How ionospheric disturbances are monitored in PECASUS?

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- Brief introduction of PECASUS and ICAO space weather advisories
- Data and models behind the PECASUS advisories on GNSS and HFCOM
- About scintillation impact on EGNOS
- Summary & Future prospects

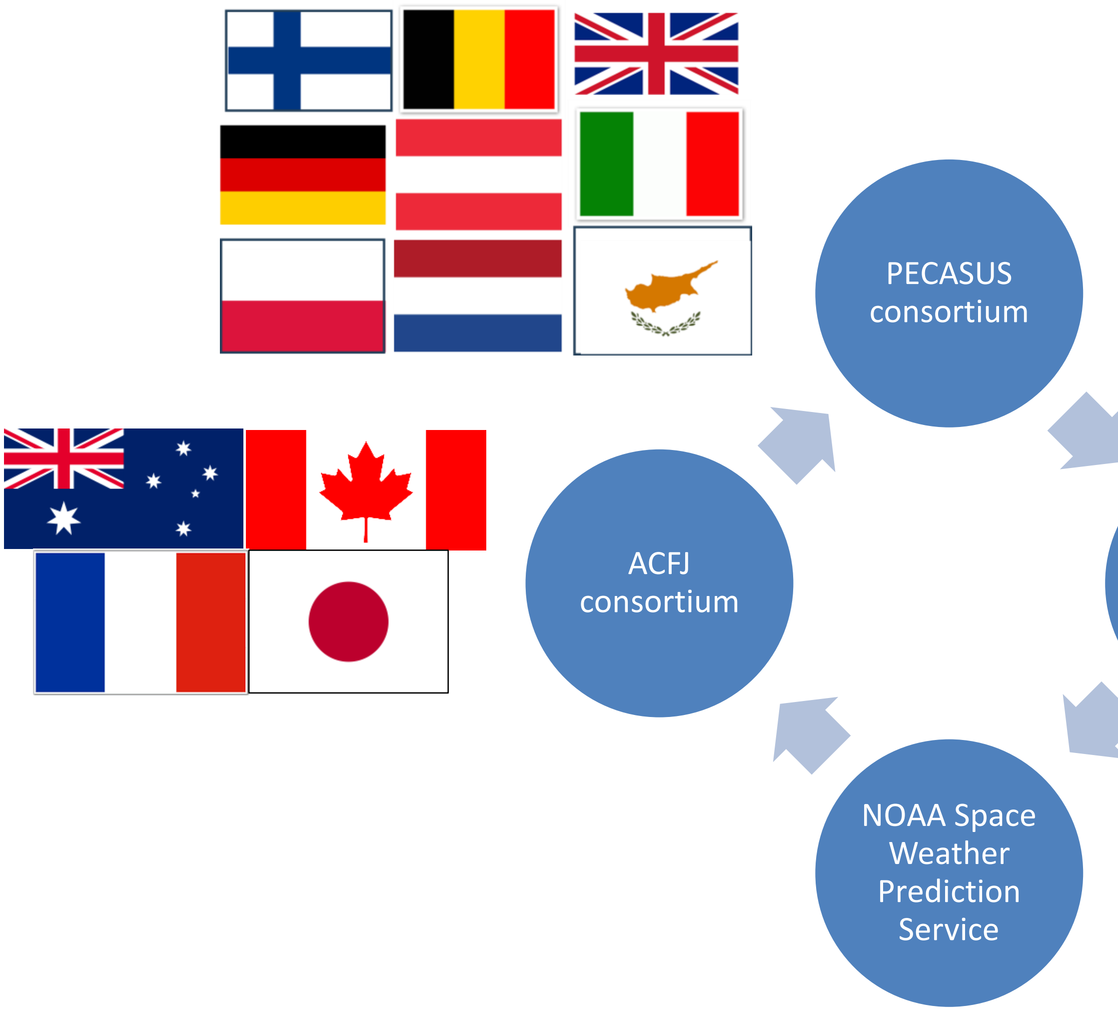
- **Consortium of ten ICAO countries:**
  - Finnish Meteorological Insitute (FMI)
  - Frederick University (Cyprus, FU))
  - German Aerospace Center (DLR)
  - Istituto Nazionale di Geofisica e Vulcanologia (Italy, INGV)
  - Royal Netherlands Meteorological Institute (KNMI)
  - Seibersdorf Laboratories in Austria (SL)
  - Solar-Terrestrial Centre of Excellence in Belgium (STCE)
  - Space Research Center of the Polish Academy of Sciences (SRC/CBK)
  - UK Met Office (UKMO)

