IHDEA AND DASH HYBRID MEETING
14-18 OCTOBER 2024

Low Earth orbit COSMIC-2 and geostationary GOES RO observations for the empirical models of ionosphere validation and improvement

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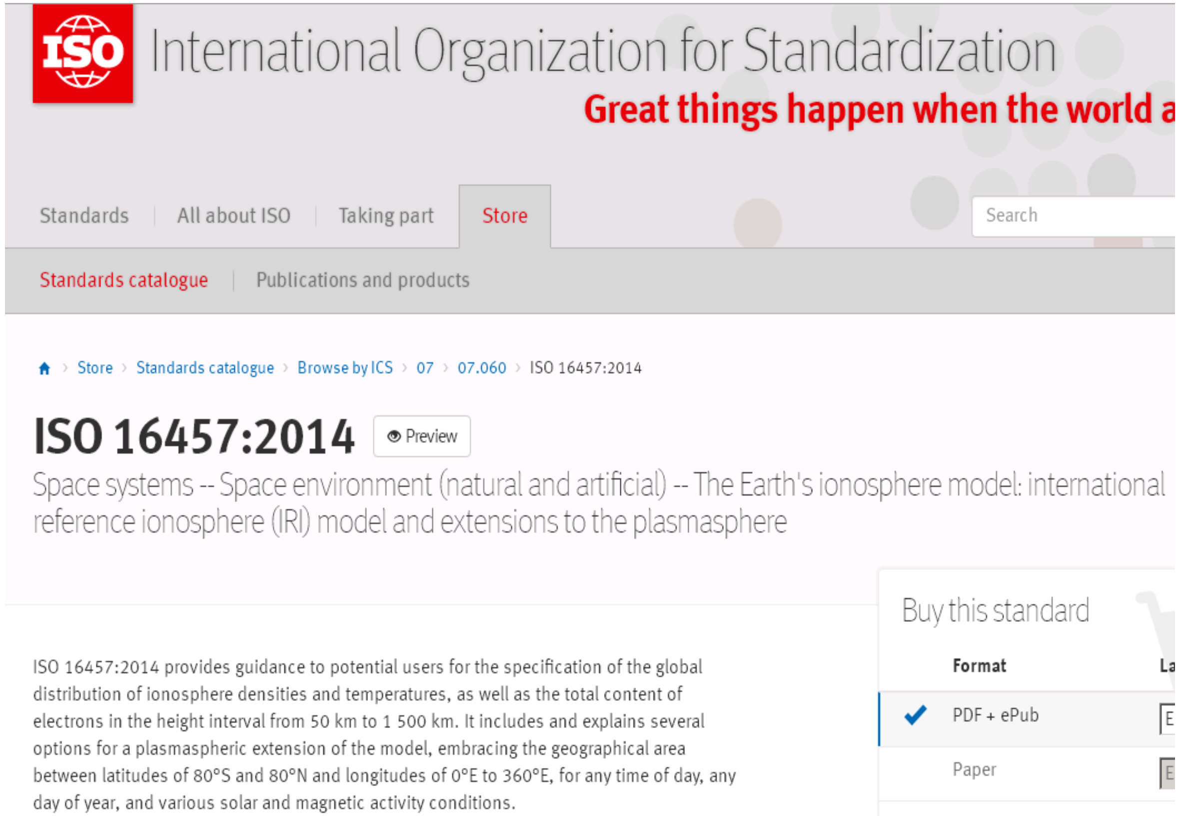
Empirical models of ionosphere

IRI



NeQuick

-- used in operational services for prediction / nowcasting of radio waves propagation conditions
-- served as core for data assimilation models
-- utilized for single frequency ionosphere correction in GNSS applications

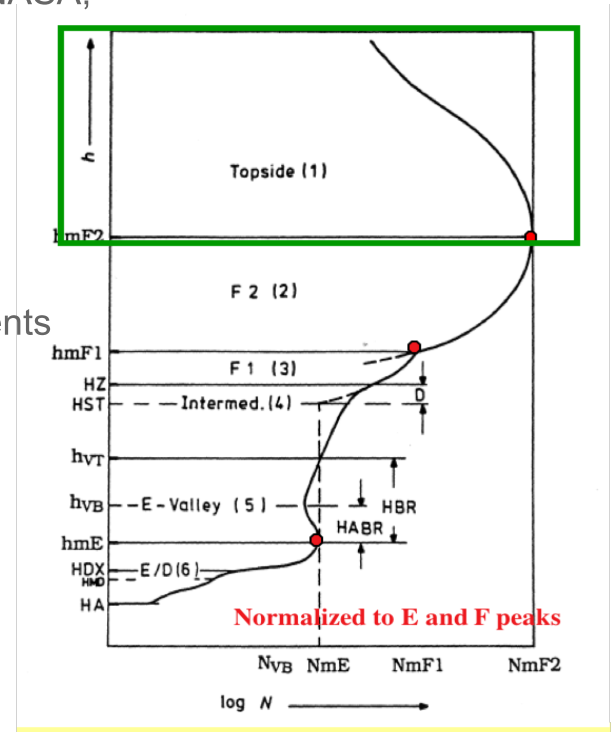
Empirical models of ionosphere. IRI and NeQuick formulation

IRI

Model Developers: Dieter Bilitza, NASA, International IRI Working Group

Model Input
Solar indices (F10.7 index, sunspot number),
Ionospheric index (IG)
magnetic indices (Ap and Kp)
URSI/CCIR maps of model coefficients (foF2)

Model Output
Height range: 80 – 2,000 km
Electron density& temperature
Ion density
Ion composition
Ionospheric total electron content (TEC)



Global models for foF2/NmF2 foF1/NmF1, foE/NmE, hmF2, hmF1 , hmE

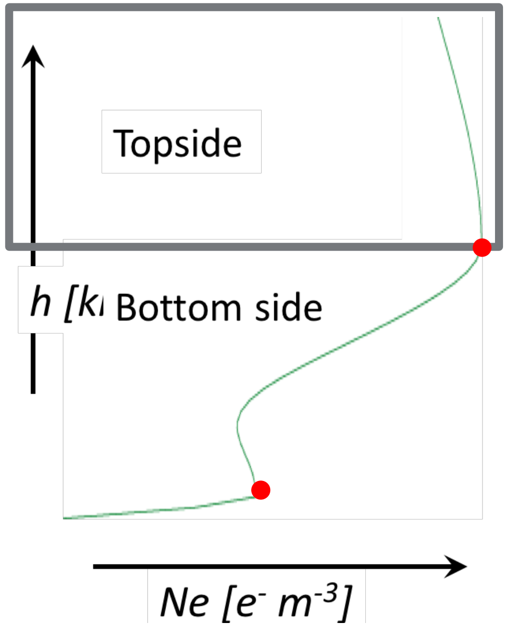
NeQuick

Model Developers: S. Radicella, B. Nava, ICTP

Model Input
Solar indices (F10.7 index, sunspot number),
ITU-R (former CCIR) coefficients

Model Output
Electron density
Height range: 80 – 20,000 km
Ionospheric total electron content (TEC): vTEC and sTEC

Profiler model - 6 semi-Epstein layers with modeled thickness parameters and is based on anchor points defined by foE, foF1, foF2 and M(3000)F2 values.



$$N_{Epstein}(h; hmax, Nmax, B) = \frac{4Nmax}{\left(1+\exp\left(\frac{h-hmax}{B}\right)\right)^2}\exp\left(\frac{h-hmax}{B}\right)$$

Profile-based empirical global ionosphere models used F2 peak parameters as the main anchor points for representation of altitudinal distribution of plasma density

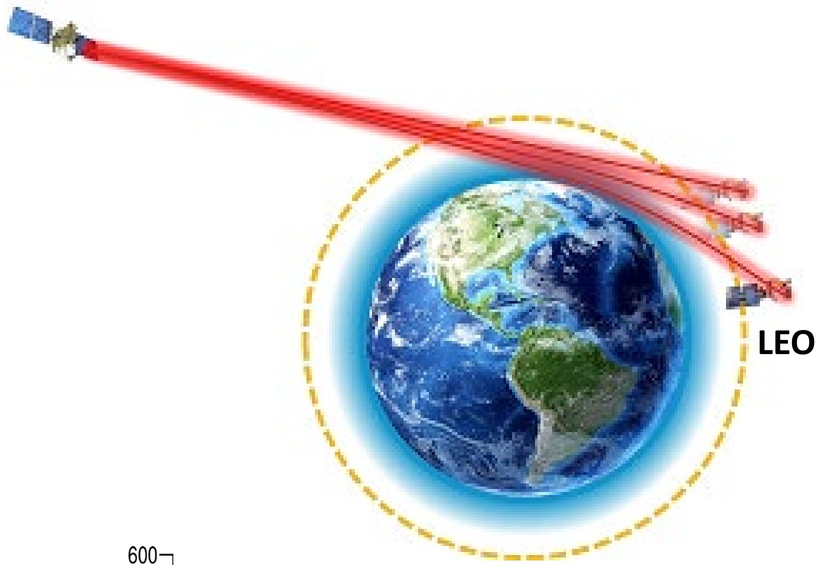
Ionosphere sounding by GNSS radio occultation from low Earth orbits

