Research for and Early-Stage Development of the First Interstellar CubeSat Powered by Solar Sailing Technology

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Abstract

Project Svarog is a student-led initiative aiming to reach the heliopause using a solar sail [1]. The sail is set to be passively stabilised and does not require gravity assists unlike previous interplanetary missions, thus making deep space exploration more feasible and flexible. Previous feasibility studies have been performed, demonstrating the potential of the mission and highlighting research focus. A high-fidelity orbital model has been developed for proving the feasibility of the trajectory and studying initial conditions. Currently, Scientific Machine Learning [2] is being implemented to study the optimal initial conditions, parameters, and the sensitivity of the trajectory with respect to those properties of the system. Initial studies show that the escape trajectory is feasible for a mass to area ratio of 12 g m^{-2}. Given the repeated close passes to the Sun, the long duration of the mission, and its sensitivity to solar events, understanding and modelling the space environment for the duration of the mission is paramount. So far, preliminary simulations of radiation dose received by the spacecraft using GRAS [3] coupled with data driven model of solar activity have been performed. Structural simulations from an in-house code which uses multi-particle model have been compared with commercial packages and paired with vacuum chamber testing for validation. Following the IKAROS team research and analysis [4], we have now developed non-dimensional analysis which will enable scaling of sail dynamics to reduce number of required simulations and enable conducting experimental validation of sail behaviour under influence of gravity. Mechanical and electronic design and prototyping have been undergoing in parallel with the research endeavours. These have made testing of deployment methods and communications architectures possible. A motor-controlled boom deployment is being studied in parallel with the flight proven spinning method [5]. Should these technologies be successful, the Svarog system could serve as a low-cost enabler for the testing of new technologies and research opportunities in deep space, piggybacking of the increasing number of interplanetary missions and fostering deep space exploration.

Keywords: Deep Space, CubeSat, Solar Sail, Orbital Mechanics, Structural Design

Nomenclature

B	bit rate
c	speed of light
E	energy
$F, F*$	mass, characteristic scale
FEM	Finite Element Model
G	antenna gain
I	mean excitation potential
k, K	stiffness, characteristic scale
k_B	Boltzmann constant
l	length
L	Lagrangian
m, M	mass, characteristic scale
n	number of particles
N	noise
P	power
r	radius
t	time
T	characteristic timescale/temperature
x, y, z	position
X	characteristic lengthscale
z	charge of particle
α, δ	Euler angles
β	v/c
γ	Lorentz factor
λ	wavelength
Ω	spin rate

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Superscripts

'	nondimensional time derivative

Subscripts

0	initial condition
i	i^{th} element
e	electron
k, p	energy type
n	noise
r	receiver
t	transmitter
x, y, z	spatial coordinate type

1. Introduction

High delta-V maneuvers are imperative for deep space exploration by the human race. They were usually conducted during missions based in the Outer Solar System, such as the Pioneer probes, both Voyagers and New Horizons. These missions provided vast amounts of data regarding the gas giants and Pluto, and currently, as they are escaping the Solar System, they will provide data on the properties of interstellar space. Similarly, considerable changes of momentum are required to go into orbits within the solar corona or out of the ecliptic plane. The former is of particular interest to the scientific community to properly build weather and climate models for the Sun. There has been no attempt at such orbits since the Ulysses mission, despite the need for data about the solar poles.

Such maneuvers were usually conducted using gravity assists from other celestial bodies encountered throughout the trajectory. While this approach achieves a high delta-V, it requires careful selection of the launch date and orbit to enable a sufficient change in velocity. As an alternative to the gravity assist approach, on multiple occasions solar sailing has been suggested. Project Svarog has been developed to take advantage of this technique in a novel approach, where a passively stabilized sail is accelerated purely by solar radiation and is capable of conducting maneuvers which go beyond the capabilities of both chemical and electric propulsion.