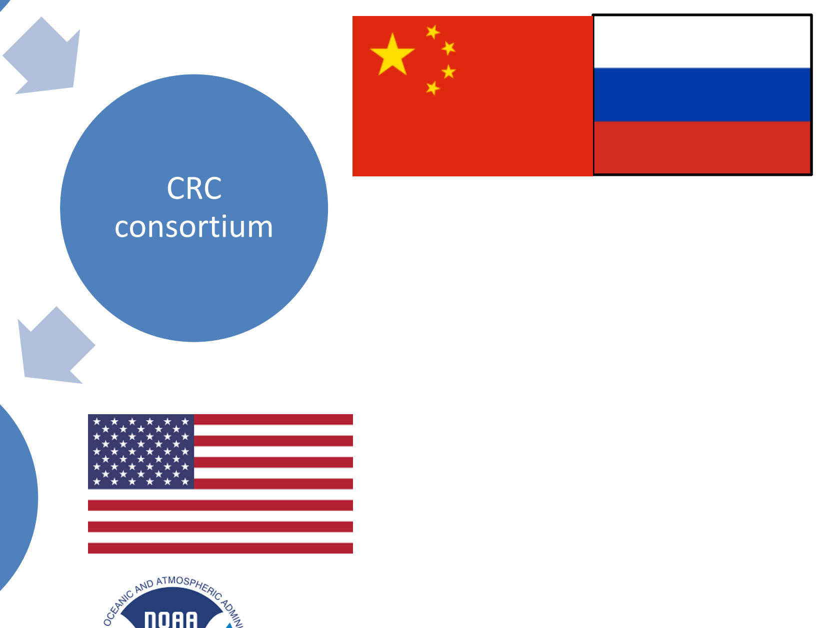
"Collaboration based on a history of strong partnerships"

Much of the R20 done in the ESA Space Safety Programme

Four global space weather centers

- Two week shifts with rotating roles of
  - On-Duty Center (ODC)
  - Primary Back-up Center (PBC)
  - Secondary Back-up Center (SBC)
  - Maintenance and Observation Center (MOC)
- ODC and PBC have the obligation to monitor space weather continuously; SBC and MOC monitor during local office hours





Impacts of ICAO interest & Thresholds

- **Variations in Radiation at flight altitudes (RAD)**
- **Availability of GNSS based navigation (GNSS)**
- **Disturbances in HF communication (HF COM)**
- **To-be-added:**
  - **Satellite communication (SATCOM)**
  - **Solar radio bursts**

Impact	Parameter	MOD	SEV
RAD	Effective dose	30 µSievert/h	80 µSievert/h
GNSS			
Ampl. Scint.	S_4	0.5	0.8
Phase Scint.	σ_φ	0.4 rad	0.7 rad
Total el. Cont.	TECU	125	175
HF COM			
Auroral Abs.	Kp	8	9
Pol. Cap. Abs.	Riometer abs.	2 dB	5 dB
Shortwave Fadeout	Solar X-rays	10^{-4}W/m^2 (X1)	10^{-3}W/m^2 (X10)
Post Storm Depr.	MUF	30%	50%

