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Real-Time Ionospheric Products From the TOMIRIS Data Assimilation Model

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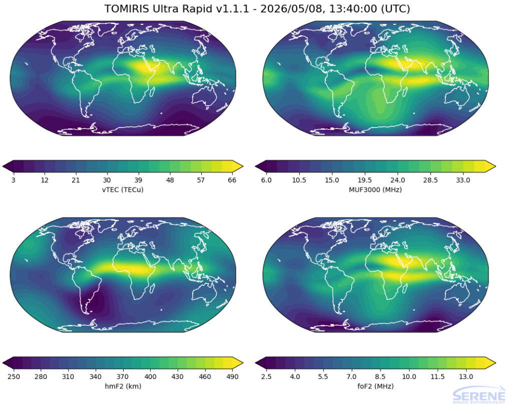
PROCESSING CENTER AND GEODETIC ANALYSIS USC

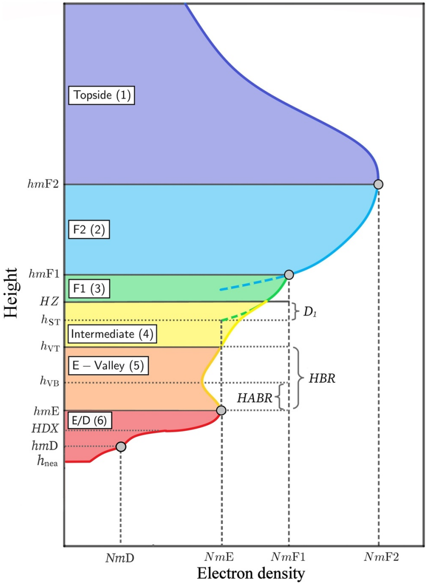
TOMIRIS

- Global model of 3D electron density
  - Uses spherical harmonics (18th order)
  - Vertical profile is parameterized
  - 5-minute time resolution



TOMIRIS

- International Reference Ionosphere (Bilitza et al. 2022)
  - Used as a background model for TOMIRIS
  - Also defines the vertical parameterization
  - E-, F1- layers in TOMIRIS are the same as the IRI



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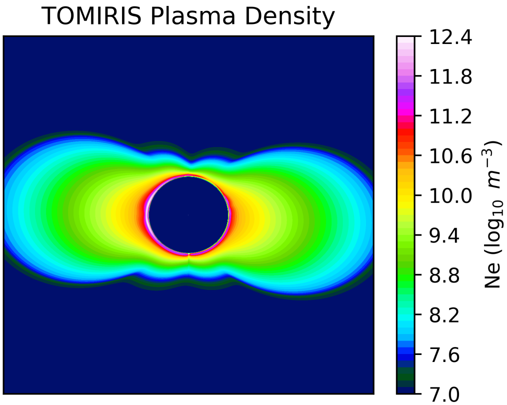
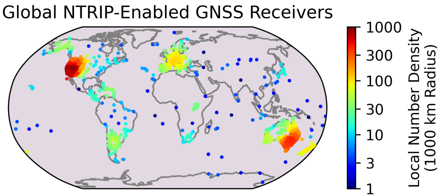
TOMIRIS

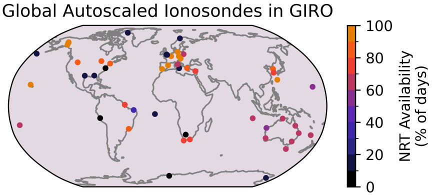
- Plasmasphere extension
  - Uses the Neustrelitz Plasmasphere Model (NSPM) (Jakowski and Hoque 2018)
  - Electron density defined up past GNSS satellite altitude



