IGS 2026 WORKSHOP
SANTIAGO DE CHILE
33°26' S 70°39' O

1–5 June 2026

*Vinícius A. Stuani Pereira (UTFPR) – vpereira@utfpr.edu.br
João F. Galera Monico (UNESP) – galera.monico@unesp.br
Bruno C. Vani (IFSP)
Guilherme P. S. Rosa (UNESP)
Ítalo Tsuchiya (UNESP)
Cláudio J. B. Dal'Cól (VALE)

Monitoring ionospheric irregularities in Brazil using multifrequency and multiconstellation GNSS data

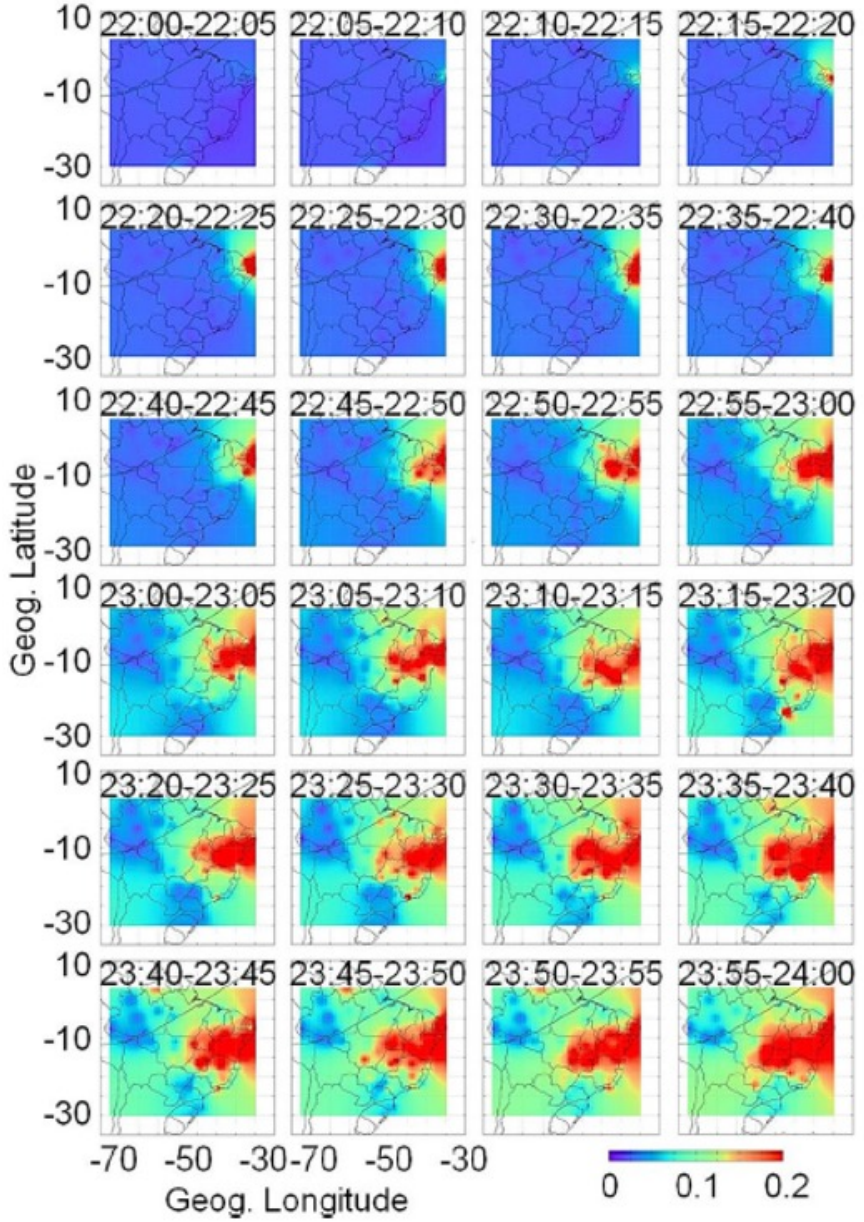
INTRODUCTION

- **Brazil** → located in the equatorial and low-latitude region, is among the countries most affected by ionospheric impacts on GNSS signals

Precision Agriculture

Autonomous Vehicles

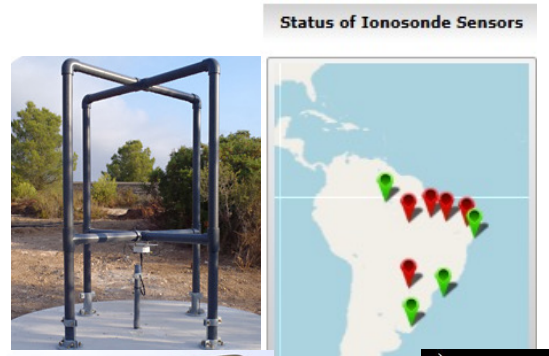
ROTI (GPS L1/L2)
22-24h UTC
Mar. 1, 2014



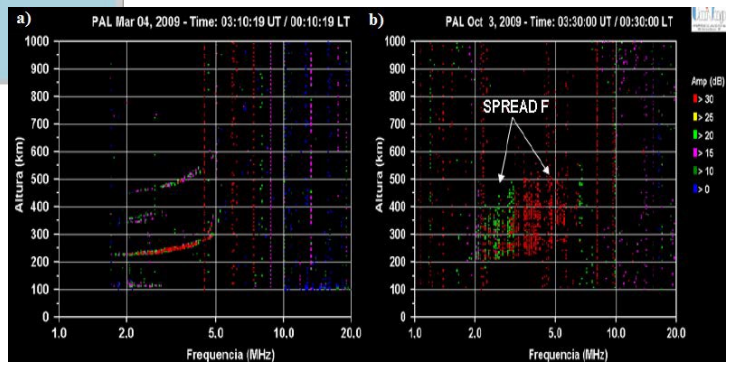
Stuani-Pereira, V. A.; Camargo, P. O - GPS Solutions (2017)
https://link.springer.com/article/10.1007/s10291-016-0589-y

INTRODUCTION

- Ionospheric monitoring is a challenge task, as the number of instruments dedicated to ionospheric observations in Brazil remains limited

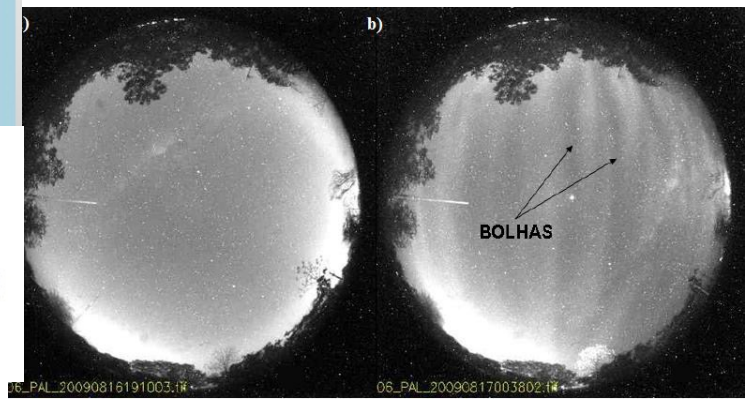


Ionosondes / INPE



INCT GNSS-NavAer Network
ISMR /Septentrio

All-Sky Imager / INPE

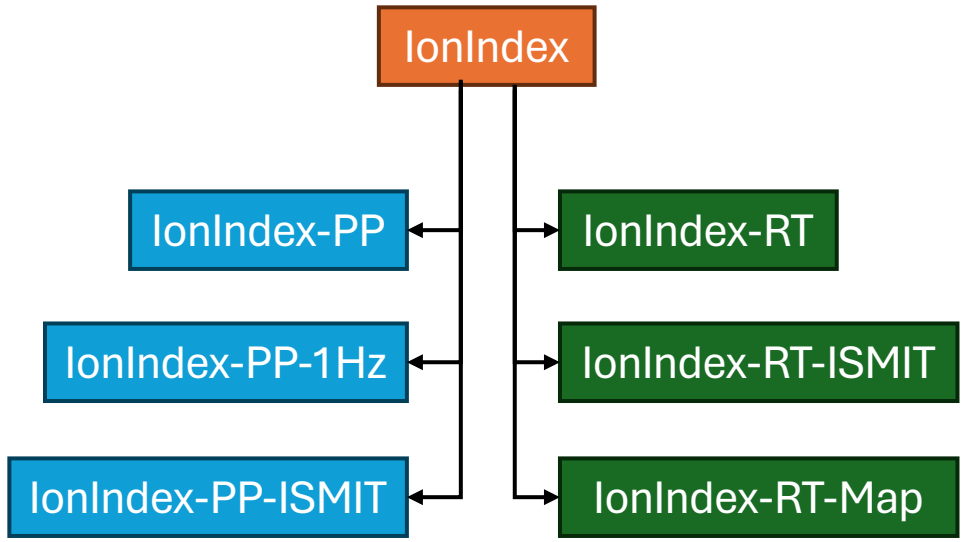


Aims

IonIndex

- **IonIndex** program → estimate the ROTI index from multifrequency and multiconstellation (MFMC) GNSS data, leveraging the existing infrastructure of active networks such as the RBMC and the INCT GNSS-NavAer network
  - Correlate post-processed results and the S4 index
  - Evaluate the accuracy of coordinates, with and without mitigation of irregularities
  - Provide a mechanism (map) that may establishes early warning for the occurrence of serious irregularities

