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Ionosonde observations as the reference for the global ionosphere specification

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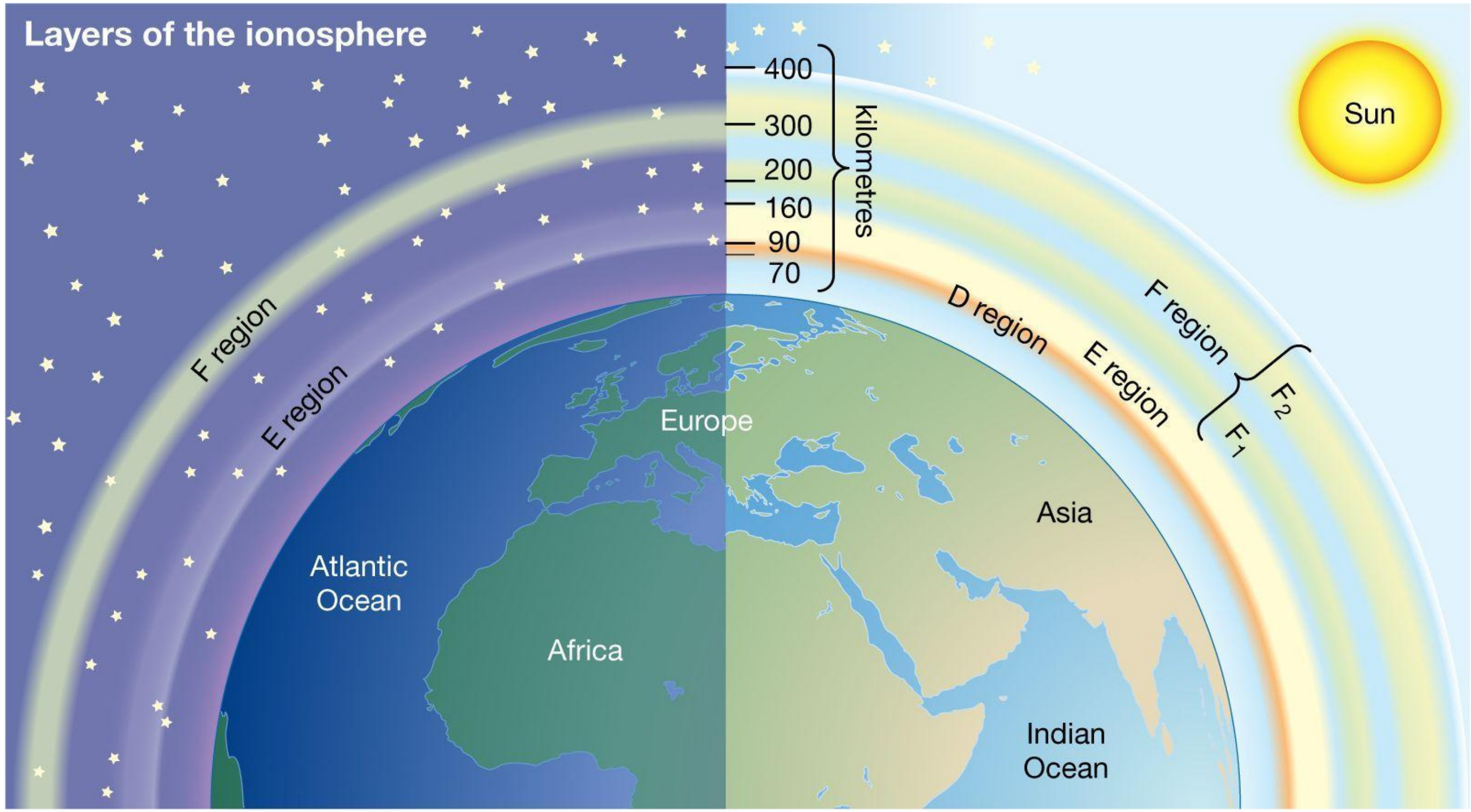
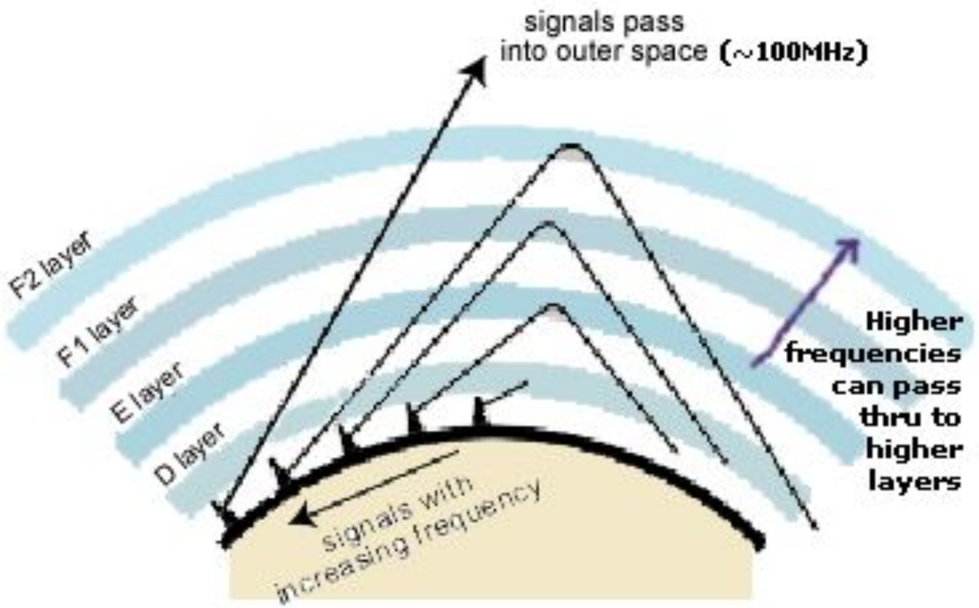
Ionosphere

