSM of the interfaces between the subsystems of a Melonsat.

The deployment sequence to be followed is the one described in the mission concept of operations in Figure 3. The commissioning sequence gives priority to critical subsystems, EPS, TCS, CDH, COM, ADCS if these work fine we may be able to accomplish at least partial mission success for a restrained period of time. In safe mode, only the EPS, TCS, CDH and occasionally ADCS with COM are to be active.

3.4. Redundancy Scheme

To mitigate system failures during operations a few strategies have been devised:

- Materials are chosen to survive the space environment.
- Radiation hard components are used where possible.
- Every critical system has hardware duplicates on board.
- Every system implements redundancies at the interfaces and within its own when feasible and judged necessary.

- Multiple types of sensors are used to avoid failure of all in a single event.
- Multiple frequencies are used for different types of communications but may be interchanged when alternatives fail.
- Housekeeping data sent to the ground station serves for troubleshooting anomalies.
- The on board computer can be reprogrammed from the ground station.

An Annex Risk Analysis is also available considering some failure scenarios and mitigations.

3.5. Other Considerations

All the Melonsats do not have to be identical. Because of the orbit inclination, the ones on the inclined planes will need to provide a greater Δv compared to the others while those on the equatorial plane are more likely to be solicited more often for communications and will see a greater data flow as the equator is where our future missions will land first. For such reasons, making two sets of slightly different satellites should be considered.

3.6. Logistics

This mission being very international will require cooperation between many different parties. It wouldn't be a surprise if long delivery/production delays were to arise. Different studies might be interdependent, and with many processes running in parallel a deadlock might take place. This is why a model based system engineering approach is suggested for this project's development. It will prevent misinformation and information delays.

Once built, and even during production, the Melonsat will require considerable amounts of testing and specialized facilities. This implies quite a lot of travelling will be involved and then, depending on the production site, one more trip to the launch vehicle. At all stages the Melonsat will have to be manipulated so the structure will need different adapters (ignored in this report) and places for ladders during assembly etc. The best approach is to think about possible logistics problems during planning and design phases of the projects to anticipate as many as possible.

4. Electrical Power

4.1. Description

The attitude electrical power subsystem (ADCS) is basically the power company, electricity provider of the satellite. It generates electricity from solar radiation, stores it and distributes it in the form desired by the other systems.

The EPS consists of solar arrays, batteries and power electronics. Its status is monitored by the CDH that may restrain operations if the satellite reaches an undesired battery level.

4.2. Power Source

Solar arrays provide many advantages for this mission, they are readily available, simple, inexpensive, relatively lightweight, efficient, do not require cooling, and the cells can be mounted so as to generate a specific voltage or current. The disadvantages are that they are bulky, hard to stow for launch, sensitive to the sun position, require a mechanism to deploy, degrade relatively quickly (no supplier has been found to guarantee more than 7 years of lifetime) and thus require additional safety margins for long missions. We also need to account for the fact that solar power available on Mars is about 4/9 of the power available on Earth, see Figure 10.

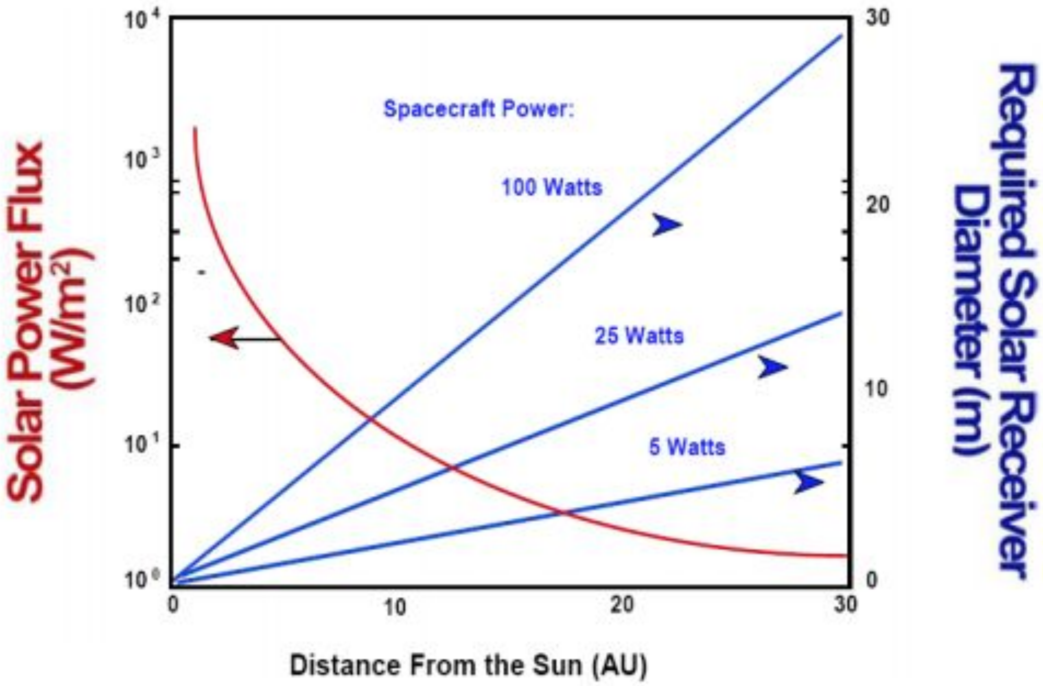

Figure 10: Solar power available at a given distance from the Sun. Mars is at 1.5 AU which represents about $590 W/m^2$. Copied from the lecture slides [20].

4.3. Power Budget

We will use a simplified design process [20] to estimate the power the solar arrays must generate during daylight to power the satellite during the entire orbit. We will use values based on the CTJ30 solar cells provided by CESI [19]. It is further assumed that the satellite requires constant power during the orbit even though it won't need to communicate with Earth when in eclipse nor do we account for it not using its thrusters all the time, that is why 60% of the power budget is considered here, it can be viewed as the upper margin of the duty cycle of components with a considerable margin. On the other hand, the Melonsat is designed to point Nadir at all times so the solar panels can't make use of all the Sun's radiation to the best of their ability, to compensate for that a 70% margin is added to be generated by the Psa, which is directly reflected in the area in Table 6. Results are shown in Table 5.

Power Budget	2,674	W
Duty Cycle	0.60	
Degradation Factor	0.97	
T daylight	9,803	s
T eclipse	2,419	s
Efficiency daylight	0.80	
Efficiency eclipse	0.60	
Psa +70%	4395	W

Table 5: Power budget for the solar arrays to provide according to lecture slides [20].

From the power budget and the solar flux we can then estimate the area of solar cells needed to provide that power $area = P_{sa}/\Phi_{sun}(d)$ where $\Phi_{sun}(d) = 590 W/m^2$ for Mars. The result is in Table 6.

Psa	4,394.98	W
Power Flux Mars	590	W/m^2
Cell Efficiency	0.29	
Area	25.69	m^2

Table 6: Solar cell CTJ30 - Thin area needed to cover power requirements.

To cover an area this size 9595 standard CTJ30 cells, each measuring 69x39 mm need to be assembled together (for one Melonsat) to then be deployed in space.

4.4. Power Storage

For this application, the reference battery choice is VES16 provided by SAFT [21]. They have a guaranteed lifetime of 18 years and come in several configurations, one of which can reach 80% depth of discharge. Using the power budget from Table 5 we establish the energy needed during the time spent in eclipse and determine the battery capacity accounting for a 30% margin. Results are shown in Table 7.

Psa	4395	W
T eclipse	2,419	s
Energy need for 2 eclipses with 30% margin	4671	Wh

Table 7: Battery energy requirement.

A single battery cell can hold 16Wh so we would need 292 batteries to store that power. It is assumed the margins taken at different levels are sufficient for the batteries to charge without orienting the Melonsat towards the Sun to maximise the use of incoming solar power. Also, because the source [21] doesn't specify the number of cycles the battery can tolerate during its lifetime of 18 years we suppose here there is no limit to that and thus no need to plan for greater capacity or start imagining more complex systems that would for example block every other charge cycle to avoid battery damage.

The excess energy produced by the solar arrays, that cannot be stored, must be dissipated by radiators.

4.5. Distribution Architecture

We introduce a regulated, maximum power point tracking (MPPT) topology as shown in Figure 11. The MPPT is to compensate a little for the lack of a charging mode in which the Melonsats would point towards the Sun. The choice to regulate is based on some research that suggests regulated circuits are better for satellites in geostationary orbits [22], but, given the technological advances in electronics since the writing of that article this is now applicable to most missions as well.

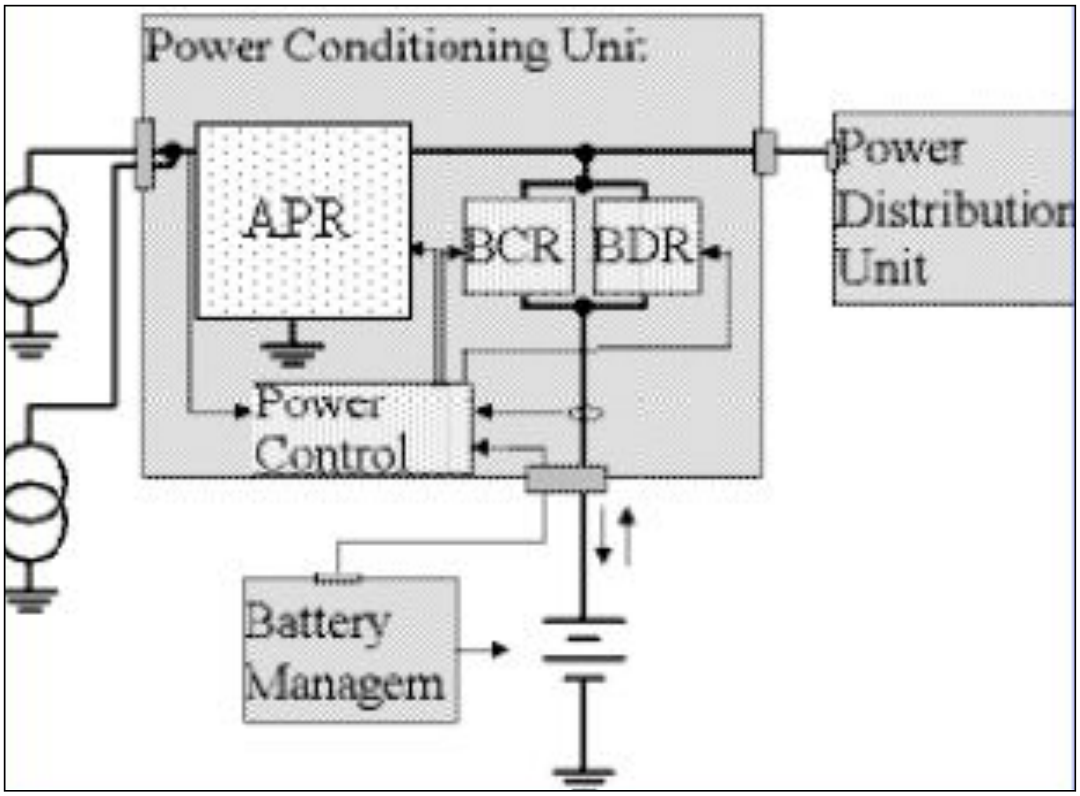

Figure 11: Topology for regulated maximum power point tracking.
Copied from lecture slides [20].

4.6. Nuclear Transition

The opportunity cost of solar arrays is the potential of nuclear power. Recently researchers developed a betavoltaic device based on nickel-63 that has a power density of 3.3kWh/kg and a half-life of 100 years which is far better than the current tritium standard. A dream for space technologies.

If that technology were close to ready during phase C of the project it would be good to reevaluate the use of solar panels. Using a nuclear power source, there would be no eclipse problem, no orientation dependent battery charging (or any dependency on solar power whatsoever), no logistical nightmares for assembly or stowing of solar panels and no more need for batteries, or at least not this many. On the other hand, the technology would likely be more expensive, would require shielding from radiation, and dissipation of the constant surplus energy through radiators. The nuclear option has been discarded for now, mainly because the technology is not ready yet but also because there is still enough solar energy around Mars to use solar arrays, and because the current nuclear sources do not provide enough power to not be accompanied by heavy batteries.

5. Attitude Determination and Control

5.1. Description

The attitude determination and control subsystem (ADCS) is basically an autopilot responsible for attitude and position control. To that effect it acts as the navigator of the spacecraft. Its duties are to first, get the spacecraft into orbit, and second, to monitor and adjust the attitude as necessary for mission operations while compensating disturbances.

The ADCS consists of star trackers, momentum wheels and thrusters. It may receive specific instructions from the CDH when something unusual comes up.

5.2. Sensors

The sensors chosen to determine the attitude of the Melonsat are wide angle star trackers and an inertial measurement unit (IMU). Star trackers are cheap, light, simple and have a ±0.01deg accuracy which is sufficient for the required 1deg pointing knowledge. The IMU has integrated gyroscopes and accelerometers that are reliable complementary sensors when combined by a Kalman filter. A representation of the two is in Figure 12.

An infrared sensor could be added in for redundancy but might not be as effective as when used for Earth detection due to the colder temperature of Mars. In case of failure, a redundant mechanism could be for the CDH to gather the missing information from the network of Melonsats whose sensors are, supposedly, still working.

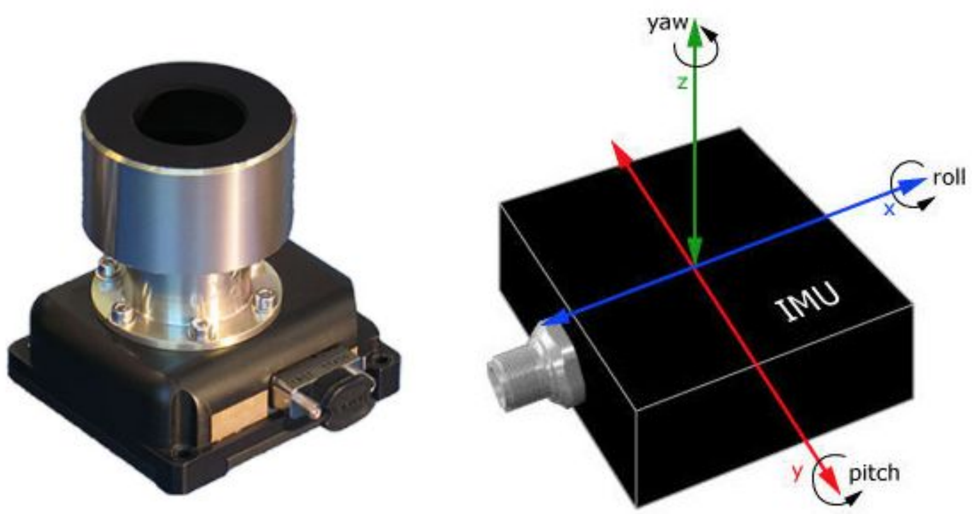

Figure 12: Sensors used for ADCS: star tracker ST-16RT2 (left) and schematic IMU (right).

5.3. Disturbances

Various forces disturb free movement in space. The ones considered for Musknav are atmospheric drag, solar radiation pressure, magnetic field, gravity gradient and internal disturbances. Only disturbances endured once in orbit are considered in this analysis. Any disturbance endured on the way to Mars and during orbital insertion are single events and are compensated for in the design margins.

There is no atmosphere at Musknav's altitude, hence there is no resulting disturbance. In addition Mars has no magnetic field (worth considering at least), thus this disturbance is also null. When it comes to internal disturbances, moving parts include solar panels, some of the antennas and the Xenon gas in its tank. Those movements are occasional. They should be performed symmetrically and thus cancel out most of the time. However, because of the uncertainty involved, let's assume that they are dominant at 0.1Nm (1000x the next highest disturbance) and add 50% contingency on top of that. The result is in Table 8. Note that the Moment Arm is assumed to be 2.50m away from the center of mass, outside the body of the Melonsat. The calculations of the inertia are available in section 10. Formulas are taken from the course slides [52] and a Valispace tutorial [53].

Disturbances	Parameters		Torque [N m]
Atmospheric Drag	—	—	0
Solar Radiation Pressure	v	v	9.75E-05
Solar pressure at Mars	3.93E-06	N/m^2	
Body Reflectivity	0.90	–	
Body Area	3.89	m^2	
Panels Reflectivity	0.25	–	
Panels Area	25.69	m^2	
Moment Arm	2.50	m	
Magnetic Field	—	—	0
Gravity Gradient	v	v	1.42E-04
Gravity μ	4.28E+13	m^3/s^2	
Orbital Radius	5.45E+06	m	
Max Inertia Difference	2066.84	kg m^2	
Max Angle Difference	5.00	deg	
Internal	—	—	1.00E-01
Total +50%			1.50E-01

Table 8: Disturbance Torques endured by the Melonsat once in orbit.
Internal disturbances are merely an estimation made to be dominant over the others.