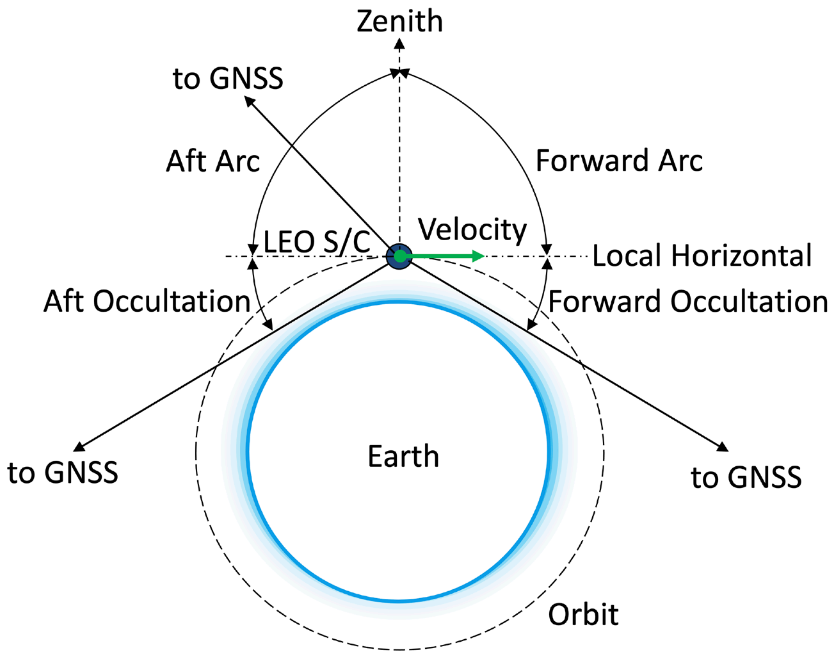
Radio occultation observations:
- full profile up to LEO altitude (500-700 km)

