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ADITYA SAVIO PAUL

Advancing the study of small solar system bodies through multi-agent mapping and characterization

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UNIVERSITY OF TARTU
Press
1632

This study was carried out at Tartu Observatory, University of Tartu, Estonia.

The Dissertation has been accepted for the commencement of the degree of Doctor of Philosophy (PhD) in Physics on June 26, 2025 by the Council of the Institute of Physics, University of Tartu.

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The public defense will take place on Sept 04, 2025 at 14:00 in Tartu Observatory, University of Tartu.

UNIVERSITY OF TARTU
Tartu Observatory
1632

ISSN 1406-0647 (print)
ISBN 978-9916-27-958-8 (print)
ISSN 2806-2523 (PDF)
ISBN 978-9916-27-959-5 (PDF)

University of Tartu Press
`http://www.tyk.ee/`

To my grandparents, parents, family and friends - all who are a constant source of my motivation to pursue knowledge and be virtuous.

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LIST OF ABBREVIATIONS

Acronyms

3D 3 Dimension. 31, 35
3U 3 Unit. 12

AIDA Asteroid Impact and Deflection Assessment. 37

CDR Critical Design Review. 12
CI Comet Interceptor. 34
CoCa COmet CAmera. 36

DART Double Asteroid Redirection Test. 37, 38
DEM Digital Elevation Model. 31
DFP Dust, Fields and Plasma. 36
DNC Dynamically New Comet. 34
DTM Digital Terrain Model. 31

EnVisS Entire Visible Sky Camera. 36
ESA European Space Agency. 12, 14, 18, 34, 38

GOCE Gravity field and steady-state Ocean Circulation Explorer. 23
GRACE Gravity Recovery And Climate Experiment. 23

HI Hydrogen Imager. 36

IAU International Astronautical Union. 20
ISO Interstellar Object. 34

JAXA Japan Aerospace Exploration Agency. 14, 34
JPL Jet Propulsion Laboratory. 30
JWST James Web Space Telescope. 22

KBO Kuiper Belt Object. 16, 38

LPC Long-Period Comet. 34

MANiaC Mass Analyzer for Neutrals in a Coma. 36
MIRMIS Modular InfraRed Molecules and Ices Sensor. 36
ML Machine Learning. 32
MLP Multi-Layer Perceptron. 32
MPC Minor Planet Center. 18

NAC Narrow Angle Camera. 36
NASA National Aeronautics and Space Administration. 14, 18, 30, 37
NEO Near-Earth Objects. 20, 22
NERF Neural Radiance Fields. 31

OPIC Optical Periscopic Imager for Comets. 12, 35

PDR Preliminary Design Review. 12
PHA Potentially Hazardous Asteroids. 20
PI Principal Investigator. 35
PS Plasma Suite. 36

SBN Small Body Node. 18
SEL2 Sun-Earth L2. 35
SRP Solar Radiation Pressure. 16
STScI Space Telescope Science Institute. 22

TAG Touch and Go. 22
TO Tartu Observatory. 27
TRL Technology Readiness Levels. 39

WAC Wide Angle Camera. 36

YORP Yarkovsky–O'Keefe–Radzievskii–Paddack. 16

LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following publications (full text included at the end of the thesis)

- **I** **Aditya Savio Paul** and Michael Otte (2023). “Simultaneous Motion Replanning and Gravity Model Refinement near Small Solar System Bodies". In: *AIAA Journal of Aerospace Information Systems* 20.11, pp. 747-762. DOI: 10.2514/1.I011200
- **II** Jones, G. H. et al. (2024). “The Comet Interceptor Mission". In: Space Science Reviews 220.1. [Tartu Observatory-Mihkel Pajusalu, Iaroslav Iakubivskyi, Mihkel Kama, Artiom Nikolajev, Aire Olesk, **Aditya Savio Paul**, Herman Proosa, Andris Slavinskis]; This article is licensed under an Open Access Creative Commons Attribution 4.0 International License; Available: http://creativecommons.org/licenses/by/4.0/, p. 9. ISSN: 1572-9672. DOI: 10. 1007/s11214-023-01035-0
- **III** **Aditya Savio Paul**, and Mihkel Pajusalu (2021). “Towards endogenous mapping of small solar system bodies during multi-agent rendezvous". In: *72nd International Astronautical Congress 2021*. URL: https://dl.iafastro.directory/event/IAC-2021/paper/65229/
- **IV** **Aditya Savio Paul** and Naghma Afreen (2021). “Design approach to quantify inter-ground station distances by doppler-based ranging experiment for small satellite missions". In *72nd International Astronautical Congress 2021*; URL: https://dl.iafastro.directory/event/IAC-2021/paper/65231/
- **V** **Aditya Savio Paul** and Naghma Afreen (2025). “Multi-agent positioning for optimal dynamic event coverage". In: *Journal of Intelligent Robotic Systems*. submitted on 10 Feb 2025; Currently on second review (first manuscript draft is included in the print version)
- **VI** **Aditya Savio Paul** and Mihkel Pajusalu (2024), “Radiance Field Mapping for Small Body Surface Morphologies". In: *IEEE Transactions on Field Robotics*. submitted on 26 December 2024; Currently under review (first manuscript draft is included in the print version)

Author's contribution to the publications

The publications associated with this thesis are the results of multi-national efforts involving cross-disciplinary thoughts, discussions and scientific exploration.

I The author developed the methodology and the algorithms. He performed the experimental studies, compiled the manuscript and handled the submission and the review process. The author also organized weekly meetings, provided regular updates, and maintained documentation.

II The author is a member of the Optical Periscopic Imager for Comets (OPIC) instrument team at Tartu Observatory. He co-developed the small body flyby setup at the Tartu Observatory, which helped to simulate views for testing and calibrating the OPIC instrument. He also initiated and contributed to relevant European Space Agency (ESA)-defined documentation, Preliminary Design Review (PDR) and Critical Design Review (CDR), along with other ongoing agile development-based tasks. The author contributed to the mission with the background study and examined the scientific outcomes of the OPIC instrument.

III From a multi-agent perspective, it was essential to develop a simulation environment that could simulate the motion of the target body, which could be observed by multiple agents. The author worked on the methodology and developing the environment. He performed the simulations and data gathering along with generating the 3D reconstructed models. He compiled the final manuscript and handled the submission process.

IV The author has been a part of the Estonian Student Satellite team since 2018 and worked on the ranging experiment for the 3 Unit (3U) ESTCube-2 satellite. The author co-developed the methodology, supervised the experiments and analysis, and was responsible for coordinating and communicating with the other members of the ESTCube team. He contributed to the manuscript with the background, methodology, further revisions, final compilation, and submission of the manuscript.

V The author developed the methodology and performed the related study. He designed and participated in the experimental campaigns and supervised the workflow and data analysis. He coordinated the scientific rationale and procedure with the co-author, contributed majorly to the writing, compiled, and submitted the final manuscript.

VI The author performed the related study and progressed on the methodology. He designed the approach, developed the workflow and performed the study. He was actively involved with the data-gathering campaigns at the Tartu Observatory Space Mission Simulation Center. He was responsible for setting up the different configurations for acquiring data for the experiments and validation. The author majorly wrote, compiled and submitted the final manuscript.

PREFACE

The modern era invigorates scientific progress, demanding a multidisciplinary approach, which is essential for ensuring humanity's continued existence against internal conflicts and external dangers. Beyond terrestrial knowledge, space exploration grants us reflections on our own world. By probing unique worlds near and far, we realize our fragile yet opportune existence on the *pale blue dot* (Sagan 1994). Addressing fundamental questions—such as the role of asteroids and comets in planetary formation, extinction events, and the potential for life beyond Earth—requires integrative strategies. With growing scientific and technological fervors, dedicated study and pursuit of purposeful space exploration are essential for unlocking the mysteries of the Universe, its dynamic nature, and evolution.

The ideas and concepts within this thesis emerge from the author's discussions and experiences while being involved in a growing academic team as opposed to larger agencies and industrial consortiums. In a country where space heritage is germinating, the author finds himself within a research ecosystem that is willing to expand the frontiers of small-body exploration. This journey has corroborated self-learning, active participation in pioneering projects, and the autonomy to drive reasonable and responsible scientific inquiries.

This dissertation is stimulated by our enduring quest to understand the silent wanderers that hold the echoes of our solar system's birth. Through a collection of studies, this thesis resonates in advancing small-body sciences, with the optimism for tangible and continued study to the progress of planetary sciences. It presents resonating views and ideas that embrace affordability, sustainability, and technological innovation to deepen our understanding of the vast cosmos, only to be humbled and gratified with the gifts of nature bestowed to humanity. Overall, this serves as a testament that a small nation like Estonia, has the capability of manifesting profound impacts, similar to small solar system bodies.

Wanderers of the Universe
carry tales of the past
& thoughts for future

`AdityaSavioPaul`
`Tartu2025`

1. INTRODUCTION

The celestial space is recognized to be in a state of perpetual dynamism and chaos. Since the immediate aftermath of the Big Bang, the cosmos has remained in a continuous state of transformation and evolution. Bodies like Moon and Mars, which appear static, are subjected to gradual and long-term geological processes, including erosion, and impact events, which altogether affect significant changes over cosmological timescales. The irregular trajectories of asteroids and the ephemeral appearances of comets further exemplify the dynamic nature of the solar system, illustrating that stars, planets, and small solar system bodies are influenced by the celestial evolution throughout their vastness and intrinsic complexity.

Small solar system bodies, including asteroids, comets, and meteoroids, play a critical role in advancing our understanding of planetary system formation and evolution. These bodies are widely regarded as remnants from the early solar nebula, preserving primordial material. Asteroids, predominantly located in the main belt between Mars and Jupiter, provide key insights into the thermal and collisional history of the early solar system. Comets, originating from the trans-Neptunian regions such as the Kuiper Belt and the Oort Cloud, are composed primarily of volatile ices and dust. Offering empirical evidence of their composition and activity through their coma and tails, during their passes by the Sun, they serve as valuable targets for understanding volatile transport and the delivery of prebiotic compounds to the early Earth. Meteoroids, representing smaller fragments of asteroids or comets, frequently enter Earth's atmosphere, where they become visible as meteors. Those that survive atmospheric entry and impact the surface as meteorites constitute critical sources of geochemical data, often used to constrain models of planetary differentiation and accretion.

The night sky has inspired humans to perform systematic observation and inquiry. From drawing star-maps to establishing observatories and documenting celestial phenomena to be used for navigation and timekeeping, human endeavors have ever since been motivated in the pursuit of cosmological understanding. This has majorly led to the evolution of scientific methodology, transforming this curiosity into empirical investigation.

The advent of space exploration marked a significant milestone in the scope of planetary science, especially for small solar system bodies. Robotic missions have extended the reach of observation beyond terrestrial realms, enabling both remote measurements and proximity exploration of small solar system bodies. Notable examples include National Aeronautics and Space Administration (NASA) Dawn mission, which surveyed Vesta and Ceres, ESA Rosetta mission, which successfully orbited and deployed a lander on Comet 67P/Churyumov-Gerasimenko, and Japan Aerospace Exploration Agency (JAXA) Hayabusa sample return mission from Itokawa. These missions have yielded unprecedented insights into the structure, composition, and activity of minor bodies, revealing the presence of complex organic molecules that provide clues to hypotheses regarding exogenous delivery of volatiles and organics to the early Earth. In lieu of understanding celestial dynamism, humanity has emerged as an investigative species that is progressively developing methodologies to understand transient terrestrial and extraterrestrial phenomena. From volcanic eruptions to tectonic movement to impact cratering, modern scientific disciplines are increasingly capable of constructing more detailed and educated models of planetary development. With advancing technological capabilities and theoretical frameworks, small solar system bodies continue to offer vital insights into their own formation and existence while elucidating the processes that have shaped and continue to shape our planetary neighborhood and beyond.

To advance the study of small solar system bodies, understanding their environment and morphology, this thesis considers the following research questions that have been explored through the articles and publications **I, II, III, IV, V, VI** and presented in sections 3.1, 3.2, 3.3 (full texts of the articles are attached at the end of the thesis; some figures have been converted to grayscale to conserve color. Refer to online publications for the color version of the articles).

First, given an inherently erratic and relatively lower intensity gravity field model of a small body (obtained through remote observations or theoretical models), can an orbiting spacecraft map a higher-fidelity model through proximity measurements and in the process perform incrementally stable maneuvers while simultaneously respecting the updated gravity field model?

Second, to inquire into the applicability of a mission profile in space that envisages a multi-agent topology to optimally position spacecraft, gather data to reconstruct surface morphologies, and to gain insight into transient activities on small bodies like asteroids and comets or even pristine bodies, never visited before?

