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GNSS RTK single-base measurements under higher ionospheric activity: results, analysis and mitigation technology

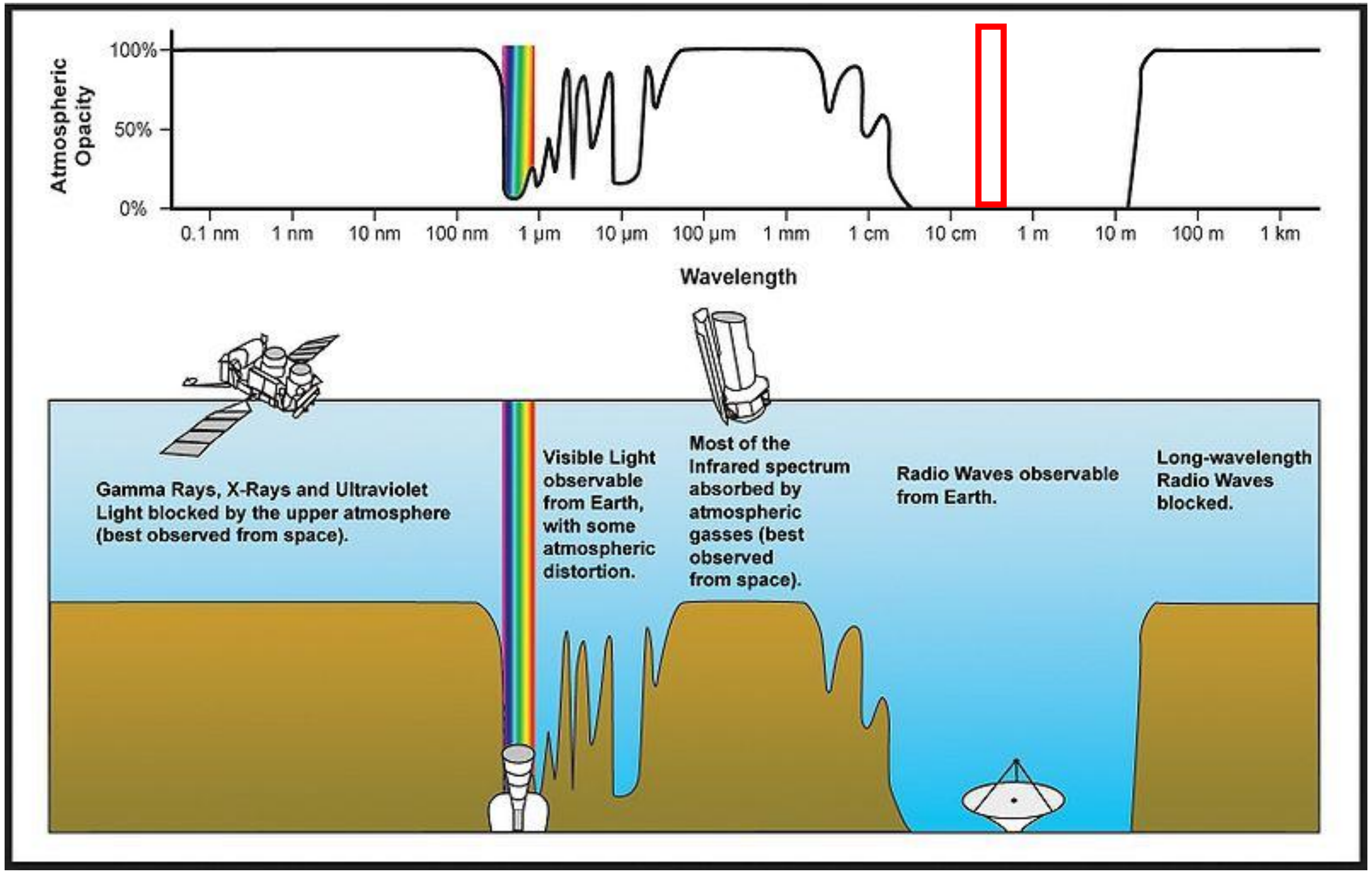
Konference GNSS 2025

Brno, 4th February 2025

Outline:

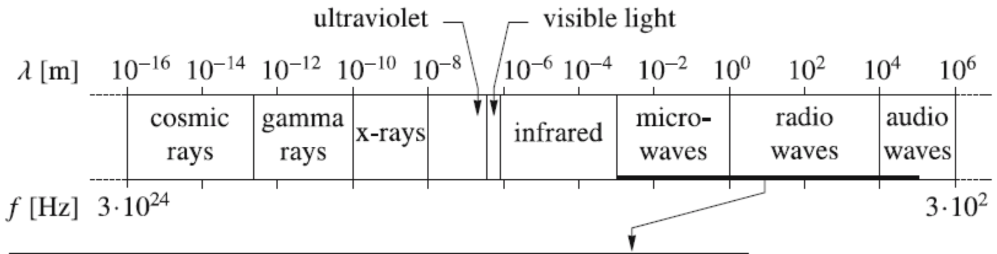
- Atmospheric electromagnetic permeability
- Ionosphere and TEC
- Solar Cycle 25
- RTK single-base measurements (15-11-2024)
- Results
- Mitigation measures
- Conclusions

Atmospheric electromagnetic permeability



https://commons.wikimedia.org/wiki/File:Atmospheric_electromagnetic_transmittance_or_opacity.jpg

EM spectrum



Notation	Wavelength λ	Frequency f
Extremely high frequency (EHF)	0.1–1 cm	300–30 GHz
Super high frequency (SHF)	1–10 cm	30–3 GHz
Ultra high frequency (UHF)	10–100 cm	3–0.3 GHz
Very high frequency (VHF)	1–10 m	300–30 MHz
High frequency (HF)	10–100 m	30–3 MHz
Medium frequency (MF)	0.1–1 km	3–0.3 MHz
Low frequency (LF)	1–10 km	300–30 kHz
Very low frequency (VLF)	10–100 km	30–3 kHz

Band	f [GHz]
K	26.5–18
Ku	18–12.4
X	12.4–8
C	8–4
S	4–2
L	2–1

L (2-1 GHz) → λ = 15 – 30 cm

Hofmann-Wellenhof, B.; Lichtenegger, H.; Wasle, E. (2008): GNSS – Global Navigation Satellite Systems GPS, GLONASS, Galileo, and more, Springer, Wien, New York,

GNSS – Global Navigation Satellite System

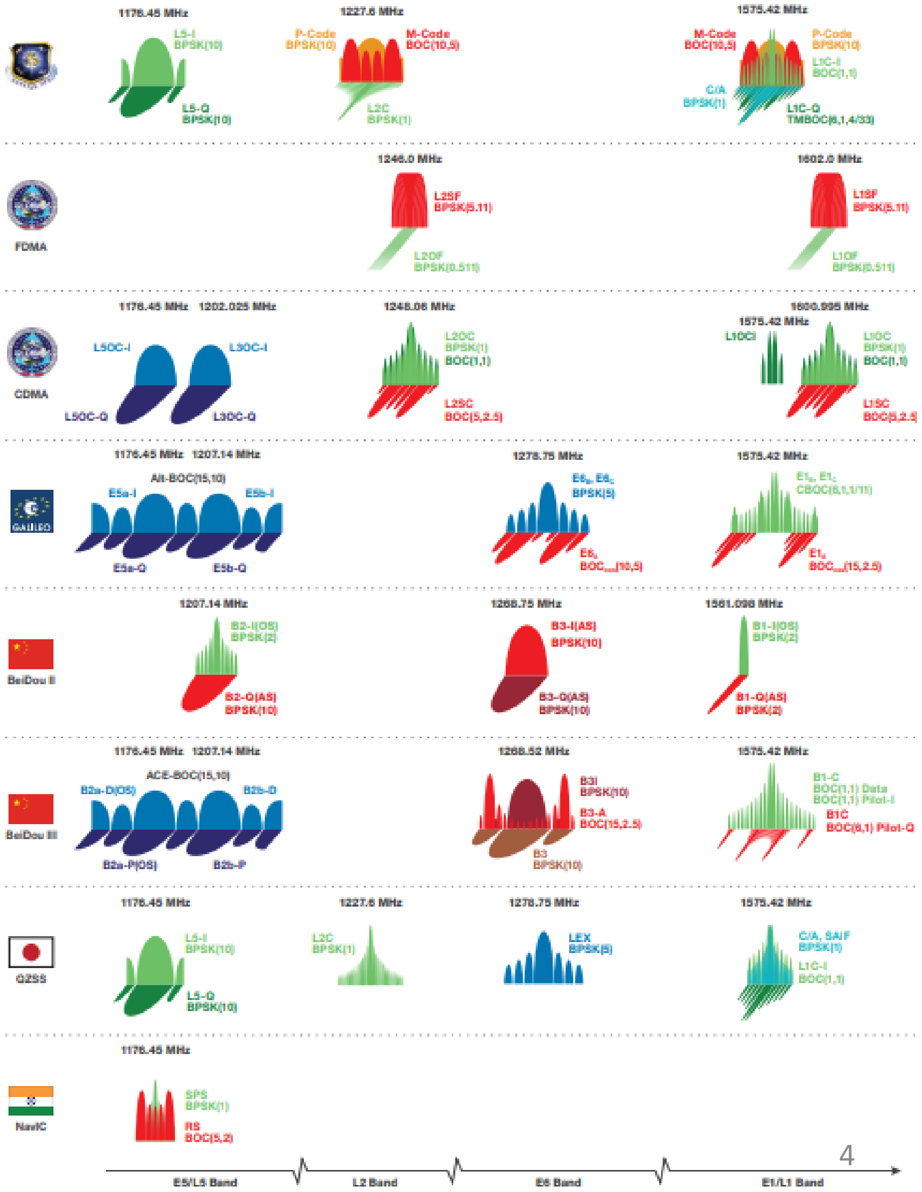
GNSS constellations

Parameter	GPS	GLONASS	Galileo	BeiDou III
Orbital Period (MEO)	11hrs 58min	11hrs 15mins	14hrs 04mins	12hrs 37min
Orbital Height (MEO)	22,200 Km	19,100 Km	23,222 Km	21,528 Km
Inclination (MEO)	55°	64,8°	56°	55°
Number of Orbital Planes (MEO)	6	3	3	3
Number of satellites	24 MEOs + 6 spares	24 MEOs + 2 spares	24 MEOs + 6 spares	24 MEOs + 3 GEOs + 3 IGSOs + spares
Reference frame	WGS-84	PZ-90	GTFR	CGCS 2000
Reference time	GPS Time (GPST)	GLONASS Time (GLONASST)	Galileo System Time (GST)	BeiDou Time (BDT)