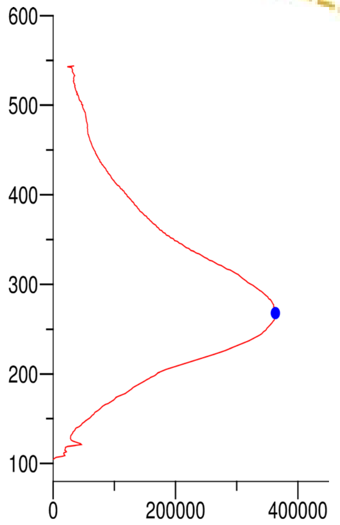
- global data coverage

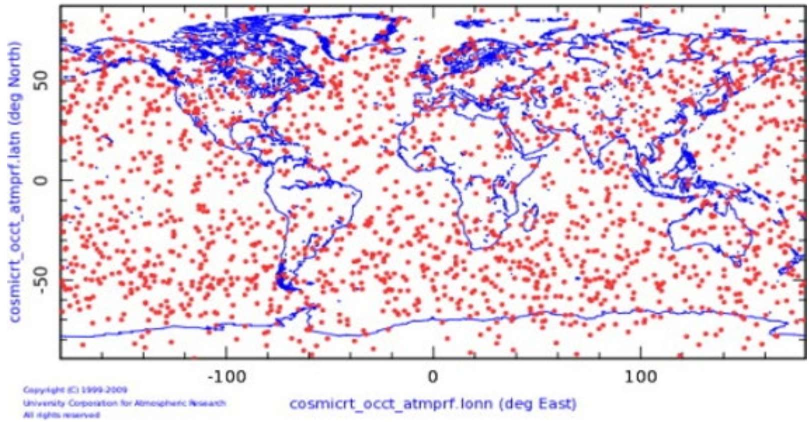
- continuous observations

 - suitable for ionosphere climatology analysis

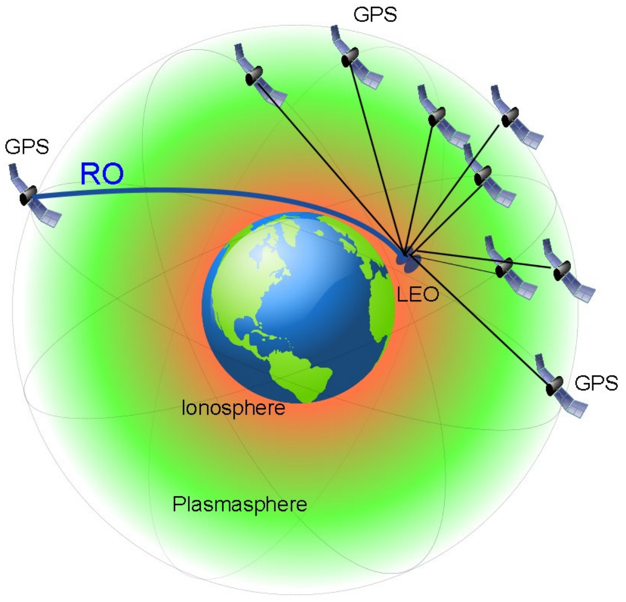


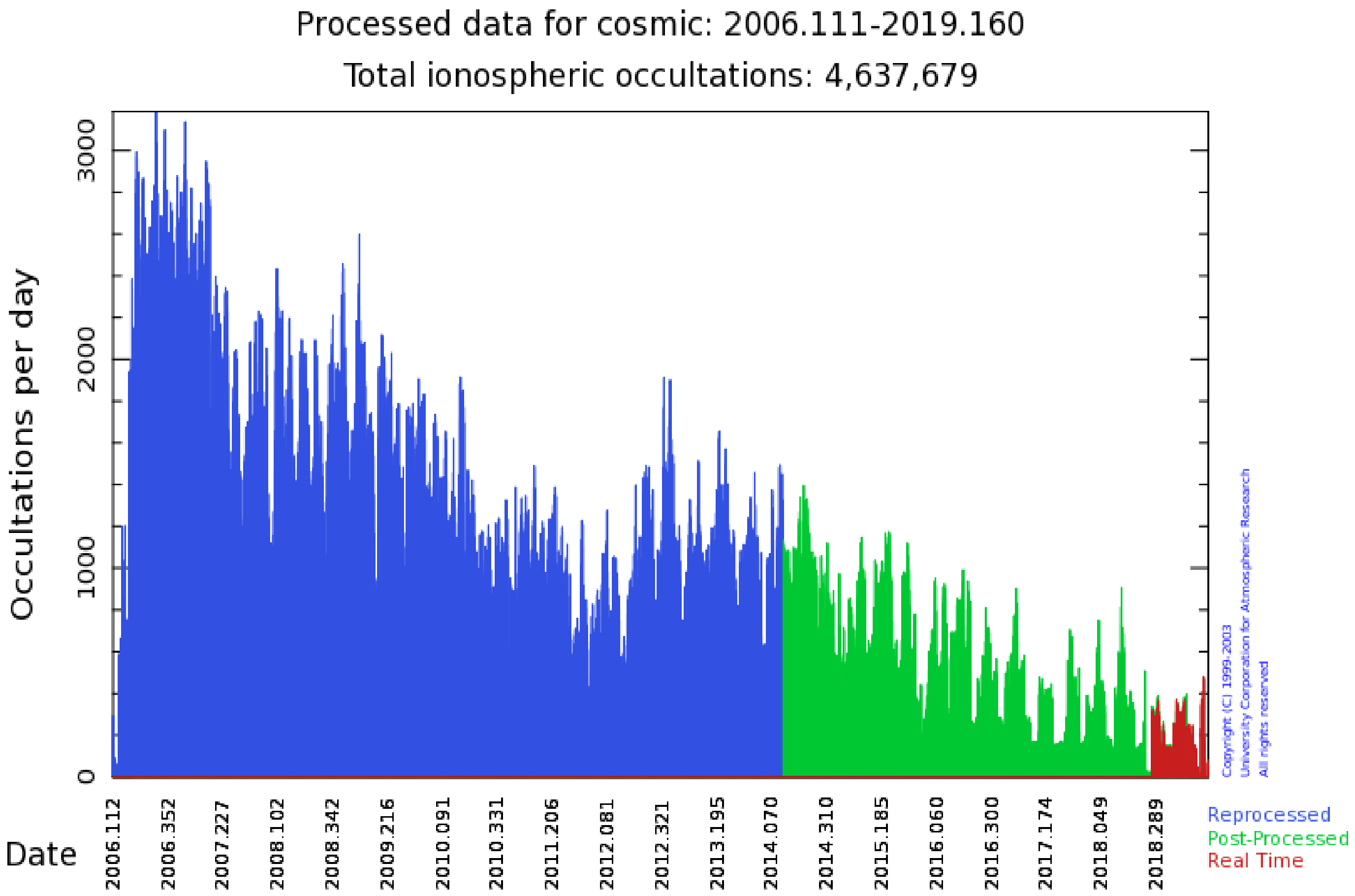






COSMIC RO as a core observations for ionosphere climatology

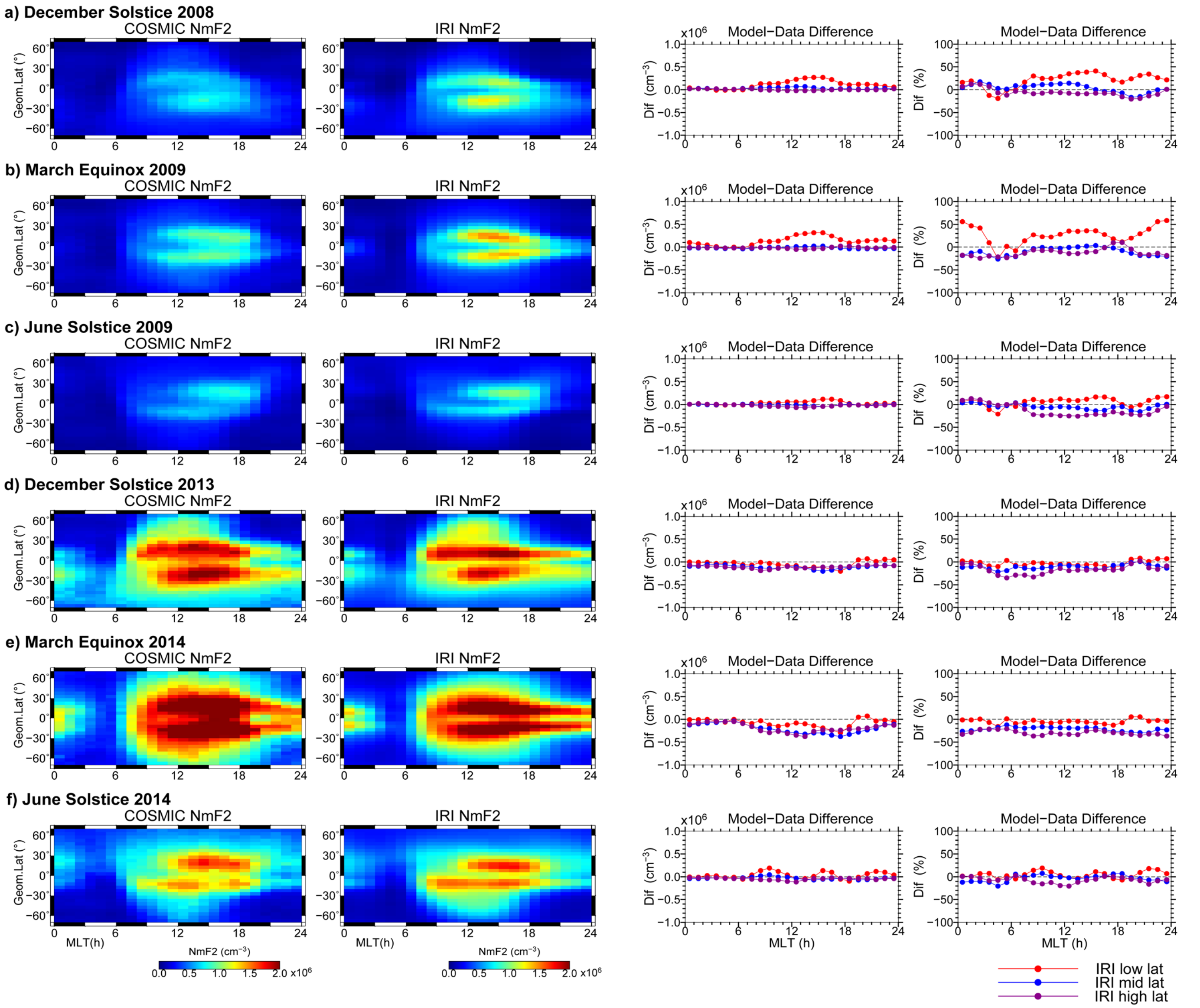




COSMIC-1 on CDDAC:
More than one solar cycle of RO data is available

COSMIC Data Analysis and Archive Center (https://doi.org/10.5065/t353-c093).

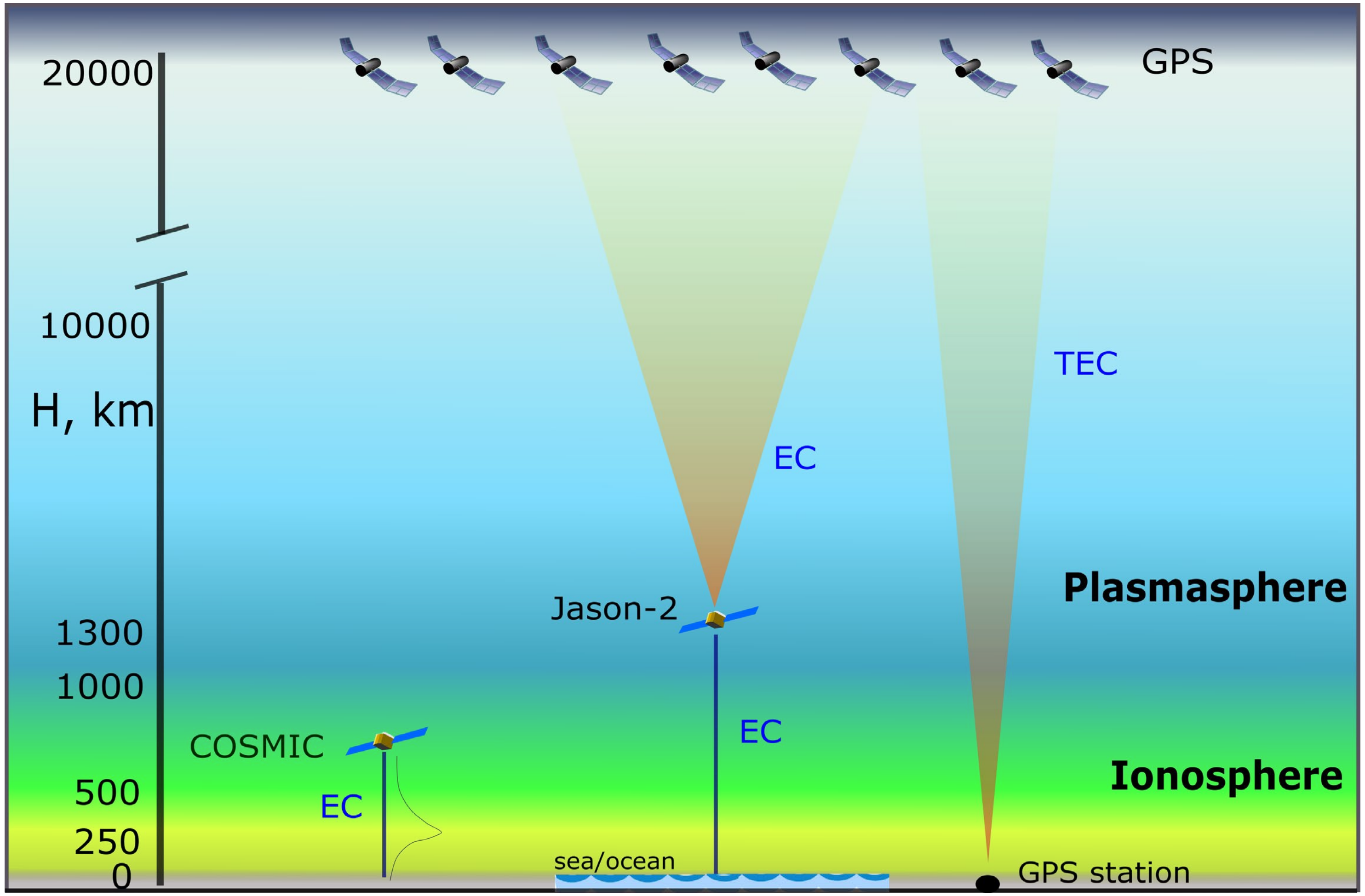
COSMIC RO peak electron density distribution and model-data comparison



Direct comparison of COSMIC RO F2 peak density shows pretty good overall performance of the profile based empirical models over midlatitudes.

The most pronounced discrepancies appeared in the equatorial anomaly region.

Topside ionosphere and plasmasphere - data/model difference



Application of multi-satellite GNSS observations for estimation of electron content at different altitudinal ranges

