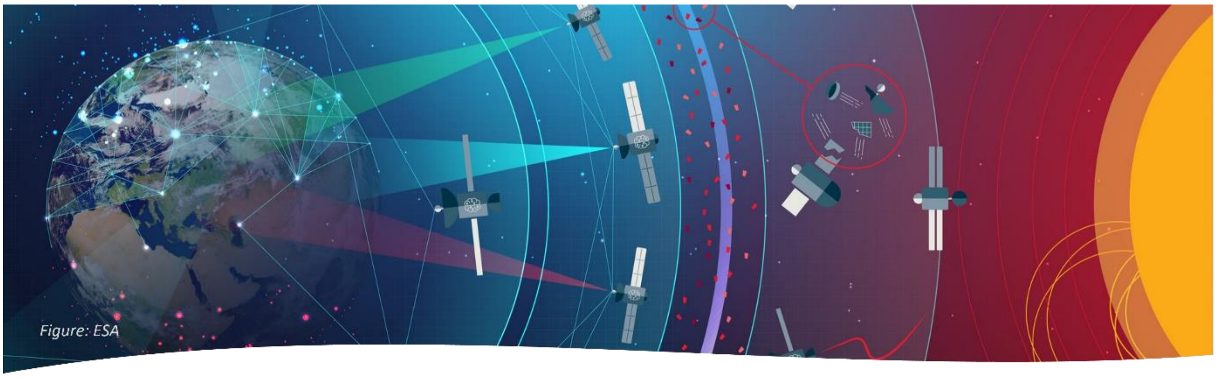
The Arctic Space Weather Demonstrator in the European Accelerators Programme



Final Report

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1. Introduction

1.1 Purpose

This document is the Final Report of a survey about space weather impacts on some critical infrastructures and widely used services in Finland and Norway. The survey was conducted in collaboration with the authorities and companies maintaining and developing the addressed systems (hereafter called Partners). The consortium which collected and analysed the information of this report is composed of the Finnish Meteorological Institute (FMI), the Norwegian Mapping Authority (NMA), and the Norwegian Space Agency (NoSA). The project was conducted during Oct 2023 – Feb 2024 under the European Space Agency (ESA) Space Safety Programme (S2P) as an in-kind contribution by Finland and Norway to the Protection of Space Assets initiative which is one of the three main themes under the European Space Accelerators partnership [URL01].

1.2 Scope

Finland and Norway volunteered to conduct this pilot study, because both countries reside at latitudes where space weather phenomena are common. Operators both in commercial and safety sectors can therefore be expected to have useful insights into space weather impacts on critical solutions facilitating everyday life. This project can be considered as a pilot for a broader mission, where awareness on space weather related risks and their mitigation by improved preparedness is increased on European level.

Comprehensive user engagement in the development of European space weather services is an essential prerequisite for their successful implementation. The overall objective of this pilot and its successor is to familiarise actors in all relevant societal fields with the pre-operational Space Weather Service Network (SWESNET) that has been developed as multinational collaboration under ESA S2P. Discussions in the SWESNET context are foreseen to bridge the gap between the user community expectations for operational space weather services and the capabilities that can be offered from the basis of current understanding on solar-terrestrial linkages.

1.3 Document Structure

References and abbreviations used in this document are introduced in Section 2. Section 3 gives brief descriptions of the Partners of this project. Examples of use cases are discussed in Section 4 and main points from the feedback by the Partners are listed in Section 5. Conclusions from this project are presented in Section 6.

2. References and Abbreviations

2.1 References

RD01 Burns, A. G., S. C. Solomon, W. Wang, L. Qian, Y. Zhang, L. J. Paxton, X. Yue, J. P. Thayer, and H. L. Liu (2015), Explaining solar cycle effects on composition as it relates to the winter anomaly, J. Geophys. Res. Space Physics, 120,5890–5898, doi:10.1002/ 2015JA021220.

URL01: Accelerators: a vision and call for action – ESA Vision

URL02: https://sesolstorm.kartverket.no/

URL03: https://www.forsvaret.no/en/news/publications/military-advice

URL04:	https://www.regjeringen.no/no/dokumenter/nou-2023-17/id2982767/
URL05:	Manuals and Tutorials - Space Weather (esa.int)
URL06:	https://sesolstorm.kartverket.no/radioburst/index.xhtml

2.2 Abbreviations

AIS	Automatic Identification System
API	Application Programming Interface
COTS	Commercial Off The Shelf
EHF	Extreme High Frequency (a.k.a. Very High Frequency, VHF)
ESA	European Space Agency
EUV	Extreme Ultraviolet radiation
FMI	Finnish Meteorological Institute
FSSAC	Finnish Space Situational Awareness Center
GBAS	Ground Based Augmentation System
GIC	Geomagnetically Induced Currents
GNSS	Global Navigation Satellite System
GPI	GNSS Performance Indicator
IATA	International Air Transport Association
IoT	Internet of Things
LEO	Low Earth Orbit
NMA	Norwegian Mapping Authority
NOAA	National Oceanic and Atmospheric Administration
NoSA	Norwegian Space Agency
NRT	Near-Real-Time
OSL	IATA code for Oslo airport at Gardermoen
RF	Radio Frequency
RFI	Radio Frequency Interference
ROTI	Rate of TEC Index
RSP	Recognized Space Picture
RTK	Real-Time-Kinematic
SAR	Synthetic Aperture Radar
SBAS	Satellite Based Augmentation System
SSA	Space Situational Awareness
SWESNET	Space Weather Service Network
SWPC	Space Weather Prediction Center

TEC	Total Electron Content
TECU	TEC Unit = 10^16 electrons/m^2
TID	Total Ionizing Dose
ULF	Ultra-low Frequency
UV	Ultraviolet radiation
WAM	Wide Area Multilateration

3. User engagement: Partners in the Demonstrator

Below we give brief introductions of the Partners whose views on space weather impacts on their services have been collected during the project. Figure 1 gives an overview on the impact areas addressed in this survey.

Avinor is a state-owned company under the Norwegian Ministry of Transport and Communications and is responsible for 43 state-owned airports. It provides safe and efficient travels for around 50 million passengers annually, half of which travel to and from the Oslo Airport.

Destination Lofoten AS (Visit Lofoten) is a Norwegian company promoting tourism in the region of Lofoten Islands.

Findmy is a Norwegian company which develops tracking for livestock. Findmy offers a varied selection of tracking products for animals and grazing areas. Animal tracking ensure good animal welfare and sustainable food production. The founders are Norwegian sheep farmers who know the challenges of keeping sheep in varied landscapes.

Fingrid Oyj is Finland’s transmission system operator owned by the Finnish state and Finnish pension insurance companies. Fingrid secures Finland’s energy supply by transmitting electricity through the main grid from production facilities to industrial customers and electricity companies.

ICEYE is a Finnish microsatellite manufacturer, which operates globally from several locations. ICEYE owns the world's largest synthetic aperture radar (SAR) satellite constellation. It serves as a trusted partner to governments and commercial industries delivering information that supports decision making for improved community resilience and sustainable development.

National Land Survey of Finland (NLS-Finland) performs cadastral surveys, produces map data and promotes the use of such data. It maintains information about properties and housing company shares in its registers and takes care of the registration of ownership and mortgages. Other tasks of the agency include spatial data research and application. NLS-Finland works under the Ministry of Agriculture and Forestry of Finland.

Norwegian Mapping Authority (NMA, Kartverket) provides its users with the national geodetic frame, digital maps, land registry, property information, place names, and positioning and nautical chart services. It serves as the nationwide coordinator of geodata and is involved in a wide range of geospatial research and activities. NMA works under the Ministry of Local Government and Regional Development.

Statnett is a state enterprise owned by the Norwegian state. It maintains and develops the Norwegian energy system with the mission to secure power supply through operations, monitoring, and preparedness. Statnett works under the Ministry of Energy.

The Finnish Transport and Communications Agency (Traficom) is a government agency which works to ensure the availability of well-functioning, safe, secure, and reasonably priced transport and communications connections and services in Finland. Traficom is also an authority serving people and businesses in licence, registration, and supervisory matters. Traficom works under the Ministry of Transport and Communications.

Yeti Move AS is a Norwegian company which delivers systems and services to optimize the utilization of various industrial machines and connected equipment, through different levels of automation. The company started its activities with autonomous vehicles for airports and it is now in the process of broadening its scope to cover also other areas such as port logistics, industry, and construction.

Maskinstyring AS is a Norwegian company which represents 3,000+ users throughout Norway where approximately 2,400 are users of the Norwegian Mapping Authority's CPOS service, while the rest use similar services or local base stations on larger projects. The users mainly consist of excavators and bulldozers that use machine control systems, but hand-held machines are also used on the projects. The difference here is that the machine control systems are connected mostly all day, while the hand-held equipment is used more sporadically throughout the day.

Indra Navia AS is a high-technology company delivering safety-critical air traffic management solutions to 1400 airports in more than 120 countries. Indra Navia has been an industrial company in Norway since 1916 and is now a subsidiary of the global Indra group.

Figure 1: A mosaic summarizing the Partners and the main impact areas of space weather addressed in this study.

4. Use case examples

This section presents a set of concrete examples where Arctic operators have observed some anomalies in their products or services due to enhanced space weather activity. Also, approaches to mitigate space weather risks by enhanced preparedness and some plans on how space weather services can support new business ideas are discussed.

4.1 Space weather storm on Feb 26-27, 2023: Impacts on accurate positioning

As the coupling of solar activity with space weather in the near-Earth space and upper atmosphere is non-linear in several respects and affected by the prevailing background conditions, moderate solar bursts can cause surprises in their technology impacts. The geomagnetic storm that took place during Feb 26 – March 1, 2023 is a good example for such a case. It was associated with two M-class solar flares that occurred on the evenings of Feb 24 and Feb 25. The flares were accompanied by bursts of ultraviolet and extreme ultraviolet radiation (UV and EUV) which are visible in the data of the LYRA instrument on-board the Proba2 satellite monitoring solar activity at a sun-synchronous orbit (c.f. Figure 2). The solar bursts launched two Coronal Mass Ejections (CMEs), the latter of which caught the former one and consequently the Earth was exposed to their combined effect. The geomagnetic storm which started in the evening of Feb 26 intensified during Feb 27 (c.f. Figure 3).

