ORPHEUS MISSION

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Abstract
The Orpheus mission is an innovative series of small satellite constellations that will provide insights into the geodynamo within the Earth's outer core. Orpheus will continue on the dataset produced by SWARM until 2055 as well as complementing it by additionally providing measurements of the ionospheric current density. This additional current and magnetic field gradient data will provide corrections for the ionospheric day-side measurements.

The mission will be realised using 30 individual 12U CubeSats in 5 batches of 6 satellites launched over a period of 25 years. A new constellation of 6 will be launched every 5 years to replace those in orbit. These will fly in an augmented helix-cartwheel formation at 700 km altitude and 95° inclination. Each satellite will carry identical instrumentation on deployable booms providing isolation for state-of-the-art scalar and vector magnetometers. The instrumentation is supported by a bus which aligns with the expanding markets of standardised satellite components and with affordable smallsat launches to low earth orbit.

1. Introduction

1.1 Scientific Background

Knowledge of the Earth's core dynamics are imperative to understanding its magnetic field. Earth's magnetic field is vital for life as it serves to deflect the solar wind which would otherwise strip away the ozone layer. As such, modern day society depends heavily on the stability of the magnetic field, which is generated by a geodynamo operating in the Earth's outer core. Current physical models of the Earth's core dynamics use models of daytime disturbances in the ionosphere to remove the contribution of ionospheric currents to the magnetic field [1]. To further the state of the art, these models require verification and improvement of their accuracy through comparison with direct measurements [2].

The dynamics of the Earth's core are complex and changes in the magnetic field of Earth happen over centuries. The past 50 years of space-based magnetometry have clearly shown that continuation of magnetic field observation from space remains a high scientific priority [3]. Phenomena that occur as a result of core dynamics, which are not completely understood, include magnetic field polarity reversal, geomagnetic jerks and the South Atlantic Anomaly (SAA). Similarly, the core dynamics of other planets are not entirely understood. Studying Earth's core dynamics will not only provide insight into the planet on which the existence of humanity depends but also the source and evolution of the magnetic field of all planets.

More refined ground-based measurements over the past centuries have revealed variations in the secular acceleration of the magnetic field observed on time scales of months to years. These variations are called geomagnetic jerks and are a global phenomena observable at different locations at different times. Simulations exist that suggest that jerks are caused by the arrival of localised Alfvén wave packets radiated from sudden buoyancy releases inside the core [7]. This is a well-grounded hypothesis but is in need of experimental verification.

The SAA is a geographic region in which the inner Van Allen radiation belt comes closer to the Earth's surface which leads to an increased flux of energetic particles in the region [8] due to a local decrease in magnetic field intensity. The field intensity varies over timescales of decades to centuries, while the mainly steady westward drift is observable on a yearly basis [9]. A connection between the solar cycle and a brief eastward drift of the SAA has been proposed but it seems unlikely that the core is affected by the solar cycle and needs verification [10]. Regions of reduced magnetic field pose a challenge to satellite-based measurements since they are exposed to increased levels of radiation. It is therefore of interest to monitor the movement and intensity of such regions.

1.2 Past Missions

The Earth's magnetic field is a fingerprint of the complex dynamics of the Earth's core structure and merits detailed investigation. Past missions, including SWARM, CHAMP and Ørsted, have made magnetic field measurements which provided data resulting in accurate models for crustal and tidal fields [11] [12] [13]. However, few missions have been optimised for studying the core. By applying a curl $\vec{B}$ technique to the vector field data from SWARM, estimations of nighttime ionospheric current density have been made [4]. Orpheus proposes to measure the dynamics of the Earth's core and to estimate local current density in the ionosphere by measurement, using a tetrahedral configuration of satellites. This will allow for use of magnetic field measurements of the day-side ionosphere, increasing Orpheus' scientific return while enabling the re-analysis of past mission data.

