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IAROSLAV IAKUBIVSKYI

Nanospacecraft for Technology Demonstration and Science Missions

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To my mother, father, grandmother and all close friends who steered me to learn and pursue the knowledge.

“We question life to seek out some meaning. Yet to preserve all the simple human truths we need mysteries” from Solaris (1972) by A. Tarkovsky from S. Lem.

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LIST OF ABBREVIATIONS

Acronyms

ADCS Attitude Determination and Control System. 26
ADR Active Debris Removal. 27
AOCS Attitude and Orbit Control System. 32, 34
AU Astronomical Unit. 30–33, 37, 38, 41, 44, 47

CDP Coulomb Drag Propulsion. 8, 19, 21–28, 46, 47, 49
COTS Commercial Off-The-Shelf. 40, 48

E-sail Electric Solar Wind Sail. 8, 19, 21, 22, 26, 29, 30, 32–34, 46, 47, 49, 62
ESA European Space Agency. 27, 37, 38, 44, 48, 49

FoV Field of View. 8, 41, 42

LEO Low Earth Orbit. 18, 19, 21, 22, 26–28, 46, 47

MAB Main Asteroid Belt. 22, 29–31, 47
MAT Multi-Asteroid Touring. 7, 8, 14, 19, 22, 29–33, 35, 36, 42, 47–49

OASIS Optical Aberrations for Still Images Simulator. 44
OpenGL Open Graphics Library. 44
OPIC Optical Periscopic Imager for Comets. 7–9, 14, 19, 36–42, 48, 49

PANGU Planet and Asteroid Natural Scene Generation Utility. 44
PMD Post-Mission Disposal. 27

RU Remote Unit. 8, 31–35
RW Reaction Wheel. 34

SISPO Space Imaging Simulator for Proximity Operations. 7, 14, 36, 39, 41–45, 48, 49
SRM Spin-Rate Modification. 25

TO Tartu Observatory. 62
TRL Technology Readiness Level. 17

UT University of Tartu. 21, 48, 49, 62

LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following publications:

I **Iakubivskyi, I.**, P. Janhunen, J. Praks, V. Allik, K. Bussov, B. Clayhills, J. Dalbins, T. Eenmäe, H. Ehrpais, J. Envall, S. Haslam, E. Ilbis, N. Jovanovic, E. Kilpua, J. Kivastik, J. Laks, P. Laufer, M. Merisalu, M. Meskanen, R. Märk, A. Nath, P. Niemelä, M. Noorma, M. R. Mughal, S. Nyman, M. Pajusalu, M. Palmroth, A. S. Paul, T. Peltola, M. Plans, J. Polkko, Q. S. Islam, A. Reinart, B. Riwanto, V. Sammelselg, J. Sate, I. Sünter, M. Tajmar, E. Tanskanen, H. Teras, P. Toivanen, R. Vainio, M. Väänänen, and A. Slavinskis (2020). "Coulomb drag propulsion experiments of ESTCube-2 and FORESAIL-1". In: *Acta Astronautica* 177, pp. 771–783.
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II Slavinskis, A., M. Pajusalu, I. Sünter, J. Dalbins, **Iakubivskyi, I.**, T. Eenmäe, D. Mauro, J. Stupl, P. Janhunen, P. Toivanen, E. Ilbis, H. Ehrpais, A. S. Rivkin, K. Muinonen, A. Penttilä, M. Granvik, T. Kohout, M. Gritsevich, and W. F. Bottke (2018). "Nanospacecraft fleet for multi-asteroid touring with electric solar wind sails". In: *2018 IEEE Aerospace Conference*. IEEE, pp. 1–20.
DOI: `10.1109/AERO.2018.8396670`.

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DOI: `10.1016/j.asr.2020.07.023`.

IV Pajusalu, M., J. Kivastik, **Iakubivskyi, I.**, and A. Slavinskis (2020). "Developing autonomous image capturing systems for maximum science yield for high fly-by velocity small solar system body exploration". In: 71st *International Astronautical Congress, IAC-20-A3.4B.4*. Cyber Space: International Astronautical Federation, pp. 1–8.
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V Pajusalu, M., **Iakubivskyi, I.**, G. J. Schwarzkopf, T. Väisänen, M. Bührer, O. Knuuttila, M. F. Palos, J. Praks, and A. Slavinskis (2021). "SISPO: Space Imaging Simulator for Proximity Operations". In: *Plos One*.
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VI Csuka, J., S. Adeli, M. Baqué, **Iakubivskyi, I.**, N. Kopacz, A. Neubeck, A. Schnürer, A. Singh, B. R. Stockwell, O. Vilhelmsson, and W. D. Geppert (2020). "Linking biological and geochemical data from

Icelandic lava tubes: insights for upcoming missions in the search for extant or extinct life on Mars”. In: 3rd *International Planetary Caves*. Vol. 2197. San Antonio, Texas: Lunar and Planetary Institute, p. 1051.
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X **Iakubivskyi, I.**, H. Ehrpais, A. Slavinskis, H. Kuuste, I. Sünter, E. Ilbis, E. Oro, J. Kütt, P. Janhunen, P. Toivanen, and J. Envall (2017). “ESTCube-2 plasma brake payload for effective deorbiting”. In: 7th *European Conference on Space Debris*. Ed. by T. Flohrer and F. Schmitz. Darmstadt, Germany: European Space Agency Space Debris Office, pp. 1–7.
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URL: `https://dl.iafastro.directory/event/IAC-2017/paper/36914/`.

XII **Iakubivskyi, I.**, H Ehrpais, J. Dalbins, E. Oro, E. Kulu, J. Kütt, P. Janhunen, A. Slavinskis, E. Ilbis, I. Ploom, I. Sünter, R. Trops, M. Merisalu, and K. Rejnkubjas (2016). “ESTCube-2 mission analysis: Plasma brake experiment for deorbiting”. In: 67th *International Astronautical Congress, IAC-16.E2.4.4.x33190*. Guadalajara, Mexico: International Astronautical Federation, pp. 1–10.
URL: `https://dl.iafastro.directory/event/IAC-2016/paper/33190/`.

XIII Sünter, I., H. Kuuste, A. Slavinskis, A. Agu, E. Ilbis, G. Olentšenko, **Iakubivskyi, I.**, J. L. L. Seco, J. Kütt, R. Vendt, S. Chopra, T. Eenmäe,

V. Allik, and M. Noorma (2016). “Design and Testing of a Dual-Camera Payload for ESEO”. In: 67th *International Astronautical Congress, B4.4.3.x31978*. Guadalajara, Mexico: International Astronautical Federation, pp. 1–10.
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XV Sünter, I., H. Kuuste, J. Kütt, E. Ilbis, A. Agu, **Iakubivskyi, I.**, S. Chopra, T. Ani, J. L. L. Seco, T. Eenmäe, V. Allik, G. Olentšenko, J. Kalde, S-P. Ojanen, S. Hariharan, A. Kustavus, K. Kahn, I. Ploom, R. Vendt, S. Lätt, U. Kvell, and M. Noorma (2016). “DUAL-CAMERA PAYLOAD for ESEO”. In: *The 4S Symposium*. Valletta, Malta: ESA, pp. 1–10.

Author's contribution to the publications

The publications presented in this dissertation is multinational teamwork that involves a cross-disciplinary approach. The author contributed to the articles in the following ways:

I The author was a member of the ESTCube-2 team from 2015 to 2017; he has contributed to developing the mission concept, requirements, design, platform, the definition of scientific objectives, and payloads selection. He was a visiting researcher in the FORESAIL-1 team during the 2019 spring semester. The author wrote most of the paper content, handled review and managed the input from two large teams accompanied by multiple international partners and payload providers. Mainly he developed the narrative by writing the introduction, deriving experiment requirements and design, performance estimations and risks assessment, parts of the ESTCube-2 satellite, prospects and scaling, and conclusions.

II The author was a member of the initial investigation group for the MAT mission concept and contributed to the requirement definition, preliminary mission design, designed the preliminary spacecraft architecture and assessed the radiation environment. His contribution to the text was low intermediate. This research led to the more detailed article III.

III After a preliminary Concurrent Design Facility study of the MAT mission by the European Space Agency, it became apparent that a more detailed assessment of the spacecraft architecture and environmental analysis is needed to mature the mission and increase its chance to fly in the future. The author has assembled a team and suggested the concept for spacecraft. He made the design and performed the following: power budget, mass budget, radiation calculations, E-sail operation, deployment strategies and risks assessments. The author has written most of this paper and handled the review process.

IV The author has been involved in the instrument development project for the Comet Interceptor mission from the beginning of the OPIC proposal. He is a core team member of the OPIC instrument development. According to European Cooperation for Space Standardization and ESA requirements, the author performed structural design, finite element analysis, thermal analysis, documentation writing, and other required periodic tasks of agile development. The author has been supervising students/interns on various topics. Iaroslav's contribution to the paper writing was minor.

V The author has been a SISPO development team member since the beginning of 2020. The author had written a significant part of the paper, handled the review process and contributed the following: performed image generations, proposed the idea and performed particular case outlined in the subsurface exploration section, performed image reconstruction for fly-by and orbiting use-cases with the detailed numerical comparison of both.

PREFACE

The dissertation you are going to read is based on innovative engineering and technology for space applications, and it contributes to advancing various auxiliary disciplines like planetary science. **Contemporary science** erases borders between disciplines and essentially requires multidisciplinarity to achieve novelty.

This notion has been developed in a relatively small team compared to a space agency or large industry. University-based access for space exploration, especially in a country without extensive space heritage, is fresh. The author is grateful that he took the path that provides a rigid means for self-education, participation in numerous fascinating projects and autonomy to govern individual interests.

A combination of multiple disciplines in the XVIII-–XIX century defined natural sciences in order to describe the natural world; as knowledge grew, in the XX century, specialisation became more common for the following reasons: the creation of new disciplines and inability to sustain broad knowledge by a single person (Cockell, 2002). However, the answer to fundamental questions (e.g., the meaning of life through a prism of understanding its origin, evolution, distribution and future, the role of asteroid and comets in extinction and cross-contamination, panspermia, etc.) demands a multidisciplinary strategy. Besides, due to the physical constraints of Earth-based space science, the only way to advance the knowledge and understanding of the Early Solar System, its future and its existential context in the universe requires dedicated space missions, which are an inevitable part of modern space science. Furthermore, cosmic exploration has an undeniable revolutionary contribution to understanding our home planet's state and how to live sustainably. For instance, a study of extraterrestrial atmospheric processes, presumably on Titan or Venus or in fact elsewhere, might have, in the long term, a significant impact on understanding our atmosphere and the ways to sustain it tolerable for living beings, including primates.

This dissertation contributes to the miniaturisation of planetary missions and instruments as a collection of articles by involving a multidisciplinary approach. It contributes to small affordable nanosatellites and small probes to increase the knowledge about the vast cosmos we all live in and sustainable ways to explore it.

TARTU, 2021

1. INTRODUCTION

Human's view on their place in the universe has changed throughout history in the anthropogenic context: first, the reality has been pursuit as geocentric, in which all heavenly objects spun around the ancient Greek observer; later, the heliocentric model was proposed by Copernicus, and only subsequently our solar system was placed as miscellaneous part of the moving galaxy within the universe. In the historical context, the novelty was not always accepted, and the transition between theories and hypotheses took a long time (in the context of human life span) and sacrifices. For example, Giordano Bruno (1548–1600) was conceptually connected to the Copernican model and advocated for cosmic pluralism – a historical cosmological view claiming that stars are other suns having their orbiting planets, which might host life and intelligence, and that the universe is centreless and infinite. He was found guilty of such views and was burned alive in Rome's Campo de' Fior in 1600.

Significant changes and progress in cosmic understanding were made in the XX century, primarily due to robotic space exploration. The era of satellite-based exploration began in the middle of the last century with launching the first object into orbit known as Sputnik-1 by the Soviet Union and lead by S. Korolev[1] (Siddiqi, 2000). The era of space exploration is only six and a half decades old but incorporates the rapid development of space technology during the Space Race and later with the computational revolution's hand and commercial privatisation.

State-funded agencies dominated the pioneering mission developments; now, the field is consolidated with academia, public and thriving private sectors. The countries without space programs now can build small satellites and purchase a launch service, thanks to the rapid technological progress, general quality of education, access to information and commercialisation of space products and services. Tens of companies compete in small boosters business, while some target to bring a price as low as approximately 10 kEUR$\cdot$kg^{-1} (Frick and Niederstrasser, 2018), which is, for instance, a purchase equivalent of a few high-end laptops by the university. For example, Estonia successfully engineered and operated its first student-built nanosatellite ESTCube-1[2] in 2013 without previous experience and expertise (Slavinskis, Pajusalu, Kuuste, et al., 2015). The global space access provided by nanosatellites is visualised in Figure 1, totalling 76 countries (Kulu, database 2021), with clear coverage of small and developing nations.

Different types of satellites exist, including artificial satellites, and in the present work, satellite or spacecraft means an artificial satellite that actively

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[1] Who also was behind Y. Gagarin's flight and first soft lunar landing in 1966, a Soviet Ukrainian who was almost killed by the Soviet regime under Stalin's purges in the late 1930s.

[2] Science popularisation article: `https://space-travel.blog/ec1-1st-818b12cb4d53`.

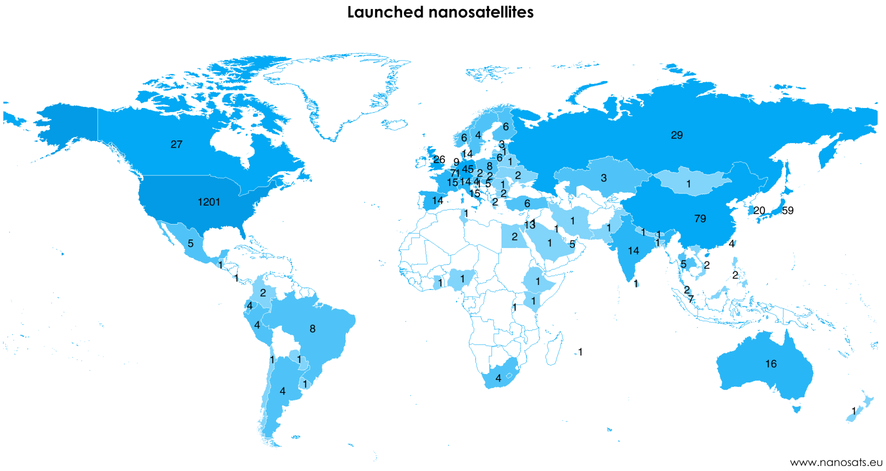

Figure 1: Launched nanosatellites by countries.

As of August 20, 2021 (Kulu, database 2021). For instance, Estonia is one of the leading countries in Eastern Europe, the Nordic and Balkan regions.

fulfils a function. Characterisation of the satellite by mass and volume is an important factor when it comes to mission classification (which is also orbit dependent) and cost estimation (which is also Technology Readiness Level (TRL) correlated). The satellites general categories are listed in Table 1. In the opposition of a single complex mission, the formation-flying mission becomes a widely used approach. Also, around a third of all proposed missions between 2000 and 2025 are nanosatellites or nanospacecraft (Di Mauro, Lawn, and Bevilacqua, 2018).

