THE ARTIC SPACE WEATHER DEMONSTRATOR IN THE EUROPEAN ACCELERATORS PROGRAMME

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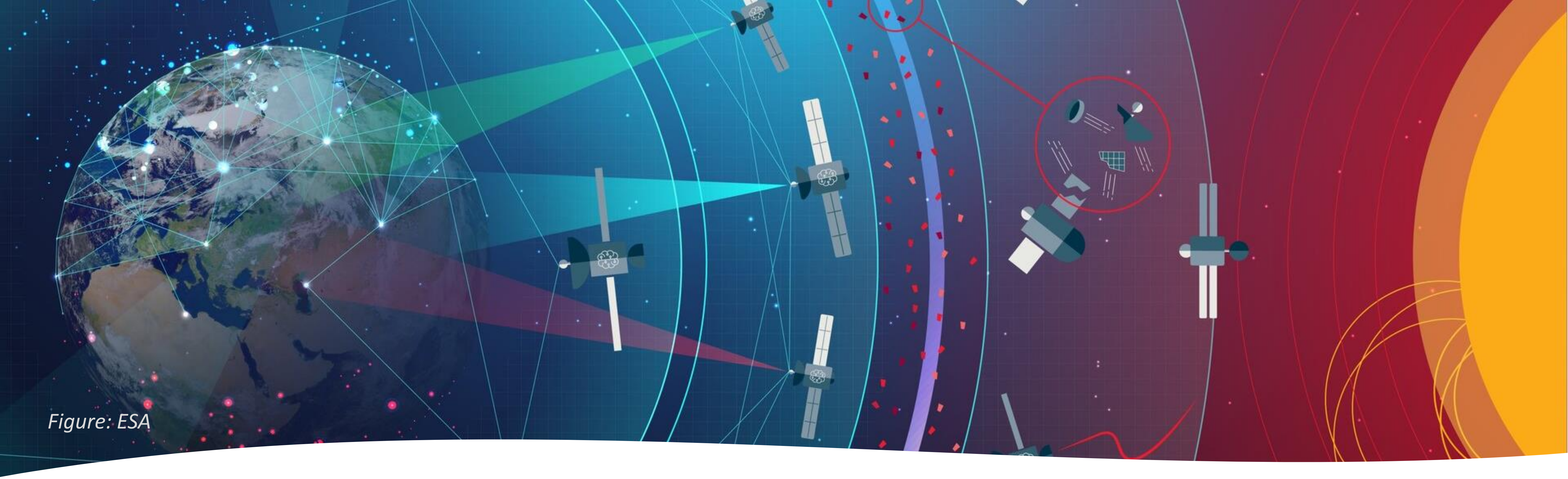
Matosinhos Manifesto: resolution adopted on 19 November 2021 at ESA's Intermediate Ministerial Meeting in Portugal

- To recognize and utilize the strength of a united Europe to deliver services to its citizens by accelerating space for the betterment and advancement of its people and of the planet overall.
- The European space sector is accelerated under three Thematic priorities
- Through the Accelerators, partners will:
  - Set the goals to drive and **accelerate the use of space** to tackle global challenges;
  - **Build synergies** across their objectives, action plans, and instruments;
  - Identify areas of mutual interest and opportunities for **impactful cooperation**;
  - Contribute effectively to the development and scale of **proven space solutions**.

Space for a green future

Rapid and resilient crisis response

Protection of space assets



Protection of space assets

- Utilisizing the capabilities under development in the ESA Space Safety Programme
  - Zero Debris approach
  - ESA pre-operational Space Weather services
- Arctic Space Weather Demonstrator:
  - Goal: Enhance user engagement
  - Why Arctic? Space Weather events are frequent and thus effecting every day operations
  - Timeline: October 2023 – Jan 2024

User engagement: Partners in the Demonstrator

GNSS as system impacted by Space Weather

- Known problems in GNSS performance
  - **Ionospheric delay**: can be tackled with augmenting services
  - **Scintillation of the signal**: More difficult to handle
- Monitoring of small scale ionospheric structures and consequent scintillation can be done with specific scintillation receivers with high sampling rates (50 Hz).
- High resolution (50 Hz) receivers are used to derive parameters that characterize the the strength of scintillation in amplitude (S4) and in phase (σ_ϕ).
- Standard resolution receivers are used to derive Rate of TEC and Rate of TEC index (ROTI) which also characterize rapid variations in the ionosphere
- TEC= Total Electron Content (TEC unit = TECU = 10^{16} electrons/m^2) can be derived from the geometry free phase combination of L1 and L2 signals.

S4 (dimensionless): Standard deviation of L1 carrier S/N computed typically determined with 1 min resolution

σ_φ(rad): Standard deviation of de-trended L1 carrier phase typically determined with 1 min resolution

ROTI (TECU/min): Standard deviation of rate of TEC typically determined with 1 or 5 min resolution

GNSS as a system supporting Space Weather monitoring

- The geometry free phase combination of L1 and L2 signals can be used to derive Total Electron Content along the signal path from the satellite to the ground-based receiver.
- Slant TEC (STEC) is TEC along the path
- Vertical TEC (VTEC) is STEC converted to TEC along a vertical path with a geometric conversion factor
- Ionospheric Piercing Point (IPP) is the point where the signal crosses the ionosphere at ~350 km altitude