IonIndex



- ROTI-MF proposed
- C language
- 6 modules (3 PP, 3 RT)
- MF (L1, L2, L5, G1 …, B2a)
- MC (GPS, GLO, GAL, BDS)

System	Carriers	Signals	Combina-tions
GPS	L1, L2, L5	C1C, L1C, C1L, L1L, C1X, L1X, C2L, L2L, C2W, L2W, C2X, L2X, C5Q, L5Q, C5X, L5X	Comb1_2 Comb1_5
GLO	G1, G2, G3	C1C, L1C, C1P, L1P, C2C, L2C, C2P, L2P, C3Q, L3Q, C3X, L3X	
GAL	E1, E6, E5b, E5, E5a	C1C, L1C, C1X, L1X C5Q, L5Q, C5X, L5X, C6B, L6B, C6C, L6C, C7Q, L7Q, C7X, L7X, C8Q, L8Q, C8X, L8X	
BDS	B1c, B1, B3, B2, B2a	C1P, L1P, C2I, L2I, C5P, L5P, C6I, L6I, C7D, L7D, C7I, L7I	

ROTI-MF

- Because multiple ROTI combinations can be derived for the same satellite within a given constellation, a new index, termed ROTI-MF (ROTI MF), is proposed

- ROTI-MF is defined as the mean of all available ROTI combinations for a given satellite at a specific epoch

$$TEC_r^s = \frac{f_i^2 f_j^2}{40.3\left(f_i^2 - f_j^2\right)}\left[\left(\lambda_j \phi_{j_r}^{\ s} - \lambda_i \phi_{i_r}^{\ s}\right) - \left(\lambda_i N_{i_r}^{\ s} - \lambda_j N_{j_r}^{\ s}\right) - e_{\phi_{ij}}\right]$$

$$ROT = \frac{TEC_{t_2} - TEC_{t_1}}{t_2 - t_1} = \frac{\Delta TEC}{\Delta t}$$

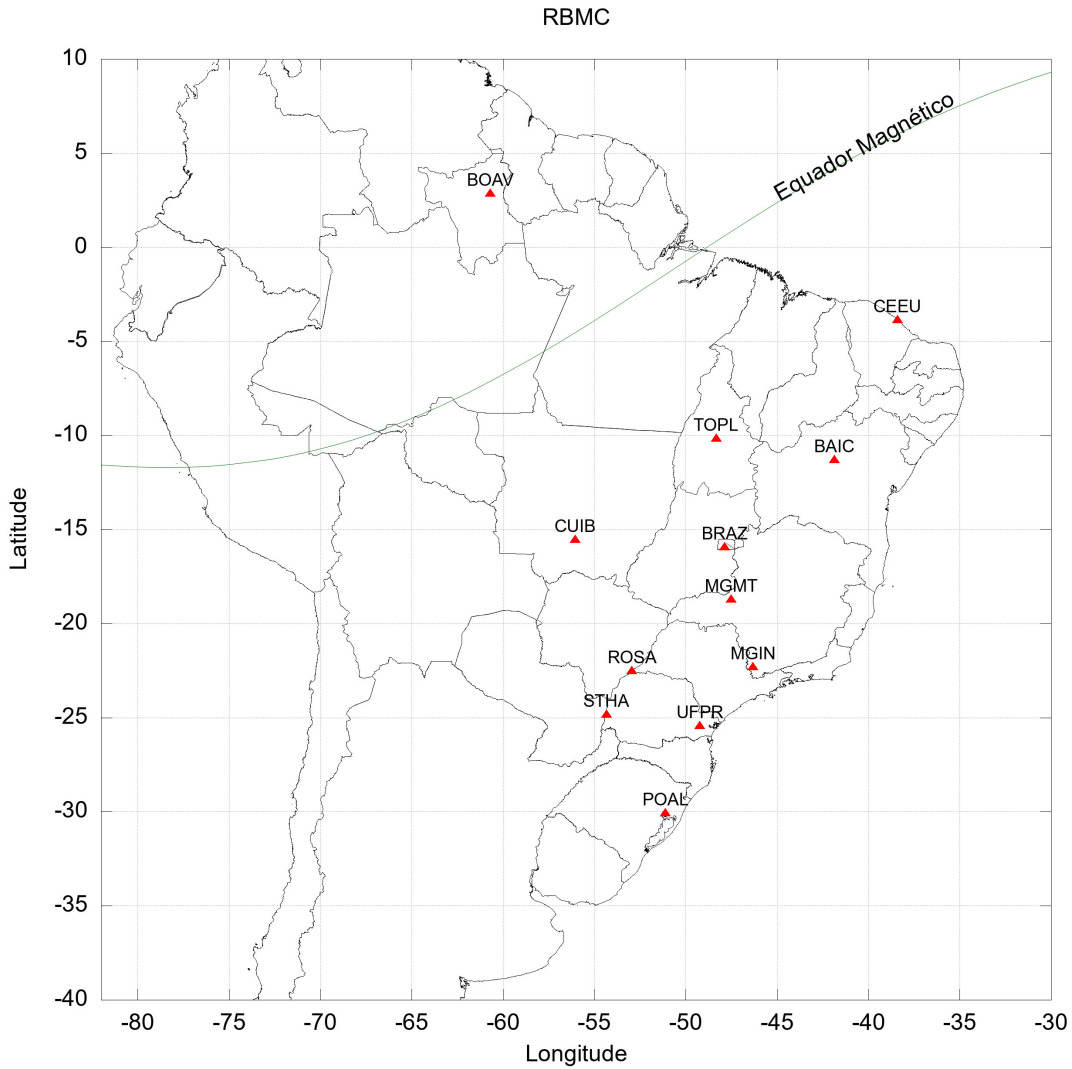
$$ROTI = \sqrt{\langle ROT^2 \rangle - \langle ROT \rangle^2}$$

$$ROTI\text{-}MF^t = \frac{\sum_i^{n^\circ\ combinations} ROTI_i^t}{n^{\underline{o}}\ conbinations}$$

For each constellation (MC)

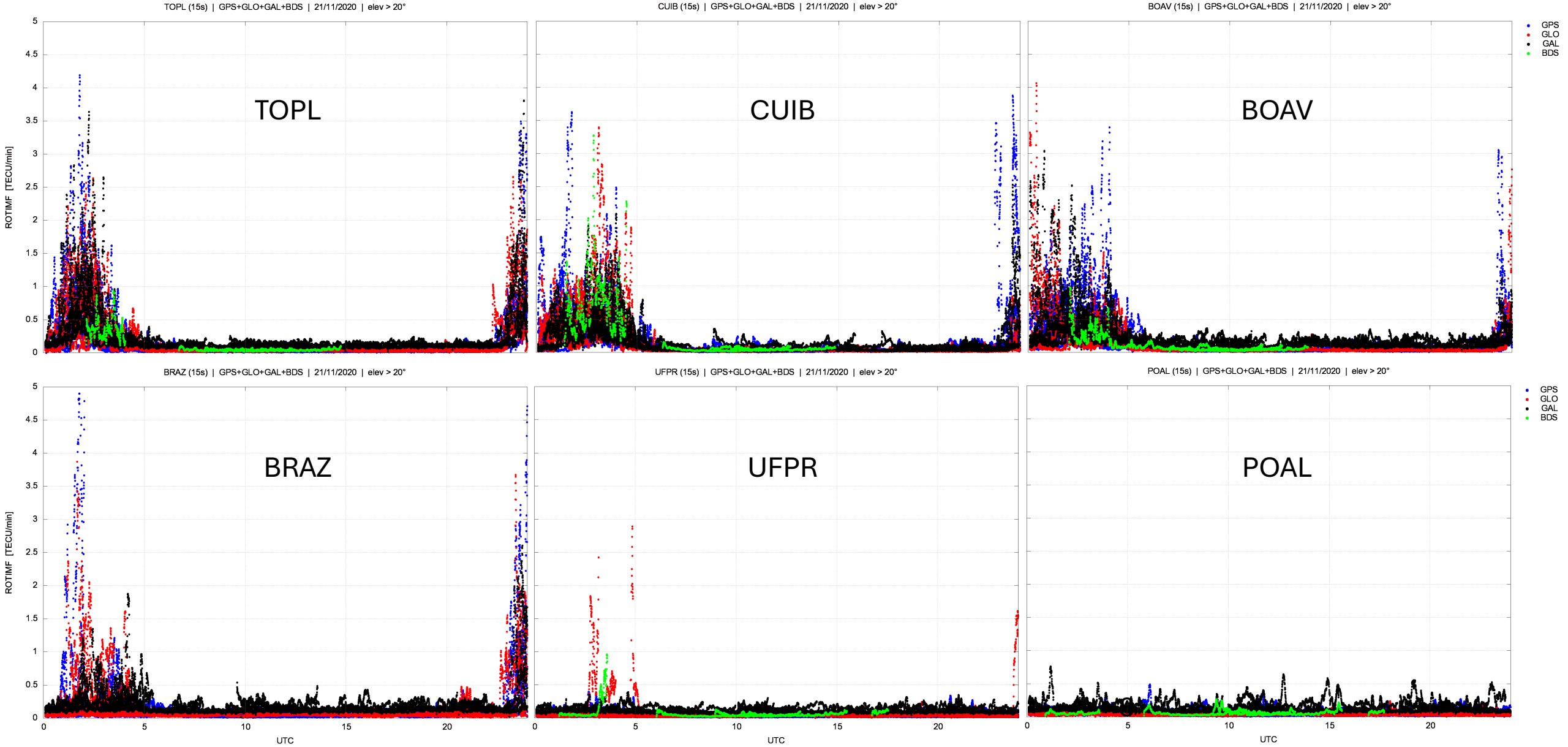
ROTI-MF POST-PROCESSED (PP)