1.3 Scientific Return

Earth's magnetic field can be described in terms of a spherical harmonic series expansion. In order to resolve core field dynamics, a higher order spherical harmonic degree is of interest. Orpheus is interested in spherical

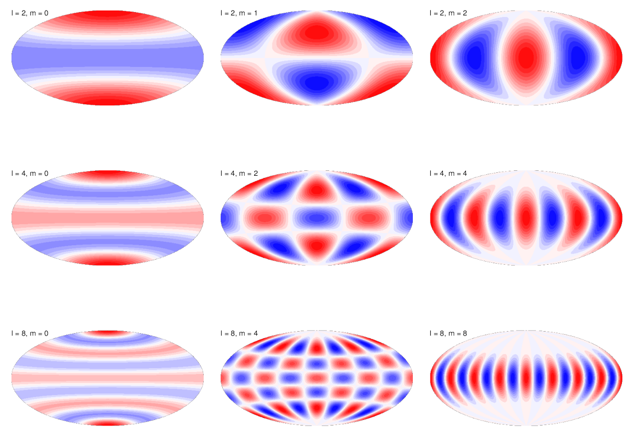

Figure 1. A visual representation of spherical harmonics for different orders. (University of Texas, Teaching: Spherical Harmonics (2019))

harmonics of degree $m = 25$ and to optimise the gain, a satellite separation between the chaser and the tetrahedron of 860 ± 60 km is desirable.

1.4 Mission Profile

The Orpheus mission has been designed to provide long-term, scalar and vector measurements of the geomagnetic field appropriate for core dynamo investigation. Orpheus proposes to measure the dynamics of the Earth's core and to estimate local current density in the ionosphere by measurement, using a tetrahedral configuration of satellites. This will allow for use of magnetic field measurements of the day-side ionosphere, increasing Orpheus' scientific return while enabling the re-analysis of past mission data. This unique mission involves five successive deployments of six identical satellites flying in formation in a near-polar Low Earth Orbit (LEO) at 700 km altitude.

2. Science

2.1 Scientific Questions

Studying the Earth's core magnetic field will contribute to answering the following scientific questions:

- Q1: How does the core magnetic field vary over long timescales?
- Q2: Is there a link between dynamic events in the geomagnetic field and core processes?
- Q3: What is the mechanism behind the magnetic polarity reversal?

Table 1. Allocated delta-v for one Orpheus satellite over a 5 year lifetime.

	Allocated Delta-v (m/s)	Fuel Mass - Butane (g)
Injection	54-68 (per satellite)	1188.77
Collision Avoidance	1	17.48
Formation + Station Keeping	40 (per satellite per year)	3500
Deorbit	51 per satellite	897.35
Total	320	5600

These questions have been broken down to achievable objectives for the Orpheus mission.

2.2 Scientific Objectives

The goal of Orpheus is to study the magnetic field of the Earth's core on a global scale in order to better understand its fine structure dynamics.

The science questions identified in the previous subsection have been quantified to produce the following scientific objectives:

SO-1: Provide state-of-the-art measurements of the fine structure and dynamics of the Earth's core over long time scales. This scientific objective shall help to answer science Q1 and Q2.

SO-2: Separate the contributions from various other magnetic field sources. This objective helps to answer all of the scientific questions previously mentioned.

SO-3: Study the ionospheric current system contribution to the total magnetic field. This scientific objective shall help to answer Q1.

SO-4: Characterise and link the core dynamics to dynamic events observed in the geomagnetic field (shorter time scale). This scientific objective shall help to answer Q3.

2.3 Scientific and Measurement Requirements

The following scientific requirements follow from the aforementioned scientific objectives.

SR-1: Measure all three components of the magnetic field vector with an accuracy of 1 nT using an instrument capable of measuring the magnetic vector field and be able to determine the instrument attitude with an accuracy of 0.1 degrees to precisely determine the magnetic vector field. Electromagnetic interference measured by magnetometers shall be lower than 1 nT.

SR-2: Measure the magnetic field magnitude with an accuracy of 0.3 nT. Vector field magnetometer and star trackers responsible for determining the VFM attitude shall be aligned to 1 arcsec.

SR-3: Earth's magnetic field shall be continuously monitored.

SR-4: Contributions from non-core internal fields, such as the mantle and the crustal field must be removable through measurement or mission configuration.

SR-5: Contributions from external fields, such as the tidal and ionospheric field, must be removable through measurement or mission configuration.

SR-6: The mission shall have a nominal duration of 25 years. Long-term monitoring of the magnetic field is necessary because core dynamics vary over long timescales. The solar cycle contributes noise to the external field. Therefore, measurements should last for at least two solar cycles in order to remove solar cycle contributions from our data.

SR-7: The system shall be able to measure the ionospheric current density in the vicinity of the satellite.

SR-8: The system shall have global coverage.

SR-9: The orbital revisit period shall be shorter than two weeks. Core dynamics have a lifetime of minimum 3 months; this revisiting requirement will permit the tracking of changes at specific locations.