Third, given a small-body flyby scenario, characterized as a transient event in space, can multiple agents, like spacecrafts, observe and eventually produce more-informed 3D reconstructed surface models of the target body?

Furthermore, can a fleet of multiple agents be positioned at optimal locations and produce morphological representations for which the optical data of small bodies is naturally challenging to capture owing to non-illuminated regions, occlusions and limited on-board budgets and opportunities?

1.1. Dynamic Worlds: Small Solar System Bodies

Small solar system bodies provide a fascinating illustration of the dynamic nature of the cosmos. Once considered static remnants from the origins of planetary formation, these objects are revealing themselves to be active entities, constantly evolving under the influence of both internal and external forces. In a constant state of flux, asteroid terrains are evolving, while volatile cometary plumes suggest activities involving emanating gases, ices, and dust. Meanwhile, the cryovolcanic activity of dwarf planets (characterized at the cusp of small bodies and planetary bodies) showcases eruptions of icy materials, hinting at complex environments. These bodies have exhibited profiles that have challenged our basic understanding of their characteristics. Besides, they have helped us to closely investigate on properties that not only pertain endogenously to these bodies but also perform study on externally influencing natural forces, like gravity, Solar Radiation Pressure (SRP), Yarkovsky–O'Keefe–Radzievskii–Paddack (YORP) and resonances from other bodies, to name a few; knowledge of which has helped us elevate our reasoning for planetary dynamics as a whole.

Asteroids have displayed surprising levels of complexity. These bodies exhibit surface activity, including particle ejection, landslides, and regolith motion driven by solar heating and rotation-induced stresses. Their surfaces are constantly modified by micrometeorite impacts, solar wind irradiation, and thermal fracturing, which gradually change their appearance and structure over time. Missions to asteroids Bennu and Ryugu have shown that they are not just solid monolithic rocks but exist as rubble piles. Moreover, certain asteroids demonstrate rapid rotation, binary systems, and induced spin changes, further emphasizing their dynamic nature. Comets, known for their spectacular tails and volatile behavior, are quintessential pieces of evidence of small dynamic worlds. During their approach to our Sun, solar heating causes sublimation of ices, which drives jets of gas and dust from the surface. This activity not only sculpts the nucleus but also leads to the formation of temporary atmospheres, or coma. Data from missions such as Rosetta's exploration of Comet 67P/Churyumov–Gerasimenko revealed seasonal changes, surface collapses, and the formation of new pits and cliffs - all driven by the interaction between solar energy and volatile materials. Such findings highlight that cometary activity is more nuanced and varied than previously understood. Even distant Kuiper Belt Object (KBO), assumed to be frozen and unchanging, have revealed unexpected dynamism. The New Horizons mission demonstrated that distant bodies could possess layered terrains, possible cryovolcanism, and complex internal processes. Understanding small solar system bodies as dynamic worlds has profound implications. It enriches our knowledge of the solar system's history and evolution, offering clues about planetary formation and the migration of materials.

Additionally, through a variety of missions, it has been analyzed that no two small solar system bodies have exhibited identical characteristics (Novaković et al. 2022), i.e. different small bodies have showcased contrasting sets of characteristics, highlighting their remarkable diversity. The presence of such bodies comes as a boon for human learning, given the unique information that we achieve from every mission that has retrieved scientific data from the bodies that they have visited. Moreover, their current positions in the solar system suggest their overall evolutionary state, providing insights into the various processes that influence their motion and drive them to different regions. Figure 1 illustrates approximate positions of small bodies observed and visited through various missions (Image used under License No. 6037211113846 provided by Springer Nature and Copyright Clearance Center (Zhang et al. 2021)). Studying the dynamics of small solar system bodies (including small bodies beyond the solar system) is key to enhancing human understanding of their origin, presence, and influence on other planetary bodies. Given the highly erratic environment hosted by these bodies, it is essential that continually advanced methods and approaches are devised that can model and validate the various transient events that occur in the vicinity, on the surface, and in the subsurface regions of these bodies.

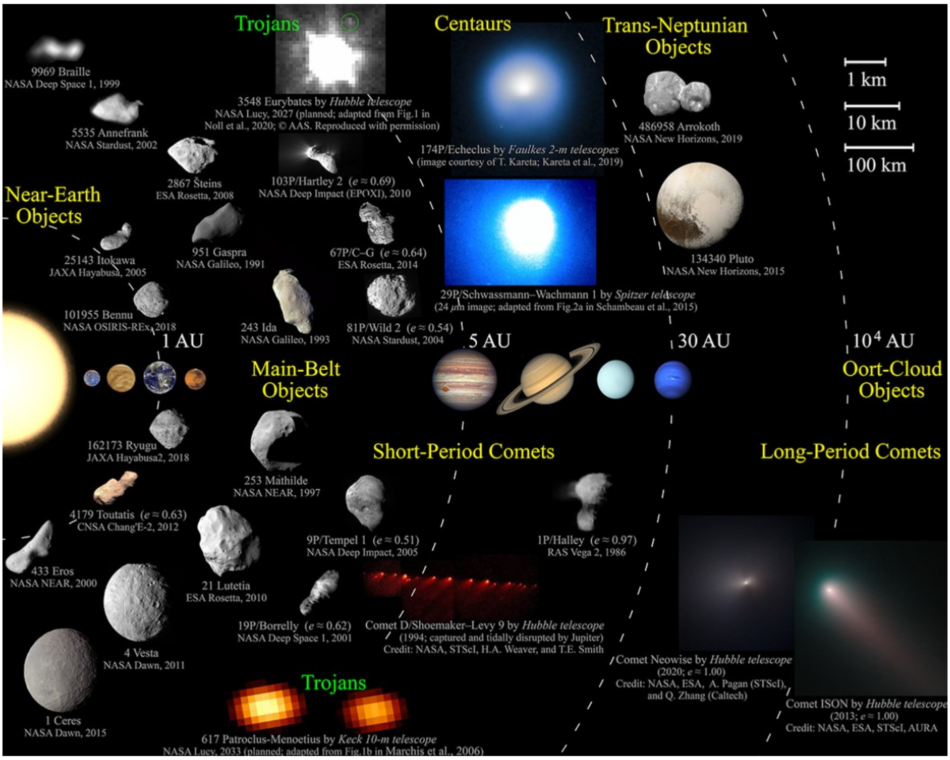

Figure 1: Populations and distribution of small bodies in the solar system

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2. NEED AND MOTIVATION

Unearthing the dynamic activities on small bodies is of high priority within leading space agencies. ESA has an active research group dedicated to ‘Small Bodies and Rosetta Group’, and NASA maintains multiple online resources that contribute to data archiving, like Planetary Data System: Small Body Node (SBN) (NASA 2025a), Minor Planet Center (MPC) (Astrophysics 2025), Small Body Database Lookup (NASA 2025b). Along with data from missions, SPICE archives (Acton 1996, Spice 2025) also host hypothetical event data (Near Earth Object Studies 2025) to simulate potential events and progress on varied mission scenarios.

The need and motivation for studying small solar system bodies are prioritized over two significant domains (discussed further in sections 2.1 and 2.2) -

- Enhancing our knowledge of planetary science, dynamics and space exploration.
- Executing reasonable and responsible efforts for planetary defense and protection.

Both of these domains encompass a non-exhaustive list of distinct categories presented by Azadmanesh et al. 2023 that motivate the study of small bodies. They include 1) Life’s origin, 2) The Moon’s origin (including debatable origins of moons of other bodies like Phobos and Deimos for Mars and for binary asteroid system, Didymoon for Didymos), 3) The origin of water on Earth, 4) Vast reservoirs of valuable resources, 5) Colonization, 6) Threats, and 7) Advancing our understanding of physics.

With the rapid increase in observational technologies, both from the ground segment and space segment, there has been a continuous interest in visiting these bodies and performing studies from close proximity. Given the dynamics of these bodies, it is essential that continually improved methods involving navigation, multi-point observations, and surface mapping are developed. In the context of this thesis, these domains are explored, and methodologies are developed that help in improving our capabilities of studying, mapping, and characterizing these unique bodies in space.

2.1. Advancing Planetary Science and Dynamics

During the solar system and planetary formation phases, collisions and impacts played essential roles in shaping the various inhabitants of the solar system, including their compositions and their presence within the celestial expanse. Out of the many theories of the presence of water on Earth, a prominent theory is that it was brought by comets that impacted the Earth’s surface. In current times, it is well known that comets are primarily composed of water in the form of water ice (including other ices, dust and organic compounds). Scientifically, this signifies that knowledge of the composition of a comet or similarly characterized small body reveals significant clues about the composition of the solar nebula where these bodies were formed. Moreover, the presence of primordial material within these bodies that has remained unperturbed since the formation of the solar system (Horner et al. 2010; Altwegg et al. 2015) is adjunct to the study.

Foundational small body motion in space is described by combined translational and rotational dynamic models. Translational motion, governed by Newton's second law, describes the acceleration of the target's center of mass in response to external forces like gravity. The rotational motion is governed by Euler's equations, accounting for the target's spin behavior based on its moment of inertia and external torques. In the combined form (Equation 2.1), these attribute a dynamic system allowing for modeling trajectory and orientation. This framework is essential in understanding the natural evolution of asteroid motion and is widely used in spacecraft navigation, landing site analysis, and studying effects like tumbling. These models are foundational to planetary science and mission design (Goldstein 1980; Park et al. 2010).

$$\begin{cases} \ddot{\mathbf{r}} = \dfrac{1}{m}\mathbf{F} \\ \dot{\omega} = I^{-1}\left(\mathbf{M} - \omega \times (I\omega)\right) \end{cases} \tag{2.1}$$

where, $\ddot{\mathbf{r}}$ is the acceleration of the center of mass, m is the mass of the small body, $\mathbf{F}$ is the net force acting on the body, $\dot{\omega}$ is the angular acceleration, ω is the angular velocity, $\mathbf{M}$ is the external torque and I is the inertial tensor.

In addition to their composition, the orbital properties of currently existing small bodies supply vital clues about the primordial evolution of the giant planets (Malhotra 1995; Gomes et al. 2004) and can indicate the existence of unseen planets (Batygin et al. 2017). Studying these bodies' motion also improves our current mathematical models for trajectory estimation, based on the various internal and external forces (including resonances from similarly sized and/or larger planetary bodies) that govern their orbital states. Space exploration missions are largely fuel-dependent and small bodies hosting essential mineral reserves can provide fuel for interplanetary and deep space missions through in-situ resource utilization procedures. As these bodies exhibit characteristics that help understand our solar system dynamics and can be traced back to its origin, a foundational need to study small bodies is prevalent.

2.2. Planetary Defense and Protection

The Chelyabinsk event (Zuluaga et al. 2013), describing the fall of a rocky body 20 m in diameter, aroused a sense of the danger that small bodies pose to the Earth and its inhabitants. Given that the celestial body exploded at about 30 km above the Earth's surface, the resulting shockwave is of concern as it caused serious destruction and injuries. A point to note is that the body was not detected before its impact with the Earth's atmosphere. Another notable impact on the Yucatan peninsula is believed to have caused the extinction of the dinosaurs and other species. Due to their potentially destructive (and catastrophic) nature, humanity must monitor and study these bodies in order to reduce the risk of potential impacts (Hahn and Bailey 1990; Napier et al. 2015). A recent example was seen with the detection of the Potentially Hazardous Asteroids (PHA) 2024 YR4 asteroid, where the International Astronautical Union (IAU), studied the ephemerides rigorously on high priority to evaluate no-impact criteria from the body (As reported by Wasser 2025, the impact probability was measured at 2% at the time of detection and warning and is now at 0.004%, as of Feb 24, 2025). Another asteroid under scrutiny is Apophis, headed towards Earth, for which a mission to study its dynamics and tidal effects is already sanctioned and under development (Kueppers et al. 2023). Critical measurements and surveys are essential, as the behavior of Near-Earth Objects (NEO) can change over time, altering impact probabilities.

Impacts on Earth by the earth-bound small bodies can potentially result in global catastrophes and collectively $\sim$1000 NEO contribute to 90% of the impact risk (Harris et al. 2015, Morrison 1992). Thus, surveys and mission directives relay well-defined goals motivated by planetary defense, more so towards science, to survey, identify, and characterize potentially hazardous asteroids that could threaten Earth. This has also sparked interest within public media outreach, as shown in the movie Don't Look Up (McKay 2021) while nudging that planetary defense is not science fiction but a scientific fact. Ironically, small-body impacts that have been speculated to be harbingers of life and water can also threaten life as we know it.