- IonIndex-PP (15s sampling)
- 12 RBMC stations
- 21st/month (sazonal variaton) from 2020 to 2025 (long-period variation)
- 20° mask

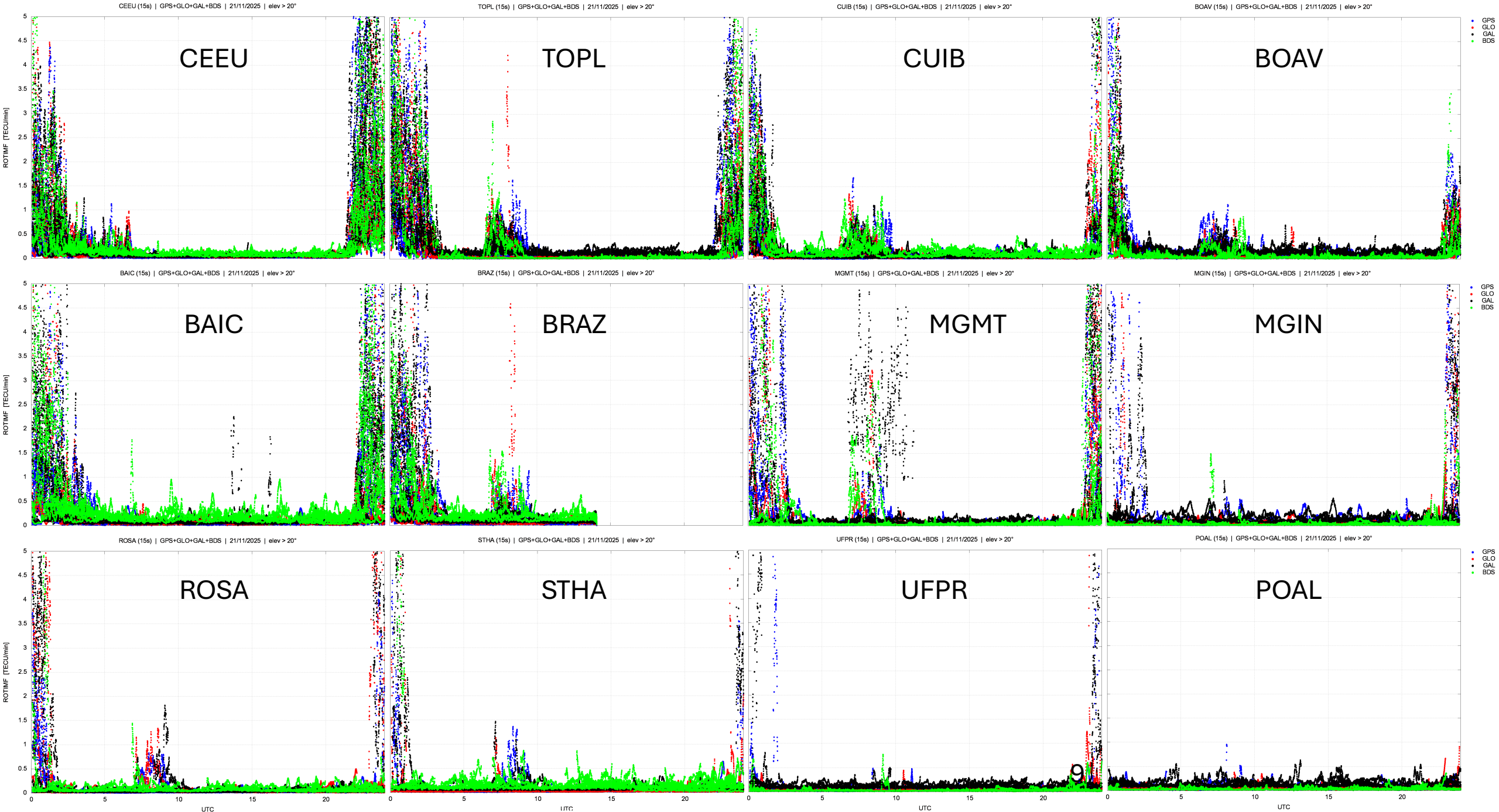


ROTI-MF POST-PROCESSED (PP)

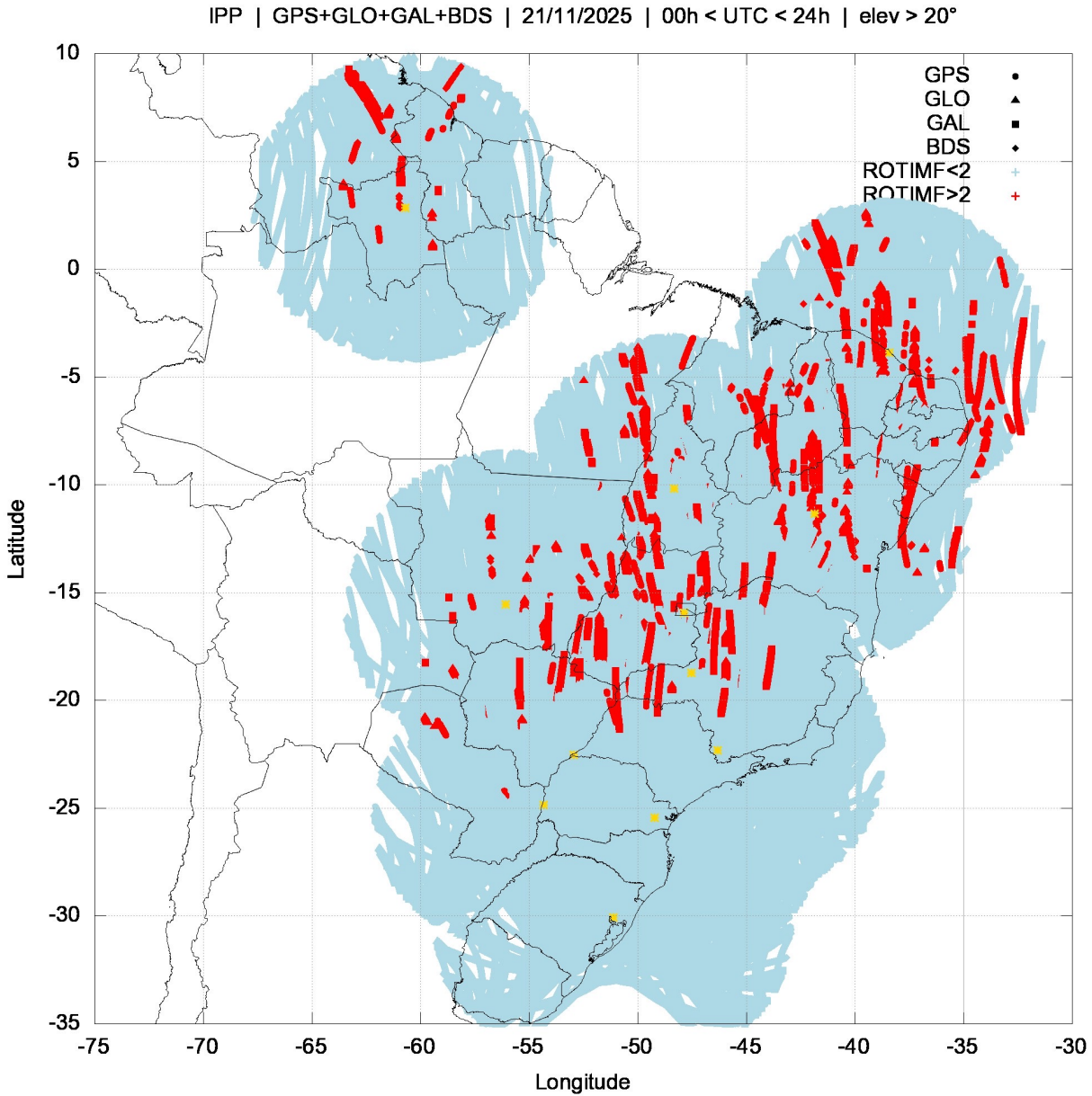
November/2020



November/2025



ROTI-MF POST-PROCESSED (PP)



