FORESAIL-2: SYSTEMS ENGINEERING CHALLENGES FOR CUBESAT MISSIONS IN HIGH RADIATION ORBITS

Marius Anger(1), **Anton Fetzer**(1), **Noel Janes**(1,2), **Ville Lundén**(1), **Bruce Clayhills**(1), **Ville-Valtteri Kettunen**(1), **Minna Palmroth**(3), **Emilia Kilpua**(3), **Rami Vainio**(4), **Pekka Janhunen**(5), **David Fischer**(6), and **Jaan Praks**(1)

(1)*Aalto University, Maarintie 8, Espoo, Finland, marius.anger@aalto.fi*

(2)*Luleå University of Technology, Kiruna, Sweden*

(3)*University of Helsinki, Helsinki, Finland*

(4)*University of Turku, Turku, Finland*

(5)*Finnish Meteorological Institute, Helsinki, Finland*

(6)*Space Research Institute, Austrian Academy of Sciences, Graz, Austria*

ABSTRACT

Foresail-2 is a proposed CubeSat mission to high elliptical orbit, developed by the Finnish Centre of Excellence in Research of Sustainable Space (FORESAIL) and funded by the Academy of Finland. It is one of the first CubeSat missions to a high radiation environment. The main mission goal of this 6U-CubeSat is to measure ultra-low frequency (ULF) waves in the magnetic field around the Earth along with radiation measurements in Earth's radiation belts. The satellite takes accurate magnetic field measurements in the continuous pulsation (Pc) 5 frequency range and measures electron and proton spectra, to study the dynamics of the most harmful radiation in the Van Allen belts.

The satellite has three main instruments: The Relativistic Electron and Proton Experiment (REPE) by the University of Turku, Magnetometer Aboard the foreSail-2 cubesaT (MAST), developed by the Austrian Space Research Institute, and Plasma Brake (PB), developed by the Finnish Meteorological Institute. The PB is designed to demonstrate orbital manoeuvres and current measurements with a thin electrostatic tether that extends tens of meters. The spacecraft also features a deployable boom for the precision magnetometer MAST.

The 6U satellite platform and electronics are developed by Aalto University specifically for this mission. The driving mission requirements are very low magnetic noise as well as durability in the high radiation environment. The Foresail-2 platforms team presents its main strategies for dealing with the challenges of the satellite design for such a mission.

1 MOTIVATION

CubeSat class satellites have significantly widened the use of satellites in business and science. Affordable satellite platforms and launch opportunities have made it possible also for smaller nations to conduct their own science missions. However, due to more affordable components, the success of CubeSats has been limited mostly to Low Earth Orbit, where radiation level is modest. One of the goals of the Finnish Centre of Excellence in Research of Sustainable Space (FORESAIL) project, is to increase the capability of CubeSats in science missions by extending the usage to higher orbits where radiation levels are extremely high but also the scientific interest is much higher. The Foresail-2 mission is designed for science mission in highly elliptical orbit inside Van-Allen belt. The mission has ambitious goals both in mission science but also platform technology.

2 SPACE ENVIRONMENT IN HIGHER ORBITS

When leaving the Low Earth Orbit, the ionising radiation level, harmful for spacecraft electronics, increases rapidly due to trapped particles in Earth magnetic field [1, 2].
Earth's radiation belts were discovered in 1958 [3], and since then many attempts have been made to describe and predict the radiation environment around Earth with mathematical models [4]. Currently there is not enough information about the seeding effects and also the dynamics of the outer belt [5]. The highly dynamic outer belt and slot regions (the void between the two main belts) have unpredictable variations in intensity and spatial extent on timescales from minutes to decades. The solar effects might be responsible for driving dynamic processes of energization and loss of high energy electrons in the outer belt [6]. Ultra-low frequency (ULF) waves in the magnetosphere seem to enhance energization in the outer regions [7]. For effective radiation mitigation of a spacecraft and its subsystems, the understanding of such anomalies in the radiation environment is key to successfully operating spacecraft in highly elliptical orbits around Earth and outer celestial bodies with radiation belts.
Extensive simulations are required to determine the shielding requirements and to identify suitable shielding solutions.