RNSS constellations (regional coverage)

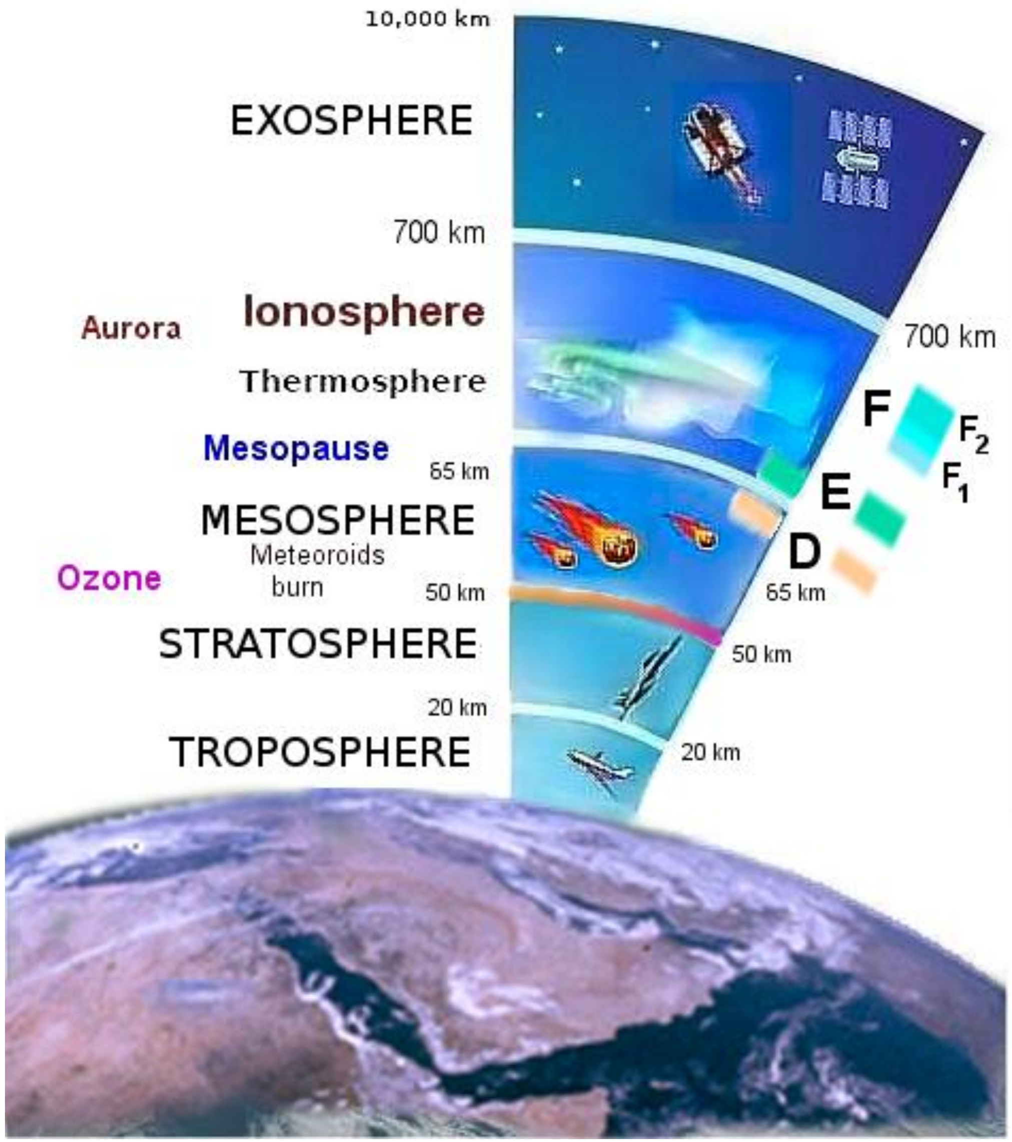
Parameter	NAVIC	QZSS
Coverage	India and a region extending 1,500 km (930 mi) around it	Asia-Oceania region
Number of satellites	5 IGSOs + 3 GEOs	3 IGSOs + 1 GEO
Reference frame	WGS-84	JGS
Reference time	IRNSS Network Time (IRNWT)	QZSS Time (QZSST)

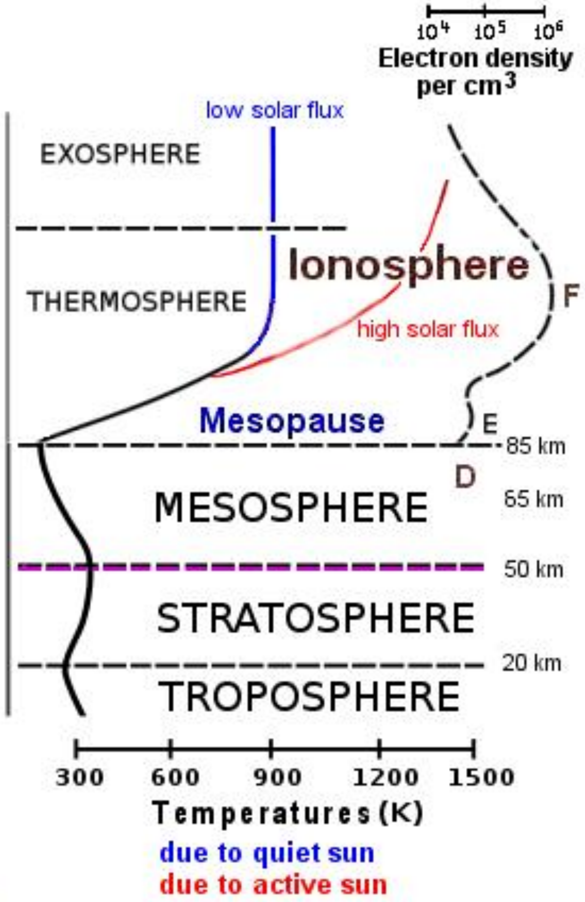
GNSS frequency bands



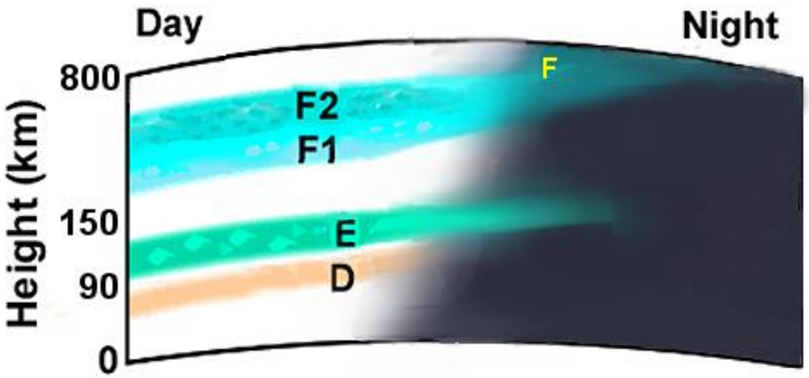
European GNSS Agency (2020): GNSS User Technology Report, Issue 3, DOI:10.2878/565013

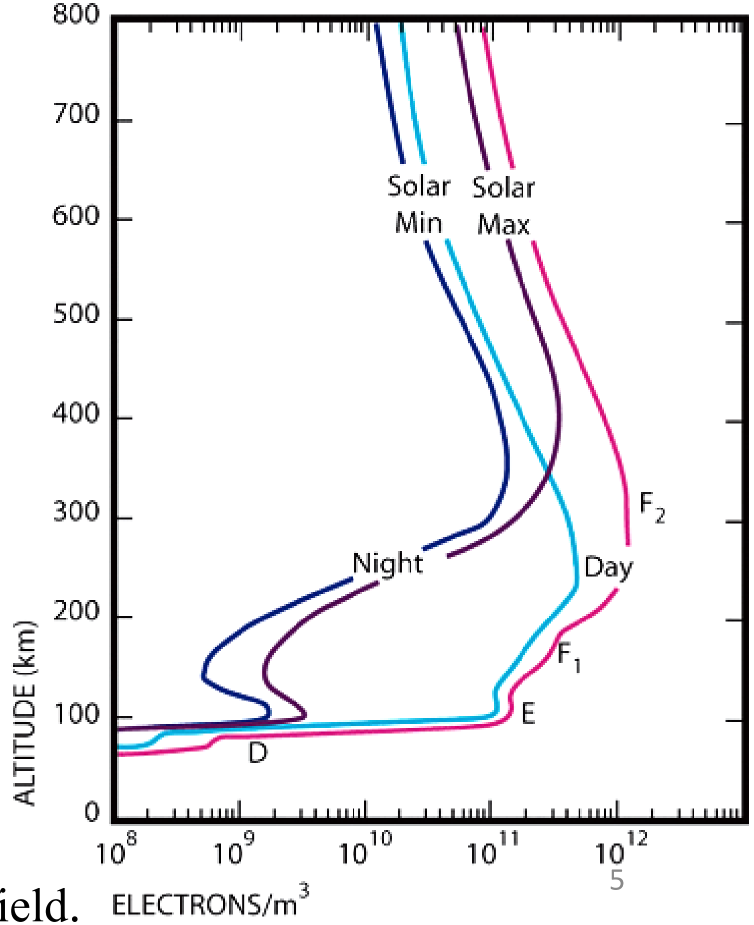
Ionosphere (50 – 1000 km)





