The LappiSat Space Program – Expanding Observatory Quality Geophysical Measurements to Orbits

Jouni Envall, Alexandros Binios, Eija Tanskanen, Juha Biström
Sodankylä Geophysical Observatory
Tähteläntie 62, FI-99600 Sodankylä, Finland; +358-50-4104304
jouni.envall@sgo.fi

ABSTRACT

For more than 100 years, the Sodankylä Geophysical Observatory (SGO) has produced a continuous stream of measured data and conducted top-tier research on various topics on space and geophysics. The main research areas include magnetic disturbances, geomagnetic activity, ionospheric composition and disturbances, radio science, seismic activity, and cosmic rays. The observatory's location in Finnish Lapland (Lappi in Finnish), 120 kilometers north of the Arctic Circle, has made it an ideal site for auroral studies and related geophysical research. It has been a time-honored tradition at SGO to design, develop and construct the observatory's most critical measurement instruments in-house. SGO's instrument network includes over 70 instruments in 27 locations – reaching from Svalbard to Antarctica. The next step in further enhancing SGO's measurement capabilities is to expand its instrument network to low Earth orbits. The LappiSat space program aims at establishing a space technology center in Sodankylä, Finland. As the center's first assignment, the first satellite LappiSat-1 shall be built together with the required ground infrastructure. The LappiSat-1 will carry multiple in-house built geophysical instruments, including auroral imagers, an auroral photometer, and a CubeSat compatible scientific grade magnetometer. The optical and system design of the imagers (i.e. auroral cameras) are optimized for auroral imaging, providing enough spatial resolution and sensitivity for low intensities to enable meaningful scientific observations of the shape and location of the auroral oval. Further information of the polar lights is obtained with the on-board photometer, designed to take narrow-band measurements at the most significant emission wavelengths of the aurorae. Simultaneous fluctuations in the geomagnetic field are recorded with the on-board magnetometer CubeMag. In addition to the instruments required to complete its scientific mission, the LappiSat-1 is expected to contain various features that are tested for future missions. These may include propulsion (also used for hastened re-entry of LappiSat-1), partial radiation shielding and use of radiation-hardened components, and telecommunication links for fast communication. The missions following LappiSat-1 are intended to reach orbits past LEO – with the subsequent goal being the Moon and beyond.

INTRODUCTION

The Sodankylä Geophysical Observatory (SGO) is located in northern Lapland, Finland – a perfect location to study geophysical events such as the aurorae. SGO has produced a continuous stream of measurement data sets since 1914, and has even produced variometer measurements already starting from the 1880s. SGO's heritage includes conducting top-tier research on various geophysical topics, designing, developing and constructing critical measurement instruments in-house, and securing monitoring capabilities of near-Earth space changes including geophysical threats to society. Geophysical threats include solar storms, which have the potential to severely harm and even destroy ground and space infrastructures, disrupt air traffic, and cause malfunctions along with total mission loss to low Earth orbit (LEO) satellites, to name a few. In order to be able to monitor, react fast, and prepare for geophysical threats, SGO's instrument network includes over 70 instruments in 27 locations which span around the globe from the northern hemisphere in Svalbard, Norway all the way to the southern hemisphere in Antarctica. The next step in further upgrading and establishing capabilities of being able to monitor the near-Earth space environment is to have multi-point and multi-temporal measurements from the combination of in-orbit measurements with small satellites along with the Earth-based in-situ instrumentation networks.

During the past few decades spacecraft have gone from large and expensive to small and affordable – especially CubeSat class satellites have made it possible to provide hands-on space technology education for over twenty years. During this time period CubeSat missions have gone from these educational purposes to technology demonstrations, and now are even used to have commercial constellations and scientific measurements. In Finland this trend has also been visible for nearly ten years, and the first CubeSat class missions started in southern Finland which led to the accumulation of know-how and capabilities being centralized there. In order to further expand the Finnish space and satellite know-how beyond southern Finland, SGO started the LappiSat Space Program which brings this know-how to new heights within Finland at northern latitudes.