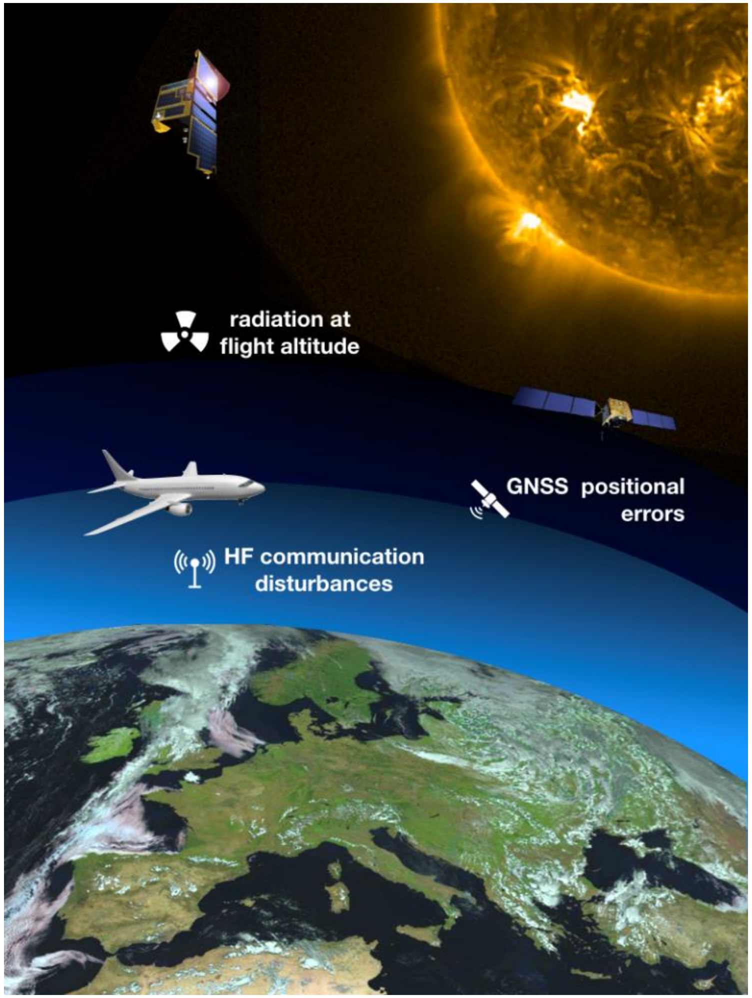


Figure: ESA/Proba-2 & EUMETSAT

Table 3. A summary of PECASUS methods and data inputs used to create ICAO space weather advisories.

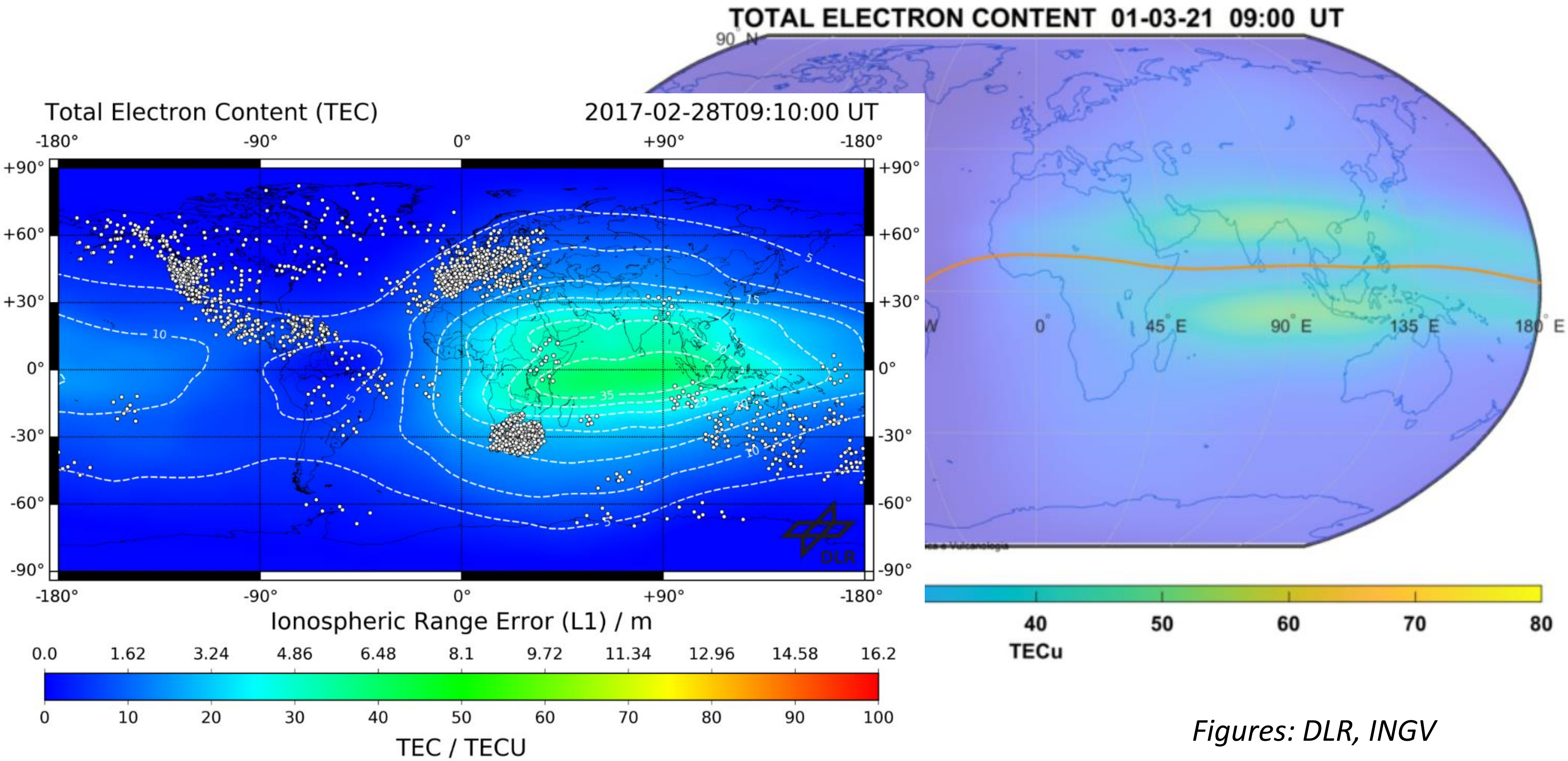
Impact Area	PECASUS Solution	Augmenting Models	Inputs
GNSS	S_4 and σ_ϕ from 16 stations TEC maps Neustrelitz TEC [24]	NeQuick [19];	50 Hz GNSS data IGS and EUREF
Radiation	Avidos	ANeMos COMESEP [39] HESPERIA UMASEP-500 [37]; [38]	Neutron Monitors GOES protons GOES X-rays
HF	EUROMAP [49] GDMF2 [48] foF2 warnings D-RAP [41]	IRI [50] MUF background [51] NeQuick [19]	ionosondes F10.7 Kp T-index GOES protons GOES X-rays
Overall Space Weather	24/7 Monitoring CACTus [61]		solar wind density, velocity, IMF Kp NRT Kp (NOAA) Local K GOES X-rays PROBA2 X-rays