TOMIRIS

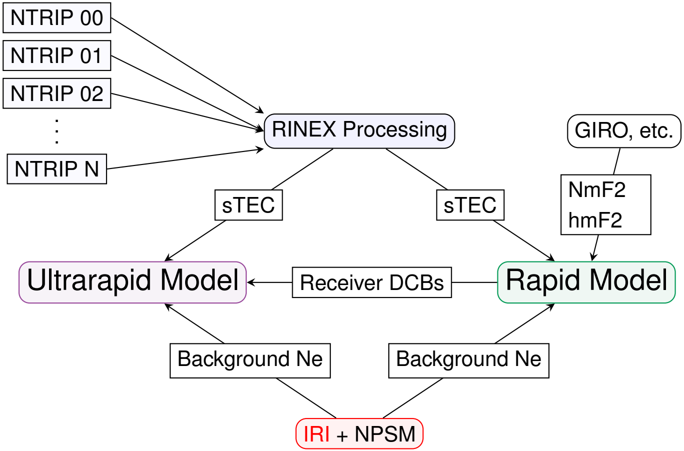
- Data assimilation model
  - sTEC from 2000+ NTRIP-enabled receivers worldwide
  - GPS and Galileo, all available combinations
  - NmF2 and hmF2 from ionosondes



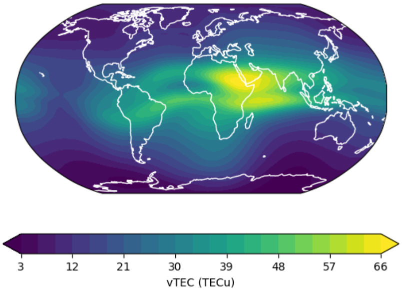


TOMIRIS Data Flow

- Operates as two interconnected models
  - **Ultrarapid** is the real-time (RTS) model
  - **Rapid** is the near-real-time (NRT) model
- Share RINEX processing
- Rapid produces DCBs for both models (Reid et al. 2024; Reid et al. 2026)



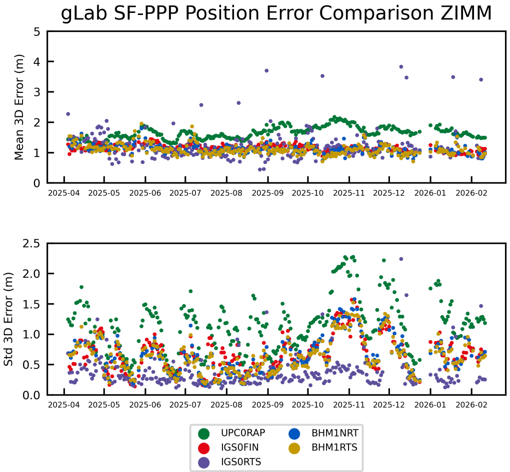
Derived Ionosphere Products




```
     1.0           IONOSPHERE MAPS     GNSS                IONEX VERSION / TYPE
TOMIRIS UR v1.1.1   SERENE             2026-05-02T02:19:09 PGM / RUN BY / DATE
This IONEX Global Ionospheric Map is generated using the   DESCRIPTION
output of the TOMIRIS Ultra Rapid v1.1.1 ionospheric data  DESCRIPTION
assimilation model. This model assimilates slant Total     DESCRIPTION
Electron Content measurements directly to produce a 3D     DESCRIPTION
ionospheric state. The TEC map in this file is produced by DESCRIPTION
vertically integrating the model electron density from 0 km DESCRIPTION
to 20 000 km. The shell height is defined as the altitude  DESCRIPTION
where an equal amount of TEC is above and below.           DESCRIPTION
serene.bham.ac.uk | Dr. Benjamin Reid | b.reid@bham.ac.uk  DESCRIPTION
  2026     1    13     0     0     0                       EPOCH OF FIRST MAP
  2026     1    14     0     0     0                       EPOCH OF LAST MAP
 300.0                                                     INTERVAL
   289                                                     # OF MAPS IN FILE
MODEL METADATA                                             COMMENT
  1 model time 2026-01-13T00:00:00.000000000               COMMENT
  F107: 112.4 source: fluxtable.nc                         COMMENT
  F107_365: 146.3 source: fluxtable.nc                     COMMENT
  F107_81: 147.9 source: fluxtable.nc                      COMMENT
  IG12: 92.46451612903226 source: ig_2025.nc               COMMENT
  NPSMFlux: 112.4 source: fluxtable.nc                     COMMENT
  Rz12: 150.5041095890411 source: EISN_current.nc          COMMENT
  Modip: IGRF                                              COMMENT
  SINEX_file: GFZ0OPSRAP_20260100000_01D_01D_DCB.BIA.gz    COMMENT
  2 model time 2026-01-13T00:05:00.000000000               COMMENT
  IG12: 92.46465053763441 source: ig_2025.nc               COMMENT
  3 model time 2026-01-13T00:10:00.000000000               COMMENT
  IG12: 92.46478494623656 source: ig_2025.nc               COMMENT
  4 model time 2026-01-13T00:15:00.000000000               COMMENT
  IG12: 92.46491935483871 source: ig_2025.nc               COMMENT
  5 model time 2026-01-13T00:20:00.000000000               COMMENT
  IG12: 92.46505376344086 source: ig_2025.nc               COMMENT
  6 model time 2026-01-13T00:25:00.000000000               COMMENT
```

