TEASPOON: a once in a lifetime opportunity to Sedna

Francesco De Cecio[1], Marco Asperti[2], Andrea Babato[2], Elia Bassetto[3], Lorenzo Beccari[3], Lorenzo Capra[3], Rosario Iaccarino[3], Gerardo Littoriano[2], Paolo Matteoni[3], Marco Modè[2] Michèle Lavagna[4]

Abstract

In the challenge of unveiling the enigmas that still surround the origin and early evolution of the Solar System, the study of trans-Neptunian objects plays a crucial role. For this purpose, Sedna is probably the most intriguing candidate for a space mission. A better understanding of its highly elliptical orbit could improve our knowledge of the evolution of the Solar System and could potentially lead to the discovery of an unknown planet. Moreover, the planetoid is expected to host a significant amount of tholins and probably a subsurface ocean of liquid water, making the analysis of its composition extremely interesting. In 2076, Sedna will reach its minimum distance of 76 AU from the Sun. This is a scientific opportunity that will not happen again in the next 11400 years.

Exploiting this instance, TransnEptuniAn Sedna PrObe for Outer exploratioN (TEASPOON) is a mission proposal to send a probe to Sedna, featuring a payload suite to perform an optical characterization, study the particle environment and conduct a radio-science experiment. Moreover, the long travel will be an opportunity to explore the Kuiper Belt looking for observations or, hopefully, discover new objects. The harsh environment, characterized by objects with unknown trajectories, requires Collision Avoidance strategies, while long-term radiation exposition demands electronics shielding and the preference for rad-hard components. More generally, the 77 AU distance and 30 years duration of the mission makes the design even more demanding. Therefore, solving those challenges would inaugurate a new generation of space missions to the edges of the Solar System and beyond.

This proposal has been developed in the framework of a Space Mission Analysis and Design course by a team of students at the master level in Space Engineering at Politecnico di Milano. A concurrent engineering approach has been followed, leading the study through its phase 0/A. This enabled them to practice in actual working conditions of a space agency's mission study, and underlined the importance of this kind of experience at a Master's level course.

Keywords

Concurrent engineering, mission proposal, Sedna, Solar System exploration, Trans-Neptunian Objects

[1] Corresponding author: Student, Politecnico di Milano, Italy, francesco.dececio@mail.polimi.it
[2] Alumnus, Politecnico di Milano, Italy
[3] Student, Politecnico di Milano, Italy
[4] Full professor, Politecnico di Milano, Italy

Acronyms/Abbreviations

ADCS	*Attitude Determination and Control System*
EPS	*Electrical Power System*
OBDH	*On Board Data Handling*
PS	*Propulsion System*
RTG	*Radioisotope Thermoelectric Generator*
STR	*Structure*
TCS	*Thermal Control System*
TMTC	*Telecommunication and Telecommand System*

1. Introduction

The objective of this paper is to present a proposal of an interplanetary science mission, developed entirely by ten Master's level students. The study was carried on in the context of the *Space Mission Analysis and Design* course of the MSc in Space Engineering of Politecnico di Milano, with a total duration of 6 months. The target of the study was to develop a mission to advance the knowledge and exploration of the Trans-Neptunian Objects, with the following given high-level requirements:

- Observation data of the composition and shape shall be obtained with at least $O(10^2)\ m$ in resolution.
- The system shall be capable to detect moons, if present.
- The spacecraft class should be $< 400\ kg$.
- Launch shall not occur earlier than 2027.

A Concurrent Design approach was followed, with each student holding the responsibility of one area of design. The entire project was developed adhering to ESA's ECSS guidelines and margin philosophy, to better simulate the experience of working at a real Space Mission proposal at ESA.

2. Scientific objectives

The Kuiper Belt is a region of space extending beyond the orbit of Neptune, whose mysteries are still to be unraveled. It collects a huge number of minor bodies and dwarf planets offering an intriguing look into the formation of the Solar System. Most of these bodies are composed of frozen volatiles and an organic compound called *tholin,* but a much better physical characterisation is deemed necessary. To date, the New Horizons mission to Pluto is the only one that targeted a Kuiper Belt object, but the interest towards this region is getting more and more traction.