Table from Kauristie et al., 2021

Two TEC methods compared

	DLR	INGV
Resolution & Update rate	2.5° lat & 5.0° lon; 5 min	2.5° lat & 5.0° lon; 15 min
Input data sources	IGS and EUREF GNSS receivers	IGS and EUREF GNSS receivers
STEC calibration	Jakowski et al., Radio Science, 2011.	Cesaroni et al., SWSC, 2015 Ciraolo et al., J. of Geodesy, 2007.
Background	Neustrelitz TEC Model (NTCM, Jakowski et al.,): • **Polynomial describing TEC variations with linear** terms • Inputs: position, solar zenith angle & activity, etc. • Based on high-precision data from IGS archives • **NRT adjustments (1/24h** and 1/5min)	NeQuick Model (Nava et al., 2008): • **3D model composed with semi-Epstein layers characterized with ionosonde parameters (foE, foF1, foF2,..)** • Covers altitudes from 90 km to the F-layer peak • Inputs: position, time, and solar flux • **NRT adjustment 1/1h**
NRT data integration with Background	NRT data fitted with NTCM with 2D Gaussian weighing factors based on distances between IPP and grid points.	1. Differences between NRT data at IPP and NeQuick are calculated. 2. Differences are interpolated by kriging for a global map 3. TEC is achieve by the sum of differences and NeQuick.