5.4. Actuators

To counter the disturbances, actuators are needed. The choice has been made to use momentum wheels for stability during operations, Figure 12, and thrusters to desaturate the wheels once per orbit. Four wheels will be used, three wheels are positioned orthogonally and inclined is a fourth one for redundancy. The pointing requirements are to have ±5deg accuracy which is the allowable motion when considering momentum storage. Formulas used were taken from the course slides [52] and a Valispace tutorial [54]. The propellant mass computed here is considered as part of the dry mass of the Melonsat in section 6.

Figure 13: RSI 12 momentum wheels by Rockwell Collins.

Other options have been considered and discarded. A mass on a boom making use of the gravity gradient to orient the Melonsat towards Mars was discarded because the system could hinder communication signals. Reaction wheels were discarded for the lack of stability that momentum wheels offer by the gyroscopic effect. Control moment gyros simply required too much energy in comparison to the momentum wheels. Magnetic torquers would have been inefficient as there is no usable magnetic field on Mars. Thrusters on the other hand would have been very costly in terms of propellant mass but were retained for the desaturation procedure.

The calculations surrounding the sizing of the momentum wheels and the propellant gas needed for their desaturation based on the disturbances of Table 8 are in Table 9.

Momentum Wheels	Parameters		Results	
Momentum Storage	v	v	1.60E+02	N m s
Orbital Period	12,222	s		
Max Disturbance	1.50E-01	N m		
Allowable Motion	5.00	deg		
Momentum Desaturation Force	v	v	2.53E+02	N
Thruster Moment Arm	1.58	m		
Thruster Burn Time	1	s		
Propellant Mass +20%	v	v	38.11	kg
Number of Wheels Used Daily	3	–		
Number of Orbits in Lifetime	38761	–		
Total Impulse	1.16E+05	N s		
Ion Thruster Specific Impulse	2000	s		
Gravity on Earth	9.81	m/s^2		

Table 9: Sizing of momentum wheels.

5.5. Other considerations

The ADCS is in charge of the Melonsat's maneuvers throughout its lifetime since its deployment from the launch vehicle. This means it will be controlling the propulsion subsystem that will be used to provide the Δv needed to reach Mars and insert the Melonsat into orbit. The CDH will then have to instruct the ADCS what to do to establish and maintain the configuration of the constellation, Musknav.

Another important point is that the main thruster is fixed to the body of the Melonsat and thus the ADCS will have to orient the Melonsat in the desired direction before using it. The secondary thrusters can be combined to produce movement in any direction.

Finally, as the propellant gets used up, the inertia changes and if not taken into account this could lead to numerous overshoots to be corrected by thrusters and uselessly use up the propellant.

6. Propulsion

6.1. Thruster Choice

Assuming we know the thruster's specific impulse, we can figure out the propellant mass needed to produce the Δv estimated in section 2.2 about orbit selection using Tsiolkovsky's rocket equation. After several iterations and research the best choice seemed to be ion thrusters. They can be used for orbit insertion and maintenance, are fairly small, pretty efficient, do not damage the Melonsat, and are the only type that actually had a reasonable I_{sp} for the Melonsat not to be a giant gas tank, see Figure 14. The main downside is ion thrusters require far more power to work, the other is cost. To compensate for the power demands, thrusters of various sizes will be incorporated and used accordingly to the needs. The larger ones will mainly be used during orbit insertion and the smaller ones for trajectory corrections during nominal operations. These thrusters are also very easy to restart so if there is enough propellant left, the lifetime of the Melonsat could be extended.

Thruster	Specific Impulse (s)	Input Power (kW)	Efficiency Range (%)	Propellant
Cold gas	50–75	—	—	Various
Chemical (monopropellant)	150–225	—	—	N_2H_4 H_2O_2
Chemical (bipropellant)	300–450	—	—	Various
Resistojet	300	0.5–1	65–90	N_2H_4 monoprop
Arcjet	500–600	0.9–2.2	25–45	N_2H_4 monoprop
Ion thruster	2500–3600	0.4–4.3	40–80	Xenon
Hall thrusters	1500–2000	1.5–4.5	35–60	Xenon
PPTs	850–1200	<0.2	7–13	Teflon

Figure 14: Typical operating parameters for thrusters with flight heritage. Copied from NASA SciTechBook series [17].

An example of these thrusters would be the Radio Frequency Ion Thruster RIT 10 Evo and its smaller version RIT μX made by Ariane Group. They are shown in Figure 15 and a general schematic is provided in Figure 16.

For information purposes, from the thruster's datasheet [18], we get the total impulse $I_t = 1.1MNs$ and nominal thrust of $F_{th} = 15mN$ and can compute the burn time at constant thrust $t_{burn} = I_t/F_{th} = 20,370h$ which corresponds to the indicated lifetime, the exhaust gas velocity $v_e = I_{sp}g_0 = 29,430m/s$ and the mass flow rate $\dot{m} = F_{th}/v_e = 0.5\mu g/s$.

Figure 15: RIT µX (left) and RIT 10 Evo (right) ion thrusters.

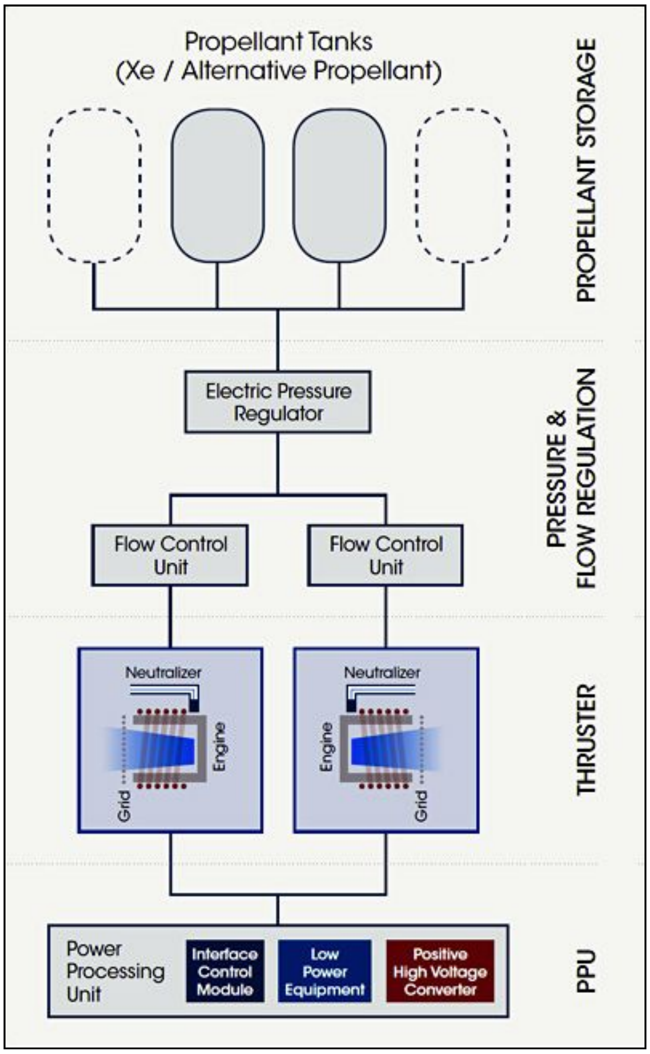

Figure 16: Radiofrequency ion propulsion flow schematic. Copied from datasheet [18].

6.2. Propellant Budget

As implied by the schematic in Figure 16, Xenon will be used as a propellant. It is the heaviest non-radioactive elemental inert gas and is easily ionized. The added mass allows for denser packing at lower pressure.

The mass of the propellant is $m_p = m_f(exp(\Delta v/g_0 I_{sp}) - 1)$ where $g_0 = 9.81 m/s^2$ is the Earth's gravity (test conditions to determine the value of the I_{sp}), Δv is as in Table 3, $I_{sp} = 3000$ is found in the datasheet of the RIT thrusters and m_f is the dry mass of the Melonsat that includes the propellant needs of the ADCS to desaturate its momentum wheels. The final propellant mass is in Table 10.

Thrusters	Parameters		Results	
Propellant Mass +20%	v	v	467.51	kg
Required Δv	11,656	m/s		
Dry Mass	763.30	kg		
Ion Thruster Specific Impulse	3000	s		
Gravity on Earth	9.81	m/s^2		

Table 10: Propellant final budget using the RIT 10 Evo thruster.

6.3. Thruster Positioning

On the mechanical structure in Annex Melonsat Design, the thrusters are represented by black circles with an X. The main thruster is on the back (Z) side of the Melonsat. Following Figure 17, the optimal positioning of 5 correction thrusters, is more or less in a pentagon shape with slightly tilted orientations. In the Melonsat's case an extra thruster is added for redundancy and thus, results in a more or less hexagon shape with slightly tilted orientations. The correction thrusters are on the top (Y) side of the Melonsat, in case of trajectory correction they are to be combined with the ADCS (the Melonsat can spin around Z all while maintaining all but its relay functionalities). All thrusters are near the gas tank.

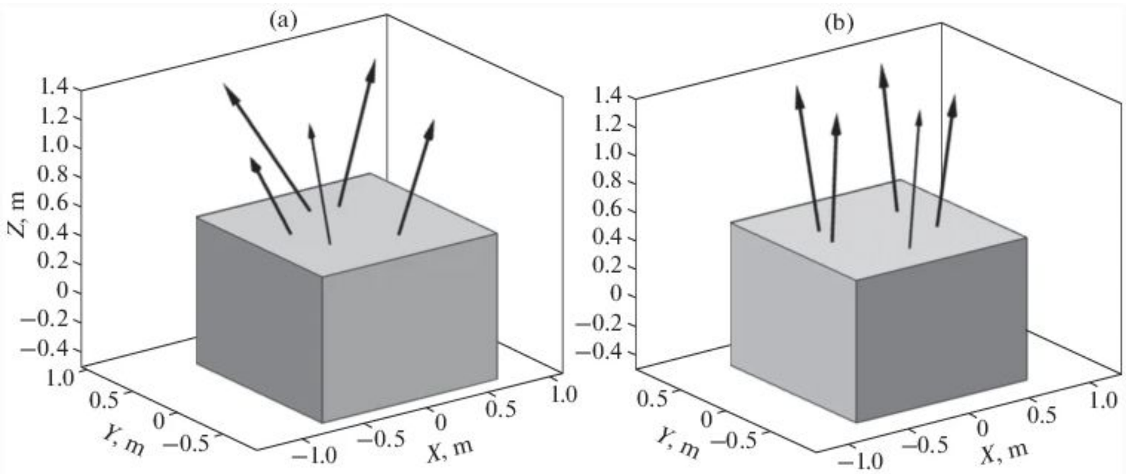

Figure 17: The local optimal (in terms of fuel consumption) distribution of five correction thrusters: (a) initial data, (b) final data. Copied Figure 10 from [61].

7. Science and Instruments

7.1. Science Objectives

The scientific objective is to try out new technologies and scientific findings. Although these objectives have not been taken as the default for the purpose of this report, the idea is to attempt ballistic capture, make use of newly developed betavoltaic cells, develop and use patch arrays of antennas, and demonstrate autonomy of a constellation of satellites for extended periods of time.

7.2. Atomic Clock for Navigation

In order for the navigation system to work, Melonsats musk broadcast a very precise time signal and an almanac of their positions. This time must be so precise that the Galileo mission chose to have two atomic clocks, two backup clocks, a monitoring and control unit as well as a navigation signal generator [12].

Let's simplify that here. Although the clocks have been reported to fail at an alarming rate, the cause of these failures has been identified and fixed [13] so let's use three clocks instead of four. The Melonsats have a greater lifespan and assuming one fails on launch and the other during nominal operations there's still one left for backup this way. It is also less expensive to invest in an extra clock than to replace a satellite. Because these failures are highly unlikely and that the precision wanted on Mars is inferior to that on Earth (also limited by the mapping resolution available), there is no need for passive hydrogen (PHM) maser atomic clocks. Only rubidium atomic frequency standard (RAFS) clocks will be used, just as for GPS and GLONASS. These rubidium are also easier to restart in case of failure [14].

One example of these clocks is sold by Excelitas Technologies. The box measures 127 x 216 x 152 millimeters and weighs 6.35 kilograms [15], see Figure 18.

Figure 18: RAFS atomic clock sold by Excelitas Technologies [15].

No information concerning the monitoring and control unit and navigation signal generator is easily found so they are here considered as a whole. The expectations are for it to fit the dimensions of the clocks and thus measure an estimated 127 x 216 x 50 millimeters. The weight is estimated to be around 1.5 kilograms.

The data generated by this clock has been estimated in the Annex SWaP-DC Budget. There are no pointing requirements for an atomic clock. There is also no data to collect, the signal generator sends the data (about 32bytes every 2s [60]) directly to the antenna points to Nadir ±5deg, guaranteed by the ADCS.

7.3. Communication Technologies

Several problems arise from combining navigation and communication means in a single mission, most importantly comes the problem of distance between Musknav and Mars as well as between Musknav and Earth. For Musknav to work, the technology used in current satellite phones will require a significant upgrade. This is explained further in section 8.7.

Even so, Musknav's scientific objectives are to demonstrate new communications technologies in space. This includes antenna arrays instead of the bulky parabolic ones and the router that will need to be developed, mentioned in section 8.8.

8. Telecommunications

8.1. Description

The telecommunications subsystem (COM) is basically a router for all communications going through Musknav. It has to deliver messages between two points that could both be on Mars or one on Earth and the other on Mars[5].

The COM consists of a router and various antennas operating in the L, X and Ka-band. Its operations may be regulated by the CDH when something unusual comes up.

8.2. General Considerations

The use of the communications system on board every Melonsat is to route communications between two points that may be on separate planets. To do this different antennas have different functions. As indicated in the requirements, these antennas are divided into 4 categories: Intercom (sections 8.3 and 8.4), Relay (section 8.5), Walkie-Talkie (section 8.7) and Navigation (section 8.6).

The type of data on the interplanetary link is unknown but is likely to include scientific measurements that can be heavy. It is assumed that up to 100TB of data a year will have to be downlinked to the ground station. The data on the local link is expected at least double that, once Mars is swarmed with robots.

As a side note, communications between Earth and Mars are subject to a 20min delay (on average) because of the distance separating the two planets. Therefore it makes phone calls and similar ‘live’ communications impractical. However, messages (text, voice, videos) are likely to be the default means of communication for humans. On the local link on the other hand, ‘live’ or short delay communications will be possible as even on opposite sides of Mars, data will pass through 3 to 4 satellites which represents a delay of 4 seconds at most.

From the Annex System ConOps, notice that in nominal operations mode this system is idle until contacted by another device that could use its services. This means there is no way of knowing when a communication might be initiated, nor how many might be happening at the same time. Furthermore, the ADCS is not responsible for the orientation of the spacecraft during communications, it solely points to Mars and corrects any trajectory anomalies for the navigation system to work correctly and maintain the constellation. Altogether this means every Melonsat needs redundant steerable antennas and a complex router integrated. Patch arrays of antennas will be used for the L and Ka-band, the X-band will likely use classical antennas with travelling wave tube amplifiers due to the difficult positioning of patch arrays on the Melonsat for this application.

Another use for this system is for self regulation within the Musknav constellation, this is done by the network of CDH communicating through the X-band antennas.

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[5] Musknav itself is considered as being on Mars.

The pointing requirements for all of the antennas used are relatively large. Navigation and communication services do not require much to work correctly but greater losses will be experienced if too far off the central line. For the L-band antennas the pointing is within the hands of the ADCS as they are fixed and pointing Nadir. For the X-band and Ka-band this is compensated by the antennas being steerable (accuracy indicated in the requirements). In addition the link budgets of the future sections consider a 2dB link margin, a sufficiently large required carrier to noise ratio and still have a little extra margin to compensate for pointing losses. Note that the BPSK with Reed-Solomon coding is considered here so the bandwidth is the bit rate, and the carrier to noise ratio is the same as the energy bit to noise ratio.

Furthermore, nothing in this analysis takes the doppler effects and other frequency shifts directly into consideration.