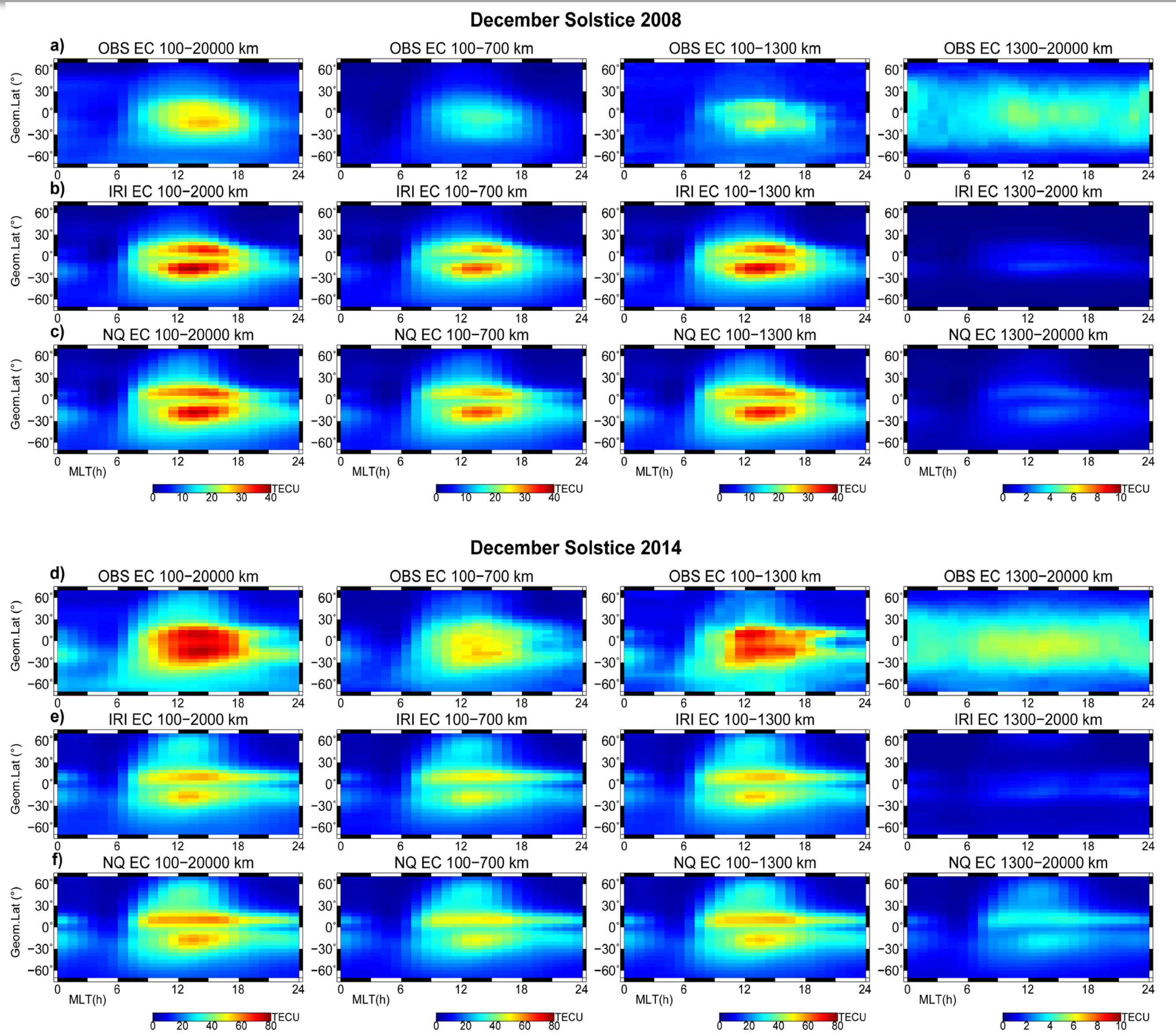
100-20000 GNSS TEC

100-700 km – COSMIC-1 RO

100-1300 Jason altimeter

1300-20000 Jason POD TEC

Data-model comparison. COSMIC GPS RO, ground-based GPS and LEO GPS observations



Cherniak and Zakharenkova, , 2018

Representation of topside ionosphere and plasmasphere are still most problematic for the ionospheric models.

It is difficult to reproduce even quiet-time seasonal variability

24th solar cycle minimum and maximum

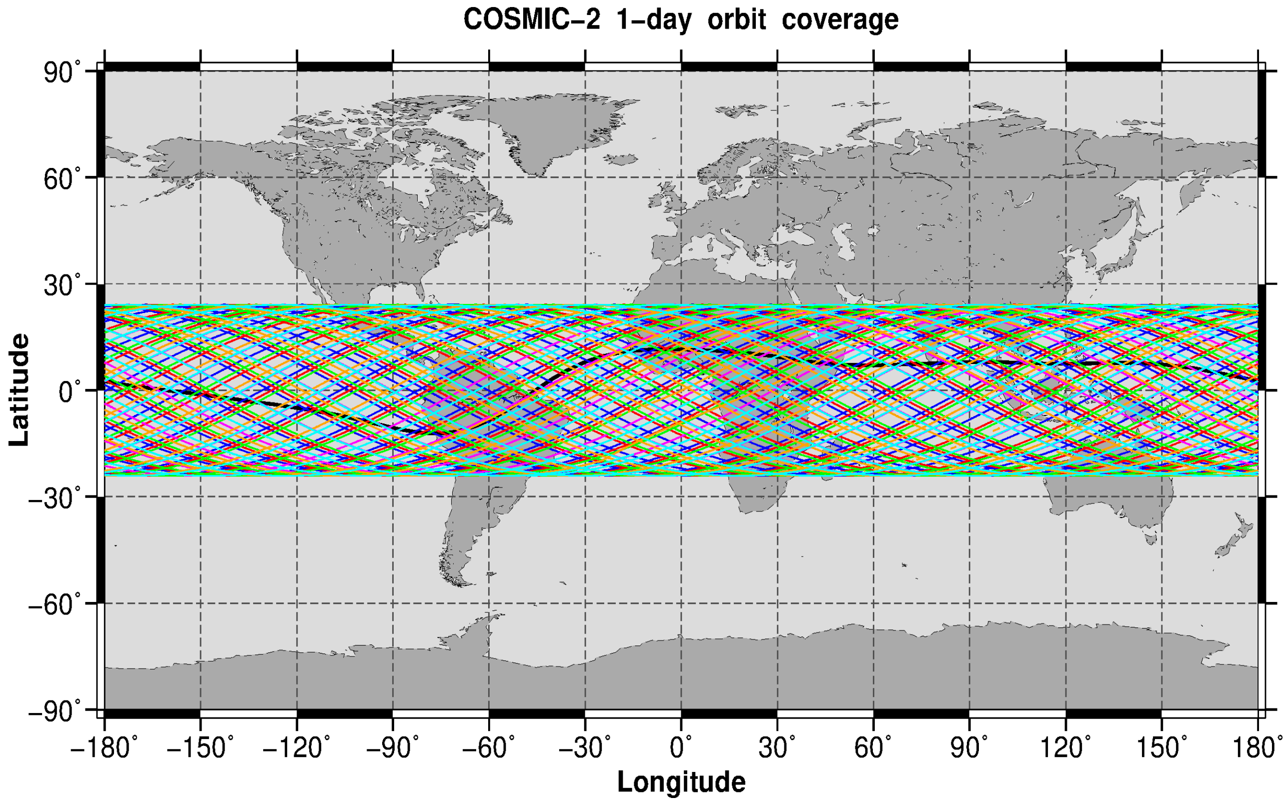
The most significant discrepancies for electron density/electron content are at altitudes above the F2 peak

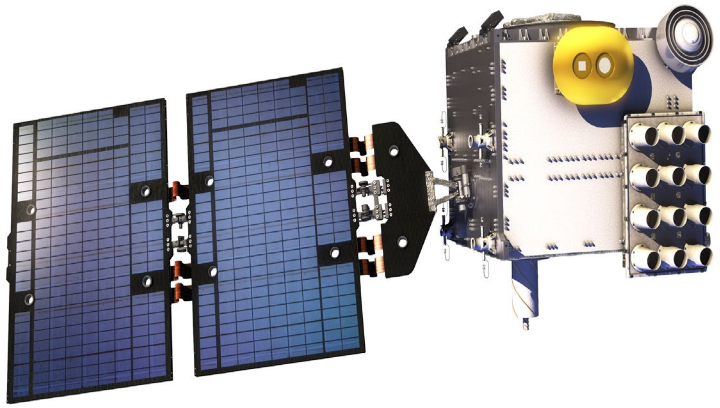
Ionosphere radio occultation LEO missions: COSMIC-2

6 satellites

Orbit inclination:
- 24°

Orbit Altitude:
- 540–550 km





COSMIC-2 RO payload

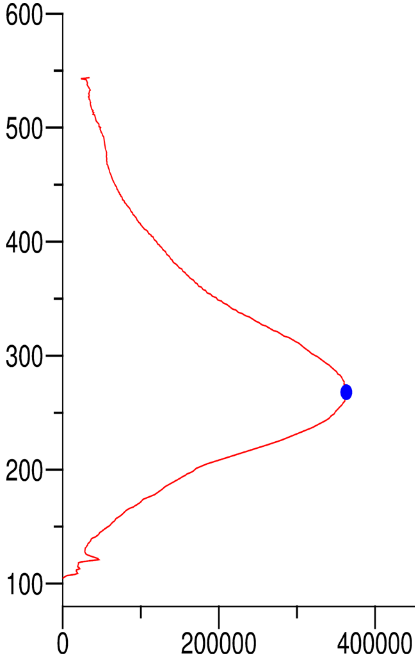
TGRS (Tri-GNSS Radio Occultation Receiver System) developed by JPL