GNSS TEC



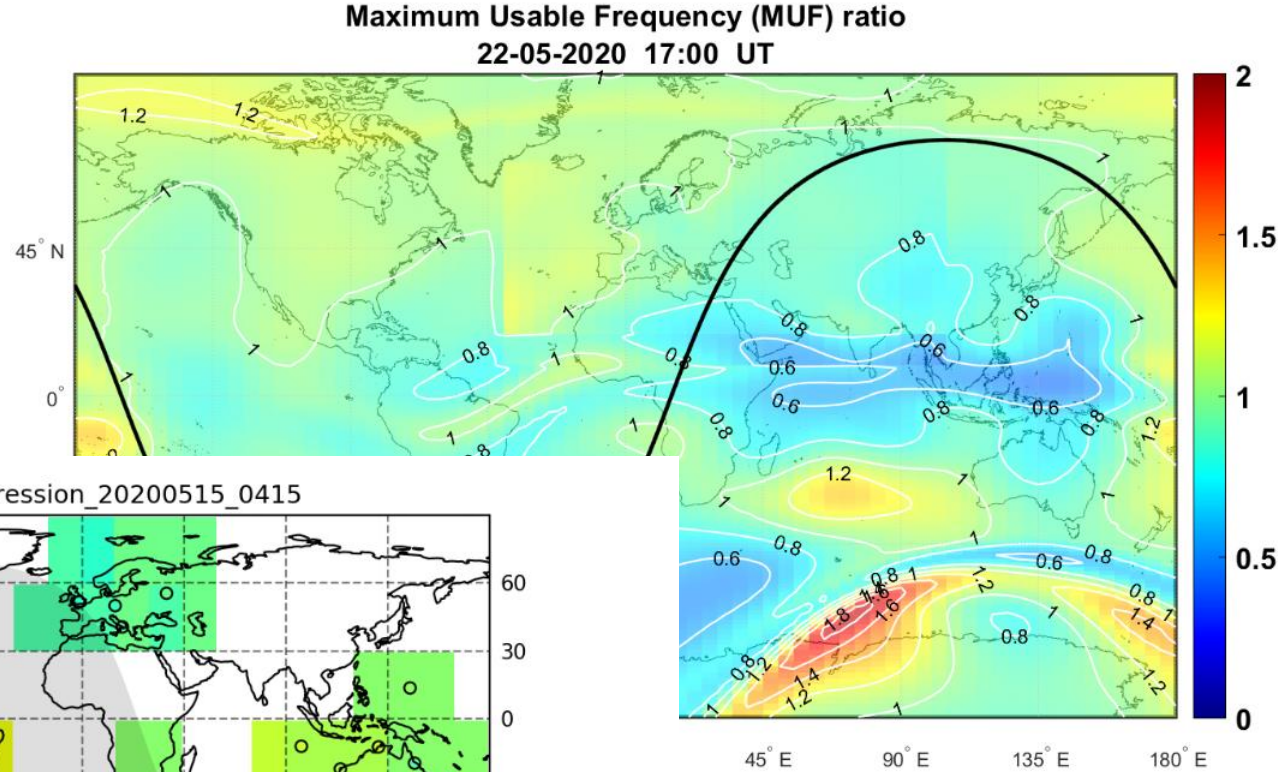
Figures: DLR, INGV

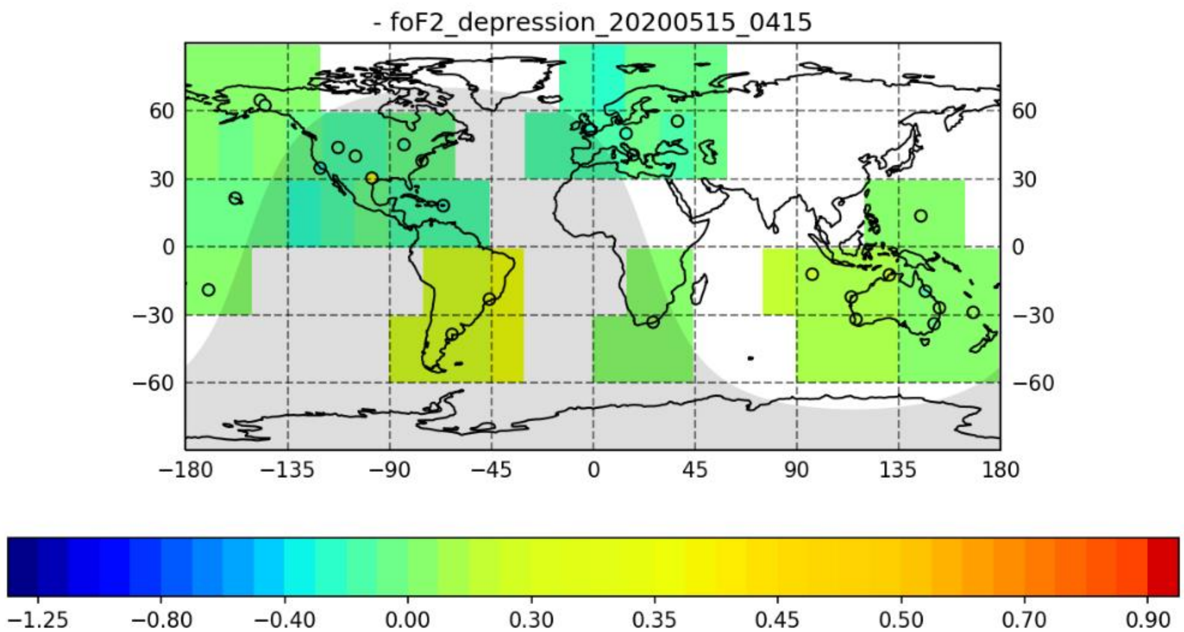
- TEC nowcasts are provided by joint efforts of DLR, INGV, SRC/PAS
- IMPC https://impc.dlr.de & eSWua https://doi.org/10.13127/eswua/tec