8.3. Ground Station

This is a mission around Mars with international interest. It therefore makes sense to use NASA's Deep Space Network (DSN), also part of ESA's Estrack network of ground stations that guarantees excellent services and has a great availability rate at 99% [25]. The communication time allocated to Musknav is to be regulated by the ground segment as Musknav is not designed to reach out in nominal operations.

These ground stations have bigger and smaller receiving dishes, it is assumed Musknav will be using the ones in Goldstone, Madrid and Canberra that have dishes of 70m in diameter and an aperture efficiency of 70% [31]. Their locations on Earth ensures visibility of Mars at all times[6], see Figure 19. These are equipped with hyper sensitive electronics operating at cryogenic temperatures to limit the dominant thermal noise. The sensitivity of these dishes has been hard to find but two sources [26] and [27] seem to indicate -175dBW (-145dBm) is a reasonable consideration and thus, nearly any energy peak will be detected. As per [32] the ground stations support up to 16 communication channels simultaneously and for deep space communications a data rate of 10Mbps is to be expected. As the maximum allowable by the DSN is at 150Mbps for near Earth communications, a bandwidth of 20MHz will be considered, increasing this would just add more noise to the system.

[6] Except when obstructed by other celestial bodies, for example, a conjunction with the Sun happens roughly every two years and lasts about two weeks.

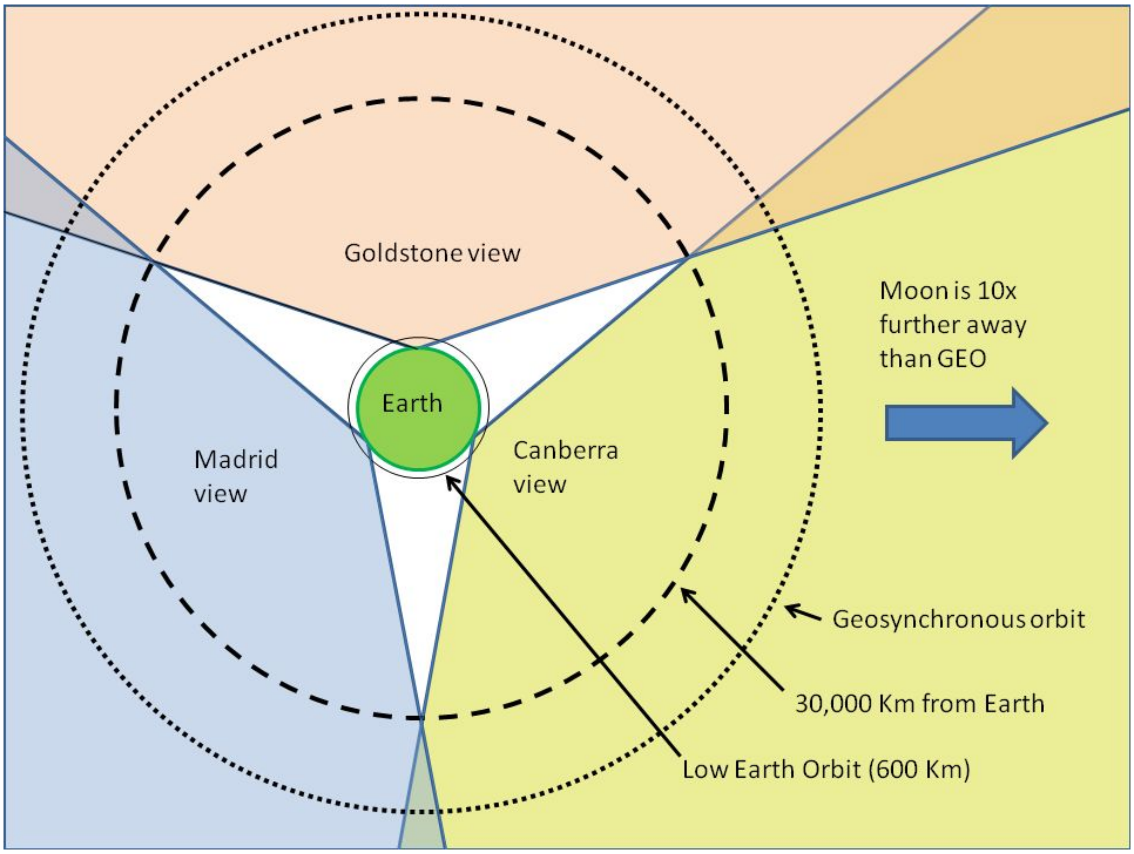


Figure 19: Coverage of the DSN stations in Goldstone, Madrid and Canberra.

The encoding chosen for all communications is the default binary phase shift keying (BPSK) with Reed-Solomon coding, which is relatively simple and has a low error rate (around one in a million), even at low power signals. A representation of this scheme is in Figure 20.

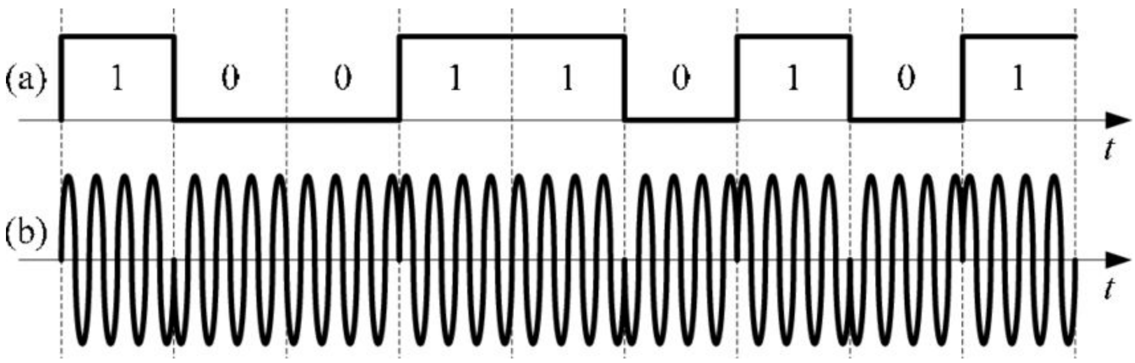


Figure 20: Representation of the BPSK modulation (b) of a digital signal (a) [36].

8.4. Communications with Earth

As part of the display of the autonomy of Musknav, the Melonsats will rarely contact the ground station. It will however need to be able to route communications between the planets at all times.

Because of the long distance communication of 401 million kilometers at its worst and limited energy for downlink, the frequency is chosen so as to maximise the gain at the ground station $G = 10\,log(4\pi A\eta/\lambda^2)$, where A the area of the dish, η the aperture efficiency and

$\lambda = c/f$ the wavelength of the wave, frequencies of the Ka-band (26.5GHz - 40GHz), compatible with the ground stations, will be used. The gain resulting from these characteristics is around 85dB, as indicated in [31].

According to [29] the total losses from communications in the Ka-band, taking into account the atmospheres of both planets and free space $L = 20\ log(4\pi d/\lambda) + L_{atm}$, are somewhere between -277dB and -294dB depending on the distance separating Earth and Mars. Unfortunately, these losses are greater at higher frequencies such as the Ka-band but are offset by the greater gains at the link ends. The use of the Ka-band is also very sensitive to rain fade but this is negligible as the dishes are located in mostly dry regions of the Earth and the increased data throughput is worth it in this use case.

When it comes to the antenna used on the Melonsat, reference made to Table 13-16 of the lecture about Telecom [33], gains around 50dB can be expected from antennas in the Ka-band. Choices for such antennas include the CubeSat deployable Ka-band reflector antenna [34] and the satcom phased array terminals by Ball Aerospace [35] that has a gain at 54dB at boresight, the latter is the one used for the calculations.

To establish the link budget a spreadsheet inspired from [31] has been used. In Table 11 is the reverse link budget, from Musknav to the DSN. Observe that starting with 26.5dBW of power at the Melonsat, the minimal power received on Earth is still within the sensitivity range of the ground station mentioned in section 8.3 and that it guarantees the minimum energy bit to noise density ratio E_b/N_0 of 1.8dB when using the Reed-Solomon code to limit the error rate to one in a million bits, mentioned in Table 3-4 of [32], with a 4.5dB margin. The forward link, from DSN to Musknav, is less delicate to establish as power is no longer such a constraint. As per Table 3-2 of [32], the DSN can provide 116dBW in the X-band but no data is available for the Ka-band, it is therefore supposed to be more than 10x less at 105dBW, thus providing a reasonable margin as the gain increases with frequency. The noise temperature of the antenna is not exactly the 4K of space because the electronics associated with it inside the Melonsats is at hotter temperatures. For the sake of argument, let’s assume it operates at 275K, at best this exaggeration only introduces greater margins. The other link parameters remain mostly the same as the antenna used is the same. The result is shown in Table 12. To ease the electronics and filtering on board the spacecraft, a signal to noise ratio of 10dB is desired as per Table 13-11 of [33]. Note that the received signal power is within the microWatt range which is still a reasonable sensitivity to have.

Musknav to DSN	**Value**	**Units**
Frequency	3.20E+10	Hz
Speed of Light	3.00E+08	m/s
Wavelength	0.00938	m
Transmitted Power	**26.50**	dBW
Gain (Satellite Antenna)	**54.00**	dBi
Max Distance	4.01E+11	m
Loss (propagation loss)	**-294.00**	dB
Diameter (Earth Antenna)	70.00	m

Earth Antenna Efficiency	0.70	—
Earth Antenna System Noise Temp.	20	K
Gain (Earth Antenna)	**85.00**	dBi
Bandwidth	2.00E+07	Hz
Atmospheric Losses	-3	dB
Design Margin	2	dB
Signal Power Received at Earth	-133.50	dBW
Noise Power at Earth	-142.58	dBW
Eb/N0	**9.08**	**dB**
Required Eb/N0	1.8	dB
Extra Eb/N0 Margin	7.28	dB

Table 11: Link budget for downlink at 32GHz from Musknav to DSN.

DSN to Musknav	Value	Units
Frequency	3.45E+10	Hz
Speed of Light	3.00E+08	m/s
Wavelength	0.00869	m
Transmitted Power (Earth DSN)	**105.00**	dBW
Diameter (Earth Antenna)	70.00	m
Earth Antenna Efficiency	0.70	—
Gain (Earth Antenna)	**85.00**	dBi
Max Distance	4.01E+11	m
Loss (propagation loss)	**-295.27**	dB
Satellite Antenna Noise Temperature	275	K
Gain (Satellite Antenna)	**54.00**	dBi
Bandwidth	2.00E+07	Hz
Atmospheric Losses	-3	dB
Design Margin	2	dB
Signal Power Received at Satellite	-56.27	dBW
Noise Power at Satellite	-131.20	dBW
Eb/N0	**74.92**	**dB**
Required Eb/N0	10	dB
Extra Eb/N0 Margin	64.92	dB

Table 12: Link budget for uplink at 34.5GHz from DSN to Musknav.

8.5. Communications within Musknav

When it comes to communications within Musknav, the objective is to be able to communicate with the furthest neighbour satellites within the constellation. These are located on the same plane and separated by a distance of 5450km. The angle separating the satellites on the same plane is indeed greater than the one separating the planes. It is therefore easier to communicate with a satellite on a different plane.

The data rates expected within Musknav will be the same as the maximum allowable for downlink to Earth, there is no added value here to provide more than that.

Operating within the X-band frequency range, following the logic of Table 13-16 of [33] we can expect to find antennas with a gain of 30dB and these are considered here, although higher gains of up to 45dB would be possible, as suggested by Table 2-2 in [57] (the sensitivity of the electronics of the Melonsat should be sufficient for -115dBW). These antennas usually have associated travelling wave tube amplifiers but here we considered them as one. In the X-band case it is unlikely patch antennas will be used because these antennas need to compensate for the losses of a Melonsat and thus require greater movements. Regular antennas and receiving dishes seem to be the better choice here. We keep the same bandwidth as for the interplanetary communications to allow for flawless transmissions from one network to another. Also, in this case we operate in space and there are no atmospheric losses at this altitude (see section 2.4 about space environment). The resulting link budget is in Table 13.

Melonsat to Melonsat	**Value**	**Units**
Frequency	8.40E+09	Hz
Speed of Light	3.00E+08	m/s
Wavelength	0.03569	m
Transmitted Power (Melonsat)	**12.00**	dBW
Gain (Transmitting Melonsat)	**30.00**	dBi
Max Distance	5.45E+06	m
Loss (propagation loss)	**-185.66**	dB
Satellite Antenna Noise Temperature	275	K
Gain (Receiving Melonsat)	**30.00**	dBi
Bandwidth	2.00E+07	Hz
Atmospheric Losses	0	dB
Design Margin	2	dB
Signal Power Received at Satellite	-115.66	dBW
Noise Power at Satellite	-131.20	dBW
Eb/N0	**15.53**	**dB**
Required Eb/N0	10	dB
Extra Eb/N0 Margin	5.53	dB

Table 13: Link budget for crosslink between Melonsats at 8.4GHz.

8.6. Navigation Signals

For navigation signals there is a need to compensate for the weak and cheap detectors with a high signal to noise ratio. Although cheap, these receptors usually have a sensitivity around -150dB [59]. It is assumed the GNSS chips used on Mars will have double the gain of those used on Earth, effectively passing it to 9dB instead of 4.5dB and require a signal to noise ratio of only 20dB instead of 44dB required here on Earth due to numerous interferences from similar frequencies [37] and atmosphere related issues that won't be present on Mars. Even with these considerations, it is necessary for the link budget to work to lower the bandwidth of 10MHz expressed in [38] to 500kHz, which should be enough to transfer ephemeris data and the almanac of Musknav. Also, according to [58], the coding scheme used for GNSS is AltBOC while here the budget is established assuming BPSK is used. According to [46] the data rate for GPS signals is around 50bps so a 500kHz bandwidth should be sufficient in any case. Another point to consider is the operating temperature range. Mars being particularly cold compared to Earth (good for noise reduction), the temperature is set to 320K, the maximum ever recorded on Mars. The resulting navigation link budget is presented in Table 14.

Melonsat to Surface GNSS	**Value**	**Units**
Frequency	1.20E+09	Hz
Speed of Light	3.00E+08	m/s
Wavelength	0.24983	m
Transmitted Power (Melonsat)	**22.00**	dBW
Gain (Melonsat Antenna)	**19.00**	dBi
Max Distance	4.77E+06	m
Loss (propagation loss)	**-167.60**	dB
GNSS Receiver Noise Temperature	295	K
Gain (GNSS Receiver Antenna)	**9.00**	dBi
Bandwidth	5.00E+05	Hz
Atmospheric Losses	-3	dB
Design Margin	2	dB
Signal Power Received on Mars	-122.60	dBW
Noise Power on Mars	-146.91	dBW
Eb/N0	**24.31**	**dB**
Required Eb/N0	20	dB
Extra Eb/N0 Margin	4.31	dB

Table 14: Link budget for navigation signals at 1.2GHz considering some technological improvements of the receivers to be used on Mars compared to the ones used on Earth.

8.7. Satellite Phone Service

Current satellite phone services operate in the L-band at around 1.6GHz [39]. To remain compatible with the technology this won't be changed much, a slight increase to 1.7GHz is made to further avoid possible interferences with the navigation signals. Phone communications never use only one frequency (mainly because both ends can communicate at the same time) so this is a vague approximation of a frequency range over which the results would all be very similar. In cell phone communications anything better than -105dBW is considered a usable signal so Musknav aims to provide a full strength signal at -80dBW [41]. In addition to that, a signal to noise ratio around 25dB is recommended, but 20dB is sufficient, for voice applications [40]. The 20dB is considered here as there are not as many interferences on Mars as there are on Earth. Also, given the range of frequencies a human can hear is generally accepted to be at 20kHz, with a typical uncompressed data rate at 64kbps [45], a bandwidth of 100kHz should be more than enough for this application [42] (even for robots). Typical phone antennas have gains of at most 5dB [43] and usually require 7W of power, just as much will be expected from the phones that will be used on Mars [44]. The resulting link budgets are in Table 15 and Table 16.

Note that the extra margin in Table 15 is not very satisfying in this worst case scenario, considering the edge of the field of view of the satellite that is in an area also covered by another satellite; that this already includes several margins and noise at record high temperatures. However, a restraining factor that is left as is to be improved is the perceived power at the phone receptor which is not sufficient compared to the -105dBW mentioned above. Furthermore, this link budget is not satisfactory when compared to the expected 200TB of data to transfer a year at least.