3 Foresail-2 MISSION

The Foresail-2 (FS2) mission to geosynchronous transfer orbit (GTO) by the Finnish Centre of Excellence in Research of Sustainable Space, funded by the Academy of Finland, aims to provide a better understanding of the Earth's radiation belts. The study of their dynamics aims to answer the following questions:

1. What is the role of Ultra Low Frequency (ULF) waves in the acceleration, transport, and scattering of electrons in the Earth's radiation belts as a function of solar wind driving and magnetospheric activity?
2. How do ULF waves and turbulence transmit within the inner magnetosphere?
3. How does the Coulomb Drag (CD) force depend on plasma parameters and the voltage of a spacecraft attached tether?

To be able to answer these questions, three payload instruments will be used; The Relativistic Electron and Proton Experiment (REPE) by the University of Turku, Magnetometer Aboard the foreSail-2 cubesaT

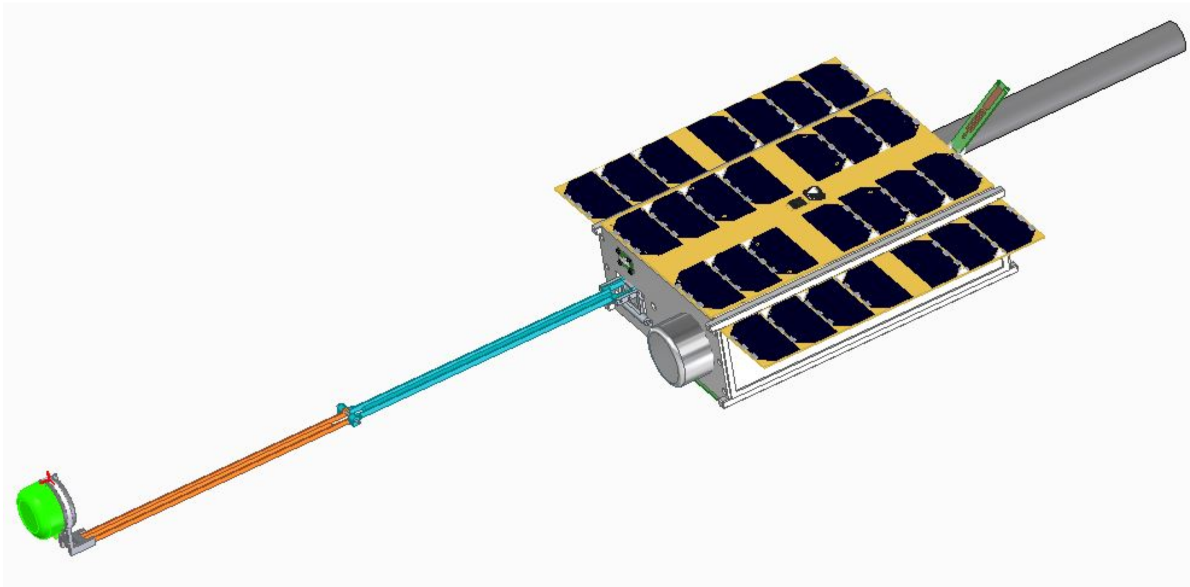

Figure 1: Foresail-2 Spacecraft with deployed solar panels and boom arm. The grey tube represents the direction of tether deployment.

(MAST), developed by Austrian Space Research Institute, and Plasma Brake (PB), developed by Finnish Meteorological Institute. The form factor for the satellite is selected to be 6U-CubeSat (seen in Figure 1).