The structure of the ionosphere is subject to continuous changes according to the changes in solar activity and Earth's magnetic field.





https://www.qsl.net/4x4xm/Propagation/Radio-Communication-and-the-Ionosphere.htm

TEC – Total Electron Content

$\text{TEC} = \int N_e \, ds_0$ along the straight signal path between the satellite and the receiver

Δ^{Iono} = measured – geometric range

$$\Delta_{\text{ph}}^{\text{Iono}} = -\frac{40.3}{f^2}\,\text{TEC}$$

$$\Delta_{\text{gr}}^{\text{Iono}} = \frac{40.3}{f^2}\,\text{TEC}$$

GNSS error sources

Contributing source	Error range
Satellite clocks	±2 m (6.6 feet)
Orbit errors	±2.5 m (8.2 feet)
Ionospheric delays	±5 m (16.4 feet)
Tropospheric delays	±0.5 m (1.6 feet)
Receiver noise	±0.3 m (1 foot)
Multipath	±1 m (3.3 feet)

TEC – Total Electron Content

TEC can be:
- measured
- estinated (modeled)
- eliminated (iono-free combination):

$$\Phi_{\text{iono-free}} = \frac{f_1^2\,\Phi_{L_1} - f_2^2\,\Phi_{L_2}}{f_1^2 - f_2^2}$$

$$R_{\text{iono-free}} = \frac{f_1^2\,R_{P_1} - f_2^2\,R_{P_2}}{f_1^2 - f_2^2}$$

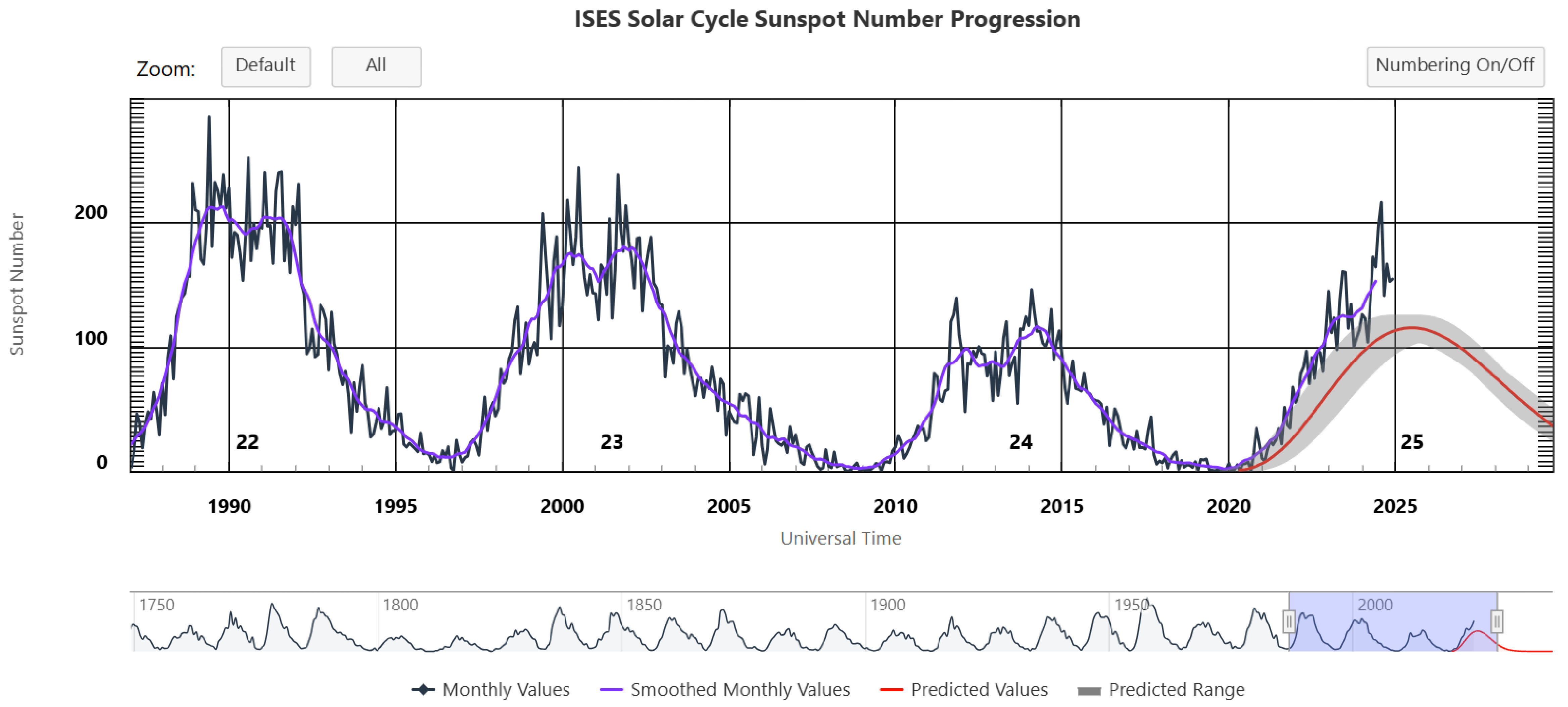
first order ionospheric effects (99.9%) can be eliminated

TEC depends on solar activity and Earth's magnetic field:
- sunspot activities (approx. 11-year cycle),
- seasonal and diurnal variations,
- line of sight (elevation and azimuth of the satellite),
- position of the observing site

Solar Cycle 25

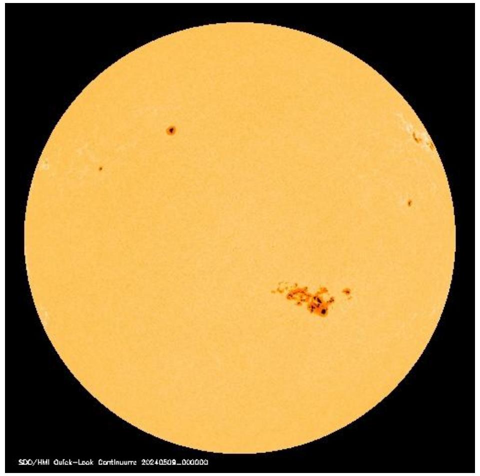
SPACE WEATHER PREDICTION CENTER
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