Ionosphere:

- Ionized part of the Earth's upper atmosphere, cold plasma
- Altitudinal range from ~60 km to 700-1000 km
- Consists of several layers with different density, able to reflect or modify radio signals propagation

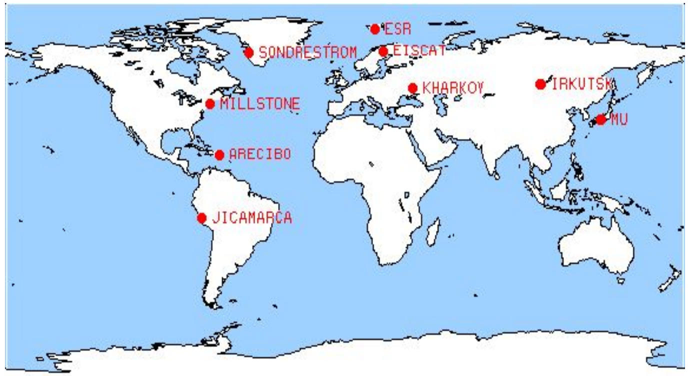




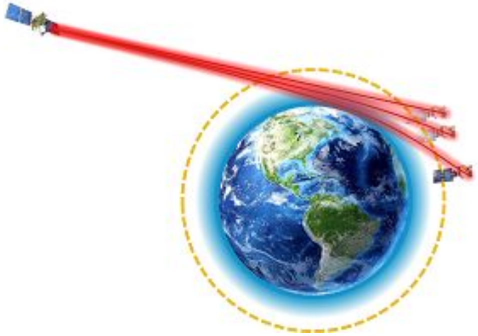
Probing of altitudinal distribution of ionospheric plasma density: radio observations

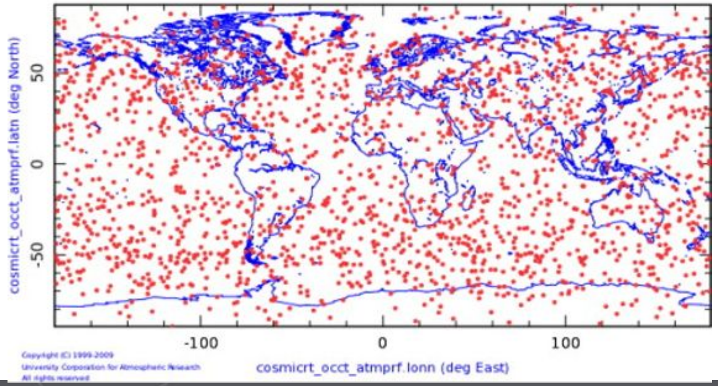
HF sounding radars - ionosondes:
- unbiased plasma density values up to F2 peak
- globally distributed network at low, high and mid latitudes
- continuous 24/7 observations, key dataset for ionospheric climatology

Incoherent scatter radars:
- full profile up to 1000 km altitude
- several sites at low, high and mid latitudes
- limited time observational complains, limitations for global climatology



Radio occultation observations:
- full profile up to LEO altitude (500-700 km)
- global data coverage
- continuous observations suitable for climatological analysis and data assimilation