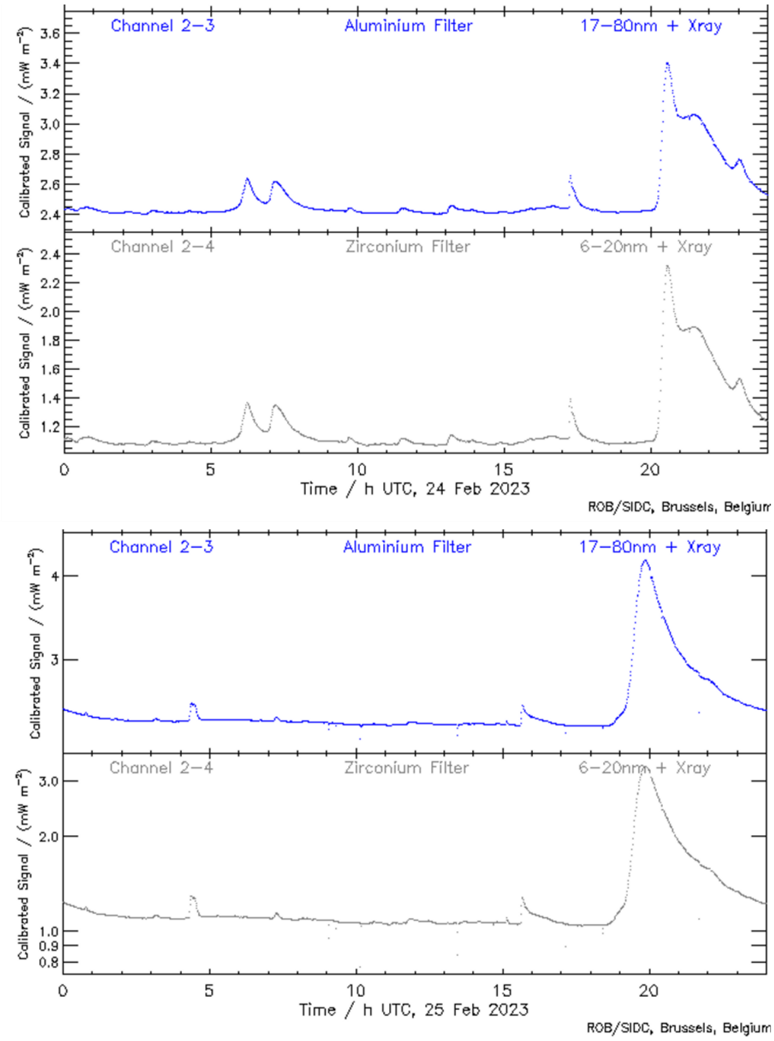


Figure 2: EUV and UV data by the LYRA instrument for Feb 24 and 25 (top and bottom panels respectively). These data are available in the SWESNET service (product S.102).

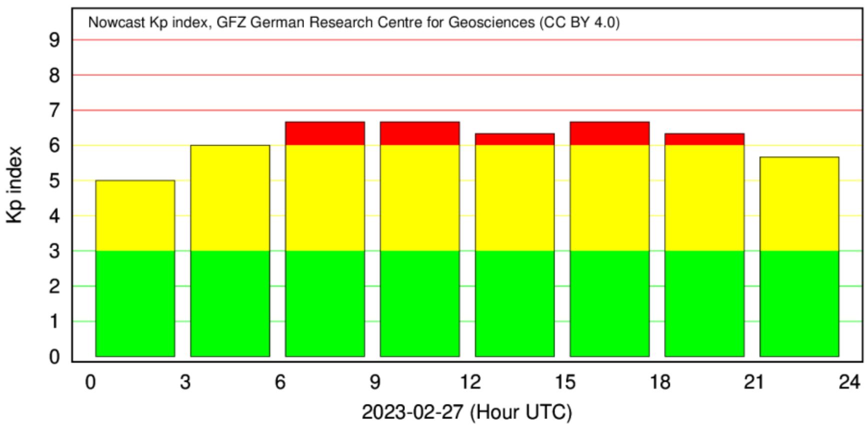


Figure 3: Time evolution of the geomagnetic storm on Feb 27, 2023, as characterized by the global Kp-index. Kp is constructed from the basis of mid-latitude magnetic field measurements. It can have values between 0 and 9. Values in the range of 6-7 are considered as moderate or strong activity. These data are available in the SWESNET service (product G.107).

The geomagnetic storm activity on Feb 27 was associated with disturbances in the dayside ionospheric electron density which lowered the performance of Finnish and Norwegian systems supporting Real-Time-Kinematic (RTK) positioning. Ionospheric Total Electron Content (TEC) had a strong latitudinal gradient at latitudes of mid-Finland and mid-Norway. On the poleward side of this gradient the electron density showed rapidly varying small-scale structures, which caused enhanced values in the Rate of TEC Index (ROTI). Both these phenomena are clearly visible in the Near-Real-Time (NRT) maps of TEC and ROTI (c.f. Figure 4) which NMA generates for the SWESNET service from the basis of dual-frequency data by GNSS receiver networks (GNSS=Global Navigation Satellite System).

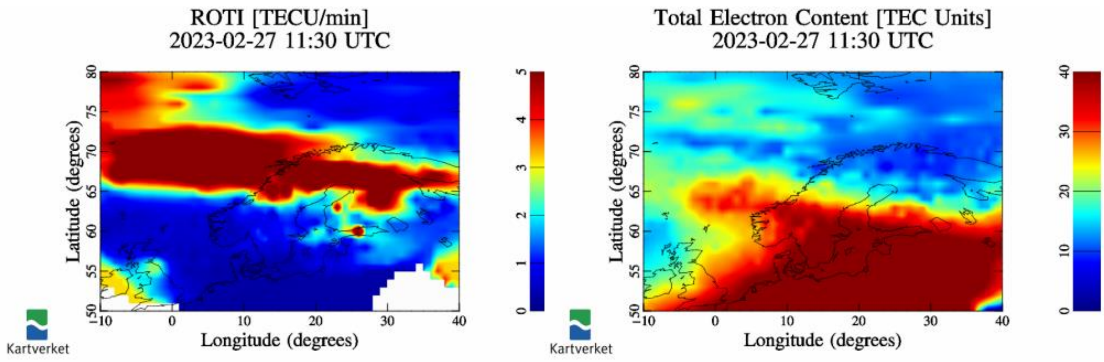


Figure 4: Daytime ionospheric disturbances on Feb 27 as characterized by the ROTI and TEC products of NMA. These maps are available in the SWESNET service (products I.107 and I.109). TECU=TEC Unit=10^16 electrons/m^2.

Detailed post-analysis of GNSS data reveals that the enhanced ROTI values in this case are associated with wave-like patterns in the electron density. The post-analysis handles signals of each GNSS satellite-receiver pair separately. For each signal its ionospheric piercing point is determined, and TEC as integrated along the signal is derived from the geometry-free combination of signals at different frequencies. Small-scale and rapid variations are extracted from the background TEC by Savitzky-Golay filtering. Wave structures become apparent when the piercing points by a dense GNSS receiver network are shown on a map and the points are coloured with a palette that quantifies the TEC difference from background conditions. Examples of results by this approach are shown in Figure 5.

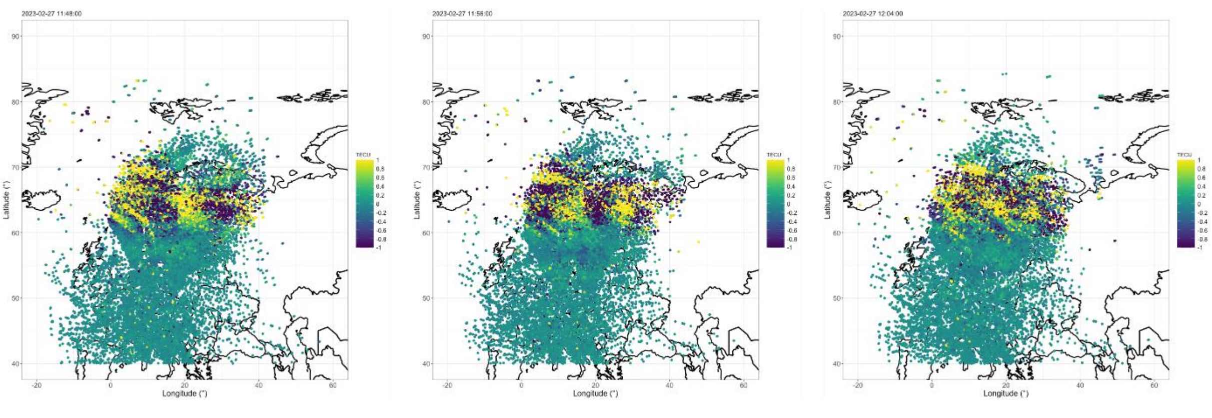


Figure 5: Wave-like patterns in the ionospheric electron density on Feb 27, 2023, as derived from GNSS dual-frequency data (for more details, see the text). Timestamps of the plots are 11:48, 11:56, and 12:04 UT. The color palette of the dots gives information about differential TEC (in TECUs) along individual receiver-satellite signal paths (plot by Johannes Norberg, FMI).

From the viewpoint of RTK services the above-described ionospheric disturbances are problematic because they take place during the daytime when the need for accurate positioning is large by several applications. In the following we describe the impacts on two Finnish and Norwegian stations. In addition, data from four GNSS scintillation stations are shown and discussed. Locations of the RTK and GNSS scintillation receiver stations are shown in Figure 6 .

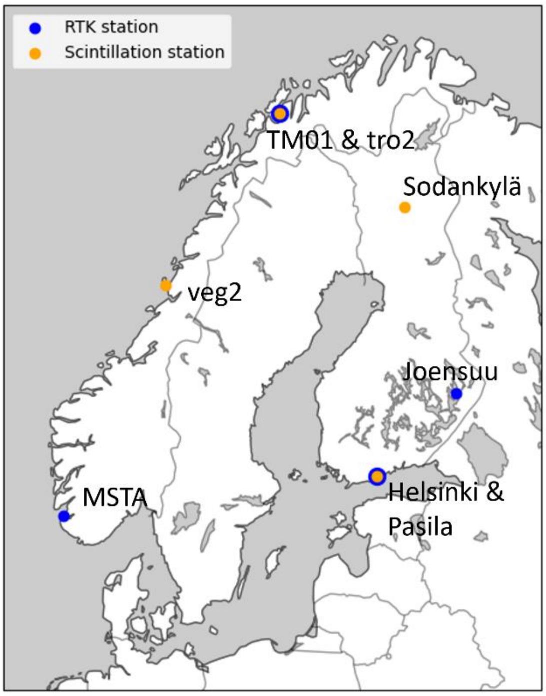


Figure 6: Locations of Finnish and Norwegian RTK and GNSS scintillation stations, whose data are presented in the following Figures (Map: Elias Hirvonen, FMI).

ROTI maps are often used as proxy information for ionospheric scintillation which can appear both in the GNSS signal amplitude and phase and can be measured more comprehensively with specific scintillation receivers offering higher sampling rates than the standard GNSS receivers provide. The ROTI map of Figure 4 fulfils this expectation as it tells quite much the same story as the data of the scintillation receivers of Figure 7 and Figure 8: Phase scintillation is enhanced in the region of high ROTI and it is on a nominal level in the Southern parts of Finland and Norway where ROTI is low, although TEC is high. Like the plots from the Finnish stations show, amplitude scintillation remains on low level throughout the day, which is typical at high and mid-latitude stations. Interestingly, the scintillation receiver in Tromsø (tro2) observes a slightly lower level of phase scintillations than Vega (veg2) and Sodankylä. This may occur during strong storms, where the auroral oval is expanded so much that the main scintillation activity takes place south of Tromsø.