SOLAR CYCLE PROGRESSION

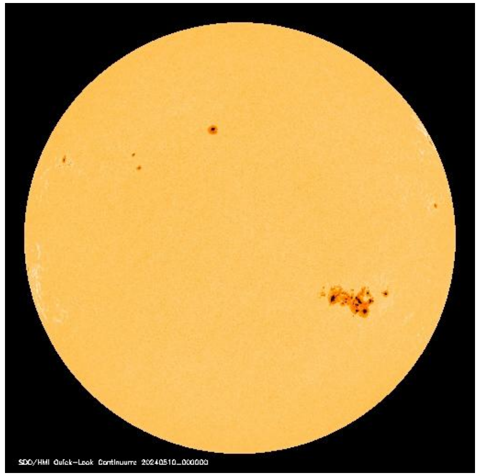


https://www.swpc.noaa.gov/products/solar-cycle-progression

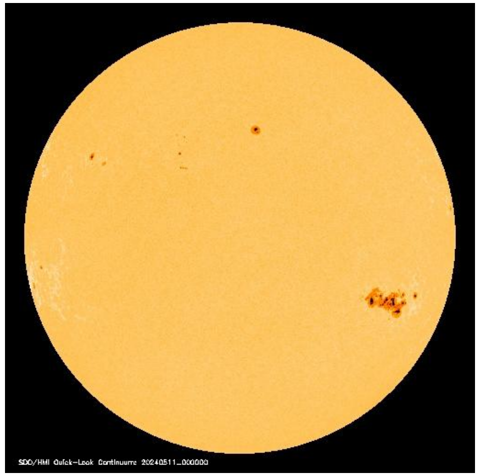
Solar Cycle 25



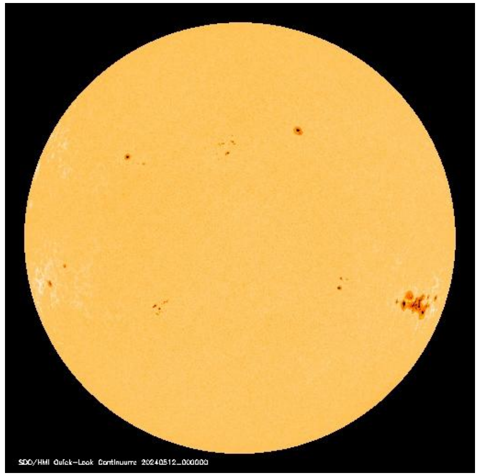
09-05-2024, 0 UTC



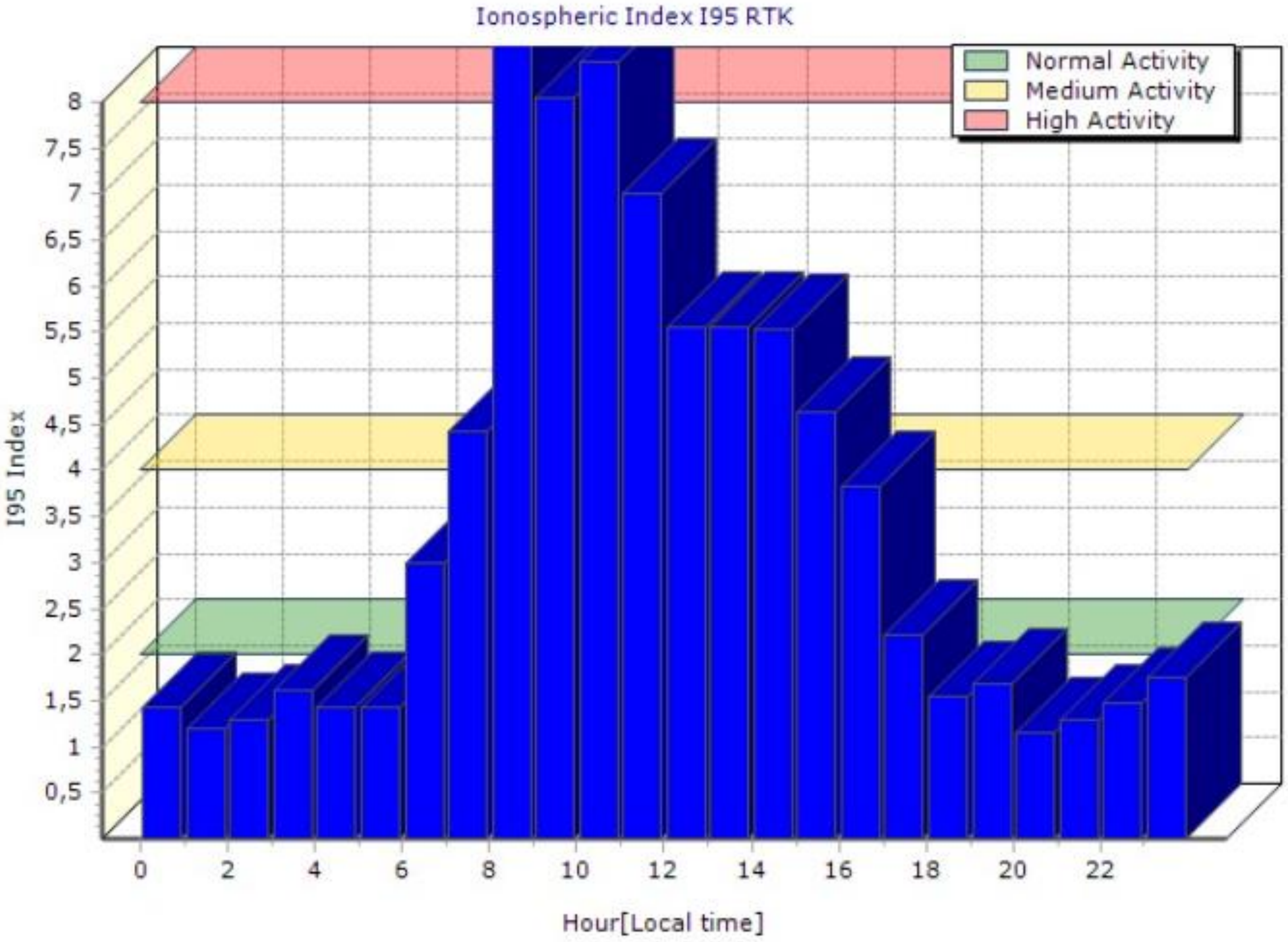
10-05-2024, 0 UTC



11-05-2024, 0 UTC



12-05-2024, 0 UTC



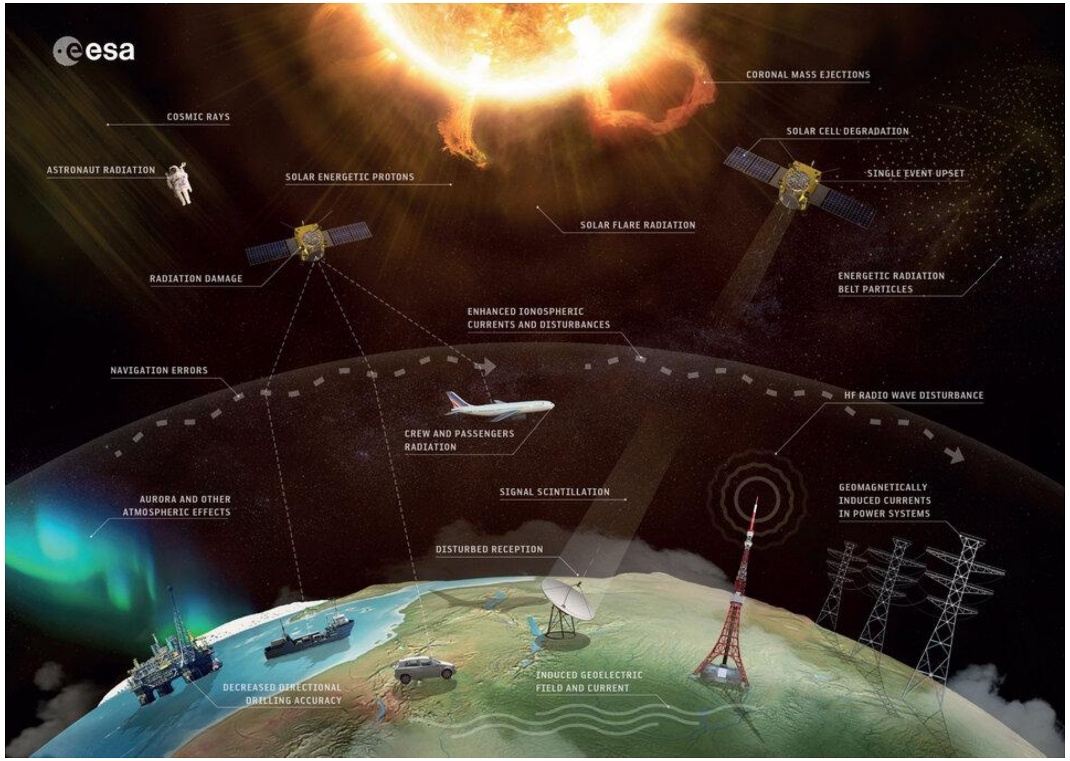
I95 is based on the differential ionospheric residuals as computed in a network of GNSS reference stations (CROPOS).

https://soho.nascom.nasa.gov/data/realtime-images.html

https://gnss.cropos.hr/MemberPagesNetwork/Ionosphere.aspx

Solar Cycle 25

- increased number of sunsposts
- Coronal Mass Ejection (CMS)
- Solar Flare Radiation
- Solar Wind etc.

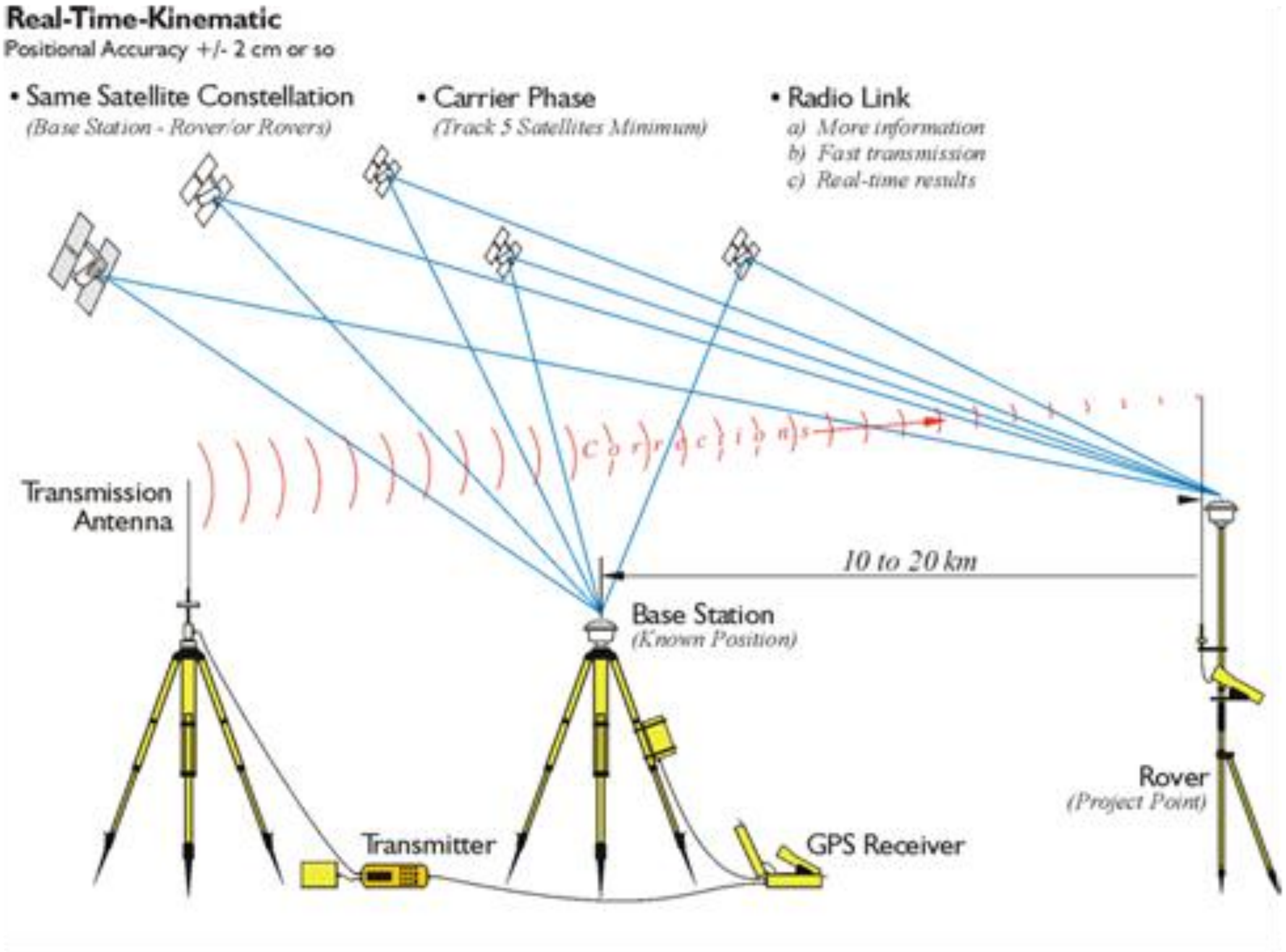


https://www.esa.int/Science_Exploration/Space_Science/The_solar_cycle_a_heartbeat_of_stellar_energy