	Class	Mass [kg]
1	Large satellite	over 1000
2	Medium satellite	500–1000
3	Small satellite	under 500
3a	Minisatellite	100–500
3b	Microsatellite	10–100
3c	Nanosatellite	1–10
3d	Picosatellite	0.1–1
3e	Femtosatellite	under 0.1

Table 1: Satellite classification by mass

1.1. Nanospacecraft and New Space

As of August 20, 2021, 1766 nanosatellites were launched, and over 92% of them are cubesats (Kulu, database 2021). Cubesat is a standardised class of a satellite or spacecraft that consists of single or multiple units. Each unit volumetrically resembles a 10 cm cube and has a typical mass in the range of 1–2 kg. The cubesats have been maturing since 1999, and the forecast points out that 1800–2400 additional nanosatellites will be launched by 2025 (DelPozzo and Williams, report 2020). The number of launched nanosatellites with the forecast is visualised in Figure 2. This increase is partially boosted by the recent industrial commercialisation of space activities, entrepreneurial approach and new frontiers for exploration, referred to as New Space (Frischauf et al., 2018; Paikowsky, 2017).

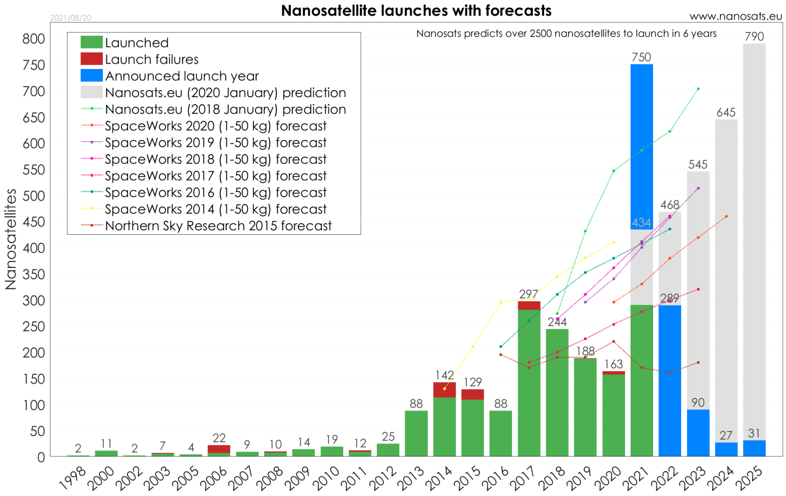

Figure 2: Launched nanosatellites with the forecast.

As of August 20, 2021 (Kulu, database 2021).

One of the distinguishing features of New Space from “conventional space” is minimal state involvement on the governmental level; it is driven by economic models of market needs, where reason overcomes bureaucracy. Numerous small and medium enterprises got involved in building and operating cubesats or technologies supporting their operation. With such a model, generally, more can be achieved in shorter times, and importantly, more reasonable risks could be taken without bureaucratic justification. The possibility to launch cubesats as a secondary payload or by small affordable boosters provides many opportunities for universities and various enterprises to operate their satellites.

The cubesat orbit classification indicates a significant technological gap between Low Earth Orbit (LEO) and deep space cubesats. In fact, only two twin spacecraft MarCO undertook interplanetary voyages (Schoolcraft, Klesh, and

Werne, 2017), and more missions are approaching by large space agencies (Crusan and Galica, 2019; Michel et al., 2018). Certainly, cubesats will not replace classic missions but will assist them by taking higher risks and contributing with multi-point measurements and rapid development. An example of a high-risk mission is a remote observation of presumable visit of an interstellar object (Fitzsimmons, Hainaut, et al., 2019; Fitzsimmons, Snodgrass, et al., 2018), which would require standing spacecraft in one or multiple locations in space for a prolonged time, similarly as planned for Comet Interceptor mission (Snodgrass and Jones, 2019). However, cubesats could be parked in various locations and times, awaiting precious visitors to appear. Hera mission, in assistance with Juventas and Milani cubesats in closer proximity (Michel et al., 2018), will assist the assessment of DART impact (Cheng et al., 2018) on the binary asteroid (65803) Didymos-Dimorphos as a part of the AIDA mission (Zhang et al., 2021). Cubesats mostly perform focused planetary research while demonstrating new technologies for future missions. The gap between LEO and deep space nanoprobes is partially due to limitations in propulsion, miniaturisation of space instrumentation, and tested deep-space components at an affordable price tag.

The development of instrumentation, propulsion (Tardivel, Klesh, and Campagnola, 2018), and mission-design approaches require novelty and prior in-orbit demonstrations (Imken et al., 2017). The author of this dissertation has contributed to the miniaturisation of planetary missions and instruments by developing missions, mission concepts, payloads and simulation tools that commit to the long-term aims of cosmic examination with nanospacecraft. Section 2 focuses on the innovative propulsion method – Coulomb Drag Propulsion (CDP), which has two applications: (i) plasma brake on the ESTCube-2 and FORESAIL-1 satellites as discussed in Subsection 2.1, and (ii) an interplanetary voyage by Multi-Asteroid Touring (MAT) mission concept with Electric Solar Wind Sail (E-sail) as discussed in Subsection 2.2. Instrumentation for space missions, such as an ongoing OPIC instrument development with the latest updates, is outlined in Subsection 3.1. The tool for instrument design, performance estimation and mission design, which was used for OPIC and MAT, is briefly presented in Subsection 3.2. Finally, the discussion and conclusions are outlined in Section 4.

2. BREAKTHROUGH SPACE TRAVEL: COULOMB DRAG PROPULSION

Miniaturisation is one of the primary directions in the evolution of technology. The exponential growth of the microprocessor performance is presently occurring (Etiemble, 2018) and contributes to general technological miniaturisation. However, miniaturisation has its limitations, which are often defined by the laws of physics. For instance, the processing power can be improved with increased clock speed, but the system's thermal performance limits it; the clock speed can be increased until it hits the "thermal wall", and parallelisation would be needed (Etiemble, 2018). Another example is the miniaturisation of the optical systems: the smaller aperture is, the less light would reach the sensor. The size limitations of space payloads and the inability to change the size or brightness of natural objects provide one controllable parameter – a reduced distance between the instrument and the target. This demands propulsion. The traditional propulsion system also has its fundamental limitation: the delta-v budget would be proportional to the mass of carried propellant. It is defined by Tsiolkovsky rocket Eq. 2.1:

$$\Delta v = I_{sp} \cdot g_0 \cdot \ln \frac{m_0}{m_f} \tag{2.1}$$

, where Δv (delta-v) is a change of velocity, I_{sp} is a specific impulse, g_0 is a standard gravity, m_0 is the initial spacecraft mass (i.e., wet mass), and m_f is the final spacecraft mass (i.e., dry mass).

Energy in the universe is conserved, and it cannot appear from anywhere and disappear into nothingness; it just migrates from one form to another. Building blocks of all matter interact in four different ways: (i) the strong interaction (e.g., quarks in the nucleus); (ii) the electromagnetic interaction; (iii) the weak interaction (e.g., leptons interaction); and iv) the gravitational interaction (Mansfield and O'Sullivan, 2020). The Solar System voyage requires much more than a rocket and propellant: dynamic flight experts plan and execute hitchhiking gravity-assist manoeuvres of nearby planets to reach desired destinations in the Solar System. Besides gravitational interaction, the electrostatic interaction is also feasible for Solar System voyages since electrically charged solar wind is available vastly in space.

Nanosatellites utilise all types of available propulsion: electrical, chemical and more advanced. The primary application for thrusters in the nanocraft scale is attitude control; it is rarely employed for orbital manoeuvres (Lemmer, 2017). Cubesats launched as a secondary payload cannot carry any pyrotechnics, which rules out igniter for solid-fuel rocketry; however, a dedicated fleet launch would allow it. Mass and volumetric constraints of cubesats limit the use of liquid and hybrid chemical propulsion for major orbital manoeuvres, although the development of non-toxic monopropellants was reported (Lemmer, 2017). Pressurised cold-gas propulsion and electric propulsion (e.g., resistojet, pulsed plasma, electrospray and miniature ion thrusters) have been evaluated and developed to fit the cubesat envelope (Lemmer, 2017; Levchenko et al., 2018). Cold-gas propulsion provides relatively low specific impulse, which might be insufficient for most orbital operation demands, except for minor orbital adjustments. Electric propulsion provides a high specific impulse. However, it requires substantial power, which is exceptionally limited[1] on nanospacecraft.

Alternative propulsion also exists on cubesat scales, such as solar wind sail (also termed photonic pressure sail (Johnson et al., 2011)), Electric Solar Wind Sail (E-sail) (Janhunen, 2004) (also termed Coulomb Drag Propulsion (CDP)[2]), electrodynamic tethers (Corsi and Iess, 2001) and laser pressure (Parkin, 2018) among others. These propulsions typically utilise available space resources, such as sunlight, ionosphere, magnetic field and solar wind. Electrodynamic tethers are used for changing orbital parameters by taking advantage of a magnetic field and a charged tether (i.e., Lorentz force). Solar sail utilises the photonic pressure of sunlight. The larger sail area grants increased thrust; however, it also increases the probability of being damaged by micrometeoroids. The thrust (T) of solar sail also decreases with solar distance R as $1/R^2$ ($\mathrm{T} \propto \mathrm{R}^{-2}$).

The improvement to solar sail, in terms of decreased thrust with heliocentric distance, is provided by E-sail, which utilises the solar wind rather than sunlight – the positively biased tether interacts with charged solar wind particles. Dr Pekka Janhunen invented the E-sail concept. His team has significantly advanced the concept at the Finnish Meteorological Institute during the last decade; the additional contribution is being provided by the University of Tartu (UT), Aalto University and Aurora Propulsion Technologies. The E-sail thrust decreases by approximately $1/R$ ($\mathrm{T} \propto \mathrm{R}^{-1}$) caused by increased Debye length at greater distances[3] despite the weaker solar wind (Janhunen and Sandroos, 2007). It works similarly to spider ballooning caused by the interaction between spider's charged silk and atmospheric electric charge (Morley and Robert, 2018). An alternative application of such a system is LEO satellite deorbiting by plasma brake (Janhunen, 2010) – a negatively charged tether flying through the relatively stationary ionosphere. In principle, any Coulomb drag device, either positively or negatively charged, would work both in solar wind and ionosphere. However, in the ionosphere, the usage of negative CDP (i.e., plasma brake) is preferred from the engineering point of view: it requires less power and can be operated without an electron emitter. In the solar wind, the negative polarity is not feasible because the high kinetic energy of solar wind ions obliges a higher voltage than

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[1] It also decreases by the inverse-square law if the heliocentric distance increases.

[2] Named after the French scientist Charles-Augustin de Coulomb (1736–1806), who used his torsion balance devise to determine how the force between charges depends on their distance.)

[3] Electron Debye length is proportional to solar wind electron temperature ($\propto \mathrm{T}_e^{-1}$), and higher temperature yields wider electron sheath and propulsive effect.

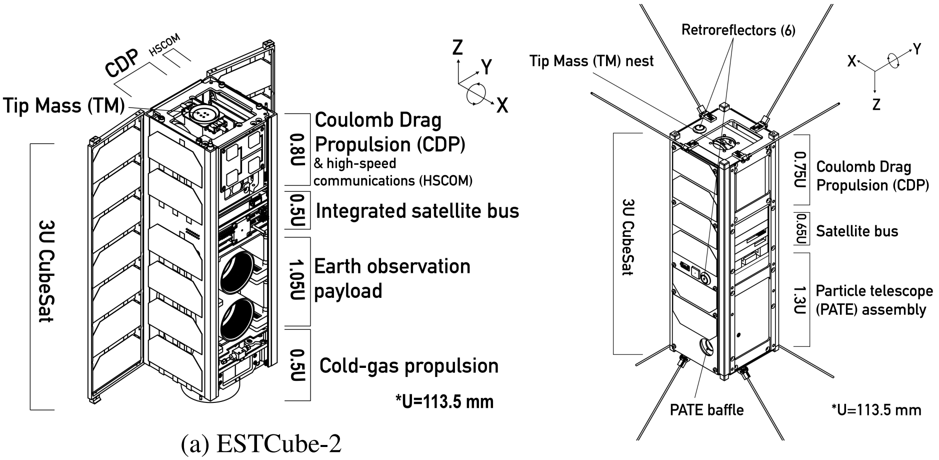
in LEO. Such high voltage would cause electron field emission from the thin wires, increasing the power consumption. Therefore, the negative polarity is applied in LEO to slow down the satellite and decrease the altitude. The positive polarity is utilised in the solar wind to accelerate and manoeuvre in space. Both CDP devices have been involved in this dissertation: (i) negative CDP is being developed and tested for ESTCube-2 and FORESAIL-1 LEO satellites for deorbiting purposes and E-sail thrust evaluation in the space environment (more details in Subsection 2.1), and (ii) MAT mission concept and satellite design for Main Asteroid Belt (MAB) flyby with a fleet of nanospacecraft equipped with CDP described in Subsection 2.2.

2.1. ESTCube-2 and FORESAIL-1

The first endeavours to test E-sail and plasma brake in space were onboard the ESTCube-1 satellite (Slavinskis et al., 2015) and then Aalto-1 (Praks et al., 2021), the first national satellites for both neighbouring countries – Estonia (University of Tartu) and Finland (Aalto University), respectively. Despite their inability to deploy the tether, they provided precious lessons for their younger siblings: ESTCube-2 and FORESAIL-1, 3U nanosatellites. The mission objectives and payloads are discussed in great detail by Ehrpais et al., 2016; **Iakubivskyi, I.**, Ehrpais, Dalbins, et al., 2016; **Iakubivskyi, I.**, Ehrpais, Slavinskis, et al., 2017; **Iakubivskyi, I.**, Ilbis, et al., 2017; **Iakubivskyi, I.**, Janhunen, et al., 2020. Both satellites will be equipped with the experimental modules that the Finnish Meteorological Institute, Finland designs for testing CDP and E-sail propulsive effect in LEO. The module is hosted at the end of the longer side of the satellite and is shown in Figure 3.

If equipped with CDP, a fast-moving satellite would reduce its orbital velocity and altitude. Plasma brake, a negative CDP, is an artificial process of lowering the spacecraft's velocity by electrostatic interaction between the negatively charged tether and ions. The atoms in the ionosphere are stable compared to orbiting spacecraft at 7–8 $\text{km}\cdot\text{s}^{-1}$, causing the tethered satellite to slow down. The working principle is visualised in Figure 4.

The same tether is used for both the E-sail and plasma brake. The tether production has strict requirements for the processes involved and materials used, outlined in **Iakubivskyi, I.**, Janhunen, et al., 2020. The basic structure of the tether composes of multiple interconnected conductive wires in the Heytether structure (Seppänen et al., 2011). The individual cells of Heytether provide immunity to single event damage by micrometeoroid impacts and weathering (e.g., atomic oxygen and dust erosions, thermal cycles, aluminium sputtering). The controlled spinning around one axis is an essential part of the CDP tether management. Centrifugal force and end mass of the tether's tip assist the tether(s) deployment and maintenance (i.e., keep them stretched) during the operation. In the case of ESTCube-2 and FORESAIL-1 is a small aluminium



(a) ESTCube-2

(b) FORESAIL-1

Figure 3: ESTCube-2 and FORESAIL-1 anatomies.