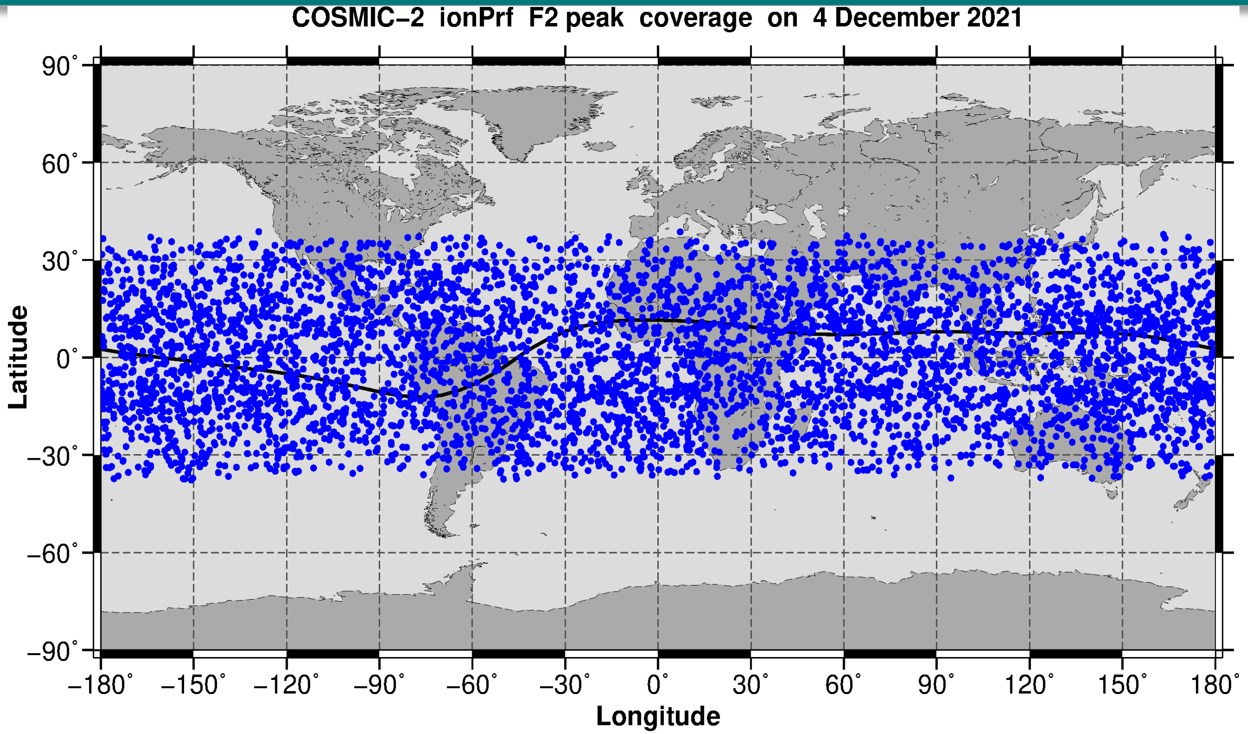
RO with GPS and GLONASS signals

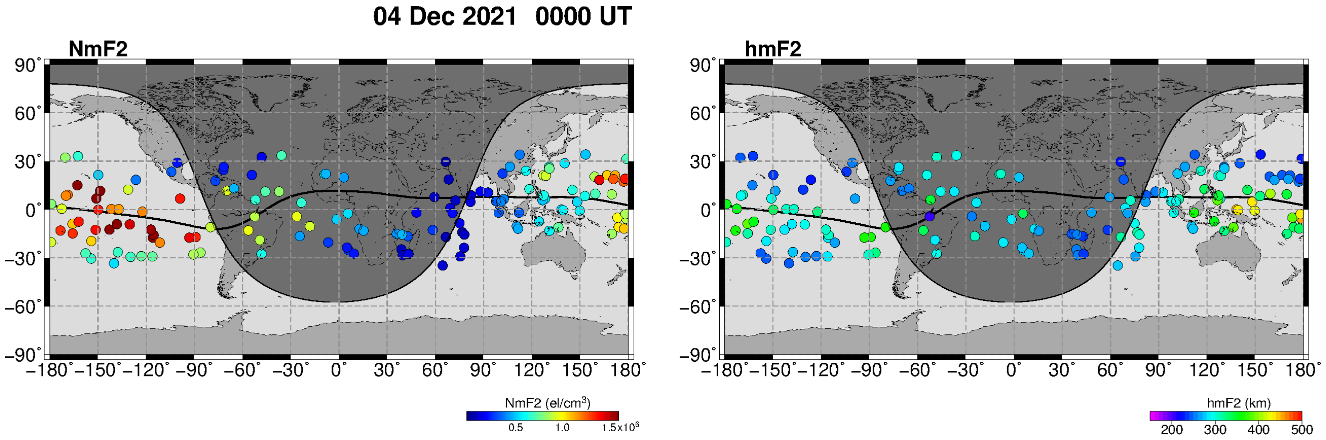
- ✓ Slant TEC above and below an orbit
- ✓ RO electron density profiles

Ionosphere radio occultation from LEO : COSMIC-2 EDP product

C2 Ionospheric Electron Density Profiles Level 2 data product







~ 5000 electron density profiles per day

~ 200 profiles per 1 hr

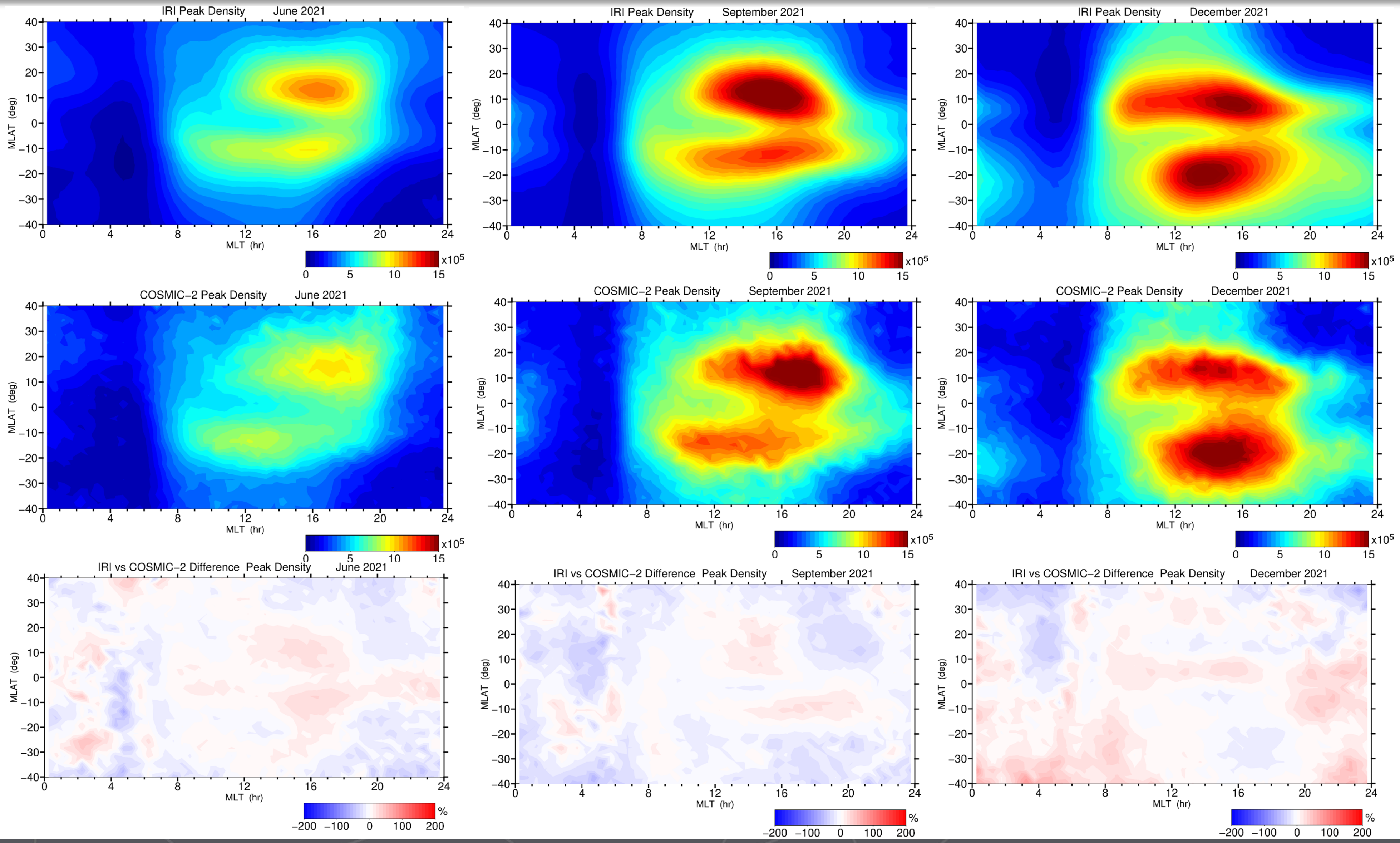
Available on COSMIC Data Analysis and Archive Center (CDAAC)

COSMIC-2 EDP product ionospheric climatology applications

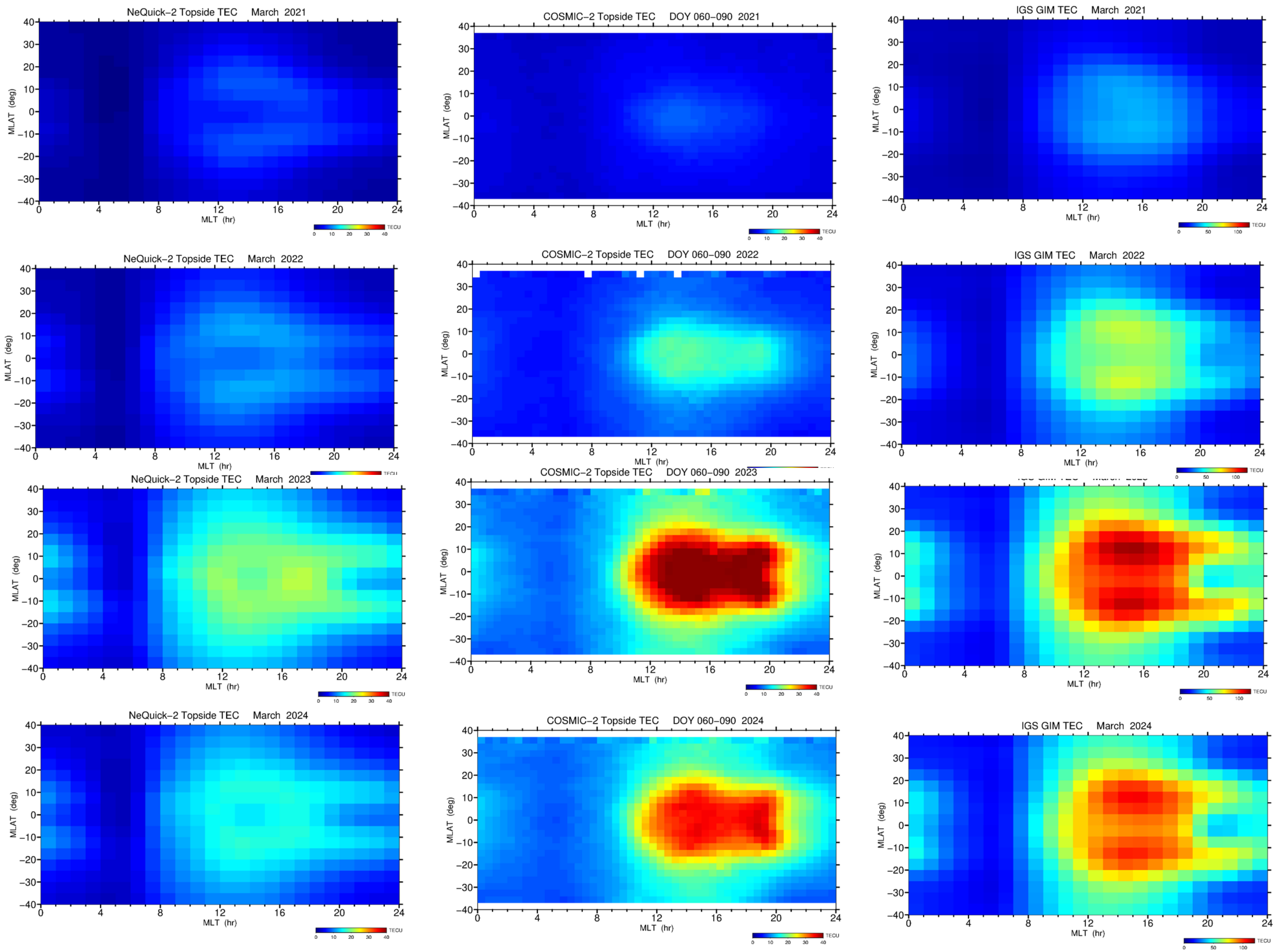
Being validated by benchmark ionosondes data