The bandwidth that seems to work here for human communications is not sufficient to transfer all the data generated by robots and scientific instruments. This is limited by the current technology and power of the satellite phones that are considered in this analysis. The Musknav constellation is simply too far from the surface. Two possible solutions are: increase the L-band antenna gains and/or increase the power provided by high data throughput devices to gain an extra 25dB at least. It remains a better choice than having each of these devices provide enough power to communicate directly with Earth or establishing relay antennas everywhere on Mars.

Alternatively, we could accept a significantly lower data budget or increase the number of Melonsats orbiting Mars. A more unlikely alternative could be to set up smaller satellites that relay the L-band used on the ground to the X-band of the Melonsats but at this stage the whole purpose of Musknav would be lost.

Surface to Melonsat COM	**Value**	**Units**
Frequency	1.70E+09	Hz
Speed of Light	3.00E+08	m/s
Wavelength	0.17635	m
Transmitted Power (Phone)	**8.45**	dBW
Gain (Phone Antenna)	**5.00**	dBi

Max Distance	4.77E+06	m
Loss (propagation loss)	**-170.62**	dB
Satellite Antenna Noise Temperature	275	K
Gain (Satellite Antenna)	**19.00**	dBi
Bandwidth	1.00E+05	Hz
Atmospheric Losses	-3	dB
Design Margin	2	dB
Signal Power Received at Satellite	-143.17	dBW
Noise Power at Satellite	-154.21	dBW
Eb/N0	**11.03**	**dB**
Required Eb/N0	10	dB
Extra Eb/N0 Margin	1.03	dB

Table 15: Link budget for uplink through a satellite phone operating in a range of frequencies around 1.7GHz and having similar characteristics to those used on Earth.

Melonsat to Surface COM	**Value**	**Units**
Frequency	1.70E+09	Hz
Speed of Light	3.00E+08	m/s
Wavelength	0.17635	m
Transmitted Power (Earth DSN)	**22.00**	dBW
Gain (Melonsat Antenna)	**19.00**	dBi
Max Distance	4.77E+06	m
Loss (propagation loss)	**-170.62**	dB
Satellite Antenna Noise Temperature	295	K
Gain (Phone Antenna)	**5.00**	dBi
Bandwidth	1.00E+05	Hz
Atmospheric Losses	-3	dB
Design Margin	2	dB
Signal Power Received at Satellite	-129.62	dBW
Noise Power at Satellite	-153.90	dBW
Eb/N0	**24.28**	**dB**
Required Eb/N0	20	dB
Extra Eb/N0 Margin	4.28	dB

Table 16: Link budget for downlink to a satellite phone operating in a range of frequencies around 1.7GHz and having similar characteristics to those used on Earth.

8.8. Router

To provide the communication service the Melonsats will need to receive and transmit information from/to a place on Mars to/from another or even to/from Earth. The basis for this already exists but there is always a ground station involved. In Musknav's case this will be done from satellite to satellite and planet to planet.

This router will be handling both local and interplanetary communications, see Figure 21, and thus presents a series of new challenges. The added communication constraints due to the distance between the two planets are quite a burden, luckily the traffic on Mars is not expected to be very heavy anytime soon and this system should not be easily overloaded. The router will require a sufficient buffer storage space and parallel processing of the communications but this is to be determined when the number of communications the router shall handle at once has been established.

To simplify the router's job, it would be good to establish a protocol for interplanetary communications that indicates in the package header the planet of destination.

9. Command and Data Handling

9.1. Description

The command and data handling subsystem (CDH) is basically a computer that is responsible for carrying out the mission operations. To that effect it acts as the commander of the spacecraft. Its duties include executing commands from the ground station, supervising the actions of the other subsystems and allocating resources for their operations, and solving issues as they arise. The CDH operates in a network with the CDHs of the other Melonsats within Musknav to maintain the configuration of the constellation and provide Musknav’s services, even if a Melonsat is out of order.

The CDH consists of an FPGA integrating an ARM processor with RAM and Flash memory, several inputs and outputs connecting to other subsystems through serial buses, a few safety features and a software to handle the whole.

9.2. Architecture

The centralized architecture has been chosen for the CDH for two reasons. First, it is highly reliable and can be easily handled by the real-time operating system. Second, it allows for different interfaces with each subsystem. A schematic of this is shown in Figure 21.

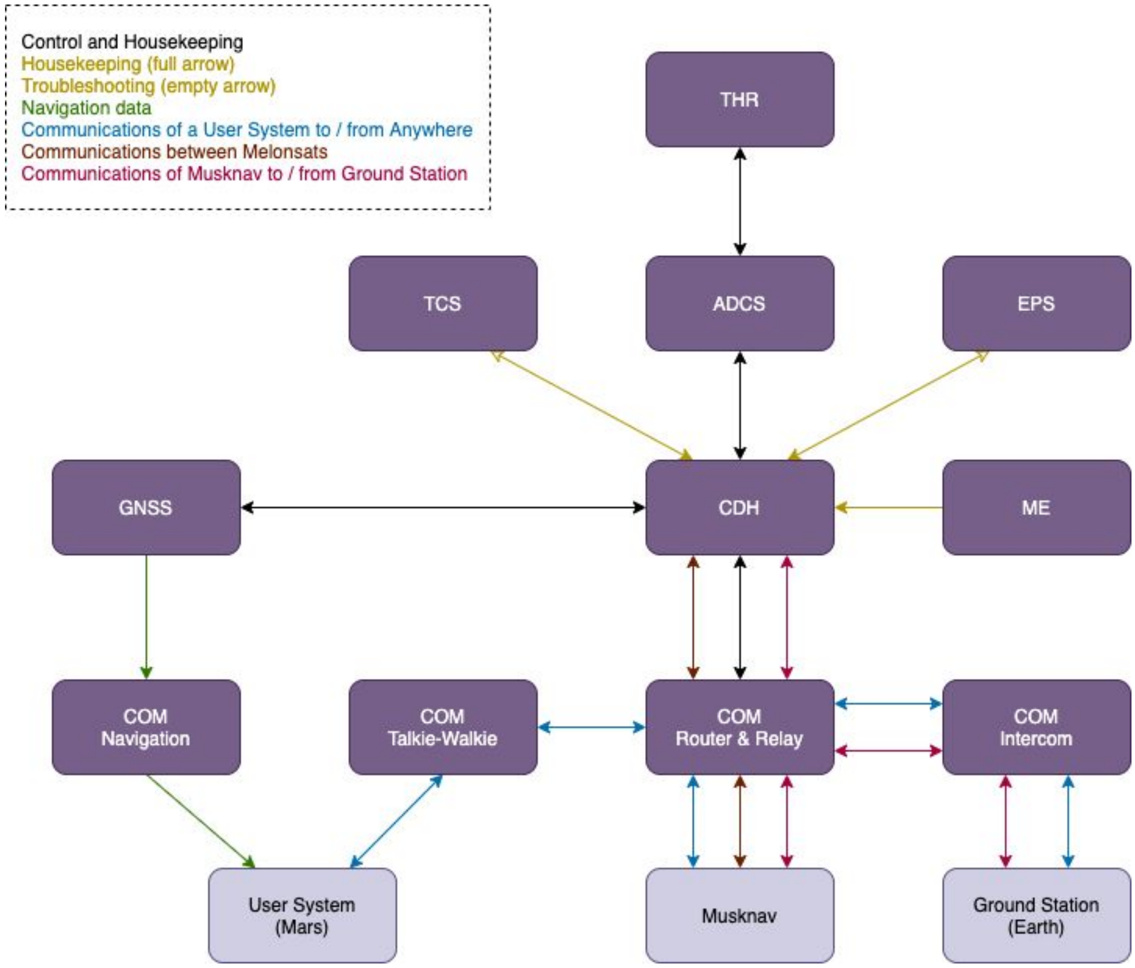


Figure 21: The centralized architecture of the CDH subsystem with the different data flows. Can also be viewed as the chain of command, with the CDH at the core.

9.3. Data Budget

The data budget is available in the Annex SWaP-DC Budget. Various assumptions have been made. It is supposed the software will take up to 500MB of the flash memory (50% contingency). It is assumed that every subsystem connected by a black or yellow arrow in Figure 21 generates under 500kB of housekeeping data every 30min from its different sensors (200% contingency). That equates to 1176MB for the 7 subsystems over a week, which easily fulfills the related requirements. Let's further assume that there is a backup software preloaded in the memory as part of the risk mitigation plan and that there are 250MB of troubleshooting commands and another 250MB are needed for commissioning.

Given that a flash memory of 32GB is allocated to this system and that all the above adds up to roughly 2GB of data, the chosen capacity is an overkill. With this capacity, 6 months of housekeeping data could be stored before being for downlink to the ground station.

Note that all this is possible because the communications system has an integrated router with data buffers of its own. This is discussed in section 8 reserved to Telecom.

9.4. Protocols

The default protocol has been chosen to be SpaceWire [49], an adaptation of the IEEE1355 for space applications. It is an asynchronous type of communication that can reach speeds of up to 200Mbps. Error rates are very low thanks to the data strobe encoding scheme in Figure 22. Another feature is that it allows for the propagation of interrupts, essential when using a real-time operating system. The main drawback is it requires 8 wires and a ground.

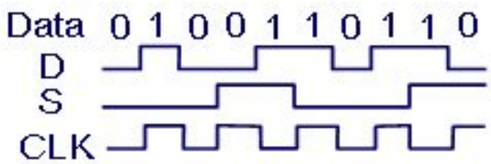


Figure 22: Data strobe encoding [48]. The strobe switches its state if the data didn't switch, the clock can be recovered by XORing the two.

Information that is to be sent by the antennas will be compressed using the lossless extended Rice algorithm which is recommended by the Consultative Committee for Space Data Systems (CCSDS). Rice adapts to different message lengths and can achieve greater compression factors than its alternatives without being computationally heavy [50] [51].

10. Mechanical Structure

10.1. Description

The mechanical structure (ME) is basically the box that holds everything together and protects its interior from the space environment. To that effect it acts as the protective shield of the spacecraft.

The ME consists of the structure itself equipped with a few sensors that monitor the overall health of the spacecraft over time and inform the CDH of incoming radiation bursts so it can switch to a protective safe mode.

10.2. Design Configuration

A sketch of the design configuration is available in the Annex Melonsat Design. An attempt is made at reducing the cabling and spreading the components according to their thermal needs and mass for homogeneity but it does not include all the interfaces between the subsystems. The thermal needs are detailed a little further in section 11 about thermal management and the interfaces are discussed in section 3 about system engineering.

10.3. Dimensions and Inertia

The structure's design can be approximated by two rectangular boxes as in Figure 23. The first one is the body depicted by sides L,W,H and the second one are the panels that don't really go through the body but to ease the calculations it has been supposed that they do. Doing so actually adds to the 20% contingency considered in Table 17 containing the results.

Dimensions	Length [m]	Height [m]	Width [m]
Body	1.800	1.200	1.500
Panels	20.773	0.040	1.380
Body +20%	2.160	1.440	1.800
Panels +20%	24.928	0.048	1.656
Inertia	X [kg m^2]	Y [kg m^2]	Z [kg m^2]
Body	581.67	865.41	737.72
Panels	31.02	1469.65	1463.19
Body + Panels	612.69	2335.05	2200.92
Total +20%	735.23	2802.06	2641.10

Table 17: Mechanical structure dimensions and inertia.

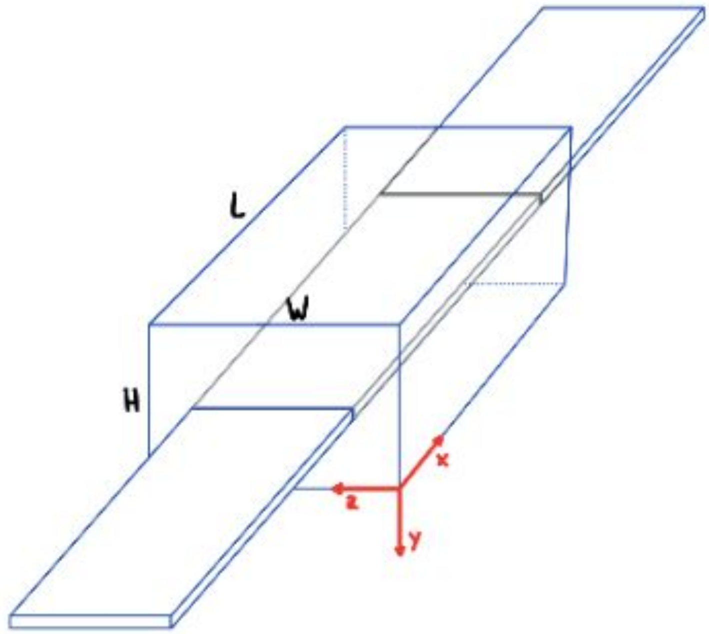


Figure 23: Very simplified mechanical structure of a Melonsat.

10.4. Choice of Materials

The material choice represents a trade-off between the manufacturability of the structure and its performance, the cost is not considered a factor for this project as long as the other factors can discriminate a clear winner. The performance criteria to optimise are individually briefly discussed below. A few materials that could fit the bill are then listed at the end.

Low density, the material must be as lightweight as possible because every kilogram adds up to the Δv propellant budget of the satellite and launch vehicle. While still on Earth, a lightweight satellite is also easier to maneuver (logistics).

Great damping properties, mainly to absorb the vibrations during launch but also useful when hit by a micrometeoroid.

Excellent strength and stiffness, need to withstand the forces involved throughout the mission, especially the gravitational changes. This will also ensure the structure does not deform under stress, so that no screws come off and similar unwanted phenomena.

Reflective surface, the radiation for the sun would be too much energy to take for the satellite if some of it weren't reflected away.

Thermal properties in the form of low thermal dilation coefficient and great heat dissipation to even out the temperature gradients are very key in space. The latter could be helped by great electric conductivity that could also perhaps withstand some of the ionising radiation.

Wear resistance and chemical inertness are also necessary to prevent degradation.

The list is probably not exhaustive but it is already clear all those are hard to satisfy and will require high end materials. A detailed analysis could be conducted by starting off with Ashby plots and then moving on to more detailed numerical analysis. However, the choice here is to stick to a stainless steel alloy for its thermal properties (similar to the one used for the Starship SpaceX is building) and default to titanium, aluminium or composites if needed as those have already been accepted as a solution for numerous other missions. On top of that, a standard coating/plating will be applied to protect the body from the space environment. See more about that in section 11.2.

10.5. Adapters

While still on Earth, the structure will have to go through various processes and tests that will require special logistics during manufacturing and assembly, part of which, a main one is transport. Not to have to adapt the structure to something that does not help its operations, adapters through which it will be manipulated will have to be built. This does obviously imply the structure will have some fixtures for the adapter but these should be minor. A trade-off to be made during detailed design stages.

On bound to leave for Mars, an adapter will be needed for the launch vehicle to successfully deliver the Melonsat into orbit, for that all the details are known and provided in the user guide [3] and is in most part provided by the launch provider.

11. Thermal Management

11.1. Description

The thermal control subsystem (TCS) is basically a temperature regulator, like an air conditioner, without the air part because it operates in space. Its duties are to maintain the temperature inside the spacecraft within the working range of the different components.

The TCS consists of temperature sensors, heaters and radiators. It works in tandem with the ME that has some passive measures for heat management as well. In case of trouble, it may always contact the CDH for help to find an alternative solution using the other subsystems.

11.2. Thermal Balance

11.2.1. General

Different sources of heat have to be considered in this analysis. They come either from the inside of the Melonsat, heat generated through power consumption, or form the outside environment, through radiation. Throughout this section, the temperature of the Melonsat is assumed to be homogeneous (although some subsystems, such as the gas tank, might have specific temperature requirements of their own).

For the heat generated from the inside, 60% of the total power, excluding the TCS power, is assumed to be dissipated by heat. When it comes to the outside, radiations endured during nominal mission operations are considered, namely, solar, albedo and black body infrared radiations. The computations in the following sections consider that the area affected by these radiations corresponds to the two largest sides of the Melonsat's body and that the four smaller ones can be used for cooling. As mentioned in section 10, a coating/plating is applied on the satellite: white paint (silicate), it has remarquable absorptance and emittance coefficients available in Figure 24. Note that the use of stainless steel suggested in section 10 has amazing thermal properties but let's ignore that here. A thermal balance is obtained when the heat flows between the inside and the outside of the Melonsat compensate each other ($Q_{in} = Q_{out}$).

The goal is to maintain the subsystems of the Melonsat within their operating range. Following the tables on slide 17 of [56] we assume this to be at 12°C ~ 285K ± 10K.