Effects on GNSS:

- spatial and temporal variation of the TEC
- possible poor signal tracking and in some cases complete loss of lock on the GNSS satellite
- scintillation (rapid fluctuations in GNSS signal amplitude and phase as well as signal fading) leading to poor tracking, complete loss of lock, and/or carrier phase cycle slips
- increased measurement and position noise
- RTK initialization degradation

Real-Time Kinematic (RTK)



https://www.e-education.psu.edu/geog862/node/1845

- Due to the spatial decorrelation of errors (iono, tropo, orbit), the RTK method is limited to the range of 10 to 20 km
- The spatial decorrelation of the ionospheric delay is especially pronounced under high ionospheric activity hindering or disabling the fixed ambiguity resolution

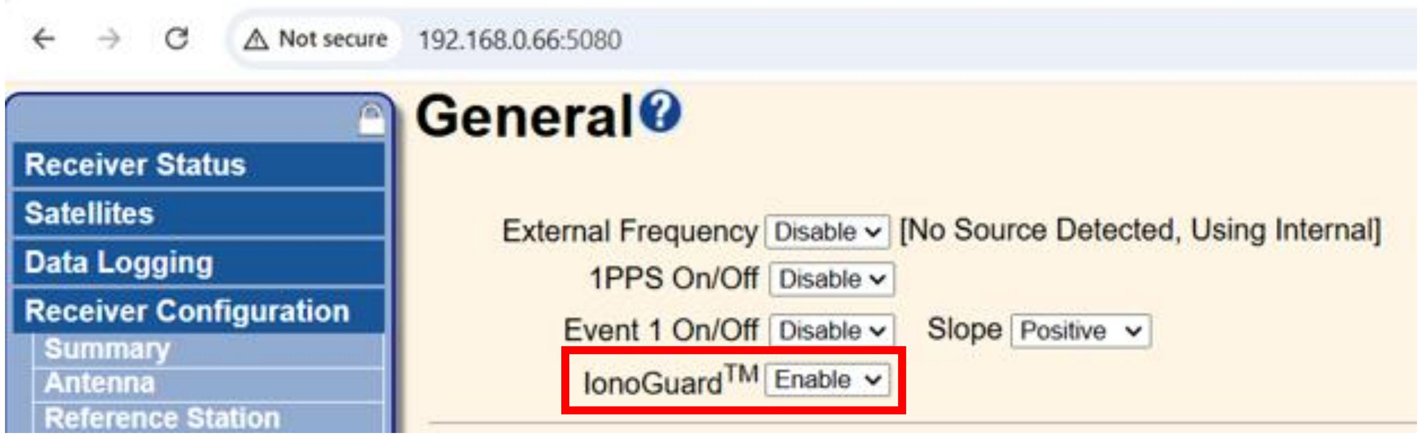
IonoGuard

- lauched in October 2023
- mitigation of ionospheric disruptions in RTK positioning with Trimble ProPoint enabled receivers
- the algorithm addresses the issue on two levels: in signal tracking and in RTK algorithms (it is directly implemented in the ProPoint RTK engine)
- optimum performance in RTK: IonoGuard technology is enabled on the base and rover receivers
- ionospheric information for each satellite is transmitted via proprietary CMRx or RTCM MSM protocol

https://geospatial.trimble.com/en/resources/i/1523829-trimble-ionoguard-rtk-gnss-techpub/0?

RTK single-base measurents

- Base receiver: Trimble Alloy
- Rover receivers: Trimble R12i, R780, R980
- ProPoint engine + IonoGuard
- Baselines: approx. 8 km, 16 km, 24 km
- Survey style: RTK & Logging (T04);
- Measurement method: Continuou Topo (1 sec)
- Mobile Internet; CMRx
- WUI (Web User Interface)



24 km

16 km

8 km

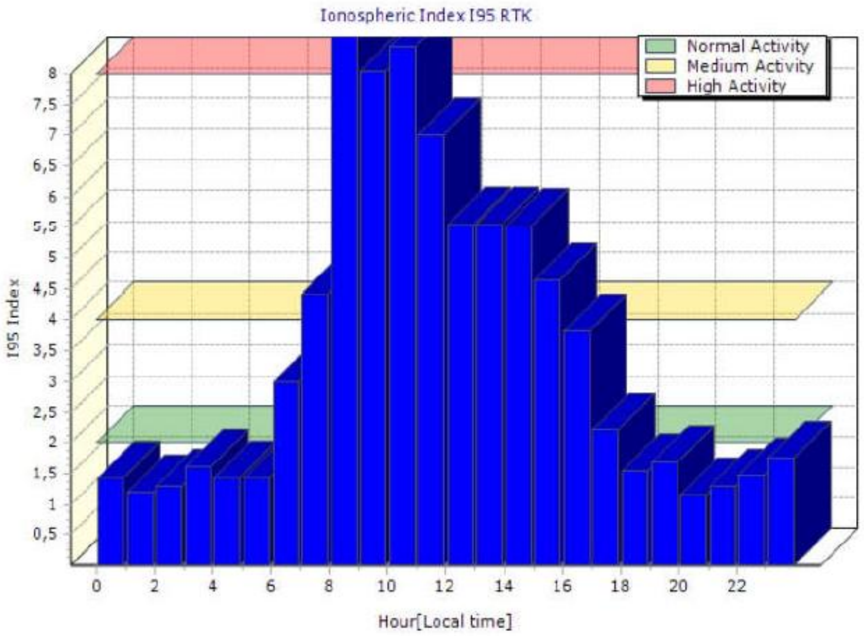
0 km

Observation plan: 15-11-2024

Session	Planned (GPST) Start	Planned (GPST) Stop	BASE	ROVER	Duration	Realized (GPST) Start	Realized (GPST) Stop	Duration	RANGE [m] ΔE	RANGE [m] ΔN	RANGE [m] Δh
1	07:00	07:30	NO	NO	00:30	07:08	07:32	00:24	0.019	0.031	0.043
2	07:35	08:05	IONO	IONO	00:30	07:34	08:05	00:30	0.026	0.048	0.061
3	08:10	08:25	IONO	NO	00:15	08:08	08:25	00:16	0.117	0.101	0.114
4	08:25	08:40	NO	IONO	00:15	08:28	08:40	00:11	0.115	0.108	0.151
5	08:45	09:15	IONO	IONO	00:30	08:45	09:15	00:30	0.021	0.033	0.069
6	09:20	09:50	NO	NO	00:30	09:18	09:50	00:31	0.015	0.032	0.048
7	09:55	10:25	IONO	IONO	00:30	09:54	10:25	00:30	0.029	0.050	0.164
8	10:30	11:00	NO	NO	00:30	10:27	11:00	00:32	0.023	0.026	0.054
9	11:05	11:35	IONO	IONO	00:30	11:02	11:35	00:32	0.024	0.027	0.061
10	11:40	12:10	NO	NO	00:30	11:37	12:10	00:33	0.015	0.023	0.046
11	12:15	12:45	IONO	IONO	00:30	12:12	12:45	00:33	0.023	0.031	0.056
12	12:50	13:20	NO	NO	00:30	12:46	13:20	00:33	0.020	0.033	0.063
13	13:25	13:55	IONO	IONO	00:30	13:24	13:55	00:31	0.022	0.039	0.075
14	14:00	14:15	IONO	NO	00:15	13:58	14:15	00:16	0.012	0.019	0.035
15	14:15	14:30	NO	IONO	00:15	14:18	14:31	00:12	0.015	0.020	0.058
16	14:35	15:05	IONO	IONO	00:30	14:34	15:05	00:30	0.021	0.031	0.078
17	15:10	15:40	NO	NO	00:30	15:07	15:40	00:33	0.020	0.030	0.048