C2 EDPs product can serve as excellent dataset for ionospheric climatology studies and ionospheric models assessment

Performance of International Reference Ionosphere (IRI) model at low latitudes vs COSMIC-2 F2 peak density climatology



Topside ionosphere - plasmasphere to ground-based GNSS TEC and empirical models



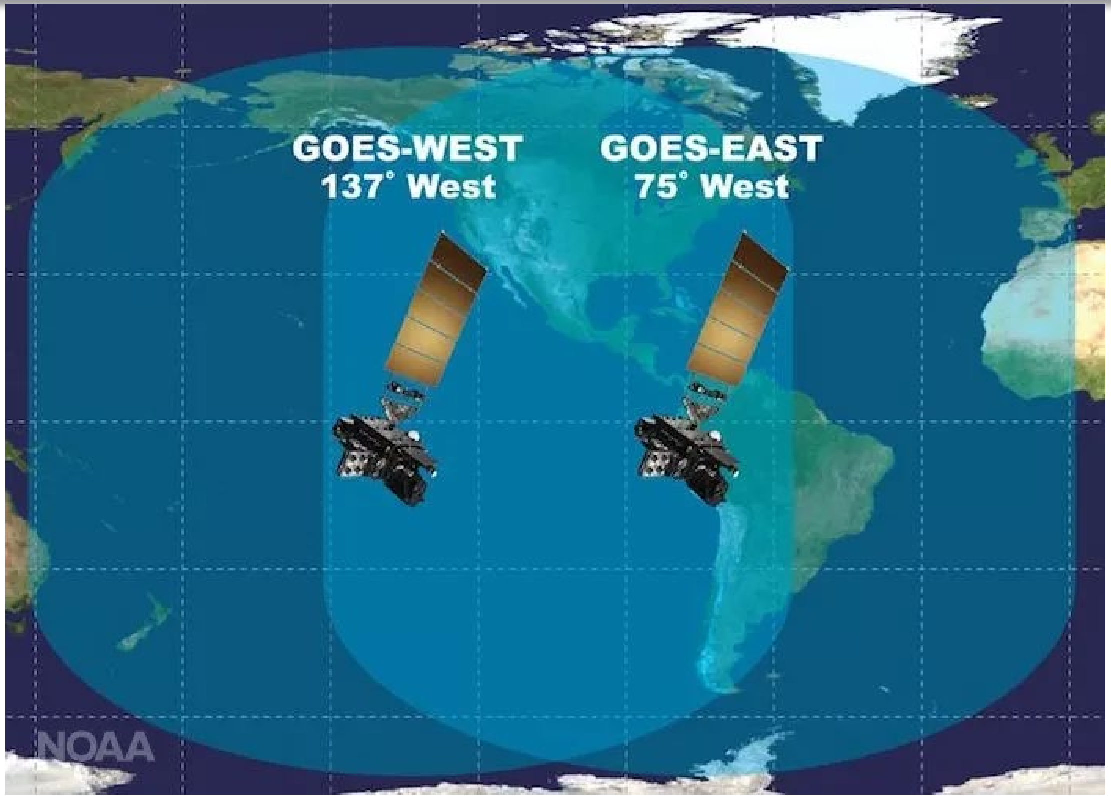
topside ionosphere and plasmasphere climatology specified by empirical profile based model (NeQuick), COSMIC-2 observations and ground-based total electron content (TEC) measurements.

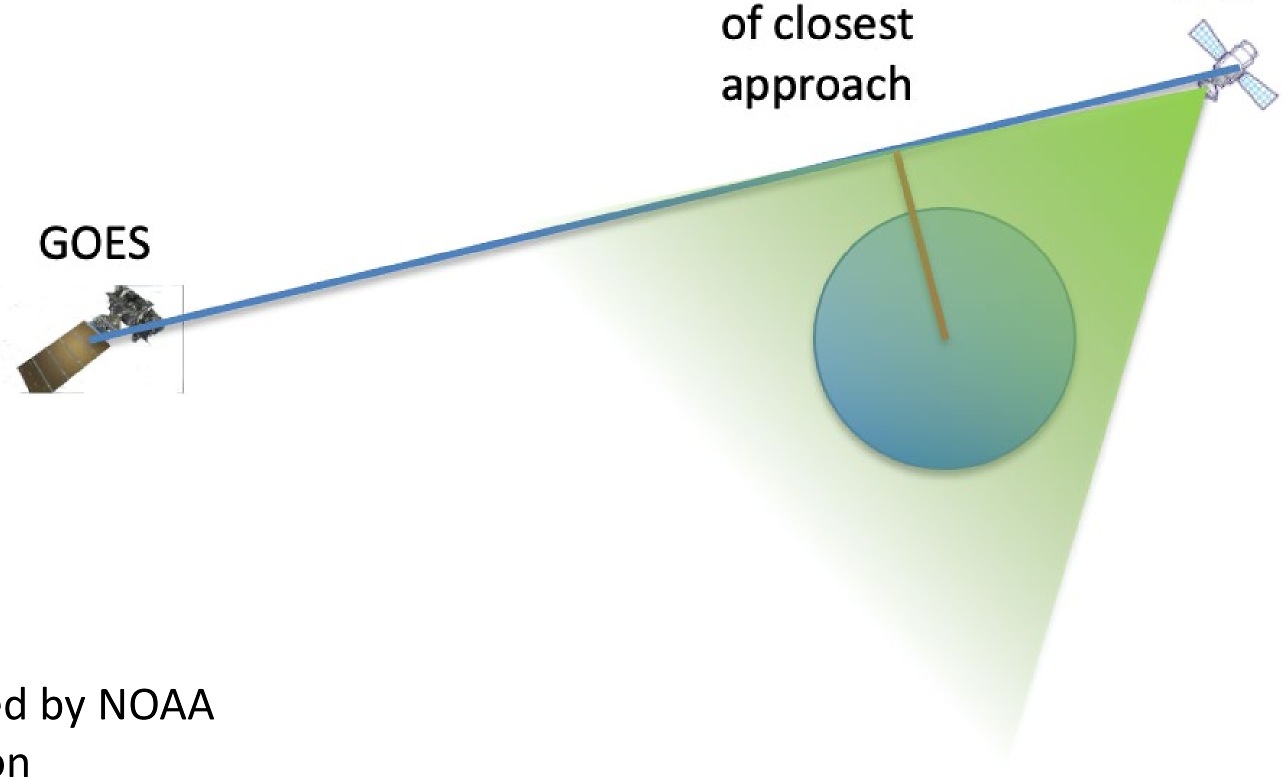
25th solar activity rising part.
March equinoxes of 2021-2024.

- Noticeable data-model discrepancies for topside ionosphere and plasmasphere. Differences in absolute electron content values, as well as equatorial ionization anomaly shape

- Significant contribution of topside ionosphere and plasmasphere to ground-based TEC

RO from geosynchronous GPS observations: GOES system





Geostationary Operational Environmental Satellite (GOES) used by NOAA and NASA for real-time Earth monitoring and weather prediction

GOES system are equatorial satellites with orbit altitude is ~35800 km.

•**GOES-16,** GOES-East (75.2°W)

•**GOES-17,** GOES-West (137.2°W)

•Satellites are equipped by single frequency GPS receiver for orbit tracking

Due to GPS antenna beam width limitations, all GPS visible from GOES are behind the Earth

GOES GPS Observations: challenges and possibilities for RO

- Within the framework of NASA ROSES GOES Radio Occultation project, data from GOES-16 and GOES-17 onboard GPS receiver made available for the UCAR/COSMIC.

- **Technical challenges**:

- absolutely different geometry comparing with traditional LEO RO
- single-frequency L1 observations only
- GOES clocks are less stable than those typically used for RO

- The COSMIC team developed an **innovative strategy** for effective GOES GPS data filtering, alternative clock correction, and single-frequency processing.