(**Iakubivskyi, I.**, Janhunen, et al., 2020)

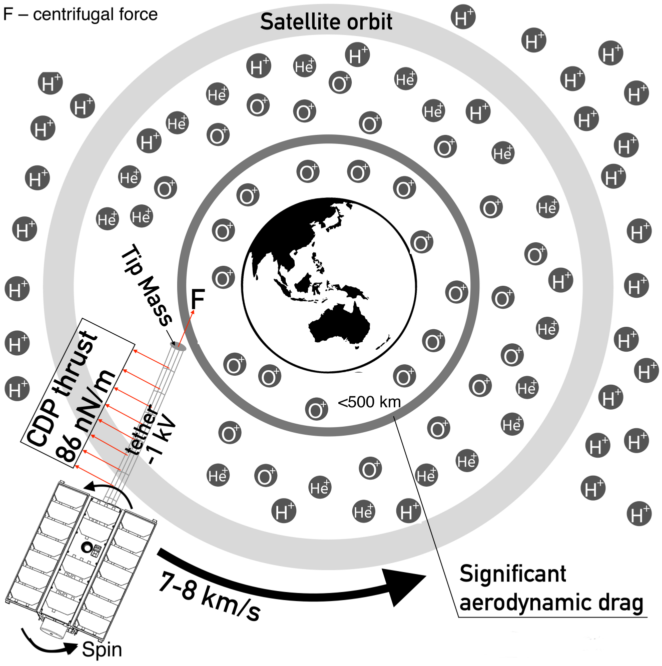


Figure 4: Operational concept of CDP.

The ionospheric distribution is not uniform and is dynamically driven by solar activity (**Iakubivskyi, I.**, Janhunen, et al., 2020).

mass of 2–2.5 g. The multi-wire tether is stored on the reel. A stepper motor turns the reel to release the well-packed tether. The schematic of the experiment is shown in Figure 5.

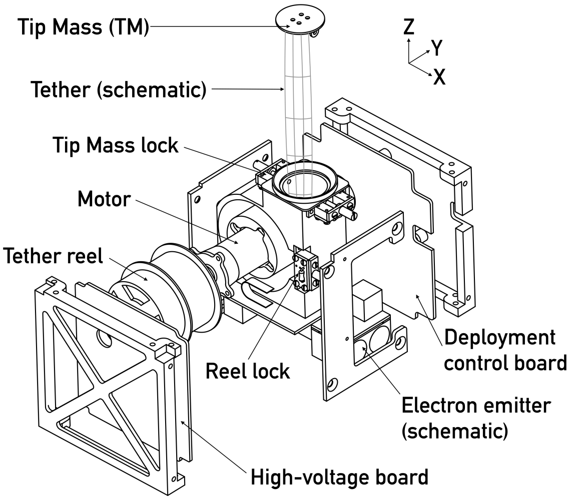


Figure 5: Negative CDP (plasma brake) schematics.

(**Iakubivskyi, I.**, Janhunen, et al., 2020)

The most straightforward system, as in the ESTCube-2 and FORESAIL-1 case, is single tethered. This system is sufficient for nanoprobes operation and technology demonstration while reduces the risks and complexity. A multi-tether system would be needed for larger space assets and longer Solar System voyages, providing higher thrust and more control over manoeuvrability.

A previous particle-in-cell simulation study obtained the thrust per unit length calculation for a CDP plasma brake, given in Equation 2.2 (**Iakubivskyi, I.**, Janhunen, et al., 2020; Janhunen, 2014).

$$\frac{dF}{dz} = 3.864 \times P_{dyn} \sqrt{\frac{\varepsilon_0 \tilde{V}}{e\, n_0}} exp(-\frac{V_i}{\tilde{V}}) \tag{2.2}$$

where $P_{dyn} = m_i n_0 v_0^2$ is the dynamic pressure, m_i is the ion mass, and v_i is the plasma flow with respect to the satellite; $\tilde{V}$ is given in Equation 2.3.

$$\tilde{V} = \frac{V_w}{\ln(\lambda_D^{\text{eff}}/r_w^*)} \tag{2.3}$$

where r_w^* is the effective electric radius of tether, $\lambda_D^{\text{eff}} = \sqrt{\varepsilon_0 V_w / e n_0}$ is the effective Debye length and $V_i = m_i v_0^2/2e$ is the bulk ion flow energy.

Using Equation 2.2 for the negative CDP experiment, the thrust per unit length is approximately 86 nN·m^{-1}, considering the tether's width of 2 cm, the single-wire diameter of 35 μm, the mean ion mass of 10 amu, and a -1 kV voltage for the tether (**Iakubivskyi, I.**, Janhunen, et al., 2020). The tether resembles the Heytether structure with four parallel and numerous perpendicular wires, creating cells that provide tether's resistance to micrometeoroid impacts (tether sketch is shown in Subsection 3.2 of **Iakubivskyi, I.**, Janhunen, et al., 2020).

Numerous models predict an approximate density and distribution of the atmosphere and ionosphere at various altitudes. Among popular models are:

- *Mass-Spectrometer-Incoherent-Scatter (NRLMSISE-00)* (Hedin, 1983);
- *Marshall Engineering Thermosphere (MET-V 2.0)* (Owens and Vaughan, 2002);
- *Drag Temperature Model (DTMB78)* (Barlier et al., 1979);
- *Horizontal Wind Model (HWM93)* (Hedin, 1991);
- *International Reference Ionosphere (IRI2001)* (Bilitza, 2001);
- *NeQuick Ionosphere Electron Density Model (NeQuick v2.0)* (Nava, Coïsson, and Radicella, 2008).

Including various factors in **Iakubivskyi, I.**, Janhunen, et al., 2020, the deorbiting rates for a typical three-unit cubesat (4.5 kg, which approximately corresponds to ESTCube-2 and FORESAIL-1) are visualised in Figure 6 (**Iakubivskyi, I.**, Janhunen, et al., 2020).

The thrust is controllable by the voltage applied to the system. The highest thrust would be achieved at full voltage and could be gradually decreased by tuning the voltage. The voltage variations are also used for orbital adjustments by spin plane modifications (more information in Section 2.2).

The following requirements for CDP are derived from **Iakubivskyi, I.**, Janhunen, et al., 2020:

- The CDP experiment should support two modes of operation:
  1. Spin-Rate Modification (SRM) measurement when the tether is charged either positively or negatively in synchronisation with the satellite's rotation: the spin rate increases when moving downstream and decreases when moving upstream. The change in spin rate during one polar pass is expected to be ≈ 0.1 deg$\cdot$s^{-1} for the CDP negative mode; for the positive mode it is expected to be ≈ 0.06 deg$\cdot$s^{-1}.
  2. Deorbiting with the plasma brake when the tether is continuously charged negatively. It is estimated that the satellite will deorbit by 10 km in six months with an unwrapped 30 m tether. Effective deorbiting requires at least 150 m of deployed tether.
- The CDP payload should perform the following operations:
  1. Reel out the tether at ~ 1 mm$\cdot$s^{-1}.
  2. Charge the tether negatively.
  3. On board ESTCube-2, charge the tether positively and remove electrons.
  4. Turn the charging on and off in a seconds-long time frame (SRM mode).

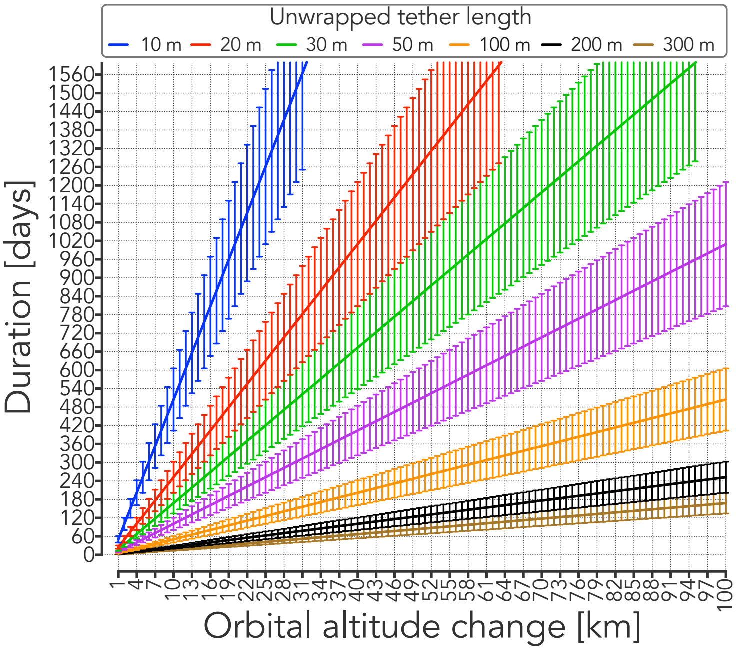


Figure 6: Expected deorbiting rates by the CDP for a three-unit cubesat (4.5 kg) with various unwrapped tether lengths.

The wide area is caused due to uncertainties in the spin plane in relation to the orbital vector. The atmospheric drag will additionally contribute to deorbiting rate. The following environmental factors will also influence the deorbiting rates: 1) ionospheric plasma density and distribution at various latitudes, longitudes and altitudes and its migration enhanced by the solar wind, and 2) the ion ratio of oxygen to hydrogen (**Iakubivskyi, I.**, Janhunen, et al., 2020).

5. Provide an angular momentum to deploy at least 30 m of the tether (preferably all 300 m) starting from the initial 11 m, for which the angular momentum is provided by the Attitude Determination and Control System (ADCS).
6. Keep the tether charged for a period of at least six months (deorbiting mode).

ESTCube-2 will also test a positive mode for the actual E-sail application and is equipped with the electron emitter developed at the Dresden University of Technology, based on the NanoFEEP propulsion system (Bock and Tajmar, 2018). The design uses a cold-field emission electron emitter of multi-walled carbon nanotubes (Tajmar, 2002). The electron emitter is essential for implementing positive CDP in its native environment – the solar wind.

2.1.1. Sustainable Space Utilisation

Global space access and demand for satellite-based services introduce challenges to the ever-growing uncontrolled space debris in LEO. The risk of collisions between the functional and non-functional satellites create enormous amounts of small debris in the process. At some point, the number of debris would initiate inevitable cascade collisions and result in unusable LEO with a debris belt, predicted by Kessler and Cour-Palais, 1978. It is referred to as "Kessler Syndrome" and was well visualised in the 2013 *Gravity* movie (*dir. A. Cuarón*) when the missile strikes the LEO satellite and initiates an uncontrollable cascade effect inspired by the work of Kessler and Cour-Palais, 1978. For instance, it is predicted that the 2009 equivalent accident to Cosmos 2251 and Iridium 33 would happen every five to nine years (Wang, 2010). The actual damage by a centimetre sized object can be observed on Sentinel-1a solar panel (Krag et al., 2017). It was also proposed that the explicit introduction of economic incentives suggests an alternative in which orbital space becomes economically unprofitable, perhaps well before it becomes physically unusable (Adilov, Alexander, and Cunningham, 2018).

United Nation's Committee on the Peaceful Uses of Outer Space developed guidance for sustainable space usage and limitation of a post-mission lifetime in orbit to 25–30 years (Klinkrad et al., 2004). However, the policies are not legally binding and require many synergies and agreements in the international political arena. In order to tackle the debris problem, one needs to include Post-Mission Disposal (PMD) device, which would lower the altitude of the spacecraft to the point when atmospheric drag would naturally decompose the object. There is also a need to follow the design philosophy "design for demise", which would ensure complete disintegration of the vehicle before it potentially reaches populated areas on Earth (Trisolini, Lewis, and Colombo, 2018). Additionally, Active Debris Removal (ADR) is planned with a dedicated satellite to remove nonfunctional satellites (Forshaw et al., 2016; Juillard et al., 2020). European Space Agency (ESA) dedicates many resources and efforts to tackle this problem; however, this process is expensive and requires resources equivalent to science mission planning. There are few PMD devices, but the CDP plasma brake has advantages over other systems (more details in **Iakubivskyi, I.**, Janhunen, et al., 2020). The simplistic overview is visualised in Figure 7.

The main advantages of CDP plasma brake are: (i) a semi-autonomous system that can be designed to function when the satellite fails, (ii) resistance to micrometeoroid impacts, (iii) low power, mass and volume, iv) scalable for larger satellite and higher orbits. For instance, a 200-kg object can be deorbited from a 1200-km altitude, and an 800-kg satellite from an 850-km altitude in 11 years (Janhunen, Toivanen, and Envall, 2017). ESTCube-2 and FORESAIL-1 are technology demonstration missions designed to mature CDP plasma brake and make it viable for space vehicle builders and constellation designers.

Global satellite constellations bring numerous challenges to LEO satellite traffic. While service, such as global internet access, would improve the quality of life for millions, it introduces challenges associated with space junk. SpaceX Starlink constellation's initial orbital plane was in 1100–1325 km altitude and

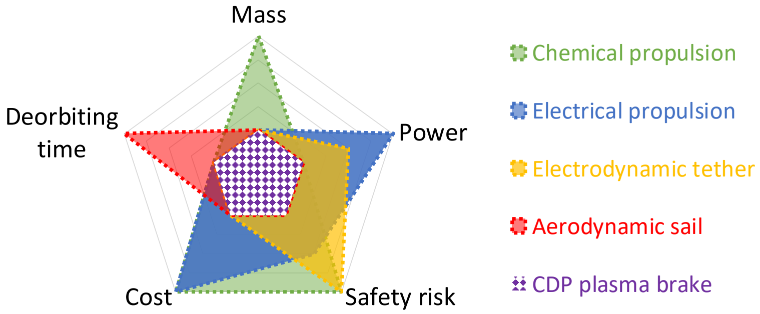


Figure 7: Simplistic comparative overview of deorbiting modules.

The CDP is the pentagon in the middle (**Iakubivskyi, I.**, Janhunen, et al., 2020).

later was resubmitted to 550 km altitude; now, it is operated at approximately 340 km (del Portillo, Cameron, and Crawley, 2019; Space Exploration Holdings, LLC, 2018). Perhaps, such orbital parameters are the most sustainable way to operate the constellation: very low altitude, maintained with active propulsion to compensate for the atmospheric drag per unit mass $\overline{F_D}$, which is mathematically described in Eq. 2.4. Once the satellite runs out of fuel or fails, it quickly deorbits naturally. However, such a low LEO fleet introduces another distinguishable problem – light pollution for ground-based observation. Lately, it has become a dramatic issue for astronomers globally, as a constellation of satellites interferes with data from optical and radio astronomy, and valuable and expensive time on the telescopes is lost (Levchenko et al., 2020). This is a complex problem, and there is no straightforward solution that would satisfy all involved parties. The current solution is anti-reflective coatings, which still requires significant improvements.

$$\overline{F_D} = -\frac{1}{2} C_D \frac{A}{m} \rho |\overline{V}| \overline{V} \tag{2.4}$$

, where C_D is a drag coefficient, $\frac{A}{m}$ is the area to mass ratio of the craft, ρ is atmospheric density (the models for numerical estimation have been provided in Subsection 2.1), and $\overline{V}$ is the relative satellite velocity to the atmosphere (it is typically assumed that atmospheric angular velocity is the same as of Earth). As it is clear from Eq. 2.4 without adequate atmospheric density, the drag would be insufficient; above 700 km, the atmospheric density becomes so low that the satellite would require propulsion to deorbit in the timely manner defined by the international agreements. Since all planned constellations would not be able to operate in orbit under the International Space Station, the CDP is a potentially helpful independent module to deorbit dysfunctional space assets from higher orbits.