GNSS Positioning

- ZIMM (Switzerland)
- $46.8770946^o N,\ 7.4652732^o E$
- Well instrumented, should be best-case scenario for all models
- Used gLab (Hernandez-Pajares et al. 2010) on each RINEX daily observation file.
- Single-frequency PPP



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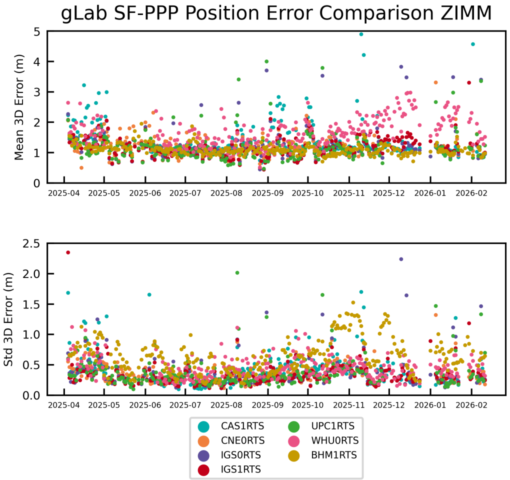
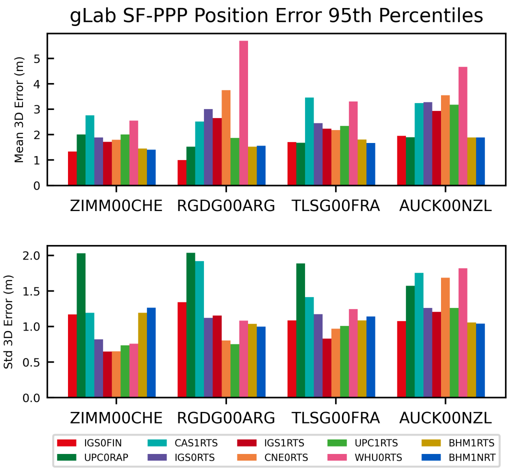


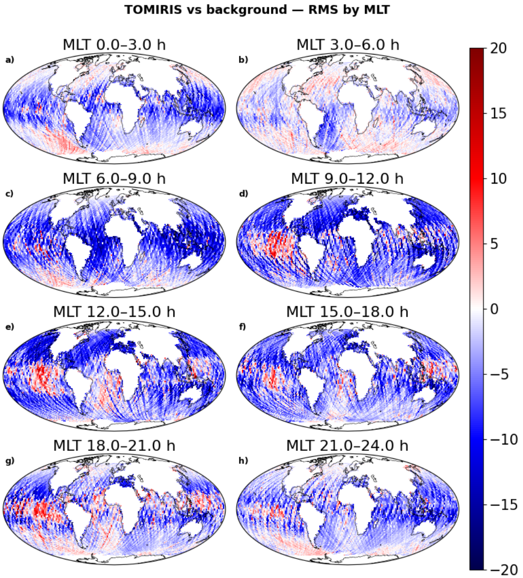
GNSS Positioning

- In mean 3D error, TOMIRIS-derived products perform comparably to IGS Final product
  - This is better than most other real-time products
- In standrd deviation, TOMIRIS-derived products again perform comparably to IGS Final product
  - Here the real-time IGS products tend to perform better than other products



Jason vTEC

- Comparing TOMIRIS vTEC to background model (essentially IRI)
- Consistent improvement with some exceptions:
  - South Pacific
  - Equatorial Pacific