Post storm depression: Two methods compared

	SRC/PAS (NRT data)	INGV (long term archives)
Resolution & Update rate	ICAO grid with cells of 15° in lon and 30° in lat; 15 min	2.5° lat & 5.0° lon; 1 hour
Parameter monitored	$$\delta foF2 = -\frac{foF2 - \langle foF2 \rangle}{\langle foF2 \rangle}$$ Where <> is **median of 30 days' data**	Ratio of MUF3000F2 from the models given below to MUF3000F2 **from the model by Shubin (2017)**
Data sources	NRT ionosonde data from 10-30 stations	Input parameters for the models listed below & NRT ionosonde data
Models supporting	NeQuick for the 30 days median if ionosonde data has long gaps.	Global dynamic model of foF2 (Shubin and Anakuliev, 1995): • **Depression at mid-latitudes** • Inputs: F10.7, ap(τ) EUROMAP (Mikhailov and Perrone, 2014) with two elements for each ionosonde: • **Storm time regression model** based on > 20 years' archive) • **Training model using data from 28 previous days** • Inputs: F10.7, ap(τ), T-index IRI (Bilitza, 2018) • Used for foF2 → MUF conversions

HF COM/MUF





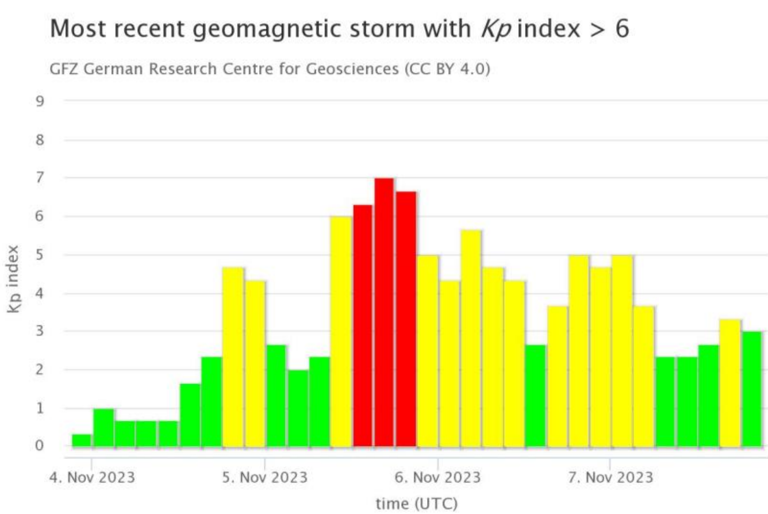
Plots by INGV
and SRC/PAS

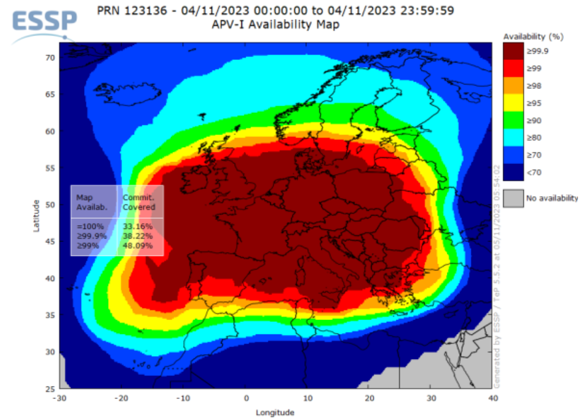
Scintillation and EGNOS performance:

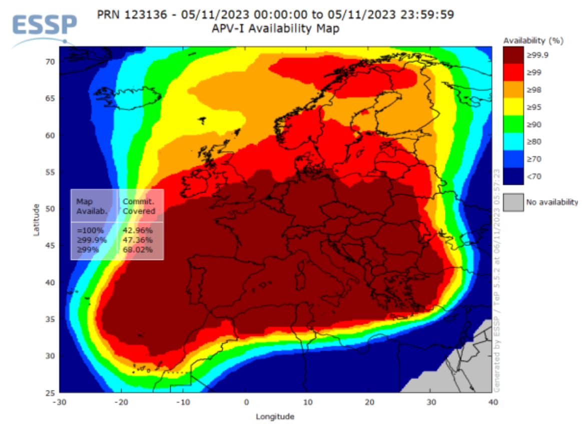
A recent space weather storm on Nov 5-6, 2023.