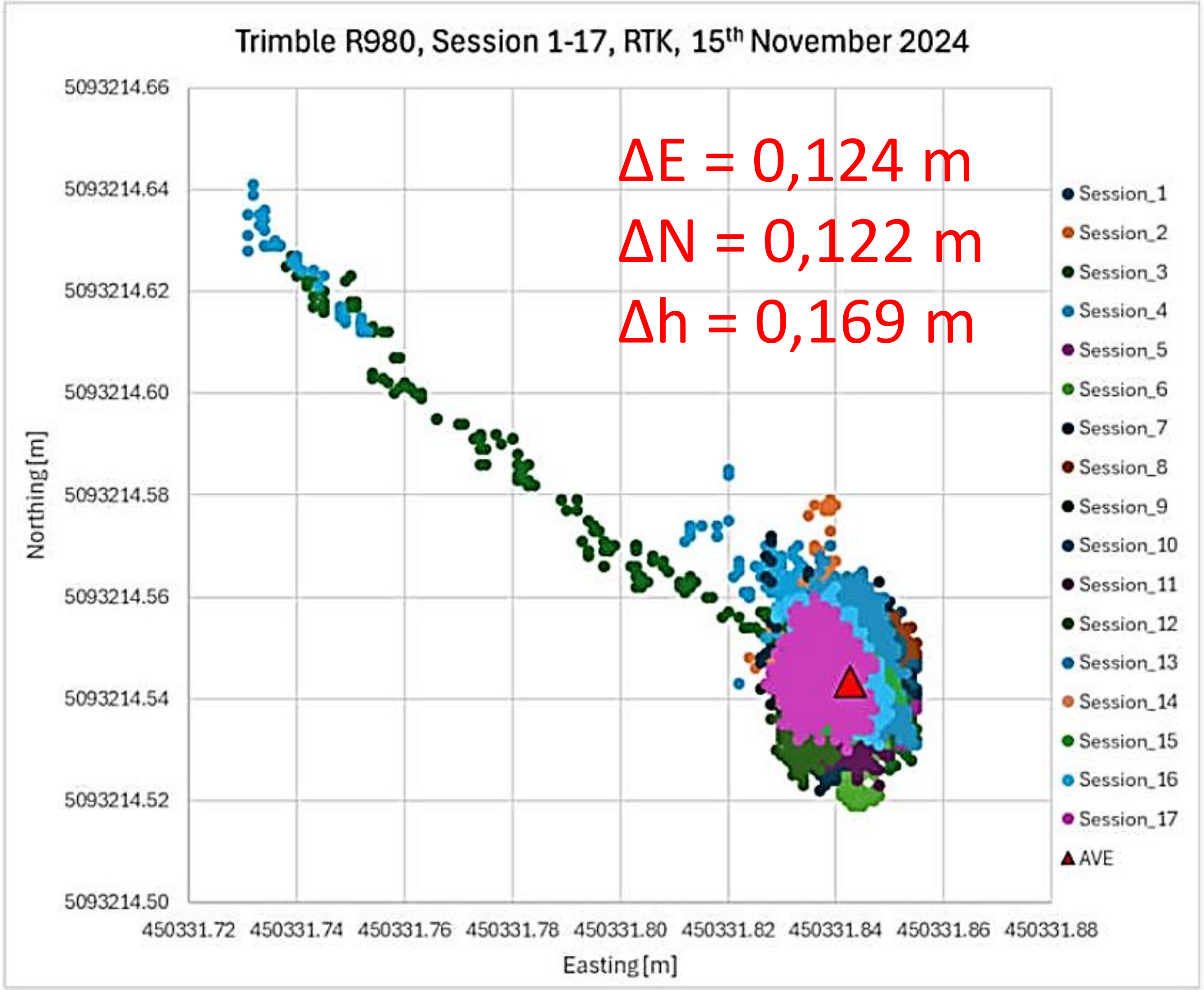
NO = IonoGuard **DISABLED**
IONO = IonoGuard **ENABLED**

	ΔE	ΔN	Δh
MIN:	0.012	0.019	0.035
MAX:	0.029	0.050	0.164



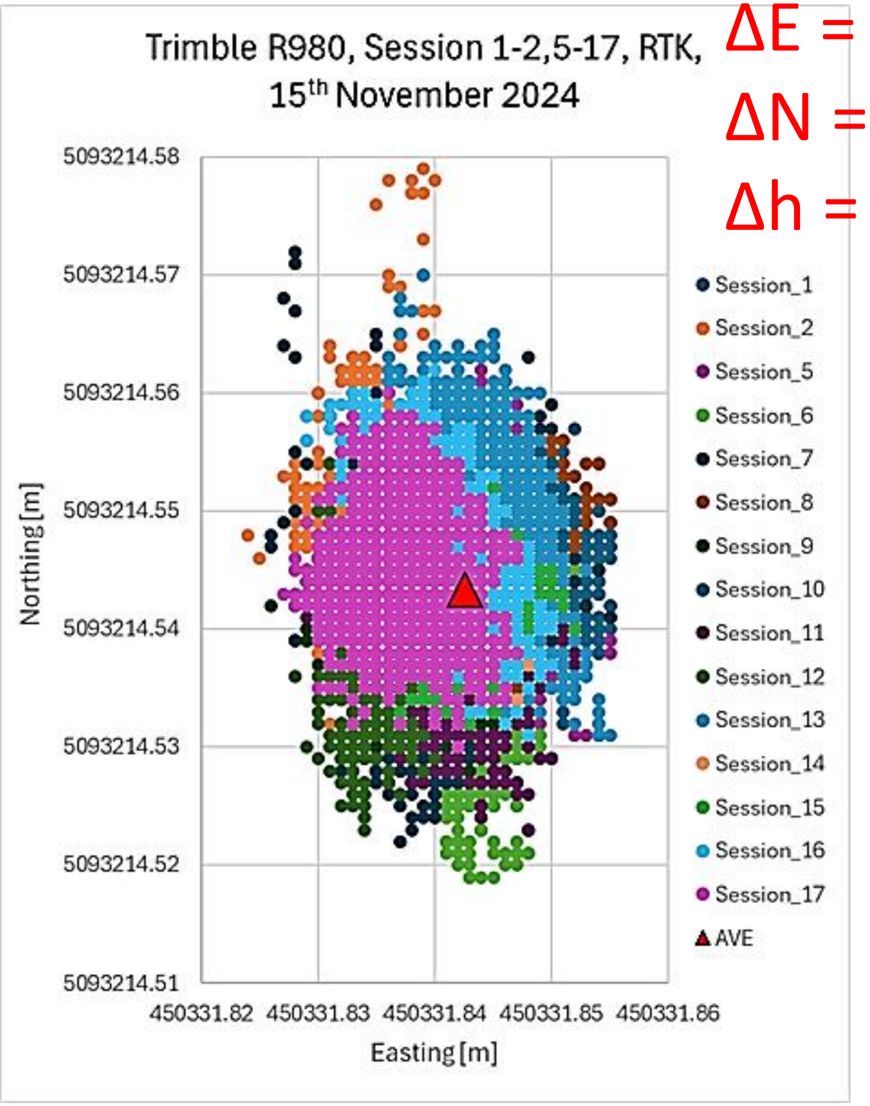
Results (E, N)

- 27975 results, 17 sessions



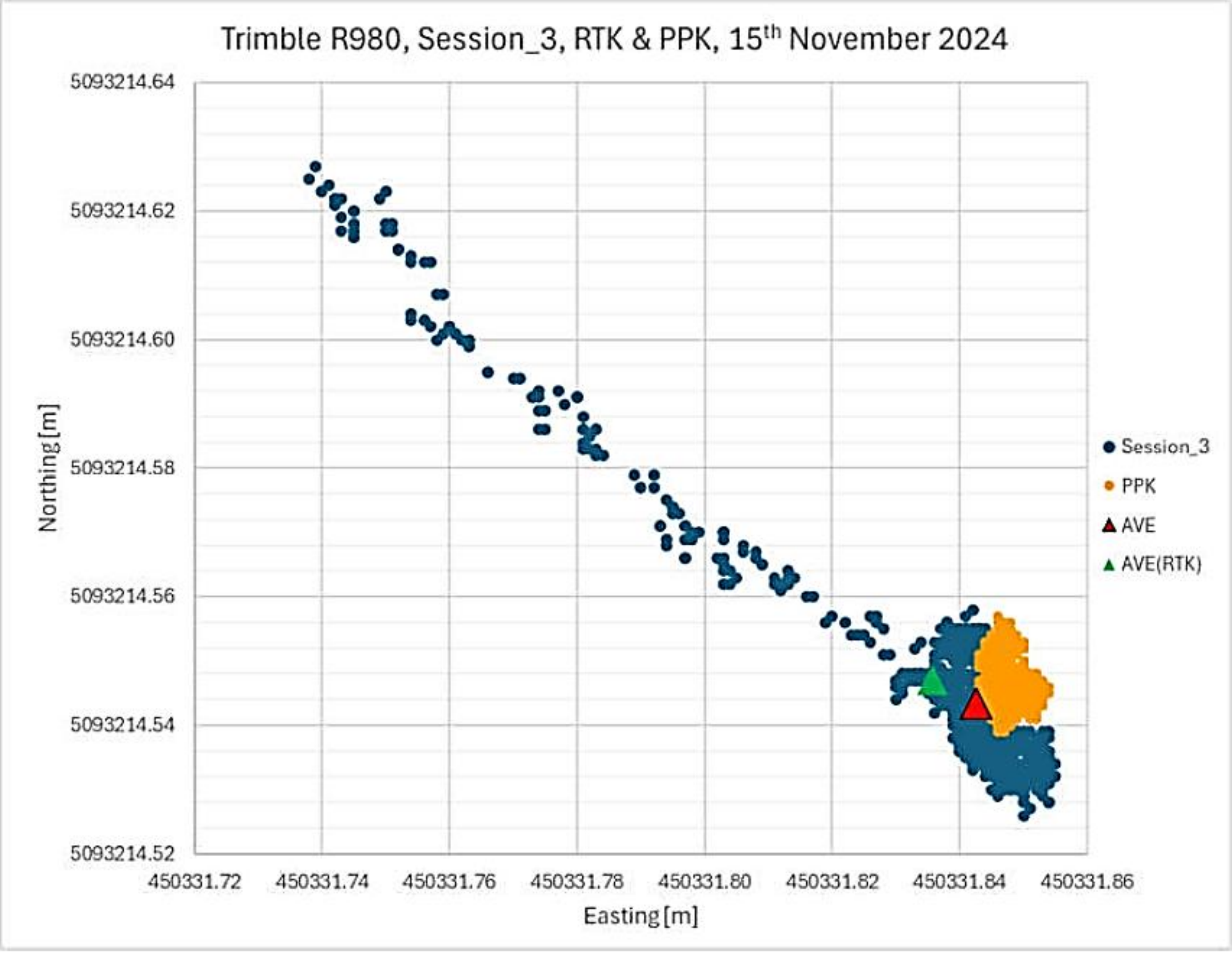
- 26274 results, 15 sessions

ΔE = 0,031 m
ΔN = 0,060 m
Δh = 0,164 m



Results: Session_3, I95 High activity (> 8)