3. Mission

3.1 Orbit Selection

The orbit selection has been driven mainly by the scientific requirements for the mission:

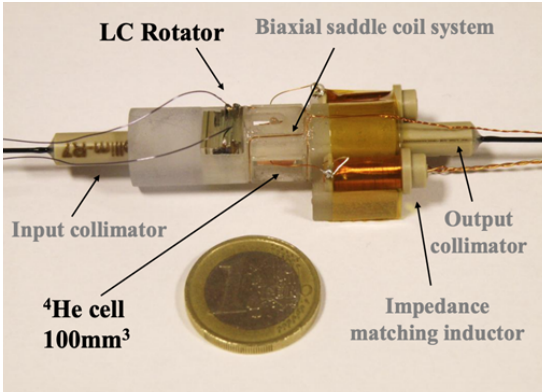

Figure 2. Optically pumped He magnetometer.

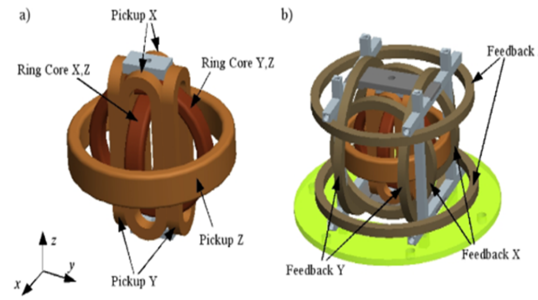

Figure 3. A THEMIS miniaturised fluxgate magnetometer.

- *Terrestrial global coverage* necessitated a near-polar orbit.
- *Low-altitude magnetospheric noise* defined a lower limit for the chosen altitude.
- *Revisit time limit of two weeks* constrained the inclination selection to non-SSO orbits.

The selected near polar orbit at a 700 km height and 95° in inclination ensures that all scientific requirements are satisfied, while also trading-off between environmental and engineering constraints such as the strength of orbital and attitude perturbations, the radiation environment, ground station coverage and launcher availability.

3.2 Formation Selection

The chosen formation, a helix-cartwheel (HC) augmented by leader and chaser satellites, has been selected from our scientific goals.

- *Investigation of the geodynamo* called for simultaneous measurements of the geomagnetic field at a inter-satellite spacing designed to resolve core structures captured around the twenty-fifth term of the spherical harmonic expansion [21].
- *3D magnetic gradient estimation* necessitated four satellites in close formation.
- *Ionospheric current estimation* led to the helix-cartwheel formation which enables a four-point measurement method pioneered by ESA's Cluster mission [17].

The configuration comprises of a relative spacecraft separation of 50 km within the HC formation (allowed drift 20-100 km). It also comprises of a baseline separation of 860 $\pm$ 60 km between the leader-cheaserspacecraft and the HC formation (allowable drift 800-920 km). This has been selected by performing trade-offs between station-keeping propellant consumption, measurements' resolution, and mission redundancy.

3.3 Constellation Deployment & Renewal

Considering the overall mission lifetime of 25 years and the durability limits of CubeSat platforms, a total of 5 launches is foreseen on a 5 year basis for refurbishment of the HC formation. The limited manoeuvring capabilities of CubeSat platforms and the non-standard orbit profile led to the selection of a single dedicated launcher for each satellite formation consisting of six spacecraft. In particular, the small launcher provider Rocket Crafters [22] has been selected based on their promised performance and flexibility. Following the launch from the Cape Canaveral complex and the baseline orbit insertion with the rocket upper stage, the six spacecraft will be deployed subsequently using standard launch adaptors sized for CubeSats. After solar panel deployments and commissioning of key subsystems, a series of successive manoeuvres will be performed for formation acquisition [24], including:

- A *reduction of mean eccentricity* for the four spacecraft in the HC formation.
- A *temporary change of inclination* to initiate a relative RAAN drift (inclination is restored once target offset is reached).
- The introduction of *offsets in the argument of perigee*.
- *Orbit phasing* to adjust the mean anomaly.

Table 1 summarises the Delta-V budget required to acquire the formation and compensate for differential gravity and drag effects as well as baseline orbit maintenance. Once the target lifetime of 5 years is reached, the current formation will be replaced entirely by a subsequent one and will reduce its baseline semi-major axis to accelerate its altitude decay, eventually reentering the atmosphere for disposal. However, a certain amount of measurement overlap at handover is foreseen to allow for payload commissioning while continuously collecting scientific measurements.