Note that the effect this has on solar panels has been neglected here as they actually benefit from the heat and nothing much can be done for the cold but design them for survivability.

Table 11.4 α and ε values for several surfaces and finishes [5,6,7]

Surface	Absorptance (α)	Emittance (ε)	α/ε
Polished beryllium	0.44	0.01	44.00
Goldized kapton (gold outside)	0.25	0.02	12.5
Gold	0.25	0.04	6.25
Aluminium tape	0.21	0.04	5.25
Polished aluminium	0.24	0.08	3.00
Aluminized kapton (aluminium outside)	0.14	0.05	2.80
Polished titanium	0.60	0.60	1.00
Black paint (epoxy)	0.95	0.85	1.12
Black paint (polyurethane)	0.95	0.90	1.06
—electrically conducting	0.95	0.80–0.85	1.12–1.19
Silver paint (electrically conducting)	0.37	0.44	0.84
White paint (silicone)	0.26	0.83	0.31
—after 1000 hours UV radiation	0.29	0.83	0.35
White paint (silicate)	0.12	0.90	0.13
—after 1000 hours UV radiation	0.14	0.90	0.16
Solar cells, GaAs (typical values)	0.88	0.80	1.10
Solar cells, Silicon (typical values)	0.75	0.82	0.91
Aluminized kapton (kapton outside)	0.40	0.63	0.63
Aluminized FEP	0.16	0.47	0.34
Silver coated FEP (SSM)	0.08	0.78	0.10
(OSR)	0.07	0.74	0.09

Note: SSM, Second Surface Mirror.
OSR, Optical Solar Reflector.

Figure 24: Table for absorptance and emittance coefficients of different surface finishes. Copied from course slides [56].

The following sections will also require data regarding the albedo coefficients, visibility factor and infrared radiation affecting Musknav. The table and graph in Figure 25 contain this data.

TABLE 11-45B. Albedo and IR Emission of the Planets. This table shows representative values of albedo and IR emission for the planets of our Solar System. Perihelion and aphelion represent the points in the orbits of Mercury and Mars where they are closest and furthest from the Sun.

Planet or Moon	Visible Surface	Geometric Albedo	Orbit-Average IR (W/m²)
Mercury	Solid	0.12	4150 (perihelion) 1810 (aphelion)
Venus	Clouds	0.80	153
Earth	Solid/Clouds	0.37*	231
Moon	Solid	0.07	430
Mars	Solid	0.29	162 (perihelion) 120 (aphelion)
Jupiter	Clouds	0.34	13.5
Saturn	Clouds	0.34	4.6
Uranus	Clouds	0.34	0.63
Neptune	Clouds	0.28	0.52
Pluto	Solid	0.47	0.5

* Use 0.27 if the Sun is in the orbit plane. This is were albedo heat loads are the most significant.

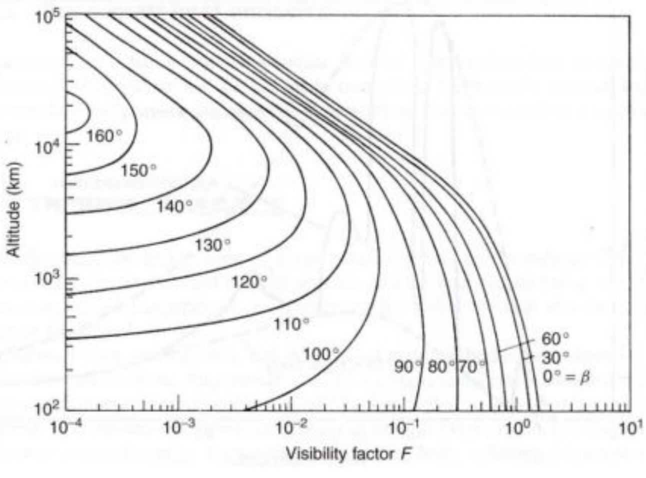


Figure 25: Albedo coefficient, visibility factor as a function of the altitude, and IR radiation to consider in orbit around various celestial bodies. Copied from course slides [56].

11.2.2. Hot Extreme in Daylight

Values used to obtain the results in Table 18 are mainly taken from Figure 25. However, for the black body estimation, a quarter of the value of infrared radiation is considered. The perihelion value is used as it is the maximum to be expected but it is reduced because the altitude of the orbit considered in Figure 25 is not specified and is expected to be low, at around 500km while Musknav operates at 2000km, which would reduce the radiation power indicated by 16x. Even when taking a quarter we still have a 400% margin on that number.

Hot Extreme IN	Parameters		Result [W]
Solar Radiation	v	v	615
Sun Radiation Power	3.856E+26	W	
Distance from the Sun	2.16E+11	m	
Radiation Intensity	659	W/m^2	
Affected Surface	7.776	m^2	
Absorptance Coefficient	0.12	–	
Albedo Radiation	v	v	143
Albedo Constant	0.29	–	
Visibility Factor	0.8	–	
Distance from Mars	2.06E+06	m	
Radiation Intensity	153	W/m^2	
Affected Surface	7.776	m^2	
Absorptance Coefficient	0.12	–	
Black Body Radiation	v	v	283
Mars IR Emission (max)	40.5	W/m^2	
Affected Surface	7.776	m^2	
Emittance Coefficient	0.9	–	
Self Generated Heat	v	v	1245
Melonsat Power	2074	W	
Fraction Dissipated by Heat	0.6	–	
Total +20%			2742

Table 18: Heat flows going in the Melonsat in daylight.

Hot Extreme OUT	Parameters		Result [W]
Power Radiated to Space	v	v	3840
Boltzmann Constant	5.67E-08	W/m^2/K^4	
Emittance Coefficient	0.9	–	
Effective Surface	11.405	m^2	
Desired Temperature	285	K	
Total -20%			3072

Table 19: Heat flows going out the Melonsat in daylight.

11.2.3. Cold Extreme in Eclipse

Values used to obtain the results in Table 20 are mainly taken from Figure 25. There is no effect from solar or albedo radiation because the Melonsat is in eclipse. For the black body estimation, a quarter of the value of infrared radiation in Figure 25 is taken for the same reason as cited above, only this time the minimum value at the aphelion is used.

Cold Extreme IN	Parameters		Result [W]
Solar Radiation	—	—	0
Albedo Radiation	—	—	0
Black Body Radiation	v	v	210
Mars IR Emission (min)	30	W/m^2	
Affected Surface	7.776	m^2	
Emittance Coefficient	0.9	–	
Self Generated Heat	v	v	1245
Melonsat Power	2074	W	
Fraction Dissipated by Heat	0.6	–	
Total +20%			1745

Table 20: Heat flows going out the Melonsat in eclipse.

The heat power passively radiated to space in eclipse is the same as in daylight, it is estimated in Table 19.

11.2.4. Conclusion

In both cases, the thermal balance is negative. In daylight there is a 120W and in eclipse a 1120W excess heat flowing out. Note that this budget was made considering all of the systems are active all of the time. Therefore, it could make sense to play more on the types of coatings or their repartition, for example, having a black side and a white side.

Even so, in this case we have a cold bias and an active heat management system is necessary to maintain the Melonsat at 285K ± 10K. Note that with the 10K uncertainty concerning the optimal working temperature of the subsystems, when in eclipse, heating instead of cooling might actually be required, contrary to what the thermal balance seems to suggest.

11.3. Active Heat Control

Given the high temperature ranges and uncertainty surrounding this topic. Heaters and radiators will be added.

The Melonsat is already biased towards the cold so only louvers to allow more radiation to escape should suffice for cooling.

On the other hand, for heating, insulation is needed on the inside of the Melonsat to prevent too much heat from dissipating. Further active control over this is added by resistive heaters placed throughout the Melonsat.

The time delays of temperature changes are not considered anywhere in this report but to prevent fast wear of the components, a requirement on the temperature gradient should be considered and is initially set to 0.2K/s in the Annex Requirements.

Annex Mission Abstract

Musknav - a constellation of satellites providing navigation and communication means on Mars.

Filip Slezak, EPFL Course Project (filip.slezak@epfl.ch).

Introduction: With the privatization of the space industry in recent years, there has been a real hype about making human life multiplanetary. The spirit of exploration surrounding missions of the likes of Apollo has been brought back to life.

The next best choice of a planet for humans to live on is Earth's neighbour in the solar system, Mars. The main problem with Mars is that its environment is not exactly human friendly. Numerous robotic missions have already conducted searches for water, soil and atmosphere analysis and even looked for life.

Now, with the technology available in this day and age, it finally seems possible to get people to live on Mars, and eventually bring them back. With such a seemingly inevitable scenario come several needs, and this is where this project kicks in.

Life on Mars: It is still a long shot before humans populate Mars. Before that happens, preparations have to be made to accommodate the environment to our needs and make the planet habitable, namely, provide water, food, oxygen and shelter.

In a closer future, it is likely robots will be the main actors on the planet. They won't be there solely for scientific reasons, as is currently the case, but also to prepare the place for humans.

This is however impossible within a reasonable cost and time frame without robotic autonomy and collaboration on the planet.

Musknav: Musknav addresses both needs by providing navigation and communication means on Mars. Its navigation solution is pretty standard, in fact most of it can be copied from existing navigation satellites, but its advanced communication system will relay communications not only between points on Mars but also to Earth. This feature will relax the energy and communication needs of the robots and later, allow for human interplanetary communications with a simple satellite phone (although not live because delays remain inevitable, voice or video messages would be a pleasing alternative solution).

Scientific Objectives: Musknav will attempt a few scientific feats of its own. It all starts at launch, with an attempt at ballistic capture of its satellites. A technique already proven to work for lunar missions but never attempted in a different context. If successful, ballistic capture could save propellant in future missions and waiting for specific launch windows, when Mars is closest to Earth, would no longer be required.

On the energy side of things, Musknav will pave the way for nuclear power through betavoltaic cells in space applications. These have a much greater energy density than the existing alternatives and can last nearly a century.

For communications, Musknav will be using next generation microengineered high gain antennas coming in the form of patch arrays. These are very promising and still not standard for most missions.

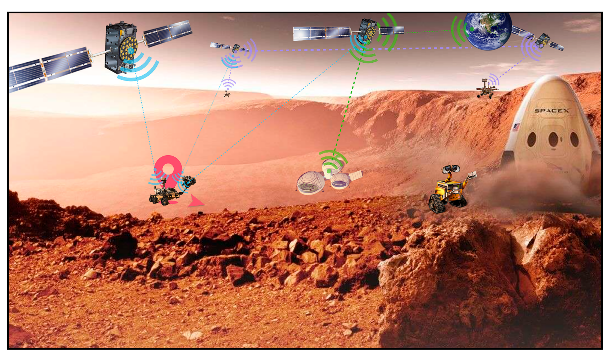
All in all, the greatest scientific feat will probably be the autonomy of Musknav itself. The satellites of the constellation will operate in a network and autoregulate their attitude for extended periods of time, with minimal need for a ground station (they will still be monitored from Earth but no intervention will take place if not necessary).

Stakeholders: Various parties play a role in such an ambitious project: space companies, governmental space agencies, the scientific community, outside investors, space and exploration enthusiasts, the media, and everybody else as they witness humanity becoming interplanetary.

Cost and Timeline: Such a project obviously doesn't come free and is expected to be financed by the various stakeholders.

A project of this scale is inherently of international interest and becomes impossible without the collaboration of all parties involved over time.

Based on previous missions, the cost is estimated at $15 billion over 20 years with concept studies starting in 2024 and the first launch taking place by 2044. This can be delayed as necessary if the services provided by Musknav would be rendered useless within this time frame.



Conclusion: Musknav is nothing but an enabling technology in the quest to colonize Mars. It will be on the frontlines as one of the first missions to launch in this great endeavor and hope is that it will bring people together in this formidable journey.

(31.12.2020)

Annex Requirements

How to use this spreadsheet ?

For each requirement a unique ID is assigned, it is written down, a verification method is chosen, its status (whether it has been met or not) and dependencies are recorded in the respective columns for traceability.

The requirement's ID consists of the abbreviation of all the supersystems it is part of, indicating its level of depth, and a number, for differentiation.

Eventual clarifications are to be expressed as notes in the "wording" column. Uncertain values are marked as to be defined/confirmed between square brackets **[ ]**.

Levels of Requirement:

No L0 that is usually defined by customer (none) = mission objectives in the abstract

L1 (15)	L2 (41)	L3 (130)	
MIS	**Mis**sion		
>>	MUSK	**Musk**nav Constellation	
>>	ELON	Me**lon**sat Satellite	
—	>	ME	**Me**chanical Structure
—	>	THR	**Thr**usters
—	>	ADCS	**A**ttitude **D**etermination and **C**ontrol **S**ystem
—	>	TCS	**T**hermal **C**ontrol **S**ystem
—	>	EPS	**E**lectrical **P**ower **S**ystem
—	>	CDH	**C**ommand and **D**ata **H**andling
—	>	COM	Tele**com**munications
—	>	GNSS	**G**lobal **N**avigation **S**atellite **S**ystem
>>	GS	**G**round **S**tation	

Categories of Requirements:

Functional
Performance
Constraints
Interface
Environmental
Safety
Human Factors
Others

ID	Wording	Verification	Status	Dependencies	Comments
MIS-01	The mission shall provide navigation means on Mars.	Test	...		
MIS-02	The mission shall provide communication means on Mars.	Test	...		
MIS-03	The mission shall provide communication means between Earth and Mars.	Test	...		
MIS-04	The mission shall embrace new ideas and test new technologies.	Demo	ok		
MIS-05	The mission shall begin by [2024] for a launch to take place by [fall of 2044].	Analysis	X		Exact date is to be agreed upon by the main stakeholders
MIS-06	The mission shall have an operational lifetime of [15 years].	Analysis	X		
MIS-07	The mission shall be monitored from Earth.	Test	X		
MIS-08	The mission shall establish a plan for its end of life.	Analysis	ok		Could be to prolong the mission, not necessarily terminate it
MIS-09	The mission shall follow the ECSS standards where possible.	Inspection	...		
MIS-10	The mission shall use the international system of units.	Inspection	...		
MIS-11	The mission cost shall not exceed [$15 billion].	Analysis	X		
MIS-12	The mission shall be the result of an international collaboration.	Analysis	X		
MIS-13	The mission shall collaborate with the private sector when possible.	Analysis	X		
MIS-14	The mission shall openly share its progress with the public.	Demo	X		
MIS-15	The mission shall comply with planetary protection guidelines.	Inspection	...		