The main reasons for SGO to develop and provide small satellites along with space-qualified instruments are related to the previously mentioned monitoring of near-Earth space changes and providing hands-on education in space technology and sciences for northern Finland. The LappiSat Space Program will expand SGO's heritage of observatory-quality geophysical measurements from ground to orbits. The first steps have been taken with the careful planning and designing of the first mission LappiSat-1 along with the needed infrastructure, such as clean room facilities and a ground segment. The LappiSat-1 will pave the way for future missions to higher Earth orbits, and even to orbits beyond conventional Earth orbits, including lunar orbits, and deep space missions. These will enable long-term measurements, for instance related to space weather, which will support and make continuous human presence possible even on our closest celestial bodies, and thus push the boundaries from only having human presence in our immediate backyard, i.e. in LEO.

MISSION OBJECTIVES

The prime objectives of the LappiSat-1 mission are to remain functional for a minimum period of 18 months, successfully perform measurements with the in-house developed instruments (i.e. the main payloads), accomplish two-way communication with the satellite, and finally de-orbit the satellite in a sustainable manner as an end-of-life procedure. Secondary objectives include in-orbit and technology demonstrations which will prepare the upcoming missions for harsher environments than LEO, e.g. lunar orbits, in order to have reliable instruments and satellite platforms with less chances of experiencing critical failures, potentially resulting in total mission loss.

The scientific objectives of the LappiSat-1 are to provide data sets of aurorae in wavelengths ranging from near-infrared to ultraviolet along with magnetic measurements with a high-resolution of 1 nT. These will provide crucial and supporting data that are going to supplement the ground measurements.

The LappiSat Space Program's most visible part is its space technology center where key activities are performed in dedicated space laboratories and clean room facilities. The main objective of the space technology center is to be able to provide all the necessary facilities for iterating, constructing and developing spacecraft and instruments. The center will also enable the software testing and related 'flatsat' activities, other testing procedures such as thermal vacuum and vibration tests are to be carried out by participating partners. The other visible part will be the upcoming ground segment intended to support future missions – and the LappiSat-1 mission in the best-case scenario.

The educational activities and subsequent objectives are related to bringing hands-on space education to northern Finland in different locations with the SGO's main premises being the primary location of training.

The overall goals of the LappiSat Space Program is to have a flight model of the first satellite LappiSat-1 by the Q2/2023 with a launch following afterwards, secure ground segment possibilities, and have world-class facilities for satellite manufacturing, commanding and educational activities.

LAPPISAT-1

The first spacecraft of the LappiSat Space Program is named LappiSat-1 – Lappi meaning Lapland in Finnish. The technical details of the satellite are being finalized at the time of writing. The satellite shall be a six-unit (6U) CubeSat with deployable solar panels. The most critical subsystems, such as the power system, the onboard computer, the communications system, and the attitude control system, shall be acquired commercially and shall have proven flight heritage, i.e. being able to perform flawlessly while in-orbit. The scientific payloads shall be designed and built in-house at least partly. More details about the payload instruments are presented in later sections of this paper.

The primary objective of the scientific mission of LappiSat-1 is to make observations of the aurora and the magnetic fluctuations at the satellite altitudes. It is therefore imperative that the satellite is able to orient itself accurately, in order to offer the imaging instruments a direct view at the regions of interest, and to be able to detect magnetic fluctuations properly. The preliminary requirement for the precision is 0.1 degrees. To achieve this, the satellite is planned to be three-axis stabilized. The attitude determination and control system (ADCS) is based on the use of reaction wheels, accompanied with magnetorquers. In addition to magnetorquers, the satellite shall be equipped with a secondary attitude control system, utilizing cold gas thrusters. Besides adding redundancy, the cold gas system shall provide useful experience for future missions, which are expected to take place outside the

Earth's magnetosphere, making the magnetorquers unusable. At the end-of-life phase of the mission the cold gas thrusters are used to slow down the satellite's orbital speed, aiming at hastened re-entry to the atmosphere.

The communication between the satellite and the ground station is realized utilizing rather conventional, commercially available solutions. A two-way radio communication link at S band shall be the workhorse, while a faster option for downlink at X band is being considered. The decision over including the X band depends on several variables, one being the capabilities of the ground station. Currently, SGO is not operating a satellite ground station by itself. For the LappiSat-1 mission, several options exist, including building SGO's own ground station, purchasing link time from commercial operators, or teaming up with local partners, utilizing either existing hardware or one that is under development.

In addition to concluding its own scientific mission, LappiSat-1 shall serve as a testbed for technological experimentation. The subsequent LappiSat satellites are aimed at going further than Earth orbits. Adding cold gas thrusters to test their applicability for such missions was already discussed earlier in this section. To prepare for harsher radiation environments, certain key systems of LappiSat-1 are made excessively radiation tolerant for the LEO environment. This is achieved with a combination of radiation-hardened components and extra shielding. Also, while making the final choices over which telecommunication bands and link speeds are used, some surplus capacity may be added with the future missions in mind.