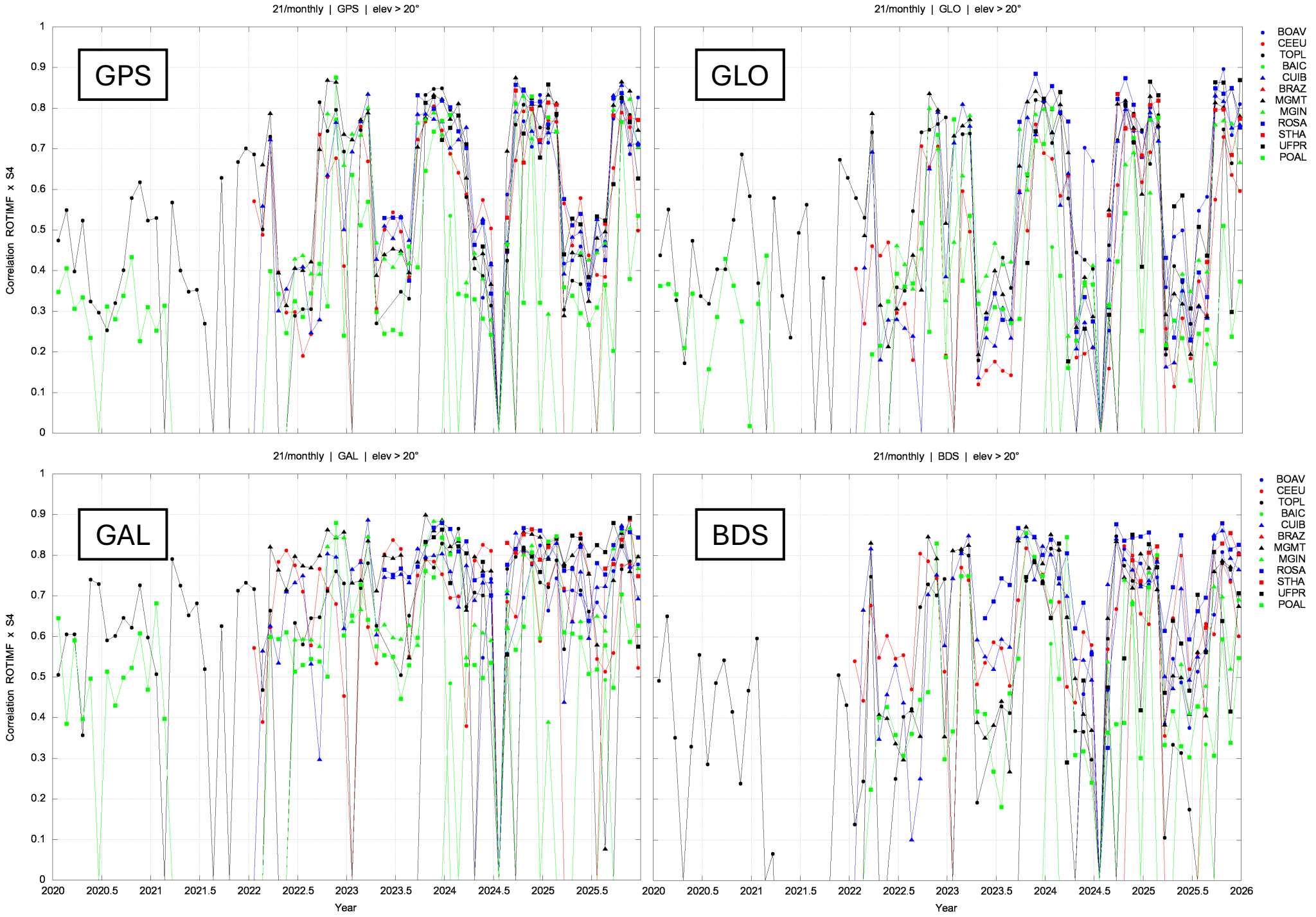
- Fountain effect (Equatorial Ionization Anomaly)
  - Near the Geomagnetic Equator and in mid-latitudes → smoothly values
  - Region of the southern and northern crest of the EIA → high ionospheric irregularities

CORRELATION ROTI-MF x S4

- ROTI-MF:
  - IonIndex-PP
  - 12 RBMC stations
  - 21st/month – 2020 to 2025
  - 20° mask

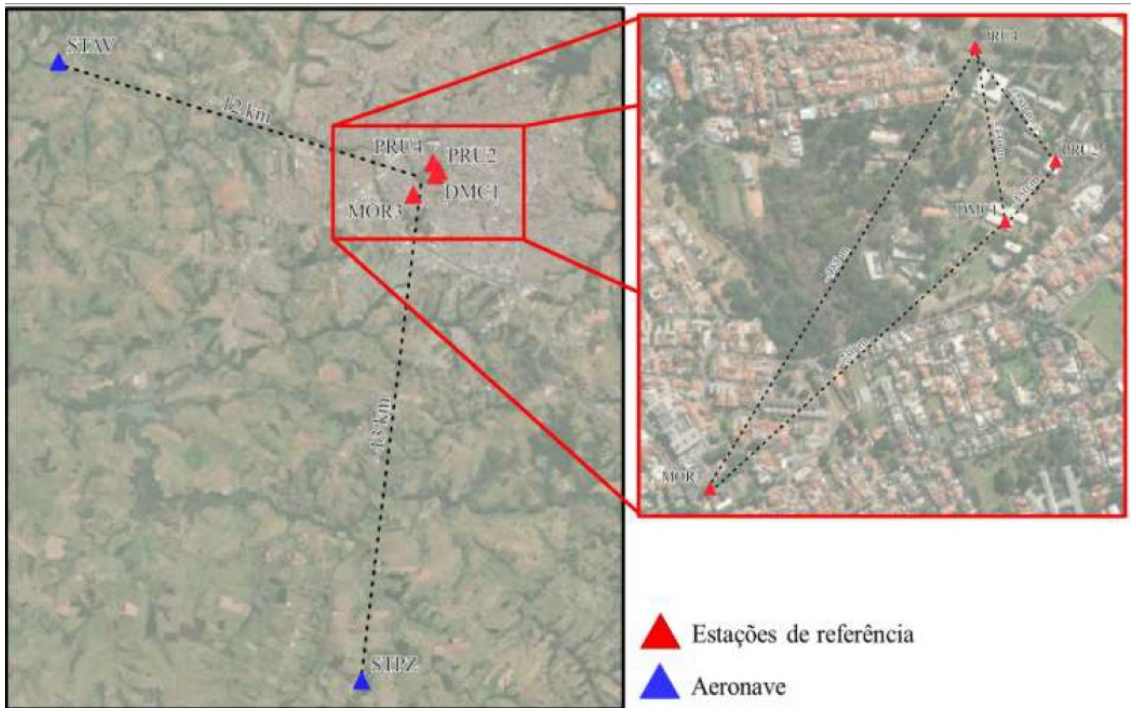
- S4:
  - ISMR Query Tool
  - 12 INCT nearest stations
  - 21st/month – 2020 to 2025
  - 20° mask

RBMC	INCT	Distance [km]
BOAV	STBV	1.3
CEEU	FRTZ	36.7
TOPL	PALM	3.8
BAIC	STSB	212.3
CUIB	STCB	0.1
BRAZ	SBTZ	20.5
MGMT	STMC	0.1
MGIN	INCO	0.1
ROSA	ROSA	0.1
STHA	STSH	0.2
UFPR	STCT	1.1
POAL	POAL	0.1


21/monthly | GPS | elev > 20°
GPS
21/monthly | GLO | elev > 20°
GLO
21/monthly | GAL | elev > 20°
GAL
21/monthly | BDS | elev > 20°
BDS
Correlation ROTIMF x S4
Year
BOAV
CEEU
TOPL
BAIC
CUIB
BRAZ
MGMT
MGIN
ROSA
STHA
UFPR
POAL

ROTI-MF x PPK x MITIGATION

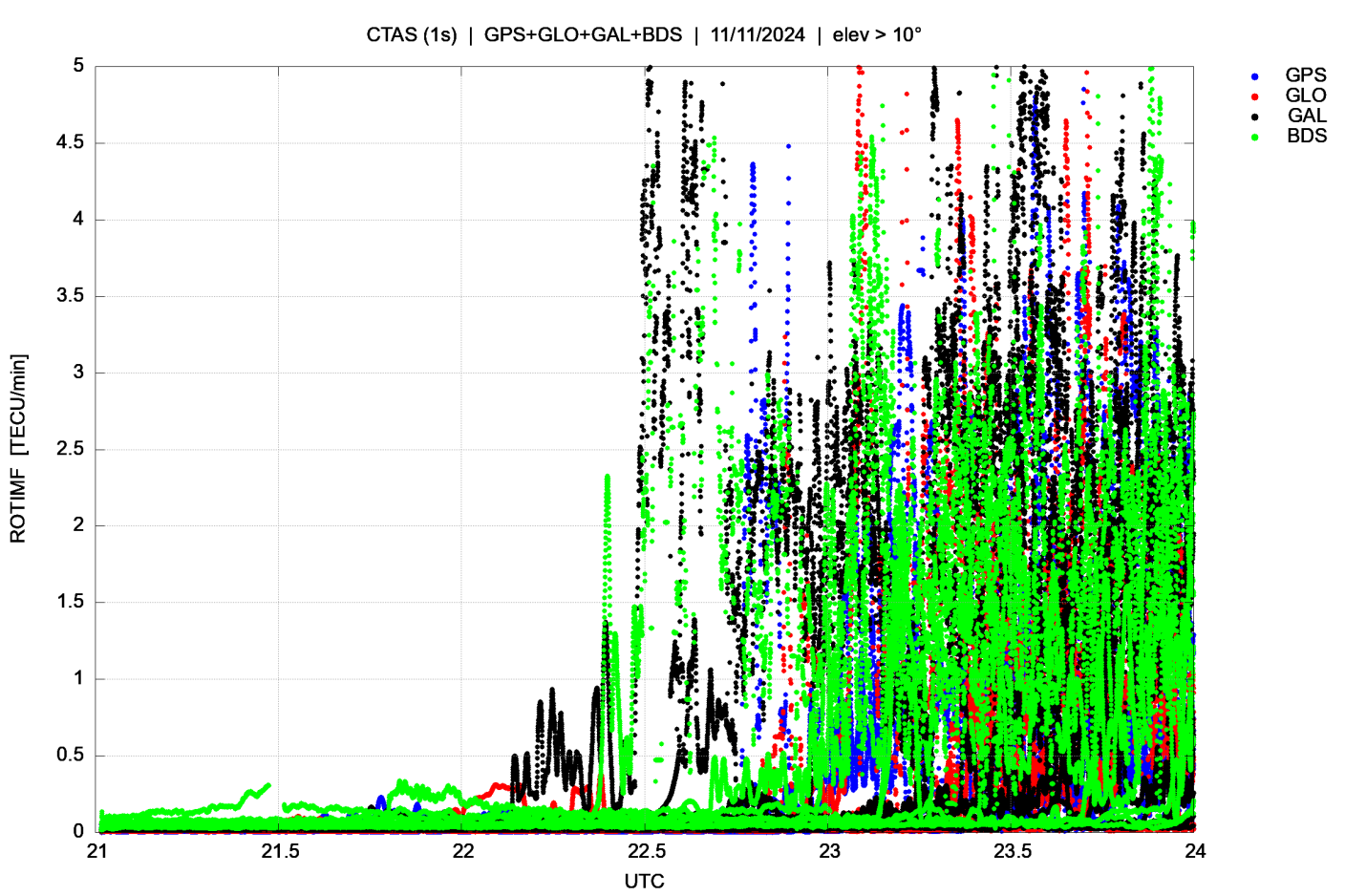
- IonIndex-PP-ISMIT / RTKLib
- Date:
  - Nov. 11, 2024 → high ionospheric irregularity
- Time interval:
  - 21h - 24h UTC
- Baseline:
  - Short → Base: CTAS Rover: MOR3 (~0,7 km)
  - Long → Base: CTAS Rover: STAV (~9,9 km)
- Ionosphere mode:
  - Baseline Short → BRDC
  - Baseline Long → DUAL-FREQ
- Ambiguity solution:
  - continuous