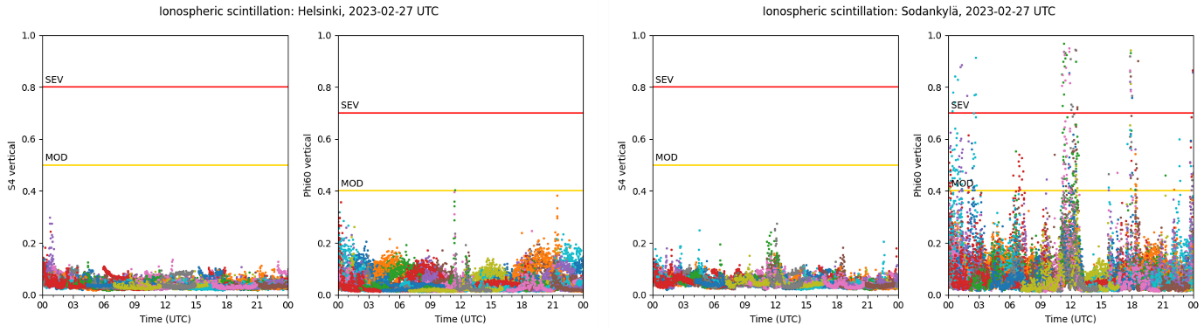


Figure 7: Plots showing both amplitude scintillation (characterized with the S4 index) and phase scintillation (characterized with the SigmaPhi index) at Helsinki and Sodankylä. The yellow and red horizontal lines show the thresholds that are used in the issuances of advisories on moderate and severe level for civil aviation according to the regulations of the International Civil Aviation Organization (ICAO) (Plots by Petri Koskimaa, FMI).

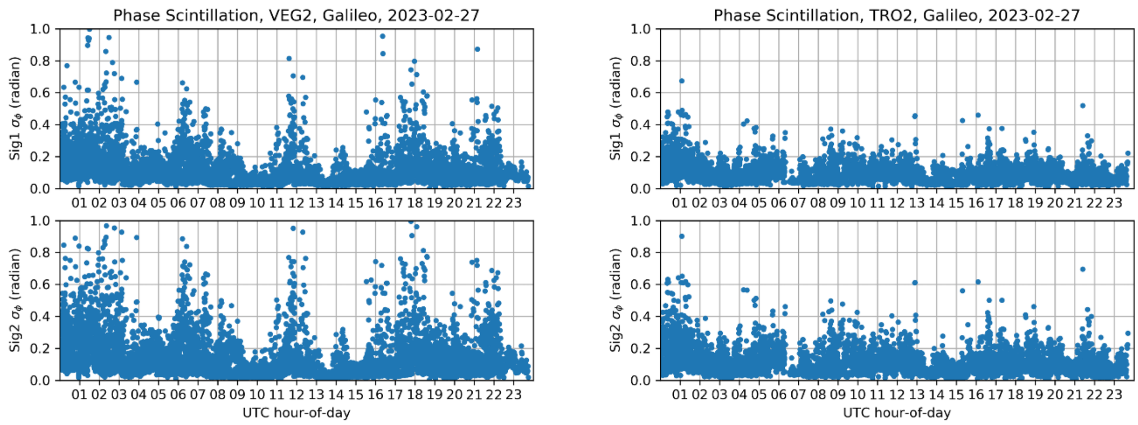


Figure 8: Phase scintillation data from the Norwegian scintillation stations veg2 (left) and tro2 (right). Sig1 and Sig2 refer to phase scintillation measured in the E1 and E5a frequencies of Galileo data. (Plots by Knut Stanley Jacobsen, NMA).

Figure 9 shows residual errors measured at the Finnish and Norwegian RTK stations of the map in Figure 6. These errors are the differences between the station actual locations and the estimated locations based on positioning with RTK network support. In optimal situation these errors should be below 2-5 cm. High residual errors during nights are expected due to auroral activity, but enhanced errors appearing also during daytimes is a feature that has become more typical during recent years. In the case of Feb 27, residual errors are large (occasionally 40-50 cm) in the Northern Finnish and Norwegian stations which are under the ionosphere of high ROTI values. During this event ROTI disturbances also reached the southern stations at nighttime (See Figure 10), causing coordinate errors even at the most southern station MSTA.

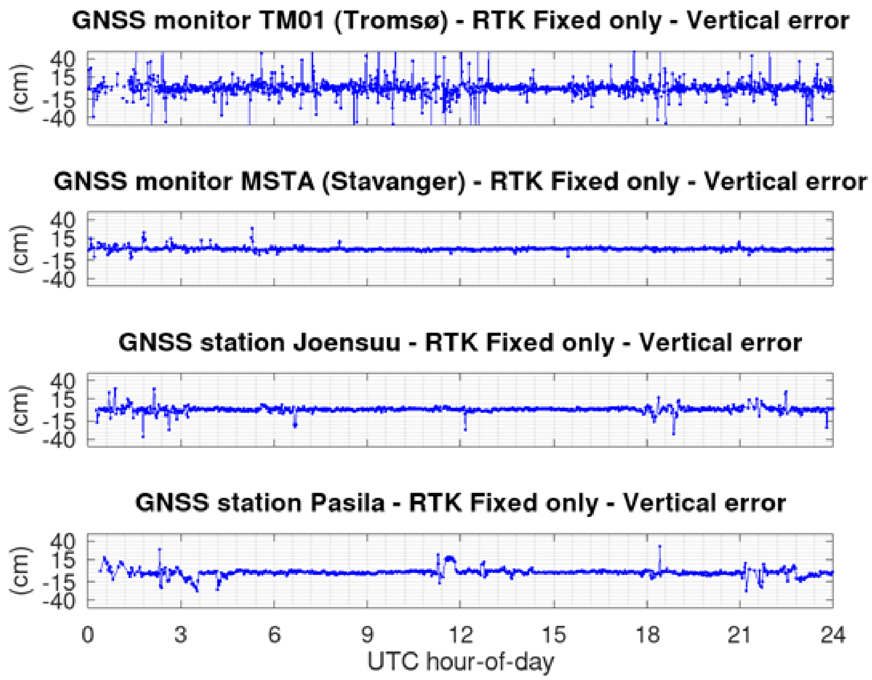


Figure 9: Residual errors at the Norwegian and Finnish RTK stations. (Plot by Knut Stanley Jacobsen, NMA)

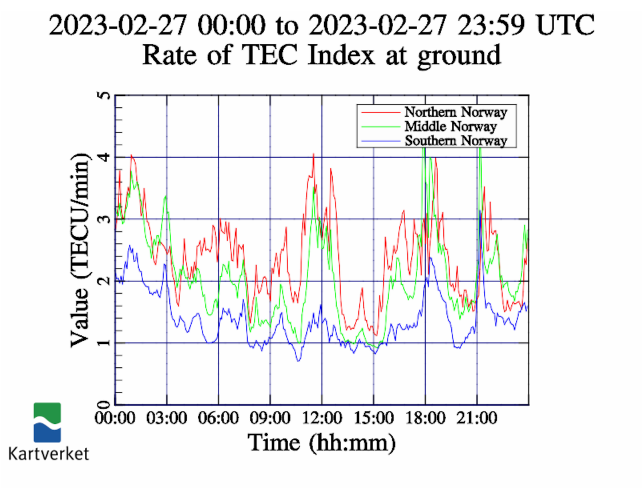


Figure 10: Time series of ground effect of ionospheric disturbances on Feb 27 as characterized by the ROTI products of NMA. These time series are available in the SWESNET service (product I.109).

As mentioned above, dayside problems in RTK have become more common during recent years which gives a reason to assume that they have some kind of linkage with the approaching solar maximum. The high TEC values in the Southern parts of Finland and Norway shown in Figure 4 exhibit most likely the winter anomaly behaviour where ionosphere-thermosphere interactions increase electron densities in the F-layer. The anomaly gets more pronounced during the solar maximum years when compared to minimum years [RD01]. The large density gradient at the poleward boundary of the anomaly has some potential to host some ionospheric irregularities which has been observed also in our case. As the problems do not appear systematically every day during the wintertime, it seems that the winter anomaly alone cannot cause strong enough disturbances. Comprehensive understanding of the physical processes that cause the daytime RTK problems obviously requires still some additional research.

4.2 RTK applications recognizing the benefits from space weather services

Applications using GNSS positioning represent in the commercial sector one of the most rapidly expanding fields harvesting support from space-based infrastructures. Many enterprises in the Nordic Countries are aware on a general level about the challenges that space weather can cause in accurate positioning. With this knowledge the urge to increase preparedness against the most harmful impacts by space weather services is growing continuously. As examples of business cases with some adaptation to occasional space weather activations, the use cases by the Norwegian companies Findmy, Yeti Move AS and Maskinstyring AS are described in the following sub-sections.

4.2.1 Livestock tracking with GNSS

Every summer, thousands of sheep graze in forests and mountains all over Norway. Over 100,000 of them never return. Since the sheep tend to wander in small herds over large geographical distances, it can be a demanding task for the farmer to keep track of his own animals. Loss of sheep can be caused by many factors. It is often difficult to determine the cause of death, either because the carcass is not found or because it is found too late. In some areas, the number lost to unknown causes are large. This can impact insurance or government remuneration payments for lost livestock, which depend on cause of death.

Equipment for tracking livestock is nothing new on the market, but the technology is constantly improving. With the help of a smart sheep bell and the Internet of Things (IoT) Norwegian farmers get help to keep track of sheep grazing in open fields. More and more farmers are equipping their sheep with electronic monitoring. Animal tracking ensure good animal welfare and sustainable food production. Findmy develops tracking for livestock and offers a varied selection of tracking products for animals and grazing areas (c.f. Figure 11). The founders are Norwegian sheep farmers who know the challenges of keeping sheep in varied landscapes.

Findmy produces electronic bells with satellite tracking for livestock on pasture. With this electronic bell the owner of the livestock has always a full overview of where the livestock are. More and more farmers are becoming dependent on the tracking system and are finding great help and efficiency in the system. The electronic bells are equipped with a stress warning so that the owner is informed as soon as the animals exhibit abnormal behaviour. The bell uses IoT networks to send messages between the animal and the farmer. With the use of a mobile phone, it is possible to search for the bell in the terrain. Via Bluetooth, you can now enter an internal Geofence in the bell which is checked by bell itself. If the animal has left or entered a Geofence area, the bell will immediately notify the owner by sending a message to the mobile phone.

Figure 11: Findmy produces electronic bells with satellite tracking for livestock on pasture. With this electronic bell the owner of the livestock has always a full overview of where the livestock are (Photos: Findmy).

Findmy delivers their system to more than sheep. The company provides tracking for many different types of livestock. They offer customized setups for each animal type on all models to give the owner and the animals the best tracking experience. As an example, Findmy has developed a solution in terms of being able to save the lives of reindeer in connection with train accidents. Reindeer are herd animals and travel in areas where train tracks run. The system they have developed works so that a geofence is set up around the moving locomotive. The reindeer wear a bell around their necks and when the reindeer pass the geofence, a notification is sent to the locomotive driver, who is given the opportunity to slow down so that the reindeer can pass without an accident. The system also notifies the reindeer owner that the reindeer has passed the geofence on a locomotive and that they are therefore in danger.