To achieve this goal, numerous aspects of the mission need to be matured and solutions to the various problems need to be suggested. The main difficulty associated with passively stabilized sails is the presence of disturbing torques due to the non-uniformity of the surface. This results in significant coupling between the structural dynamics and the orbital mechanics of the system. Beyond that, the dynamic deployment of the sail is a complex process to model, which in this paper is tackled both from a theoretical and an experimental point of view. Furthermore, to establish communication with the ground, a sufficient link budget must be provided in the design of the onboard transmitter. Finally, as the predicted duration of the mission is in the order of decades, sufficient consideration for environmental effects should drive the design process. The main focus of this paper is to present the approach taken by Project Svarog to design a mission within these constraints and provide solutions to challenges encountered in the process.

2. Mission Concept and previous work

Passively stabilised solar sails are a prominent area of research at Imperial College London. The initial trajectory analysis for such missions was conducted by Hotston-Moore and Knoll in 2019 [6]. Since the current development is being undertaken by a student society (Imperial College Space Society), great consideration is made for the affordability of the mission. Thus, the launch trajectory is designed to start as a piggyback mission to Mars or Venus. From the conducted simulations, it was determined that selecting a transfer trajectory to Venus results in a considerably lower time required to reach escape velocity from the Solar System. After deployment, the spacecraft is then spun for stability, in the orientation determined to be optimal for achieving a minimum time to heliopause under the given constraints. Preliminary trajectory design can be performed by considering the average perturbation along the orbit depending on the selected initial angle with respect to the Sun's incoming radiation.

Initial work towards a systematic orbit investigation was done in 2020 by Filippos [7] using GMAT to propagate different mission profiles. This provided a deeper insight into the constraints related to the mission regarding its temperature requirements, ranging constraints and the validity of pre-existing models. From these studies, and a comparison against flight data from the IKAROS mission, it was determined that an investigation of the full six degree-of-freedom motion of the spacecraft is essential for the success of the mission, as solar radiation torques create a non-negligible perturbing effect on the sail's rotation.

This aspect of the mission became the main focus of the design team over the span of 2021 and 2022, while the orbital mechanics team focused on developing methods for solving the coupled equations of motion for the spacecraft and quantifying the uncertainties of the orbit due to perturbations resulting from attitude changes. In parallel, the structural mechanics team focused on developing numerical models of the membrane as well as an experimental setup, which would be used for testing membrane dynamic behaviour under conditions of

Earth gravity and provide a means for validating the numerical models. Initial results of this investigation were published in the Journal of the British Interplanetary Society [1]. From that point onward, improvements were made both from theoretical and experimental perspectives. A brief overview of these areas will be presented in this paper.

In its current state, the mission is focused on developing a spacecraft capable of achieving an escape velocity and demonstrating this through received telemetry. The primary objective of the project is stated as *"Construct a spacecraft that will reach the Sun's escape velocity and the heliopause (assumed at 123 AU from the Sun) within 100 years from launch by using solar sail technology."* [1].

Secondary objectives, mainly dictated by the scientific requirements of the mission, are defined as: 1) *"Measure the trajectory of the craft up to 10 AU from the Sun and validate it against theoretical models"*, 2) *"Get a visual confirmation of deployment"*, and 3) *"Carry a payload representing human ingenuity on board"* [1].

3. Mission Development

3.1. Orbital Mechanics

The orbital feasibility of the trajectory has previously been studied by Fil et al., Hotston-Moore, and Geragidis [1, 6, 7] using MATLAB, Python and GMAT. For more detailed analysis of the coupling between the spacecraft's attitude and trajectory, a re-derivation of the six degree-of-freedom solar radiation pressure model introduced by Tsuda et al. [8] was implemented in quaternion notation with specifications given in Project Svarog's first paper [1]. The new derivation incorporated gravitational forces from nine bodies using general relativistic (GR) corrections, and currently, the effect of plasma drag is being studied using environmental simulations.

The first test to be carried out on this model was a feasibility study. After several manual trials it was noted that the heliopause could be reached within 100 years for a mass to area ratio of 12 gm^{-2}, which increases the previously known limit by 33%. The first 37 years of the trajectory and energy for such a mission is given in Fig. 1 and 2. The maximum mass to area ratio on the sail could however be increased by choosing suitable initial conditions, and for this, an optimisation code using Scientific Machine Learning [2] is currently being developed. The mission time span constraint as well as a temperature constraint needs to be applied, with the optimisation goal being set to maximise payload mass and the free parameters taken as the initial attitude.