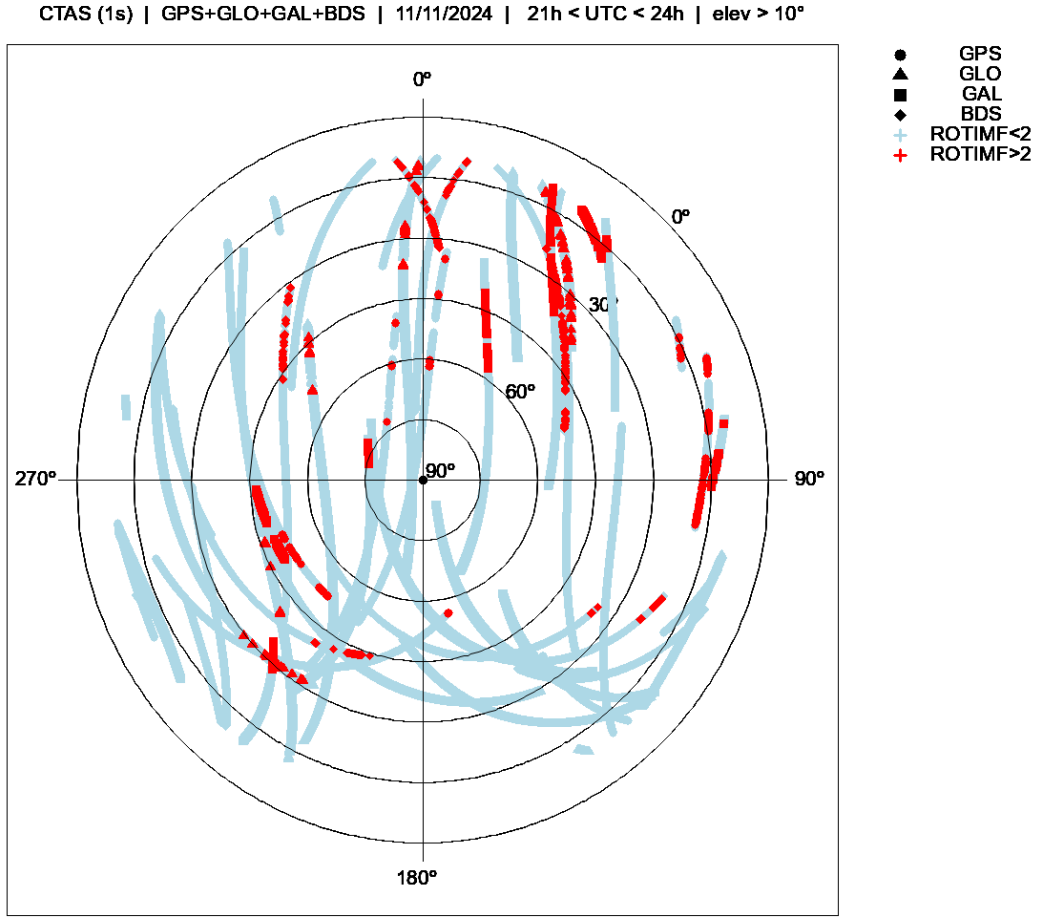


- Carriers:
  - L1 + L2
- Constellations:
  - GPS + GAL + BDS

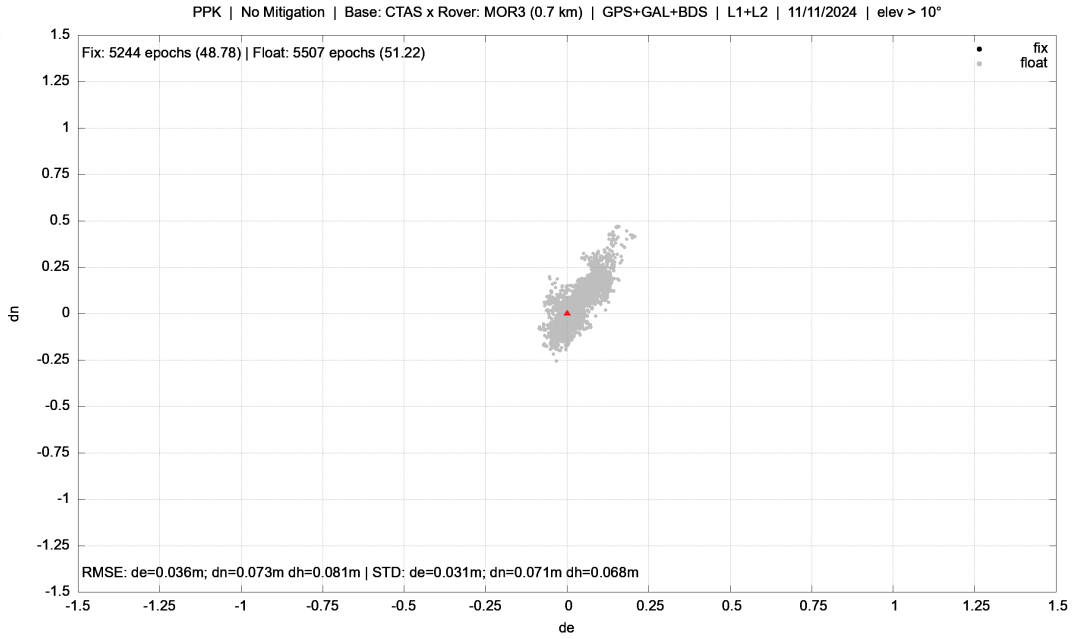
- Mitigation (weighting by ROTI-MF):
  - No
  - Yes (maxvar = 0,10 e quarepochs = 1)
- Mask:
  - 10°