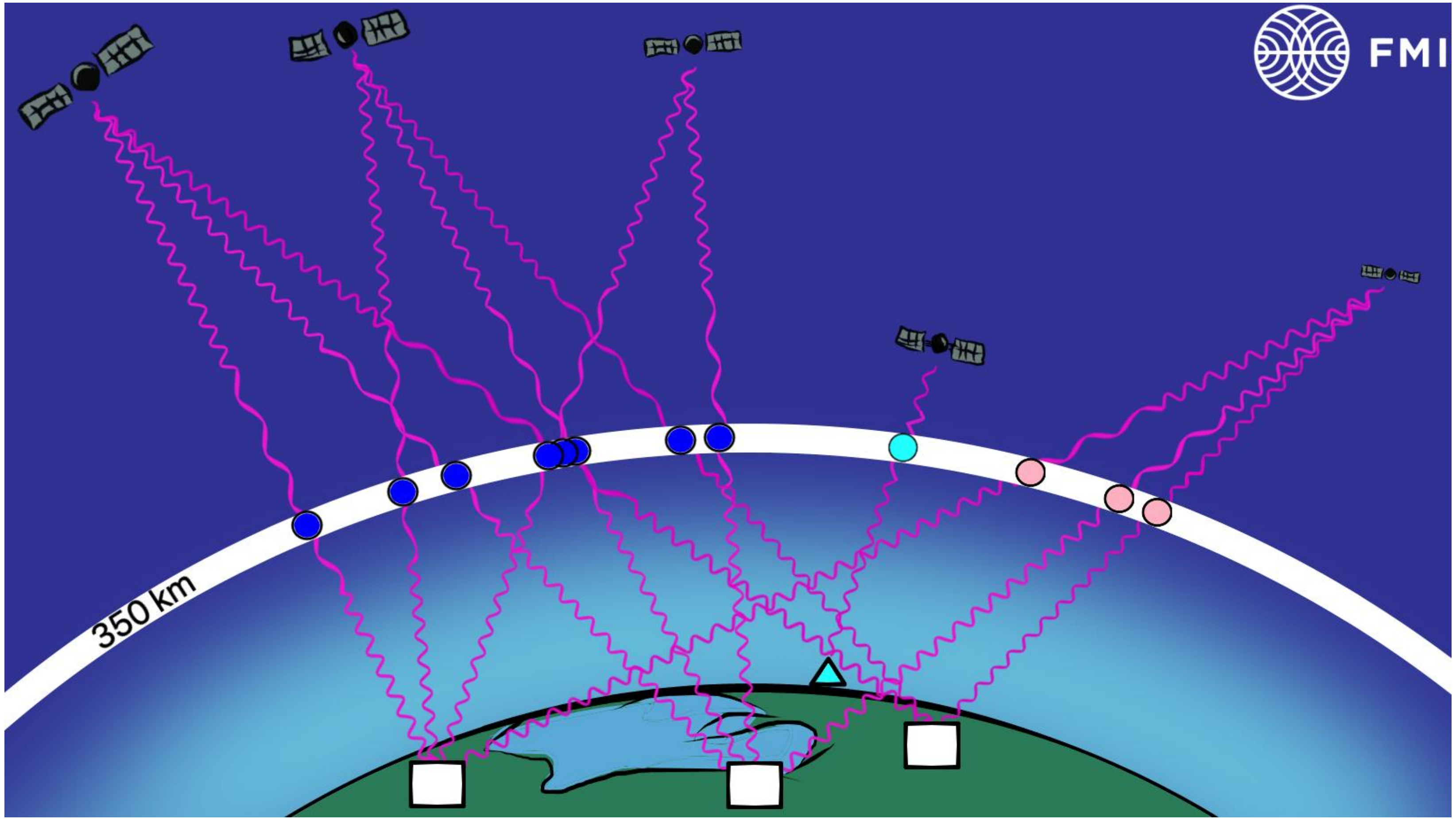
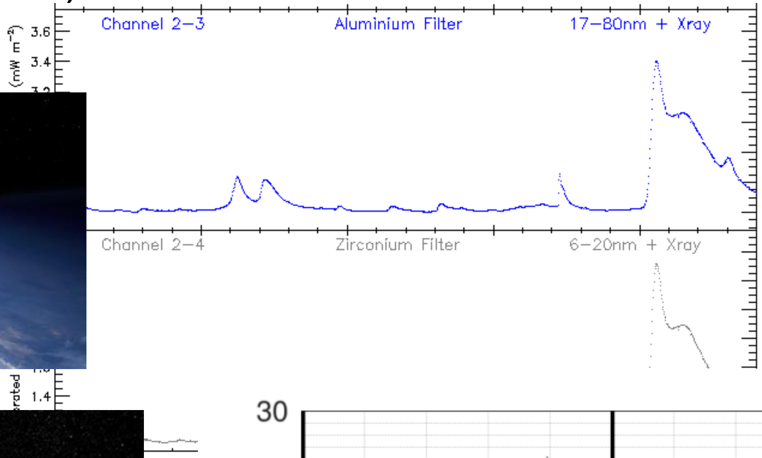
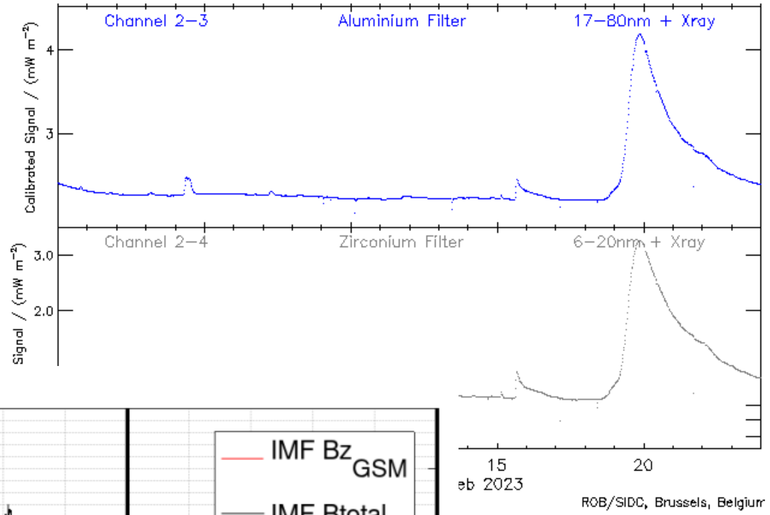