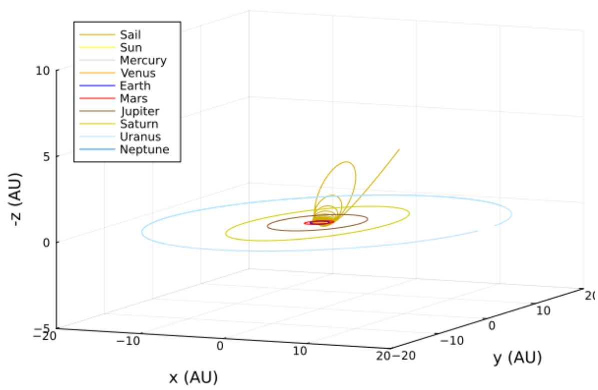

Figure 1: Potential trajectory of the sail in the first 37 years.

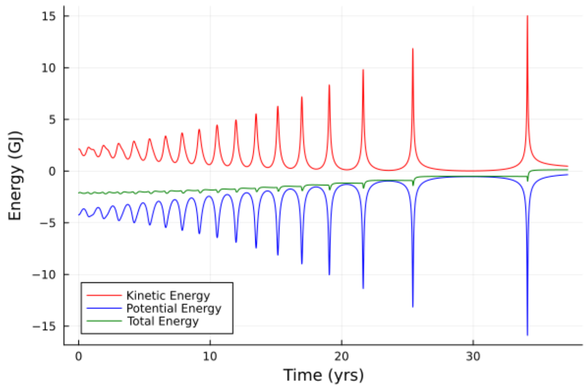

Figure 2: Plot of the energy of the sail in the first 37 years.

From the initial trajectory tests it was also noted that the system is highly non-linear, so an initial global sensitivity analysis using the Morris method [9] was conducted. The sensitivity of the trajectory with respect to the initial conditions was noted, and the mean sensitivities of the results are presented in Table 1. Firstly, it can be noted that the system is highly sensitive with respect to its initial conditions, which is to be expected given the non-linearity of the system. Moreover, the initial attitude of the sail has a particularly large impact on the trajectory. This has the advantage of allowing higher control over the trajectory by slightly altering the initial parameters, but also has the disadvantage of increasing the risk of mission failure if the initial attitude is perturbed due to deployment uncertainties. To estimate the likelihood of such risks, it would be useful to study the timescale at which the system becomes chaotic. It must also be noted that the Morris method provides a simple measure of global sensitivity that is based on individual variations. But it does not take the coupling between variables and non-linearities into account, which in this case, play an important role. Thus, the results of this study should only be used to get a qualitative understanding of the sensitivity of the system with respect to its parameters, and does not necessarily provide any useful quantitative measure for the global sensitivity. This quantitative analysis is a point of further study, perhaps using methods such as the Sobol method [10].

Table 1: Sensitivity of the the final orbital radius with respect to initial conditions.

Independent variable	Mean sensitivity
x_0	0.069 AU/m
y_0	0.50 AU/m
z_0	-0.38 AU/m
$v_{x,0}$	-30 AU/(m/s)
$v_{y,0}$	-22 AU/(m/s)
$v_{z,0}$	-1.1 AU/(m/s)
α_0	-390 AU/rad
δ_0	38000 AU/rad
Ω_0	-490 AU/(rad/s)

Moreover, tests were also conducted to evaluate which terms in the acceleration of the sail had the lowest impact on its trajectory. The term which was most notably small was the GR correction since the relative differences of the state vector after 34 years were on the order of 1e-5 when comparing the case with and without general relativity. Nevertheless, due to the high sensitivity of the trajectory with respect to its states, neglecting this term could still impose highly inaccurate results. This could potentially be tested using a bifurcation analysis.

3.2. Structural Mechanics

In the case of this mission, the orbital mechanics of the spacecraft can not be solved without careful consideration of its structural behaviour. Due to interactions with the environment, the shape of the structure becomes deformed. Thus, torques due to the solar radiation pressure act as the main perturbation in attitude motion. The modelling of the structure, while can be simplified to an analytical case for circular sails, requires the use of numerical methods such as multi-particle models or shell dynamics solutions in FEM software such as ABAQUS [11]. Additionally, to conduct experimental testing, non-dimensional equations of motion need to be considered, so that it is possible to scale down the tested sail and use gravity to represent solar radiation pressure.