2.1. Why Sedna?

A preliminary screening is performed to select the mission target. Smaller objects are discarded, and further relevance is given to the hypothetical surface composition and the presence of natural satellites. Lastly, feasibility of the proposal is accounted for. The outcome of this survey is the selected target: Sedna. It is a large planetoid, very enigmatic as neither its mass nor dimensions have been measured with an acceptable accuracy [1]. Models of internal heating via radioactive decay suggest that Sedna might be supporting a subsurface ocean of liquid water [2], its surface homogeneously coated by tholin [3], and its apparently long rotation period could be justified by the presence of unidentified natural satellites [4]. Thus, the scientific interest for this planetoid is unobjectionable.
Its main attractive feature is the extremely elongated orbit: with an eccentricity $e = 0.849$, it has an estimated perihelion of $76\ AU$ and an aphelion of $937\ AU$. A visual representation of its orbit is presented in Figure 1.

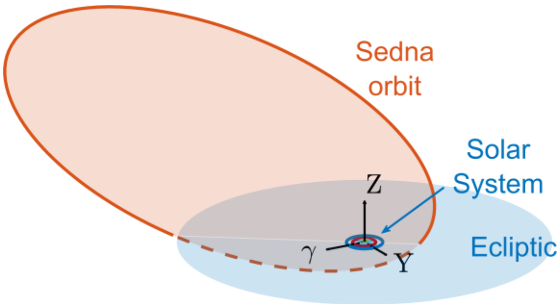

Figure 1. Sedna orbit

Such an eccentric and extreme orbit implies a tremendously long orbital period of about 11400 years, the second longest one of any known objects in the Solar System.
Due to its formation by accretion of smaller bodies, Sedna's initial orbit is assumed to have been almost circular. Therefore, the gravitational interaction with another body must have tugged it into its current singular orbit. Many theories have been proposed, but perhaps the most fascinating one is the presence of an unseen planet beyond the Kuiper Belt, the cryptic Planet X [5]. As of 2020, Sedna was at approximately $85\ AU$ from the Sun and will reach its perihelion around 2076. Thus, the window of time available to prepare an explorative mission towards this peculiar body is exceedingly narrow and cannot be missed out. This scientific opportunity is unique

to better understand the Solar System evolution and investigate a planetoid that will not be available to human reach for thousands of years.

2.2. A rewarding challenge

Besides its scientific importance, the manifold complexity represented by planning and operation adds up to the reasons that make such a mission of absolute interest. Following the successes by *Voyager* and *New Horizons*, time is ripe for further raising the bar.
A mission to the boundaries of the Solar System would practice the capability of managing a decades-long effort and push the technological development towards safer and more reliable solutions, all at once: the expedition would turn into a rehearsal which paves the way for the future of interplanetary missions. Paramount importance should be given to all the aspects related to robustness and integrity, considering the long-lasting journey and the presence of hazardous elements (threat of collisions and radiation exposure among the others).

2.3. Payloads and experiments

A payload suite is selected to comply with the scientific objectives outlined in §2.1. The full list, together with their usage, is shown in Table 1.

Table 1. Payload suite

Payload	Usage/objective
Pan Camera	Imaging of Sedna (surface topography, planet radius).
Near Infrared Spectrometer	Composition of Sedna's atmosphere and surface.
Energetic Particle Spectrometer	Characterisation of interplanetary and interstellar media; composition of Sedna's atmosphere.
Dust Flux Monitor	Analysis of the dust flux in the interstellar medium, Kuiper Belt and Sedna's proximity.
Solar Wind Instrument	Interaction between Solar Wind and Sedna's atmosphere; characterisation of the Heliopause (extended mission).
Telescope	Imaging of Sedna; survey of the Kuiper Belt (discovery of new objects); assessment of collision avoidance manoeuvres.
Radio-science Experiment	Search for Sedna's atmosphere (occultation); gravimetric analysis.

3. Mission Design

3.1. Mission timeline

The mission analysis foresees the launch on 12/05/2033, followed by gravity assist around Jupiter on 05/09/2034, and the closest approach to Sedna on 24/06/2059, with a total duration of 26 years and the possibility to further extend it, if applicable. As the scientific operations at Sedna end, the spacecraft will transmit all the data to Earth over the next 1.5 years. The timeline and the trajectory are shown in Figure 5 and Figure 2, respectively.