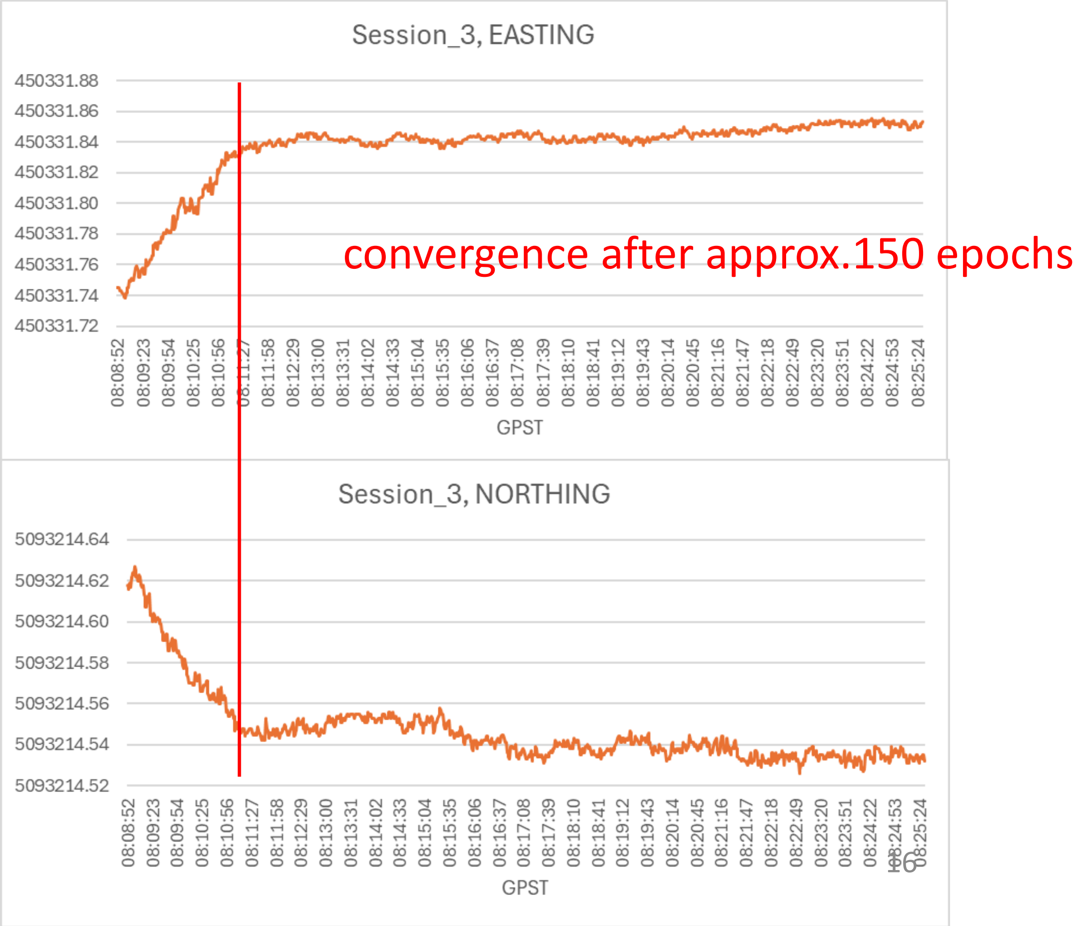
BASE	ROVER
IONO	NO



1000 results, 30-33 SV

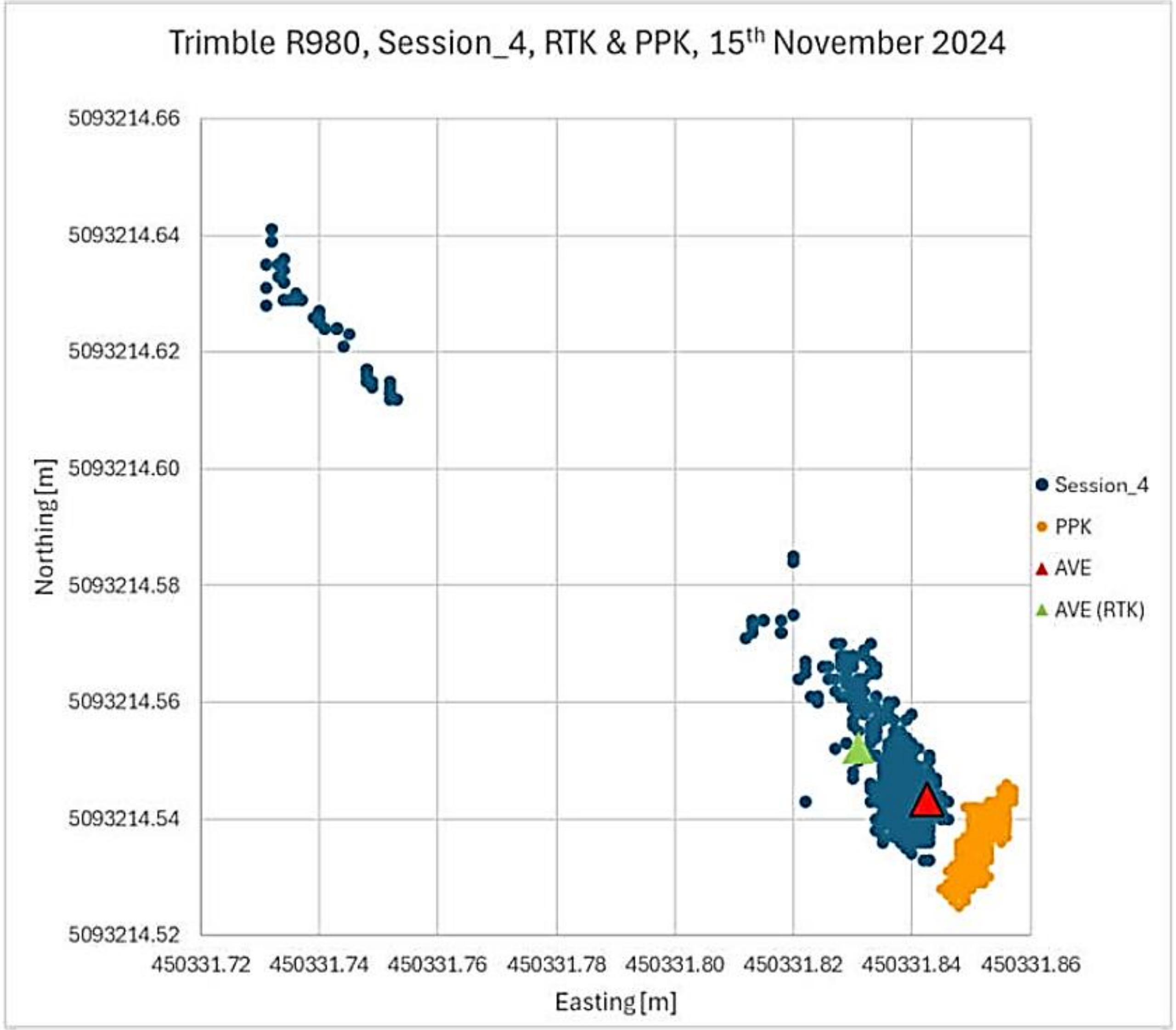
RTK:
ΔE = 0,117 m
ΔN = 0,101 m
Δh = 0,114 m

PPK:
ΔE = 0,011 m
ΔN = 0,018 m
Δh = 0,108 m



Results: Session_4, I95 High activity (> 8)