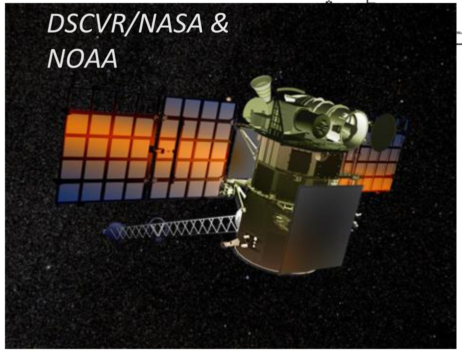
Figure: Johannes Norberg, FMI

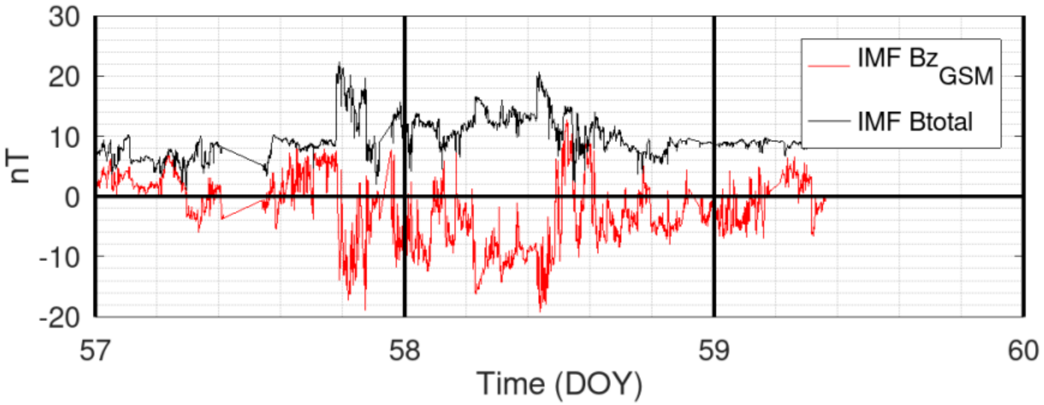
Space weather storm on Feb 26-27, 2023

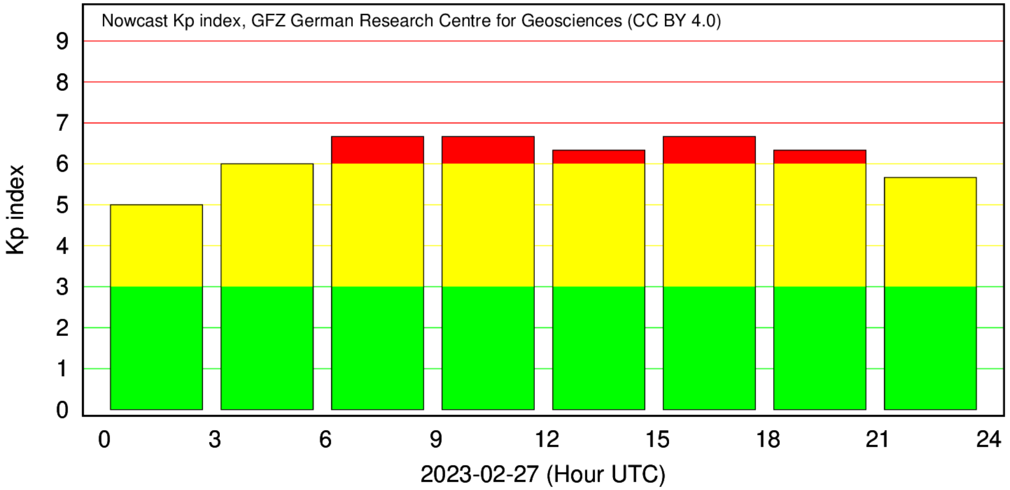
- Two solar flares on Feb 24 and Feb 25→
- Impact by two combined Coronal Mass ejections →
- Geomagnetic storm during Feb 26-Feb 28→
- Disturbed ionosphere