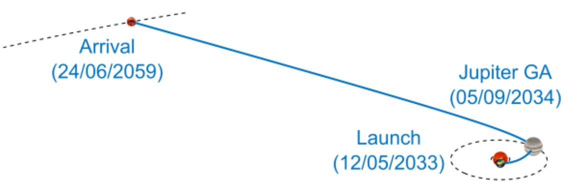

Figure 2. Baseline trajectory

3.2. TEASPOON configuration

The configuration obtained through the process up to phase A is presented in Figure 3 and Figure 4. From Figure 3, the 3-metres-diameter High Gain Antenna can be noticed, which has been designed to communicate with Earth up to 77 AU and beyond (reducing the data rate).
The power source for the mission is represented by the RTG, placed at the opposite face with respect to the payloads, to reduce radiations; moreover, the tank between RTG and payloads mitigates the radiation and thermal fluxes whilst the fuel is kept warm.
Figure 3 introduces the concept of MLI and louvres for thermal control.

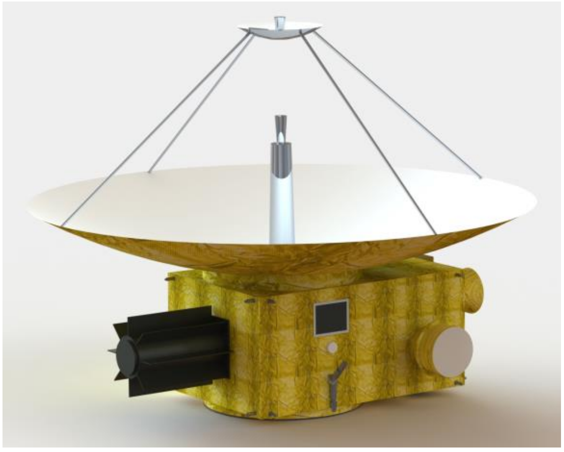

Figure 3. TEASPOON external configuration

The ADCS thrusters are placed at the corners of the lateral surfaces, while reaction wheels allow fine pointing. Attitude determination is

carried out by means of two star trackers. The orbital manoeuvres are performed, instead, by 4 thrusters aligned with the spacecraft centre of mass. Within the structural cylinder, a spherical hydrazine-based fuel tank is characterised by a blow-down pressurising system.
The On-Board Data Handling components are collocated in the payload section, due to both limited radiation from the RTG and space efficiency.
A structural analysis has been performed to assess the feasibility of such a configuration, which has the most critical elements in the RTG weight, its cantilevered position and payload section distribution.

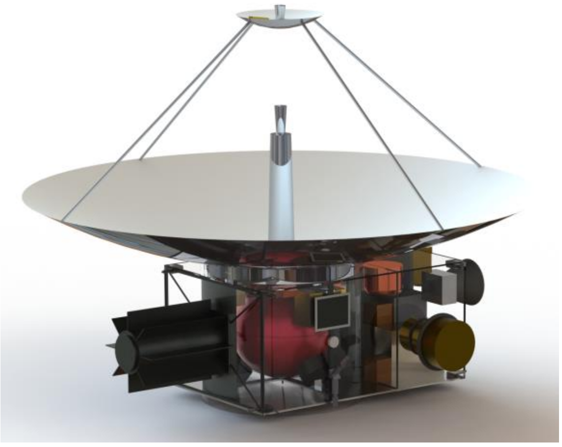

Figure 4. TEASPOON internal configuration

3.3. Mass Budget and Mass Breakdown

The TEASPOON mass budget, including total dry & total wet mass at launch, is computed following the ESA margin policy [6]. Each subsystem accounts for Design Maturity Mass Margin and then the System Level Mass Margin (equivalent to 20% of the nominal dry mass – $47\ kg$ in this analysis) is included. The details about the total mass budget and its breakdown are provided in Table 2 and Table 3.

Table 2. Mass Breakdown

	Dry mass (w/o margin)	Margin		Total	
	[kg]	%	[kg]	[kg]	%
STR	29.30	10	2.93	32.2	13.71
EPS	33.18	7.3	2.42	35.6	15.15
OBDH	6.20	5	0.31	6.5	2.77
TMTC	53.57	10	5.4	58.9	25.07
ADCS	32.36	5.1	1.64	34.0	14.48
TCS	4.50	25	1.13	5.6	2.39
PS	33.94	5	1.7	35.6	15.16
Payload	25.20	5	1.26	26.5	11.26
Nominal dry				**235.0 kg**	

The harness mass is estimated to be the 5% of the nominal dry (equivalent to $11.7\ kg$). It is worth to notice that the total wet mass is below the constraint of $400\ kg$. Finally, the total mass at launch is computed by considering also the selected apogee kick engine ($2137.0\ kg$ [7]), the Launch Vehicle Adapter and Payload Separation Ring system ($84.3\ kg$ [8]).