- These efforts are discussed in the papers:

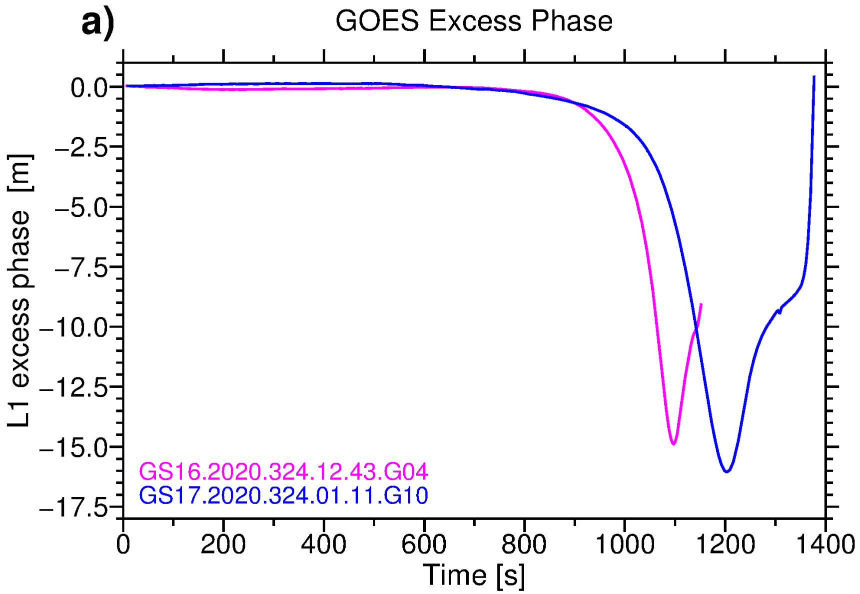
S. Gleason et al. The First Atmospheric Radio Occultation Profiles From a GPS Receiver in Geostationary Orbit. IEEE Geoscience and Remote Sensing Letters, vol. 19, pp. 1-5, 2022, Art no. 1005605, doi: 10.1109/LGRS.2022.3185828.

Zakharenkova et al. Statistical Validation of Ionospheric Electron Density Profiles Retrievals from GOES Geosynchronous Satellites. JSWSC, 2023.

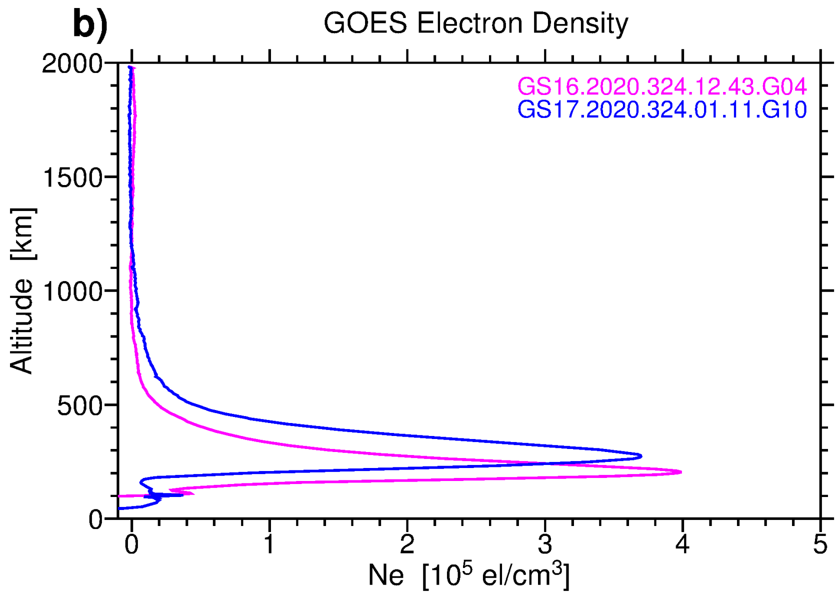
GOES-based RO electron density profiles

- The first altitudional distributions of ionospheric electron density are derived from GEO RO.
- GOES RO dataset covers ~5 years (07/2017 – 05/2022) for GOES-16 and ~3.5 years (11/2018 – 05/2022) for GOES-17 satellite.
- The GOES RO EDPs cover altitudional range from the bottom border of ionosphere up to 2000 km (much wider than that of current LEO RO missions).

a)

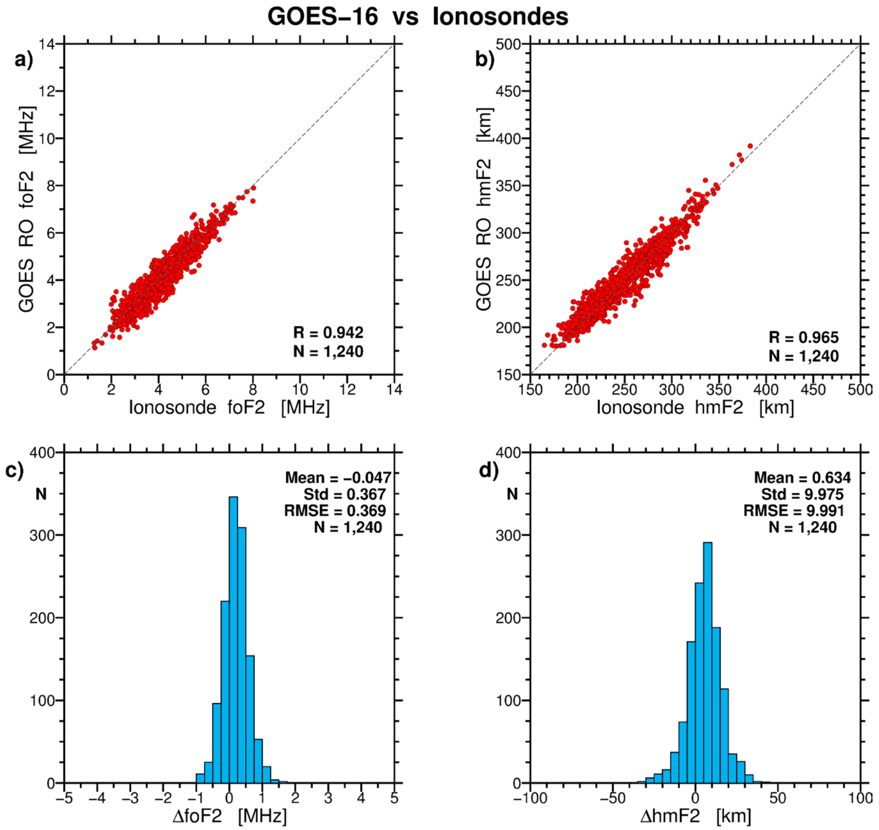


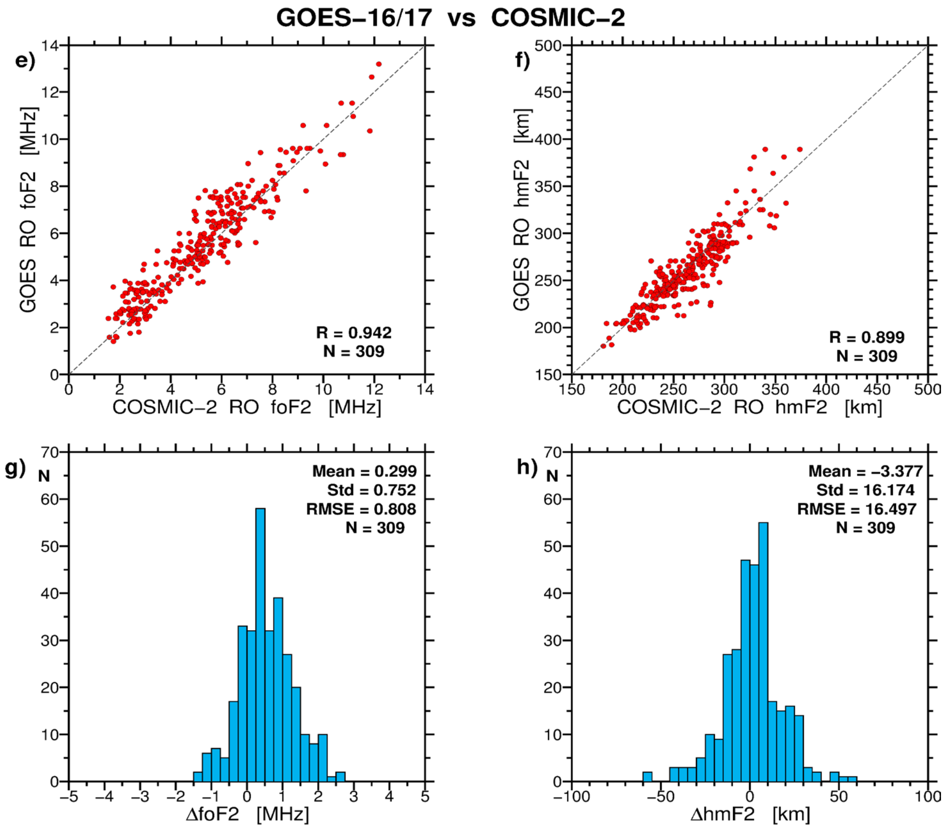
b)