The study of these small yet captivating celestial bodies emphasizes the significance of viewing change as a fundamental aspect of nature which encourages further exploration. This thesis elaborates on the now-established understanding that small solar system bodies are, in fact, dynamic worlds teeming with unique characteristics that yearn for comprehensive investigation. It emphasizes the necessity to examine their intricate environments, varied compositions, diverse surface topologies, and the dynamic processes that relate to the endogenous and exogenous profiles. From a high-level mission scenario, given optimal spatial locations, a system comprising multiple spacecraft can observe the target body from varied angles and perform efficient surface and environmental mapping.

To progress on this, in order of discussion within the thesis, Section 3.1 delves into environmental mapping during in-orbit maneuvers to survey and update the gravitational influence in the immediate vicinity of the small body of interest. Section 3.2 is on strategic spatial positioning of multiple observational agents, to pursue observations of transient small-body events. In Section 3.3 multi-point observations of the target body are accomplished from spatial positions to produce morphological representations of the target body. The studies are correlated to ensure a high scientific return in lieu of mission profiles like that of the Comet Interceptor mission (Section 4.1), which aims to perform a multi-agent rapid flyby reconnaissance of a pristine interstellar comet. This comprehensive approach enhances our understanding of these celestial entities and sheds light on their complex behaviors and interactions within the solar system.

3. SMALL BODY MAPPING AND SURVEY

In the context of small-body mapping and surveys, primary postulates are obtained through remote observations that help generate a basic understanding of the target body. Information regarding their shape and size, including the rotational and orbital parameters, is precursor data that can be derived through observations. Further observations and analysis reveal intrinsic properties like albedo and surface composition, through which further study regarding the force field interactions, surface granular mechanics, and surface evolution can be inferred. These are baseline essentials to designing space missions involving different configurations like flybys, rendezvous, orbiting, Touch and Go (TAG), and landing, to name a few, that supplement our observations and provide validation to the models.

Our ability to observe small bodies has drastically improved, thanks to the initiation of ground-based observation campaigns which have been conducted by the NEO Observations Program (Stokes et al. 2000, Jedicke et al. 2012, Bolden et al. 2010) and surveying through space-based telescopes (Bancelin et al. 2012, Müller et al. 2023). In times of immediate concerns, observation times of these telescopes are also sanctioned, for example, with the James Web Space Telescope (JWST) being utilized for time-critical observations of the 2024 YR4 asteroid as proposed in Proposal-9239 2025 (Space Telescope Science Institute (STScI)) and observed on Mar 08, 2025. This has contributed to our ability to observe and analyze the target bodies by studying them in varying wavelengths, performing spectroscopy as shown by Lim et al. 2011, and advancing the spectral distinctions of asteroids at different heliocentric distances as explored by Gartrelle et al. 2021. Corroborated with improved modeling techniques of estimating various dynamical parameters of asteroids (Ďurech et al. 2015), including their rotational states, orbital parameters, spectra, as well as surface regolith, and subsurface activities, has significantly produced more pronounced models. Moreover, scientific dissemination and public outreach are promoted through citizen science programs as well as within conferences and workshops, such as the Planetary Defense Conferences. (IAA-PDC 2025), Asteroid Research and Training workshop (Tartu Observatory 2023) and Lunar and Planetary Science Conference (LPSC-LPI 2025).

There has been increased interest in the development of advanced techniques that contribute to human endeavors in visiting other small bodies and gathering novel data, as well as appending our catalog of small bodies that have already been visited by spacecraft. Figure 2 illustrates a montage of small bodies photographed from proximity, as of September 2022.

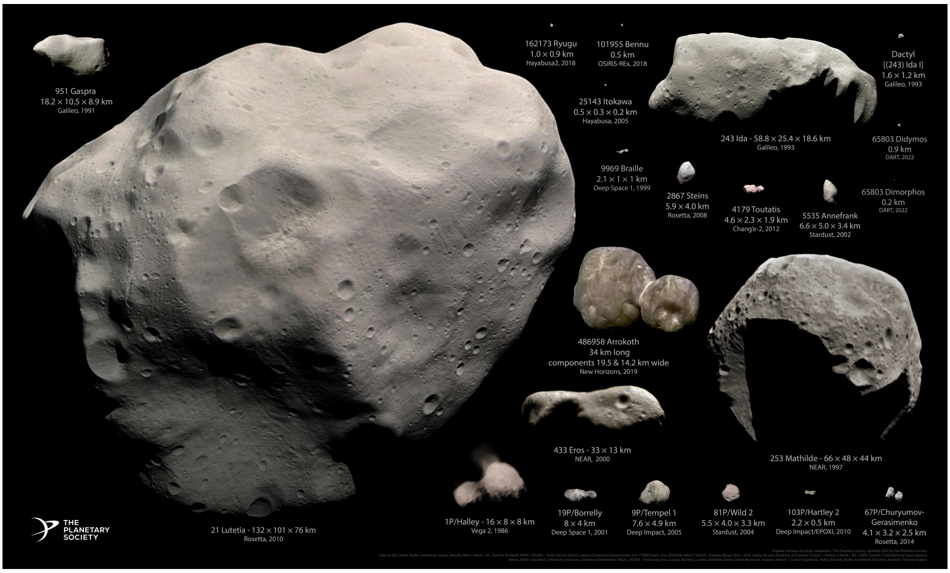

Figure 2: Asteroids and comets visited and imaged by spacecraft

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3.1. Environmental Mapping

The study of the environment in the vicinity of small bodies is challenging due to the irregular shape and composition of the bodies that influence an erratic gravitational field. Moreover, owing to their relative sizes and densities, the gravitational influence is naturally weak. Comparatively, for larger planetary bodies like that of Earth, multiple opportunities exist to perform near-body and surface mapping through in-orbit missions like Gravity Recovery And Climate Experiment (GRACE) and Gravity field and steady-state Ocean Circulation Explorer (GOCE), described by Tapley et al. 2004 and Visser 1999 for gravity and ocean circulation mapping. With regards to small body environment mapping, these opportunities are posed by limited measuring opportunities. They require detailed mission designs considering various factors, including the spacecraft's form factor and the onboard budgets (fuel consumption, power utilization, instruments etc.) to perform in-orbit maneuvers in their erratic gravity fields.

From a general understanding of near-body influences exerted by small bodies, measurements of their gravitational field can be interpreted by remote observations through their shape, size, density, and rotational parameters (Park et al. 2010). From a mission design perspective, study **I** considers the continued mapping and updating of the gravitational field by performing in-orbit maneuvers. The orbiting spacecraft is modeled as an isolated accelerometer radially measuring the gravitational influence in a body-centered frame of reference.

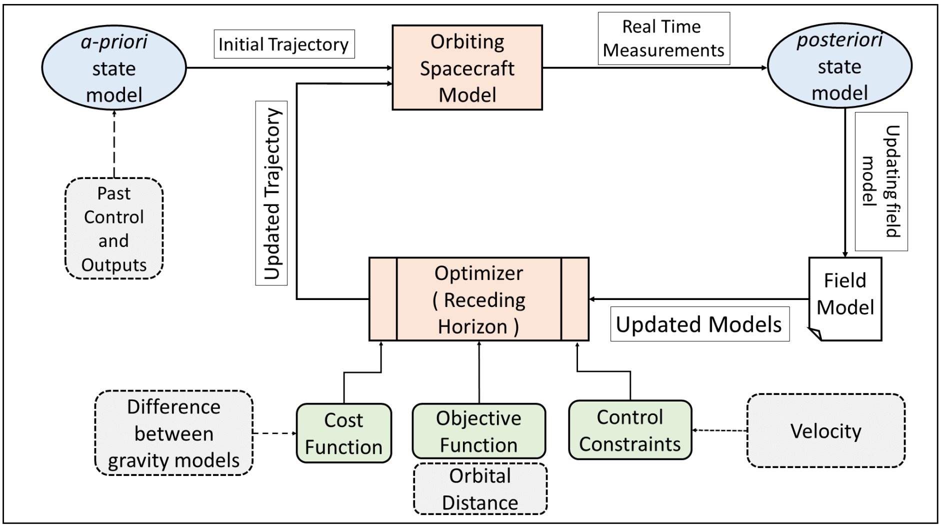


Figure 3: Simultaneous motion replanning and gravity model refinement

The gravitational influence ($\mathbb{G}$) is mapped by virtue of the gravity potential the spacecraft experiences, owing to its position within the exploring orbit and is expressed analytically in equation 3.1 (taken from study **I**)

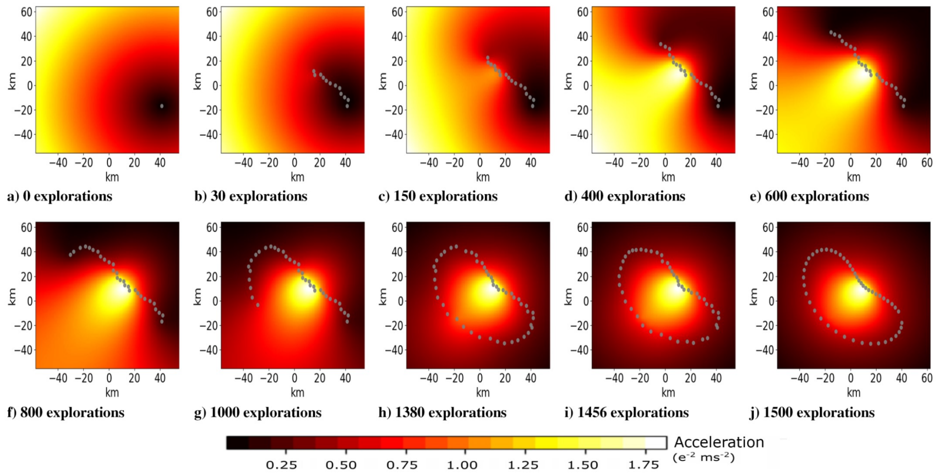
$$\mathbb{G} = G\sigma\pi abc \int_0^\infty \frac{\delta(p,v)}{\Delta v} dv \tag{3.1}$$

where G is the gravitational constant, σ is the mascon density and πabc is the ellipsoidal volumetric extent. The integral accumulates the gravitational contributions over the mascon function $\delta(p,v)$ observed by the spacecraft's position p and velocity v over the changing velocity Δv in response to encountering a shift in the gravitational influence. Figure 3 shows the iterative model for replanning trajectories and updating the gravity model during progressive spacecraft maneuvers (study **I**).

Simultaneously, the spacecraft is able to perform increasingly stable maneuvers respecting the updated gravity field map of the target body and, in the process, optimizes the onboard fuel utilization. A receding finite-time horizon motion planning optimizes the trajectory replanning as follows–

- Consider the initial field model to plan the initial trajectory.
- Perform real-time updates to the onboard gravity model.
- Simultaneously optimize the trajectory that minimizes the cost.
- Replan and execute the trajectories based on the updated gravity.

Given an *a-priori* gravity field model, smoother orbital maneuvers are performed progressively, ensuring that updated gravitational influence is respected while ensuring that optimized fuel utilization with each orbit as illustrated in Figure 4 and Figure 5, respectively. The maneuvers are planned over in-orbit waypoints as explored and sampled during real-time measurements (see algorithm 3



a) 0 explorations **b) 30 explorations** **c) 150 explorations** **d) 400 explorations** **e) 600 explorations**

f) 800 explorations **g) 1000 explorations** **h) 1380 explorations** **i) 1456 explorations** **j) 1500 explorations**

Figure 4: Updating gravity model and spacecraft trajectory

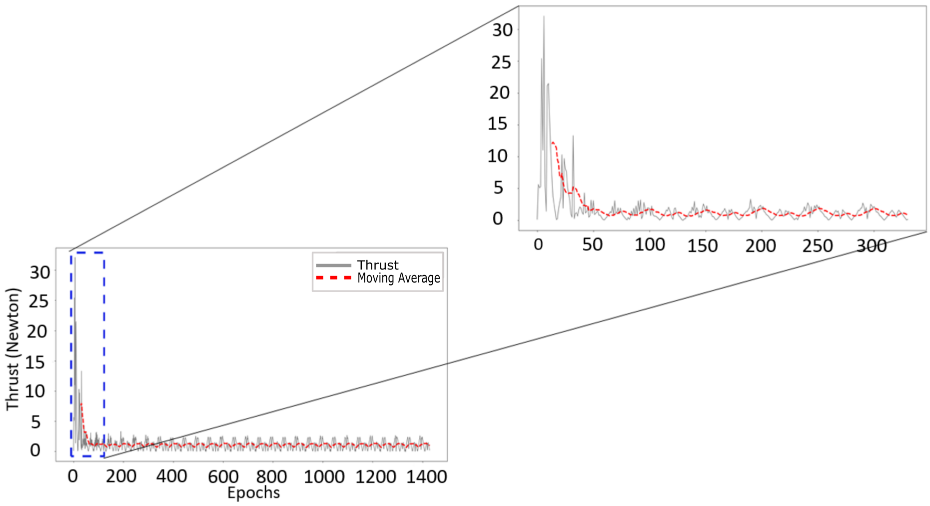


Figure 5: Thrust trends using the replanning model

in study **I**). This work develops a motion planning approach that considers an ever-changing gravitational field to produce a set of viable in-orbit waypoints for the spacecraft to safely navigate in the vicinity of the small body. In the process of performing the maneuvers, the spacecraft updates its onboard gravity field model, hence producing a more detailed force field as compared to remote observations. The approach to performing multi-point measurements is synonymous with a multi-agent system performing spatial observations as discussed in Section 3.2 in the context of this thesis.