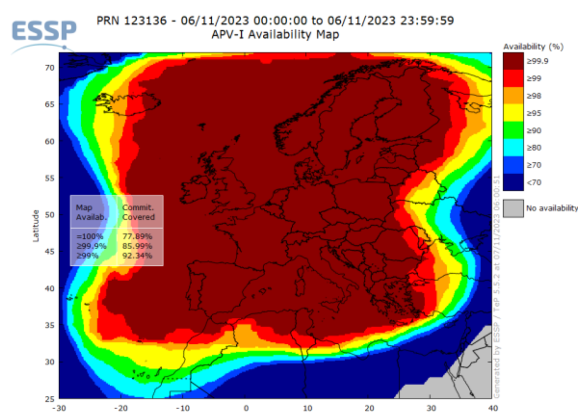
GNSS phase scintillation observed in Finland on the night of Nov 5.

EGNOS performance was compromised during Nov 4 and Nov 5

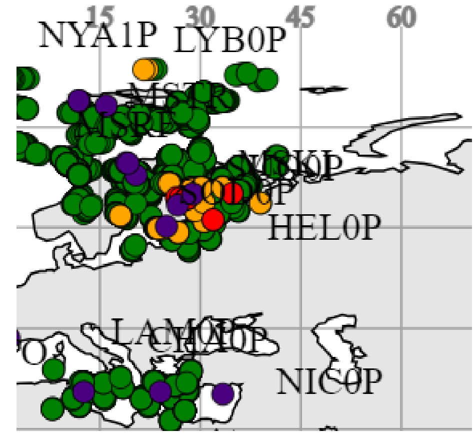








PECASUS Dashboard
Nov 5, 19:25



PECASUS Dashboard
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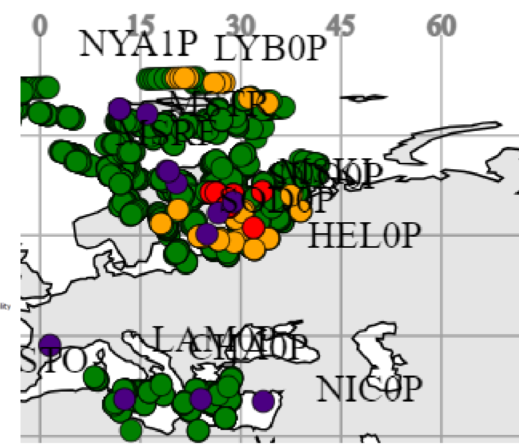


Summary and Future prospects

Currently ICAO advisories on ionospheric disturbances cover the following phenomena:

- Solar X-ray flux bursts
- D-layer absorption in Polar cap (SEP)
- D-layer absoption at auroral latitudes (magnetospheric electrons)
- Post-storm depression in ionosheric electron density
- Enhancement in the Total Electron Content
- Ionospheric small scale irregularities causing amplitude and phase scintillation in GNSS signal.

Ensuring unified services across the four centers have appeared to be challenging. Differences appear particularly in scintillation advisories.

Discussions for future modifications are on-going in the ICAO METP space weather working groups

Using temporal and spatial gradients of TEC as triggers for advisories has been mentioned in the discussions, but currently the hottest debates are related with the RAD advisories.

Recent events of compromised EGNOS performance have been noticed by aviation authorities → more research is needed about this topic.

Epilogue

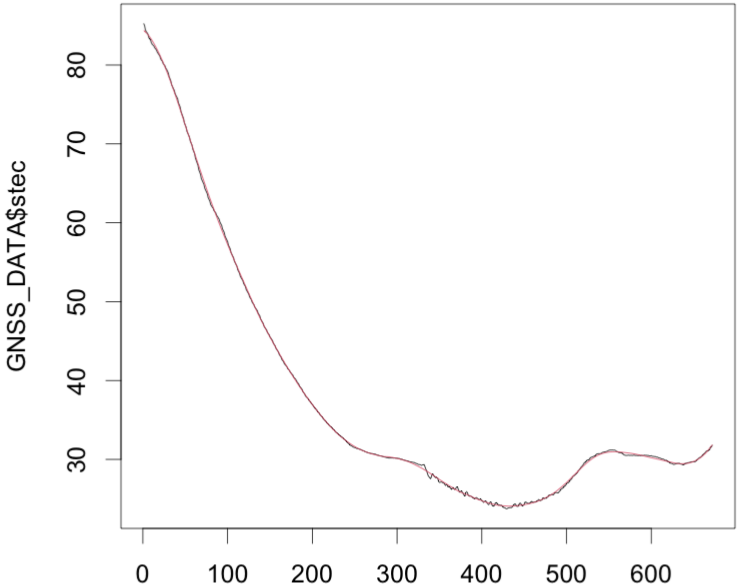
TIDs in the high latitude dayside ionosphere?