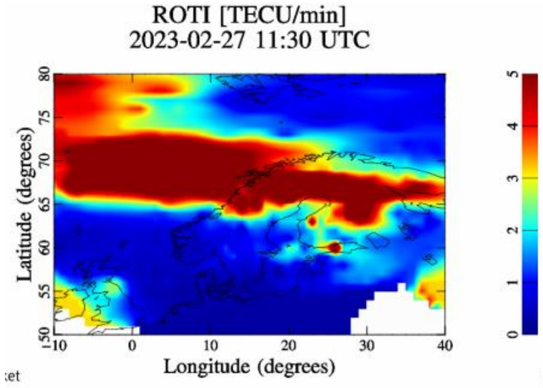


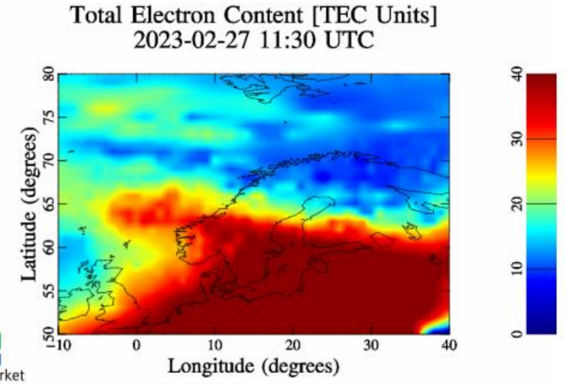




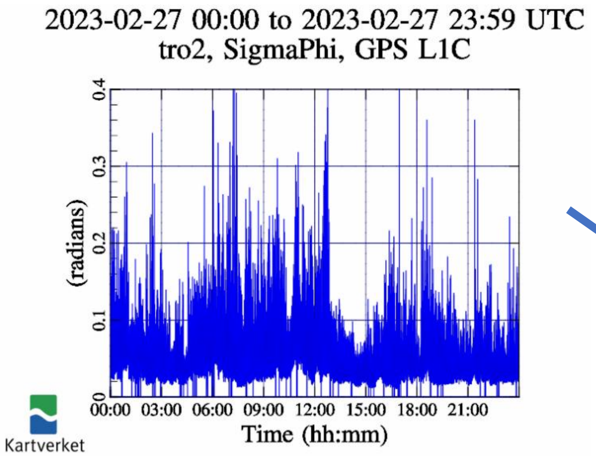


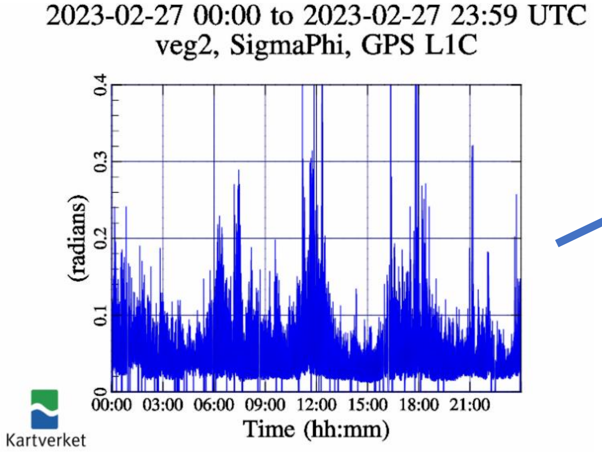


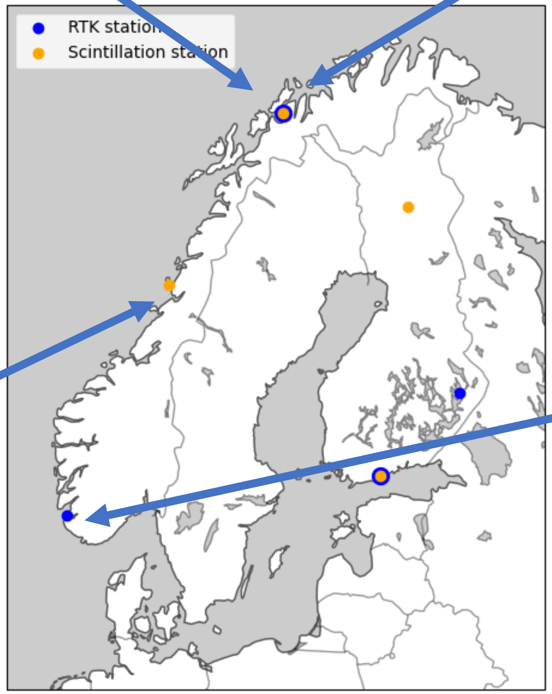




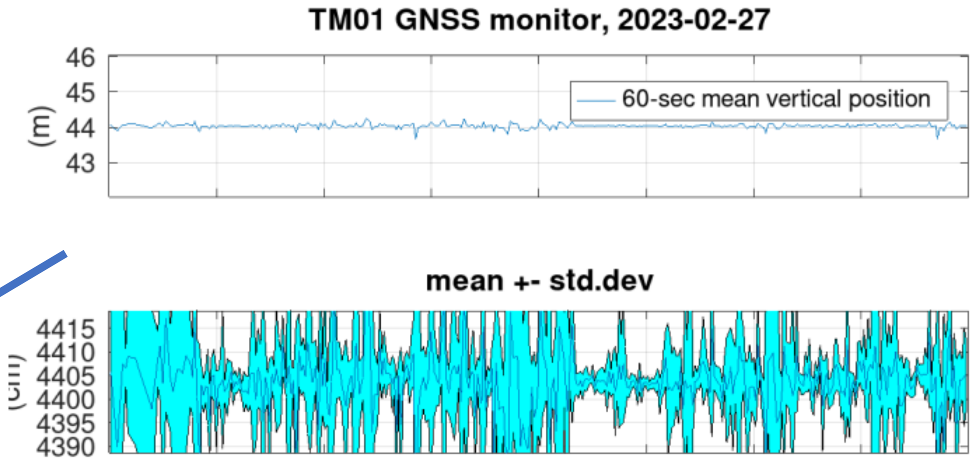
Impact in accurate positioning around noon on Feb 27: Norway