3.2. Multi-Agent Rendezvous

The concept of multi-agent rendezvous with small solar system bodies presents a significant opportunity for advancing our understanding of these celestial objects, which are often characterized by high traveling velocities and transient surface events. Traditional flyby missions conducted by individual spacecraft are typically focused on specific regions of the target body, potentially resulting in the oversight of critical features or phenomena that hold considerable scientific and galactic importance. In contrast, a multi-agent mission has the capacity to gather data from diverse spatial locations, thereby enhancing the breadth of observations compared to missions reliant on a single spacecraft. This capability is particularly essential when interacting with pristine celestial bodies. The systematic mapping of such targets through the deployment of multiple spacecraft is crucial, especially in scenarios where measurement opportunities are restricted by both time and spatial constraints. Consequently, the acquisition of comprehensive information regarding the target body can be greatly improved through coordinated spacecraft maneuvers from various orbital positions, ensuring substantial scientific returns.

Transient events relating to small bodies include the emancipation of jets from their surfaces (Knollenberg et al. 2016), morphological evolution (Zhang et al. 2021), high rotational parameters (Panicucci et al. 2023), and other intrinsic attributes that are characterized by rapidly changing states. From an extrinsic point of view, the velocities at which bodies like comets traverse through the celestial space are also transient given their briskly changing positions. This makes it challenging to observe the bodies, where the scientific objectives are subjected to incident solar angles, the environment of the body (in comets, the presence of volatile ices - Oza et al. 2024 and interstellar dust making it difficult to observe the nucleus), and apparent distances of the observing spacecraft from the body. Given an event scenario where the object's motion in space is dynamically characterized by high velocities, relatively low observing opportunities prevail. This is akin to efficiently utilizing the onboard resources to maximize the scientific returns. In lieu of performing proximity observations and surveys, a multi-agent system proposes a more concrete return of data and understanding than single-agent exploration, especially for a fly-by scenario. For example, according to Bull et al. 2021, assuming realistic mission conditions, a multi-agent system would be able to obtain mass estimates of previously visited asteroids and achieve better than 25% 1σ accuracy in mass measurements.

On the value of multi-point measurements, study **II** elucidates on missions like Giotto (Wilkins 1988) offering large-scale measurements, however performed, on a single flyby path, and Rosetta (Villefranche et al. 1997) lacking large-scale multi-point measurements to survey the cometary activity. Moreover, a multi-spacecraft encounter allows exploration over various trajectories covering both large and small-scale surveys, from different positions, to allow the 3D modeling of the target or event.

Figure 6: Comet 67P-CG imaged by Rosetta (6a) and in TO Facility (6b) and in the simulation environment (6c)

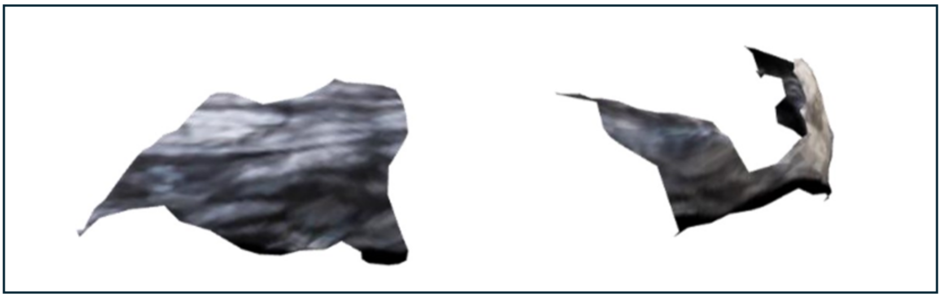
The work presented in study **V**, samples spatial positions for a multi-agent system whose positions can be prescribed within a volumetric space and optimized over the observing constraints. The solutions from the sampler are used to observe the flyby event instance to evaluate the observational criteria. While respecting the observational extents, the agent's positions are assimilated at the instance with the highest target coverage by the onboard sensors.

$$\lambda_i = \lim_{n \to \infty} \frac{1}{n\Delta t} \sum_{k=0}^{n-1} \ln \| J(x_k) \cdot \mathcal{W} \| \tag{3.2}$$

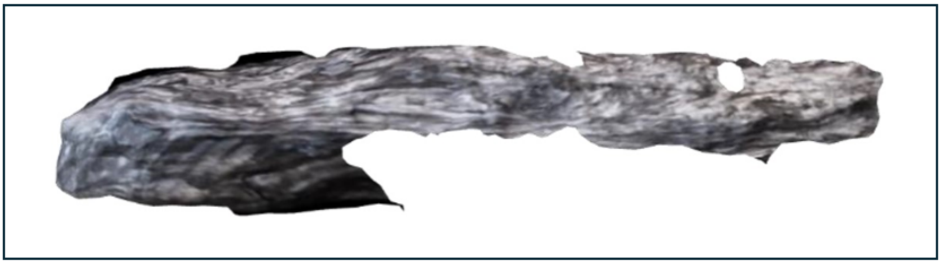
where λ_i formulates the positions within time averaged over n steps between Δt intervals. The long-term behavior ($n \to \infty$) over Jacobian J defines the asymptotic sampling for the basis vector $\mathcal{W}$, together, which gives the dynamic state of the system. In principle, it defines the evolution of the trajectory of the target body for which the optimal positions are to be ascertained.

Tartu Observatory Space Mission Simulation Center, as a physical site, offers the possibility to perform experiments and validate the developed method. The site was digitally reconstructed to simulate optimal positions. The experiments were then replicated and performed at the physical site. Images shown in Figure 6 depict similar views of Comet 67P-CG (a) Image taken during the Rosetta mission (Vincent 2014); (b) Imaged at Tartu Observatory (TO) facility; (c) Image rendered from the simulation environment (study **V**). A 3D printed scaled-down model of Comet 67P (public archive ESA Science et al. 2020, model obtained from Bruno 2020 License-CC 4.0, Attribution 4.0 International) was used to capture the images of Comet 67P, as shown in Figures 6b and 6c. Both figures illustrate the target body captured from the position sampled by the aforementioned sampler, substantiating the methodology and coherence between data obtained from a planned mission and the ability to represent data from physical facilities. This promotes the development of scenarios for potential upcoming missions as well as to be able to reconstruct heritage mission observations for further investigation. A line camera setup, discussed in Section 4.2.2, simulates a small-body flyby scenario aiding in optimally placing agents to observe the target on its fleeting trajectory.

Fusing multi-agent measurements expands the study on the exploration and characterization of pristine bodies to better understand their constitutional elements, map natural dynamic phenomena, and progress in situ resource utilization. It also progresses the development of efficient landing strategies, tag-along companion missions, and develops a holistic understanding of complex cometary processes like outgassing (discussed in study **II**). Reconstructing the terrain perturbations helps in studying surface intrinsic and craters formed due to the probable impact of foreign bodies and micrometeorites.



a. single-agent reconstruction



b. multi-agent reconstruction

Figure 7: Surface reconstruction of a simulated Oumuamua flyby

With spatial positioning and multi-point measurements, discrete geometric reconstructions are performed to produce a more informed surface reconstruction than single-view observations, as shown in study **III**. A flyby event of the Oumumua target model (obtained from Pillitteri 2021; License-CC 4.0, Attribution 4.0 International) was developed and observed using a fleet of observing spacecraft, and surface reconstruction was performed from the images obtained to produce the surface profile. Figure 7 shows the surface reconstruction of a target model of Oumuamua. Significant surface-coverage differences are presented through the reconstruction performed using the observations from a single agent (Figure 7a) versus multiple agents (Figure 7b) from different spatial locations, thus asserting that visually comparable returns can be obtained through a multi-agent system for studying more dynamic targets.

Participating spacecraft can be positioned in relatively optimal spatial locations to be able to observe a *once-in-a-lifetime* target. The multi-agent configuration, as discussed in this section, produces the ability to develop more informed reconstructions based on spatially acquired optical data. Moreover, given a dynamic event, in the likes of a high-velocity small body fly-by or jets erupting from the surface of a comet, a chaotic sampler is developed that produces a set of optimal locations within a defined space, where multiple participating agents can be positioned in order to observe the event. This formalism can be extended to heterogeneous agents where the spacecraft fleet can be tracked using multiple participating ground stations, as shown in study **IV**.

3.3. Morphology Survey and 3D Reconstruction

Identifying surface features on small bodies is based on the ability to return high-resolution data using the onboard capabilities, essentially provided by different instruments measuring different parameters of the target body. This requirement is applicable to all planetary surface studies, but it poses particular challenges for small bodies due to their irregular shapes and diverse surface formations, which include boulders, ravines, ridges, granular materials, craters, fissures, and cliffs (Murdoch et al. 2015). Some common features and formations appearing on asteroid surfaces are shown in Figure 8 (acquired from NASA and Jet Propulsion Laboratory (JPL) public archives). The features depict (a) pit chains formed on Lutetia, (b) boulders on Bennu, (c) craters on Eros, (d) modification of topography by grooves on Vesta (e) formation of ridges on Eros. Geological mapping of small bodies, as demonstrated by El-Maarry et al. 2015 and Michikami et al. 2019, indicates that accurate geological interpretation of surface features necessitates a representation capable of delineating surface morphology for further analysis related to composition, as well as the transportation of local and foreign regolith and materials.

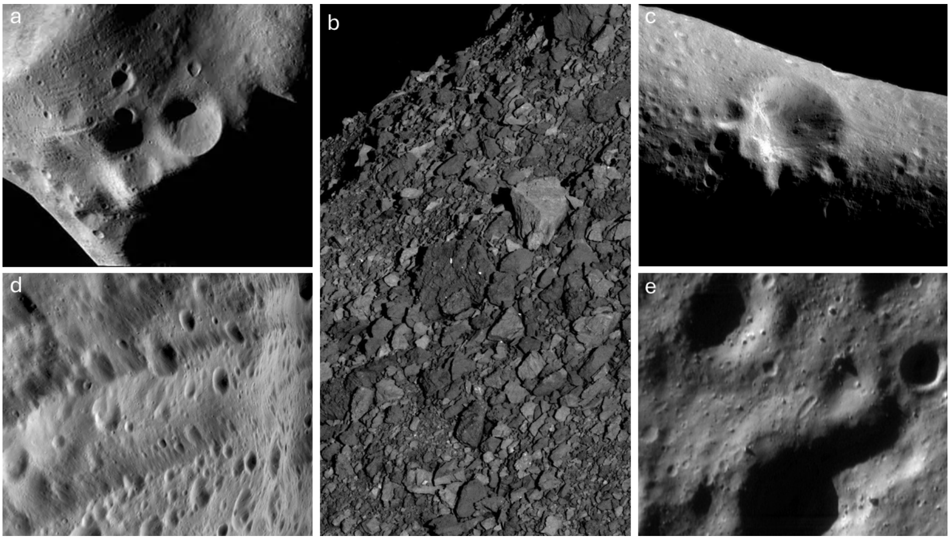


Figure 8: Lineaments observed on asteroid surfaces

Besides the instrument and sensor suite, the mission relies on the efficient trajectories and *observing in the right directions* - aspects which are always challenging for missions to bodies hosting dynamic environments. For a single-agent flyby mission, it is likely that roughly half the target remains unobserved, i.e. it is not illuminated and not visible. To gain some form of reconstruction bias, the observed map of the nearside, which is constructed from a series of images using methods of photo-clinometry, stereo-photogrammetry (Preusker et al. 2015, Palmer et al.