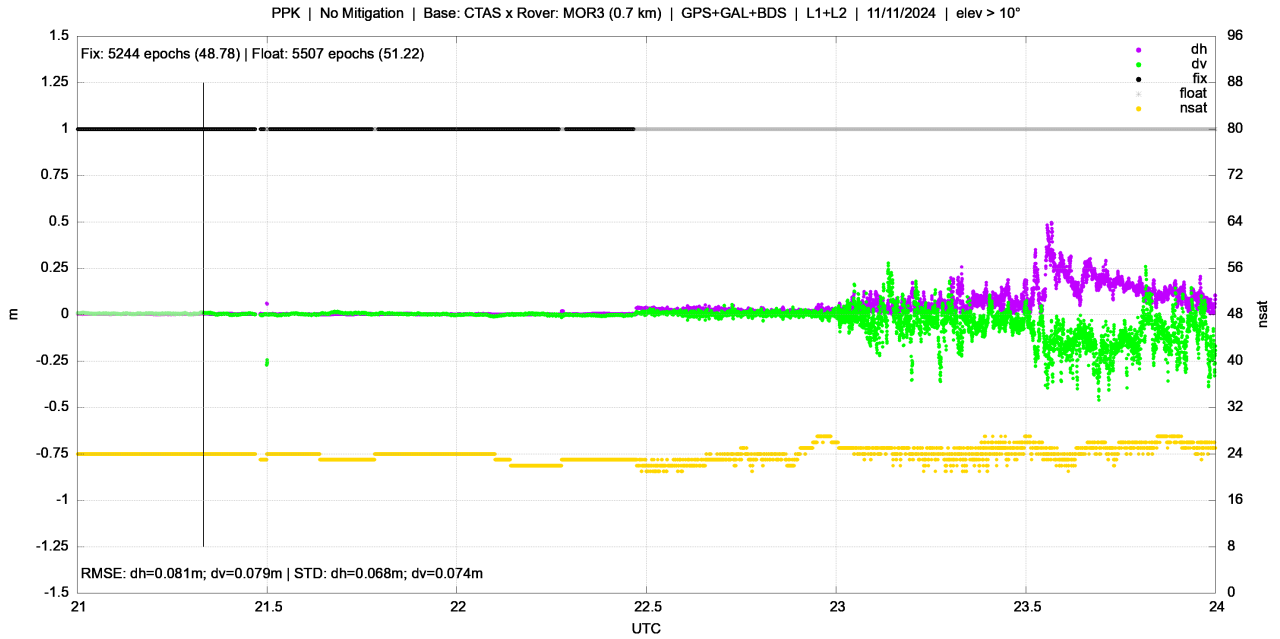
ROTI-MF x PPK x MITIGATION

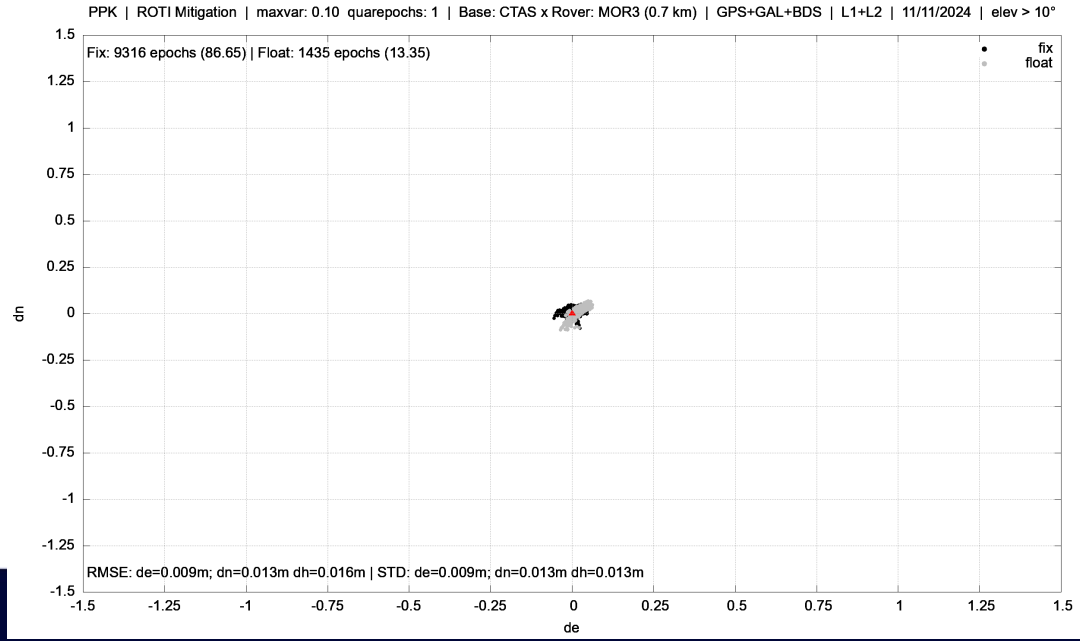


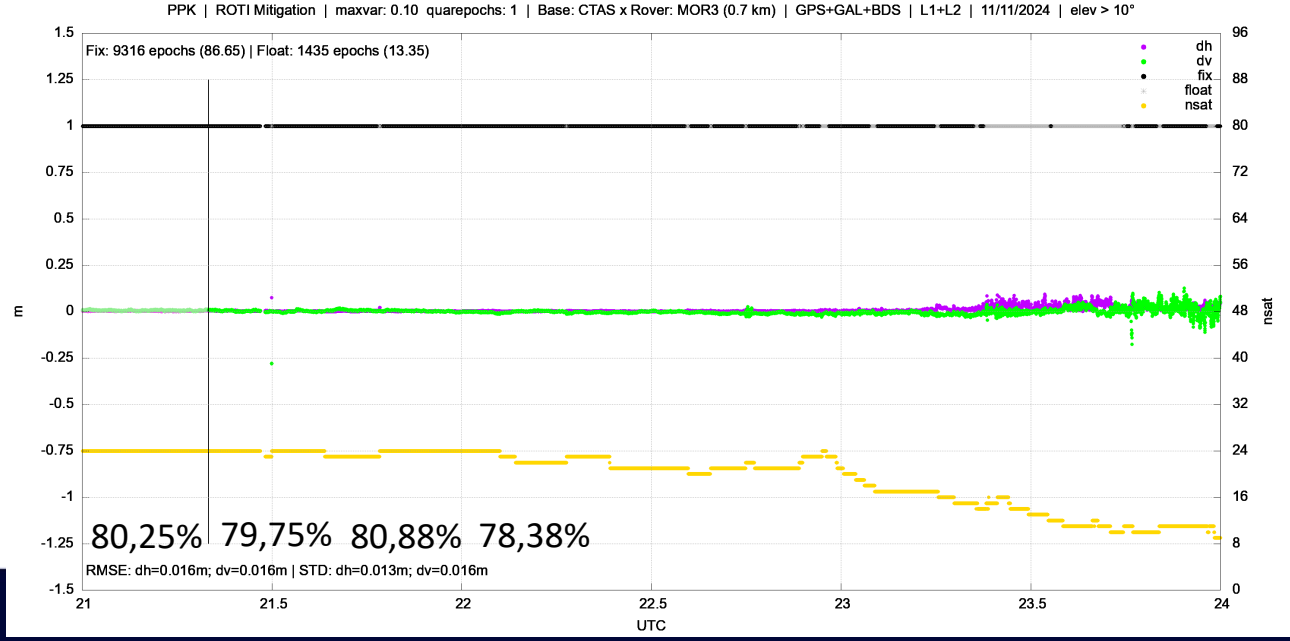


- Nov. 11, 2024 (high ionospheric irregularity)
  - Short baseline (CTAS x MOR3)