2.2. Multi-Asteroid Touring mission

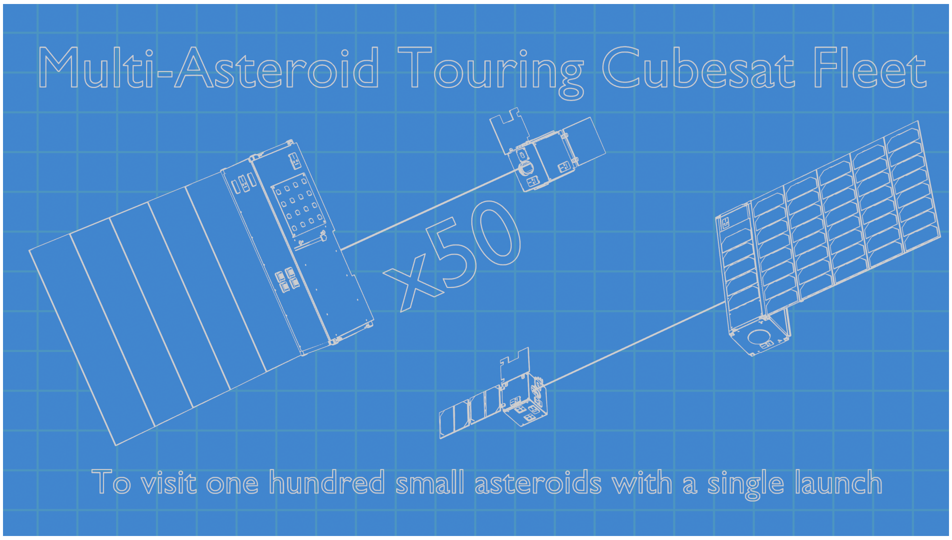


Figure 8: MAT blueprint.

Asteroids are thought to be leftover planetesimals that are closely related to the precursor bodies that formed both the terrestrial planets and the cores of the giant planets; the most primitive ones contain a record of the original composition of the solar nebula in which the planets formed (Michel, DeMeo, and Bottke, 2015). Self-surviving mechanisms also trigger human interest in small solar system bodies: some asteroids intercept Earth's trajectory and, therefore, create a risk of collision; the historical phenomenon, such as the Chicxulub impact, caused, most likely, Cretaceous–Paleogene mass extinction event and killed dinosaurs 65.5 Ma (Alvarez et al., 1980).

E-sail provides a feasible solution for spacecraft to operate in deep space and fly by an asteroid by utilising practically unlimited resources available in a solar system, essentially solar wind. The Multi-Asteroid Touring (MAT) mission concept was proposed to visit tens of asteroids in the Main Asteroid Belt (MAB) with a fleet of nanospacecraft operated by E-sail (Slavinskis, Pajusalu, Sünter, et al., 2018).

Small Bodies Assessment Group recommends[4] a balanced program of telescopic observation (ground-based, airborne and space-based), laboratory studies, theoretical research and missions to MAB utilising the full spectral range from ultraviolet to far-infrared to investigate next outstanding fundamental questions in the decade 2023–2032: (i) physical properties and processes, (ii) chemical composition and (iii) evolution and dynamical evolution (McAdam et al., 2020). Until today, fewer than 20 out of over a million known asteroids have been studied by space missions. Visualisation of visited small bodies is

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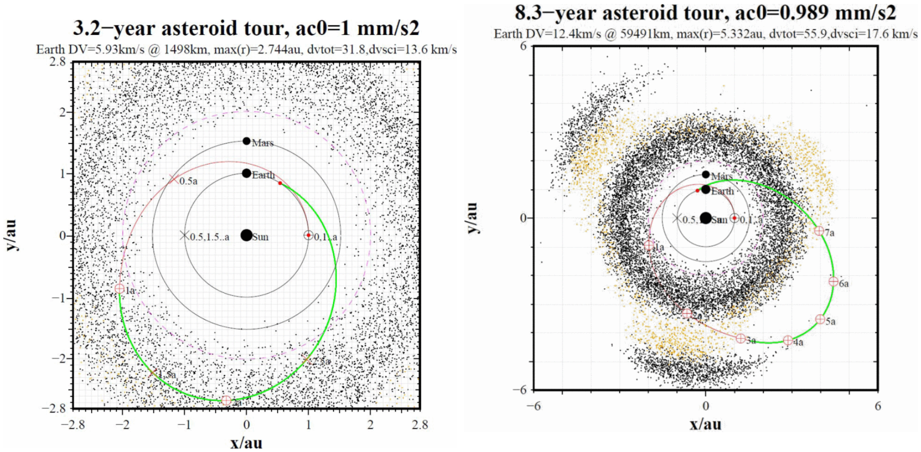
[4] Expressed in the 2020 White Paper (McAdam et al., 2020).

presented in Subsection 3.1. In the case of orbiting missions, the target is 1–2 objects; alternatively, the flyby can target more asteroids (Bowles et al., 2018; Clark et al., 2018; Snodgrass et al., 2018). MAT is a mission concept dedicated to a distributed close-range spectral survey of hundreds of asteroids by a fleet of nanospacecraft to increase statistical knowledge of asteroids with resolved surfaces[5].

The initial paper by Slavinskis, Pajusalu, Sünter, et al., 2018 defined the mission and system requirements and proposed few feasible orbits for a single tethered nanoprobe. The range of the proposed orbit differs from 3.2 to 8.3-years-long journeys. This resulted in the more detailed spacecraft assessment in **Iakubivskyi, I** et al., 2021 to fulfil the mission requirements while keeping the mass below 6 kg for a spacecraft with a 20-km-long tether charged to 15–30 kV. The resulting acceleration from the thrust (in order of hundreds of nanonewtons per meter, depending on tether structure) produced by the system is approximately 1 mm·s^{-2} at 1 Astronomical Unit (AU). This number is strongly correlated with the solar activity driven by the solar cycle and, therefore, affects solar wind conditions. Depending on space weather, this can be compensated by adjusting the voltage using an algorithm that interprets the accelerometer readings and adjusts tether voltage for required acceleration management. A variety of models exist to forecast roughly solar wind conditions for a particular sailing day (MacNeice et al., 2018).



(a) MAB trajectory

(b) Jupiter trojans, Hilda and MAB trajectory

Figure 9: Various original E-sail orbits for the MAT mission.

(Slavinskis, Pajusalu, Sünter, et al., 2018)

A foundation for designing a more complex mission case and system-level design in **Iakubivskyi, I** et al., 2021 were following mission-level requirements

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[5] Science popularisation article: `https://space-travel.blog/mat-101d13b76f9b`.

derived from Slavinskis, Pajusalu, Sünter, et al., 2018:

1. Launch to marginal escape or other solar-wind intersecting orbits with a small rocket (e.g., PSLV or Epsilon).
2. Acquire elliptical heliocentric orbits between 1 and 3 AU. Specific orbital parameters differ from spacecraft to spacecraft.
3. Withstand four years in an elliptical orbit to the main belt or equivalent environment.
4. Perform flybys of 20—40 primary targets at distances between 200 and 1000 km.
5. When possible, maximise the number of primary targets (minimise the number of spacecraft) by using one spacecraft to fly by multiple primary targets.
6. Locate targets by scanning the sky.
7. When located and if needed, perform relative orbital corrections to reach the required flyby distance.
8. Maximise the illuminated and imaged surface coverage.
9. Observe active asteroids at different phase angles, including the Sun behind the asteroid.
10. Store science data until the Earth flyby.
11. Transmit science data during the Earth flyby.

2.2.1. MAT spacecraft adaption

The baseline orbit for the design and analysis was 3.2 years MAB orbit[6] shown in Figure 9a. It was adapted for the structural and thermal analysis and split into simplistic operational steps shown in Figure 10.

The main operational modes derived from **Iakubivskyi, I** et al., 2021 are following:

1. Deployment (near the Earth at 1 AU):
   i) Deployment from a launch vehicle's fairings;
   ii) Commissioning of spacecraft, detumble, spin-up around a controlled axis and deployment of the Remote Unit (RU) with the tether;
   iii) Deployment of solar panels on the RU;
   iv) Testing low- and high-data-rate communications.
2. Acceleration (1–2 AU):
   i) Activation of navigation, high-voltage source and electron emitters;
   ii) Acceleration with the E-sail;
   iii) The angle between the spin plane and the Sun is 33.4° at 1 AU and linearly decreases (active control) to 0° at 2 AU;

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[6] Visualisation of deployment and flyby: `https://vimeo.com/577117925`.

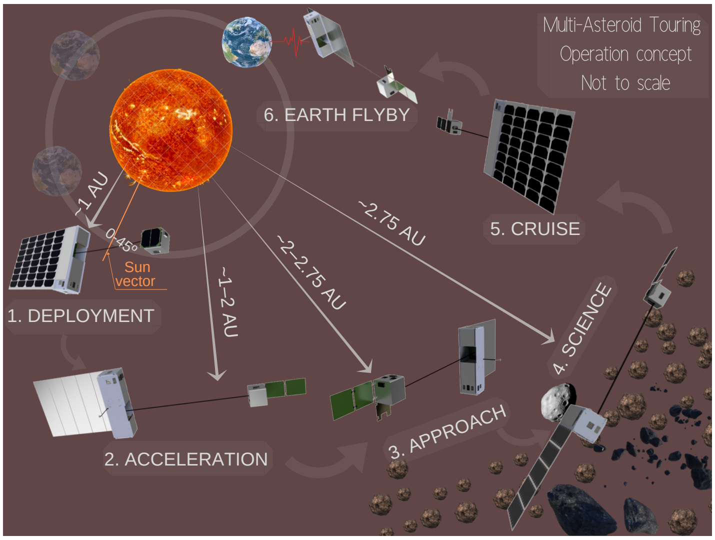


Figure 10: Simplified operation MAT concept for the analysis.

(**Iakubivskyi, I** et al., 2021)

    iv) Low-data-rate communications with the Earth.

3. Approaching the main asteroid belt (2–2.75 AU):
    i) Deployment of a thermal screen on the RU;
    ii) Active Attitude and Orbit Control System (AOCS) and E-sail manoeuvres to minimise the flyby distance;
    iii) Low-data-rate communications with Earth.
4. Science (≈ 2.75 AU)
    i) Approaching the target;
    ii) Remote sensing during flyby (Pajusalu and Slavinskis, 2019);
    iii) Low-data-rate communications with Earth.
5. Cruise (2.75–0.95 AU)
    i) Returning back to the Earth's proximity with scientific data stored on board;
    ii) Low-data-rate communications with Earth, transmitting the scientific data, if possible.
6. Earth flyby (0.95–1 AU)
    i) High-data-rate communications: downlink the scientific data during Earth flyby.

The spacecraft was designed to operate with a 20-km-long tether, and the total mass limit is 6 kg. The baseline design is a cubesat according to Planetary System Corporation dispenser design (Tullino and Swenson, 2017) and nearly 1U deployable Remote Unit (RU). The RU is designed to operate independently and assist the deployment and maintenance of the E-sail. The exploded view of the spacecraft is shown in Figure 11.

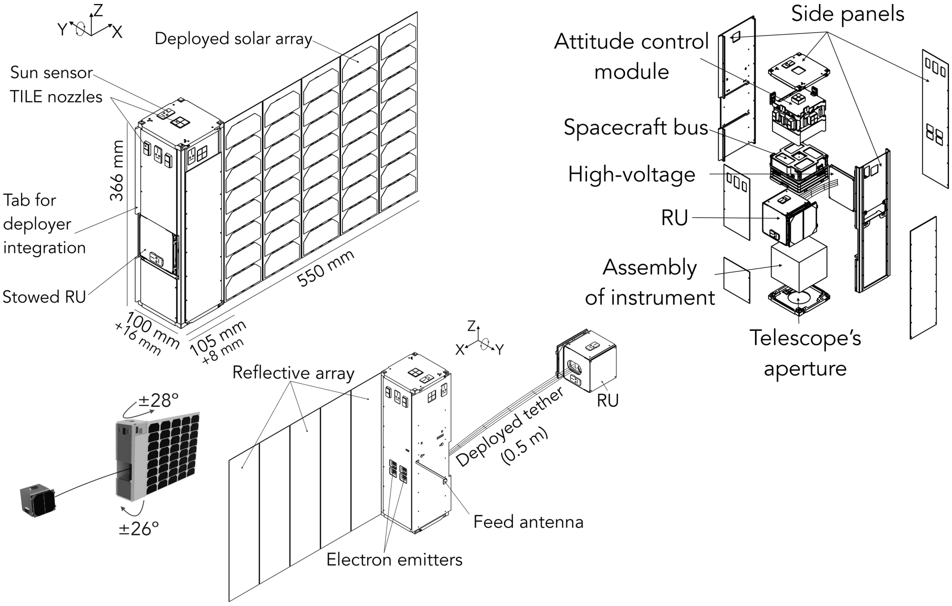


Figure 11: MAT spacecraft anatomy.

(**Iakubivskyi, I** et al., 2021)

The RU is equipped with electrospray propulsion to adjust the trajectory and deploy the tether. The trajectory is adjusted by the spin plane corrections, which are done by (i) applying full voltage (i.e., maximum thrust) during the first half rotation and zero-thrust during another half or (ii) by applying electrospray thrust in the RU in the desired direction, or by the combination of both. The RU's thruster firing would be critical for manoeuvrability during the critical scientific operation (i.e., attitude and trajectory adjustment for target imaging). The angular velocity of the spin-plane trajectory correction is calculated by Equation 2.5 from **Iakubivskyi, I** et al., 2021. The anatomy of RU is shown in Figure 12.

$$\omega = \frac{1}{2\cdot\pi}\cdot\sqrt{\frac{dF/dr}{k\cdot m}}, \tag{2.5}$$

where dF/dr is the E-sail thrust per length, which is 250 nN·m^{-1} for MAT at 10 kV average voltage at 1 AU, and three times smaller at 3 AU (Janhunen et al., 2010); k is the ratio between the tether tension and E-sail force, which can be as low as 3 for a single-tether system at 1 AU, and 9 at 3 AU; m is the RU mass (0.75 kg). It results in approximately 10.9 deg·h^{-1} at 1 AU and 3.6 deg·h^{-1} at 3 AU, if the spin periods and voltages are constant.

Preliminary system budgets and power equilibrium used for thermal analysis are derived from **Iakubivskyi, I** et al., 2021 and are shown in Table 2.