As part of this project NMA representatives have been in contact with Findmy to find out to what extent they possibly use space weather services and what their wishes are for a future solution for space weather services in their product. As of today, the company does not use space weather services, but sees a clear need to adopt a space weather service that may in some cases help to explain anomalies in the sheep's position, which in some cases is far outside the area in which they would normally graze.

Sheep herding usually starts at the beginning of September and lasts for a few weeks. The gathering must be extended long enough to make use of the supply of forage in the mountains, but the sheep must also return to the farm before the snow begins to fall and before the frost arrives on the autumn mountain. Winter weather in the mountains in Norway comes quickly and brutally, often within just a few hours. Large parts of the sheep are collected within a couple of weeks, but there are often sheep that are not included in the first couple of collections. When looking for a single individual, it is essential to know where the sheep are so that an effective collection can be carried out. A solar storm can make this job difficult, and a solar storm can cause you to look in the wrong place. This can mean that the sheep remains in the mountains and eventually freezes to death. The reindeer solution has similar needs. Here, the locomotive driver's warning must not fail, as this could lead to the train running down a whole herd of reindeer.

4.2.2 Automated snow ploughing at the Gardermoen airport

Yeti Move AS delivers systems and services to optimize the utilization of various industrial machines and connected equipment, through different levels of automation. One example is the RS600 autonomous runway sweeper delivered by Øveraasen AS to Avinor, which operates on Oslo Airport Gardermoen (c.f. Figure 12). During the 2022/2023 winter season, the system was tested both day and night under various conditions. On March 24th, 2023, Yeti Move together with Avinor were going to perform verification of snow plans, with a group of six vehicles covering both runways and taxiways. The test started 00:30 local time, but only 4 minutes later, the operation came to a full stop. The safety system reported RTK issues across all vehicles. The team quickly checked the space weather service by NMA [URL02] which reported about significantly enhanced ROTI values above the Oslo-region (c.f. Figure 13), potentially threatening the test activities. The team decided to proceed manually for a few hundred meters, and 10 minutes later, the vehicles regained RTK fix. After this, the test was completed without further RTK dropouts. The dropout did, however, provide valuable experience.

Figure 12: Yeti Move utilizes NMA's RTK-service to ensure precise positioning of the autonomous sweepers. The vehicles shall operate without driver interference on Oslo Airport Gardermoen (OSL), except for an operator located in the first machine. Without the aid of GNSS correction signals, both safety and operational performance would be reduced (Photo: Yeti Move).

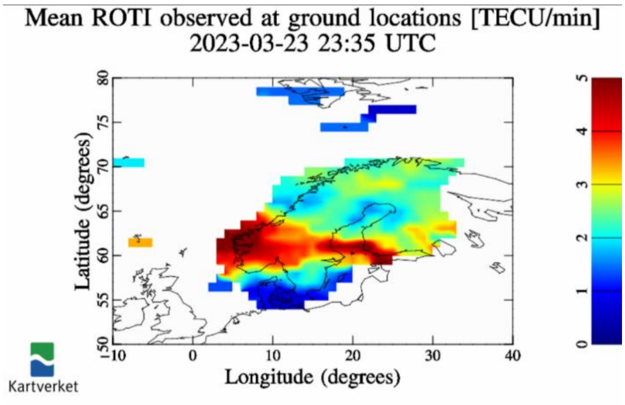


Figure 13: Enhanced ROTI values in the Oslo region measured during a test campaign of Yeti Move's automated snow ploughing solution at the Gardermoen airport. This map is available also in the SWESNET service (product I.109).

A non-moving fleet of runway sweepers will have an impact on the local traffic flow on the airport, and that may in turn influence the air-traffic situation far beyond the Norwegian borders. In an acute situation and during an operational context, the vehicles will have to be quickly manned and maneuvered manually. This means that resources will have to be reallocated from other ongoing tasks, tasks that need to wait until the snow removal is completed. For an airport operator like Avinor, it will be risk-mitigating knowing upfront of a snow removal operation if any rough space weather is expected, that may impact the quality of the position services, and use this information to determine whether the operation should be planned as a manual operation from start, to avoid unwanted stops on the runway or taxiway.

4.2.3 Space weather impact on machine control systems

Maskinstyring AS represents several thousand users of machine control systems in Norway. In general, the space weather will affect the customers negatively in the form of the wrong position for the work being carried out. This is difficult to detect in the equipment at an early stage in the development of "bad space weather", because this type of equipment does not warn of elevated noise values with consequent poor position accuracy until approaching 3 TECU/min. However, harmful deviations in position can be experienced already at lower levels of activity (1.5+ TECU/min; c.f. Figure 14).

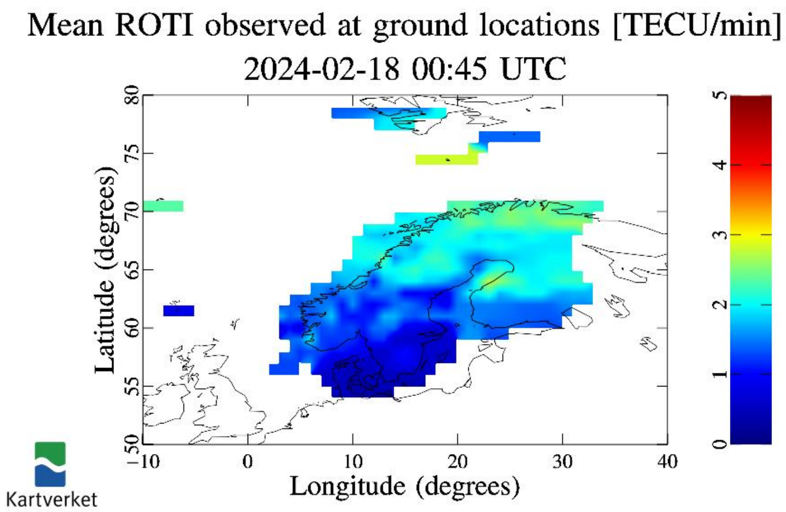


Figure 14: Some machine control system operators are aware of the possibility of space weather impacts and consult space weather monitoring services such as ROTI maps. This map shows an example of moderate-level space weather disturbances (~2 TECU/min) that can result in position errors without triggering built-in warnings in the equipment. This map is available in the SWESNET service (product I.109).

When using an excavator for unloading in a construction pit, you may unknowingly unload too much material if the equipment is exposed to strong space weather over time. The equipment will most likely not notify the user in any way. If the unloading is conducted as evening time piecework the deviation may not be discovered until the next day. When bulldozers (c.f. Figure 15) are used to lay out stone masses for road construction, the problem will be the same as for the excavator, especially as the deviations become significant over time. The gradually accumulating deviations do not become noticeable until you perform a check of the work done or restart the system. In both cases described, the consequences will be extra work to make up for the deviations, but also extra costs linked to the addition and removal of masses. The size of the project and the machines that have carried out the work will be decisive for the costs involved. It is not inconceivable that in the period of 16.00-19.30 in local time on a normal working day with a large capacity for road construction the mistakes made due to space weather can cost NOK 100-200,000 per machine, assuming the mistake is discovered the next day. If work continues without discovering the mistake, the costs to correct the mistake would increase.

Figure 15: Example view of a bulldozer operator equipment. The left and right parts of the image show the front and side views. The numbers at the bottom indicate the altitude setting that should be used for the blade. During space weather activity these numbers fluctuate, even when the bulldozer is stationary, but if the activity is moderate there are no warnings in the display that the numbers cannot be trusted (Photo: Maskinstyring AS).

In everyday operations access to NRT space weather information would help in understanding the background of deviations in position with the condition that the user knows where to look and what to look for. For most of the machine control users who do their work out in the field and drive machines, this access is not helpful unless it comes directly to the systems that they use. The colleagues working in offices need to be active and notify the field workers about increased activity and encourage them to do more frequent checks against fixed marks on the plant. In the absence of space weather data, the field worker may notice deviations in the systems that cannot be explained. If there are no warnings about degraded signal quality, then the user has no opportunities to take measures to reduce the risk of errors and potentially large costs. Obviously, a notification service for space weather alone will not be enough for machine control users to prevent errors in everyday work.

A warning service for space weather should work so that an expected development of the space weather is produced for a given time in the future, as is done for the weather forecast. The services should also offer its user the opportunity to choose how big changes in the activity he/she can tolerate before getting a notification on enhanced activity in the form of e.g., email, SMS, or by a mobile phone application. This will help make everyday life a little easier by making users aware of the risks that are likely to occur soon.

In addition to warning about possible developments in space weather, there is also a need to know exactly how space weather affects work at specific work sites. Here we are talking about local stations that measure actual deviations in position towards a known point continuously, to record the coordinate deviations over time. Here, too, the solution must make it possible to notify users based on how big a deviation those users tolerate. By using such a service locally on a project site, it will also be possible to document the impact the space weather has had on the project.

4.3 Interests in satellite operations and aviation sector

Infrastructures in space are using solutions based on small-sat constellations and Commercial off the Shelf (COTS) technologies in increasing amounts. With these tendencies the need for more versatile and accurate information on the space environment where the infrastructures are operated becomes an essential issue in the risk mitigation under aerospace activities. This topic was addressed in the discussions with the ICEYE company, Norway Space Agency, Indra Navia, and Avinor. Use case examples from those discussions are the following.

4.3.1 Space weather monitoring for a satellite constellation

ICEYE is monitoring the space environment of its microsatellite constellation on daily basis (c.f. Figure 16). The company collects systematically information about the changes in satellite orbits and bitflips in electronics and follows space weather activity for improved preparedness against the impacts. ICEYE has used the Space Weather Prediction Center of National Oceanic and Atmospheric Administration (SWPC/NOAA, US) as the primary source for space weather information. SWPC products of particular interest include three-day forecasts of overall space weather activity (Solar radiation, Geomagnetic activity, Radio blackouts), specific forecasts on geomagnetic activity, and forecasts of solar cycle progression.

In the context of this project a brief introduction of SWESNET was given to the flight dynamics team of ICEYE. It appeared that the network contains some products which can nicely complement the information provided by SWPC. The opportunity to extract numeric data in NRT and for post-processing is considered as a useful asset, which the company plans to utilize in its daily monitoring. Proton and electron fluxes by GOES and Proba-V, and Total Ionisation Dose (TID) are examples of measurements that are relevant for ICEYE constellation operations. On modelling side, the company is interested about the model of thermospheric density for satellite drag estimates with the forecasts of its input parameters (solar and geomagnetic indices). Forecasts of the solar cycle progression (c.f. Figure 17) are needed in the planning of future launches to maintain appropriate performance of the satellite constellation. The company has some previous experience on the usage of the SPENVIS system of space environment models and impact assessments which is now available also in SWESNET.