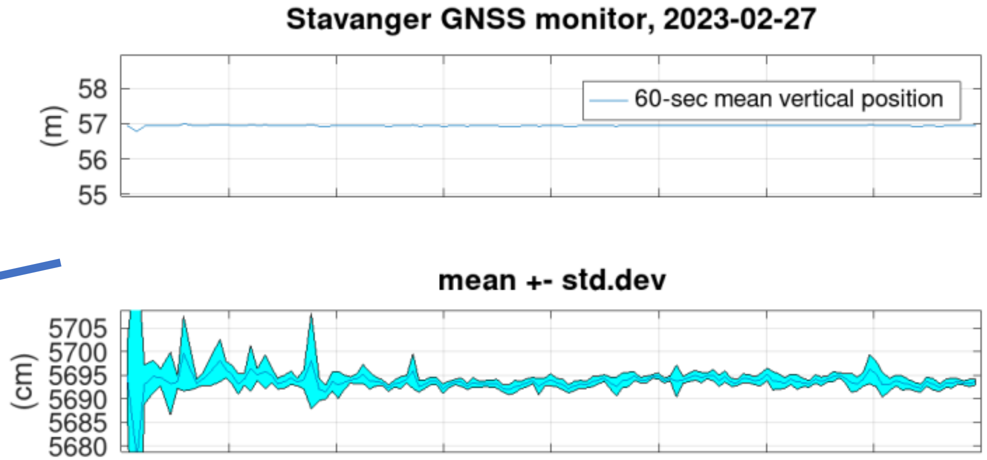




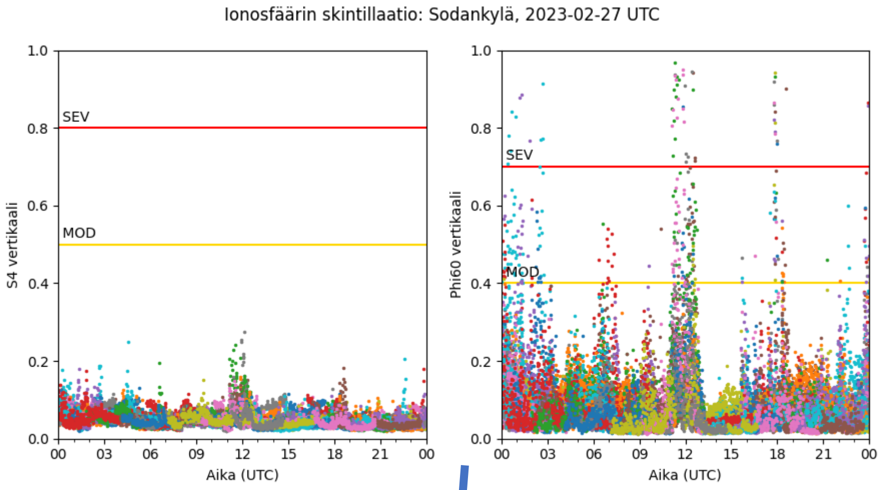


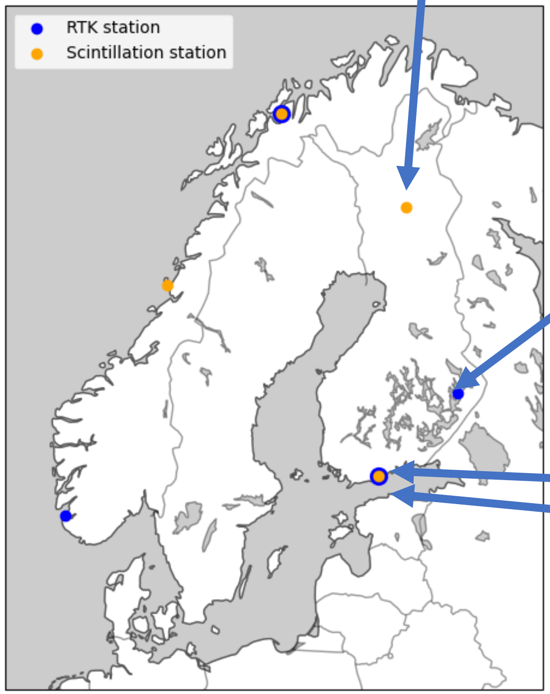
Map: Elias Hirvonen

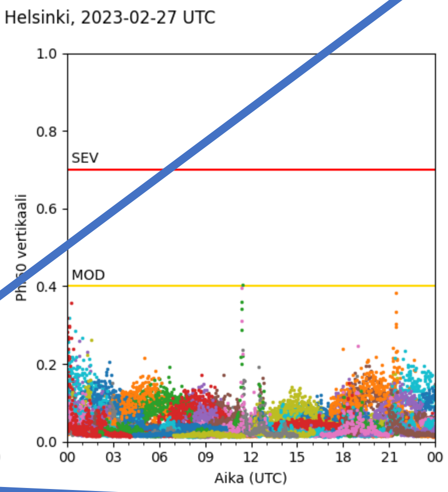


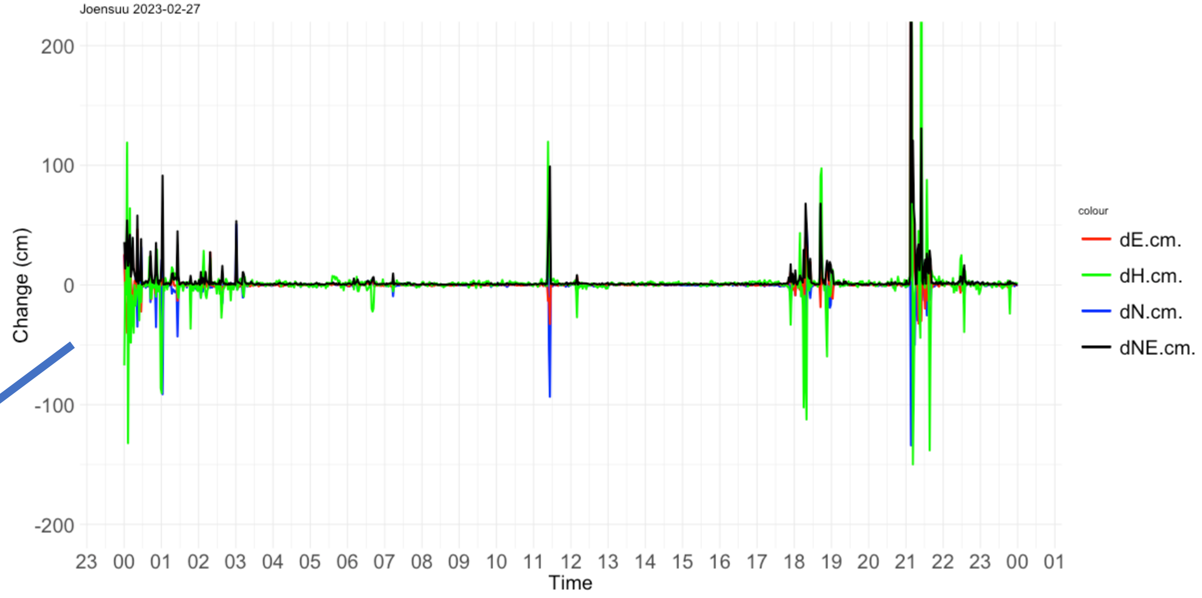


Impact in accurate positioning around noon on Feb 27: Finland

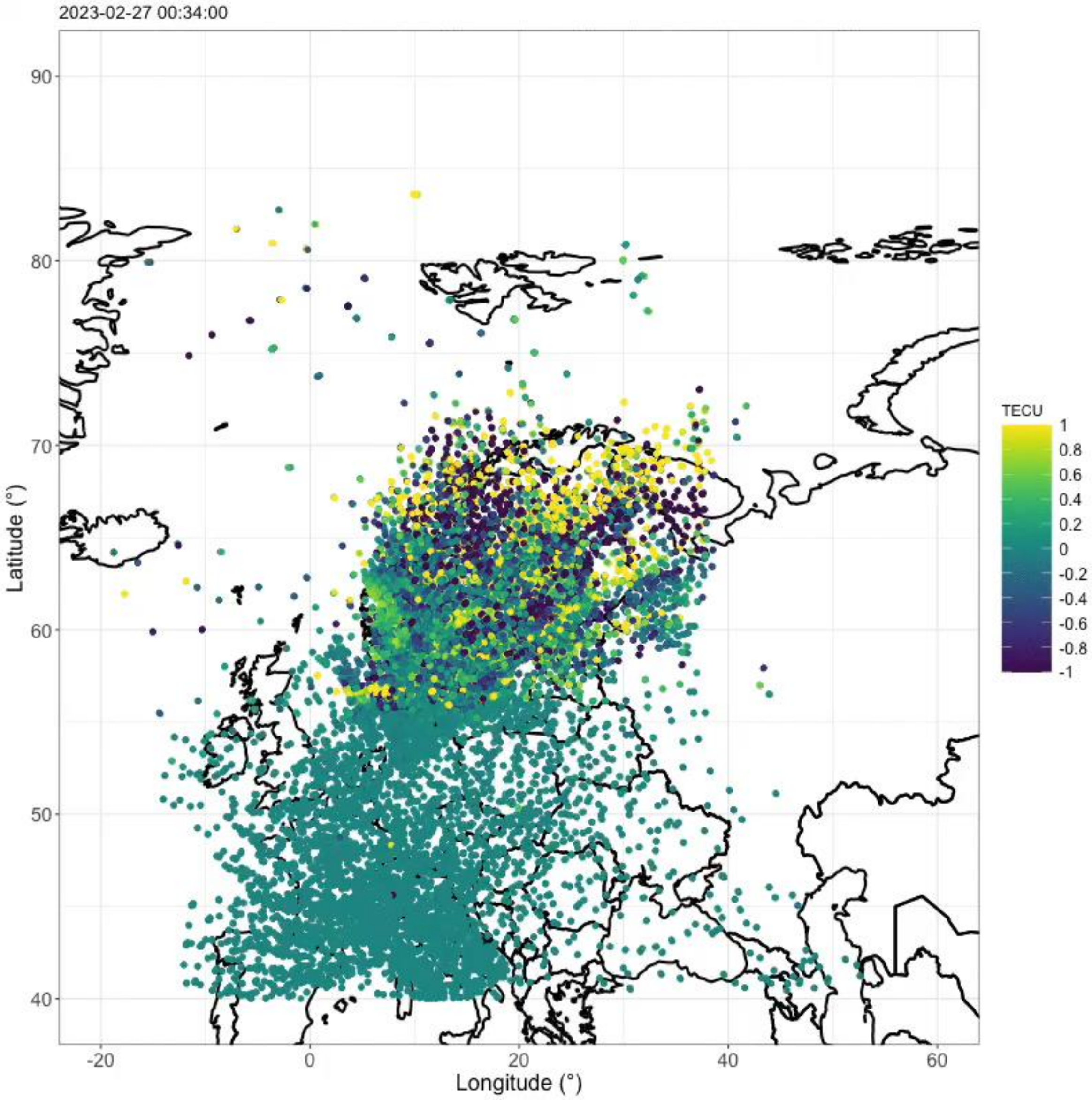








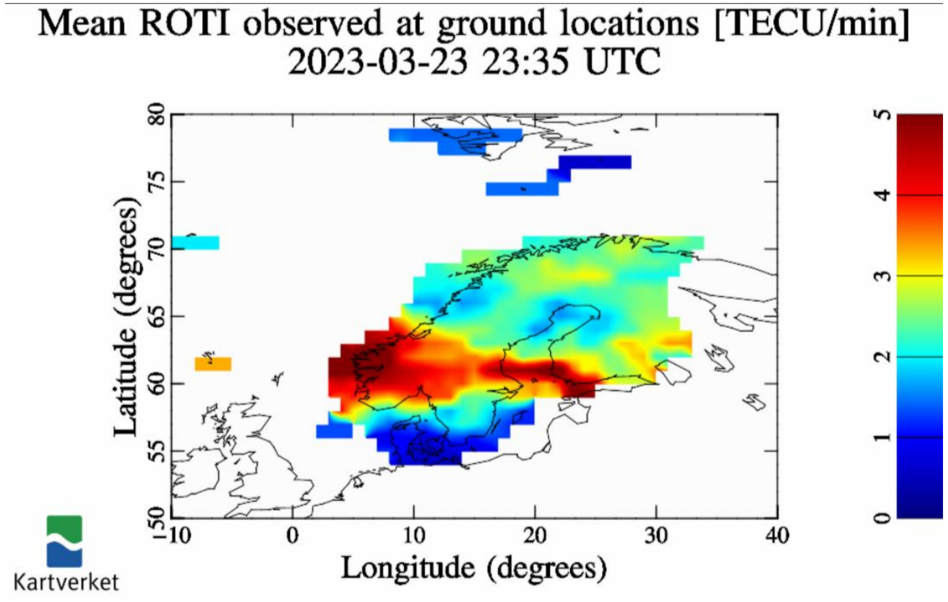
Feb 27, Variations of TEC around the baseline curve



Animation: Johannes Norberg
Data from the Madrigal database
[Madrigal database at CEDAR (openmadrigal.org)]