Component	Modes power consumption and equilibrium [W]					
	1.Dep.	2.Ac.	3.Ap.	4.Sc.	5.Cr.	6.E. f.
Main Spacecraft						
E-sail	0.1	7–3	3–0.1	0.1	0.1–3	0.1
TILE	1.5	0.5	1.5–0.5	0.5	0.5	0.5
Main bus	0.5	0.5	0.5	0.5	0.5	0.5
Heater	0	0	0–1.6	1.6	1.6–0	0
Transmitter	0.5	0.025	0.5	0.025	0.5	10
Instrument	1	1	1	1	1	1
Reaction Wheel (RW) x	0.25	0.5	0.25	0.5	0.25	0.5
RW y	1.05	0.5	0.25	0.5	0.25	0.5
RW z	0.4	0.075	0.1	0.075	0.1	0.1
COM to RU	0.1	0.1	0.1	0.1	0.1	0.1
$\boldsymbol{P}_{output}$	5.4	10.2–6.2	7.2–4.9	4.9	4.9–6.2	13.3
$\boldsymbol{P}_{available}$	37.8	34–8.9	8.5-5.4	5.4	5.4–30.8	30.8
Margin	32.4	23.8–2.7	1.3–0.5	0.5	0.5–24.6	17.5
Remote Unit						
Motor	1	0	0	0	0	0
AOCS	0.1	0.18	0.18–0.1	0.1	0.1–0.18	0.18
Bus	0.2	0.2	0.2–0.1	0.1	0.1–0.2	0.2
Heater	0	0	0–0.25	0.25	0.25–0	0
COM to MS	0.1	0.1	0.1	0.1	0.1	0.1
$\boldsymbol{P}_{output}$	1.4	0.48	0.48–0.55	0.55	0.55–0.48	0.48
$\boldsymbol{P}_{available}$	1.9	1.9–1.08	1.05–0.67	0.67	0.67-4.7	4.7
Margin	0.5	1.42–0.6	0.57–0.12	0.12	0.12–4.22	4.22

Table 2: Subsystems' power budget and power equilibrium at various mission modes.

P–power, COM–communications. The table is taken from **Iakubivskyi, I** et al., 2021.

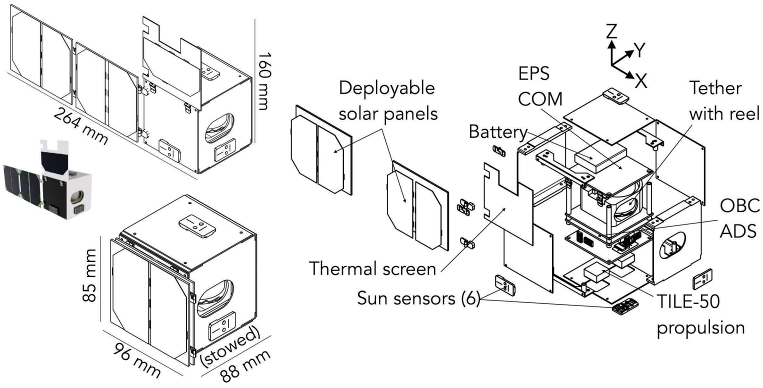
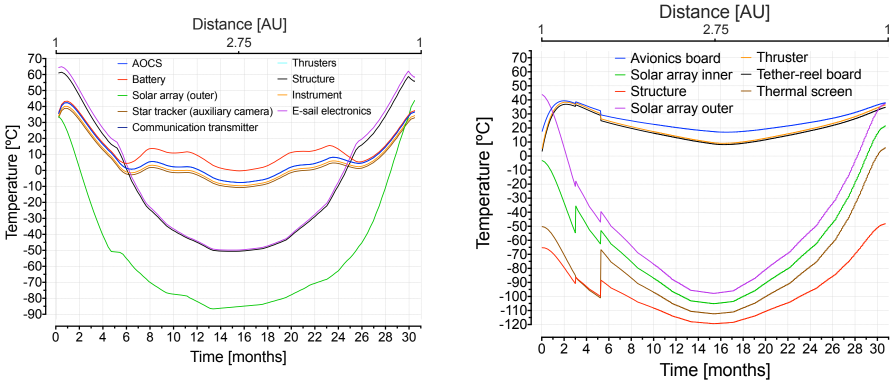


Figure 12: RU subspacecraft anatomy.

(**Iakubivskyi, I** et al., 2021)

The environmental analysis demonstrated the feasibility of such spacecraft to operate with passive thermal design in deep space and accomplish the scientific objectives. The thermal distribution during the mission for the main spacecraft and RU are shown in Figure 13.



(a) Main spacecraft

(b) RU

Figure 13: MAT thermal profile.

(**Iakubivskyi, I** et al., 2021)

3. INSTRUMENTATION AND SIMULATIONS

An optical instrument is one of the most common instruments on space missions. Various phenomena are observed and characterised by visual cameras. There is a tendency in camera's miniaturisation and an increase in the number of cameras per satellite. For example, the Mars 2020 Perseverance rover is equipped with 23 cameras and, during its first 147 sols, produced over 112k images. The first Estonian satellite, ESTCube-1, was equipped with a camera that brought great success to the mission (Slavinskis, Pajusalu, Kuuste, et al., 2015). This camera led to the development of the European Student Earth Orbiter dual-camera payload (Sünter, Kuuste, Kütt, et al., 2016; Sünter, Kuuste, Slavinskis, et al., 2016). Later, it led to the development of a double-camera set-up for the ESTCube-2 satellite scheduled for the launch in 2022 (Ehrpais et al., 2016; **Iakubivskyi, I.** et al., 2016). ESTCube alumni Pajusalu and Slavinskis, 2019 also built the instrument prototype for the MAT mission. Essentially, almost every satellite requires an optical instrument and the development of new, innovative and custom ideas for the era of New Space. The following Subsection 3.1 discusses the current instrument, Optical Periscopic Imager for Comets, development in Tartu Observatory. In order to evaluate the performance, develop autonomy algorithms and imaging strategies for an instrument, such as OPIC and optical instrument for MAT, a highly capable physically-based Space Imaging Simulator for Proximity Operations (SISPO) was developed and is presented in Subsection 3.2.

3.1. Optical Periscopic Imager for Comets (OPIC)

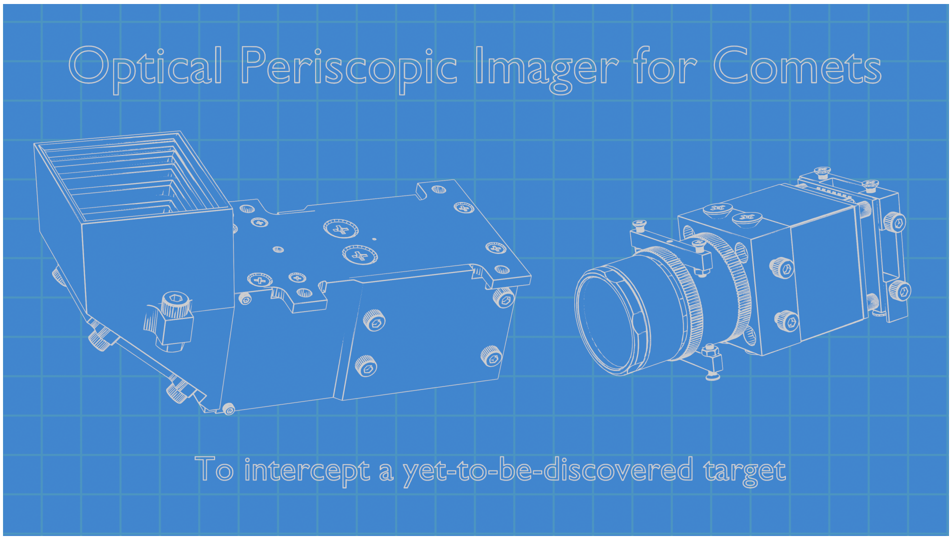


Figure 14: OPIC blueprint.

Cometary science started with basic direct observations and can be naturally divided into five conceptual periods: (i) before 1600, comets were interpreted as heavenly omens, possibly meteorological atmospheric phenomena; it is hard to date the first observations, but known records exist from Old Babylonian period (early second millennium B.C.) (Steele, 2001); (ii) the discovery of the universal gravitational law contributed to positional measurements during two following centuries, and two critical events occurred: the successful prediction of the March 1759 return of 1P/Halley's comet and the discovery of the non-gravitational motion of Comet 2P/Encke; (iii) in 1835, the spatial structure of a comet was described in detail for the first time with the passage of 1P/Halley, and this started a new field of cometary physics; iv) 1950 marked the modern view in cometary structure as an ensemble of solar system objects composed of primordial ice and dust, generally on long-period orbits and shaped by their interactions with the solar radiation field and the solar wind; v) the current era of space missions, *in situ* observations and sample return began with comet 21P/Giacobini–Zinner flyby in 1985 and 1P/Halley in 1986 (Dones et al., 2004a).

Ernst Julius Öpik, an Estonian astronomer and astrophysicist, predicted that comets should arrive from the cloud far beyond Pluto, lately named the Öpik–Oort cloud. Öpik, 1932 and Oort, 1950 pointed out that once the comet's orbit becomes large enough, passing stars affect it; in fractional terms, stars change cometary perihelion distances much more than they change the overall size of the orbit (Dones et al., 2004b). In dedication to his discoveries, Tartu Observatory is now developing an instrument, called OPIC, to fly by a long-period comet or an interstellar object in a prominent case. The family of visited small bodies in the current exploration era is meagre and requires investigation of a vast number of small bodies, especially unweathered comets, in order to fill in the knowledge gaps; currently visited small bodies are visualised in Figure 15.

OPIC is the first Estonian deep space instrument being developed for the ESA-JAXA F-class mission Comet Interceptor[1] (Snodgrass and Jones, 2019). Three probes will assist the study of a long-period or dynamically new comet, or an interstellar object by fast rendezvous. The main goal is to investigate how a long period comet differs from a short period one. One of these probes, B2, is equipped with the miniature OPIC instrument (a 500 g camera); the probe is spin-stabilised at 4–15 RPM. OPIC shall take full-frame images of coma to identify dust particles. The mission will arrive at Earth-Sun Lagrange point L2 on a shared ride with ESA's ARIEL telescope (Pascale, Eccleston, and Tinetti, 2018) and will remain in quasi-halo orbit for up to three years (Sánchez et al., 2021). It will depart to intercept a yet-to-be-discovered target at a relative velocity of 10–70 km$\cdot$s^{-1} at a suitable time and conditions with an expected heliocentric distance of 1.1–1.25 AU. The mission consists of a mothercraft A (ESA) parked at L2 until the departure to the target's interception orbit is

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[1] The presentation about the mission can be watched here: `https://vimeo.com/521276732`.

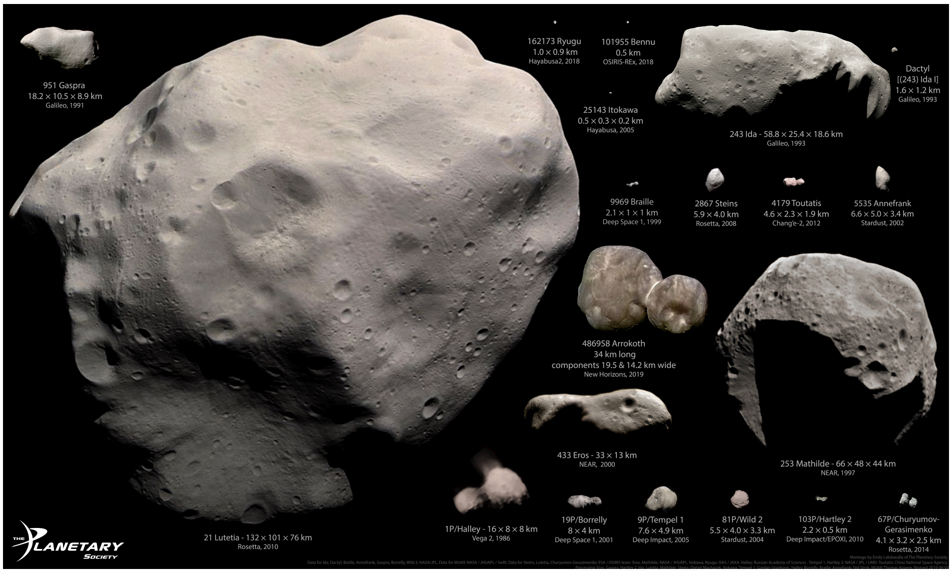

Figure 15: Asteroids and comets bothered by spacecraft.

A montage of 18 of the 20 asteroids and comets that have been photographed up close as of December 2018, when New Horizons flew past Arrokoth. This version is in color but does not show the bodies at their correct relative albedo or brightness. Not included are Vesta or Ceres, both of which are many times larger than Lutetia. Montage by Emily Lakdawalla for The Planetary Society. Data from NASA / JPL / JHUAPL / SwRI / UMD / JAXA / ESA / OSIRIS team / Russian Academy of Sciences / China National Space Agency. Processed by Emily Lakdawalla, Daniel Machacek, Ted Stryk, Gordan Ugarkovic / Thomas Appéré. This work is licensed under a Creative Commons Attribution 3.0 Unported License.

confirmed. The B1 (JAXA) and B2 (ESA) daughter spacecraft will be deployed from A to enhance the scientific return by performing multi-point measurements. The B2 probe's planned trajectory incorporates the closest approach of roughly 400 km. The full operation time is relatively short, equals 72 hours of planned operations at most, unless the probe survives the encounter with a near environment. The data collected before the possibly fatal closest approach will be transmitted in compressed packages at 10 kbit·s^{-1}.

The instrument evolved since the publication by Pajusalu et al., 2020; some modifications are introduced in this section. The general view and basic components are demonstrated in Figure 16.

The periscope is a vital element of OPIC design. It protects the camera from the impact of high-velocity particles produced by the comet. The body of the study object might be weathered by Sun for the first time. The typical activity of the comet evolves from roughly 3 AU. The sublimation-driven process produces non-volatile material (i.e., dust) motion that reaches escape velocity; there is also evidence of accumulation of non-escaping particles of various sizes (Thomas et al., 2015). These particles have high impact energy due to their velocity. The periscope's aluminium mirror protects optics and other parts of the instrument

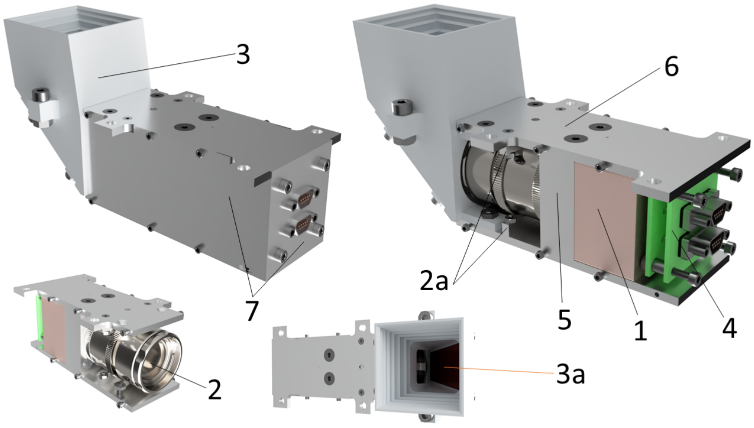

Figure 16: OPIC anatomy.

The view represents external and internal parts which are described in Table 3.

from being damaged during close interaction. The viewing geometry is shown in Figure 17.

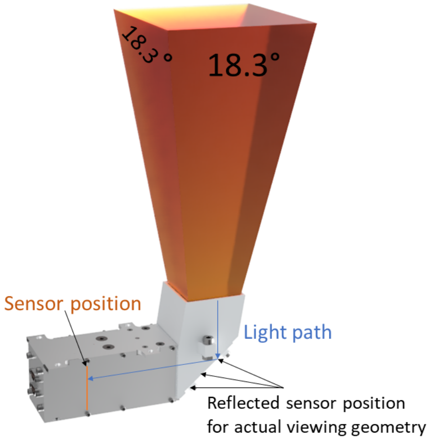

Figure 17: The viewing geometry of OPIC.

The actual preliminary performance of the instrument is shown in Figure 18. It shows captured frame while approaching the comet at 600 km on a 400-km closest-approach trajectory. The trajectory was simplified as a straight line since the integration of Keplerian orbital parameters would have a negligible effect on the performance estimation. The development of such image simulations is done by Space Imaging Simulator for Proximity Operations (SISPO), described in Subsection 3.2.