2022, Jorda et al. 2016), is used to estimate the surface properties of the farside. In principle, if half of the target is accurately reconstructed, with virtually no margin for error, then the fluctuation margin of the farside reconstruction is also significantly smaller (Ďurech et al. 2015). Data obtained through remote and proximity missions using methods like photometry (Chiorny et al. 2023) and spectroscopy (Popescu 2012) have helped produce 3 Dimension (3D) models, Digital Terrain Model (DTM), Digital Elevation Model (DEM) of the surface morphology. The reconstruction fidelity, however, depends on the data being directly usable (containing identification points on the surface, etc.) and of high resolution (there is no ill-posedness). This has advanced investigations into their surface activities and potential evolutionary states regarding active small solar system bodies (Lin et al. 2015). The study on multi-agent positioning discussed in Section 3.2, showed that being able to observe a small body holistically, requires multi-point measurements that can be produced through a multi-agent system positioned at optimal locations or a spacecraft navigation and performing strategic in-orbit surveys (see section 3.1). However, data received from spacecraft are often subjected to inevitable environmental conditions, especially for active small bodies. Factors like outgassing dust (and ices) emanating from the surface notably pollute the images. Moreover, the challenge arises when corroborating with data using spatial observation, in the nature of space exploration, which is limited by non-uniform illumination and viewing angles. These activities, if not modeled and corrected, pose a challenge in performing geometric reconstruction, which primarily requires high-quality images and overlapping surface features within the acquired image dataset from a mission. Additionally, instrumentation and engineering factors, like optical blurs and de-focused images, affect the geometric reconstruction. Traditionally, in-situ imaging and mapping asteroids is an extreme example of disk-resolved images from known methods of small body mapping (Durech et al. 2015). These are resolved surface modeling and reconstruction, which are generally cartographic solutions, given the availability and resolution of the data.

Using recent machine-learning-based advancements in 3D reconstruction, Neural Radiance Fields (NERF) (Mildenhall et al. 2020 and Chen, S. et al. 2024) provides the opportunity to generate high-resolution, continuous 3D representations of complex scenes from images. Given the inherently complex nature of small-body surfaces, it is essential that the sparse mission data is supplemented with ‘near-expected’ views that are occluded or challenging to acquire during the mission. To address this, study **VI** produces neural morphological representations of the target body using multi-view observations under varying illumination angles; data for which is obtained through two sources. First, multi-point spatial images of the target body is captured within the physical facility at Tartu Observatory and second, images from a physics-enabled simulation environment of the same body are rendered. Figure 9 presents the body imaged from varied locations, in both environments, presenting different views of the target. Images (a-c) are captured from the physical facility, and images (A-C) are rendered from the simulation environment. Efforts were made to capture the target from similar viewing directions, analogous to those obtained from a space mission, and from controlled lab environments. The images presented are a representative subset of a sizable dataset, containing multiple images obtained from varied angles and positions. The images are used as inputs to a Machine Learning (ML) workflow. Methodologically, the following steps are performed -

- The images are used as inputs to train a fully-connected Multi-Layer Perceptron (MLP) that maps spatial coordinates (x, y, z) and viewing directions (θ, ϕ) to corresponding view-dependent color (c) and density values (σ).
- A volumetric function renders the individual pixel colors by modeling the light interaction through the scene i.e., accumulating the contributions of sampled points along a ray.
- A continuous volumetric representation is produced as a 3D model.
- The morphological features are extracted and surface fitting is performed.

Radiance fields demonstrate capabilities to represent regions characterized by sparse image coverage and variable lighting conditions, attributes that are commonly associated with irregularly shaped and unevenly illuminated small solar system bodies. The process enables identifying the facets for performing near-realistic 3D reconstruction from data obtained from real space missions under challenging observation conditions. This is primarily an understanding that the proposed method is applicable to realistic mission data, given that we respect the requirements of the approach, data availability and facets required for training the neural network.

The process workflow demonstrates the augmentation of neural field representation toward small body morphological study, for which the surface renders are shown in Figure 10. Visual representation of the difference in the level of detail (triangulated nodal meshes) between the (a) ground truth model and (b) neural rendered model, with their corresponding meshes in Figures (c) and (d), respectively, is illustrated. The neural representations produce novel viewing directions based on the provided images that further enhance the 3D model reconstruction of the target body, which is especially occluded through natural cosmological constraints. By synthesizing the surface morphology, the approach complements standard practices in surface reconstruction, such as photo-clinometry (Craft et al. 2020) and stereo-photogrammetry (Oberst et al. 2014), with neural representation to achieve high-fidelity surface reconstructions, henceforth presenting novel yet scientifically processed views. The study also provides insights into the capabilities of the current physical setup at Tartu Observatory and identifies an emerging mapping technique that can produce scientifically relevant results, applicable to small body exploration.

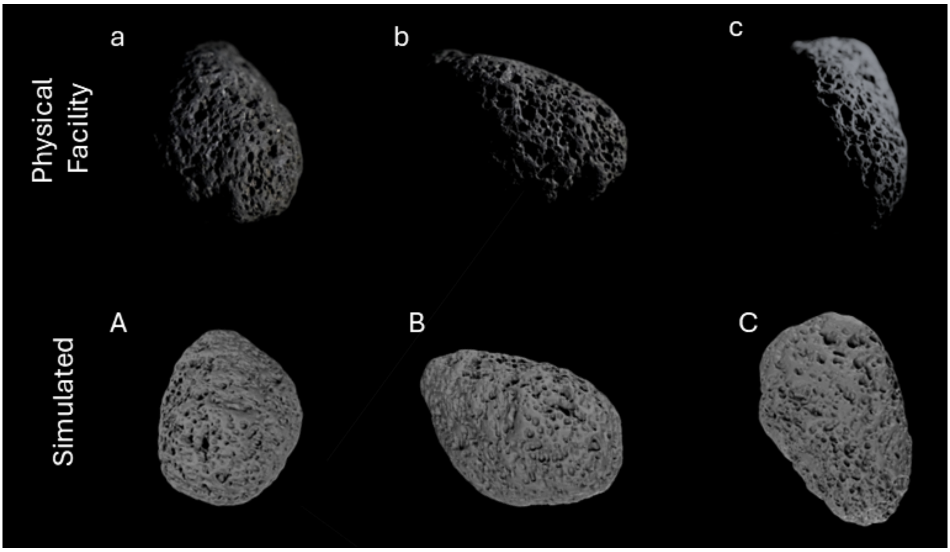
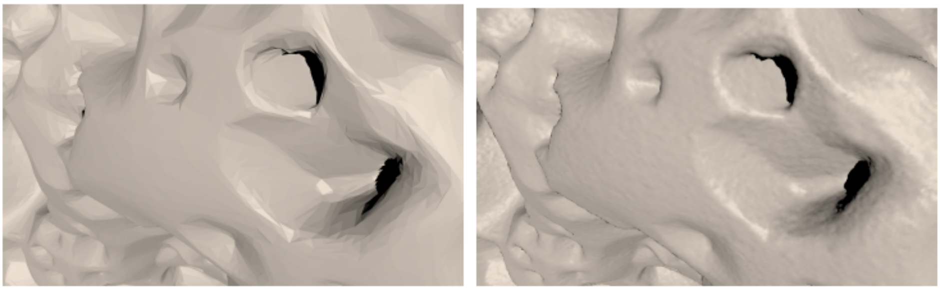
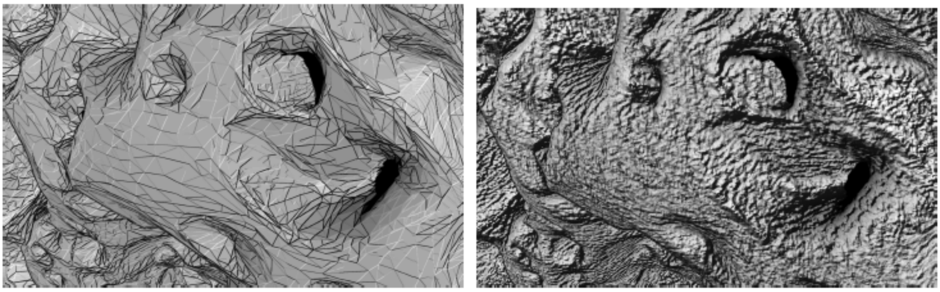


Figure 9: Small-body target imaged from different spatial locations



(a) Ground truth surface render (b) Neural surface render



(c) Meshes for the ground truth surface render (d) Meshes for the neural surface render

Figure 10: Surface render of the target body

4. MISSIONS AND ANALOG STUDY

4.1. Comet Interceptor mission

Developed by the ESA in partnership with the JAXA, the Comet Interceptor (CI) (study **II**) mission represents a strategic paradigm in both target selection and spacecraft deployment architecture. Scheduled to be launched 2029, the primary objective is to intercept a Long-Period Comet (LPC), which is potentially a Dynamically New Comet (DNC), or potentially an Interstellar Object (ISO), making its first entry into the inner solar system; thereby enabling the study of minimally processed, primordial material. The scientific theme based on the in-situ exploration of the target focuses on 1) surface composition, 2) shape, 3) morphology, and 4) structure. The intercept will involve a close-approach flyby scenario using a primary spacecraft A, and smaller probes named B1 and B2 carrying payloads until the flyby, and delivered to different flyby trajectories, allowing the remote and in situ multi-point observations of the comet and its coma as shown in Figure 11. The main spacecraft is planned to pass at a distance of 1000 km from the comet, while B1 and B2 at 850 km and 400 km, respectively. The mission profile is developed on a distributed, multi-agent system, where two relatively smaller, autonomous probes accompany a principal spacecraft. This coordinated configuration enables simultaneous, multi-point observations of the target during a high-velocity flyby, offering a more spatially resolved dataset than would not be possible with a single spacecraft.

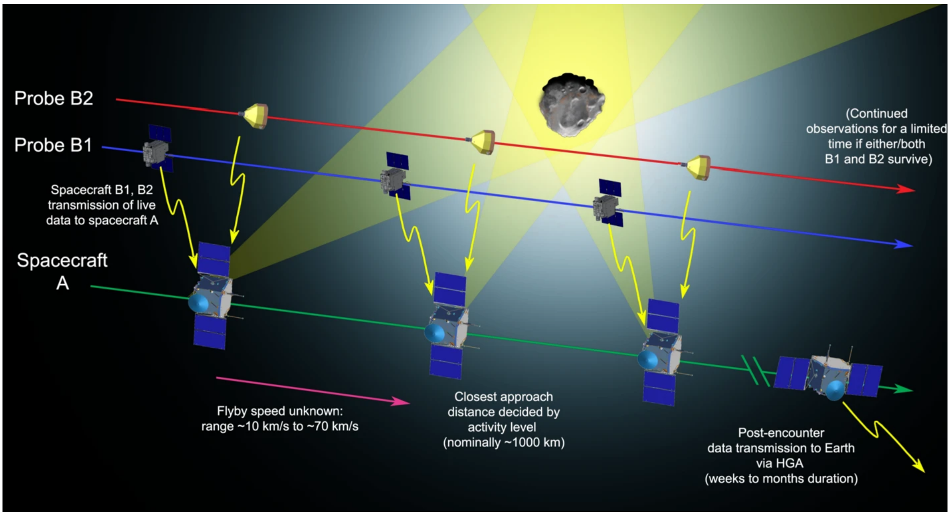


Figure 11: Sketch of the Comet Interceptor flyby

This work is licensed under Open Access Creative Commons Attribution 4.0 International License; Jones et al. 2024 (study **II**)

The mission resonates with the emerging paradigm of multi-agent exploration in the study of small solar system bodies as explored in this thesis. From the mission point of view the following operations are identified -

- Following launch, the spacecraft system will remain on standby at the Sun-Earth L2 (SEL2) point, awaiting the identification of a suitable target by astronomical surveys.
- Upon target selection, the spacecraft ensemble will execute a trajectory maneuver to intercept the target.
- As it approaches, the two probes will be released to perform synchronized flybys from differing trajectories and distances, allowing for heterogeneous data collection across the target's coma, nucleus, and surrounding environment.

OPIC instrument is planned to be placed on Probe B2 to image the comet and its near environment (Figure 12). At far away distances, where the cometary nucleus is not resolved, OPIC shall take long exposure images to image the amount and spatial distributions of gas and dust within the field-of-view. When the nucleus is resolved, the comet's nucleus shall be imaged. Simulated scenes [1] that shall be potentially observed from OPIC's observing direction are illustrated in Figure 13 (rendered by Mihkel Pajusalu-OPIC PI; Pajusalu 2019). The images captured from OPIC along with images from platforms A and B1 shall be combined to generate a 3D model of the comet.