3.4 Ground Segment

As a scientific mission proposed by a European consortium, existing ESA infrastructure has been chosen as the baseline ground segment. The primary Orpheus ground segment will find its home in the Special Mission Infrastructure Lab Environment (SMILE) recently inaugurated at ESOC [18]. SMILE features the primary S-band antenna ESOC-1, the backup UHF antenna ESOC-1a, and an operational infrastructure well-suited for the Orpheus microsat architecture. In accordance with standard ESA procedures for Earth Explorers, data storage and dissemination will be overseen by ESA/ESRIN in close collaboration with project scientists.

4. Payload

In order to meet its scientific objectives, Orpheus' primary payload will consist of two state-of-the-art magnetometers: one to collect scalar measurements of magnetic field magnitude, the other to collect vector measurements of the magnetic field in three dimensions. Since these instruments will function in tandem, their specifications (mass, power, TRL, cost) were considered together as a payload system and can be found in the appropriate tables in the next section.

4.1 Scalar Magnetometer

The scalar magnetometer provides much more accurate measurements of the magnitude of the magnetic field, at the expense of the vector components. Looking to capitalise on technology developments since the construction of SWARM, we will be flying a significantly more volume efficient (two orders of magnitude) and lower mass instrument. The selected instrument is an optically pumped helium magnetometer under development at CEA Leti with a sensitivity of 10 pT/$\sqrt{\text{Hz}}$ and a bandwidth of DC to 100 Hz [10]. Such a magnetometer represents a miniaturised version of that which was flown on the SWARM mission.

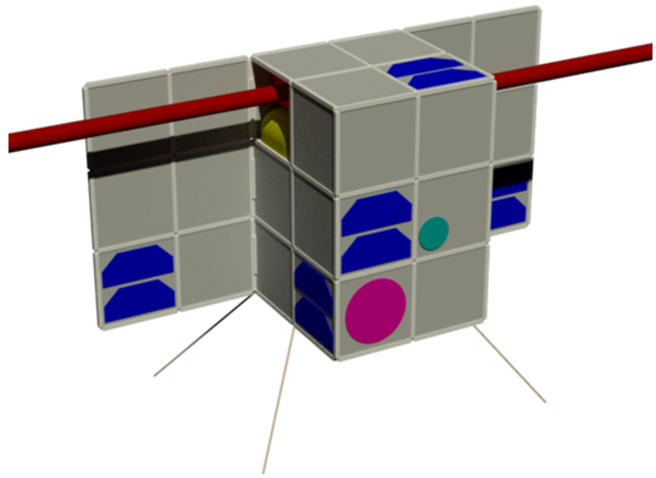

Figure 4. Spacecraft structure (back-side). Highlighted elements include: solar cells (blue), S-band antenna (magenta), star tracker (green), deployable booms (brown) and UHF backup antenna (bottom).

4.2 Vector Magnetometer

Our science requirements necessitate the measurement of the vector components of the magnetic field to an accuracy that tests the limits of current instrumentation. This has led to the choice of the state-of-the art THEMIS Fluxgate Magnetometer (FGM). The FGM will enable the mission to measure the vector component of the magnetic field to resolutions of 3 pT (24bit) with 10 pT/$\sqrt{\text{Hz}}$ of noise [23].

5. Spacecraft Design

After an iterative design process considering both instrument and mission needs, a spacecraft design was reached in line with the CubeSat standard of twelve units (12U): $20 \times 20 \times 30$ cm. This section introduces the various subsystems of the spacecraft platform and their suitability for the ultimate achievement of the Orpheus mission goals.

5.1 Structure & Mechanisms

The structure and mechanisms have been sized in line with the mass budget shown in Table 2 and have led to the spacecraft structure shown in Figure 4.

The achievement of our required measurement accuracy necessitates the use of booms to minimise magnetic disturbances from spacecraft electronics. Both magnetometers will be mounted on individual 1.2m deployable booms, protruding from opposite sides of the spacecraft.

Table 2. Mass budget for a single Orpheus satellite.

Subsystem	Total Mass (kg)	Margin	Final Mass (kg)
ADCS	0,464	5%	0,487
Electrical	1,545	5%	1,622
Payload	2,675	20%	3,210
Propulsion	7,500	15%	8,395
Structure	2,000	20%	2,400
Telecommunications	0,253	10%	0,278
Thermal	0,262	10%	0,288
Total Mass	16,68 kg		
System margin	20%		
Final mass	20,01 kg		

The first boom will deploy an instrument suite consisting of two star cameras and the vector magnetometer, while the second boom will host the scalar magnetometer.