Figure 16: Launch of ICEYE-X1, ICEYE's first microsatellite mission with a Synthetic Aperture Radar (SAR) sensor as its payload and the world's first SAR satellite in this size, on 12 January 2018, on ISRO's PSLV-C40 rocket from Satish Dhawan Space Center in India (Photo: Antrix)

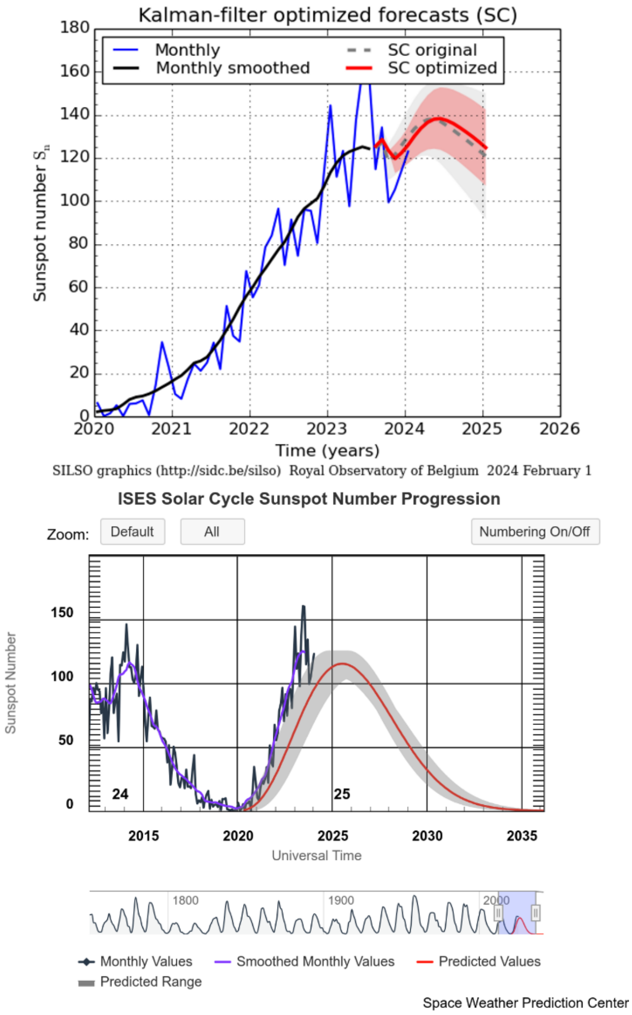


Figure 17: Forecasts of solar cycle progression by (top) SWESNET (product S.108) and by (bottom) SWPC/NOAA.

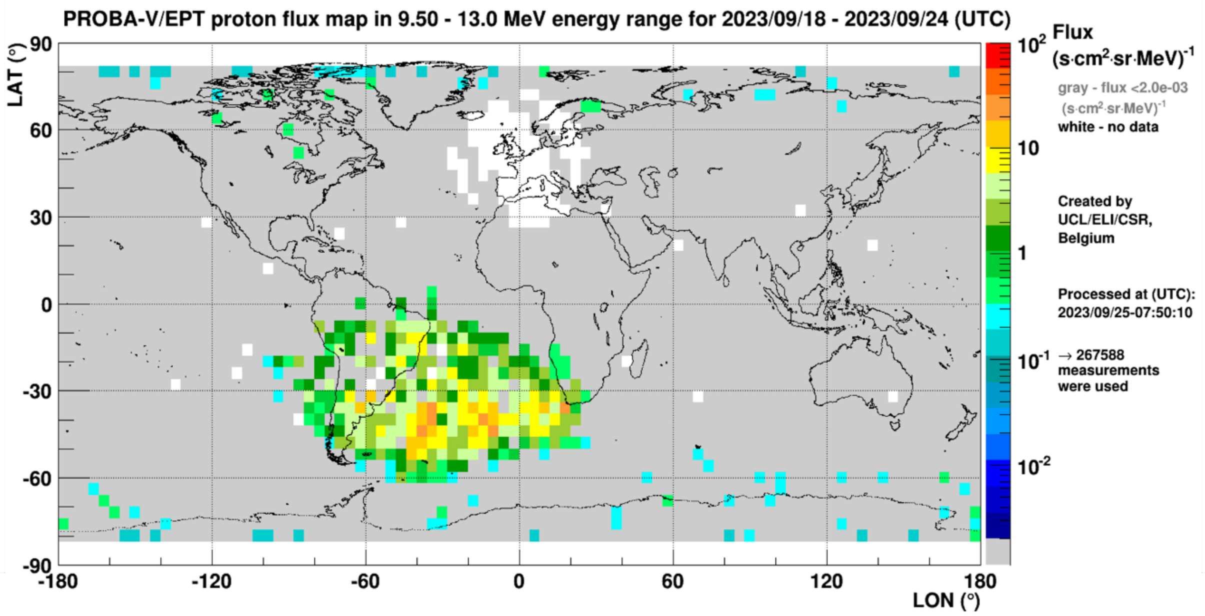
4.3.2 Technology Demonstration with a polar orbiting satellite

NorSat-TD is a Norwegian microsatellite launched in April 2023 to a polar circular orbit with the altitude of ~500 km. The NorSat-TD AIS receiver monitors maritime traffic in Norwegian and international waters via the Automatic Identification System (AIS), which all vessels above a gross tonnage of 300 are obliged to carry. The satellite also carries several test and demo payloads onboard. Concerning space weather impacts, the drag effects on the satellite have already been significant, decreasing the satellite altitude, and resulting in a need to adjust the orbit sooner than anticipated. Two relevant events affecting the electronics of the satellite have occurred in the last couple of months:

- 2nd of September 2023: The onboard bus-GPS on the satellite was affected by a current. This would normally have been quickly resolved by restarting the system. However, in this case, other circumstances resulted in this not being done until later. Around midnight between the 2nd and 3rd of September the satellite also was involved in a close approach event with another satellite. The probability of collision in this case exceeded 1%. On 3rd of September a geomagnetic storm hit the Earth. Had the storm been half a day earlier, this would probably have made the estimates less reliable and would have affected the ability to predict the close approach. This all would have taken place in a period with an outage of the onboard GPS.

- 23rd of September approximately at 13:45:26 UTC a latch-up affected one of the instruments on NorSat-TD. The event caused permanent damage to part of the payload. However, a workaround has been implemented that maintains close to full functionality.

The latch-up on Sep 23 occurred when the satellite was at the position: Lat: -57.06128098 Long: -36.83298879. In such cases it is difficult to pinpoint exactly the cause. However, based on the satellite location and space environment properties in that region one can get some indications on the probability of space weather causing the trouble. For that purpose, it is interesting to search additional information from the SWENET services which include measurements by particle and radiation instruments on-board satellites which were monitoring conditions in similar magnetospheric regions with NorSat-TD. Examples of relevant products are shown in Figure 18. The data of those products come mostly from the Proba1 and Proba-V satellites, which both are on sun-synchronous polar orbits. From their basis enhanced space weather activity may have had a contribution to the short-circuit event that NorSat-TD experienced on Sep 23. On that day the SREM instrument of Proba-1 measured radiation levels twice as high as in the average conditions. The proton flux map by Proba-V from the week of the NorSat-TD incidence shows slightly enhanced fluxes in the Southern Atlantic Anomaly region, which was in proximity of the satellite when the failure took place. Exact information on the mutual locations of NorSat-TD and the Proba satellites together with more accurate time information on the radiation and flux level variation are still needed for confirmed conclusions on the causes of the Sep 23 event.



Daily reports

Last updated on Sunday October 29, 2023 09:30 UTC

2023-09-22 | 20230923 | 2023-09-24

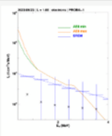
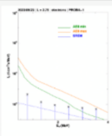
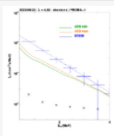
space region	#1	#2	#3	#4	#5	#6	#7	#8
	Proton belt	Proton belt	Slot region	Electron belt	Electron belt	Interplanetary	Interplanetary	Interplanetary
particle	protons	electrons	electrons	electrons	electrons	cosmics/protons	cosmics/protons	cosmics/protons
satellite	PROBA1	PROBA1	PROBA1	PROBA1	Integral	Integral	Herschel/Planck	Rosetta
L-range	1.2 ≤ L ≤ 1.3	1.6 ≤ L ≤ 1.7	2.5 ≤ L ≤ 3.0	4.0 ≤ L ≤ 5.0	6.0 ≤ L ≤ 7.0	see orbit	L2	no orbit available
status	on-going	on-going	on-going	on-going	on-going	on-going	mission completed	mission completed
radiation levels relative to								
AE8/AP8 min	-	0.1	0.0	7.0	-			
AE8/AP8 max	-	0.0	0.0	4.8	-			
SREM average	-	0.1	0.0	2.0	-	0.7	-	-
SEP alarm						no SEP	-	-
energy spectra	-				-	no SEP	-	-
SEP events						no SEP	-	-

Figure 18: Summary information on proton fluxes and radiation level around the day (Sep 23, 2023) when a short-circuit event took place on-board the NorSat-TD satellite. These summary reports are available in the SWESNET service (products R.113 and R.118).

4.3.3 Enduring operations of airport radars

On Aug 28, 2022, a solar radio burst caused strong disturbances in some operational aviation radar systems in Norway (c.f. Figure 19 and Figure 20). Because of a similar earlier event (Nov 4, 2015) which disturbed several radar systems in Scandinavia and led to a temporary closure of airspace in Sweden, both awareness of the problem and sensors for its detection had been established in Norway. This allowed the operators to quickly identify the source of the issue and handle it in a proper way. The airspace was not closed and there were no significant impacts on the flight schedules. However, the disruptions would have been greater if the cause of the disturbance was unknown, and if the false readings had a greater degree of overlap with the current traffic patterns. Avinor notes that the new technology in surveillance systems using Wide Area Multilateration (WAM), which was close to implementation at the affected location at the time of the event, is less affected by solar radio bursts. WAM does rely on transmission of signals from the aircraft transponder and appears to be less affected by stationary RFI sources such as solar radio bursts.