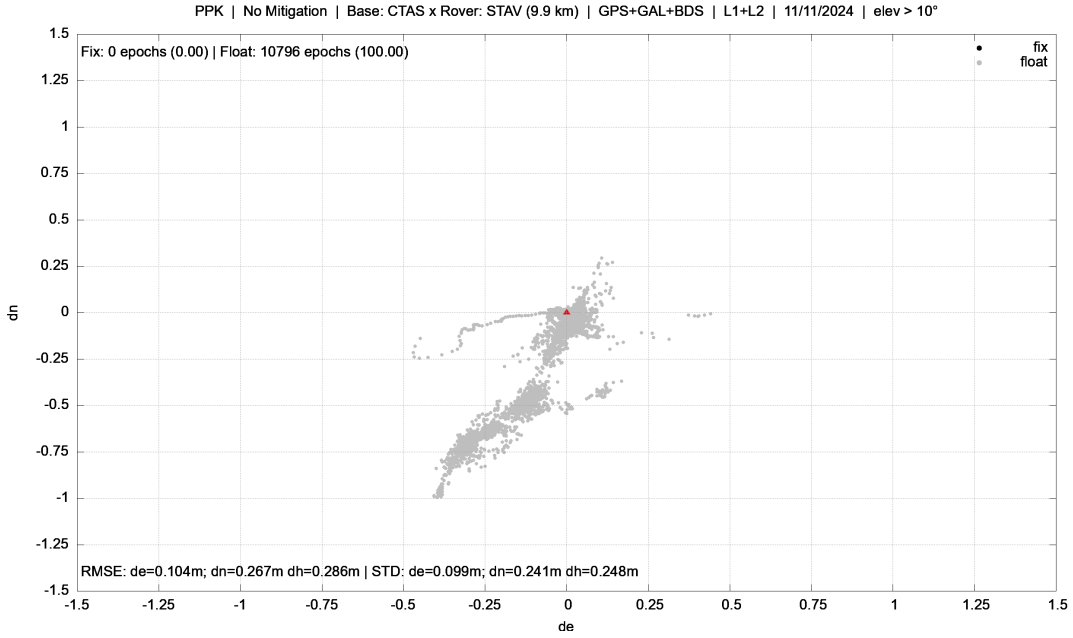


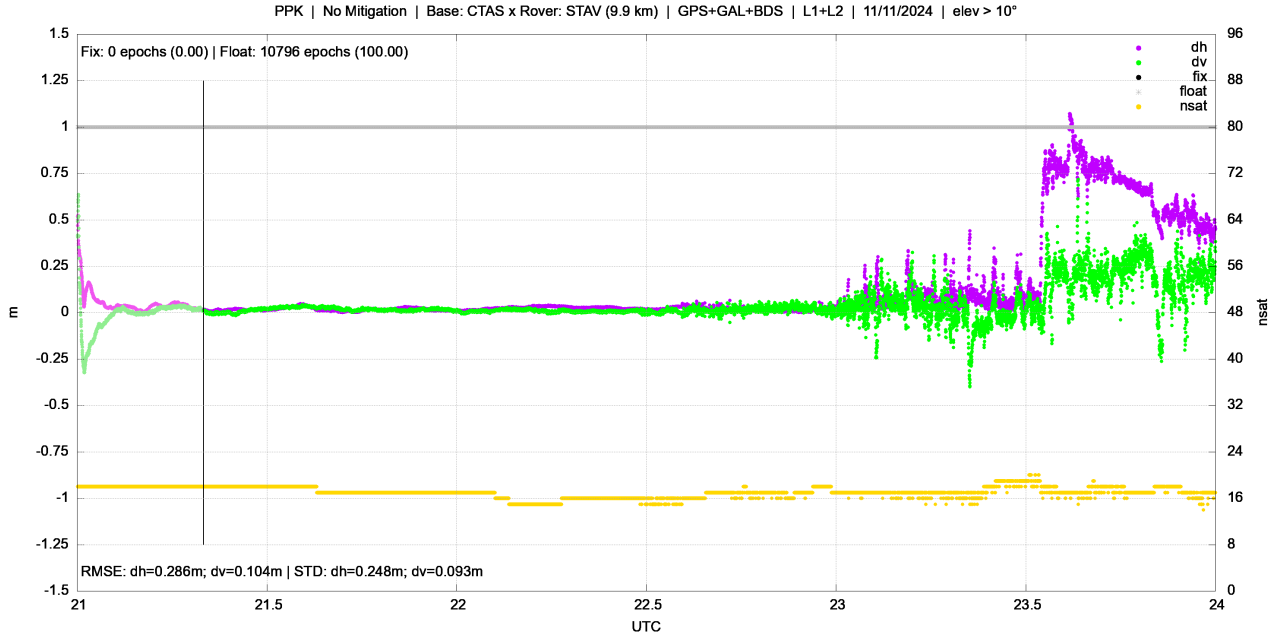


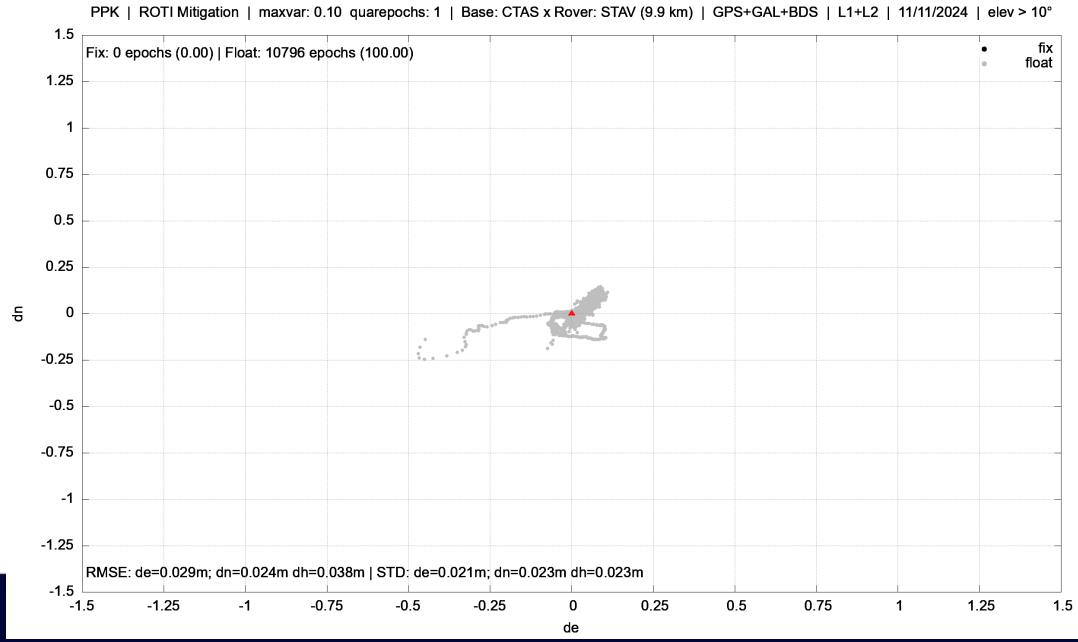


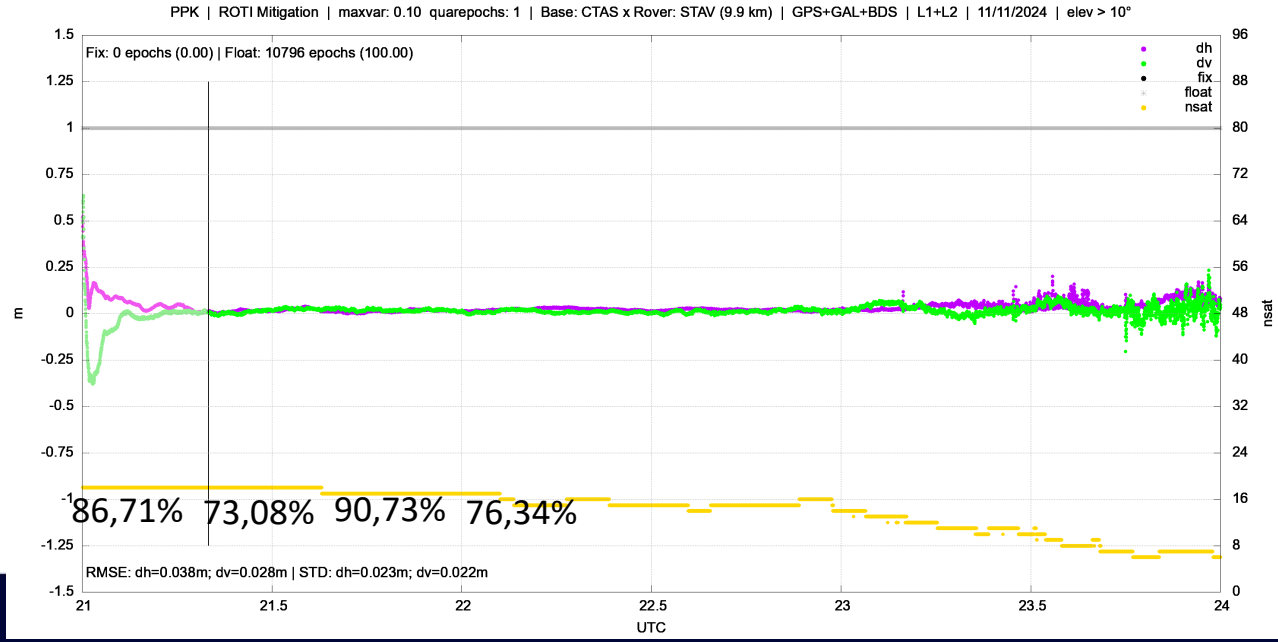


- Nov. 11, 2024 (high ionospheric irregularity)
  - Long baseline (CTAS x STAV)