SCIENTIFIC PAYLOAD OF LAPPISAT-1

The final composition and parameters of the satellite's scientific payload are currently being finalized. The payload is projected to comprise four instruments: two cameras for auroral imaging, an auroral photometer, and a magnetometer.

Auroral Imagers

The plan is to equip the satellite with two cameras. One which is optimized for scientific observations of the aurorae (the science camera) and one which is used for more conventional orbital photography (the outreach camera). The requirements and a significant share of technical design and development shall be done by the SGO led science and technical teams. This work will include e.g. mechanical and software design. Certain key parts of each camera are acquired commercially as customized products.

The purpose of the science camera is to image the auroral oval with high sensitivity. Therefore, the science camera is optimized for sensitivity rather than spectral definition. The technical requirements of the science camera must be made in tandem with the orbit selection. The orbital altitude affects the value of the optimal field of view directly. The outreach camera, on the other hand, is designed for taking aesthetically pleasing color images of the aurorae. These images are better suited for outreach and education than the ones obtained with the science camera.

Auroral Photometer

The aurorae are formed when the disturbances in the Earth's magnetosphere, caused by the solar wind, alter the trajectories of charged particles in solar wind and the magnetospheric plasma, causing them to precipitate into the upper atmosphere. Once there, the particles cause ionization and excitation within the atmospheric constituents. These excitations emit light over narrow wavelength bands, distinctive for different atoms and molecules in the atmosphere. The central wavelengths of these bands include 427.8, 557.7, and 630.0 nanometers, just to name a few. Making simultaneous observations of the intensities of multiple emission bands can reveal a lot of information about several phenomena related to the particle precipitation, such as the electron flux or the characteristic energy of the precipitating electrons.[1] The said intensities can be observed and recorded with a purpose built auroral photometer. For each wavelength band the device contains input optics, a bandpass filter, and a detector unit with control electronics. At the time of writing the photometer is in an early development phase. It is to be designed and built locally at SGO.

Magnetometer

Magnetic fluctuations and pulsations have been observed by ground-based observatories since the discovery of a magnetometer in the 1830's. Since then a large variety of different types of magnetometers have been used to monitor the magnetic environment. From 1958 onwards satellites have enabled observations of the interplanetary magnetic field, and routine synoptic solar observations of the full-disk magnetograms started in the early 1970's. But, still the coverage of magnetic observations between L1 in solar wind and ground is very limited, and far from being sufficient for a comprehensive understanding of the highly localized magnetic structures. Since the discovery of geomagnetic activity being strongly driven by the extraterrestrial conditions[2,3,4], it became evident that measurements with better coverage are needed. Improved understanding is urgent to better predict high-latitude geomagnetic activity based on the heliospheric magnetic fluctuations, waves, and topological changes of the solar magnetic field in the active regions. The CubeMag magnetometer concept started to get developed to fulfill this need of denser observations with reasonable quality, but with small size and power consumption. The first version of the CubeMag magnetometer was developed within the G-EPOS and FLEX-EPOS projects[5], which are both part of the FIN-EPOS infrastructure in the national infrastructure road map FIRI. The second CubeMag version has started to be developed within the Earth-Space Research Ecosystem (E2S), which started its operations in 2020, and is the first ever space-related infrastructure in the FIRI road map in Finland.

The CubeMag instrument is in fact a combination of a number of separate magnetometer sensors of varying types. As an experimental device, CubeMag shall provide valuable information about the performance of each sensor type, thus helping the development of subsequent designs. Besides the magnetic sensors, CubeMag includes the control electronics, a microcontroller, internal memory for data storage, and a digital communication interface. The main drivers for the CubeMag design are compatibility with CubeSats, in terms of small size and compatible interfaces (mechanical, data), adequate measurement accuracy, and moderate price. High-quality space-based magnetic observations are possible with or without boom. When doing the observations without the boom the requirements for the signal analysis are higher. The aimed accuracy for the magnetic field measurements is 1 nT. The first prototypes of CubeMag for LappiSat-1 have been built and they are about to enter the testing phase shortly.