3.1 Magnetometer Aboard the foreSail-2 cubesaT

The goal of MAST is to provide magnetic field measurements for characterizing the ULF waves around the Earth. It consists of a fluxgate sensor located at the end of a boom and auxiliary magnetometers placed inside the spacecraft. The auxiliary magnetometers are needed next to components which are known to create high levels of magnetic disturbance.

3.2 Relativistic Electron and Proton Experiment

REPE has the goal of providing measurements of relativistic electrons and protons in the radiation belts as a function of time, energy and pitch-angle. While the electron measurements in the outer radiation belt are the most important ones for the science of the mission, the same instrument can also measure protons in the inner belt, and the objective is to demonstrate the measurement of protons up to the highest energies in the radiation belts. The pitch-angle measurement will rely on the spin of the spacecraft to scan directions relative to the magnetic field.

3.3 Plasma Brake Experiment

PB aims to measure the CD force acting on a charged tether in different parts of the orbit which represent widely different plasma densities. Additionally, measurements of the electron current gathered by the charged tether can obtain an estimate of the ambient plasma density in different parts of the orbit.

4 MAIN DESIGN DRIVERS

4.1 Magnetic Cleanliness for MAST Measurements

The difficulties associated with ensuring that MAST can achieve the required magnetic measurement sensitivities, impact both the design of the instrument itself, as well as the rest of FS2. The strict magnetic measurement requirements, coupled with the relatively small dimensions of the satellite and boom, mean that even minor magnetic disturbances originating from the spacecraft can have an outsized impact on the accuracy of MAST's measurements. As such a magnetic cleanliness programme with the aim of limiting and controlling the sources of magnetic disturbances has been established. The magnetic cleanliness programme is also responsible for ensuring that the net residual magnetic moment of FS2 does not significantly impact the performance of the attitude control system. [8]

One of the most straightforward approaches to ensure that FS2 is sufficiently magnetically clean is to avoid the use of magnetic materials. However, the required sensitivity levels mean that certain non-magnetic materials, such as non-magnetic stainless steel or scrap aluminium, need to be avoided where possible, as these materials may become permanently magnetised if exposed to a sufficiently strong magnetic field at a small distance. However, this is not always possible, and the presence of these materials will be carefully monitored throughout the design, integration, and testing of FS2. Similarly, the use of magnetic tools or equipment, such as those of a magnetic screwdriver bit, during integration and testing may inadvertently magnetise components and materials on FS2, and the use of such equipment will be carefully controlled to limit the risk of unwanted magnetic contamination.

To ensure that disturbances are identified and mitigated early in the lifecycle of FS2, a magnetic model of the spacecraft has been created. As part of this model, the locations of all subsystems and major components have been specified in the spacecraft's coordinate system. Each of these units is modelled as a magnetic dipole, and the estimated magnetic field contribution, at MAST's deployed position, is then calculated for each unit. The magnetic dipoles are assumed to all be oriented such that the moment is aligned along the line connecting the component or subsystem and MAST, as this is the worst case orientation. The estimated magnetic field of the spacecraft at MAST is then calculated by summing the individual contributions using a Root-Sum-Square approach. At the current stage of development this model only considers static stray sources, however it will be maintained and extended throughout the design, integration, and testing stages. The components of each subsystem have also been analysed to identify all magnetic materials and a ferromagnetic budget has been established. The combination of the model and ferromagnetic budget allows for subsystems, and their configuration, to be analysed from a magnetic disturbance perspective. As a result potentially problematic components or designs can be identified early in the design phase and alternative mitigation strategies can be explored.

Spacecraft subsystems and instruments, as well as major components, will be characterised using the machine-vision assisted magnetic test bed at Aalto University. The results of these characterisations will then be added to the model in order to improve its accuracy. The improved model will then be used to help determine the need for mitigation strategies, for example whether the use of compensation magnets is required to reduce the residual magnetic moment. In such a case the model can be used to determine the strength and placement of the required magnet. These tests will be carried out once engineering and testing models of each subsystem become available.