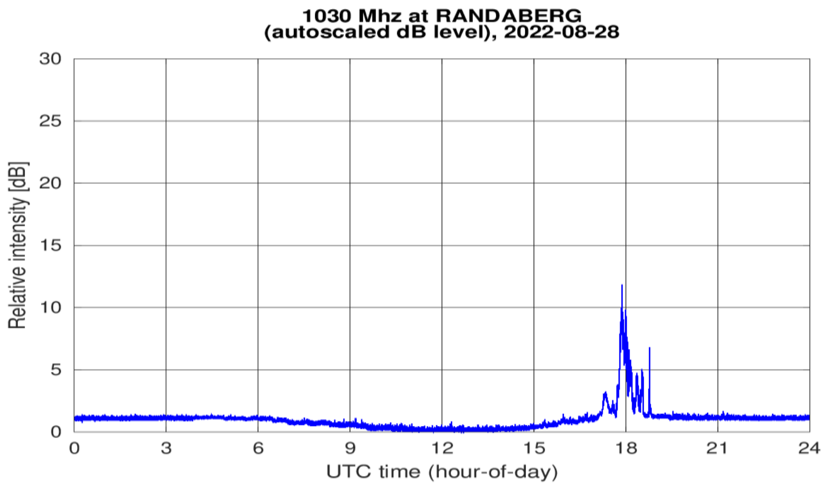


Figure 19: Time series plot from a scientific solar radio burst monitoring system, which is available to the system operations engineers in NRT and used as an important piece of information when determining the cause of the observed disturbances. This plot shows the observed radio noise for a frequency used by operational aviation systems [URL06]. https://sesolstorm.kartverket.no/radioburst/index.xhtml

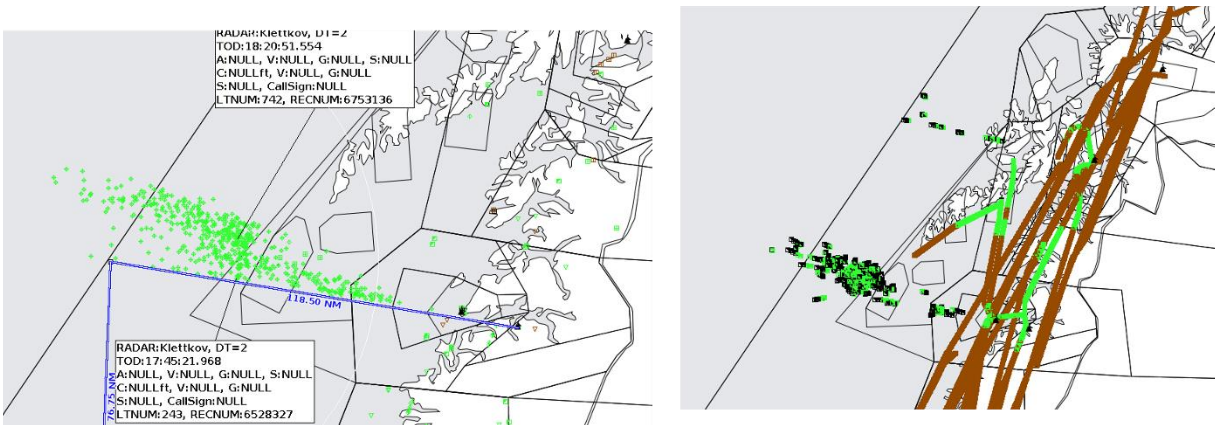


Figure 20: Impacts of solar radio bursts in airport radar systems. (left) Image from the Klettkov radar system (located at approximately 67° N, 15° E). (right) Image from the operative ARTAS system, which integrates information from several sources to form an overview of the air situation. Most of the radar echoes are not actual aircraft (Plots by AVINOR).

4.3.4 GNSS use in air navigation

Indra Navia as a company delivering air traffic management, is aware of the challenges posed by space weather to aviation. GNSS is used extensively in air navigation, in all phases of the flight. It is well known that space weather may affect GNSS signals in several ways, creating extensive local or regional signal delays, or excessive noise on the signal. This can affect the performance of the navigation service in various ways, depending on how the service is provided (standalone GNSS, or with Satellite Based or Ground based Augmentation, SBAS or GBAS respectively), and the nature of the ionospheric disturbance. The usage of GNSS is safety critical during all phases of the flight. Therefore, if the navigation performance deteriorates below the required level for the specific operation, the pilot must be warned, so that appropriate action can be taken to keep the aircraft, passengers, and crew safe.

The safety requirements to the navigation infrastructure, including the required time-to-alert, are too strict to include a human in the loop. There are also some formal safety requirements on the information that can be used to act. This generally prevents external services like space weather forecasts from being used directly with navigation receivers to maintain safety. The receivers and the facilities providing the navigation services onboard aircraft must have built-in ionospheric monitoring capabilities guaranteeing that the actual ionospheric impact at the location of the receiver is adequately monitored in NRT. The main impact of ionospheric disturbances (space weather) for aviation is decreased availability of the GNSS services, as they are considered not sufficiently trustworthy when disturbances are detected. Also, due to the strict monitoring requirements, and required safety margins, the availability of GNSS is often impacted even if the ionospheric disturbances are quite moderate. In other words, when space weather disturbs the performance of the GNSS service beyond what is tolerated, the pilot instantly loses navigation guidance.

When the GNSS service is lost, pilots must revert to alternative navigation procedures. These typically rely on conventional, ground-based navigation sources. They are generally very robust but limited in their flexibility in terms of flight procedures. This requires pilots and air traffic controllers to revise flight plans, to go through comprehensive replanning of briefings, and to reroute numerous aircraft. As the rearrangements cause increased workload and potential delays, both pilots and air traffic controllers would benefit from the preparedness that space weather warnings and forecasts could provide. With such information correct routes and procedures could be provided to pilots pre-flight, allowing them to prepare for the relevant route and procedures up-front. It is also a fact that when highly automated services such as GNSS are very reliable, pilots become less and less accustomed to using the fallback procedures. Therefore, pilots being prepared to use the fallback procedures already prior to their flights would be an additional factor enhancing safety in aviation.

4.4 Operating power networks under the auroral oval

In August 2023 ESA organized SWESNET user meetings with Fingrid and Statnett. Representatives of our project were kindly offered the opportunity to participate in these meetings. Their discussions revealed that both companies have versatile knowledge on the risks which Geomagnetically Induced Currents (GICs) can pose to the stability of power networks. This knowledge is based on comprehensive research work pinpointing the vulnerabilities in current technologies and it motivates the search of new more persistent solutions. Both companies use expertise by national research institutes in space weather data interpretation and impact assessments. Forecasts of space weather events enhancing the likelihood of high geoelectric field and GIC values would be welcome. It is recognized, however, that generating forecasts with useful lead times and actionable certainties is not possible with the current observation capabilities and knowledge on the underlying physics. Coordination on international level among the companies maintaining the main grids is considered important with the goal to establish standardized approaches for improved preparedness in the prevailing situation where networks of different countries are coupled with each other.

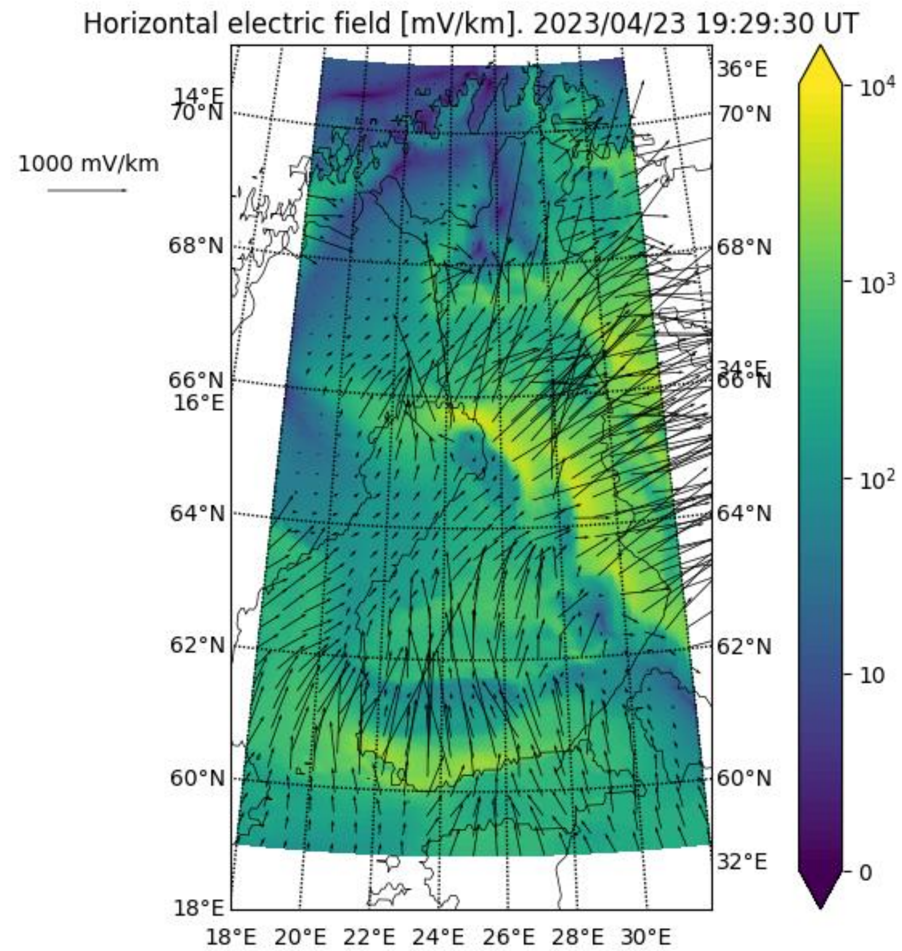


Figure 21: A map showing the estimated spatial distribution of geoelectric field by the method developed and maintained at FMI (Plot by Elena Marshalko, FMI).

As an example of a GIC risk assessment study, we describe here briefly collaboration between FMI and Fingrid where the former uses its data and models to create maps of the geoelectric field which the latter uses as an input for simulations of GIC in its power network. With this arrangement, Fingrid gets accurate GIC estimates without releasing any data on its network properties outside the company. The maps of the geoelectric field are obtained with the use of a novel approach suitable for real-time calculations. It exploits a) the concept of multi-site transfer function that relates the geoelectric field at any location with horizontal magnetic fields at a fixed number of locations, b) synchronous magnetic field measurements at multiple sites in the region of interest, c) conductivity model of the region of interest, and d) spatial modes describing the equivalent ionospheric current behaviour. Figure 21 demonstrates the geoelectric field distribution in Finland and surrounding areas at the time of the peak amplification of the geoelectric field in the region during 23-24 April 2023 geomagnetic storm. Figure 22 demonstrates the comparison of measured and simulated GIC at one of the GIC recording points in the Finnish power network during the same event. The comparison shows that the new approach gives promising results for estimating the overall behaviour of GIC in the network during different types of space weather activity including very strong geomagnetic storms.