Table 3. TEASPOON Mass budget

Total dry [kg]	Fluids [kg]	Total wet [kg]	Total launch [kg]
293.8	57.5	351.2	2572.5

3.4. Power Budget

Accounting for the ESA margin policy [6], the power consumption of each subsystem is retrieved as the output of the subsystem's preliminary sizing and reported in Table 4.

Table 4. TEASPOON Power Budget

Subsystems	Power [W]	Margin [%]	Margined [W]
Payload	4.1	5	4.3
TMTC	51.3	10	56.4
ADCS	25.8	5	27.1
PS	15.9	5	16.7
OBDH	20	5	21
TCS	15	25	18.8
EPS	10.3	10	11.3

Finally, combining these values with the estimated activity time and levels, the power consumption of each mode is computed and illustrated in Table 5.

Table 5. Spacecraft Modes Power Budget

Power/Modes	Average* [W]	Maximum* [W]
Commissioning	63.1	75.5
Check	61.6	143.8
Observation	105.1	164.8
Cruise	75.2	164.8
Hibernation	47.3	164.8
Safe	68.6	143.8
Encounter	128.9	164.8
Scan	71.4	91.5

*20% ESA system-level margin included.

3.5. *Link Design*

The measure of link reliability is naturally declined on a parameter called link margin. The huge distance reached during the Sedna flyby directly entails the difficulty to maintain the link margin larger than the $3\ dB$ margin indicated by ESA. In fact, the data rate must be drastically reduced to guarantee a safe connection: this fact obliges to make a trade-off between the data rate, the volume of the scientific data to collect, the time needed to damp all data on ground and the transmitted power request. The selected solution is reported in Table 6.

Table 6. Sedna's scientific data downlink

Link Margin [dB]	4.14
Downlink data rate [bps]	475
Total downlink time [years]	1.48
Total Volume of data [MB]	2640
Power TX [W]	60

3.6. *Cost estimation*

The mission costs were estimated with the NASA PCEC tool and are reported in Table 7.

Table 7. Cost estimation

Area	Cost [M €]
Spacecraft*	280.30
Launch	133.84
Mission operations	367.54
Other	74.96
Total	**856.64**

*Integration, assembly, and tests included.

4. Discussion of critical aspects

Several criticalities affect the mission design, leading to innovative solutions aiming at matching the scientific requirements.

Target distance is a major driving criterion, affecting crucially the telecommunication and power generation subsystems. In fact, a fundamental phase of the whole mission is the data downlink after Sedna encounter: missing this task would automatically mean to fail the main scientific objectives. Despite the favourable orbital position of Sedna, the encounter will still take place at the enormous distance of more than $77\ AU$. This issue has been overcome suggesting the adoption of the Deep Space Network (on ground) and of 3m-diameter High Gain Antenna on-board which highly impacts on the overall mass and configuration design. Just as reference, New Horizons exploited an antenna dish of $2.1\ m$. This ruled out all the examined alternative configurations and acted as the key driver for the selected one. Moreover, since the signal delay becomes more and more significant during the cruise, a high degree of autonomy in spacecraft operations is required. Regarding the power generation, the driving criterion is the distance with respect to the Sun. The adoption of an RTG is thus mandatory.

Mission Duration gives rise to additional criticalities. Since the reliability is a key requisite of this mission, all critical components shall be capable to work for more than 26 years: this is often not possible, hence redundancy is the major strategy to be followed. The downside is a considerable increment of mass. Moreover, also the ground segment is affected by such a long mission duration: training of new personnel and maintaining the motivation of the staff for the whole duration of the mission are issues that should not be taken lightly. The generational shift is leading the selection of adaptive systems that can be tuned based on current technologies developed during the mission execution. This is addressed with a software architecture that employs proper abstraction layers within an object-oriented framework.

Short residence time. The trajectory shown in Figure 2 imposes a considerable relative velocity at the encounter between Sedna and the spacecraft, requiring the collection of a significant amount of scientific data in a narrow time window (~ 40 min). The identified approach consists in a simultaneous acquisition from multiple payloads and a consequent precise planning of the on-board operations, to be executed in a fully autonomous manner. In the proposed design, the key features allowing satisfactory performances are the payload configuration (see §3.2), the 3-axis stabilised attitude control for an accurate closed-loop tracking and the OBDH designed for sustaining a large data flow from the instruments while guaranteeing autonomous operability.