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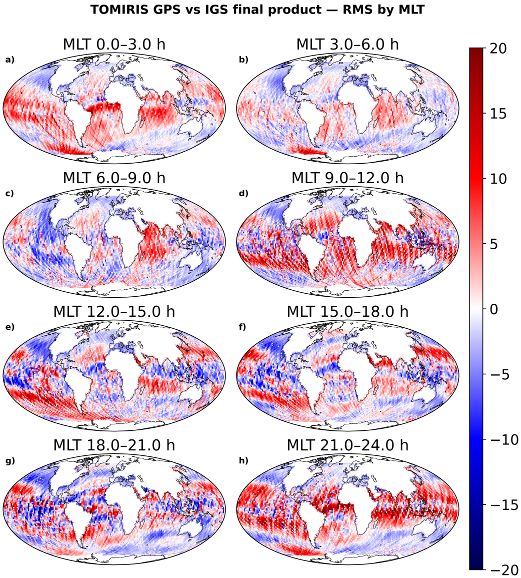
Jason vTEC

- Comparing TOMIRIS vTEC to IGS Final Model
- More complicated behaviour:
    - South Pacific and Equatorial pacific still have issues
    - Midlatitude performance generally better for TOMIRIS



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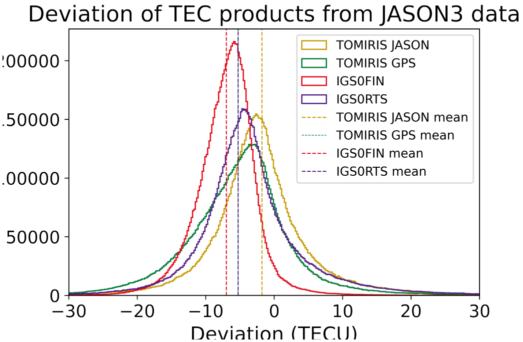
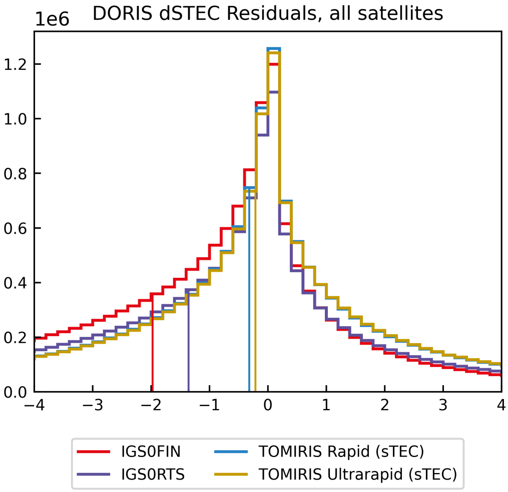
Jason vTEC - Comparison to IGS Products

Product	Bias	RMSE	Std
TOMIRIS Rapid (1340 km)	1.78	8.09	7.90
TOMIRIS Ultrarapid (1340 km)	2.17	8.13	7.83
TOMIRIS Background (1340 km)	4.89	11.32	10.21
TOMIRIS Rapid (20 000 km)	5.27	9.67	8.11
TOMIRIS Ultrarapid (20 000 km)	5.70	9.96	8.17
IGS0FIN	6.98	8.32	4.53
IGS0RTS	3.49	10.38	9.77
IGS1RTS	3.32	9.43	8.83
CAS1RTS	11.76	85.72	84.91
CNE0RTS	2.18	12.47	12.28
WHU0RTS	-0.04	13.68	13.68
UPC1RTS	4.24	12.30	11.55



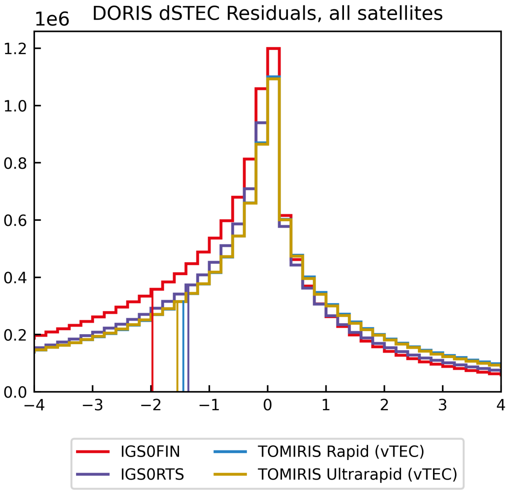
DORIS dsTEC Residuals

- Both the TOMIRIS Rapid and Ultrarapid models perform well
  - Integrated to satellite altitude
  - TOMIRIS shows less spread than IGS products
- This is with all dsTEC data
  - No elevation cuts
  - CryoSat-2, SARAL, Sentinel-3B, SWOT, HY-2C, HY-2D, Jason-3, Sentinel-6A