To turn the equations of motion into a non-dimensional form, an approach suggested by Suzuki [12] is used as a basis for the derivation. In this paper, a more systematic approach is used to determine the interactions between various elements of the spacecraft. Thus, further insight is gained into several aspects, such as attaching masses to better manage the deployment process and experimentally validating the requirements for a full scale attachment. To build the system of equations, the time and length scales first need to be normalized with respect to some characteristic parameter. For distance, the length of the sail in a flat configuration is taken and for time, the period of one rotation is taken. Then, the dimensional quantities can be expressed as Eq. (1) and Eq. (2).

$$t = T\bar{t} \tag{1}$$

$$x = X\bar{x} \tag{2}$$

Using the new non-dimensional coordinates, the dynamics can be determined by considering the Lagrangian of the system and solving the Euler-Lagrange equation with an external perturbation to model the forces acting on the sail. For the comfort of the reader, the sail will be considered as spring-mass system, which makes the formulation of the tension field easier to use. The derivation begins by scaling the forces with respect to the pressure multiplied by the area of the sail. Secondly, it follows the derivation of the equation of motion from the Lagrangian using Eq. (3) (4) (5) (6).

$$L = E_k - E_p \tag{3}$$

$$\frac{d}{dt}\frac{\partial L}{\partial \dot{x}_i} - \frac{\partial L}{\partial x_i} = F^*\bar{F}_i \tag{4}$$

$$E_k = \sum_{i=1}^{NODES} \frac{1}{2} m_i \dot{x}_i^2 \tag{5}$$

$$E_p = \sum_{i=1}^{EDGES} \frac{1}{2} k_i (|x_{i1} - x_{i2}| - l_i)^2 \tag{6}$$

Then, both mass and stiffness constants can be non-dimensionalised so that Eq. (7) (8) (9) (10) can be used

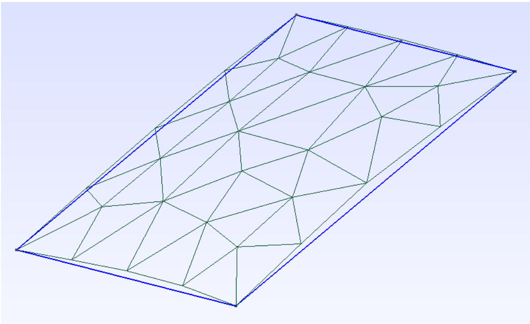

Figure 3: Visualization of sail modeled using the particle-spring system approximation.

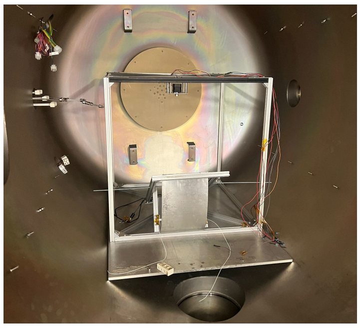

Figure 4: Photo of the experimental setup.

to find an equation of motion with the non-dimensional groups.

$$E_k = \frac{MX^2}{T^2} \sum_{i=1}^{NODES} \frac{1}{2} \bar{m}_i \bar{x}_i'^2 \tag{7}$$

$$E_p = KX^2 \sum_{i=1}^{EDGES} \frac{1}{2} \bar{k}_i (|\bar{x}_{i1} - \bar{x}_{i2}| - \bar{l}_i)^2 \tag{8}$$

$$\frac{d}{Td\bar{t}} \frac{\partial}{\frac{X}{T}\partial \bar{x}_i'}(E_k - E_p) - \frac{\partial}{X\partial \bar{x}_i}(E_k - E_p) = F^* \bar{F}_i \tag{9}$$

$$\frac{MX^2}{T^2} \bar{m}_i \bar{x}_i'' + KX^2 \sum_{j=1}^{NEIGH} \frac{\bar{x}_j - \bar{x}_i}{|\bar{x}_j - \bar{x}_i|} k_i (|\bar{x}_j - \bar{x}_i| - \bar{l}_i) = XF^* \bar{F}_i \tag{10}$$

In the final form of the equation, two dimensional groups can be identified, and experiments can now be designed by varying the mass, stiffness, size, spin rate and external forces.