4.2 Protection against Radiation

FS2 is designed for geostationary transfer orbit, where it will pass through the densest areas of the Earth radiation belts twice approximately every 10.8 hours [9]. The satellite is going to make extensive use of Commercial Off-the-Shelf (COTS) components which are sensitive to ionising radiation. Despite the harsh environment and sensitive components, FS2 is specifically optimised to survive the mission duration of six months. Therefore, the design process concentrates on the understanding and mitigation of the radiation environment inside the spacecraft. Various simulations have been performed to investigate shielding options and requirements to protect sensitive electronic components inside the satellite.
Before the shielding of the satellite can be simulated, the particle spectra along the target orbit have to be identified. For this purpose the Space Environment Information System (SPENVIS) was used, which is an ESA operational software that provides access to several space radiation models through a convenient web interface [10, 11]. The NASA AP-8/AE-8 models have been used as the de-facto standard models for the Earth radiation belt trapped particle fluxes in the three decades since their release and were used as reference models during the investigation of the GTO radiation environment of Foresail-2 [12].

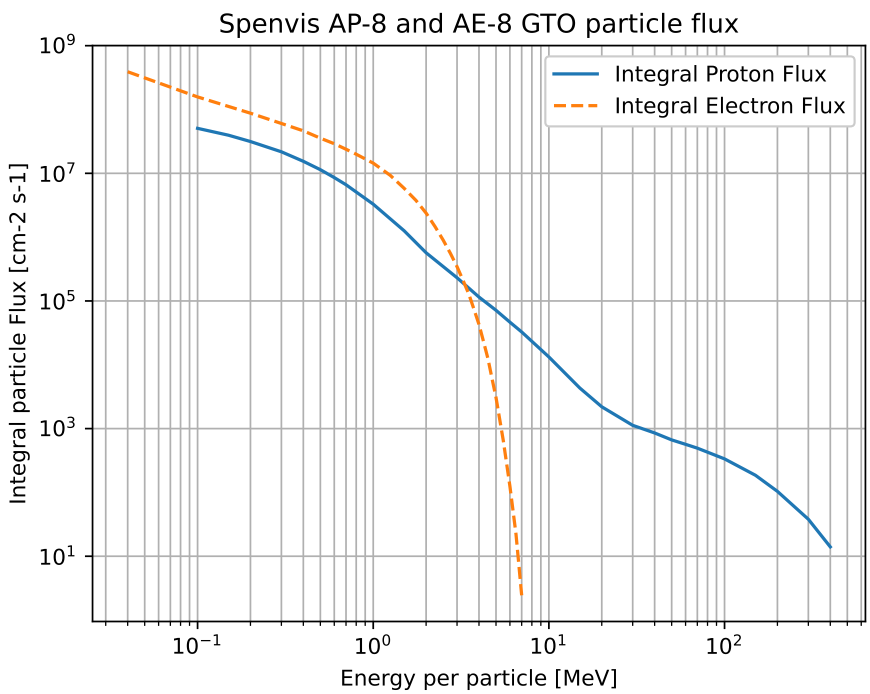

Figure 2: Average integral flux of trapped protons and electrons on GTO with 300 km perigee and 36 000 km apogee altitude, according to the AP-8 and AE-8 models for trapped particle fluxes during solar minimum with 97.725 % confidence level for the electron spectrum and 50 % confidence level for the proton spectrum [11]. The spectra range over several orders of magnitude in flux and energy, with very high fluxes at low energies and low fluxes at high energies.

Figure 2 shows the expected average integral fluxes of protons and electrons, which would be received by a spacecraft on GTO with 300 km perigee and 36 000 km apogee altitude, according to the AP-8 and AE-8 models for trapped particles during solar minimum [11]. The AP-8/AE-8 spectra were first compared to the outputs of the newer AP-9/AE-9 [12] and then the Slot Region Radiation Environment Model (SRREM) [13] for both 50 % confidence level and 97.725 % confidence level. The differences in predicted particle fluxes can be more than an order of magnitude depending on the particle energy and confidence levels, but the comparison confirmed that the spectra shown in Figure 2 are not outliers with respect to the outputs of the other models.