Part	Title	Description
1	Camera head	An integrated imaging module, 3DCM734-1 from *3D plus*, has a CMV4000 2048×2048 pixels sensor, a three million gate ProASIC3 FPGA, 1 GB of flash memory, and 64 MB of RAM. It is rated to 40 krad of total ionising dose and operating temperature from −40 to +70°C.
2	Optical assembly	Commercial Off-The-Shelf (COTS) LM35JCM-V 2/3" ruggedised 35-mm C-mount f/2 lens assembly. The filter will be integrated with the optical assembly's front element. It is designed for use in environments with strong vibrations and shocks but requires testing on the vibration bench for the Ariane 62 vibration profile.
2a	Optical supports	Two metallic supports with set screws for supporting optical assembly.
3	Periscope assembly	The periscope assembly consists of two parts and a mirror. The lower part functions as a mirror holder, and the upper part serves as a baffle.
3a	Metal mirror	The current design requires an aluminium substrate with a protected silver layer and an additional protective coat.
4	Interface	Data and power interface consists of a two-board assembly 5 mm apart, which is bolted to the enclosure. The front PCB is directly attached to the camera head with pins, and the rear PCB has two identical Micro-D connectors from *NorComp* (580-M09-213L001).
5	C-mount adapter	An aluminium adapter that provides a mechanical interface between the camera head and optics.
6	Top plane	An aluminium plate that provides a structural and thermal interface to B2 spacecraft.
7	Enclosure	An aluminium enclosure around the body and bottom plate provides structural stability and protects optics and electronics against harmful radiation.

Table 3: OPIC anatomy description.

3.1.1. Image capturing

The following cases make mission operation and fulfilment of scientific requirements challenging:

1. The high relative velocity of up to 70 $\text{km}\cdot\text{s}^{-1}$ will provide merely minutes when the nucleus can be resolved; the longer time will be available to capture the entire coma.
2. Spin-stabilised spacecraft B2 does not provide the opportunity to point the instrument (i.e., the instrument can only control the timing and length of

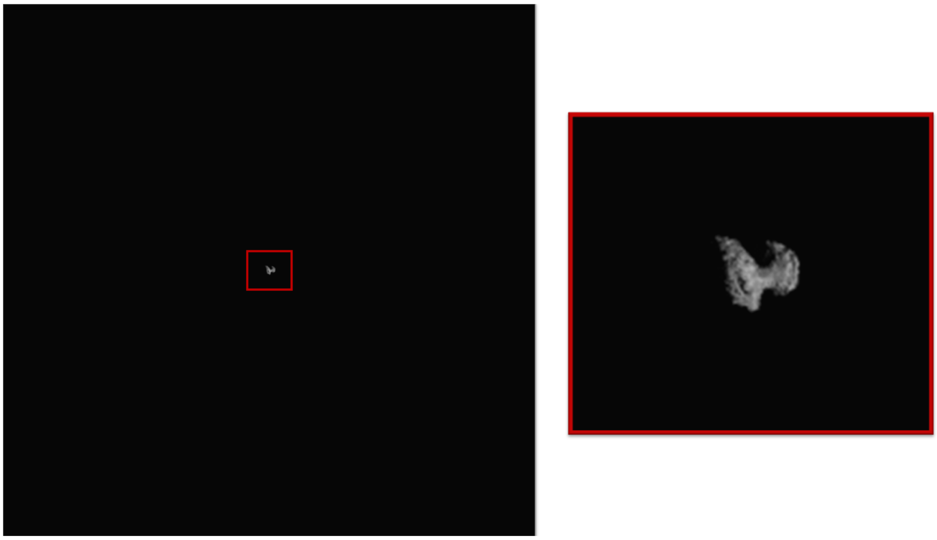

Figure 18: An expected image of the comet 67P/C–G without jets at approaching distance of approximately 600 km.

The frame on the right is the actual full-frame size image expected by OPIC instrument, which was simulated in SISPO (more details in Subsection 3.2). The right view is zoomed region. The image is simulated with a pinhole camera. The object's brightness would depend on its albedo and heliocentric distance, which is expected to be 1.1–1.25 AU.

exposure); the rotating view will intercept with nucleus closer to the edge of the frame (see Figure 19), and in specific geometrical configurations, the nucleus might not be visible.

3. The probe B2 might not survive the encounter with the comet (i.e., the kinetic energy of particles impact might be fatal) and, therefore, the data must be transmitted before the potentially damaging encounter.
4. The limited resources and low data budget provide numerous limitations on data that can reach Earth. Due to the wide Field of View (FoV), the prioritised scientific data would be the one to (i) resolve a 3D structure of the coma (in combinations with data from other payloads), (ii) capture resolved images of a nucleus, (iii) image dust particles and vi) provide means for navigation and localisation of B2 spacecraft.
5. One full frame image would take over 80 minutes to transmit. The full sky image (the FoV corresponds to $\frac{1}{6}$ of one full B2 spin) would take over eight hours, which is unfeasible in the context of probe's lifespan and data budget. Pajusalu et al., 2020 describes the roadmap of required autonomous algorithms for data prioritisation, compression and cropping.

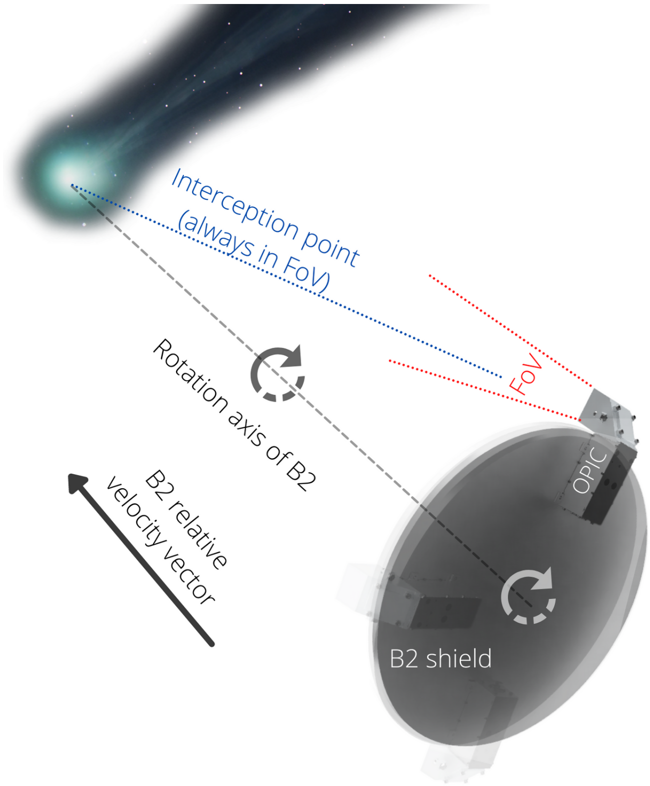

Figure 19: Flight geometry of B2 spacecraft and OPIC's FoV.

3.2. Space Imaging Simulator for Proximity Operations (SISPO)

SISPO is a newly developed physically-based space imaging simulator developed by the University of Tartu and Aalto University; other institutes also contribute to the current development. It is based on open-source Blender software and its Cycles rendering engine. SISPO is applicable for terrestrial-body mission-oriented operations, such as the design of advanced deep-space missions, the simulation of large sets of configurable scenarios, and the development and validation of algorithms for autonomous operations, vision-based navigation, localisation and image processing (Pajusalu, **Iakubivskyi, I.**, et al., 2021).

SISPO was initially used for the MAT mission development (see Section 2.2) and potential scientific data production. Currently, it is actively used for the development of OPIC (see Subsection 3.1) and EnVisS (Da Deppo et al., 2020; Pernechele et al., 2020) instruments. It can also be utilised for planetary surface missions, for example, simulating surface and subsurface rover operation environments, such as lava caves. The author of this dissertation, as a member of the international team PELE[2], develops future sampling tactics in Martian caves utilising Earth analogues as sampling ground for astrobiology research (Csuka et al., 2020; Kopacz et al., 2018), and SISPO could be potentially employed for such mission development.

SISPO main functionality includes image rendering using a fast OpenGL engine and physically-based high-detail Cycles rendering engine. It also has the following auxiliary features (more information in Subsection 3.2.2), some of which are still in development:

- 3D reconstruction;
- Gas and dust environment;
- Camera distortions;
- Attitude dynamics in the initial stage (the Orekit framework). It contains rotation from the reference frame to the satellite frame, and the angular velocity and angular acceleration of the spacecraft in its frame.

3.2.1. Blender and Cycles

Cycles, developed by the Blender project (Blender Online Community, 2021), is open-source software for realistic physically-based rendering. It uses path tracing, which is a type of ray tracing. The ray tracing is an inverted process to the natural light propagation, where light travels from the source, then reflects from the surface and reaches the sensor. In the ray tracing, the ray is shot from the camera's pixel, and then it bounces from the surface with specific shaders and textures and eventually reaches the light source. The limitation of ray tracing is an exponential growth of rays, which is computationally heavy. In path tracing, instead of sending a single ray from a pixel, it shoots multiple rays, bouncing without producing new rays. The rays bounce until they finally reach light sources or exhaust the sampling limit; the amount of light and surface shader values are then registered by specific pixels. For photorealistic surface generation, SISPO uses micropolygon displacement texture, also called adaptive subdivision or tessellation: it implements adaptive subdivision of the object, which is then displaced by micropolygon displacement during rendering. The comparison between SISPO and other available simulators is shown in Figure 4 on the example of asteroid 25143 Itokawa (Gaskell et al., 2008).

3.2.2. Auxiliary features

3D reconstruction. SISPO provides the possibility to reconstruct 3D surfaces based on structure from motion algorithms (more information in Westoby et al., 2012), which are provided by external packages, such as OpenMVG (Moulon

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[2] Planetary Analogues and Lava Tube Expedition, an international team is studying lava caves by *in situ* biological and geological sampling collection and intends to find a correlation between unconnected environments (i.e., lava caves on various geological locations, primarily volcanic islands). More information can be found in Guðlaugardóttir, 2021; Iakubivskyi, 2019.

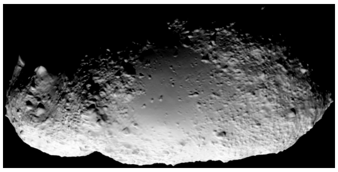
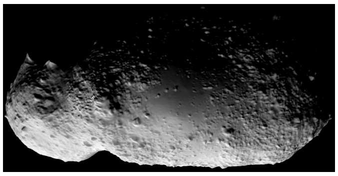
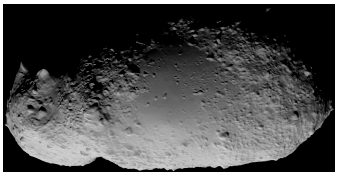
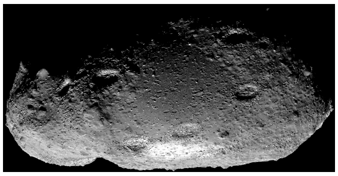
Simulator	Developer	Rendering	Example of rendered image
SurRender	Airbus	Backward ray tracing or image generation with Open Graphics Library (OpenGL)	
Planet and Asteroid Natural Scene Generation Utility (PANGU)	University of Dundee, UK and ESA	Fractal terrain generation using OpenGL	
SISPO	University of Tartu, Estonia and Aalto University, Finland	Blender Cycles physically based path tracer (the same model as above with a simple diffuse shader)	
		Blender Cycles physically based path tracer with procedural displacement and reflectance textures	

Table 4: The comparison of available simulators for space-scene image rendering.

The data was taken from Pajusalu, **Iakubivskyi, I.**, et al., 2021.

et al., 2017) and OpenMVS (Cernea, 2021). It takes the set of images as input, detects common features between various frames and reconstructs the point cloud, which then can be turned into a textured mesh. Figure 20 demonstrates the numerical comparison between the input 3D model for image generation and the reconstruction of comet 67P/C–G based on the 25 frames generated by SISPO during the simulated flyby.

Camera. Blender software does not simulate common optical aberrations and motion blur, which is expected from the hardware performance in the real environment. Tangential and sagittal astigmatisms and internal and external comatic aberrations are modelled by the SISPO-integrated external tool. The Optical Aberrations for Still Images Simulator (OASIS)[3] tool was developed by Bührer, 2020.

Gas and dust. The typical heliocentric distance for a comet to show the signs of activity is 2.5–3 AU, and H_2O, in certain circumstances, sublimates at 5–10 AU; in this process, a comet relieves its cold volatile storage, which was preserved for

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[3] `https://github.com/SISPO-developers/OASIS`.

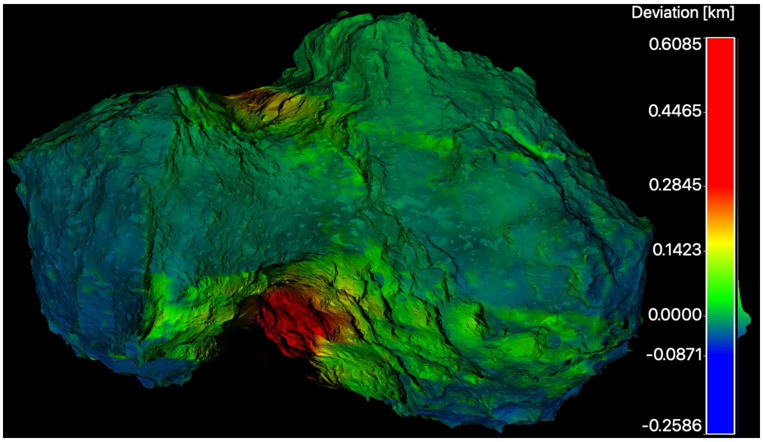

Figure 20: Comparative reconstruction of comet 67P/C–G.

The comparison was made with CloudCompare software (Girardeau-Montaut, 2011). This image is from Pajusalu, **Iakubivskyi, I.**, et al., 2021.

a long time – billions of years (Rickman, 2004). The coma is typically observed in the form of scattered light from released gas and dust particles; this mechanism is simulated and integrated into SISPO. Currently developed coma creator[4] is based on the volumetric-scattering shader from Cycles (Pajusalu, **Iakubivskyi, I.**, et al., 2021).

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[4] `https://github.com/SISPO-developers/ComaCreator`.

4. DISCUSSION AND CONCLUSIONS

Space missions and relevant technology are still relatively developing fields that have been operating for less than 70 years. There are few fundamental reasons, among many more, for that. First, it is expensive; one might call it luxury by economic standards of the first quarter of the XXI century. Secondly, it is time-consuming: the process starts from proposal writing, and it ends with the satellite commissioning, which is then transferred to the data interpretation step that reflects on the academic position creation, primarily based on the generations of master and doctoral theses. For example, if the Cassini–Huygens mission proposal would be initiated now, the famous *Grand Finale* (Edgington and Spilker, 2016) would happen in the 2060s; that is a career lifetime for a human. Thirdly, space technology is complicated and requires comprehensive expertise and synchronised teamwork, which are not exceedingly easy to congregate, especially by non-space-faring nations without a needed education, expertise and experience. Despite mentioned challenges, the field is thriving with innovation and, more noticeably, public support to space-related topics. The launch price per launched kilogram could be reduced significantly[1], which in succession with tens of other remarkable companies, such as Rocket Lab, will make the launch of nanosatellites[2] extremely affordable and feasible for technology demonstration and supportive science missions, both for Low Earth Orbit (LEO) and deep space.