ID	Wording	Verification	Status	Dependencies	Comments
MIS-MUSK-01	A constellation of satellites, dubbed Musknav, shall be deployed around Mars.	Test	X	MIS-01/02/03	
MIS-MUSK-02	Musknav shall be fully deployed within 2 years from the first launch.	Test	X		Fully benefit from the 15 years of lifetime
MIS-MUSK-03	Musknav shall be deployed so as to cover most critical areas first.	Analysis	X		Be partially operational asap
MIS-MUSK-04	Musknav shall provide its navigation service on 80% of the surface of Mars.	Analysis	...	MIS-01/02/03	
MIS-MUSK-05	Musknav shall provide its communication service on 100% of the surface of Mars.	Analysis	...	MIS-01/02/03	
MIS-MUSK-06	Musknav shall remain operational when the constellation is incomplete.	Demo	X		Guarantee service
MIS-MUSK-07	Musknav shall have autonomous capabilities that allow it to operate for [8 months], without contact with a ground station.	Test	X		

ID	Wording	Verification	Status	Dependencies	Comments
MIS-ELON-01	The satellites of the constellation, dubbed Melonsats, shall be designed for a lifetime of 15 years.	Analysis	...	MIS-06	
MIS-ELON-02	Melonsats shall perform a commissioning check with the ground station upon deployment from the launch vehicle.	Demo	X	MIS-GS-04	Ready for operations
MIS-ELON-03	Melonsats shall be able to correct their trajectories to Mars.	Demo	X		Get in position
MIS-ELON-04	Melonsats shall perform the final orbital insertion at Mars.	Demo	X		Get in position
MIS-ELON-05	Melonsats shall perform a commissioning checks every [4h] within the constellation once operational in orbit.	Demo	X	MIS-MUSK-07	Ready for operations
MIS-ELON-06	Melonsats shall be enclosed within a single structure.	Inspection	...		Simpler this way
MIS-ELON-07	Melonsats shall collect and store the energy needed for operations.	Demo	...	MIS-MUSK-07	
MIS-ELON-08	Melonsats shall control their attitude.	Analysis	...	MIS-MUSK-06/07	
MIS-ELON-09	Melonsats shall be able to withstand the space environment.	Analysis	...	MIS-01	
MIS-ELON-10	Melonsats shall regulate their temperature within operational range.	Demo	...		
MIS-ELON-11	Melonsats shall transmit ephemeris data to Mars.	Test	...	MIS-01	
MIS-ELON-12	Melonsats shall transmit an almanac of Musknav to Mars.	Test	...	MIS-01	
MIS-ELON-13	Melonsats shall serve as an communication relay between Earth and Mars.	Test	...	MIS-03	
MIS-ELON-14	Melonsats shall be usable through existing satellite phones.	Demo	...		Heritage, but might be adapted
MIS-ELON-15	Melonsats shall route the communication from sender to receiver.	Demo	...	MIS-02/03	
MIS-ELON-16	Melonsats shall execute commands received from the ground station.	Demo	...	MIS-07	
MIS-ELON-17	Melonsats shall transmit housekeeping data to the ground station upon request.	Demo	...	MIS-07	Monitor mission status
MIS-ELON-18	Melonsats shall be able to troubleshoot common failures autonomously.	Demo	X	MIS-MUSK-07	
MIS-ELON-19	Melonsats shall regulate their position and attitude within Musknav.	Test	X	MIS-MUSK-06/07	
MIS-ELON-20	Melonsats shall have redundant critical systems on board.	Inspection	...	MIS-MUSK-07	Failure management
MIS-ELON-21	Melonsats shall enter a safe mode from which they can troubleshooted or reset upon system failure [TBD by risk analysis], from the ground station if necessary.	Test	X		
MIS-ELON-22	Melonsats shall compensate for the loss of another Melonsat.	Analysis	X	MIS-MUSK-06	Guarantee service
MIS-ELON-23	Melonsats shall be decommissioned by crashing onto a safe area on Mars.	Analysis	...	MIS-08	

MIS-ELON-24	Melonsats shall comply with the requirements of the launch provider.	Inspection	...		
MIS-ELON-25	Melonsats shall measure no more than [TBD] when folded for launch.	Inspection	...	MIS-ELON-24	
MIS-ELON-26	Melonsats shall weigh no more than [1000kg].	Inspection	...	MIS-ELON-24	
MIS-ELON-27	Melonsats shall cost no more than [$80 million] each.	Analysis	X	MIS-11	

ID	Wording	Verification	Status	Dependencies	Comments
MIS-GS-01	The ground station services shall make use of existing infrastructure.	Analysis	ok		Avoid unnecessary costs
MIS-GS-02	The ground station services shall be provided by [DSN].	Analysis	...		Default for deep space missions
MIS-GS-03	The ground station shall not remain nonoperational for more than [6 months].	Analysis	X	MIS-07 MIS-MUSK-07	
MIS-GS-04	The ground station shall perform commissioning checks with the satellites upon their deployment from the launch vehicle.	Demo	X	MIS-07 MIS-ELON-02	Ready for operations
MIS-GS-05	The ground station shall be able to request housekeeping data from the satellites.	Demo	...	MIS-07 MIS-ELON-17	Monitor mission status
MIS-GS-06	The ground station shall be able to send command to the satellites.	Demo	...	MIS-07 MIS-ELON-16	
MIS-GS-07	The ground station shall be used for communications with systems on Mars.	Test	ok	MIS-03 MIS-ELON-13	

ID	Wording	Verification	Status	Dependencies	Comments
MIS-ELON-ME-01	The structure shall enclose all the Melonsats' subsystems, exception made of the radiators, thrusters, solar panels and antennas.	Inspection	...	MIS-ELON-06	
MIS-ELON-ME-02	The structure shall follow the configuration as defined by the schematic of the Melonsat Design.	Inspection	...		Base design, open to changes
MIS-ELON-ME-03	Thrusters shall protrude the structure by no more than [10cm].	Inspection	...	MIS-ELON-ME-01	Limit radiation impact
MIS-ELON-ME-04	Solar panels shall be attached to the X sides of the Melonsat.	Inspection	...	MIS-ELON-ME-01/02	
MIS-ELON-ME-05	Solar panels shall be deployable upon deployment from the launch vehicle.	Inspection	...	MIS-ELON-02	
MIS-ELON-ME-06	Antennas shall be attached to the Z sides of the Melonsat.	Inspection	...	MIS-ELON-ME-01/02	
MIS-ELON-ME-07	Antennas shall be deployable upon deployment from the launch vehicle.	Demo	X	MIS-ELON-02	Not applicable for patch arrays, and maybe not necessary for the others
MIS-ELON-ME-08	The structure shall protect its components from vibrations during launch [TBD], as indicated by the launch provider in its user manual.	Demo	X	MIS-ELON-24	
MIS-ELON-ME-09	The structure shall protect its components from radiations [TBD] encountered in the space environment around Mars.	Analysis	X	MIS-ELON-01/09	Necessary for long lifetime
MIS-ELON-ME-10	The structure shall be equipped with sensors indicating its integrity [TBD].	Inspection	X		Monitor health status
MIS-ELON-ME-11	The structure shall measure no more than [TBD].	Inspection	X	MIS-ELON-25	Design for ease of assembly
MIS-ELON-ME-12	The structure shall weigh no more than [TBD].	Inspection	X	MIS-ELON-26	The lighter the better
MIS-ELON-ME-13	The sensors on the structure shall require a nominal power of no mor	Analysis	X	MIS-ELON-EPS-01	Peak power may differ
MIS-ELON-ME-14	The sensors on the structure shall generate no more than [1MB] of data per hour.	Analysis	X	MIS-ELON-CDH-03	
MIS-ELON-ME-15	The structure shall cost no more than [TBD].	Analysis	X	MIS-ELON-27	Not really an issue

ID	Wording	Verification	Status	Dependencies	Comments
MIS-ELON-THR-01	The thrusters shall be controlled by the ADCS.	Demo	...	MIS-ELON-ADCS-02	
MIS-ELON-THR-02	The thrusters shall provide the total expected Δv of [11500m/s] needed for mission operations throughout the lifetime of the Melonsat.	Analysis	...	MIS-ELON-03/04/08	Consequent change possible if Δv to exit Earth's SOI is provided by LV
MIS-ELON-THR-03	The thrusters shall have an associated gas tank containing [370kg] of Xenon to provide the Δv expected in MIS-ELON-THR-02.	Inspection	...	MIS-ELON-THR-02	Same as for MIS-ELON-THR-02
MIS-ELON-THR-04	The thrusters shall have a main thruster that provides [15mN] of thrust in the Z direction (as defined in the schematic of the Melonsat Design).	Inspection	...		Required thrust is a guess at the moment
MIS-ELON-THR-05	The thrusters shall have side thrusters that provide [1mN] of thrust each to control the attitude in all directions.	Inspection	...		Required thrust is a guess at the moment
MIS-ELON-THR-06	The thrusters shall be be able to endure the space environment around Mars for the entire mission lifetime.	Analysis	X	MIS-ELON-01/09	Protruding the structure, there is no other way really
MIS-ELON-THR-07	The main thruster shall measure no more than [200mm x 150mm x 150mm].	Inspection	X	MIS-ELON-ME-11	
MIS-ELON-THR-08	The side thrusters shall measure no more than [100mm x 100mm x 100mm] each.	Inspection	X	MIS-ELON-ME-11	
MIS-ELON-THR-09	The main thruster shall weigh no more than [2kg].	Inspection	X	MIS-ELON-ME-12	The lighter the better
MIS-ELON-THR-10	The side thrusters shall weigh no more than [0.5kg] each.	Inspection	X	MIS-ELON-ME-12	The lighter the better
MIS-ELON-THR-11	The main thruster shall require a nominal power of no more than [450	Analysis	X	MIS-ELON-EPS-01	Peak power may differ
MIS-ELON-THR-12	The side thrusters shall require a nominal power of no more than [50\	Analysis	X	MIS-ELON-EPS-01	Peak power may differ
MIS-ELON-THR-13	The sensors on the thrusters shall generate no more than [1MB] of data per hour.	Analysis	X	MIS-ELON-CDH-03	
MIS-ELON-THR-14	The thrusters shall cost no more than [TBD].	Analysis	X	MIS-ELON-27	Not really an issue

ID	Wording	Verification	Status	Dependencies	Comments
MIS-ELON-ADCS-01	The ADCS shall control the attitude of the Melonsat throughout its lifetime, sarting from its deployment from the launch vehicle.	Analysis	X	MIS-ELON-08/19	Guide the Melonsat to Mars
MIS-ELON-ADCS-02	The ADCS shall control of the propulsion subsystem.	Demo	...		
MIS-ELON-ADCS-03	The ADCS shall detumble the Melonsat if the spin rate is above [TBD].	Analysis	X	MIS-ELON-ADCS-01	Stabilize the Melonsat
MIS-ELON-ADCS-04	The ADCS shall perform the orbital insertion of the Melonsat.	Analysis	X	MIS-ELON-04	Position for nominal operations
MIS-ELON-ADCS-05	The ADCS shall have a pointing knowledge of [±1deg] on all axis, at all times.	Analysis	ok		
MIS-ELON-ADCS-06	The ADCS shall provide a pointing accuracy of [±5deg] on all axis.	Analysis	...		
MIS-ELON-ADCS-07	The ADCS shall be able to rotate the Melonsat at a rate of [1deg/s] on all axis.	Analysis	X		Indicative value only
MIS-ELON-ADCS-08	The ADCS shall execute commands received by the CDH when not detumbling.	Demo	X	MIS-ELON-CDH-28	The Melonsat will have needs special needs the ADCS is not aware of at times
MIS-ELON-ADCS-09	The ADCS shall point nadir during nominal mission operations when not detumbling and not commanded to do otherwise by the CDH.	Analysis	X	MIS-ELON-11/12/13	Default position for best communications
MIS-ELON-ADCS-10	The ADCS shall reject disturbances affecting the Melonsat [TBD].	Analysis	...		
MIS-ELON-ADCS-11	The ADCS shall have backup hardware options.	Inspection	ok	MIS-ELON-20	Redundant wheel + thrusters are backup
MIS-ELON-ADCS-12	The ADCS shall measure no more than [TBD].	Inspection	X	MIS-ELON-ME-11	
MIS-ELON-ADCS-13	The ADCS shall weigh no more than [20kg].	Inspection	X	MIS-ELON-ME-12	The lighter the better
MIS-ELON-ADCS-14	The ADCS shall require a nominal power of no more than [30W].	Analysis	X	MIS-ELON-EPS-01	Peak power may differ
MIS-ELON-ADCS-15	The ADCS shall generate no more than [1MB] of housekeeping data every hour.	Analysis	X	MIS-ELON-CDH-03	
MIS-ELON-ADCS-16	The ADCS shall cost no more than [TBD].	Analysis	X	MIS-ELON-27	Not really an issue

ID	Wording	Verification	Status	Dependencies	Comments
MIS-ELON-TCS-01	The TCS shall maintain the temperature of the Melonsat within [250K; 300K].	Analysis	X	MIS-ELON-10	Operational range of components
MIS-ELON-TCS-02	The TCS shall prevent a temperature gradient greater than [0.2K/s].	Analysis	X	MIS-ELON-10	Avoid thermal wear
MIS-ELON-TCS-03	The TCS shall inform the CDH to enter safe mode if temperature exceeds [305K].	Demo	X	MIS-ELON-21	Stop operations and prioritize survival
	~~The TCS shall measure no more than [TBD].~~				
MIS-ELON-TCS-04	The TCS shall weigh no more than [20kg].	Inspection	X	MIS-ELON-ME-12	The lighter the better
MIS-ELON-TCS-05	The TCS shall require a nominal power of no more than [10W].	Analysis	X	MIS-ELON-EPS-01	Peak power may differ
MIS-ELON-TCS-06	The TCS shall generate no more than [1MB] of housekeeping data every hour.	Analysis	X	MIS-ELON-CDH-03	
MIS-ELON-TCS-07	The TCS shall cost no more than [TBD].	Analysis	X	MIS-ELON-27	Not really an issue

ID	Wording	Verification	Status	Dependencies	Comments
MIS-ELON-EPS-01	The EPS shall provide all the electrical power needed during mission operations, as indicated by the SWaP-DC Budget.	Analysis	...	MIS-ELON-07	
MIS-ELON-EPS-02	The EPS shall distribute regulated electrical power to the other systems.	Test	X		
MIS-ELON-EPS-03	The EPS shall have sufficient battery capacity to provide power for two eclipses.	Analysis	X	MIS-ELON-07	
MIS-ELON-EPS-04	The EPS shall keep [25%] of its battery capacity in reserve at all times.	Test	X		
MIS-ELON-EPS-05	The EPS shall follow recommended depth of discharge of its batteries.	Analysis	X		See datasheet
MIS-ELON-EPS-06	The EPS shall inform the CDH of restrained power conditions, meaning battery voltage is low [TBD].	Demo	X		
MIS-ELON-EPS-07	The EPS shall inform the CDH of critical power conditions, meaning battery voltage is very low [TBD].	Demo	X	MIS-ELON-21	
MIS-ELON-EPS-08	The EPS shall make use of power reserves to service emergency calls if necessary.	Demo	X		Saving a life is more important
MIS-ELON-EPS-09	The EPS shall make use of power reserves if necessary to the Melonsat's survival.	Demo	X	MIS-ELON-01/20	See risk analysis
MIS-ELON-EPS-10	The EPS shall measure no more than [TBD].	Inspection	X	MIS-ELON-ME-11	
MIS-ELON-EPS-11	The EPS shall weigh no more than [50kg].	Inspection	X	MIS-ELON-ME-12	The lighter the better
MIS-ELON-EPS-12	The EPS power electronics shall require a nominal power of no more than [TBD].	Analysis	X	MIS-ELON-EPS-01	Peak power may differ
MIS-ELON-EPS-13	The EPS shall generate no more than [1MB] of housekeeping data every hour.	Analysis	X	MIS-ELON-CDH-03	
MIS-ELON-EPS-14	The EPS shall cost no more than [TBD].	Analysis	X	MIS-ELON-27	Not really an issue

ID	Wording	Verification	Status	Dependencies	Comments
MIS-ELON-CDH-01	The CDH shall process communications intended for the Melonsat.	Demo	X	MIS-ELON-COM-07	
MIS-ELON-CDH-02	The CDH shall allocate resources within the Melonsat, notably time and energy.	Analysis	X	MIS-ELON-05 MIS-ELON-CDH-03/28	
MIS-ELON-CDH-03	The CDH shall collect maintenance data from all subsystems every [30min].	Demo	X	MIS-ELON-17	
MIS-ELON-CDH-04	The CDH shall store the average of maintenance data from the last [6months].	Demo	X	MIS-ELON-17	Might not be feasible without storing it all
MIS-ELON-CDH-05	The CDH shall store maintenance data of the past [7days].	Demo	X	MIS-ELON-17	Might change if MIS-ELON-CDH-04 changes
MIS-ELON-CDH-06	The CDH shall attempt to resolve issues that may come up during the mission, by rebooting the system if necessary.	Test	X	MIS-ELON-18	Demonstrate autonomy under failure Refer to risk analysis for some scenarios
MIS-ELON-CDH-07	The CDH shall switch to safe mode when it encounters a critical issue that could not be resolved as per req. MIS-ELON-CDH-06.	Test	X	MIS-ELON-CDH-06	Prevent further damage
MIS-ELON-CDH-08	The CDH shall initiate contact with the ground station after entering the safe mode.	Demo	X		Seek human help
MIS-ELON-CDH-09	The CDH shall ensure critical subsystems work when in safe mode.	Test	X		
MIS-ELON-CDH-10	The CDH shall execute commands from the ground station.	Demo	X	MIS-ELON-21	
MIS-ELON-CDH-11	The CDH shall get out of the safe mode when the issue in req. MIS-ELON-CDH-07 is resolved and commissioning checks have been passed.	Test	X		
MIS-ELON-CDH-12	The CDH shall use radiation hard components.	Inspection	X	MIS-ELON-01/09/20	
MIS-ELON-CDH-13	The CDH shall be implemented on an FPGA.	Inspection	X	MIS-ELON-CDH-12	FPGA is radiation resistant
MIS-ELON-CDH-14	The CDH shall have a dual core ARM processor operating at [50MHz].	Inspection	X		ARM is mobile friendly (ref. VA10820)
MIS-ELON-CDH-15	The CDH shall have [2GB] of RAM.	Inspection	X		RAM requires ~ 0.375W/GB
MIS-ELON-CDH-16	The CDH shall have [32GB] of Flash memory.	Inspection	X	MIS-ELON-CDH-03/04	
MIS-ELON-CDH-17	The CDH shall have a centralised architecture.	Inspection	...		
MIS-ELON-CDH-18	The CDH shall default to the use SpaceWire serial buses.	Inspection	X		IEEE 1355 tweak by ESA
MIS-ELON-CDH-19	The CDH shall run on a real-time operating system.	Inspection	X		RTOS for embedded systems
MIS-ELON-CDH-20	The CDH shall have a watchdog timer.	Inspection	X	MIS-ELON-CDH-06	
MIS-ELON-CDH-21	The CDH shall measure no more than [200mm x 200mm x 20mm].	Inspection	X	MIS-ELON-ME-11	Design for accessibility during assembly
MIS-ELON-CDH-22	The CDH shall weigh no more than [2kg].	Inspection	X	MIS-ELON-ME-12	The lighter the better
MIS-ELON-CDH-23	The CDH shall require a nominal power of no more than [10W].	Analysis	X	MIS-ELON-EPS-01	Peak power may differ
MIS-ELON-CDH-24	The CDH shall expect [7MB] of housekeeping data every hour.	Analysis	X	MIS-ELON-CDH-03	