The abundance of deployable components and sensors requiring an unobstructed field of view led to the selection of foldable solar panels, whose front side will be actively pointed towards the Sun. The chosen panel deployment system has space heritage and a high technology readiness level; however, alternative operational approaches are available in case of failed deployment as half of each panel will still be visible in its undeployed state.

5.2 Thermal

Nominal and critical temperature limits have been identified for all satellite subsystems and single node analysis was performed for the chosen 700 km orbit. First-order calculations approximate the worst case scenarios of 308 K for hot conditions and 242 K for cold conditions. As the cold case is beyond the operating conditions for various payload and platform components, extra insulation is required for key subsystems along with active heating systems in particularly susceptible areas. Power and mass budgets have been designed for tolerance towards these heating requirements.

5.3 ADCS & Propulsion

High-precision attitude determination is required for the high-precision manoeuvres which Orpheus needs to maintain its sophisticated satellite formation. Two orthogonally-aligned star trackers mounted alongside the vector magnetometer each provide single digit arc-second accuracy, allowing for accurate attitude knowledge to support vector magnetic field measurements. A third star tracker on the spacecraft's body provides redundancy and fine attitude determination before boom deployment. Finally, two sun sensors provide course pointing knowledge that can be utilised in safe mode.

The aforementioned orbital manoeuvres also require a high degree of attitude control which is provided by reaction wheels mounted in a standard pyramid formation. The wheels will be desaturated using magnetorquers which will also provide attitude control during safe mode.

For propulsion, a butane cold-gas thruster system has been selected based on our scientific requirements for mission duration and cleanliness of magnetic measurement. This is a proven technology developed at Surrey Satellite Technology [19]. While existing butane thruster systems are suitable, a tank redesign would be required to tailor existing solutions to fit size and pressure requirements imposed by our CubeSat constraints. This is accounted for in the TRL table (Table 4).

5.4 On-board Computing

The measurement requirement of a 1 Hz sample rate for all scientific instruments, leads to an expected daily scientific data rate of 11 Mbits per satellite, per day. Accounting for further data storage required for TT&C, other satellite sensors, and subsystems data, on-board storage did not emerge as a key design driver. After the inclusion of sufficient margin, 4 GB of onboard data storage has been specified.

5.5 Telecommunication / Link Budget

Spacecraft telecommunication will be performed using appropriate S-Band frequencies (downlink 1 Mb/s, uplink 50 Kb/s) or with UHF available for emergency communication (downlink 24 Kb/s, uplink 2.4 Kb/s). Downlink of all 6 satellites will be performed sequentially in one 11 minute pass every 5 days, transferring up to 24Mb of data per satellite. Such data requirements are well-suited for emerging small-sat groundstation solutions such as the recently opened Special Mission Infrastructure Lab Environment (SMILE) at ESA/ESOC in Darmstadt.

5.6 Power

Table 3. Power Consumption.

Operational mode	Total (W)	Total w/ margin (W)
Safe mode	11,18	12,66
Commissioning	23,53	26,926
Science	20,2	23,255
Orbital Maintenance	22,4	25,675
Telecom	21,58	24,586
Eclipse	19,05	21,933

The power budget seen in Table 3 has been designed considering power cycles in various operational modes, as well as peaks, efficiency, and panel degradation. Tolerant margins and power surplus allow for battery charging during sunlight hours. An area of $0.18m^2$ has been allocated for the main solar array with $0.134m^2$ of solar cell area. Solar cells have also been incorporated into every face of the satellite to sustain a minimal power production level in case of loss of attitude control.

5.7 Operational Modes

The spacecraft will transition between various operational modes as the mission timeline progresses:

- *Science Mode* is used for flux-gate and scalar magnetometer measurements. Star trackers will be active for fine attitude knowledge during data collection. Other subsystem activity will be kept to a minimum to avoid magnetic contamination.
- *Safe/Acquisition Mode* is used for detumbling after spacecraft deployment and in case of key system failures. Sun sensors and magnetometers provide coarse attitude determination and control to orient the solar panels towards the sun. Only key subsystems required for satellite re-acquisition and communication are active to minimise power consumption.
- *Orbital Control Mode* is used to perform attitude and orbital control manoeuvres for constellation maintenance, deorbiting, collision avoidance or other major orbital changes. Thrusters and reaction wheels are active and all scientific measurements are halted.
- *Commissioning Mode* is used for subsystem testing and deployment of solar panels and booms. All scientific instruments are subsequently activated for calibration (including magnetometers and star trackers).
- *Telecoms Mode* is used for ground station communication periods. Here the transceivers will be active and magnetometers deactivated.
- *Science and Heating Mode* is used for situations where low temperatures have become notably significant. Here the heaters will be activated for additional heating of key systems.