The world of nanospacecraft and the commercialisation of the space field, in general, are shaping these limitations to globally affordable and opportunistic directions. Cubesats are assisting scientific missions and contribute to the exploration of the Solar System. Propulsion, autonomy and scientific instrumentation are still limiting factors. The Electric Solar Wind Sail (E-sail), a type of Coulomb Drag Propulsion (CDP), provides a viable solution of space travel with microspacecraft: it utilises electrostatic force created by the solar wind interaction with a positively charged tether.

The first attempts to test E-sail and plasma brake were onboard the ESTCube-1 satellite and then Aalto-1. Despite the unsuccessful deployment of their tethers, they have provided precious lessons learned for the next generation of satellites. ESTCube-2 and FORESAIL-1 (see Suction 2.1) contribute to the technology demonstration missions of CDP in the form of plasma brake deorbiting. ESTCube-2 will also test a positive mode with the involvement of electron emitters for evaluating the E-sail thrust, measured by changes in spin rate. The results of these missions will be crucial for the further development of plasma brake modules and E-sail and are aiming to demonstrate an actual

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[1] For instance, SpaceX's heavy-lift Starship: the payload capacity is over 100 tonnes, and the predicted price, when reusability is achieved, is in the range of 2–10M USD, which brings the price to 20–100 USD/kg (Mann, 2020).

[2] Mainly cubesats that are operated since 1999.

deorbiting by CDP means. It will also influence the technologies for the tether deployment and maintenance of spin plane, tether production, and multi-tethered system implementation. The tether itself requires a novel implementation for manufacturing. Currently, it consists of multiple interconnected aluminium alloy filaments with diameters ranging from 25 to 100 μm in the Heytether resemblance. Such structure prevents tether from being destroyed by micrometeoroid impacts and various erosion effects, such as aluminium sputtering. Other conductive metals can also be employed in the future, such as gold, copper, titanium, nickel, steel, and silver. The latter has limitations in the LEO applicability due to atomic oxygen erosion. Density and strength are also important factors. The primary complication in the previous missions was a deployment step; therefore, ESTCube-2 and FORESAIL-1 will utilise space-grade stepper motor and undergo extensive testing to improve general system reliability. Both satellites provide a solid ground for future mission development in E-sail's natural habitat – solar wind, for example, the MAT mission adaptation.

This thesis contributes to the mission concept development of the deep-space nanospacecraft fleet to the Main Asteroid Belt (MAB) entitled Multi-Asteroid Touring (MAT). Fewer than 20 asteroids have been explored by spacecraft from close vicinity. The ground-based or remote space telescopes observations do not provide sufficient resolution to resolve the geomorphology and composition of small solar system bodies. Each 6 kg MAT spacecraft is equipped with a 20-km-long tether which ensures a total journey time of approximately 3.2 years to MAB with one heliocentric orbit. The fleet of 50 spacecraft could provide data about hundreds of asteroids in MAB with an approximate heliocentric distance of 2.75 AU. The data is stored in the onboard memory and downloaded during the Earth flyby. One of the biggest challenges for the spacecraft is to accommodate satisfactory-against-requirements thermal design and radiation protection in a small package for a long-duration trip and significant fluctuations of solar fluxes throughout the mission. The application of various surface finishes and other passive control strategies provides sufficient isolation for the craft to operate in the hot (0.95 AU) and cold (2.75 AU) cases. The MAT mission concept is an innovative way to explore the solar system. It demonstrates the capabilities of E-sail at its unparalleled excellence since there is practically no propulsion that would allow such a mission scenario with stated mission requirements (e.g., an independent fleet of cubesat launched together to study hundreds of asteroids). The Aurora Propulsion, a private enterprise, is also developing a separate E-sail-propelled concept targeting the North Star[3].

The CDP propulsive effect firmly depends on the applied voltage, length and number of tethers and space weather conditions. The space weather conditions in LEO are mainly connected to the distribution and density of the ionospheric

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[3] `https://aurorapt.fi/northstarmission/`, accessed 26/07/2021.

plasma and H/O ion ratio. Various models listed in this thesis support the preliminary estimation of ionospheric conditions in a specific orbit; however, it moves, and this migration is caused by solar activity. The same applies to deep-space operation, where the variation of solar wind is a decisive factor for the propulsive effect. It changes based on the 11 years solar cycle and short-term solar events in general. To some extent, thrust parameters can be compensated by voltage adjustment to provide the required average acceleration over time.

The optical payload for fast flyby missions for the MAT mission requires the development of autonomous operation, especially for scenarios with limited communication and short operation time. Such algorithms could be developed with the assistance of specialised simulator software. Simulation tools would also be helpful for the performance estimation, design of advanced deep-space missions, the simulation of large sets of configurable scenarios, and the development and validation of algorithms for autonomous operations, vision-based navigation, localisation and image processing. In collaboration with Aalto University, the UT has developed the Space Imaging Simulator for Proximity Operations (SISPO); it is a fully functional simulator based on the open-source Blender software and employs various additional packages for optical aberrations, coma simulations and reconstruction. It employs micropolygon displacement texture generation for realistic surface generation. In Pajusalu, **Iakubivskyi, I.**, et al., 2021, various use-cases were discussed, among them are: example of asteroid 25143 Itokawa simulation, volumetric particle effect for coma generation on the comet 67P/C–G, lunar surface generation in comparison with the actual Apollo-15 operation side, subsurface exploration on the example of the Martian analogue lava cave, and spacecraft flyby simulation. Some features require further development and integration, which include the following: attitude dynamics, image compression, spectral reluctance simulation, Solar System ephemeris integration for historical and upcoming events. SISPO is actively used for OPIC and ENVISS instruments development for the ESA-JAXA Comet Interceptor mission despite the ongoing improvements and developments.

OPIC is the first Estonian deep space instrument hosted on one of three probes of the Comet Interceptor mission. Currently, there are three probes: A, B2 and B1. The Japan Aerospace Exploration Agency is building the latter. Probes A and B2 are from ESA. The spin-stabilised probe B2 is planned to intercept the study object at the closest distance of approximately 400 km. Comet Interceptor will study a long-period or dynamically new comet or an interstellar object by fast rendezvous. The OPIC instrument on the B2 probe should take resolved images of the nucleus and full-frame coma images. In addition, it could perform 3D reconstruction and B2 localisation. It is also designed to perform image compression and prioritisation by intelligent algorithms driven by short mission operation time and limited data rates. OPIC uses a space-grade camera from *3D Plus*, COTS optics, and a custom-developed rigid structure to comply with the operational environment. It is equipped with a periscope and metallic mirror to protect the camera from the impact of high-velocity particles of ice and dust produced by the comet. This instrument is a vital payload that could help understand the unresolved questions about the origin of the Solar System, the role of asteroids and comets in life, and how we can protect Earth from any potential impacts.

To conclude, the dissertation presented here explores the author's contribution to the miniaturisation of planetary missions and instruments by developing the nanosatellites missions, mission concept, instrumentation and simulation tool for planetary research and technology demonstration. Firstly, it demonstrates the design and performance of the Coulomb Drag Propulsion (CDP) payload for deorbiting on the ESTCube-2 and FORESAIL-1 satellites, the new generation of CDP cubesats to be launched in 2022[4]. Then it leads to the more advanced CDP application – Electric Solar Wind Sail (E-sail) for the Multi-Asteroid Touring (MAT) mission concept to visit hundreds of asteroids by a fleet of nanospacecraft, which is primarily based on ESTCube-2 experience and relevant missions. The MAT mission was selected among three candidates to ESA's New Science Ideas[5], and undertook one dedicated delta session of the small-planetary-platforms concurrent-design-facility study[6]; however, it was not selected but indicated prominent interest for future E-sail missions. Thirdly, it discusses the actual Estonian instrument development and its current state for the upcoming ESA-JAXA deep-space science mission Comet Interceptor to be launched with the ARIEL space telescope to Earth-Sun L2 quasi-halo orbit in 2029. The tool, called SISPO, to simulate the optical instrument performance and develop autonomous algorithms for OPIC and MAT instrument is manifested in the last part. The UT initiated the Space Imaging Simulator for Proximity Operations (SISPO) tool, and it has an ongoing contribution from various other universities now. It is open-source software based on Blender; the team encourages everyone to use it and contribute to improvements. Overall, it is undeniable that Estonian contribution to European and global space technology and exploration is proliferating despite being a remarkably young space nation. The author believes that the projects presented here will contribute significantly to the local space community advancement and upcoming prominent space-project engagement.

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[4] Dates are subject to change.

[5] `https://www.cosmos.esa.int/web/new-scientific-ideas`, accessed: 15.08.2021

[6] `https://sci.esa.int/web/future-missions-department/-/60411-cdf-study-report-small-planetary-platforms-spp`, accessed: 15.08.2021

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Slavinskis, A., M. Pajusalu, I. Sünter, J. Dalbins, **Iakubivskyi, I.**, T. Eenmäe, D. Mauro, J. Stupl, P. Janhunen, P. Toivanen, E. Ilbis, H. Ehrpais, A. S. Rivkin, K. Muinonen, A. Penttilä, M. Granvik, T. Kohout, M. Gritsevich, and W. F. Bottke (2018). “Nanospacecraft fleet for multi-asteroid touring with electric solar wind sails”. In: *2018 IEEE Aerospace Conference*. IEEE, pp. 1–20.
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I want to mention my Ternopil school's form mistress V.Y. Narevych who revealed the beauty of mathematics, which significantly influenced me. I am thankful to my family and friends for their support and quality time accompanied by intriguing experiences; I will not generate a giant list of names, those people know. I acknowledge the Estonian underground music scenes, which served a pleasant chill on the weekend and spread the satisfaction of the good-taste sound waves propagation through the air. I want to thank my life partner Mari for all her comfort and encouragement.

SISUKOKKUVÕTE

Nanosatelliide kasutamine demonstratsioon- ja teadusmissioonidel

Kosmosemissioonide kavandite ning neis kasutatavate seadmete ja tõukurtehnoloogiate välja töötamine hõlmab tihti nii uudseid lahendusi kui ka reaalsel kosmoselennul tõestamist (Frischauf *et al.*, 2018; Paikowsky, 2017). Siinse väitekirja autor on andnud oma panuse mitme missiooni kulgu, seda nii missioonikavandi tasandil kui ka tehnilisi lahendusi ja arvutisimulatsioone arendades. Need vahendid aitavad luua tulevikku, kus uurime Päikesesüsteemi ja laiemat kosmost just väikesatelliitidega. Järgneva väitekirja võib jagada kahte ossa.

- Esimene osa keskendub uudsele satelliitide tõukurtehnoloogiale, kulonilise vastastikmõju tõukurile (Coulomb Drag Propulsion, CDP) (Janhunen, 2010), millel on omakorda kaks eristatavat kasutusvaldkonda: 1) selle toimimine plasmapidurina ESTCube-2 ning FORESAIL-1 missioonidel (**Iakubivskyi, I.**, Janhunen *et al.*, 2020) ja 2) tõukurtehnoloogia kasutamine elektrilise päiksepurjena (Electric Solar Wind Sail, E-Sail) (Janhunen, 2004) planeetidevahelise missiooni kavandis "Mitmikasteroidide turnee" ehk Multi-Asteroid Touring (MAT) (**Iakubivskyi, I** *et al.*, 2021; Slavinskis, Pajusalu, Sünter *et al.*, 2018).
- Töö teine osa hõlmab kosmosemissioonide seadmete ning tehnoloogiate arendustööd, näiteks komeetide pildistamiseks mõeldud optilise periskoopkaamera (Optical Periscopic Imager for Comets, OPIC) välja töötamist (Pajusalu, Kivastik *et al.*, 2020). Kirjeldatakse ka eelmainitud missioonideks loodud kosmose lähioperatsioonide pildistamise simulaatorit (Space Imaging Simulator for Proximity Operations, SISPO) ning selle abil tehtud instrumendianalüüsi, võimekushinnangut ja missioonikavandit (Pajusalu, **Iakubivskyi, I.** *et al.*, 2021).

Kuupsatelliitide väiksus avab neile uued võimalused tõukejõudu kasutada: päiksepurjed, elektrilised päiksepurjed, elektrodünaamilised köidikud ning laserite abil kiirendamine. Need meetodid rakendavad enamasti edukalt saadaval olevaid ressursse, nagu päikesevalgus, ionosfäär, magnetväli ja päikesetuul. Elektrodünaamilised köidikud on võimelised muutma kosmosesõiduki orbiiti, kasutades selleks laetud traadi liikumist magnetväljas. Päikesepurje töö põhineb valguse rõhul ehk footonite impulssmomendi ülekandumisel purjele. Purje pindala suurendades on võimalik suurendada ka tõukejõudu, kuid samas kasvab oht mikrometeoroidide tabamusteks. Samuti seab oma piirid asjaolu, et Päikesest eemaldudes väheneb kiirelt tõukejõud. Seda probleemi saab leevendada elektrilise päiksepurje tehnoloogia abil, mis kasutab päikesekiirguse abil päikesetuult, mille laetud osakesed satuvad vastastikmõjju satelliidist välja keritud positiivse laenguga traatidega. Sellisel süsteemil on ka teine väljund: päikesepurje tehnoloogiat saab kasutada, et tuua madalal Maa orbiidil lendavaid ja oma missiooni lõpetanud satelliite kiiremini atmosfääri tagasi Nii saaks vältida kuhjuva kosmoseprügi probleemi. 4,5 kg raskused varsti startivad kuupsatelliidid ESTCube-2 ja FORESAIL-1 rakendavad mõlemad kosmoses kuni 300 meetri pikkust elektrilist päikesepurje, millel on võimekus langetada 9–13 kuu jooksul satelliitide orbiidi kõrgust 200 km võrra.

Mitmikasteroidide turnee missiooni kavand pakuti välja võimalusena külastada kümneid asteroide peamises asteroidivöös, kasutades selleks hulka elektrilise päiksepurjega varustatud nanosatelliite. Selle missiooni eeldus on, et ESTCube-2 katsetab päikesepurje edukalt Maa orbiidil. Missiooni kaasatavad 6 kg raskused satelliidid oleksid võimelised väljutama 20 km pikkuse elektrilise päikesepurje ning tagaksid passiivse termoregulatsiooni 3,2 aastaks, kusjuures nende lennu suurim kaugus Päikesest oleks 2,75 astronoomilist ühikut. Väitekirjas on toodud arutlus missiooni kavandit puudutavate tähtsamate küsimuste ning esmase analüüsi üle.