HF sounding radars (Ionosondes): Fundamentals

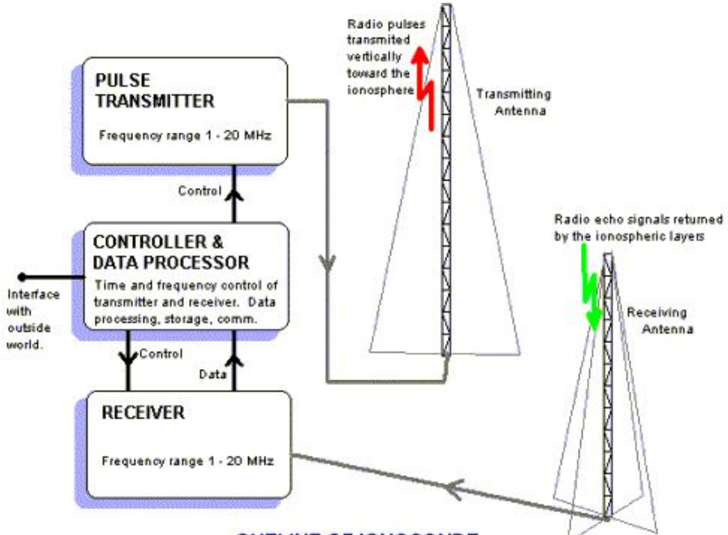
Developed in 1920s, ionosondes are still considered as the “benchmark” data source for unbiased measurements of electron density in the bottom-side ionosphere, up to the ionospheric F2 peak height. 100+ years of observation history.

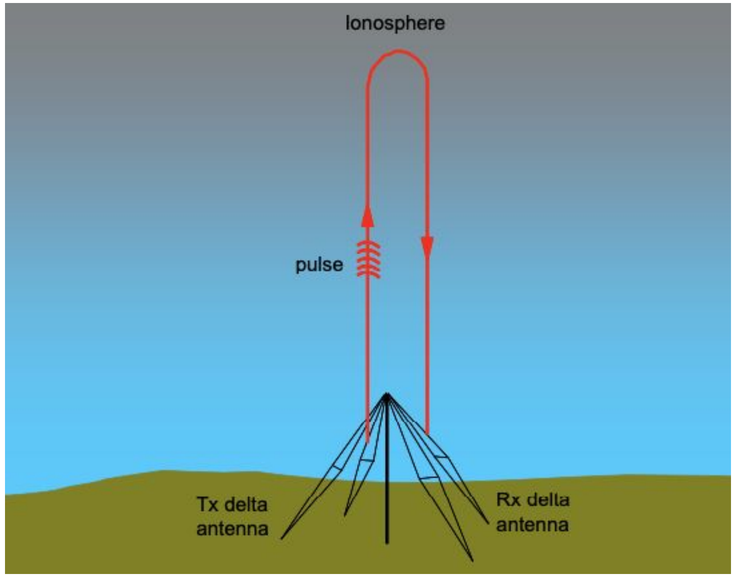
High Frequency (HF) radar is operating at 0-30 MHz band

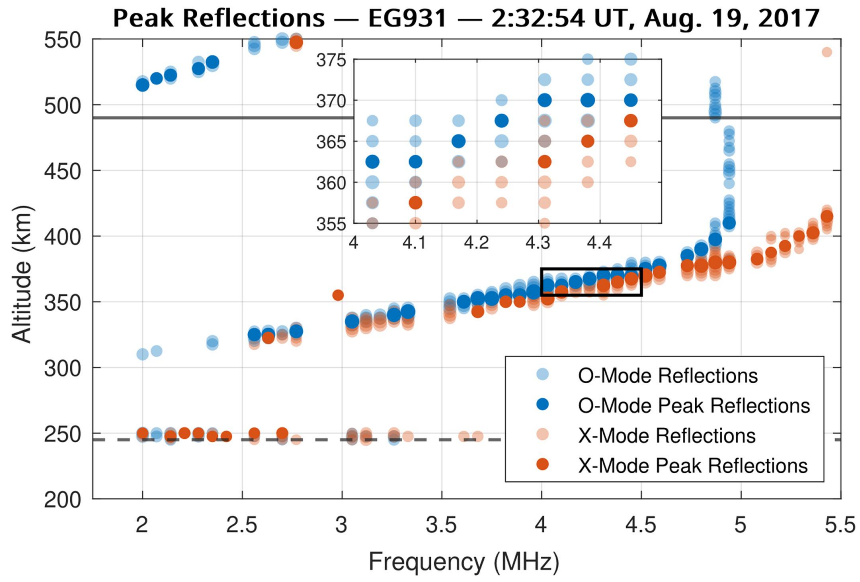
Served as ”ground truth standard” for different instruments (expert mode scaled ionograms)

Ionospheric F2 layer peak parameters (NmF2 & hmF2) for profile–based models formulation

Continuous day-to-day ionospheric variability records for multiple sites on the globe.