The trapped particle spectra were compared to output of the Solar Accumulated and Peak Proton and Heavy Ion Radiation Environment (SAPPHIRE) model, which is a probabilistic model for the solar energetic particle (SEP) fluxes in Earth orbit [14]. The SEP proton fluxes are consistently lower than the trapped proton fluxes with the solar ion fluxes being even lower than that.

Similar results were obtained from a comparison between the AP-8/AE-8 output with the ISO 15390 model for GCR fluxes [15] which is why most particle simulations for FS2 were performed with only the trapped particle spectra of Figure 2.

The particle spectra in space range over several orders of magnitude in flux and energy. Even though the vast majority of particles are found at such low energies that they are not a threat to the spacecraft, there are significant amounts of higher energy particles that can potentially penetrate shielding and cause damage in sensitive components of the spacecraft. As the CubeSat standard is limited by mass, a trade-off between the shielding mass and its volume had to be made.

For this purpose several particle Monte-Carlo simulations were performed using a C++ application written by Philipp Oleynik (University of Turku) which is publicly available on GitHub [16, 9]. It is based on the Geant4 toolkit for simulations of particle matter interactions [17, 18] which at its core is a repository of particle physics models that implement most published knowledge on all aspects of particle matter interactions at all relevant energies [19].

Figure 3 shows results for Geant4 simulations of the total ionising dose (TID) received in silicon chips inside 1U cube shaped aluminium shielding vaults with several different wall thicknesses up to 16 mm. For comparison results obtained with SHIELDOSE-2Q are also shown in the figure. SHIELDOSE is a tool for ionising dose analysis for simple geometries, which is available through the SPENVIS web-interface [20]. It calculates the dose received behind radiation shielding based on a look-up table approach [21, 22].

The data for trapped electrons and protons in Figure 3 used the AP-8/AE-8 particle spectra of Figure 2 as input, while the solar proton results are based on the proton spectra of the SAPPHIRE model and the cosmic proton data used the proton spectrum obtained from the ISO 15390 model. Figure 3 shows that trapped electrons are the dominant source of TID on GTO for shielding thicknesses below 1 cm of aluminium or equivalent, while the contribution of trapped protons should be considered also at lower shielding depths.

Several other shielding materials have been considered and simulated as well as several thousand multilayer combinations and configurations in an attempt to identify the optimum shielding composition for the given particle spectra. The results of the multilayer simulations show that combinations of low-Z materials like polyethylene on top of high-Z materials like lead show significant advantages in shielding performance compared to the same mass of aluminium against the combined trapped electron and proton spectra expected on GTO.

The advantages of such a multilayer configurations have to be weighted against the increased complexity of multilayer shielding in combination with the problems that the materials introduce as well as the available volume and mass budget. For the FS2 mission it was decided to shield the whole 6U spacecraft structure with 6 mm of aluminium.