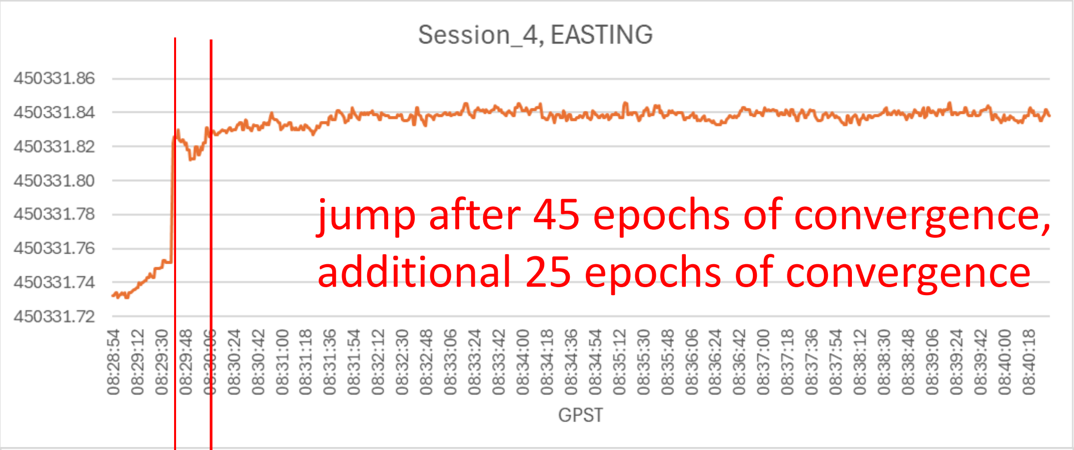
BASE	ROVER
NO	IONO

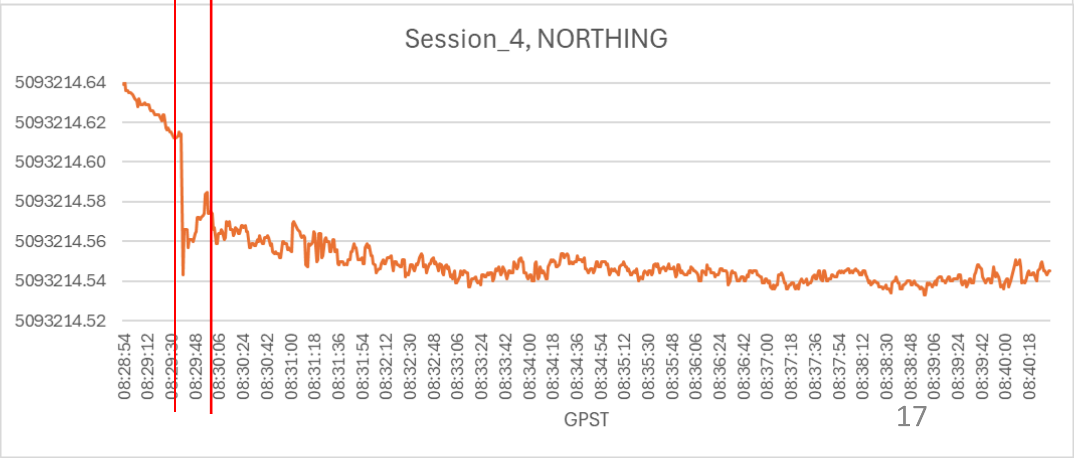


701 results, 32-34 SV

RTK:
ΔE = 0,115 m
ΔN = 0,108 m
Δh = 0,151 m

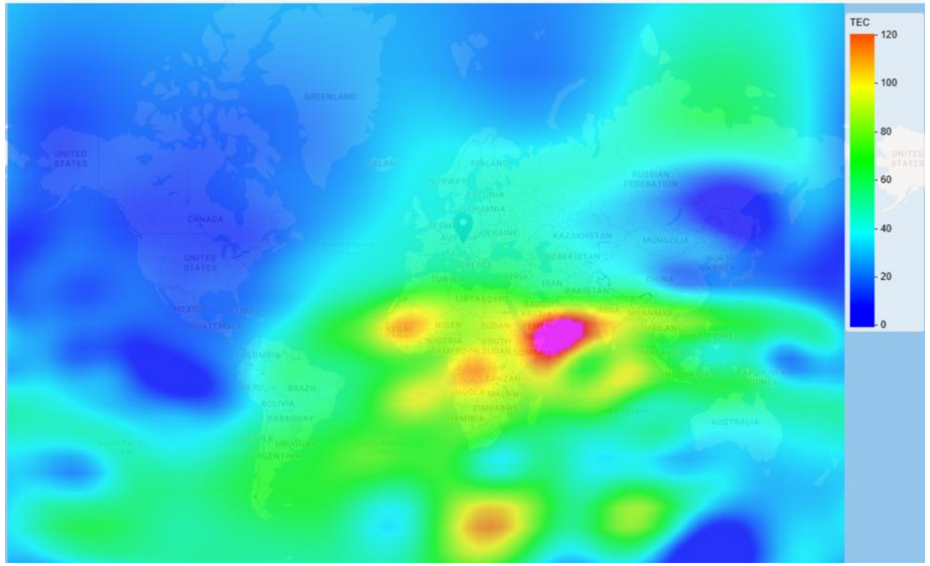
PPK:
ΔE = 0,013 m
ΔN = 0,022 m
Δh = 0,080 m

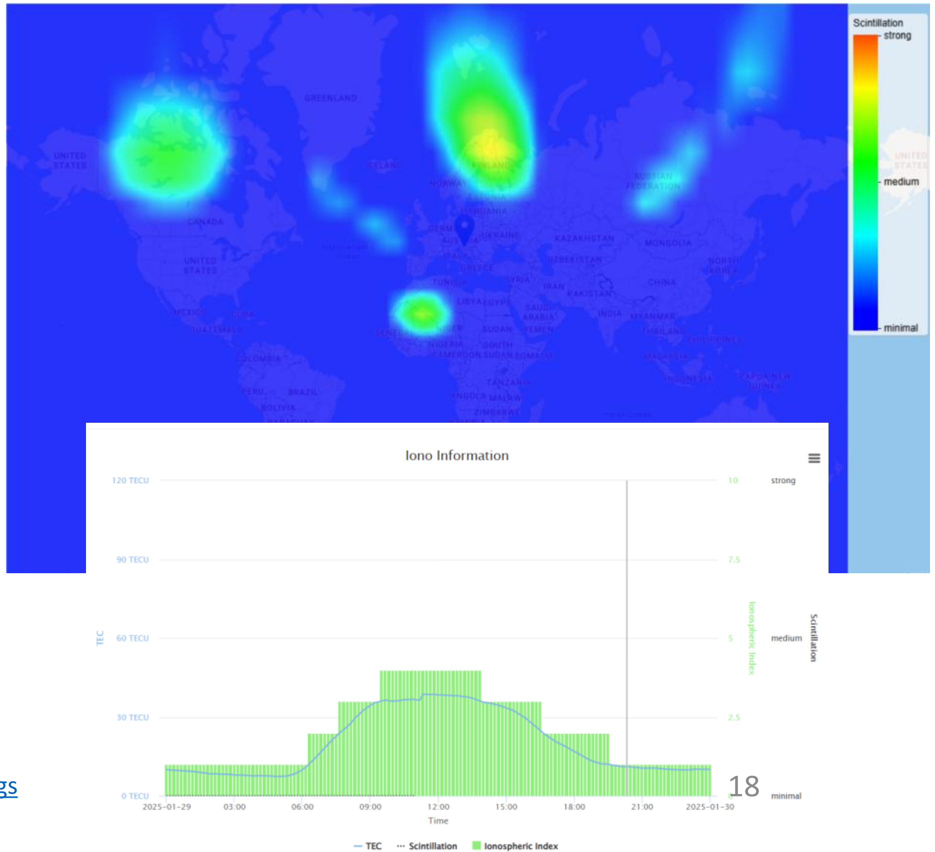




Mitigation measures

- installation of the latest firmware on the GNSS receiver to ensure best tracking and positioning performance
- use observations of multiple GNSS constellations (increased number of observations)
- use multi-frequency GNSS observations
- ensure the cut-off angle ≥ 10°
- when possible apply multiple occupations at different times under different ionospheric conditions
- check the current ionospheric impact in your region and monitor the ionospheric activity using appropriate web portals

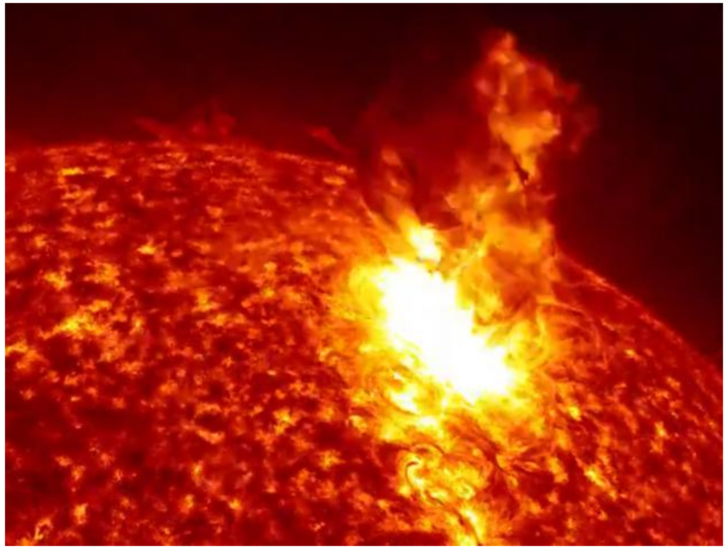


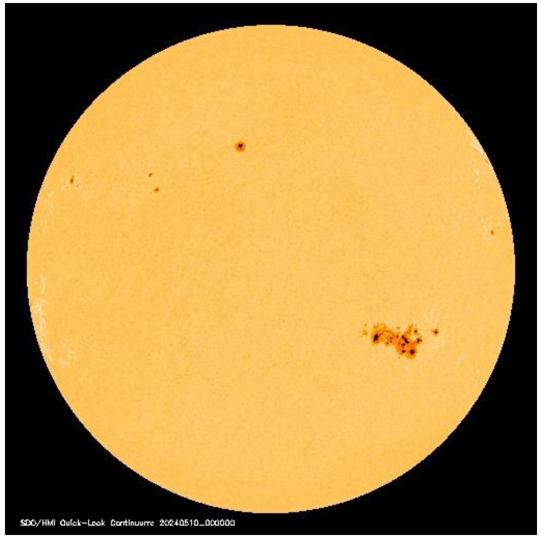


https://www.gnssplanning.com/#/settings

Conclusions:

- Ionosphere is the largest individual source of error for GNSS
- RTK method due to the spatial decorrelation of errors (iono, tropo, orbit) is specially vulnerable to ionospheric disruptions
- Ionospheric activity is pronounced under the Solar maximum
- Algorithms and technologies are being developed to mitigate the impact of ionosphere on GNSS measurements
- RTK SB positioning results at 24 km long baseline under higher iono activity have been presented
- Mitigation measures to ensure positioning performance: multi-constellation, multi-frequency, firmware update etc.
- GNSS planning taking into consideration space weather conditions (TEC, scintillation, iono indices etc.)




SDO/HMI Quick-Look Continuum 20240510_000000


UM652

Děkujeme za pozornost!