HF sounding radars (Ionosondes): Fundamentals

Ionosphere refractive index is proportional to the electron concentration Appleton-Hartree equation.

$$n^2 = 1 - \frac{X(1-X)}{1 - X - \frac{1}{2}Y^2\sin^2\theta \pm \left(\left(\frac{1}{2}Y^2\sin^2\theta\right)^2 + (1-X)^2Y^2\cos^2\theta\right)^{1/2}}$$

$i = \sqrt{-1}$ $\omega = 2\pi f$: angular frequency

$X = \frac{\omega_0^2}{\omega^2}$ $Y = \frac{\omega_H}{\omega}$ $Z = \frac{\nu}{\omega}$ ν: collision frequency

$\omega_0 = 2\pi f_0 = \sqrt{\frac{Ne^2}{\epsilon_0 m}}$: electron plasma frequency

$\omega_H = 2\pi f_H = \frac{B_0|e|}{m}$: electron gyro frequency

ϵ_0: permittivity of free space

e: electron charge

m: electron mass

B_0: magnetic field strength

θ: angle between magnetic field vector and the wave vector

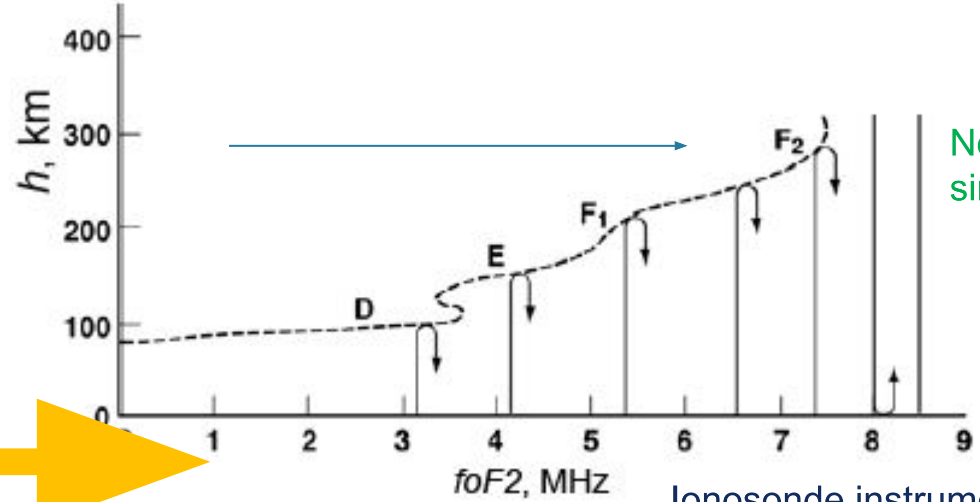
and the refractive index is inversely proportional to the frequency of the transmitted wave.

$$n^2 = 1 - \left(\frac{f_p}{f}\right)^2 \quad f_p = \sqrt{\frac{Ne^2}{4\pi^2\varepsilon_0 m}} \approx 9\sqrt{N}$$

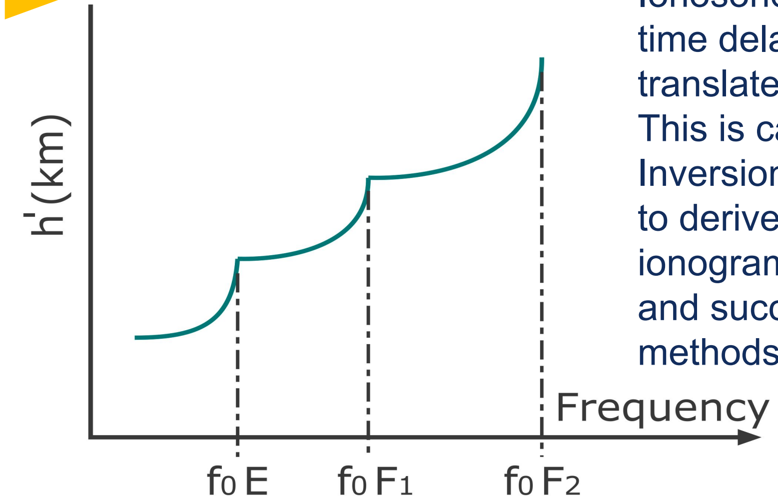
f_p – plasma frequency depends n density only

Radiowaves, which are transmitted on plasma frequency, are totally reflected by an ionized layer with particular plasma density due to interaction between electric fields of the radiowaves and plasma electrons (refractive index n=0)

When transmitted frequency increases, each wave is refracted less by the ionisation in the layer, and so each penetrates further before it is reflected.