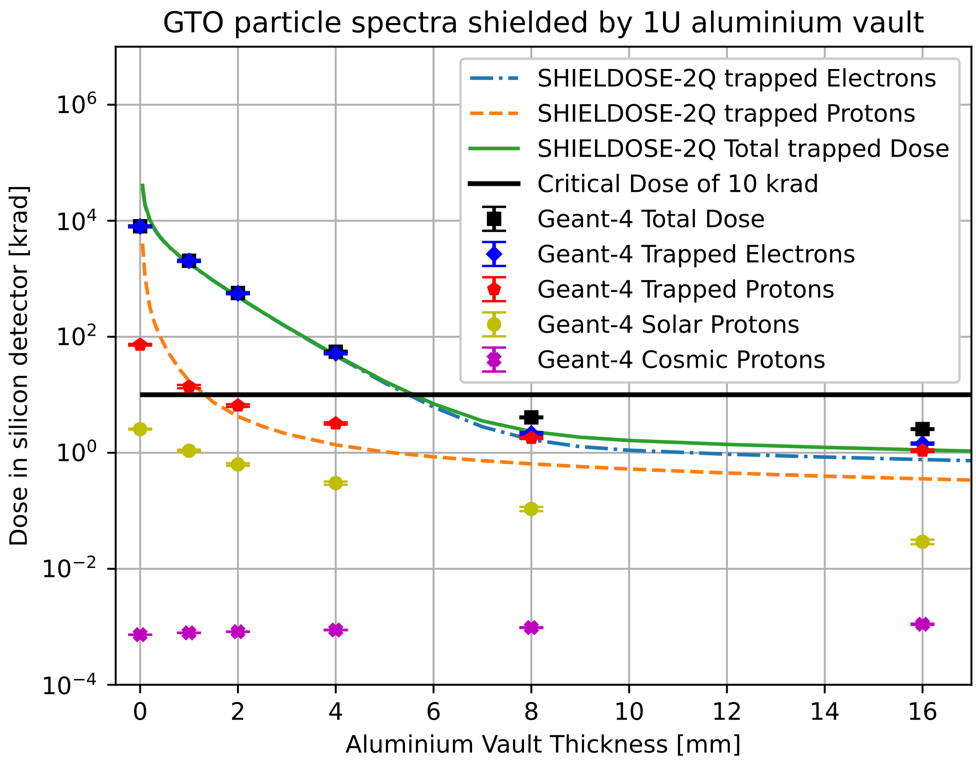

Figure 3: Ionising dose simulations for different GTO particle spectra shielded by 1U aluminium vaults with different thicknesses (points) compared with results from the SHIELDOSE-2Q tool (lines) for planar geometry but with same particle spectra [11].

4.3 Communication Considerations

The elliptical orbit of the satellite introduces requirements for the communication subsystem (COM), the most notable being the need for variable data rates as well as Effective Isotropic Radiated Power (EIRP). Another important requirement for variable output RF power is the need to adhere to the regulations and standards set by the International Telecommunication Union (ITU), which specify the maximum power flux density levels hitting Earth [23]. As the UHF- and VHF-bands are unable to provide the required data rates with the available ground stations, S-band sleeved dipole antennas will be used in a full-duplex configuration for communication. Even though the orbit of the satellite results in a challenging operating environment for the S-band antenna, it also has the benefit of a long overpass period.

The downlink and uplink freqeuencies are separated by approximately 200 MHz, with the downlink frequency allocated to the higher frequency band. A typical bandwidth of 100 kHz is used for communication, with the ability to tune this in accordance to the instantaneous data rates.

In addition, the COM system utilizes microstrip filters, designed on a commercial Rogers RO4350B substrate. The use of microstrip filters on a separate board improves the overall noise figure of the system as well as has the added benefit of not being sensitive to high levels of radiation. The design was chosen to ensure the radiation shielding of the most critical parts without compromising on RF performance.

Since reliability is one of the most important design goals of the system, the antennas have been chosen to be a set of deployable omnidirectional dipole S-band antennas. The antennas are specifically designed

for the uplink and downlink frequencies to enable full-duplex communication. However due to their omnidirectional properties, the antenna gain is low, which makes the receiver sensitivity (and noise figure) a driving factor of the design. Another drawback is also related to the total power consumption as, the transmitter must be able to transmit at a high power output (EIRP $> 30\,\mathrm{dBm}$) in order to ensure that the link closes at every point of the orbit.
In addition to the omnidirectional antennas, the system also supports a high gain patch antenna, which can be used for communication, once the satellite achieves attitude control. Despite this high gain antenna however, the omnidirectional antennas function as the primary communication antennas, as commanding and full-duplex communication must always be possible regardless of the orientation of the spacecraft.