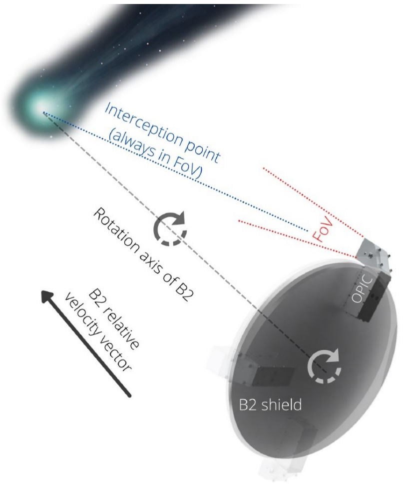


Figure 12: OPIC field-of-view with B2 flight geometry

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[1] Video simulation can be found at https://tospexgroup.space/projects/opic/

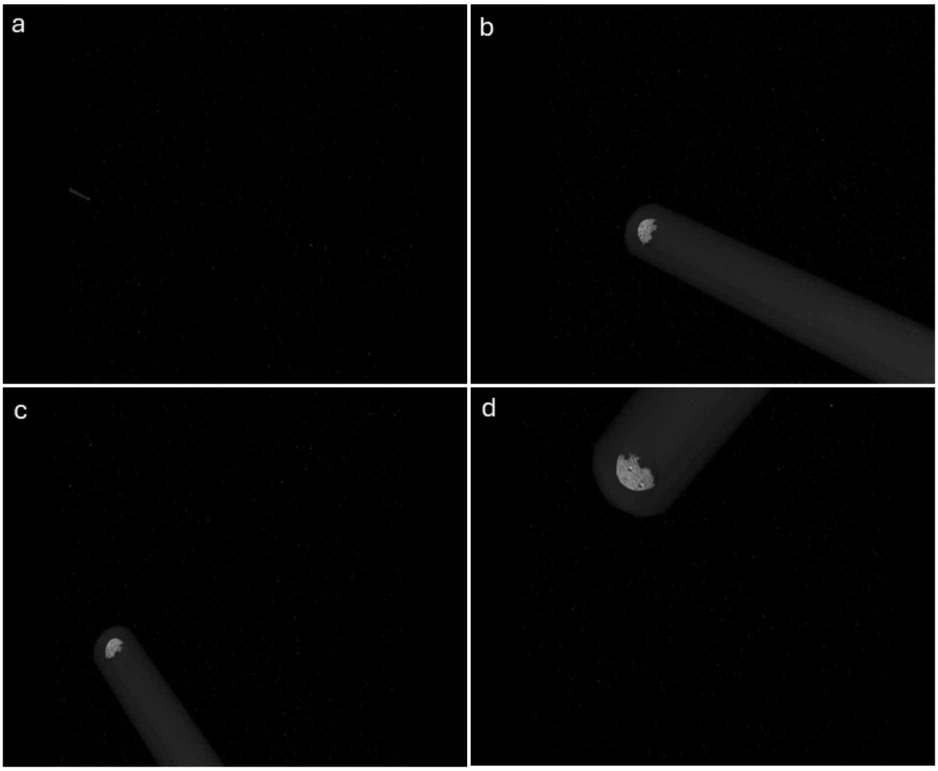

Figure 13: Simulated incremental sequence of datastream (decreasing distances a-d) expected to be observed by OPIC during cometary encounter and flyby

Each component of the multi-agent system is equipped with specialized instrumentation tailored to capture complementary datasets—including high-resolution imagery, dust and gas composition analysis, and solar wind interaction measurements, thereby maximizing the scientific return through distributed sensing and observation. Scientific instruments include COmet CAmera (CoCa), Modular InfraRed Molecules and Ices Sensor (MIRMIS), Mass Analyzer for Neutrals in a Coma (MANiaC), Dust, Fields and Plasma (DFP), Hydrogen Imager (HI), Plasma Suite (PS), Narrow Angle Camera (NAC), Wide Angle Camera (WAC) and Entire Visible Sky Camera (EnVisS). More details about specific instruments can be found in study **II**.

The multi-agent framework enhances the spatial coverage and is expected to survey transient phenomena, like morphological changes in the nucleus, dust and ice activity and significant wave activity, along various paths within the comet's vicinity; objectives that can be accomplished by a multi-spacecraft mission. By decoupling observation roles across multiple platforms, the mission mitigates risk and increases redundancy, ensuring that high-priority data can still be obtained even in the event of partial system failure. For a deep space mission, it is required that the precise location of the spacecraft with reference to the target comet is available. This can be achieved through ranging the spacecraft with the other participating spacecraft, celestial bodies, or referencing other artificial agents (study **IV**). This presents a salient feature that advocates the use of multi-agent systems. Moreover, the dynamic allocation of roles among agents during the flyby supports real-time adaptability, a capability increasingly vital for missions targeting transient or unpredictable solar system bodies. The mission architecture, being modular and reactive, is a demonstration of the symbiotic merger of space exploration with distributed robotic systems (Matsuno et al. 2022). Should the target be an interstellar object, this architecture would enable the first-ever in situ, multi-point investigation of material from beyond the solar system, underscoring the value of agent cooperation in exploring previously inaccessible scientific expeditions.

In the context of this thesis, applicable parallels related to small body exploration with regard to the Comet Interceptor mission (study **II**) are discussed below.

- Using the optimal positioning study (study **V**), the spacecrafts' spatial position can be ascertained given the knowledge of the target's trajectory, to intercept and observe it from scientifically strategic positions.
- The positions can be referenced by tailoring the ranging methodology to the mission profile (study **IV**)
- With the multi-point observations, the morphology can be reconstructed (study **III, VI**)
- Given the instantaneous flyby event, near-body environment mapping can be achieved using the onboard sensor suite to model (and update) our remote observation models of the target body with proximity mapping and measurements (study **I**).

As space exploration transitions toward more agile, reactive, and cooperative paradigms, multi-agent systems to be deployed for missions like Comet Interceptor are poised to play a central role in unlocking the complex and dynamic environments of comets, asteroids, and other small bodies. This mission, therefore, not only advances cometary science but also establishes a technological and conceptual framework for the next generation of space exploration initiatives.

Other space missions have augmented our understanding of small solar system bodies, revealing them to be dynamic and complex worlds. In the context of the thesis and the approaches, some relevant missions are briefly discussed below.

Collaborative efforts within the Asteroid Impact and Deflection Assessment (AIDA), NASA's Double Asteroid Redirection Test (DART), launched in 2021, marked humanity's first attempt to alter the orbit of a celestial body as part of efforts to test planetary defense strategies. The spacecraft targeted Didymoon, a small moonlet orbiting the larger asteroid Didymos and successfully impacted it on September 26, 2022. The orbital period of Didymoon was altered by 32 minutes, from 11 hours and 55 minutes to 11 hours and 23 minutes, with an uncertainty margin of $\sim \pm 2$ minutes (Science NASA 2020).

This demonstration proved that kinetic impactors could feasibly be used to redirect potentially hazardous asteroids, marking a major milestone in planetary defense. Following up with the ESA HERA mission (currently on route to Didymoon at the time of compiling this thesis) will study the aftermath of the DART impact and perform a detailed survey of Dimorphos and the impact crater, providing critical data about the structure and composition of the asteroid and its response to the impact. The Psyche mission, launched by NASA in 2023, targets a unique object in the asteroid belt: Psyche(16), a metal-rich asteroid proposed to be the exposed core of a protoplanet. Compared to rocky or icy asteroids, remote observations reveal Psyche to be composed of nickel and iron metals, resembling Earth's core. This presents a rare opportunity to investigate planetary differentiation. The spacecraft is planned to orbit and survey the asteroid's gravitational field influence as well as gather data using multi-spectral imaging, spectrometry, and magnetometry to analyze its endogenous properties. The Rosetta mission, led by ESA, was the first spacecraft to orbit and land on a comet. Launched in 2004, the mission revealed dramatic surface changes and volatile outgassing, reshaping our understanding of cometary activity. Accompanied by a lander Philae, Rosetta was characterized as a multi-agent mission using heterogeneous spacecraft to explore a dynamically active small body. NASA's New Horizons mission provided humanity's first close-up look at the KBO Arrokoth. The flyby of Arrokoth in 2019 offered insight into early solar system formation processes, transmitting images of a contact-binary, henceforth developing insights on different processes that could result in the morphological formation of such entities. To summarize, the approaches mentioned in Section 3.1, 3.2, 3.3 find applicability to support the mission directions and data processing. For the HERA mission, developing a terrain representation of the aftermath of the impact is plausible through the studies in study **III** and study **VI**. Using the same studies, morphological reconstruction can also be augmented for the Rosetta mission for surveying temporal surface changes. Within the Psyche mission, the approach in study **I** can be tailored for generating high-fidelity in-orbital environment maps. For a multi-agent system, participating ground stations (also reference stations in the space segment) can be used to gather orbital positions of the participating spacecrafts (study **IV**) to further optimize the trajectories, especially for deep space missions.

4.2. Analog Study

Analog study finds relevance towards all planetary science endeavors. In general, it acknowledges the output produced by the systems and instruments through campaigns performed in terrestrial environments that are characterized by extra-terrestrial attributes. While primarily these refer to outdoor environments, for example Mt. Etna as a Venusian analog (D'Incecco et al. 2024) and Barringer Crater for impact studies (Masaitis 2006), a plethora of experiments are now being performed indoors by setting up near-realistic space conditions. Indoor facilities enable setting up controlled environment conditions that are useful towards validating and verifying system and sensor responses towards varied scenarios that the spacecrafts (including and not limited to rovers, submarines, drones etc.) shall encounter during different phases of their mission. Relevant studies to different planetary bodies like the Moon (M. Pajusalu 2022; Casini et al. 2020) and Mars (Estlin et al. 2005; Allouis et al. 2015), have shown the possibilities of the performing mission operations within the framework of the analog facility to assert incremental Technology Readiness Levels (TRL) for individual instruments as well as the system, as a whole. For small body explorations, as a minimum, a dark environment, an illuminating source, and a target model suffice for a range of imaging and scenario-based studies, including testing and calibrating instruments. Further facilities, including robotic (Ragan et al. 2024) and moving platforms (Kolvenbach et al. 2016), enable additional kinodynamic scrutiny for mission development. Tartu Observatory hosts a physical analog to advance small-body studies. This section illustrates the scientific exploration of small-body scenarios within the Tartu Observatory Space Mission Simulation Center. Within the following text, we consider the cameras posing as potential spacecraft that observe the target body. Two different configurations are discussed: a small-body flyby setup and spacecraft flyby, along with performing multi-point imaging of the target body.

4.2.1. Spacecraft FlyBy

As shown in Figure 15, a taut wire runs across the length of the facility bearing a line camera. In principle, the linear path is considered to be a smaller segment of a longer spacecraft trajectory for a mission. In terms of high-velocity flybys, relative to the target object, the spacecraft maneuvers are mostly defined by a linear trajectory. The system is capable of mounting different instruments of considerable weight. Ideally, a mounted camera replicates a spacecraft performing a proximity flyby. By placing the target body to be observed within the field-of-view of the camera, at different locations, visual data for a variety of flyby scenarios can be simulated. This configuration represents the data gathering within the instrument reference frame. A sequence of images captured from the camera-mounted configuration is shown in Figure 14. From left to right (Figures 14a-14c), the images portray decreasing distances between the camera and the target body, representing the scenario of a ‘spacecraft’ approaching the target body performing a proximity flyby.

Figure 14: Views from the onboard camera captured during flyby of the target

4.2.2. Small-Body FlyBy

Converse to the spacecraft flyby mentioned in section 4.2.1, a proxy target resembling a small solar system body target can be mounted on the system (Figure 15). This can then be observed by instruments placed at different locations (study **V**) and target flyby data is gathered.

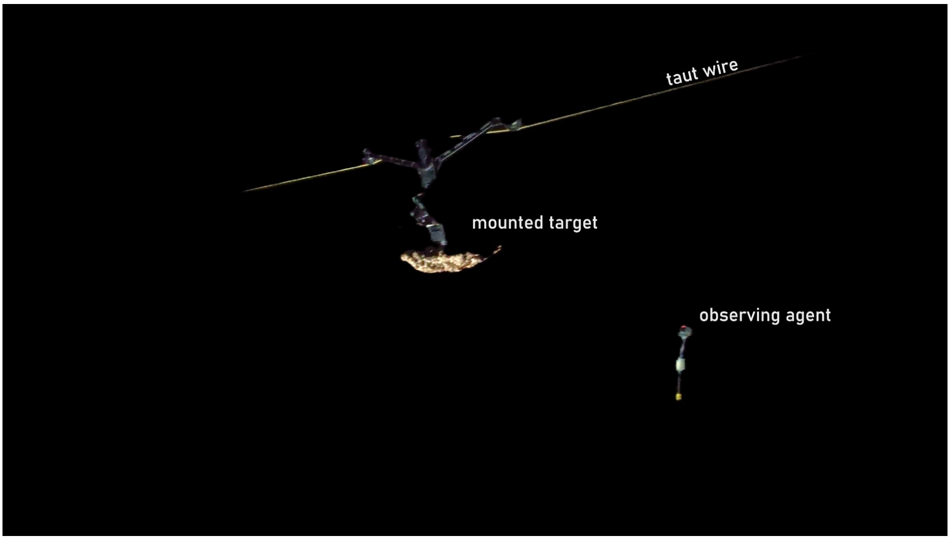

Figure 15: Target body mounted on the line camera

4.2.3. Multi-Point Imaging

Given the above-mentioned configurations, it is possible to increase the number of observing agents, especially for the small-body flyby scenario. For instance, by considering a fleet of cameras posing as spacecraft, multi-point observations can be performed for a flyby event, thus imaging the target body from varied spatial locations. Figure 16 illustrates the cameras placed at different locations to observe the target body. It is to be noted that in either case, discussed in Sections 4.2.1 and 4.2.2, the motion of the target body and the spacecraft is considered relative to each other. For higher fidelity and more realism, it is expected that both the observing agents and the target body should be in motion with respect to the laboratory frame of reference, which could be planned in future developments within the analog facility.