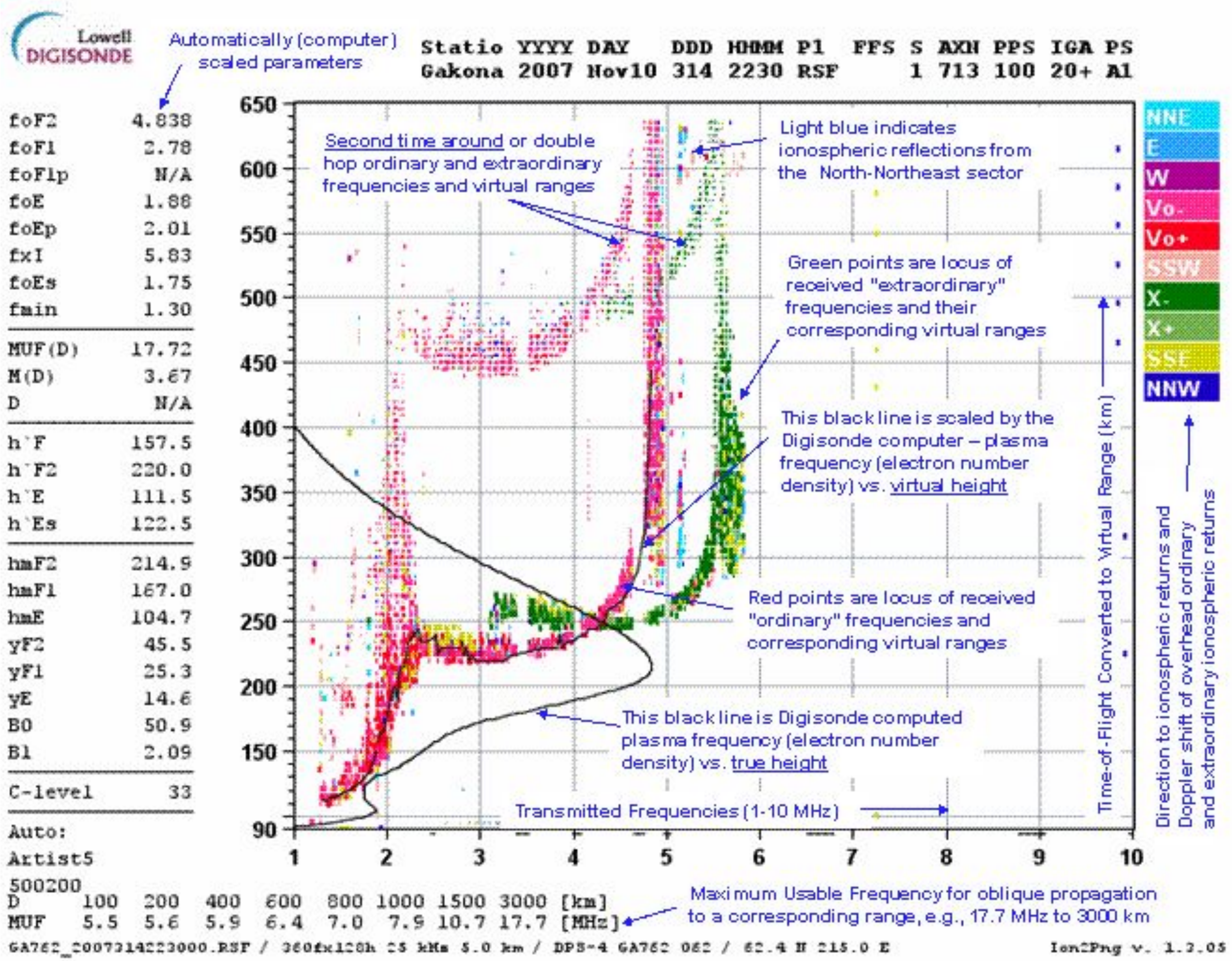
No magnetic field simplification

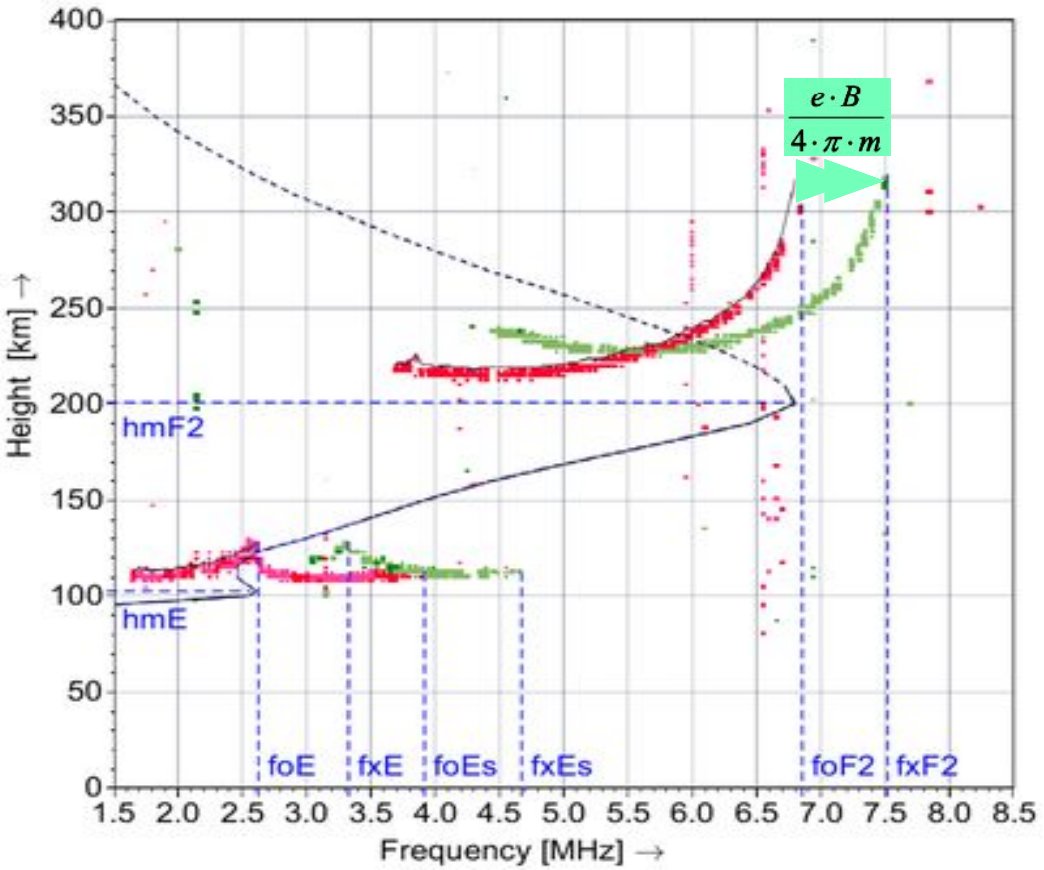


Ionosonde instrument registers time delay of the reflected signal translated to the virtual height. This is called an ionogram. Inversion processes are necessary to derive density profile from ionogram. Polynomial inversion and successive approximation methods are applied.