4.4 Attitude Considerations

To get enough electrical energy for all systems and to control the deployments, the attitude has to be managed. The tether deployment and also the pitch angle scanning of the REPE instrument require a spinning spacecraft. A rotation rate of at least $250\,°/\mathrm{s}$ is needed to get enough tension on the end of tether.
The attitude determination and control system (ADCS) will use resistojet technology, due to the weak earth's magnetic field at these distances. Due to power requirements the spin axis has to be adjusted during the mission time to point a large portion of the solar panels towards the sun. It has to be parallel to the orbital plane due to the pitch angle scanning mode of REPE. As the orbit decay is highly unpredictable, other methods such as GPS are considered for regular in orbit position updates. A combination of sun sensors, gyroscopes and magnetometers will be used for attitude determination.
Extensive simulations have to be conducted about the impact of the non rigid tether dynamics of the PB experiment. After tether deployment a sun pointing mode is not anymore possible as the angular momentum of it will prevent any slight adjustments. Therefore the time the tether is deployed has to be reduced to a minimum. Otherwise the spacecraft will end up pointing away from the sun rather quickly with advancing motion of Earth around Sun.

5 CONCLUSIONS

The Foresail-2 mission faces several different challenges. First of all the highly elliptical orbit around the Earth introduces a lot more radiation compared to a typical low earth orbit CubeSat mission. Due to this the design of the 6U satellite includes a 6 mm Aluminium shielding for the entire satellite. Because of the highly sensitive magnetometer on board the magnetic cleanliness of every component used to manufacture the spacecraft and inside of it have to be considered very thoroughly. The communication strategy for this mission is also affected by the high radiation environment and the long distance to apogee. The Foresail-2 spacecraft design will be published in detail along with in-orbit experiment results. The FORESAIL consortium hopes, that the well published design and thorough lessons-learned will help to build more durable CubeSat in the future and extends this small spacecraft class usage for demanding science missions in higher orbits.

REFERENCES

[1] C. T. Russell. 'The solar wind interaction with the Earth's magnetosphere: A tutorial'. In: *IEEE Transactions on Plasma Science* 28.6 (2000), pp. 1818–1830. DOI: 10.1109/27.902211.

[2] James A. Van Allen. 'Radiation Belts around the Earth'. In: *Scientific American* 200.3 (1959), pp. 39–46. DOI: 10.1038/scientificamerican0359-39.

[3] James Alfred Van Allen and Louis A Frank. 'Radiation around the Earth to a radial distance of 107,400 km'. In: *Nature* 183 (1959).

[4] J. Ripa et al. 'A comparison of trapped particle models in low Earth orbit'. In: *Space Telescopes and Instrumentation 2020: Ultraviolet to Gamma Ray*. 2020, p. 74. DOI: 10.1117/12.2561011.

[5] J.-F. Ripoll et al. 'Particle Dynamics in the Earth's Radiation Belts: Review of Current Research and Open Questions'. In: *Journal of Geophysical Research: Space Physics* 125.5 (2020). e2019JA026735 2019JA026735, e2019JA026735. DOI: https://doi.org/10.1029/2019JA026735. URL: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019JA026735.

[6] A. N. Jaynes et al. 'Source and seed populations for relativistic electrons: Their roles in radiation belt changes'. In: *Journal of Geophysical Research: Space Physics* 120.9 (2015), pp. 7240–7254. DOI: https://doi.org/10.1002/2015JA021234. URL: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2015JA021234.

[7] T. P. O'Brien et al. 'Energization of relativistic electrons in the presence of ULF power and MeV microbursts: Evidence for dual ULF and VLF acceleration'. In: *Journal of Geophysical Research: Space Physics* 108.A8 (2003). DOI: https://doi.org/10.1029/2002JA009784. URL: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2002JA009784.