Automated snow ploughing at Gardemoen airport

- Autonomous runway sweepers operated at the Oslo Airport Gardemoen
- Tests conducted in winter 2022/2023
- Test campaign during the night March 23-24, 2023 had to be interrupted due to problems in RTK positioning
- Checking NMA ROTI service revealed that ionospheric disturbances were the cause for the problems in RTK positioning
- Lesson learned: Forecasts of space weather situation will be used when selecting runway and taxiway sweeping approaches (automated/manual) in full scale operations



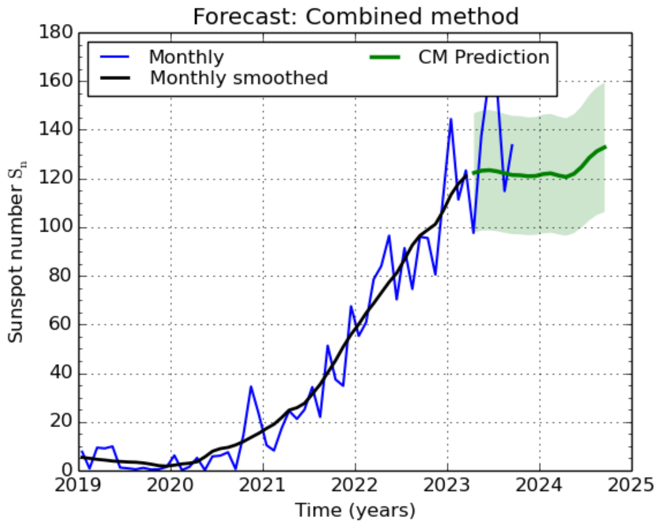
Livestock tracking

- In Norway, sheep are let out freely to graze in open fields every summer.
- 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.
- Findmy produces electronic bells with satellite tracking for livestock on pasture. With this electronic bell the owner of the livestock has a full overview of where the livestock are at all times.
- Opportunity for space weather services: Collecting sheep back to shelters before cold winter should be arranged during calm space weather conditions