6. Project Envelope

The Orpheus mission as proposed is a long-term solution that necessitates long-term planning. This section details the schedule, technology development, and investment required to make Orpheus a reality.

6.1 Schedule

A mission development schedule of 3 to 5 years is foreseen to ensure the spaceflight readiness of all payload and platform components. This schedule will allow for further constellation and formation analysis while also giving boom and magnetometer technologies time to mature. As magnetic cleanliness is a key mission consideration, the schedule allocates a full year towards a magnetic cleanliness programme which is foreseen to include component-level testing using the engineering laboratories at ESA/ESTEC.

6.2 Technology development

As evident in Table 4, Orpheus has been designed with high-TRL components in mind. The entire spacecraft bus is TRL 7 or higher thanks to the Cubesat-compatible architecture. Our only mid-TRL component is the deployable boom/magnetometer assembly. The boom itself is currently the subject of intensive development by Oxford Space Systems [16] and is anticipated to reach full maturity by our planned 2030 launch date, while sufficient time for design and test of the complete assembly has been accounted for in our program schedule.

Table 4. Technology Readiness Levels.

Subsystem	TRL
ADCS	7-9
Electrical	7-9
Payload (excl. Scalar Magnetometer)	6-9
Scalar Magnetometer	4
Propulsion	6-9
Structure	7
Telecommunications	7-9
Thermal	7-9

Table 5. Cost breakdown (million euros).

	NRE + 5RSC
Subtotal, one formation	29.90
Subtotal + 20% margin	179.40
Program Management	9.00
Operations and Ground Segment	10.00
Science Operations	9.00
Launch	27.00
20% contingency	46.88
ORPHEUS TOTAL	**281.28**

6.3 Risk

A risk evaluation exercise has been undertaken for Orpheus and resulted in the identification of seven distinct risks to schedule, payload, spacecraft, cost, and ultimately, mission. For all risks, appropriate mitigation measures were identified; the most serious risks are presented here for future consideration.

One of the major risks for Orpheus is a delay in our initial or subsequent launch due to the unavailability of the chosen launch option, Rocket Crafters. The primary mitigation of this risk is our anticipated launch date of 2030, by which time we expect Rocket Crafters or one of their many competitors [15] to offer a competitive option for smallsat insertion into LEO. This risk will be further mitigated by providing sufficient overlap with the anticipated extension of Swarm and sufficient handover between our own constellation deployments.

Other risks of note include the "dead-on-arrival" (DOA) failure common to cubesats [14] and a failure in the deployment of our mid-TRL boom. Both risks will be mitigated through extensive test campaigns and the use of a formation-based mission architecture where scientific value is not completely lost when one spacecraft is compromised. In addition, the DOA failure will be mitigated by the inclusion of an omnidirectional low-bandwidth antenna for emergency use.

6.4 Cost & Descoping Options

A subsystem-level cost breakdown can be seen in Table 5. In accordance with this breakdown, the twenty-five year mission plan will cost slightly less than 300 million euro (FY2019), providing excellent scientific return for the cost of a single medium-sized Earth Explorer.

Should cost become a critical point mission implementation, various descoping options are available. The simplest means of cost reduction is the reduction of satellites in space, impacting either mission lifetime, in-orbit redundancy, or handover period depending which satellites are descoped. These impacts could be counteracted by accepting gaps in the scientific data which would not impact the long-term goals.

6.5 Outreach

As a publicly-funded mission, Orpheus will feature a sustained outreach campaign to magnetise public interest. Of particular note is the opportunity to engage with ESA Education programmes, as magnetometers are a common instrument on student payloads within the CanSat, REXUS/BEXUS, and Fly Your Satellite programs. Orpheus experts can serve as student mentors, students can compare their data with that collected by Orpheus, and promising students will be able to intern within the Orpheus science and mission operations teams.

7. Conclusion

The proposed Orpheus mission represents a long-term solution to provide continuous magnetic measurements using an orbit formation designed to focus on the geodynamo within the Earth's core. The combination of the presented mission, payload, and platform will provide the scientific community with accurate measurements over a poorly explored region of our planet. Considering the large volume of gathered data and its high accuracy, we are confident that the results of this mission will prove of great scientific merit for years to come.

Team Orange would like to thank our organisers, tutors, lecturers, and our peers for everything they have done in support of this tremendous learning opportunity and for all the new knowledge and friendships we have gained along the way.

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