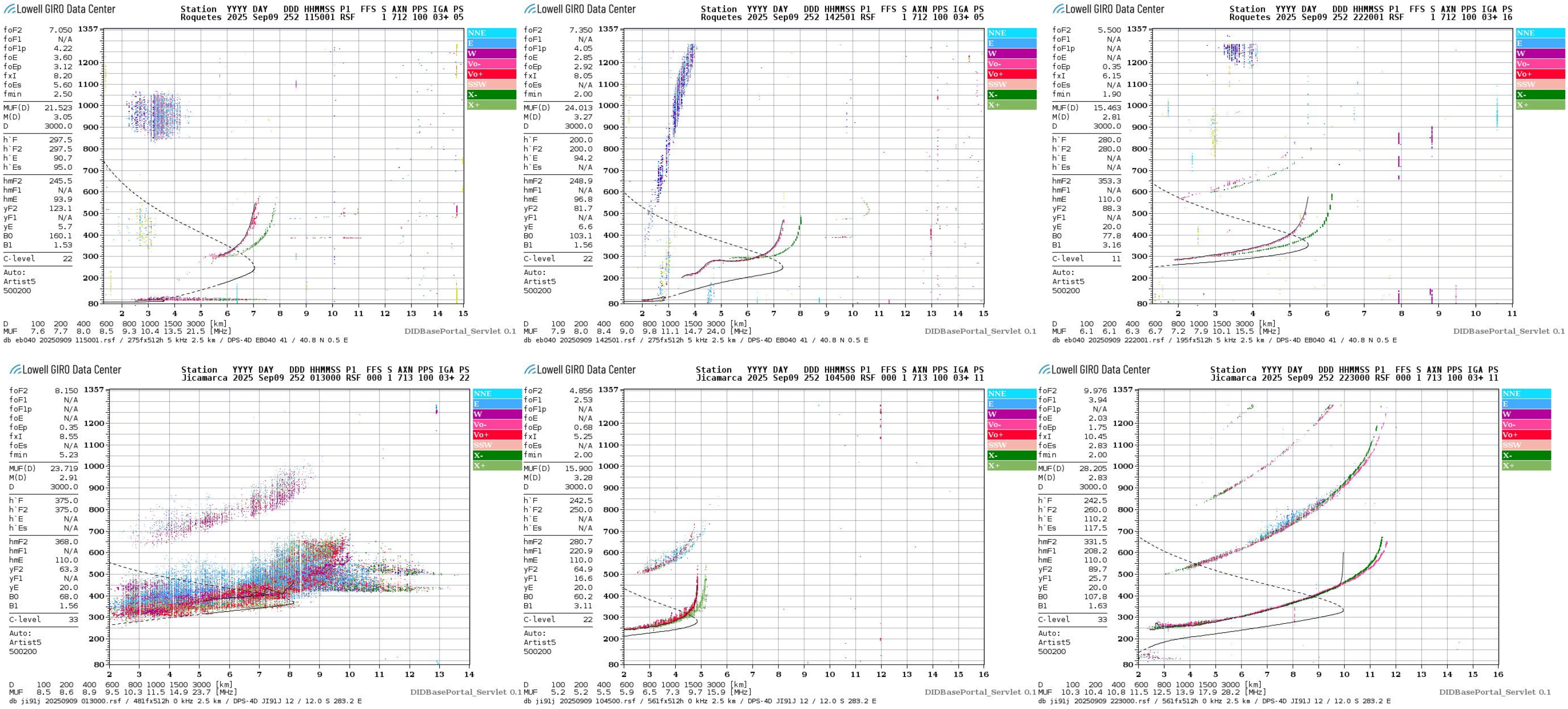
HF sounding radars (Ionosondes): Ionogram characteristics

For the real ionospheric conditions, there are two ionogram traces depending on the polarisation of the transmitted wave. This is a result of the magnetic field, which causes the ionosphere to be birefringent. These traces are called the ordinary and extraordinary components.





HF sounding radars (Ionosondes): Ionogram characteristics



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Global Ionosphere Radio Observatory (GIRO)

Hosted by UML Lowell GIRO Data Center (LGDC)

In cooperation with the URSI Ionosonde Network Advisory Group (INAG), the LGDC promotes cooperative agreements with the ionosonde observatories of the world to accept and process real-time data of HF radio monitoring of the ionosphere