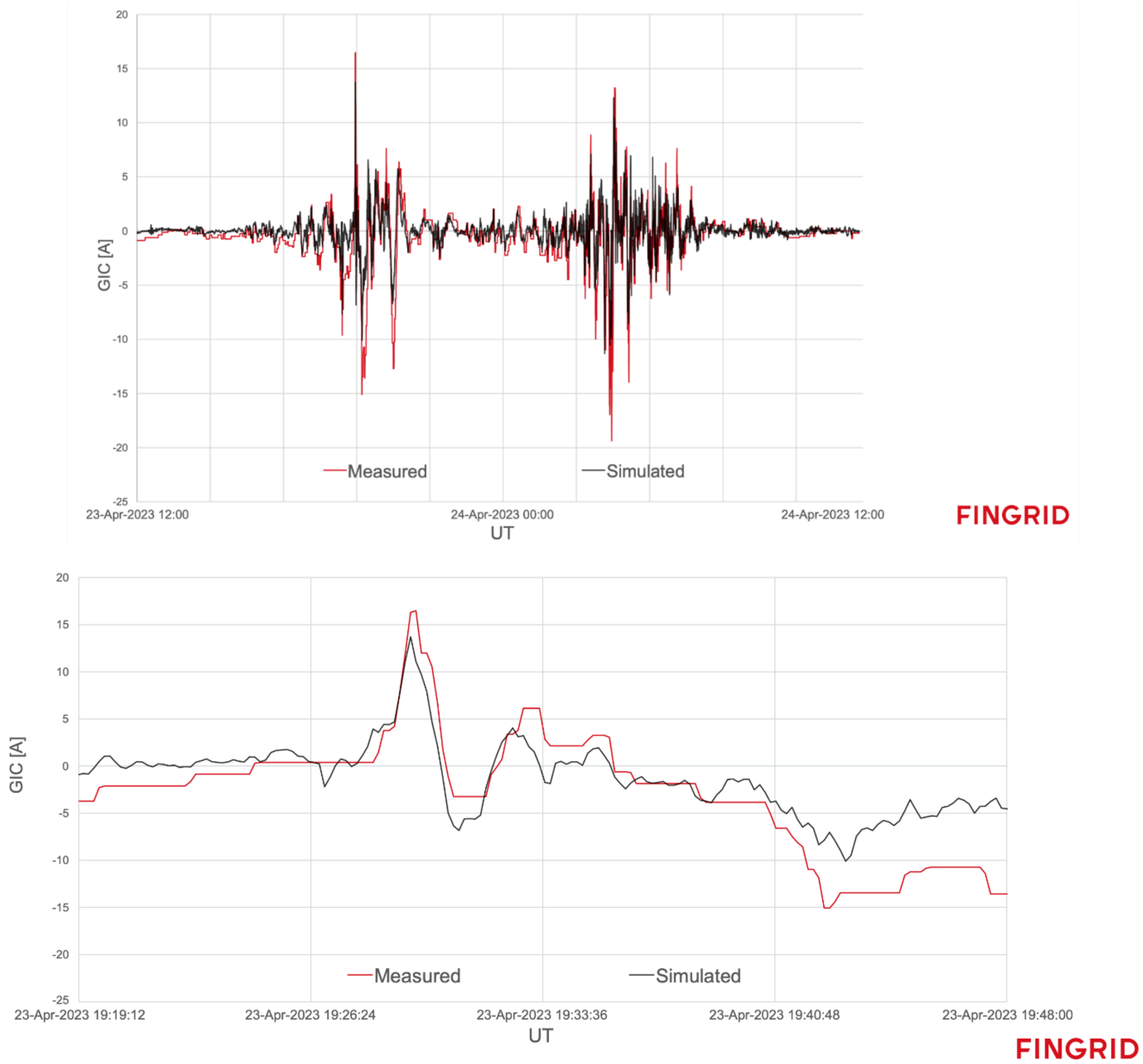


Figure 22: Measured and simulated GIC at one of the GIC recording points in the Finnish power network. Upper panel: the whole modelling interval (23 April 2023, 12:00 - 24 April 2023, 12:00 UT). Lower panel: a closer look on the 23 April 2023, 19:29:30 UT GIC peak (Plots by Fingrid).

4.5 Sustainable tourism development

Visit Lofoten is heavily investing in accommodation and visitor planning. The destination must distribute the tourist flow throughout the year to preserve nature and Visit Lofoten intends to utilize solar activity in this regard. Lofoten already has aurora tourism, but currently the region is not one of the biggest aurora destinations in Norway. Lofoten on the other hand, is a destination that has the potential to develop this type of tourism on a much larger scale than is the reality today. Tromsø, which is located a good distance further north in Norway, has over several years had far greater tourism within this segment than is the case in Lofoten. Visit Lofoten has worked for many years with housing and visitor planning and has now concretized the plan to increase the number of visitors from both the interior and abroad.

The company has plans to increase the number of tourists visiting in the winter season, and in this venture the northern lights are a prerequisite for the success of the venture (c.f. Figure 23). Visit Lofoten is aware of increased activity from the Sun in the coming years and is prepared for the peak to come. In this regard, the company has major concrete plans to utilize the increased activity from the Sun to the best of its ability and considers the solar activity as a resource that can attract more tourists to northern Norway. Lofoten has 54% free capacity in the "northern lights season" and has not previously utilized the possibility of solar activity in the season to the same extent as many other northern Norwegian destinations have done, but now the company has plans to do so in the future.

The investment in auroral tourism coincides with one of the biggest developments Visit Lofoten is working on. The development involves, among other things, getting fixed flight routes to Lofoten and work is being done with large international groups, such as Lufthansa, to get a winter flight as early as the winter of 2024-2025. To succeed in putting such a flight route in place, the company is working on all positive things that can increase the motivation for the airlines to add scheduled flights to Lofoten. An important factor in this motivational job is the information about the solar activity peak which is approaching.

If Visit Lofoten succeeds in their plans for winter flights in the winter of 2024-2025, the destination envisages local value creation of around one billion NOK. Northern Lights tourism and air routes to Lofoten will be one of the main points in the effort to become an all year around tourism destination and basis for sustainable destination development.

Today Visit Lofoten has a two-part challenge which they must solve with the good help of the tourism during the the northern lights season:

1. The destination does not have the capacity to handle the amount of tourists who come to the destination during the high season, as for now is during summertime.
2. The destination must be able to offer the local population a good offer such as infrastructure, bus transport, shopping opportunities all year around. The offers to the local population must be financed by the income from tourism.

Visit Lofoten must therefore spread tourism evenly over the year to satisfy the needs of the local population for society. And on the other hand, have enough capacity for the tourism.

The plans of Visit Lofoten have a major impact and consequences for those who live in Lofoten and, in addition, the development also has major consequences for other industries. When the destination gets winter flights to Lofoten in place, it will be important to get bus traffic and a good public transport service in place that both benefits the tourists, but also the local population, and one envisages a public transport route that is financed by tourism, but which the local population enjoys well off.

Figure 23: Auroras above the Lofoten islands (Photo: Jelle Dobma).

5. Feedback from the user interviews and other national discussions

5.1 Civil sector

As the use cases presented above show, the Finnish and Norwegian Partners contacted for this survey are familiar with the topic of space weather and its impacts on their services. However, it became clear from the interviews that SWESNET has not yet established its position as the primary source for information on space weather activity. Support in space weather impact assessments is typically searched from national research institutes which analyse the cases of interest from the basis of their own assets and external sources including e.g., SWESNET and SWPC/NOAA. It is recognized that ESA is actively increasing the awareness on SWESNET capabilities by user manuals, tutorials, and dedicated training courses [URL05] which will gradually facilitate users' direct harvesting of the services. The need for support on a national level will in any case remain simply because of language issues. Learning unfamiliar matters is much easier with guidance on your own mother language.

In the context of this survey the following comments and ideas came up from the discussions with the Partners and among the project team.

<u>The challenge of increasing awareness among the downstream service users:</u> After several conversations with a selection of both end users and providers of positioning services in Norway, there is doubt about how aware RTK users are that a solar storm could cause troublesome measurement conditions or poor measurements/positions. When we look at the statistics on the number of RTK users in Norway and at the same time observe the usage of the Norwegian Mapping Authority's solar storm service [URL02], the login activity there is small in relation to the number of RTK users. In addition, we cannot see greater use of the space weather service during periods when solar storm activity is high. These findings give us a reason to believe that there is generally little knowledge about the issue among users of satellite-based services, and there is a need to increase awareness of the issue among them. For the providers of positioning services, who offer first-line support to the users, it is generally difficult to bring up these issues as they sell the equipment and do not want to say much about the problems in the fear of bad reputation and reduced sales.

<u>Integrating space weather information to already existing systems:</u> As RTK users need information about the quality of positioning services often when working on field (c.f. the cases of Findmy and Maskinstyring), the web-interface by SWESNET is not an optimal solution for their purposes. The Application Programming Interfaces (APIs) offered by some of the products is a step towards correct direction, but not enough. In an ideal situation space weather information should be integrated to the same system that is used on the field for positioning. Obviously, such an arrangement would imply close collaboration with the companies providing the positioning services. A clear certified correlation between space weather activity as prompted by SWESNET products and problems in the positioning system of interest will be a crucial factor motivating commercial actors to make the necessary modifications to their systems. Finding the resources for demonstrating the correlation with broad enough statistics may be a challenging task, as the topic is somewhat outside of the main interests in the commercial sector.

Contributions and expertise on SWESNET side would also be necessary in the integration mission described above. As the network contains several products that are addressing partly the same space weather phenomena and thus have potential to serve as performance indicators for the selected technology, there is a need to find some consolidated solution for seamless co-operation between the two systems. The SWESNET product I.138, GNSS Performance Indicator (GPI), could be considered as a prototype for such collaboration, but its correlation with technology impacts most likely needs still some additional work. As an example, Figure 24 below shows GPI time behaviour around the day (Feb 27, 2023) when the RTK systems in Finland and Norway experienced some problems around noon (c.f. Section 4.1). This test exercise reveals that I.138 shows systematically compromised GNSS performance during dark times, but the daytime disturbances on Feb 27 were probably too localized and short-lived to be spotted by the product. However, we want to point out that in our example the prototype was used with its default settings. An advanced user may be able to fine tune the settings for a more accurate performance.

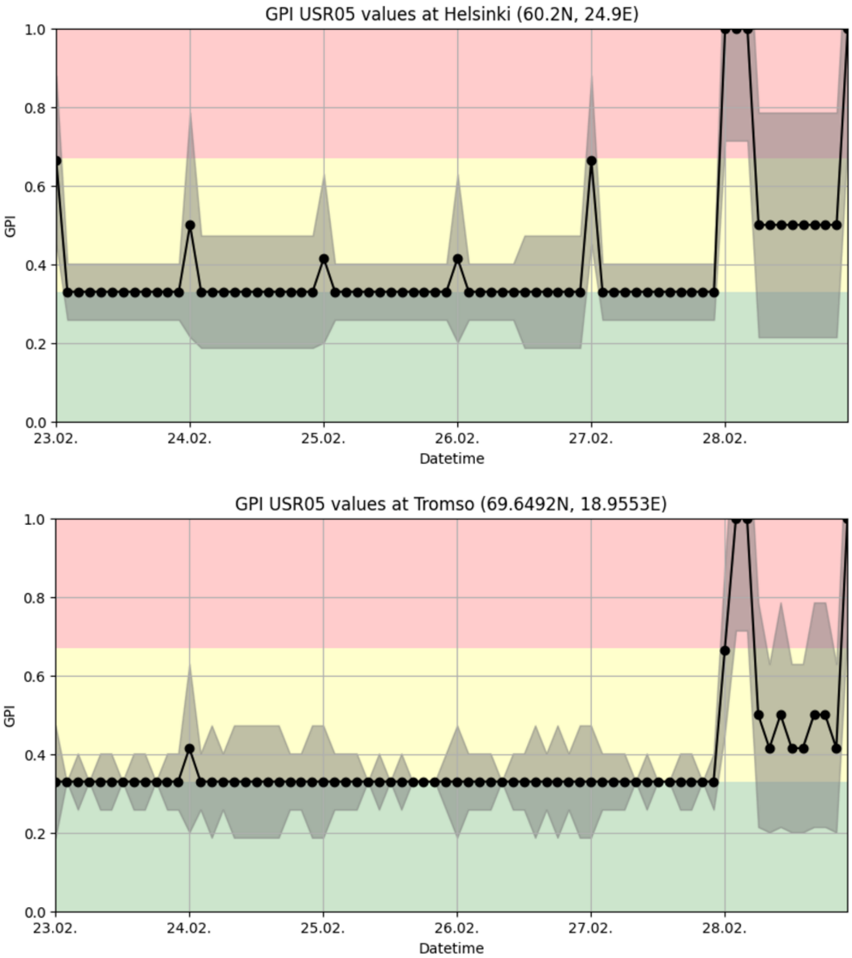


Figure 24: Times series of GPI values (SWESNET product I.138) during the last days of Feb 2023 for (top) Helsinki and (bottom) Tromsø. Larger GPI values correspond to more disturbed conditions. GPIs are accompanied with estimates of their uncertainty which are shown here with the grey shadings.