From this derivation, it is evident that the non-dimensionalised dynamics at each node must be identical for all experimental cases. If only the membrane is considered, then scaling for the main features in a gravitational and pressure field is exactly defined, but for tip masses, it is considerably more complicated to properly match spin rate and gravity to model the actual physics. An initial simulation of the results for a validation case are presented in Fig. 3, where the model of the sail is attached at the corners.

This treatment can be easily expanded to membrane elements from ABAQUS and the current focus of the structural mechanics team is to generalize this approach to shells of finite thickness. While the ABAQUS solution offers higher quality results, for the purpose of keeping within the timeline of development it is more feasible to use a particle model to capture the dynamics of the membrane for shape estimation coupled with the solar radiation pressure effect in the orbital model.

3.3. The Vacuum Chamber Experiment

To validate the described numerical models, an experimental setup for spinning membranes in a vacuum was designed. The main aim of the experiment is to analyse the dynamics of spinning sails under gravity, in an arrangement based on non-dimensional analysis which should simulate solar radiation pressure acting on a full scale sailcraft. The test rig is composed of a hexagonal truss structure, with corners reinforced with metal plates to prevent damaging vibrations under the action of the electrical motor. Over the course of the experiments it was proven that, for extreme cases, the sail and frame might resonate, which could lead to damage of the equipment inside of the vacuum chamber. The size of the test rig is 0.67m in each direction and was dictated by the dimensions of the Boltzmann vacuum chamber at the Imperial Plasma Propulsion Laboratory, where the experiments were conducted.

To spin the sail, a BLDC motor was used, which has the advantage of being able to apply a rotation rate profile corresponding to a torque profile applied to the central hub of the spacecraft during the deployment process. This requires implementing a PID controller, which sets the torque by measuring currents and controlling the associated voltages. Due to the inductive term associated with the motor present in the system, there is a phase mismatch between the current output and voltage input, which might lead to instability in the control system. To account for this, the controller requires the implementation of a differential term, as the voltage generated by the inductor is proportional to derivative of current. In the hardware implementation,

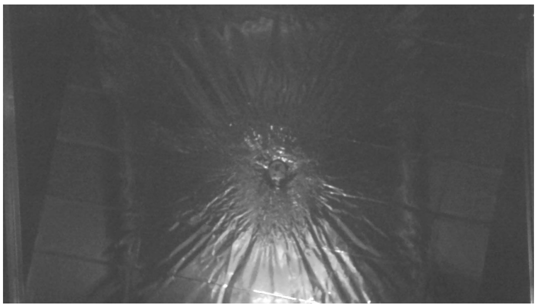

Figure 5: Buckled sail structure at spin rate of 400 RPM.

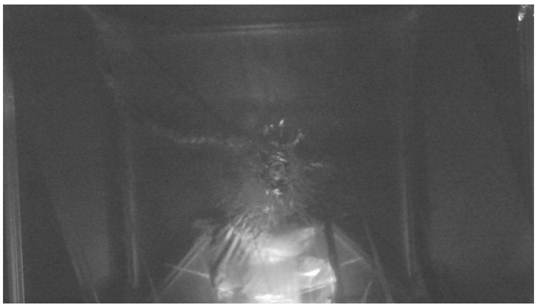

Figure 6: Stiffened sail structure at spin rate of 850 RPM.

a SimpleFOC running on B-G431B-ESC1 was used as the controller of the BLDC motor. Each motor requires careful tuning of control gains to match its characteristics, as depending on the manufacturer, different transient responses can be encountered.

The deflection of the sail was planned to be measured using a stereoscopic vision camera. For this purpose, a dual camera setup from Arducam, which used a common trigger, was designed to be used. Unfortunately, most likely due to the static discharge inside of the chamber, one of the cameras malfunctioned and due to tight time and budget constraints a backup camera was unavailable. Due to this fact, insight obtained from the experiments is more qualitative than quantitative.