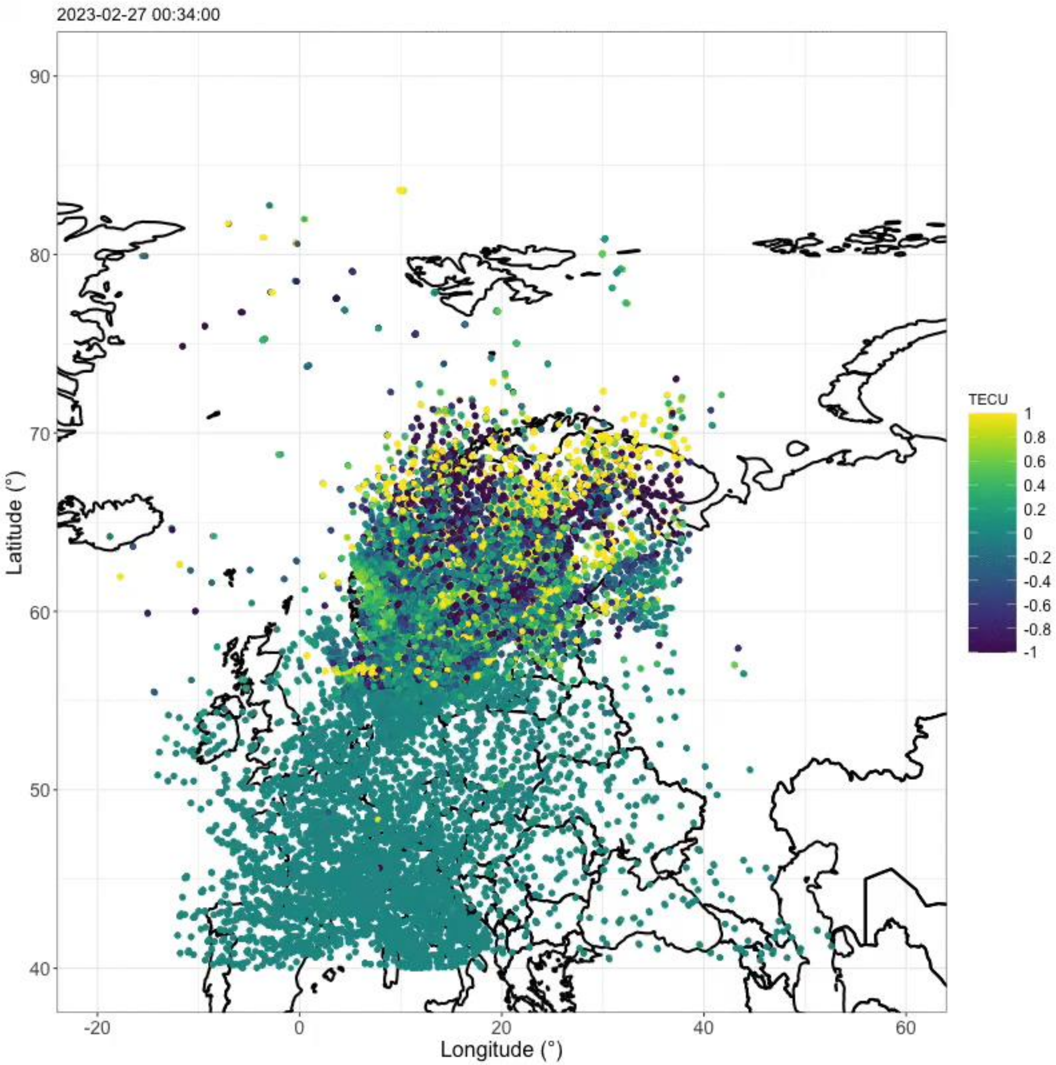
Finnish National Land Survey has reported about problems in accurate positioning durint recent years.

We have investigated some events by using STEC data from the Madrigal Archive

Each satellite-receiver link processed separately

Deviations from background detected by Savitzky-Golay filtering (difference between red and black curves in the figure below)





Animation by Johannes Norberg

Photo by Cheryl Empey