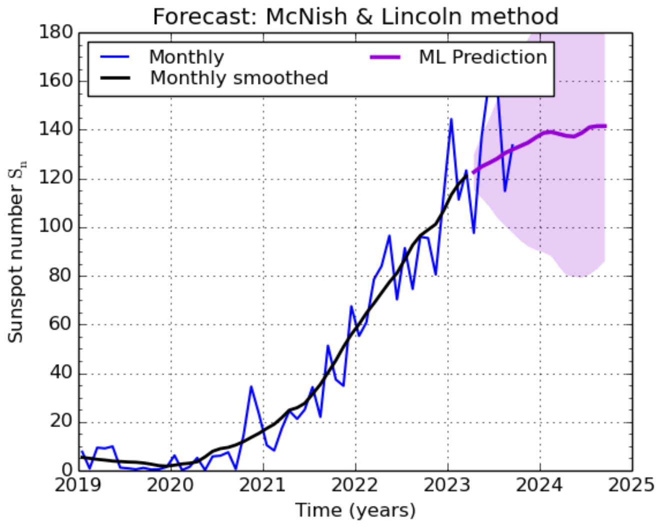
findmy

Summary and Future prospects

- Interests towards easily adoptable and reliable spaceweather services are increasing with the approaching solar max.
- Services utilizing high accuracy positioning are gradually increasing the awareness of space weather phenomena among the general public. (A new ”loss leader” for space weather services besides auroras)
- ESA space weather services are providing good support for proactive mitigation of harmful effects, but the threshold to start their usage is somewhat high.
- Getting users interested about the development of space weather services is a key factor for their increasing usage with feasible expectations.
- Experiences collected in the Artic demonstrator will be used as input for a wider user engagement mission which will address the needs on European level and thus address also preparedness against exceptionally strong space weather storms.



SILSO graphics (http://sidc.be/silso) Royal Observatory of Belgium 2023 October 17



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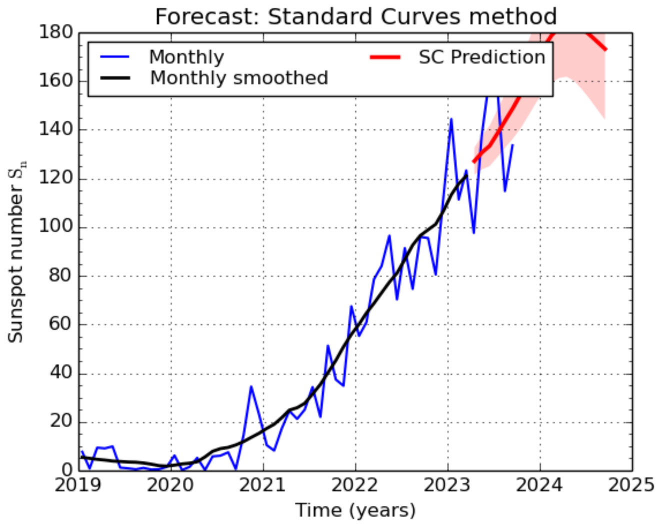

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Any Questions?

2.2.1. Definition of ROTI

ROTI is defined as the standard deviation of the Rate Of TEC (ROT) over some time interval. It is calculated as follows, where Ln, λ_n, and f_n are the phase measurement, wavelength, and frequency for the nth frequency.

$L_{GF}(i)$ is the geometry-free phase combination at time i

$$L_{GF}(i) = L1(i) \times \lambda_1 - L2(i) \times \lambda_2. \qquad (1)$$

ROT (in TECU/minute) is calculated as

$$\text{ROT}(i) = \frac{L_{GF}(i) - L_{GF}(i-1)}{\Delta t \times 10^{16} \times 40.3 \times \left(\frac{1}{f_1^2} - \frac{1}{f_2^2}\right)}. \qquad (2)$$

TECU (TEC unit) is defined as 10^{16} electrons per m^2. Δt is the time difference between the epochs, in minutes.

Finally, ROTI, calculated over N epochs, is

$$\text{ROTI}(k) = \sqrt{\frac{1}{N} \sum_{j=k-N}^{k} \left(\text{ROT}(j) - \overline{\text{ROT}}\right)^2}. \qquad (3)$$

$\overline{\text{ROT}}$ is the average of ROT for the interval $k\left(\overline{\text{ROT}} = \frac{1}{N}\sum_{j=k-N}^{k}\text{ROT}(j)\right)$.

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$$\begin{aligned}
\phi(L) &= \frac{\omega}{c}\left[\int_0^{L_0}(1+\Delta n_{tr})dz + \int_{L_0}^{L}\left(1 - \frac{N_e(z)e^2}{2\epsilon_0 m_e \omega^2}\right)dz\right] \\
&= \frac{\omega}{c}\left[L + \int_0^{L_0}\Delta n_{tr}dz - \int_{L_0}^{L}\frac{N_e(z)e^2}{2\epsilon_0 m_e \omega^2}dz\right] \qquad (6.20) \\
&= \frac{\omega}{c}L + \frac{\omega}{c}T(L) - \frac{\alpha}{c\omega}TEC(L).
\end{aligned}$$

Similarly for the group delay, combining Equations (6.18), (6.11) and (6.15) results in metres as

$$\rho(L) = L + T(L) + \frac{\alpha}{\omega^2}TEC(L). \qquad (6.21)$$

In both Equations (6.20) and (6.21), L is the range between the transmitter and receiver, $T(L) = \int_0^{L_0}\Delta n_{tr}dz$ is the tropospheric contribution, $\alpha = \frac{e^2}{2\epsilon_0 m_e}$ a combination of constants and

$$TEC(L) = \int_{L_0}^{L} N_e(z)dz \qquad (6.22)$$

is the slant *total electron content* (TEC). The last term, which includes TEC, is positive when considering phase velocity and negative when group velocity is considered. In GNSS literature temporal frequency is often used instead of angular. The coefficient in the ionospheric part is then $\frac{\alpha}{\omega} = \frac{\alpha}{4\pi^2 f^2} \approx \frac{40.3}{f^2}$.

Bayesian approach to ionospheric imaging with Gaussian Markov random field priors

Johannes Norberg