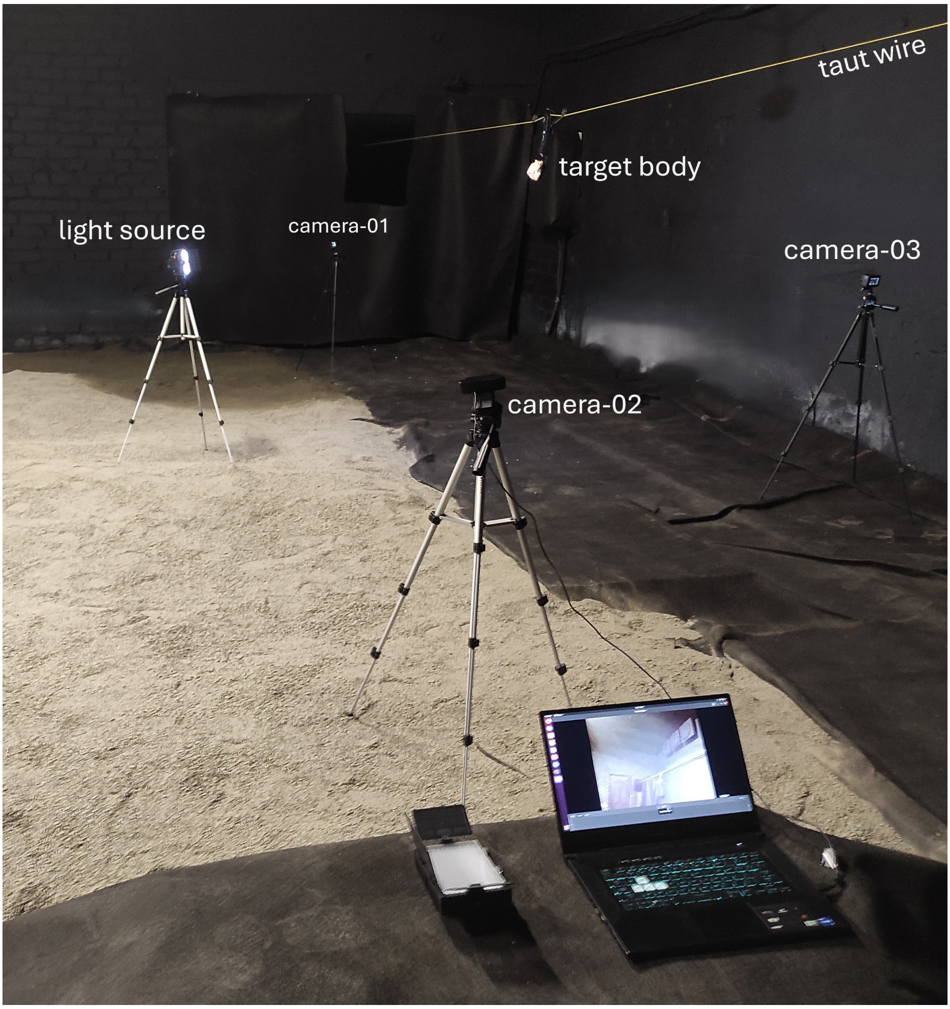

Figure 16: Multi-agent configuration observing a target-mounted flyby

5. DISCUSSION AND CONCLUSION

The traditional view of small solar system bodies such as asteroids, comets, and Kuiper Belt objects, as inert, primitive remnants of early planetary formation, has undergone a profound transformation. These objects are now recognized as dynamic, evolving entities influenced by a range of physical, chemical, and geological processes. This drives significant advancements in observational capabilities and a new era of exploratory missions, which continue to reveal the complex behaviors and characteristics of these bodies.

As active participants in the solar system's continuous evolution, these bodies exhibit signs of transient activity, such as outgassing, surface renewal, and impact-driven changes, that reflect both external influences, like solar radiation and space weather, and internal dynamics, such as structural instability or potential volcanic processes. Understanding these processes is vital not only for reconstructing the early conditions of the solar system but also for understanding celestial dynamics and guiding future exploration strategies. The growing catalogue of data acquired from telescopic surveys, in situ observations, and flyby missions has expanded our knowledge base and deepened scientific curiosity. Challenging missions have presented commitments to understanding the diversity and complexity of these small bodies. These efforts demonstrate the necessity of developing adaptive mapping and characterization methodologies that can account for their dynamic nature and transient phenomena.

This thesis contributes to advancing small body sciences by developing methods that collectively build a higher cognizance of the target small body, as briefed below.

First, in study **I**, the approach to map the gravitational influence of small bodies from the vicinity is presented. By performing in-orbit gravimetric mapping and simultaneously optimizing the spacecraft's maneuvers to attain smoother trajectories, it is shown that within a dynamically changing environment, the motion plans of a spacecraft can be modified in real time and higher fidelity surveys can be performed. This is synonymous with in-orbit multi-point measurements to produce near-environment maps of small bodies.

Second, a mission named Comet Interceptor (study **II**) was progressed to observe, image, and perform near-body measurements of a comet (potentially an interstellar body traversing at a high velocity). Using a multi-agent topology, the mission aims to study the activities in the comet's coma, produce 3D models of its nucleus, and eventually be able to holistically map and characterize the target.

Third, it is shown that performing multi-point observations (study **III**) of a spacecraft performing a flyby (characterized as a transient event in space) ensures higher coverage, resulting in producing more informed 3D reconstructed surface models of the target body. The study also elucidates the use of multiple participating ground stations to estimate the locations for the spacecraft, as in study **IV**.

Furthermore, it is demonstrated in study **V** that strategically positioning a fleet of spacecraft to observe the target leads to more efficient data acquisition and further investigation of the target body. The developed sampler helps to produce a set of viable spatial locations defined over the scientific requirements of the mission. The optical data acquired through spatial observations by multiple agents can be processed by neural reconstruction to produce novel views (study **VI**), especially for targets that present limited observational opportunities, for example, by occlusions and non-illuminated regions. By modeling light interactions with the target body, surface features can be resolved by training the neural model for the morphological convergence to produce views that provide representative estimates of the geological formations.

Overall, the methods find direct application towards challenging missions like the Comet Interceptor (study **II**), which aims to be one of a kind, to intercept an interstellar object, thus laying new paradigms towards the exploration of the inhabitants of the celestial expanse.

The use of multi-point observational strategies has proven critical in mitigating uncertainties introduced by variable external conditions and sporadic activities. Such approaches enhance the reliability of scientific interpretations and improve the resolution of spatio-temporal phenomena encountered during missions, thus advancing the study of small solar system bodies through multi-agent mapping and characterization. These bodies offer unique and invaluable perspectives on the processes that have shaped and continue to shape our solar system. They challenge assumptions and serve as natural laboratories for testing scientific hypotheses, methods, and technological innovations. Their study represents both a scientific imperative and an opportunity to refine the tools and frameworks necessary for exploring the dynamic and chaotic nature of the universe.

In conclusion, this thesis conceives the following ideology -

By asserting optimal spatial locations for a multi-agent system, optimizing the motion plans, and respecting the expendable budgets, our missions can effectively map near-body environment, perform morphological surveys, and characterize the dynamics of small solar system bodies.

From a philosophical perspective, this ideology is foundational for establishing rudimentary definitions and developing procedural workflows to build temporal cognizance of ephemeral events.

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ACKNOWLEDGEMENTS

I am greatly obliged to the Republic of Estonia and the Estonian Research Infrastructure, including the Institute of Physics, Tartu Observatory, and the University of Tartu, that enabled me to pursue this thesis with positive support and enthusiasm. Along with the city of Tartu, which provided the scope and reason for bearing good health and vigor throughout. This work resonates through all the people I have met and interacted with during the journey.

Tartu Observatory has been home to numerous techno-scientific research accolades. I am privileged to be a part of this esteemed institution, which rendered aid and assistance towards my research with the necessary guidance, equipment, and foremost, a friendly atmosphere. My gratitude to Dr. Pajusalu, who shaped a researcher in me in his very benign presence, enabling me to wander and pursue my scientific calling. To the Director of Tartu Observatory, Dr. Antti Tamm; Dr. Riho Vendt, Ms. Ulvi Nigol and Ms. Karin Pai who extended a helping hand to all my yearnings. To Prof. Anu Noorma, who nudged my research with a welcoming environment at Tartu Observatory. To Dr. Jaan Einasto, whose very presence nurtured my belief in scientific growth, one day at a time. I am grateful to the TOSpEx for their companionship. This thesis results from the multiple aspirations and goodwill of my grandparents, parents, and brother, who believed in me and supported my endeavors. I owe a great deal to Laima, my life partner, for providing me with comfort, encouragement and bearing with my spontaneous musings. I would like to mention (Lt.) Dr. SVK Dilawar, (Lt.) Mr. Narendra Singh and Mr. Mani Abraham, who laid the foundation of thought and perseverance, that enabled me to develop a scientific rationale towards my research and life. I fervently acknowledge the grants and scholarships, including the Jaan Einasto Scholarship, Charles Villmann Scholarship, and funding from Tartu Observatory, that enabled me to travel to conferences, present my work, and expose my caliber to novel research. Special mention to Dr. Michael Otte and his unwavering support that made my PhD journey valuable. To Jānis Dalbiņš and Dr. Shishir Sankhyayan for their counseling that gave me confidence regarding my work. To Sarthak and Divyansh who never stopped backing me. To Mr. Tanna and Mr. G. Dalbiņš, who through their talks and actions, instilled in me the values of good character and humility. To every other colleague at Tartu Observatory, with whom a simple '*Tere*' (hello in Estonian) made every day worth the effort.

During the development of this thesis, I was made aware of mission designs and concepts to explore planetary bodies and beyond that *vis-à-vis* to the scientific objectives achievable through the fruitful development of the studies presented. I am grateful to the scientists who undertake challenging missions to small bodies that inspire the next generation of research, and in the process, help build candidatures for upcoming planetary scientists.

For in the brightest times of Summer, the warmth paved my way
For in the chilly days of Autumn, the breeze wrapped me with comforting leaves
For in the darkest hours of Winters, the cold nights motivated me.
Estonia, for your times, thank you.

SISUKOKKUVÕTE

Päikesesüsteemi väikekehade uurimine mitme agendiga kaardistamise ja iseloomustamise abil

Päikesesüsteemi väikekehad on juba andnud palju infot meie päikesesüsteemi ajaloo ja kujunemise kohta. Lisaks on nende uurimine aidanud paremini mõista taevaruumi dünaamilist ja kaootilise olemust, sealhulgas erinevate ainete, näiteks vee, levikut kogu Päikesesüsteemis. Vaatamata oma suhteliselt väiksemale suurusele võrreldes planeetidega, on asteroidid ja komeedid planeetide kujunemise, dünaamika ja evolutsiooni puudutava info aardelaekad. Kuna paljud väikekehad mööduvad meist kiiresti või lausa on oma orbiidi kuju tõttu lühikese elueaga, on nende uurimiseks vaja järk-järgult välja töötada, testida ja rakendada uusi meetodeid. Käesolevas töös näitame, et väikekehade uurimist saab edendada arendades meetodeid, mis kasutavad uurimiseks mitut agenti. See võimaldab sihtmärke tõhusalt kaardistada ja iseloomustada ning selle käigus nende kehade läheduses toimuvaid endogeenseid ja eksogeenseid protsesse paremini mõista. Selles väitekirjas esitatakse kolme olulisema uuringu tulemusi. Esimeses uuringus näitasime, et väikeste kehade ebakorrapärase gravitatsioonivälja järkjärgulise kaardistamise abil saab kosmoselaev manöövreid sihtmärgi ümber teha järk-järgult sujuvamaks, luues samal ajal väga peeneteralise gravitatsioonivälja mudeli (võrreldes kaugmõõtmistega). Järgmisena uurisime kosmosemissiooniga Comet Interceptor sarnast juhtu, et selgitada kuidas oleks mõistlik Päikese poole esimest korda sisenevat üsnagi tundmatut objekti mitme agendiga uurida. Comet Interceptori missiooni eesmärk on kolme kosmosesondi abil samaaegselt kaardistada ja uurida puutumatut (potentsiaalselt tähtedevahelist) väikekeha, mõista selle läheduses toimuvat ja luua selle tuuma 3D-mudeleid. Kolmandas uuringus käsitlesime väikekehade jälgimist erinevatest ruumilistest asukohtadest, et tagada mõõtmiste suurem katvus, võimaldades nii luua sihtkehast täpsemaid pinnamudeleid. Lisaks, teades mõõtmisteks optimaalseid ruumilisi asukohti, saab kosmoselaevastik tõhusamalt väikekehade kaardistamist ja nendel toimuvate dünaamiliste nähtuste uurimist plaanida ning kasutada selleks lühikesi kiireid möödalende. Kogutud ruumiandmeid saab kasutada nendest kehadest närvivõrgupõhiste mudelite loomiseks, mis võimaldavad geomorfoloogiliste tunnuste täpset hindamist. Kõik need lähenemisviisid on kasutatavad Comet Interceptori missiooni, mille jaoks Tartu Observatoorium ehitab OPIC-instrumenti, toetamiseks. Teised rakendused selle töö sisule on erinevad väikekehade missioonid, sealhulgas möödalennud, orbiidil toimuvaid uuringud, maandumised ja proovide tagastamised; Kõik need on annavad ainulaadset teavet nii uuritava keha kui ka selle liikumist mõjutavate väliste protsesside kohta. Selle väitekirja eesmärk on panustada tulevaste missioonide kavandamisse ja arendamisse ning uurida pärandandmetest pärinevaid arhiiviandmeid, aidates kaasa teaduslike aspektide uurimisele. Märkimisväärne uurimissuund on ka nende lähenemiste rakendamine planeetaarkaitses.