During the experimental campaign, multiple sail arrangements were tested. During the analysis of the collected data it was determined that two prominent states of the structure can be observed depending on the spin rate of the structure. The first one, presented in Fig. 5, is a buckled structure, where radial wrinkles are visible on the surface of the sail. This deformation can be attributed to the structure reaching a minimum energy arrangement under the coupled stiffness, gravity and kinetic energy fields. Similar behaviour can be observed in a cloth supported at one point. With increasing spin rate, the minimum energy arrangement shifts towards a flattened plate, as can be observed in Fig. 6. Similar behaviour was also observed in other cases, but changing the boundary conditions leads to a change in the non-dimensional spin rates corresponding to stiffening. It warrants further investigation, which will be conducted in parallel to transient response testing.

Prototypes using booms for increased structural rigidity were also tested. The work of Soykasap [13] was used to size the booms to buckle in a static state, minimising mass. However, manufacturing constraints, mainly due to the low budget, rendered the analysis unfruitful since the expected behaviour was not observed.

3.4. Mechanical Prototyping

One of the major challenges faced by solar sailing missions is the sail deployment subsystem, primarily due to its various complex moving parts. In the case of Project Svarog, the team has begun early-stage mechanical prototyping to address this obstacle effectively. This will enable the identification of areas of difficulty before undertaking the preliminary design stage and gain valuable insight into the dynamic behaviour of the sail during deployment.

Solar sail deployment methods can be broadly divided into two main categories. The first, is the spin deployment method, which saw its first great success in 2010 during the IKAROS mission. This method makes use of the centrifugal force generated by the spacecraft's rotation to deploy and tension the sail. Since it has no rigid support structures, this method offers a lightweight and compact solution for the stowage and deployment of large solar sails. Second, is the boom deployment method which allows for a controlled expansion of the sail and has been successfully implemented in various missions such as LightSail 2. Although it is more mechanically complex, this method offers a high degree of control over the sail's deployment and is well suited to smaller sails.

A simple prototype mechanism has been developed to further understand the associated mechanical complexities of boom deployed systems. The blades of disassembled tape measures are being used to model the rigid, yet collapsible behaviour of the booms but in practice would be replaced by technology such as Triangular Rollable and Collapsible (TRAC) booms [14] or the newly developed Deployable Composite Booms (DCB) [15]. Similar to the early concepts of NASA's ACS3 system, this prototype makes use of four booms individually wrapped onto spools – Fig. 7, employing a simple geared mechanism that enables their simultaneous release while the strain energy stored in the spooled booms acts to self-deploy them. A casing designed to closely outline the contours of the four spools allows the booms to exit the deployer at 90 degrees and applies a radial constraint.

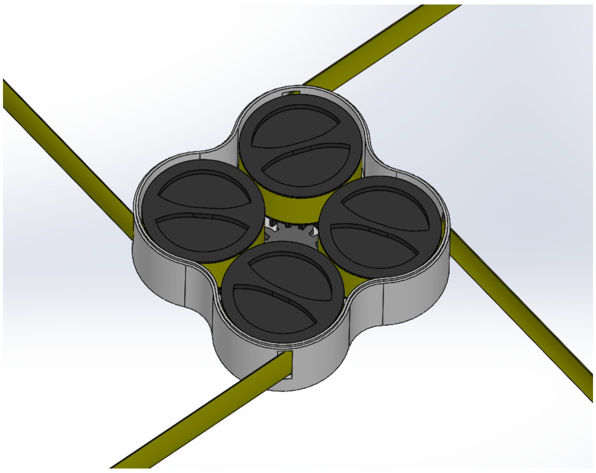

Figure 7: Four boom geared deployment prototype.

Testing of this prototype demonstrated that the overall mechanism satisfied its intended outcome and effectively highlighted areas with potential for improvement as outlined below:

1. The use of stored strain energy to self-deploy the booms led to a violent release that would pose a significant risk of tearing of the sail. In future prototypes, a stepper motor will be used to regain control over the deployment while still using the stored strain energy in the booms to minimise power consumption.
2. The packing efficiency of the deployment system can be improved significantly by wrapping all four booms around a single spool. This will also eliminate the need for the geared simultaneous release mechanism.
3. Despite the constraint applied by the casing, the system exhibited a reaction known as 'blooming' whereby the boom wraps expand radially inside of the case, leading to excessive friction and jams. 'Blooming' is a well-known issue in boom deployed mechanisms and extensive strategies such as those presented during development of the NEA Scout boom deployer [16] have been designed to mitigate it. These will be implemented and tested in future prototypes.