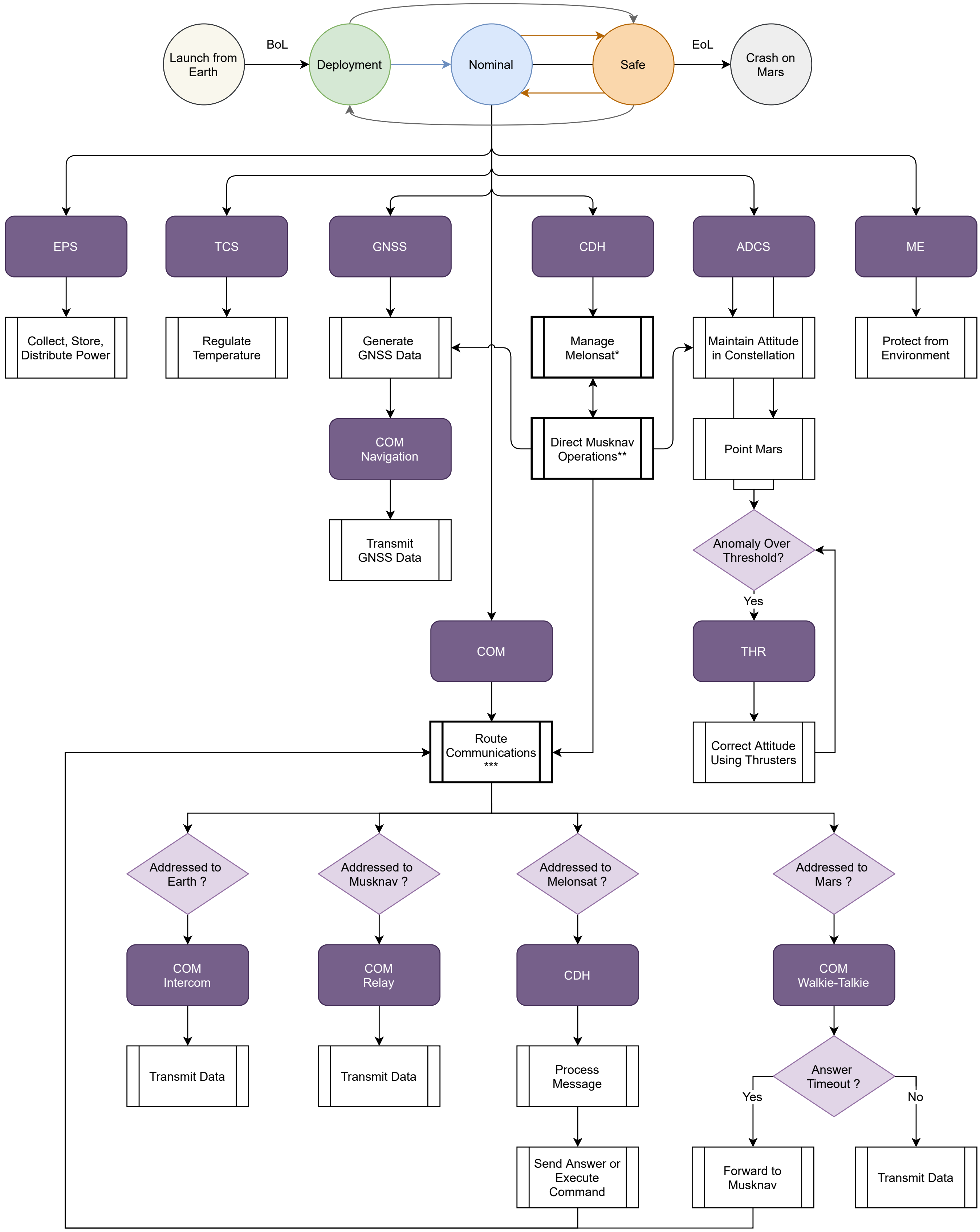
MIS-ELON-CDH-25	The CDH shall cost no more than [TBD].	Analysis	X	MIS-ELON-27	Not really an issue
MIS-ELON-CDH-26	The CDH hardware shall have double redundancy.	Inspection	X	MIS-ELON-20	Redundancy
MIS-ELON-CDH-27	The CDH software shall be reprogrammable from the ground station.	Demo	X	MIS-ELON-21	Failure management
MIS-ELON-CDH-28	The network of CDH shall coordinate the mission operations of Musknav using the COM and the ADCS.	Analysis	X	MIS-ELON-19	Necessary for autonomy
MIS-ELON-CDH-29	The network of CDH shall keep the almanac of the constellation up to	Demo	X	MIS-ELON-12	For GNSS and control purposes
MIS-ELON-CDH-30	The network of CDH shall compensate for the temporary loss of a Melonsat.	Analysis	X	MIS-ELON-22	When in safe mode for example
MIS-ELON-CDH-31	The network of CDH shall not change the configuration of the constellation if not commanded to do so by the ground station.	Analysis	X		Preserve fuel

ID	Wording	Verification	Status	Dependencies	Comments
MIS-ELON-COM-01	The COM shall have a fixed L-band patch array of antennas to use for navigation signals, referred to as Navigation antennas.	Demo	...	MIS-ELON-11/12	
MIS-ELON-COM-02	The COM shall have a steerable Ka-band patch array of antennas to use for interplanetary communications, referred to as Intercom antennas.	Demo	...	MIS-ELON-13/15 MIS-ELON-COM-06	
MIS-ELON-COM-03	The COM shall have two steerable X-band antennas to use for communications within Musknav, referred to as Relay antennas.	Demo	...	MIS-ELON-13 MIS-ELON-COM-05	Not patch array as it might have to move too much
MIS-ELON-COM-04	The COM shall have a fixed L-band patch array of antennas for communications on Mars, referred to as Walkie-Talkie antennas.	Demo	...	MIS-ELON-13 MIS-ELON-COM-05	
MIS-ELON-COM-05	The COM shall route communications with no [Earth] package header to the recipient, first through Walkie-Talkie and then through Relay antennas if necessary.	Demo	...		Header is there for efficiency, to be discussed with stakeholders
MIS-ELON-COM-06	The COM shall route communications with the [Earth] package header through the Intercom antennas.	Demo	...		Same as for MIS-ELON-COM-05
MIS-ELON-COM-07	The COM shall transmit communications intended for the Melonsat to the CDH.	Demo	...		
MIS-ELON-COM-08	The COM shall transmit the GNSS data through its Navigation antennas.	Demo	...	MIS-ELON-GNSS-03	
MIS-ELON-COM-09	The COM shall have a dedicated router capable of handling [TBD] communications at once.	Test	X		Technical characteristics TBD
MIS-ELON-COM-10	The COM shall be subject to special commands [TBD] coming from the CDH.	Test	X	MIS-ELON-CDH-28	Related to risk analysis
MIS-ELON-COM-11	The COM shall not be used for communications under restrained power conditions, even in emergency situations if other Melonsats can cover the service.	Demo	X		
MIS-ELON-COM-12	The COM shall not be used under critical power conditions.	Demo	X		
	~~The COM shall measure no more than [TBD].~~				
MIS-ELON-COM-13	The COM antennas shall weigh no more than [100kg].	Inspection	X	MIS-ELON-ME-12	The lighter the better
MIS-ELON-COM-14	The COM router shall weigh no more than [10kg].	Inspection	X	MIS-ELON-ME-12	
MIS-ELON-COM-15	The COM antennas shall require a nominal power of no more than [2000W].	Analysis	X	MIS-ELON-EPS-01	Peak power may differ
MIS-ELON-COM-16	The COM router shall require a nominal power of no more than [20W].	Analysis	X	MIS-ELON-EPS-01	
MIS-ELON-COM-17	The COM shall generate no more than [1MB] of housekeeping data every hour.	Analysis	X	MIS-ELON-CDH-03	
MIS-ELON-COM-18	The COM shall cost no more than [TBD].	Analysis	X	MIS-ELON-27	Not really an issue

MIS-ELON-COM-19	The communications going through Musknav shall use the BPSK coding scheme.	Analysis	...		To be discussed with stakeholders but this isn't really defined by Musknav
MIS-ELON-COM-20	The communications going through Musknav shall not exceed the link budget.	Analysis	...		Restrictions on other devices due to the physical limitations of Musknav
MIS-ELON-COM-21	The steering accuracy of the Intercom antennas shall be [±1deg], on all axis.	Demo	X	MIS-ELON-COM-02	Pointing knowledge given by ADCS
MIS-ELON-COM-22	The steering accuracy of the Relay antennas shall be [±2deg] on all axis.	Demo	X	MIS-ELON-COM-03	Pointing knowledge given by ADCS
MIS-ELON-COM-23	The COM shall allow for the data transfers expressed in the SWaP-DC Budget.	Analysis	X	MIS-ELON-13/14	Imposes requirements on satellite phones to be used on Mars

ID	Wording	Verification	Status	Dependencies	Comments
MIS-ELON-GNSS-01	The GNSS shall provide ephemeris data of the Melonsat.	Demo	X	MIS-ELON-11	
MIS-ELON-GNSS-02	The GNSS shall request updates on the almanac of Musknav from the CDH.	Demo	X	MIS-ELON-12	
MIS-ELON-GNSS-03	The GNSS shall send its ephemeris and almanac data to the COM.	Demo	...		
MIS-ELON-GNSS-04	Ths GNSS shall not be used under critical power conditions.	Demo	X		
MIS-ELON-GNSS-05	The GNSS shall have redundant atomic clocks.	Inspection	...	MIS-ELON-20	Navigation is key for Musknav
MIS-ELON-GNSS-06	The GNSS shall measure no more than [TBD].	Inspection	X	MIS-ELON-ME-11	
MIS-ELON-GNSS-07	The GNSS shall weigh no more than [30kg].	Inspection	X	MIS-ELON-ME-12	The lighter the better
MIS-ELON-GNSS-08	The GNSS shall require a nominal power of no more than [15W].	Analysis	X	MIS-ELON-EPS-01	Peak power may differ
MIS-ELON-GNSS-09	The GNSS shall generate no more than [1MB] of housekeeping data every hour.	Analysis	X	MIS-ELON-CDH-03	
MIS-ELON-GNSS-10	The GNSS shall cost no more than [TBD].	Analysis	X	MIS-ELON-27	Not really an issue

Annex System ConOps



* Manage Melonsat: Allocate resources, monitor subsystems and make sure it follows this ConOps. Jump to Safe Mode and back when problems arise.
** Direct Musknav Operations: Coordinate with the network of CDH to provide Musknav's services without the need for regulation by a ground station.

*** Route Communications: The router of the Melonsat is very tricky. It has to keep track of all communications to efficiently allocate ressources and not keep sending the same messages over and over, or when there's no answer from the receiving end. It won't keep the data to be transmitted, if there is no ACK from the receiving end, the communication will timeout and a new communication request has to be sent by the sender. The communication protocol employed should have a header indicating known devices/locations so the router can efficiently tell if a communication is destined to Earth, a Melonsat, or even to a frequent contact point on Mars.

Annex SWaP-DC Budget

Component [1]	Quantity #	Mass kg		Power W		Data Bytes/Day [2]		Cost $ [3]		Dimensions mm x mm x mm [4]		Shape — [5]
Structure												
> Custom Made Box	1	179.61 [6]	20%	–		–		??		2160x1440x1800	20%	box LxWxH
> Solar Panel Holders	–	84.77 [7]	20%	–		–		??		24928x48x1656 [8]	20%	frame LxWxH
> Sensors	??	0.35	15%	1	20%	3.60E+06	50%	24	20%	??		
Solar Cells & Batteries												
> CTJ30 - Thin	19,386 [9]	28.26	10%	4395 [10]	70%	–		??		69x39x5	5%	thin sheet LxWxH
> VES 16	292	49.77	10%	4671 [11]	30%	–		??		33x60	5%	cylinder DxH
Power Distribution												
> Sensors	??	0.69	15%	1	20%	3.60E+06	50%	24	20%	??		??
> Power Electronics	1	7.50	50%	30	50%	–		??		??		??
> Cables	–	67.15 [12]	30%	–		–		??		–		–
On Board Computer												
> FPGA	2	4.80	20%	24	20%	6.00E+09	100%	??		300x200x20	10%	box LxWxH
Heat Control												
> Coating	–	19.50 [13]	30%	–		–		??		–		–
> Heater	–	9.00	50%	1207 [14]	20%	–		??		??		
> Radiator (Louvers)	–	3.00	20%	5	20%	–		??		??		
> Sensors & Controller	1	1.04	15%	2	20%	3.60E+06	50%	24	20%	200x100x10	20%	??
Antennas												
> L-band (Navigation)	1	13.00	30%	174	10%	1.56E+06	20%	??		500x50	40%	patch DxH
> L-band (Walkie-Talkie)	2	26.00	30%	222	40%	2.88E+11	5%	??		500x50	40%	patch DxH
> X-band (Relay)	2	52.00	30%	19	20%	3.74E+11	5%	??		100x200	40%	cylinder DxH
> Ka-band (Intercom)	1	60.00	20%	625 [15]	40%	2.88E+11	5%	??		1190x500x50	10%	box LxWxH
Communications												
> Routers	2	24.00	20%	36	20%	9.49E+11 [16]	5%	??		300x250x70	20%	box LxWxH
> Steering Motors	2	1.80	20%	5	20%	–		??		50x50	10%	cylinder DxH
Attitude Sensors												
> ST-16RT2	2	0.48	20%	0.6	20%	1.94E+06	50%	308,000	10%	62x56x68		box LxWxH
> IMU & Others	??	0.69	15%	1	20%	3.00E-01	50%	24	20%	??		??
Attitude Control												
> RSI 12	4	17.76	20%	24	20%	–		??		222x85	5%	wheel DxH
> RIT µX	6	2.90	10%	330 [17]	10%	–		??		78x76	5%	cylinder DxH
> RIT 10 Evo	1	1.98	10%	500 [18]	15%	–		??		186x134	5%	cylinder DxH
> Drive Electronics	1	8.40	20%	30	20%	3.60E+06	50%	??		120x170x40	5%	box LxWxH
Propellant												
> Xenon	–	467.50 [19]	20%	–		–		437,117	10%	–		–
> Tank & Pipes	1	70.00 [20]	30%	–		–		??		??		oval AxPxH
GNSS Instruments												
> RAFS Clock	3	22.86	20%	46.2	10%	–		??		127x216x152	10%	cube LxWxH
> Signal Generator	1	6.00	20%	4.5	50%	1.67E+06	10%	??		127x216x50	15%	cube LxWxH
Total (estimation) with contingency	—	1477	20%	2674	20%	9.97E+11	5%	~150 million [21]	30%	–		–
		Weight	^	**P**ower	^	**D**ata	^	**C**ost	^	**S**ize	^	
							Contingencies (%)					
Galileo GNSS Satellites [2	1	675.00	kg	1900	W	256.00	its/msg	~40 million	$	2.7x1.2x1.1	m^3	cube LxWxH

[1] – Not applicable
?? Unknown

[2] Mostly based on requirements
3.6MB/day housekeeping
190GB/day communications - Musknav's greatest challenge, might not be possible with a different coding scheme etc. It's already not possible with current L-band tech to transmit this much data from Mars to Musknav

[3] Very little info without requesting quotes

[4] Estimates or datasheet

[5] Indicative for drawing

[6] Rule of thumb 30% dry mass

[7] Triple the mass of solar cells

[8] Deployed, includes body (end to end)

[9] (both sides)

[10] To exclude from sum for power need

[11] To exclude from sum for power need

[12] Rule of thumb 10% of dry mass

[13] Just a guess

[14] Seems off the charts but calculations seem to be correct too. Requires an in depth thermal analysis, quite a lot of uncertainty...