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2018-2020 **Masters of Science - Robotics and Space Technology (*cum laude*)**
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2013-2017 **Bachelor of Technology - Mechatronics Engineering**
University of Petroleum and Energy Studies, India

Professional Experience

Jul 2020-Present **Junior Research Fellow**
Space Mission: Design and Development
Tartu Observatory, Estonia

Jun 2018-Jun 2021 **Orbital Dynamics Engineer**
ESTCube-2 Satellite
Student Satellite Foundation, Estonia

Jun 2019-Aug 2020 **Graduate Researcher (MSc Thesis)**
Autonomous Motion Planning for Spacecrafts
Tartu Observatory - University of Maryland, USA

Jun 2018-Aug 2019 **Satellite Communication Engineer**
Estonian Student Satellite Foundation
Tartu Observatory

Jun 2017-Jul 2018 **Mechatronics Engineer**
Autonomous Navigation of Unmanned Vehicles
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Professional Training / Workshops

03.2025 **Astrophysical Dust Ices**
Physical Research Laboratory(online)

2024,2025 **EuroPlanet Geology & Planetary Mapping(GMAP) School**
Europlanet Society(online)

09.2024 **Exohost Planet Formation and Population**
Tartu Observatory, Estonia

08.2024 **Microsatellites and their use in planetary and astrobiology research**
Tartu, Estonia

02.2024 **Satellite Data in Water Remote Sensing**
Tartu Observatory, Estonia

09.2023 **ExoHost Stellar Spectroscopy Workshop**
Tartu Observatory, Estonia

08.2023 **EuroPlanet Asteroid Research Training Workshop**
Tartu Observatory, Estonia

08.2022 **IEEE RAS Multi-Robot Systems(MRS)**
Czech Technical University, Prague, Czechia

Conferences

03.2025 **Oral Presentation: Advancing Small Body Sciences: Dynamic Mapping and Characterization**
Tartu Observatory Science Conference, Estonia

02.2024 **Oral Presentation: Morphological Scene Representations-Exploring Small Solar System Bodies** Planets, Exoplanets and Habitability; Physical Research Laboratory, India

09.2024 **Oral Presentation: Environment Scene Representation for Dynamic Event Cognition: Towards mapping and characterizing transient events in planetary bodies** Europlanet Science Congress, Berlin, Germany

09.2024 **Poster Presentation: Radiance Morphological Mapping for Small Body Surface Investigations** Europlanet Science Congress, Berlin, Germany

03.2023 **Oral Presentation: Mapping and characterization of small solar system bodies over simulation-defined multi-spacecraft trajectory models** Flight Software Workshop 2023, JPL | CalTech, USA

01.2023 **Oral Presentation: On the multi-agent monte-carlo convergence for gravimetric distance approximation of pristine targets** Finnish Satellite Workshop, University of Aalto, Finland

01.2023 **Poster Presentation: Tartu Observatory Space Bunker as a Comet Fly-By Analogue Environment** Finnish Satellite Workshop, University of Aalto, Finland

10.2021 **Oral Presentation: Towards endogenous mapping of small solar system bodies during multi-agent rendezvous** International Astronautical Congress (IAC)

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08.2021 **Poster Presentation: Optical Periscopic Imager for Comets (OPIC) Instrument for the Planned Comet Interceptor Mission", Iakubivskyi, I, Paul, A.S. et al.** 35th Annual AIAA/USU Small Satellite Conference, Utah State University, Logan, UT, USA.

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Seminar/Talks

05.2024	**Observations in the right direction - Making sure nothing is left out** Space Technology Seminar, Tartu Observatory
05.2024	**Exploration into Exoplanetary Research** Steallar Physics Seminar, Tartu Observatory
02.2024	**Science of the New Ages - Discourse on India‘s Strategies for Space Exploration;** Seth Anandram Jaipuria School, Kanpur, India
01.2023	**Advancing robotics and space technology towards extra-terrestrial exploration** University of Tartu
05.2022	**Exploring long-period planetary objects** Space Technology Seminar, Tartu Observatory
05.2022	**Towards Multi-Agent Exploration of small solar system bodies** Maryland Robotics Center Research Symposium, University of Maryland, USA
10.2021	**Development of a space environment facility - Motivation and Requisites** Space Technology Seminar, Tartu Observatory
06.2021	**Multi-agent rendezvous with small solar system bodies** Space Technology Seminar, Tartu Observatory
10.2020	**Trajectory design: missions to small solar system bodies** Space Technology Seminar, Tartu Observatory

Supervision

- **Optimal agent positioning for dynamic event monitoring and analysis;**
  Naghma Afreen. MSc. Robotics and Computer Eng., University of Tartu, 2024
- **Comet cooking and flyby simulations;**
  Tartu Observatory, University of Tartu
- **Transient event modelling and data analysis;**
  Tartu Observatory Space Mission Simulation Facility
- **Satellite communication with software-defined radios;**
  ESTCube-2, Tartu Observatory

Scholarships/Awards

2021	**Winner - 3 Minute Thesis Competition** University of Tartu
2019	**Charles Villmann Scholarship - Space Technology** Tartu Observatory
2019	**Jaan Einasto Scholarship - Space Technology** University of Tartu

Positions of Responsibility

2024- Present	**Early Career Officer, Estonia** EuroPlanet Society
2019- **2021**	**Event Manager - International Student Ambassador** University of Tartu
2015- **2016**	**Team Leader - International Cansat Program** UPES | American Astronautical Society(AAS)

Extra Curricula

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  - Estonian Beginner
  - Latvian Beginner
- Cricket, Soccer, Cycling
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Töökogemus

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Jun 2018- Jun 2021	**Orbiidi Dünaamika Insener** ESTCube-2 Satelliit Tudengisatelliit, Eesti
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Jun 2018- Aug 2019	**Satelliitside Insener** Eesti Tudengisateliit Tartu Observatoorium
Jun 2017- Jul 2018	**Mehhatroonika Insener** Mehitamata sõidukite autonoomne navigeerimine India

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08.2024	**Microsatellites and their use in planetary and astrobiology research** Tartu, Eesti
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Konverentsid

03.2025	**Suuline ettekanne: Advancing Small Body Sciences: Dynamic Mapping and Characterization** Tartu Observatooriumi Teaduskonverents, Eesti
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03.2023	**Suuline ettekanne: Mapping and characterization of small solar system bodies over simulation-defined multi-spacecraft trajectory models** Lennundustarkvara Töötuba 2023, JPL | CalTech, USA
01.2023	**Suuline ettekanne: On the multi-agent monte-carlo convergence for gravimetric distance approximation of pristine targets** Soome Satelliidi Töötuba, Aalto Ülikool, Soome
01.2023	**Postri esitlus: Tartu Observatory Space Bunker as a Comet Fly-By Analogue Environment** Soome Satelliidi Töötuba, Aalto Ülikool, Soome
10.2021	**Suuline ettekanne: Towards endogenous mapping of small solar system bodies during multi-agent rendezvous** Rahvusvaheline Astronautika Kongress (RAK)
10.2021	**Postri esitlus: Design approach to quantify inter-ground station distances by doppler-based ranging experiment for small satellite missions** Rahvusvaheline Astronautika Kongress (RAK)
08.2021	**Postri esitlus: Optical Periscopic Imager for Comets (OPIC) Instrument for the Planned Comet Interceptor Mission", Iakubivskyi, I, Paul, A.S. et al.** 35 AIAA/USU Väikesatelliitide Iga-Aastane Konverents, Utah Osariigi Ülikool, Logan, UT, USA

08.2021 **Suuline ettekanne: Towards mapping and characterizing small solar system bodies** Soome Satelliidi Töötuba, Aalto Ülikool, Soome

Seminar/Loengud

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05.2024 **Exploration into Exoplanetary Research**
Tähefüüsika Seminar, Tartu Observatoorium

02.2024 **Science of the New Ages - Discourse on India's Strategies for Space Exploration;** Seth Anandram Jaipuria Kool, India

01.2023 **Advancing robotics and space technology towards extra-terrestrial exploration**
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05.2022 **Exploring long-period planetary objects**
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05.2022 **Towards Multi-Agent Exploration of small solar system bodies**
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06.2021 **Multi-agent rendezvous with small solar system bodies**
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10.2020 **Trajectory design: missions to small solar system bodies**
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Järelevalve

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- **Comet cooking and flyby simulations;**
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- **Transient event modelling and data analysis;**
  Tartu Observatooriumi Kosmosemissiooni Simulatsioonikeskus
- **Satellite communication with software-defined radios;**
  ESTCube-2, Tartu Observatooriumi

Stipendiumid/Auhinnad

2019 **Jaan Einasto Stipendium - Kosmosetehnoloogia**
Tartu Ülikool

2019 **Charles Villmanni Stipendium - Kosmosetehnoloogia**
Tartu Observatooriumi

2021 **Võitja - 3-Minutiline Lõputöö Võistlus**
Tartu Ülikool

Vastutavad Ametikohad

2024- **Noorema Karjääriga Ametnik, Eesti**
... EuroPlaneti Ühing

2019- **Ürituste Korraldaja - Rahvusvaheline Tudengisaadik**
2021 Tartu Ülikool

2015- **Meeskonnajuht - Rahvusvaheline Cansati Programm**
2016 UPES | Ameerika Astronautika Selts (AAS)

Lisaõppekavad

- Keeled
  - Hindi Emakeel
  - Inglise Oskuslik
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- Kriket, Jalgpall, Jalgrattasõit
  - Kriket: Eesti Kriketkoondis
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1. **Andrus Ausmees.** XUV-induced electron emission and electron-phonon interaction in alkali halides. Tartu, 1991.
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4. **Ergo Nõmmiste.** Leelishalogeniidide röntgenelektronemissioon kiiritamisel footonitega energiaga 70–140 eV. Tartu, 1991.
5. **Margus Rätsep.** Spectral gratings and their relaxation in some low-temperature impurity-doped glasses and crystals. Tartu, 1991.
6. **Tõnu Pullerits.** Primary energy transfer in photosynthesis. Model calculations. Tartu, 1991.
7. **Olev Saks.** Attoampri diapasoonis voolude mõõtmise füüsikalised alused. Tartu, 1991.
8. **Andres Virro.** AlGaAsSb/GaSb heterostructure injection lasers. Tartu, 1991.
9. **Hans Korge.** Investigation of negative point discharge in pure nitrogen at atmospheric pressure. Tartu, 1992.
10. **Jüri Maksimov.** Nonlinear generation of laser VUV radiation for high-resolution spectroscopy. Tartu, 1992.
11. **Mark Aizengendler.** Photostimulated transformation of aggregate defects and spectral hole burning in a neutron-irradiated sapphire. Tartu, 1992.
12. **Hele Siimon.** Atomic layer molecular beam epitaxy of A^2B^6 compounds described on the basis of kinetic equations model. Tartu, 1992.
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14. **Toomas Rõõm.** Paramagnetic H^{2-} and F^+ centers in CaO crystals: spectra, relaxation and recombination luminescence. Tallinn, 1993.
15. **Erko Jalviste.** Laser spectroscopy of some jet-cooled organic molecules. Tartu, 1993.
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