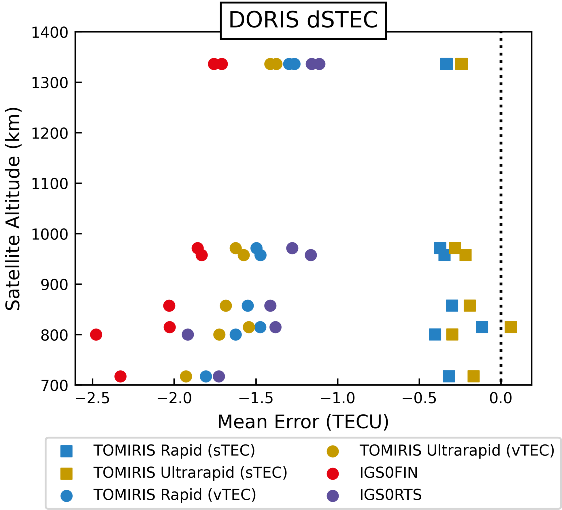
DORIS dsTEC Residuals

- Integrated to GPS altitude (20 000 km) the performance of TOMIRIS is similar to the IGS0RTS
  - Significant negative bias (models overestimate dsTEC)
  - Part of this overestimation comes from plasmasphere!



DORIS dsTEC and Satellite Altitude

- dsTEC is dependent on the 3D structure of the ionosphere
  - Sorting mean bias by altitude shows clear altitude dependence



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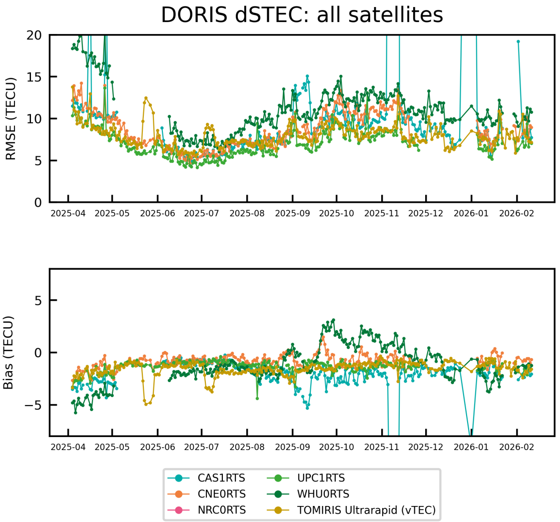
DORIS dsTEC RMSE and Bias

Product	Bias	RMSE	Std
TOMIRIS Rapid (sTEC)	-0.31	7.07	7.06
TOMIRIS Ultrarapid (sTEC)	-0.20	7.00	7.00
TOMIRIS Background (sTEC)	-1.70	8.71	8.55
TOMIRIS Rapid (vTEC)	-1.48	7.94	7.80
TOMIRIS Ultrarapid (vTEC)	-1.59	7.97	7.81
TOMIRIS Background (vTEC)	-3.41	10.59	10.03
IGS0FIN	-1.98	6.39	6.08
UPC0RAP	-1.09	5.10	4.98
CAS0FIN	-1.57	6.96	6.78
IGS0RTS	-1.38	7.97	7.85
IGS1RTS	-1.31	7.39	7.28
CAS1RTS	-2.44	31.65	31.56
CNE0RTS	-0.86	8.81	8.77
UPC1RTS	-1.36	7.19	7.06
WHU0RTS	-1.25	11.42	11.35



Conclusions

- TOMIRIS is able to produce IGS-like products (with RMS) in real time
  - Positioning performance is comparable to IGS Final products
  - Jason-3 vTEC is slightly better than most other RTS products
  - DORIS dsTEC is comparable to other RTS products
- Hoping to start the process to become an official Analysis Centre
  - Unique technique would provide additional resilience in combined products
- Provides real-time receiver DCBs
  - Could be extended to calculate satellite DCBS, GLONASS/Beidou/QZSS/SBAS

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