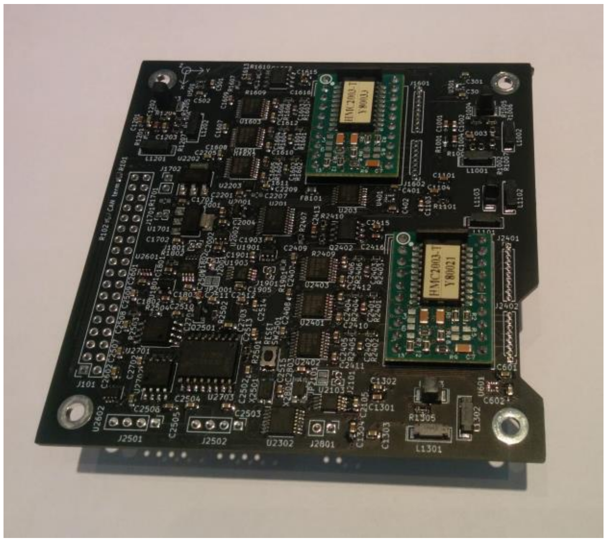

Figure 1. Prototype of CubeMag magnetometer.

FUTURE PLANS AND MISSIONS

LappiSat-1 is envisioned as an initial stepping stone for a series of future LappiSat satellites, which will include stand-alone missions and constellations for near-Earth orbits and to our closest celestial bodies. As such, the LappiSat-1 begins this journey in the convenience of low Earth orbit, carrying SGO's geophysical instruments as its main payload. However, as discussed in this paper, the next steps are already being planned.

The upcoming satellite missions, e.g. LappiSat-2A, LappiSat-2B, and LappiSat-3, will take SGO's heritage of building instruments and satellites beyond conventional low Earth orbits. These include high Earth orbits, lunar orbits along with lunar surface instruments, and missions beyond the Earth–Moon system. Such missions are vital in understanding and predicting near-term and long-term changes that are critical to society and for future space exploration purposes, including crewed missions to the Moon and lunar infrastructures.

In addition to designing, building and operating satellite missions, the space technology centre aims at building scientific instruments, which may be included in missions of other institutes and joint collaborations as well. These include collaboration efforts within academia and industry, and in addition opportunities with national space agencies, such as NASA and ESA, and their calls.

In the intermediate future SGO aims at building its own satellite ground segment with multiple ground stations. The near-future plan is to have an operational ground station dedicated for SGO's purposes. Whether this ground station is already functional at the time when the operation of LappiSat-1 begins is still uncertain. Because of this, alternative plans have been made for LappiSat-1, as discussed earlier. The requirements set by the upcoming satellite missions are taken into account when planning the ground stations. These include the incorporation of certain main frequencies – VHF, UHF, S band and X band – that are used in small satellite missions frequently, and additional frequencies, such as the Ka band, that are listed as near-future standards by space agencies such as NASA and ESA.

The northern locations of SGO's primary operating sites in Finland, such as Tähtelä, Sodankylä at 67°25'N, make these locations excellent homes for ground stations which can operate satellites, especially stationed in polar orbits. These can be extended to operate as national and international ground station networks.

REFERENCES

1. Nozawa, S. et al., “A new five-wavelength photometer operated in Tromsø (69.6°N, 19.2°E),” Earth, Planets and Space, vol. 70, 193, 2018.

2. Kallio, E.I., T.I. Pulkkinen, H.E.J. Koskinen, A. Viljanen, J.A. Slavin, and K. Ogilvie, “Loading-unloading processes in the nightside ionosphere,” Geophys. Res. Lett., vol. 27, No. 1, 627, 2000.

3. Tanskanen, E.I., T.I. Pulkkinen, H.E.J. Koskinen, and J.A. Slavin, “Substorm energy budget near solar minimum and maximum: 1997 and 1999 compared,” J. Geophys. Res., vol. 107 (A6), 2002. doi:10.1029/2001JA900153

4. Tanskanen, E.I., J.A. Slavin, A. Tanskanen, A. Viljanen, T.I. Pulkkinen, H.E.J. Koskinen, A. Pulkkinen, and J. Eastwood, “Magnetospheric substorms are strongly modulated by interplanetary high-speed streams,” vol. 32, No. 16, Geophys. Res. Lett., 2005. doi: 10.1029/2005GL023318

5. Väänänen, M., From analog to digital magnetometers: DigiMAG digitization and CubeMAG magnetometer concepts, Master’s Thesis, University of Helsinki, 2019. https://helda.helsinki.fi/handle/10138/304887