Excluding the possibility of hostile activity: During failure situations or anomalous behaviour in operational systems where the error source appears to be external, and especially if there is Radio Frequency Interference (RFI), the operators are faced with the question of why this is happening and who or what is causing it. Particularly at airports it is important to determine the cause quickly for further measures to be taken. Can the system still be used? And is there a need to restrict air traffic? Are examples of questions that should be solved promptly. A current concern is intentional hostile acts of jamming to degrade or disable operational systems. By recognizing quickly that the source of RFI is space weather such suspicions can be dismissed, and the systems declared "healthy" much faster. It is also a benefit during normal quality controls that discrepancies in quality, such as false tracks from a radar system, can be attributed to space weather and not to quality issues with the equipment itself or noise sources in its immediate surroundings.

On space weather side a typical source of RFI is a solar radio burst, which can cover a wide frequency range including frequencies of GNSS and airport secondary surveillance radars. Information on solar radio bursts in SWESNET is provided by the e-Callisto system of solar radio telescopes (e.g. product S.105b). As the spectrograms by e-Callisto give comprehensive information over wide frequency ranges, they serve their purpose well from research viewpoint. However, from SWESNET user viewpoint it would be valuable to have an easy way to get information only on the frequencies of the impacted systems (c.f. the example of Figure 19).

Some more specific suggestions by the Partners of this project:

- More accurate estimates on ground conductivities are critical for improved estimates of geo-electric fields to be used in GIC calculations. Forecasts of space weather events enhancing the likelihood of high geoelectric field and GIC values would be welcome.
- From satellite flight dynamics perspective, getting historic and predicted trends (at LEO altitudes of 300-600 km, where applicable) of the following products would be useful. The trends would be nice to get visualized by charts via the website Graphical User Interface and with backing data retrievable via API.
    - Solar Activity in terms of Sunspot # and Solar Flux Units (SFU)
    - Kp index
    - Proton & Electron Flux Levels
    - TID
    - Atmospheric density

5.2 Military sector

Military forces have long been affected by space weather, as they make heavy use of several different types of radio-based communication. Todays armed forces typically have a high degree of networked information flow in which several different systems are integrated into complex solutions to maximize the operational usefulness of information. Various communication systems use frequencies from the ultra-low (ULF) to the extremely high (EHF) frequency bands. Systems may utilize this for line-of-sight, over-the-horizon or satellite-based communication. Information regarding the concrete impacts of space weather on specific systems is generally not available in unclassified form. However, it is generally known that radio frequency (RF) communications can be affected by space weather. Knowing whether space weather is the cause of observed disruptions, or if there is another cause (e.g. jamming), is of high interest. Having forecasts of conditions is also of high interest to take space weather into account during planning of operations.

By the treaty of its foundation ESA's purpose is to promote, for exclusively peaceful purposes, cooperation among European States in space research and technology and their space applications. Therefore, the target of SWESNET is to provide space weather information for its civilian users. The need for coordination between civilian and military oriented space weather services is recognized on both sides as there are clear synergies e.g. in maintenance of some key infrastructures (e.g. space-based observations of solar activity) and in harvesting of their data. With this background we present below some public general level statements by the Norwegian and Finnish Military forces on the relevance of space weather services in their activities. Obviously, these statements are not linked with SWESNET products as closely as the feedback and examples given above, but they may contain some interesting viewpoints that can be used e.g. to support ESA aspirations concerning the Distributed Space Weather Sensor System (D3S).

5.2.1 National preparedness in Norway

It is important for the Norwegian Armed Forces that there is a national capability for space weather monitoring, encompassing sensors, services, and competence. This should be as far as possible be a civil task with a civil-military cooperation, so that civil society also benefits, and duplicate efforts are avoided. It should be complimentary to the data and services available from international sources and focus especially on the local impacts. This is of obvious benefit for the national forces, but there have also been several instances where allied forces on exercises at high latitudes in Norway have benefited from the additional support from local sensors and knowledge.

During several recent national and NATO exercises, the Norwegian Armed Forces have had a co-operation with the national space weather community to provide daily space weather forecasts. Having an expert-in-the-loop during space weather events is ideal, as the interpretation of the total space weather situation is challenging for non-expert personnel. In the frame of NATO space weather is an important topic for the NATO Space Working Group, in which most member countries actively participate.

In November 2022, the Norwegian Government asked the Chief of Defence for his recommendation for how the Armed Forces should look in the future. The official response from the Chief of Defence has been published on the Internet [URL03]. In the same year the Government also appointed the Total Preparedness Commission to survey Norway's overall preparedness with the task to encompass both civil and military parts of society. The Commission delivered their report in 2023 (available in Norwegian, [URL04]). The Chief of Defence foresees the space domain to become increasingly important for the Armed Forces. Therefore, Armed Forces' capability for operations in the space domain must be strengthened, and the Chief recommends further developing and strengthening the ability to plan, execute and coordinate operations in space. Furthermore, the Armed Forces must have the ability to understand the situation in space, also in cooperation with civilian authorities and international partners. One of the topics addressed in the Total Preparedness Commission report is satellite-based services. Specifically, on the topic of space weather in relation to satellite-based services, the report states (translation):

"The commission has noted that the national responsibility for continuous space weather warning services has not been assigned. As seen in table 21.1, space weather can, at short notice, have significant consequences for functions that are important for society. The commission is of the opinion that it is necessary to establish the responsibility for such a service so that relevant parties can be informed in a timely manner. This will contribute to the reduction of consequences and avoid misunderstandings regarding the cause of events. It has also been pointed out the need to define and establish warning services for near-Earth objects, and to investigate the need for national situational awareness in the space domain."

5.2.2 National preparedness in Finland

In discussions among several ministries, including the Ministry of Defence, it has been recognized that disruption-free functioning of society and securing its well-being depend to an increasing extent on space activities and satellite-based services. These services support the work of the Defence Forces among other authorities maintaining critical infrastructures. The importance of space activities in safety, security and defence policies increases and the amount of commercial space activities grows. With this background it has been concluded that a national space situational awareness centre would allow the authorities, including the Defence Forces, to receive an up-to-date situation picture as well as early warnings of threats posed to Earth by space and space activities. A steering group was established in October 2022 with the goal to make review on the necessary preparatory work and a set of recommendations for the establishment of the Finnish Space Situational Awareness Centre (FSSAC). The group presents a plan for the centre establishment and recommends that the operations could be started by 2026.

Finland acknowledges the EU recommendation for national Space Situational Awareness (SSA) centers to cover both civilian and military users in their services. Dual-usage of SSA services is a cost-efficient way forward for Finland because some already existing organizational structures can be utilized in FSSAC operations. The steering group foresees the civilian and military sides both have their own mission statements and governance solutions, although close collaboration between the two sides is expected for unified SSA resolutions. The main task on the military side will be maintenance of the Recognized Space Picture (RSP) which will require collaboration with international entities conducting similar tasks. For NRT knowledge on space weather conditions both military and civilian sides will use mostly the same national and international data sources.

6. Conclusions and future prospects

In this project we have interviewed both authorities and operators of critical infrastructures in Finland and Norway with the goal to collect concrete examples on space weather impacts in their everyday operations. Solutions for enhanced preparedness against space weather risks by the ESA SWESNET products have been a central topic in our discussions with the aspiration to widen the user engagement in the future development of the network services. Our project with its examples from Finland and Norway can be considered as a pilot for a broader initiative on European level where the awareness on space weather with its hazards is recognized as one of the main elements in the Protection of Space Assets theme under the European Space Accelerators partnership. Informing mid-European authorities and operators on space weather risks is important, because storms appearing at their latitudes are rare but very intensive.

Contents for this project have been collected mostly by representatives from FMI and NMA. Both these institutes are active partners in the maintenance of several products in SWESNET and they have central roles as space weather service providers in their own countries. Topics and products familiar to these two institutes may be somewhat over-represented in this report, but it is anyway fair to state that during the project its team members have gathered plenty of new experiences in usage of SWESNET with its pros and cons. Therefore, the main conclusions that we summarize below are not based just on the feedback that has been collected from the project Partners. They also contain views from the team members as experienced service providers:

Serving users with different levels of awareness: In its current form the SWESNET web-interface is very research oriented, which is understandable as space weather scientists have had a central role in building the service. The number of products is impressive, but the products are partly addressing the same impacts and their naming have roots in research codes which in many cases are cryptic. For a beginner in the field, it requires some amount of persistence and motivation to get so familiar with the network that its usage becomes fluent. The other side of the coin is the wealth of information that the network offers. A standardized API which is common for all products and accompanied by detailed guidance for all the most widely used operation systems would be a welcome treat for advanced services users. Several users have noted their desire to acquire notifications (e.g. by SMS or e-mail) with user-configurable thresholds. With APIs this would be possible with reasonable effort.

Stability of the system and easy access: It is noted that ease of access to information is very much valued by most users. The data presentation should be usable for them and immediately available when they open the webpage. Any additional steps are a barrier to usage. In an optimal arrangement, even a non-experienced user should get by his/her first glance without any registration the knowledge whether there is a storm ongoing or not. Breaks in the products' availability can be tolerated in pre-operational services, but they should be avoided in the future 24/7 fully operational service. It is unclear whether the approach of federated services running in several computers with varying maintenance levels is a feasible solution for the future fully operational services.

Tailoring of the products according to user needs: How far SWESNET should go in tailoring its products is a strategic question to be addressed in the transition from pre-operational to fully operational services. Should tailoring be left at least in some cases to national service providers or to the commercial sector? Discussions directly between research institutes as product providers and the user representatives would ensure transparency in communication and flexibility in the management of minor changes of the products. Based on our discussions with RTK applications users, their awareness of space weather impacts and access to NRT information is limited. For field experiments, it would be good to have space weather information integrated into the applications used for accurate positioning. Clearly, such a job cannot be conducted in the SWESNET framework alone as collaboration with the commercial RTK provider sector is needed. In the cases where tailoring is conducted outside SWESNET, the centralized network would still have a crucial role in providing certified input data for product generation and professional user interfaces by graphics and APIs.

Quality versus quantity: Instead of expanding SWESNET with new products, the next steps in network development should focus on improving the quality of its user interface. Luckily such a trend is already visible in the most recent portal releases of SWESNET. Many aspects of this upgrading work are mentioned already above: General level, easily adoptable information on prevailing space weather activity should be available for the users without registration. Homogenizing the products with their APIs and with the web-interfaces for archived data would be a welcome improvement. Consolidated information from products addressing the same processes in space weather should be offered. First attempts in that direction (e.g. I.138) show that building products that harvest a collection of other products is not straightforward in the current SWESNET framework.