OPIC on Eesti esimene süvakosmosemissiooniks arendatud instrument, mis on osa Euroopa Kosmoseagentuuri (ESA) ja Jaapani Kosmoseuuringute Agentuuri (JAXA) koostöös ellu viidavast F-klassi missioonist Komeedipüüdur (Comet Interceptor, CI) (Snodgrass ja Jones, 2019). Komeedipüüduri põhieesmärk on uurida pika perioodiga või uudsete komeetide või Päiksesüsteemi väliste kehade ehituslikke erinevusi võrreldes juba tuntud lühikese perioodiga komeetidega. Seetõttu moodustavad missiooni kolm eri suuruse ja eesmärgiga sondi, mis lähenevad sihtmärgile eri kaugustelt. Väitekiri esitleb OPIC-u instrumendi disaini ning annab hinnangu selle oodatava võimekuse kohta, kasutades spetsiaalselt selleks loodud SISPO simulatsioonitarkvara. Väitekirja viimane osa selgitab põhjalikumalt SISPO kui tööriista tööpõhimõtteid. SISPO-t saab kasutada eri taevakehade missioonipõhiseks analüüsiks. Programm võimaldab luua keerukaid süvakosmosemissioonide kavandeid, simuleerida arvukate erinevate parameetritega stsenaariume, rakendada pildipõhist navigatsiooni ja lokalisatsiooni ning kasutada erisuguseid pilditöötlusvõimalusi. SISPO on arendatud eraldiseisva laiendusena vabavaralisele programmile Blender ning see kasutab pindade loomiseks mikropolügoonide nihutamisel põhinevat tekstuuri.

PUBLICATIONS

CURRICULUM VITÆ

Iaroslav Iakubivskyi (May 21, 1992)**

EDUCATION

2017–present	**PhD candidate** in Physics, University of Tartu, Estonia
2015–2017	**M.Sc. in Engineering**, University of Tartu, Estonia. *Robotics and Computer Engineering: Space Technology.*
2012–2013	**Exchange**, Warsaw University of Technology, Poland. *Airplane and propulsion design; flying on simulators.*
2009–2014	**BA**, National Aviation University, Ukraine. *Gas turbines and jet engines engineering.*
1999–2009	School. Ternopil, Ukraine.

EXPERIENCE

VOCATIONAL

5.2020–present	**Comet Interceptor's Science Team Associate** *OPIC instrument development for ESA–JAXA mission.*
9.2017–present	**Junior Research Fellow**, Tartu Observatory,Estonia.
A/2019	**Teaching** *Responsible lecturer for the course LTTO.00.011 "Introduction to Space Technology" (3 ECTS), UT.*
2–6.2019 & 6.2020–2.2021	**Visiting researcher**, Aalto University, Finland. *Space technology and science.*
10.2018–2019	**Visiting researcher**, Columbia University in the City of New York, USA. *PELE Astrobiology research: Martian analogue caves.*
5.2016–8.2017	**Engineer**, Tartu Observatory, Estonia.
2015–2017	**ESTCube-2 subsystem leader**, Tartu, Estonia *Structural subsystem leader and a member of the system engineering team; supervision of summer trainees.*
2015–2016	**ESEO optical payload**, Tartu, Estonia *Team member of dual-camera optical payload for the ESEO mission. Training in ALMASpace/SITAEL, Italy.*

MISCELLANEOUS

2005–2009	**Scouting, Plast**, Ukraine. *Survival in extreme conditions.*

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INTERNATIONAL TRAINING EVENTS

07–08.2019	“Small satellites in planetary research”, Tartu, Estonia.
08.2018	“Nanosatellites and their role in planetary and atmospheric research”, Tartu, Estonia.
08.2017	“Impacts and Their Role in the Evolution of Life”, Saaremaa, Estonia.
07.2017	Opticon astronomy instrumentation school, University of Copenhagen, Denmark.
03.2017 & 03.2018	“Astrobiology Introductory Course” (part 1 and 2) Le Teich, France.
08.2016	“Volcanism, Plate Tectonics, Hydrothermal Vents and Life”, Terceira island, Azores.
07.2016	“Biosignatures and the Search for Life on Mars”, Iceland.

SCIENTIFIC EXPEDITIONS

Planetary analogs and Exobiology lava caves Expeditions (PELE)

Our international team performs: pXRF, XRD, Raman spectroscopy, water analysis, 16s rRNA extraction and lipids characterisation, thin section analysis and SEM. The main focus is volcanic islands with planetary analogue sites.

21.04–5.05.2019	Sampling in Pico and Terceira islands caves, Azores.
3–16.07.2018	Iceland: Laki, Óðáðahraun lava fields and other shield volcanoes, Hverfjall explosion crater.
01–02.2017	Reconnaissance Expedition on Terceira island, Azores: cave mapping, gas measurements and spot scouting.

AWARDS

Scholarships: The 2021 Jaan Einasto Annual Scholarship; Charles Villmann annual award 2019; Higher education speciality in smart specialisation growth areas (2018); Dora Plus short-term mobility (5.2016, 5.2018, 3.2019); Kristjan Jaak study periods abroad (4.2017, 4.2019, 2.2020); Dora Plus doctoral students mobility (09.2018); Estonian Ministry of Foreign Affairs (2015); Macedonian Ministry of Foreign Affairs (2014); East-West European Network on Higher Technical Education (2012); Ministry of Education and Science of Ukraine (2009, 2014).

Prizes: 1) Vega Fund and Enterprise Estonia for the ESTCube-2 cameras at sTARTUp day 2016, Estonia; 2) Second prize in the International Business Competition NGAL supported by Harry and Reba Huge Foundation, SC, USA.

CONFERENCES

09.2021	Flash talk “OPIC instrument on Comet Interceptor mission” at the AbGradCon, Tokyo, Japan (online).
09.2021	Co-convener at the virtual EPSC: “Planetary Missions, Instrumentation, and Mission Concepts: New Opportunities for Planetary Exploration”.
08.2021	Poster “OPIC Instrument for the Planned Comet Interceptor Mission” at the 35th AIAA/USU Annual Small Satellite Conference.
10.2020	Oral presentation “Cubesat for refining ephemerides for the Ariel mission” at the Ariel virtual consortium meeting.
01.2020	Poster “Design of Nanospacecraft for Main-Belt Voyage” at the Finnish Satellite Workshop, Finland.
06.2019	Oral presentation “Coulomb drag propulsion experiments of ESTCube-2 and FORESAIL-1” at the 6th International Conference on Tethers in Space, Madrid, Spain.
03.2019	Oral presentation “Platform design for Multi-Asteroid Touring concept” at the Europlanet Planetary Instrumentation Workshop, Saariselkä, Lapland, Finland.
09.2018	Poster “Nanospacecraft design and mission overview for statistical asteroid prospecting” at the EPSC 2018, Berlin, Germany.
05.2018	Oral presentation “Nanospacecraft design for an interplanetary fleet formation propelled by E-sails” at the 7th Interplanetary CubeSat Workshop, Paris, France.
05.2018	Oral presentation “Statistical asteroids survey with nanospacecraft” at the Yearly Meeting of the Stockholm Univ. Astrobiology Centre.
10.2017	Oral presentation “ESTCube-2 structure development” at the 68th International Astronautical Congress (IAC), Adelaide, Australia.
08.2017	Poster “Nanospacecraft and their role in astrobiology” at the Early History of Planetary Systems and Habitable Planets, Estonia.
04.2017	Oral presentation “ESTCube-2 plasma brake payload for effective deorbiting” and poster “Design of Coulomb drag plasma brake for 800 kg/850 km satellites” at the 7th European Conference on Space Debris, ESA/ESOC, Darmstadt, Germany.
09.2016	Oral presentation at the 67th IAC, Guadalajara, Mexico.
07.2016	Poster “Moon colonisation”, Reykjavik, Iceland
03.2016	Oral presentation “ESTCube-2 mission” at the 59th Scientific Conference "Open Readings", Vilnius, Lithuania.

LANGUAGES

English (advanced), **Ukrainian** (native), **Russian** (advanced),
Polish (intermediate), **Estonian** (beginner).

ELULOOKIRJELDUS

Iaroslav Iakubivskyi (21. mai 1992)[††]

HARIDUS

2017–…	**Füüsika doktorantuur**, Tartu Ülikool, Tartu Observatoorium.
2015–2017	**MA, Tehnikateaduse magister**, Tartu Ülikool, Loodus- ja täppisteaduste valdkond. *Arvutitehnika ja robootika: kosmosetehnoloogia.*
2012–2013	**Erasmus – vahetusõpilane**, Varssavi Tehnikaülikool, Poola. *Energia ja lennundus inseneeria.*
2009–2014	**BA**, Rahvuslik Lennundusülikool, Ukraina. *Energia ja lennundus inseneeria (gaasiturbiinide ja reaktiivmootorid).*

TÖÖKOGEMUS

5.2020–…	**Comet Interceptori teadustiimi liige.** *Komeet lenda. OPIC: komeetide optiline pildistaja, ESA ja Jaapani kosmoseagentuuri JAXA jaoks.*
9.2017–…	**Nooremteadur**, Tartu Observatoorium, Eesti.
A/2019	**Õpetamine** *Vastutav õppejõud kursusel LTTO.00.011 “Introduction to Space Technology”, Tartu Ülikool.*
2–6.2019 & 6.2020–2.2021	**Külalisteadlane**, Aalto Ülikool, Soome. *ESTCube-2 ja FORESAIL-1 missioonid.*
10.2018–2019	**Külalisteadlane**, Columbia Ülikool New Yorgis, Ameerika Ühendriigid. *Astrobioloogia. Laavakoopad kui maapealsed Marsi analoogid.*
5.2016–8.2017	**Insener**, Tartu Observatoorium, Eesti.
2015–2017	**Allsüsteemi juht**, Tartu, Eesti *ESTCube-2 struktuuri ja mehhanismide arendus.*
2015–2016	**ESEO satelliidi kaamerasüsteem**, Tartu, Eesti *Praktikant Itaalias SITAELis.*

ERIOSKUSED

2005–2009	**Skautlus**, Ukraina. *Plast — National Scouting Organisation.*

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RAHVUSVAHELISED KOOLITUSÜRITUSED

07–08.2019	“Small satellites in planetary research”, Tartu, Eesti.
08.2018	“Nanosatellites and their role in planetary and atmospheric research”, Tartu, Eesti. Organisatsioonikomitee ja osaleja.
08.2017	“Impacts and Their Role in the Evolution of Life”, Saaremaa, Eesti.
07.2017	Opticon astronoomia instrumentaarkool, Kopenhaageni Ülikool, Taani.
03.2017 & 03.2018	“Astrobiology Introductory Course” Le Teich, Prantsusmaa.
08.2016	“Volcanism, Plate Tectonics, Hydrothermal Vents and Life”, Terceira, Assoori saared.
07.2016	“Biosignatures and the Search for Life on Mars”, Island.

TEADUSLIKUD EKSPEDITSIOONID

Planeetide analoogid ja eksobioloogia laavakoobaste ekspeditsioon (PELE)
pXRF, XRD, Raman spektroskoopia, veeanalüüsid, 16s rRNA ja lipiidide iseloomustamine, õhukese analüüsi jagu ja SEM.

21.04–5.05.2019	PELE, prooviekspeditsioon laavakoobastes Pico ja Terceira saarel, Assoori saared.
3–16.07.2018	Islandi laavakoobaste ja plahvatuskraatri uurimine. Laki laavaväli, Odadahrauni laavaväli ja teised kilpvulkaanid, Hverfjalli plahvatuskraater.
01–02.2017	Terceira, Assoori saared. 1) Võimalike potentsiaalsete koobaste uurimine tulevaste mikroobiuuringute tarvis; 2) Atmosfääri gaasilise koosseisu hindamine erinevates koobastes; 3) Teabe kogumine temperatuuriprofiilide kohta koobastest; 4) Ligikaudne mikrobioloogiliste koosluste hindamine koobastes.

AUHINNAD

Stipendiumid: 2021. aasta Jaan Einasto rahvusvaheline stipendium; 2019. aasta Charles Villmanni stipendium; Kõrghariduse eriala nutika spetsialiseerumise kasvualadel (2018); Lühiajalise õpirände toetused (5.2016, 5.2018, 3.2019); Kristjan Jaagu stipendiumid (4.2017, 4.2019, 2.2020); Doktorantide õpirände stipendium (09.2018, 06.2021); Eesti Välisministeerium (2015); Makedoonia välisministeerium (2014); Ida- ja Lääne-Euroopa kõrghariduse võrgustik (2012); Ukraina haridus- ja teadusministeerium (2009, 2014).

Auhinnad: 1) (12.2016) Vega Fondi ja EASi auhind summas 28 tuhat eurot, Eesti; 2) (07.2017) Harry ja Reba Suurte Fondide toetatud rahvusvahelise ettevõtluskonkursi NGAL III teine koht, Ameerika Ühendriigid.

LIIKMELISUS

Alates 2019. aastast	European Astrobiology Institute
Alates 2018. aastast	Europlanet

KEELED

Inglise keel (C2), **Ukraina keel** (emakeel), **Vene keel** (C1),
Poola keel (B2), **Eesti keel** (A1).

KONVERENTSID JA ESINEMISED

09.2021	Kaasesimees virtuaalsel EPSC-l 2021. aastal: “Planetary Missions, Instrumentations, and Mission Concepts: New Opportunities for Planetary Exploration”.
08.2021	Postri esitlus “Optical Periscopic Imager for Comets (OPIC) Instrument for the Planned Comet Interceptor Mission” 35. igaastasel Väikesatelliitide konverentsil, USA.
10.2020	Suuline ettekanne “Cubesat for refining ephemerides for the Ariel mission” Arieli virtuaalsel konsortsiumi kohtumisel.
01.2020	Postri esitlus “Design of Nanospacecraft for Main-Belt Voyage” Soome satelliitide töötoas.
06.2019	Suuline ettekanne “Coulomb drag propulsion experiments of ESTCube-2 and FORESAIL-1” 6. Rahvusvahelisel konverentsil Tethers in Space, Madrid, Hispaania
03.2019	Suuline ettekanne “Platform design for Multi-Asteroid Touring concept” Europlaneti planeediseadmestiku töötoas, Saariselkä, Lapimaa, Soome.
09.2018	Postri esitlus “Nanospacecraft design and mission overview for statistical small asteroid prospecting”, Euroopa Planeediteaduse kongressil, 2018, Berliin, Saksamaa.
05.2018	Suuline ettekanne “Nanospacecraft design for an interplanetary fleet formation propelled by E-sails” 7. Interplanetaarne CubeSat töötuba, Paris, Prantsusmaa.
05.2018	Suuline ettekanne “Statistical asteroids survey with nanospacecraft” igaastasel Stockholmi Ülikooli Astrobioloogia Keskuse kohtumisel.
10.2017	Suuline ettekanne “ESTCube-2 structure development”, 68. Rahvusvahelisel Astronautika Kongressil, Adelaide, Austraalia.
08.2017	Postri esitlus “Nanospacecraft and their role in astrobiology” konverentsil ”Planeedisüsteemide varajane ajalugu ja elamiskõlblikud planeedid” Tartu, Eesti.
04.2017	Suuline ettekanne “ESTCube-2 plasma brake payload for effective deorbiting”, 7. kosmoseprahiteemaline Euroopa Konverents, ESA, Darmstadt, Saksamaa.
04.2017	Postri esitlus “Design of Coulomb drag plasma brake for 800kg/850km satellites”, 7. kosmoseprahiteemaline Euroopa Konverents, ESA/ESOC, Darmstadt, Saksamaa.
09.2016	Suuline ettekanne “ESTCube-2 mission analysis: Plasma brake experiment for deorbiting” 67. Rahvusvaheline Astronautika Kongress, Guadalajara, Mehhiko.
07.2016	Postri esitlus “Moon colonisation”, Reykjavik, Island.
03.2016	Suuline ettekanne 59. teaduskonverentsil “Open Readings 2016”, Vilnius, Leedu.

DISSERTATIONES PHYSICAE UNIVERSITATIS TARTUENSIS

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