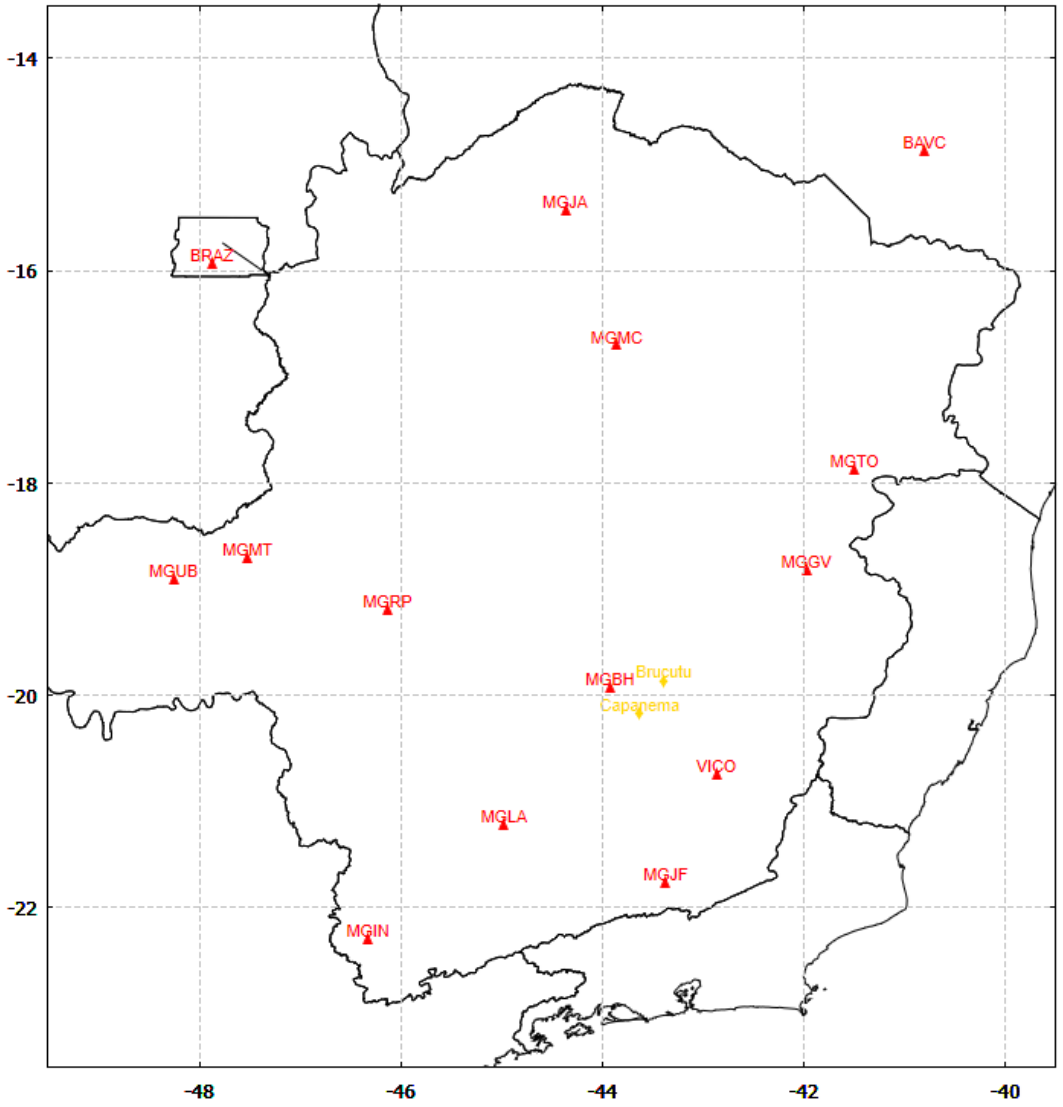


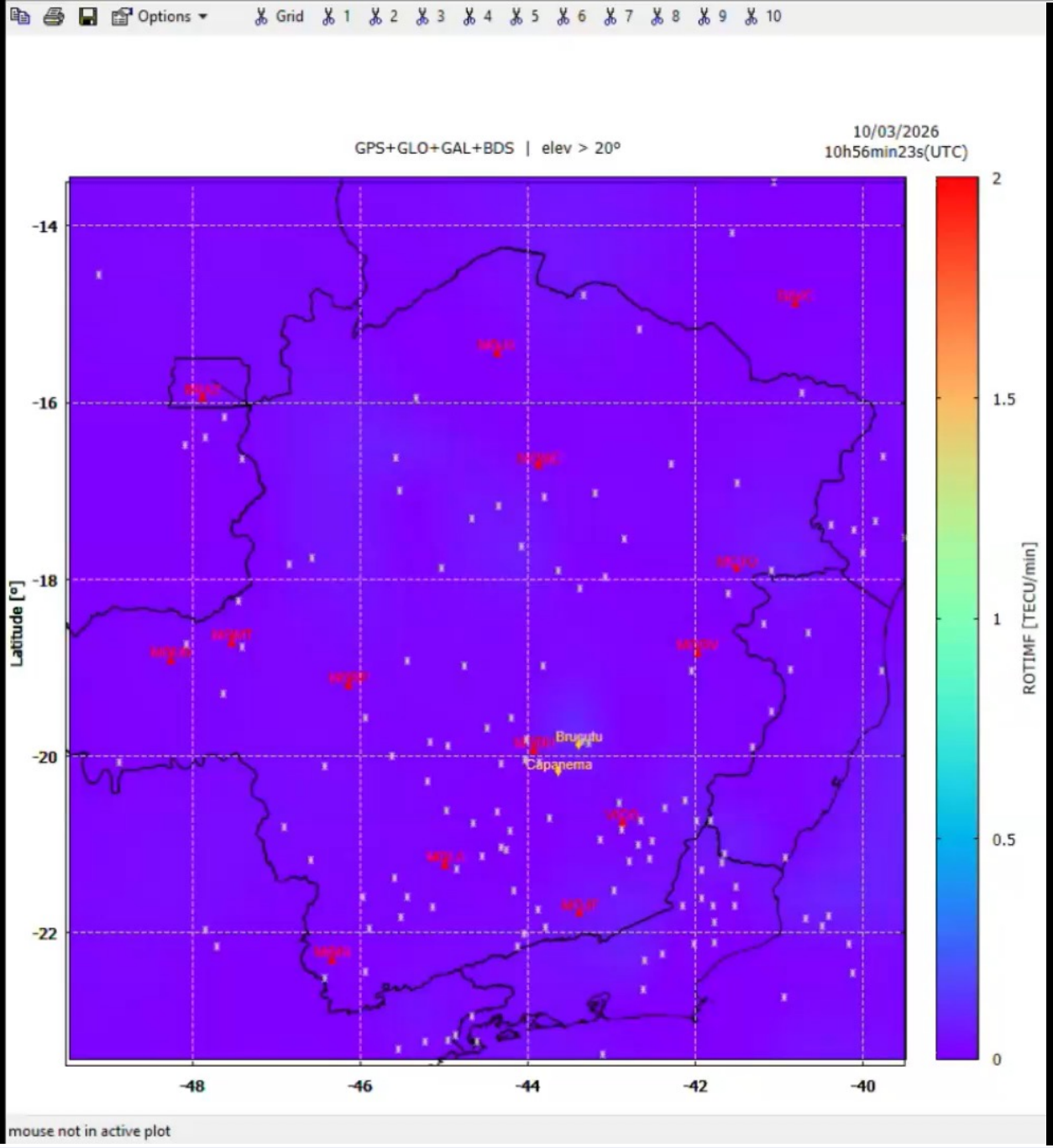


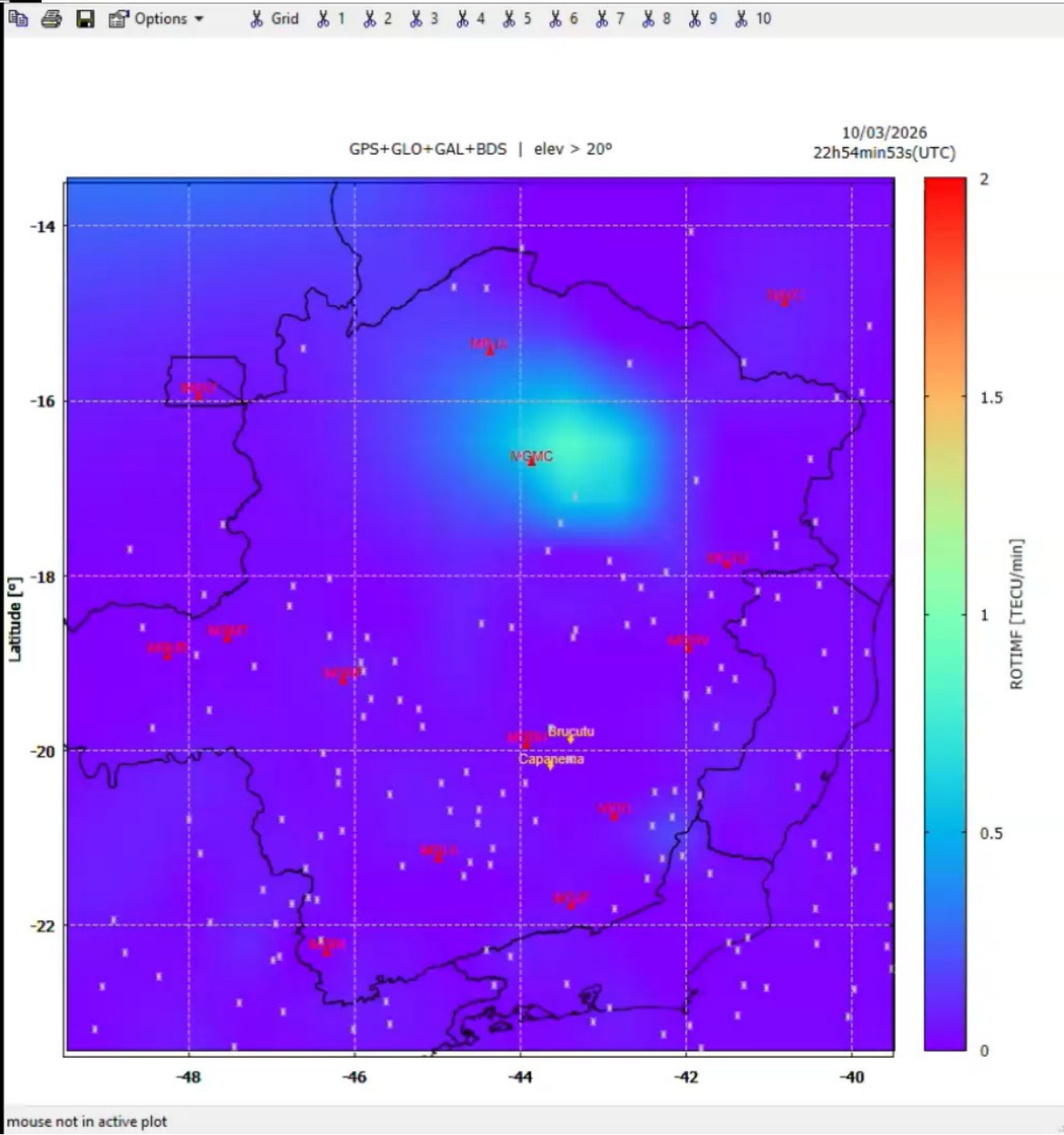


REAL TIME ROTI-MF MAPS

- IonIndex-RT-Map
- 14 RBMC-IP stations in Minas Gerais State
- BNC Caster IBGE connection
- Real time ROTI-MF estimation and plotting on IPP + interpolation
- Generating 1s maps




Options
Grid 1 2 3 4 5 6 7 8 9 10
GPS+GLO+GAL+BDS | elev > 20°
10/03/2026
10h56min23s(UTC)
Latitude [°]
-14
-16
-18
-20
-22
-48
-46
-44
-42
-40
Brucutu
Capanema
ROTIMF [TECU/min]
2
1.5
1
0.5
0
mouse not in active plot


Options
Grid 1 2 3 4 5 6 7 8 9 10
GPS+GLO+GAL+BDS | elev > 20°
10/03/2026
22h54min53s(UTC)
Latitude [°]
-14
-16
-18
-20
-22
-48
-46
-44
-42
-40
Brucutu
Capanema
ROTIMF [TECU/min]
2
1.5
1
0.5
0
mouse not in active plot

CONCLUSIONS

- The program **ionindex** enables the monitoring of the ionospheric layer for any region that has a GNSS station, both post-processed and in real time
- The use of MFMC data ensures greater reliability in ROTI estimates
- Mitigating ionospheric effects on PPK, through weighting by ROTI-MF, has shown that it is possible to improve accuracy in positioning under anomalous ionospheric conditions.

- Next steps:
  - Generate ionospheric bulletins for specific locations
  - Make IonIndex available to end users

ACKNOWLEDGMENT