GOES-based RO RO electron density profiles validation

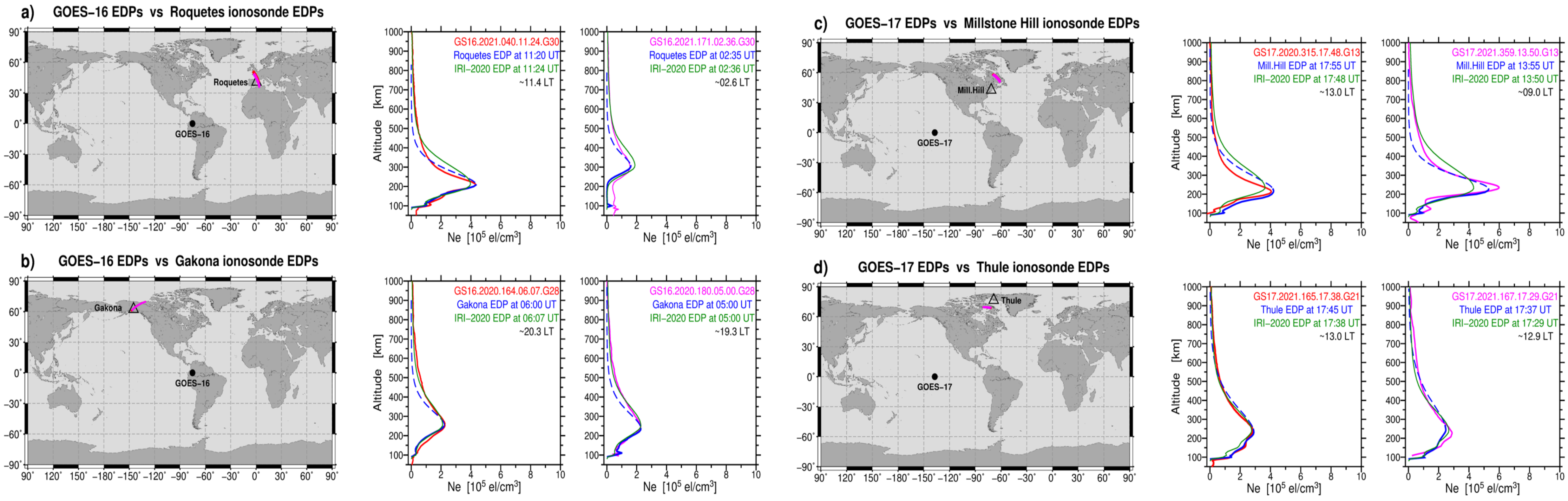
From the provided GOES observational dataset that covers several years, we retrieved in total 10K+ RO-based ionospheric EDPs within an altitudinal range of 80–2000 km.
The obtained dataset with RO ionospheric profiles from GEO GOES satellites were analyzed and validated in terms of the ionospheric F2 peak parameters using пround-based ionosondes and COSMIC-2 RO profiles





Application of GOES-based RO EDPs for empirical models validation

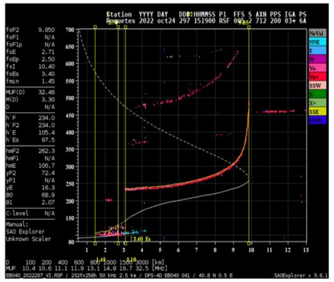
- GOES RO EDPs have been carefully validated by benchmark observations, they can serve as a reference dataset for the empirical models quality and accuracy assessment
- Limited observational coverage, mainly in Northern Hemisphere midlatitudes
- RO profiles are repeatable each day with same tangent point projection and with only slight drift in time

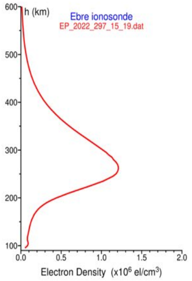


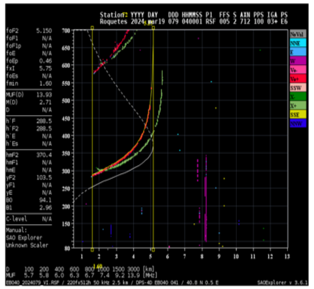
Combination of COSMIC-2 RO and high-rate ionosonde measurements for the reference ionosphere

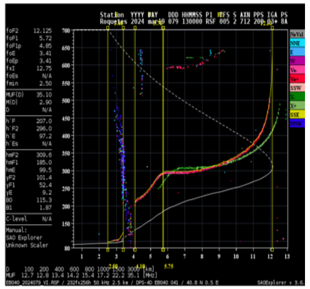
Ebre ionosonde high-rate campaigns with 1-minute resolution HF soundings supported by Ebre observatory team.

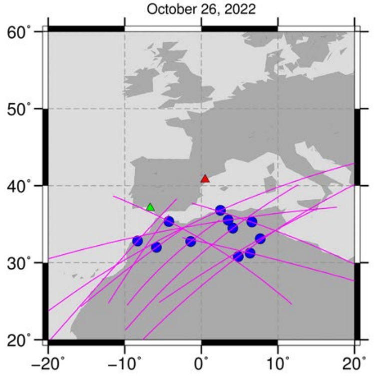
Ionosondes provide unbiased measurement of electron density in bottomside ionosphere, while GNSS RO gives precise information on the altitudinal shape of EDPs and information about plasma distribution above the F2 layer peak.

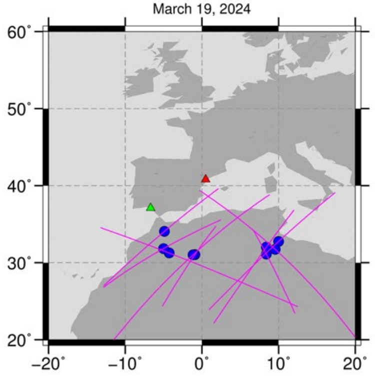


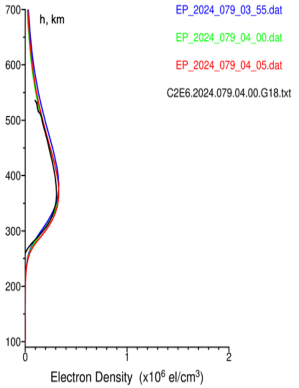


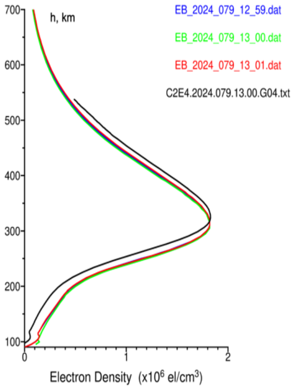


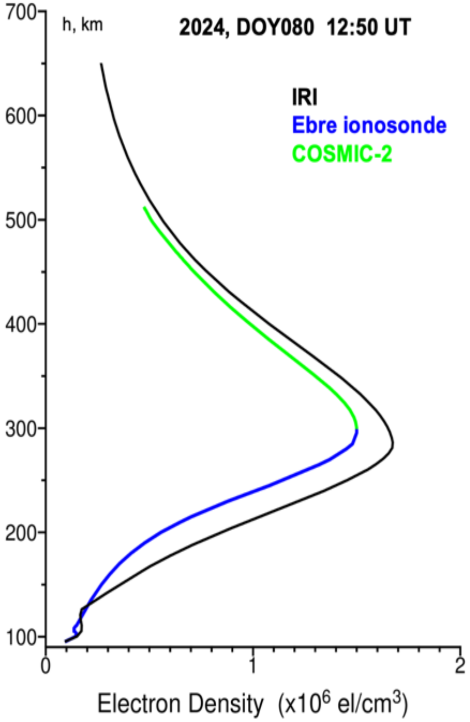


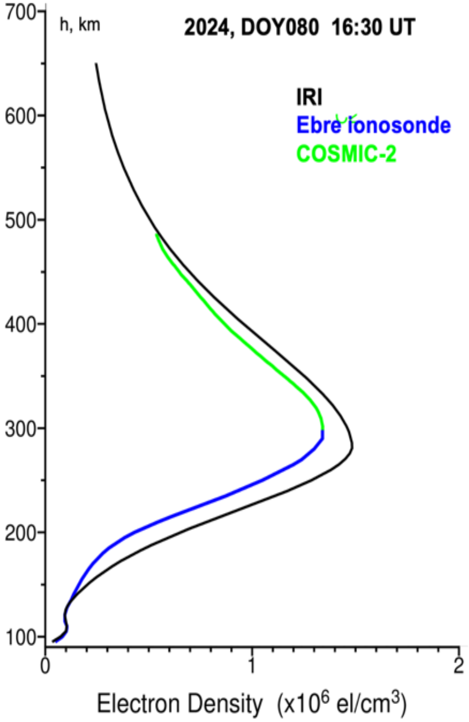












Two different techniques of the ionosphere probing allows to obtain set of the reference EDPs that covers an altitude range from ~100 to 500–550 km

Combined electron density profiles are created solely based on actual observations, without any artificial extrapolation

Summary

- Profile-based empirical global ionosphere models used F2 peak parameters as the main anchor points for representation of altitudinal distribution of plasma density
- COSMIC ionospheric products can make significant contributions for ionospheric models, including improvement in understanding of the equatorial ionosphere climatology. More than 13 years of COCMIC-2 and 5+ years of COSMIC-2 observations are available at: https://data.cosmic.ucar.edu/gnss-ro/
- Direct comparison of COSMIC RO F2 peak density shows pretty good overall performance of the profile based empirical models, but shows discrepancies in for equatorial anomaly region.
- Representation of topside ionosphere and plasmasphere are still most problematic for the empirical ionospheric models
- The COSMIC team developed and validated strategy of RO data processing from GPS observations onboard geostationary GOES satellites to retrieve electron density profiles. The GOES RO EDPs cover altitudinal range from bottom border of ionosphere up to 2000 km, much wider than that of current LEO RO missions which is valuable for evaluation of empirical ionosphere models in topside part.
- The first results of ionosonde high-rate campaigns and COSMIC-2 RO soundings combination demonstrate a good potential to create reference dataset covers ionospheric altitudes 100-500 km and based only on real measurements

Acknowledgements

We acknowledge the IRI Working group for providing and evaluating the IRI model (http://irimodel.org/IRI-2020/) and ICTP T/ICT4D Laboratory for the NeQuick 2 model (https://t-ict4d.ictp.it/nequick2)

COSMIC CDAAC providing RO electron density profiles and absolute TEC products from COSMIC-1 and COSMIC-2 missions.

We acknowledge NASA (Doug Freesland, Alexander Krimchansky, Joel McCorkel) and Lockheed Martin Corporation (Graeme Ramsey, Jim Chapel) for providing GOES GPS observations.

Raw ionograms from Ebre ionosonde are available through GIRO (http://giro.uml.edu/; http://spase.info/SMWG/Observatory/GIRO).

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Thank you for your attention!