Subsequent work in the mechanical prototyping team at Project Svarog will focus on applying these insights into new prototypes that will be iteratively designed, built, and tested upon. The development of a reliable deployment mechanism will also allow for experimentation with various sail folding patterns and stowage arrangements.

3.5. Tracking and Communication

To validate the dynamics of the probe it is essential to track the satellite up to the point when the orbit becomes hyperbolic and the spacecraft enters an escape trajectory. Within the initial scope of the mission this was considered to be a sufficient condition to prove that the spacecraft escapes the Solar System. For more sophisticated communication, a phased array is suggested as a possible improvement to the communications system.

Regardless of the applied method of communication, Eq. (11) can be applied to investigate the signal to noise ratio.

$$P_r/N = \frac{P_t G_t G_r \lambda^2}{4\pi R^2 k_B T_n B} \tag{11}$$

Using this formula, the signal to noise ratio for detection using a single radio telescope can be evaluated. This mission aims to avoid active communication systems, so the only feasible approach for determining velocity and position is Doppler effect measurements. These will recover the spacecraft's velocity using the telescope's orientation and Very Long Baseline Interferometry (VLBI) to determine the position of the spacecraft. To conduct a more detailed trade-off, a preliminary transmitter design was conducted and the signal received on Earth at 10 AU was modeled. The time variation of the signal is presented as a moving spectra averaged with a period of 1.5 seconds. This is presented in Fig. 8 and the phase shift required for further analysis is given in Fig. 9.

Despite the evidently high quality of the signal during the short frame presented, for the entire period of the mission, the Brownian drift in frequency of the onboard oscillator becomes non-negligible. To mitigate this, a high precision cesium reference could be used. This would significantly increase the complexity of the solution, as components on the market use customer electronics, which are not space grade and cannot withstand Deep Space conditions.

In this case, only VLBI remains as a feasible method of tracking, which can be applied to this mission concept. This method is based on the detection of the probe using multiple radiotelescopes scattered across the globe and correlating their signal to act as a single huge interferometer. This method has been applied

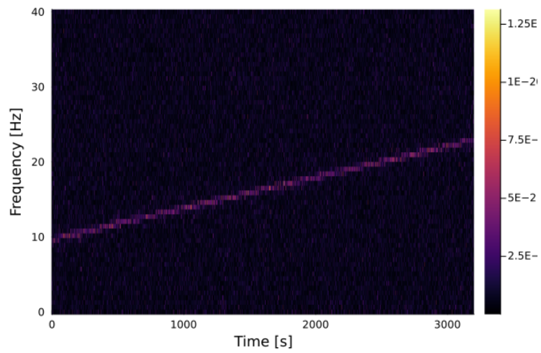

Figure 8: Time variation of averaged spectra received on the ground.

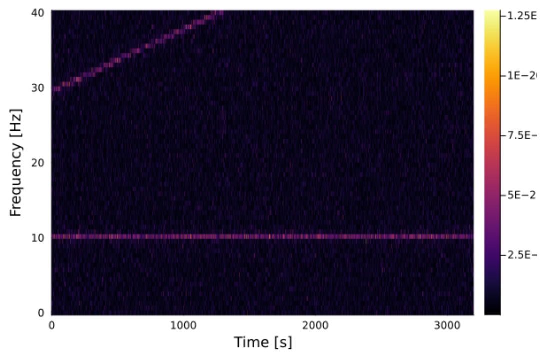

Figure 9: Phase corrected spectra of spacecraft signal.

in multiple previous missions and enables high precision measurements of distances in the Solar System. The processing pipeline for VLBI follows an algorithm developed for tracking the Huygens probe and is used by various other spacecrafts. Currently, the focus of work in this area is related to creating a fully simulated pipeline for generating a simulated signal received on each station, cross-correlating the given signals, and determining the position of the spacecraft [17].