[15] Remove 50% from budget

[16] Total antenna data budget

[17] Remove 90% from budget

[18] Remove 90% from budget

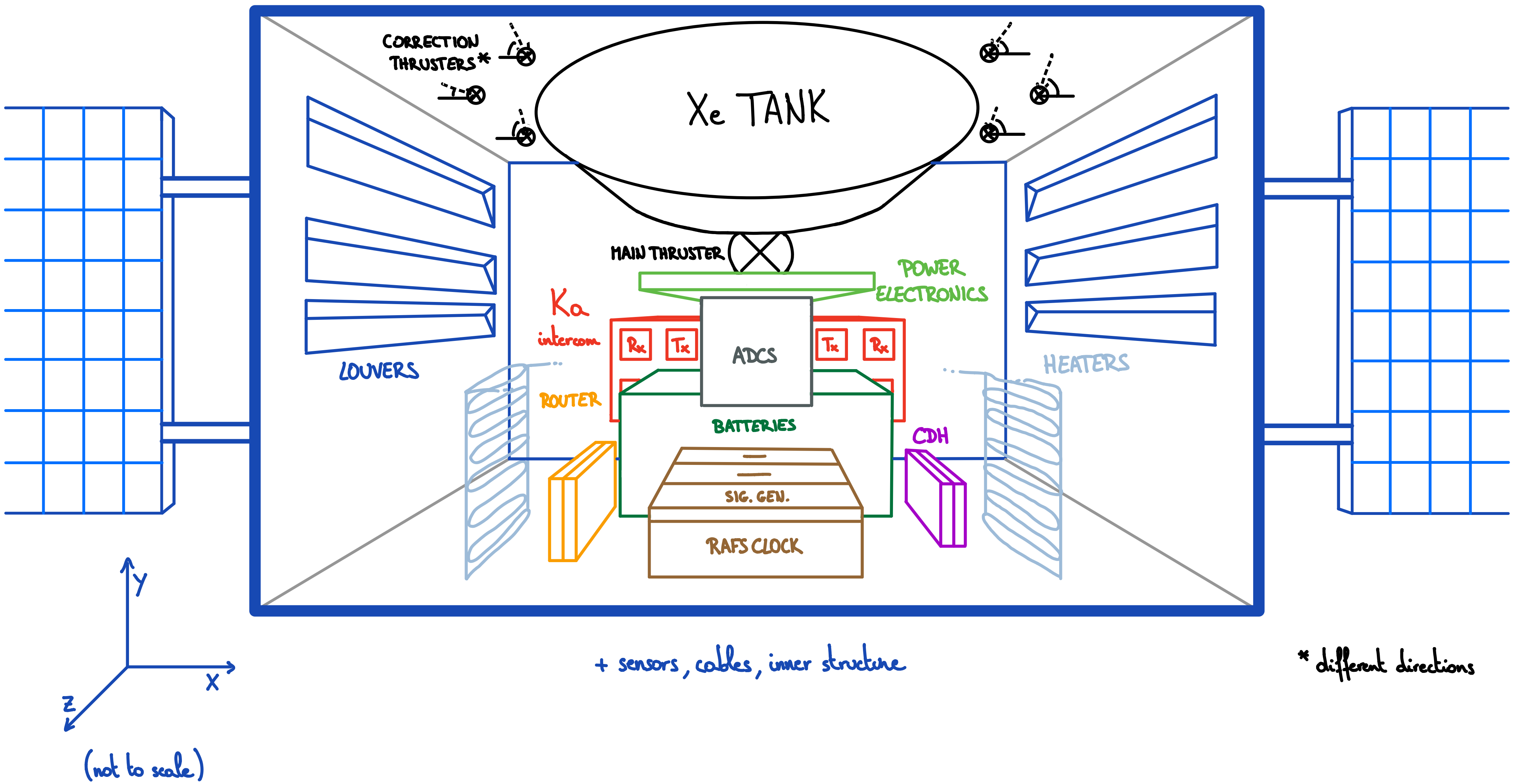
[19] To exclude from sum for dry mass

[20] Just a guess

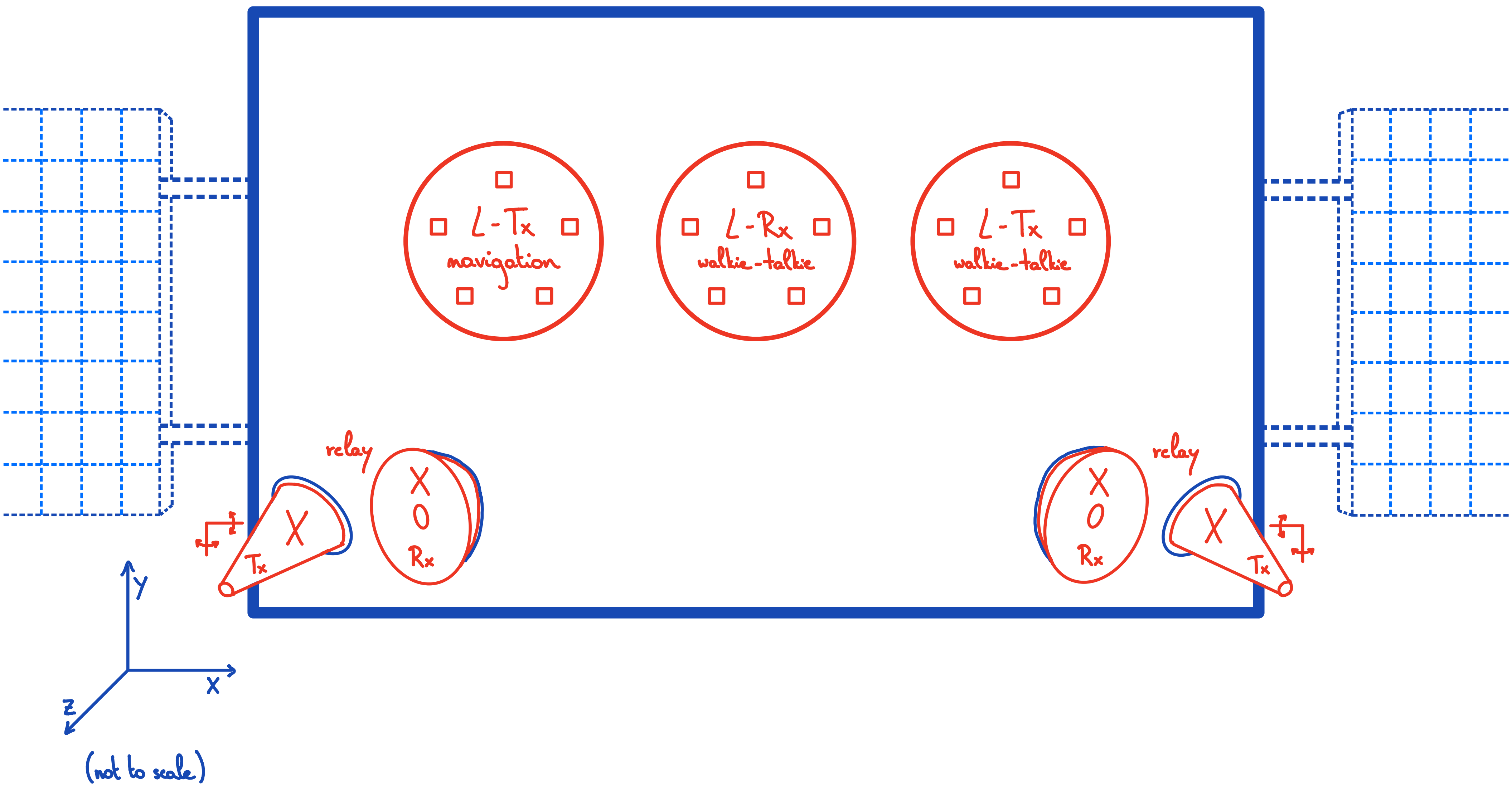
[21] Estimate based on Galileo, including launch/operations

[22] For comparison purposes (data not very useful as two different functions but size, weight and power seem to match)

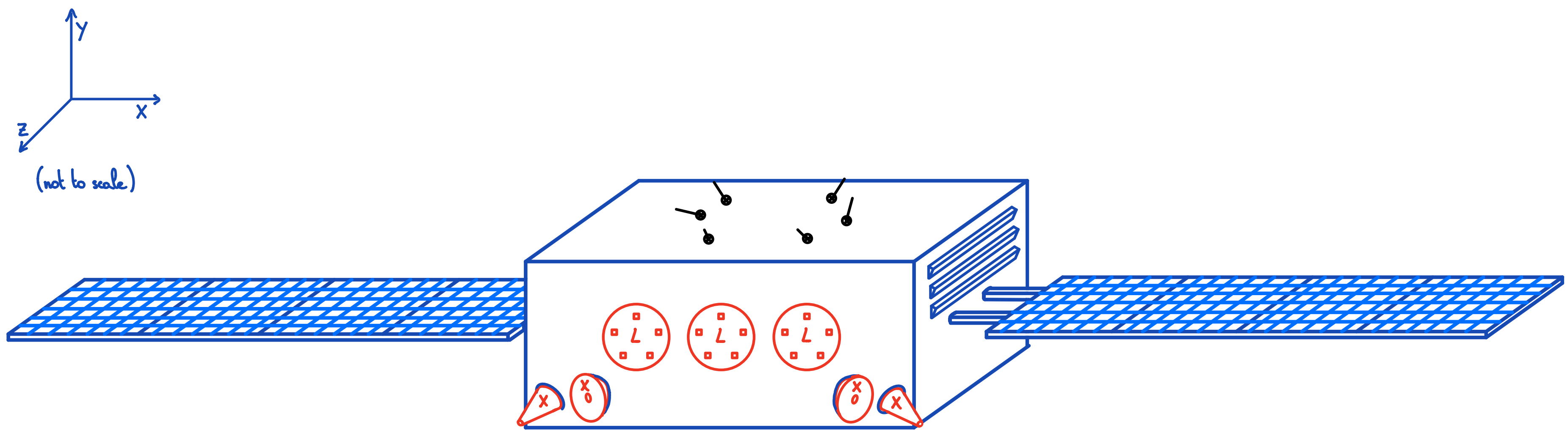
Annex Melonsat Design

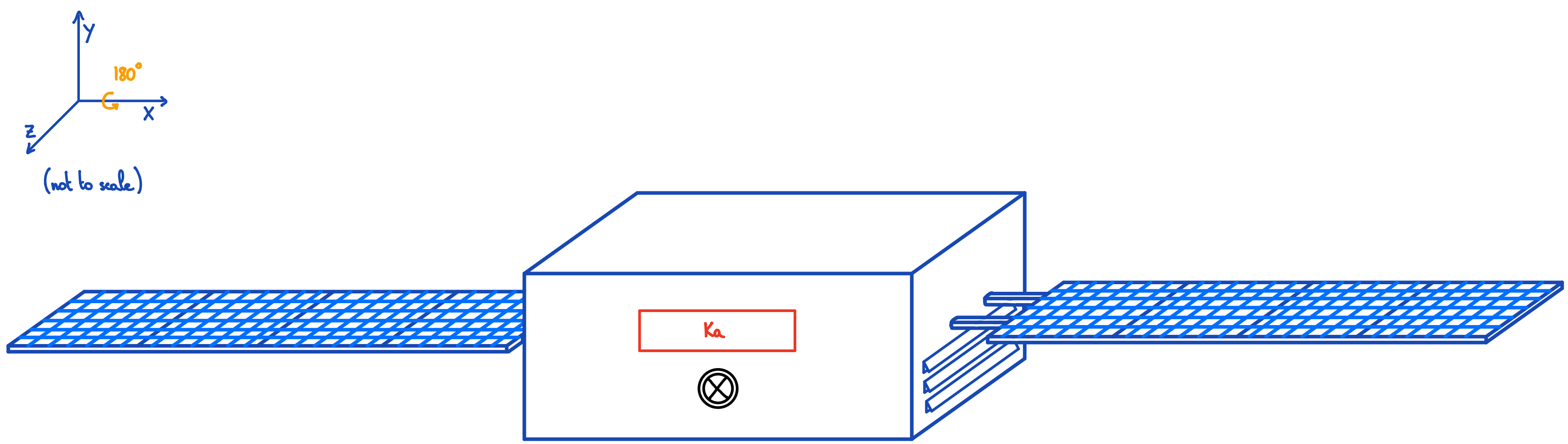


CORRECTION THRUSTERS*
Xe TANK
MAIN THRUSTER
POWER ELECTRONICS
Ka intercom
Rx
Tx
ADCS
Tx
Rx
LOUVERS
HEATERS
ROUTER
BATTERIES
CDH
SIG. GEN.
RAFS CLOCK
+ sensors, cables, inner structure
* different directions
Y
X
Z
(not to scale)



L-Tx
navigation
L-Rx
walkie-talkie
L-Tx
walkie-talkie
relay
Tx
Rx
relay
Rx
Tx
Y
X
Z
(not to scale)


Y
X
Z
(not to scale)
L
L
L
X
X
X
o
X
o


Y
180°
X
Z
(not to scale)
Ka

Annex Risk Analysis

Risk	Probability %	Consequence max 100	Severity max 100	**Mitigation** (if severity = 4+)
during preparation phase				
Lack of funding for the mission	80	100	80	None, accept fate or try other private investors
Substantial delay in mission start	80	5	4	Call off everything, reallocate resources at a later date
during execution phase			0	
Lack of funding during the mission	2	80	2	
Collaboration issues	15	30	5	Respect each other, look for another partner
Logistics issues	40	15	6	Anticipate various scenarios
Technology not ready yet	20	20	4	Delay mission
during deployment phase				
Launch vehicle related issue	2	50	1	
Launch survival	10	100	10	Follow all procedures and test rigorously to lower probability
Melonsat commissioning failure (antenna/solar panel deployment & system checks)	5	70	4	Attempt to troubleshoot spacecraft. Can use the others at proximity for communication. Accept partial operations if unsuccessful, e.g. relay satellite only.
Ballistic capture failure	40	70	28	Control the spacecraft trajectory at the expense of fuel and reduced mission operations lifetime. Use classical Hohmann transfers for future launches until model corrected
Orbital insertion failure	5	70	4	Correct orbit over time at the expense of fuel and reduced mission operations lifetime
Musknav commissioning failure	10	70	7	Attempt a commissioning for at least partial operations in solo, e.g. navigation (controlled from Earth then)
Problem with ground station (DSN)	1	50	1	
during nominal operations				
Lack of energy	5	80	4	Inform constellation, go into safe mode, orient solar panels towards the sun
Temperature regulation	15	40	6	Hot: shut down some operations. Cold: activate systems producing heat. Goal is to survive
Antenna not working	5	80	4	Use backup the other antennas try to reach ground station passing through the other satellites for troubleshooting. Accept partial operations if no solution
Communications router failure	5	100	5	Have a backup
Attitude determination failure	2	80	2	
Attitude control failure (thrusters/wheels)	5	100	5	Have backup system, use thrusters if wheels fail
Lack of gas before estimated end of life	10	70	7	Proceed to anticipated end of life
Structure degradation (radiation/impact/failure)	10	70	7	Accept reduced lifetime. Good choice of materials and shape before launch needed
Main computer failure	5	100	5	Have a backup
Atomic clock failure	10	60	6	Have backup, accept partial operations
Problem with ground station (DSN)	1	10	0	
Inability to deal with an internal failure	40	100	40	Go into safe mode and contact ground station for help
Inability to establish a fully operational constellation	10	70	7	Provide service to a select area on Mars
Constellation gets out of control	2	100	2	
Musknav cannot compensate for the loss of a Melonsat	5	40	2	
Message loss/corruption	10	20	2	
System overload	1	10	0	
Musknav failure in autonomous mode	10	50	5	Default to supervision from Earth
during safe operations				
Cannot establish contact with ground station	20	80	16	Establish contact through constellation
Failure when reprogramming CDH	5	100	5	Have a backup OS on board to default to upon reception of a specific command to be processed by the router
Problem with ground station (DSN)	1	80	1	

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