[8] N. Janes. 'Small Satellite Design for High Sensitivity Magnetic Measurements'. MSc Thesis. Luleå University of Technology, 2022. URL: http://urn.kb.se/resolve?urn=urn%5C%3Anbn%5C%3Ase%5C%3Altu%5C%3Adiva-89892.

[9] Philipp Oleynik. 'Charged particle observations in near-Earth space: Design and verification of particle instruments for CubeSat experiments'. PhD. Turku: UNIVERSITY OF TURKU, 2021. URL: https://urn.fi/URN:ISBN:978-951-29-8705-4.

[10] Michel Kruglanski et al. 'Last upgrades and development of the Space Environment Information System: SPENVIS'. In: (2009).

[11] Erwin De Donder, Neophytos Messios, Stijn Calders, Antoine Calegaro, Sami Mezhoud. *SPace ENVironment Information System: SPENVIS*. 2018. URL: https://www.spenvis.oma.be/ (visited on 01/04/2022).

[12] G. P. Ginet et al. 'AE9, AP9 and SPM: New Models for Specifying the Trapped Energetic Particle and Space Plasma Environment'. In: *Space Science Reviews* 179.1-4 (2013), pp. 579–615. DOI: 10.1007/s11214-013-9964-y.

[13] I. Sandberg et al. 'Development and Validation of the Electron Slot Region Radiation Environment Model'. In: *IEEE Transactions on Nuclear Science* 61.4 (2014), pp. 1656–1662. DOI: 10.1109/TNS.2014.2304982.

[14] Piers Jiggens et al. 'The Solar Accumulated and Peak Proton and Heavy Ion Radiation Environment (SAPPHIRE) Model'. In: *IEEE Transactions on Nuclear Science* 65.2 (2018), pp. 698–711. DOI: 10.1109/TNS.2017.2786581.

[15] ISO. *ISO 15390*. ISO.org, 2004. URL: https://www.iso.org/standard/37095.html.

[16] Philipp Oleynik. *instrument-simulation: Small and flexible tool for charged particle simulations.* GitHub, 2022. URL: https://github.com/phirippu/instrument-simulation (visited on 31/03/2022).

[17] J. Allison et al. 'Recent developments in Geant4'. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 835 (2016), pp. 186–225. DOI: 10.1016/j.nima.2016.06.125.

[18] The Geant4 collaboration. *Geant4: A simulation toolkit*. 2022. URL: https://geant4.web.cern.ch/ (visited on 31/03/2022).

[19] S. Agostinelli et al. 'Geant4—a simulation toolkit'. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 506.3 (2003), pp. 250–303. DOI: 10.1016/S0168-9002(03)01368-8. URL: https://www.sciencedirect.com/science/article/pii/S0168900203013688.

[20] SPENVIS. *Ionising dose model SHIELDOSE*. 2018. URL: https://www.spenvis.oma.be/help/background/shieldose/shieldose.html (visited on 30/03/2022).

[21] Stephen M. Seltzer. *SHIELDOSE : a computer code for space-shielding radiation dose calculations*. 1980.

[22] Stephen M. Seltzer. *Updated calculations for routine space-shielding radiation dose estimates: SHIELDOSE-2: SHIELDOSE-2*. 1994.

[23] ITU Radiocommunication Assembly. *Rec. ITU-R SA.1273 "POWER FLUX-DENSITY LEVELS FROM THE SPACE RESEARCH, SPACE OPERATION AND EARTH EXPLORATION-SATELLITE SERVICES AT THE SURFACE OF THE EARTH REQUIRED TO PROTECT THE FIXED SERVICE IN THE BANDS 2 025-2 110 MHz AND 2 200-2 290 MHz"*. 1997. URL: https://www.itu.int/dms_pubrec/itu-r/rec/sa/R-REC-SA.1273-0-199710-I!!PDF-E.pdf.