3.6. *Plasma environment*

During the mission, the spacecraft will be subject to considerable variations in environmental conditions. During close passes to the Sun, both solar, wind and radiation flux increase considerably and so these parameters need to be considered in the design process. All environmental models considered in the design adhere to the ECSS standard, which describes how various aspects should be designed and which environmental properties should be modelled.

The standard radiation flux model in ECSS is CREME96. This model provides a standard for cosmic background coupled with solar particle flux and depends on solar activity. The spectrum from the model can then be used as an input to a code for analysing the impact of the radiation on the electronics. At this stage, two approaches with different levels of feasibility are being assessed.

The first order approximation in the model would be to model the particle propagation in the structure using the Bethe-Bloch equation for the propagation of ionized particles with higher order corrections for interactions with electron shells. This formulation is given by Eq. (12).

$$\frac{dE}{dx} = 2\pi r_e^2 m_e c^2 n_{el} \frac{z^2}{\beta^2} \times \times \left[\ln\left(\frac{2 m_e c^2 \beta^2 \gamma^2 T_{up}}{I^2} \right) - 2\beta^2 - \delta \right] \tag{12}$$

It can be seen that there is a prominent Bragg peak as the energy of the particle decreases. It is particularly important to consider this behaviour in order to minimize placement of the peaks in the volume of the electronics. This approach, while providing an initial solution, does not account for secondary emission in the material and needs to be validated against high fidelity Monte-Carlo simulations.

For conducting high fidelity numerical simulations, ESA guidelines suggest using GEANT4, a software for modelling particle physics problems developed at CERN. There is a GRAS toolbox developed as the extension of this library, which is aimed at providing a module for reading arbitrary spacecraft geometries, and conducting inverse ray tracing to estimate the total energy deposited in the electronics, without the need to model flux throughout the entire spacecraft. Due to the highly eccentric orbit used in this mission and the variable incidence with respect to the Sun, the simulation environment needs to be extended to consider a non-isotropic source of radiation. This is given as a modification of the ray tracing weight implementation in GEANT, done by implementing a classifier function to assess which diversions from the initial direction are physically plausible. With this modification, the flux on the surface of the electronics can be matched with any directional source and thus, it can be applied to the analysis of missions where the spacecraft is in a Sun-pointing attitude. An initial test of the solver for the inverse ray-tracing of particles propagating through a lead block to an ion source is presented in Fig. 10.

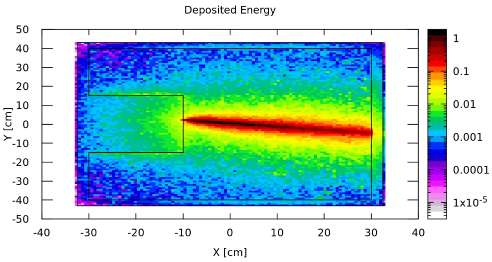

Figure 10: Backpropagation of proton radiation.

4. Further Steps

Currently, most of the efforts are directed towards creating an accurate mission definition. Due to the high complexity of the system, this is a crucial stage, providing an opportunity to minimize the chance of experiencing unexpected risks, and to understand the couplings between various design variables.

The main further area of development at the current stage is to polish the software system required for the development and validation of the mission requirements. This includes an in-house orbital propagator, a structural dynamics solver, a communications simulator, and environmental models. Beyond that, based on the findings from initial testing in the vacuum chamber, transient deployment experiments with 3D vision setup are planned to be conducted in the coming months and will be used as a means of validation of the structural models, providing data for future development designs.

The ultimate aim of said activities is to develop sufficient understanding of the mission to create a preliminary design review and then conduct the interstellar mission in early 2030s, when an appropriate launch window is available.

5. Conclusions

In conclusion, the conducted research indicates that the proposed mission is feasible within the requirements stated in the initial section. However, there are still unresolved challenges associated with the structural behaviour of the sail and manufacturing of the satellite. With further development and creating a broad network of partnerships with providers of subsystems, all of the issues will be mitigated and the mission will become the first civilian mission to enter an escape trajectory from the Solar System.

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