Collision risk. During the long cruise in the harsh environment of the Kuiper Belt, several objects could jeopardize the mission's safety. Three classes of threats have been identified and a mitigation strategy has been proposed for each:

- Dust particles ($< 1\ mm$): possible degradation of exposed surfaces. All the instruments shall include a protective shutter. MLI erosion shall be considered.

- Small objects ($1\,mm \div 1\,m$): cannot be detected but an impact could cause severe performance degradation. The structure shall be designed to withstand possible minor impacts, shielding properly critical components.
- Larger bodies ($> 1\,m$): can be detected up to the resolution threshold of the instruments. A collision would cause a catastrophic failure. Hence, an autonomous collision avoidance system has been proposed for the mission. Exploiting the spinning motion of the spacecraft, a continuous mapping is performed whenever a higher density of objects is expected. Propellant has been allocated for possible Collision Avoidance Manoeuvres.

Radiation exposure is another threat stemming from the environmental conditions of the mission**.** The accumulated total ionising dose and the hazard of single events effects during the Jupiter fly-by as well as the Deep Space travel, demands specifical solutions as the shielding of sensitive components, the adoption of rad-hard equipment, the implementation of Error correcting code.

5. Conclusions

TEASPOON is an incredibly ambitious mission, due to the extreme mission environment and its challenging objectives. Nevertheless, this work has clearly stated the main criticalities to address and how the proposed design is intended to tackle them. The result is a feasible and consistent proposal which fulfils the scientific objectives while respecting mass, power, link and management constraints.
However, to increase the chances of full success, further work needs to be done on what remain the most critical challenges. It is indeed considered necessary to improve the resistance to radiation, the reliability of the components and the collision avoidance system. The remoteness of the launch window must be exploited for the technological improvement of the implemented solutions and even more importantly, for extensive and prolonged testing campaigns.
Although the huge efforts and investments to be put in place, mission success would allow not only to greatly improve our knowledge of the Solar System, but also to carry out one of the most ambitious technological demonstrations ever attempted in space, opening the door to future interstellar missions.

Acknowledgements

This work was carried out under the supervision of Prof. Michèle Lavagna and Astra Team in the context of *Space Mission Analysis & Design* course at Politecnico di Milano.

References

[1] A. Pál, et al. TNOs are Cool: A survey of the trans-Neptunian region, *Astronomy & Astrophysics*, 541 p. L6, 2012.

[2] H. Hussmann, et al. Subsurface oceans and deep interiors of medium-sized outer planet satellites and large trans-neptunian objects, *Icarus*, 185.1 pp. 258-273, 2006.

[3] M. A. Barucci, et al. Is Sedna another Triton?, *Astronomy & Astrophysics*, 439.2 pp. L1-L4, 2005.

[4] B. S. Gaudi, et al. On the Rotation Period of (90377) Sedna, *The Astrophysical Journal*, 629.1 pp. L49-L52, 2005.

[5] M. E. Brown, et al. Discovery of a Candidate Inner Oort Cloud Planetoid, *The Astrophysical Journal*, 617.1 pp. 645-649, 2004.

[6] ESTEC, Margin philosophy for science assessment studies, *ESA,* 3.1 pp. 1-11*,* 2012.

[7] Star 48B rocket motor specifications: http://www.astronautix.com/s/star48b.html, last visited: 2nd March 2022.

[8] ULA, Atlas V User's Guide, 2010

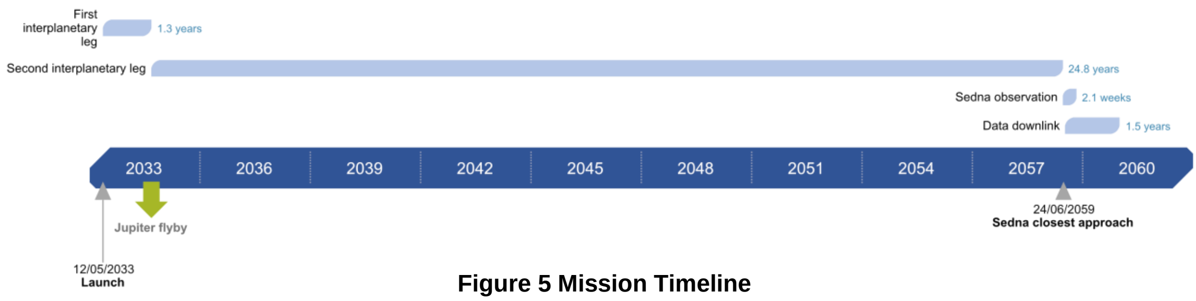

Figure 5 Mission Timeline