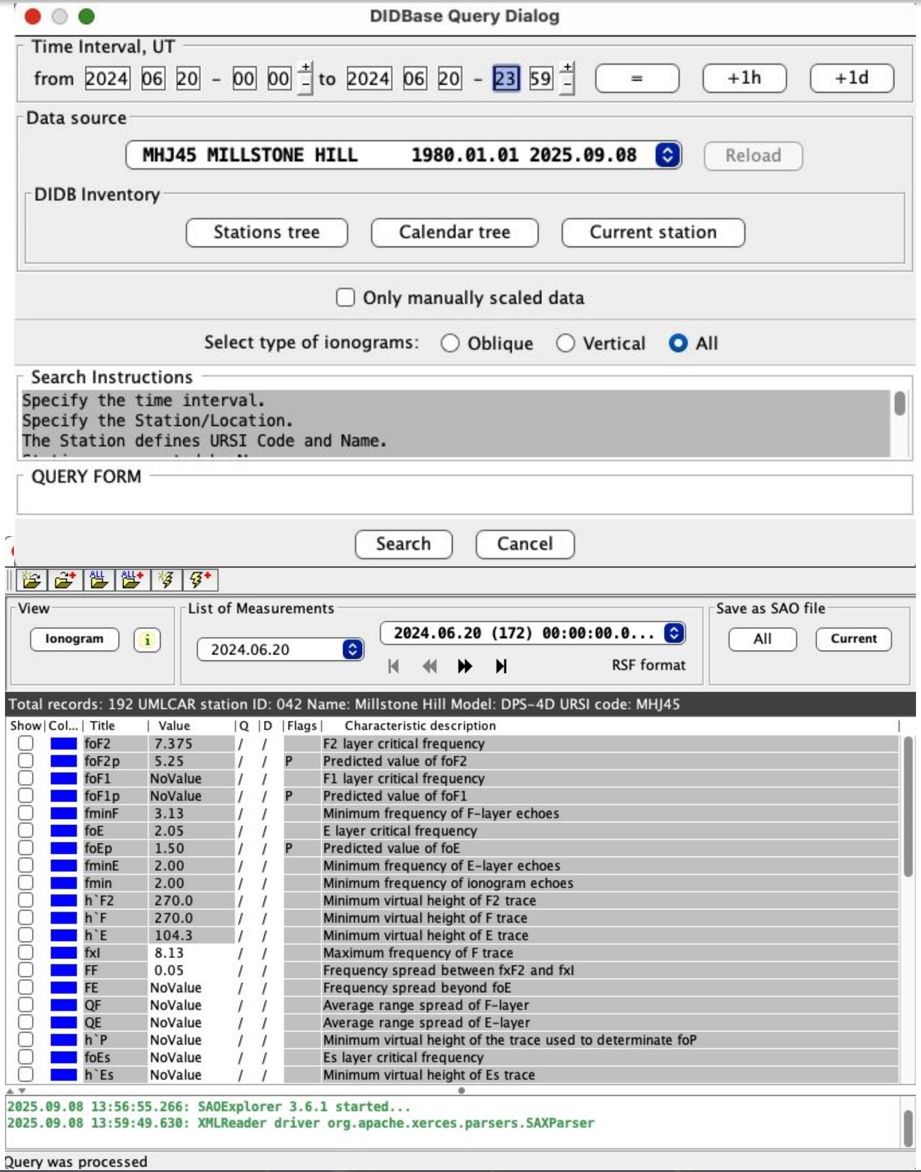
Digital Ionogram DataBase

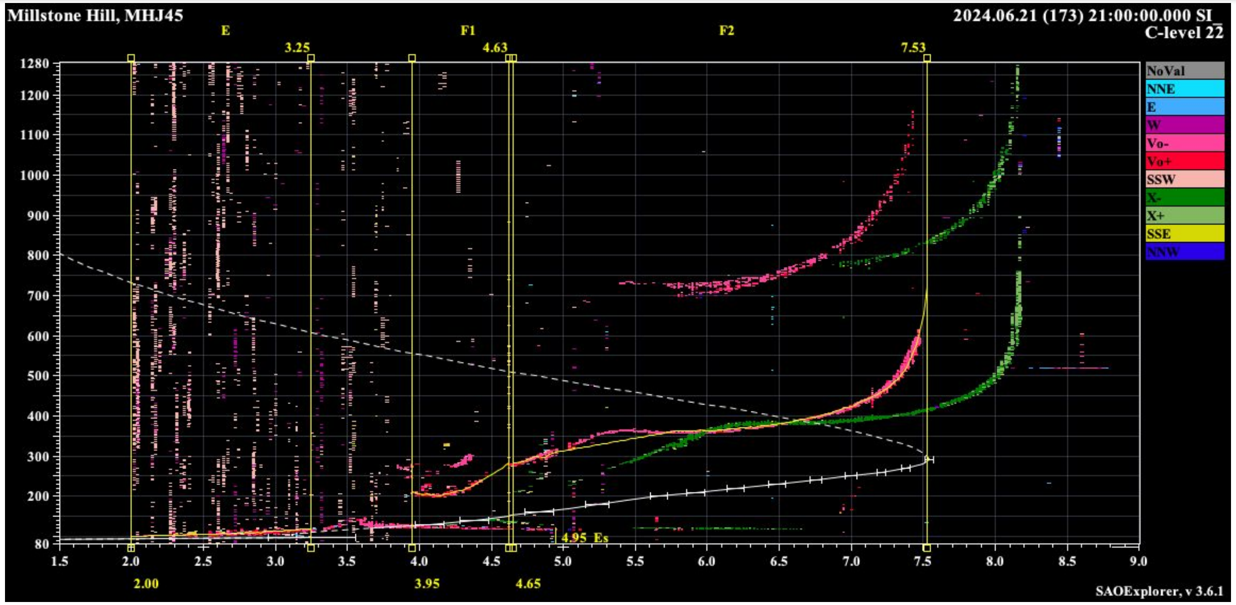
(on https://giro.uml.edu/didbase/)

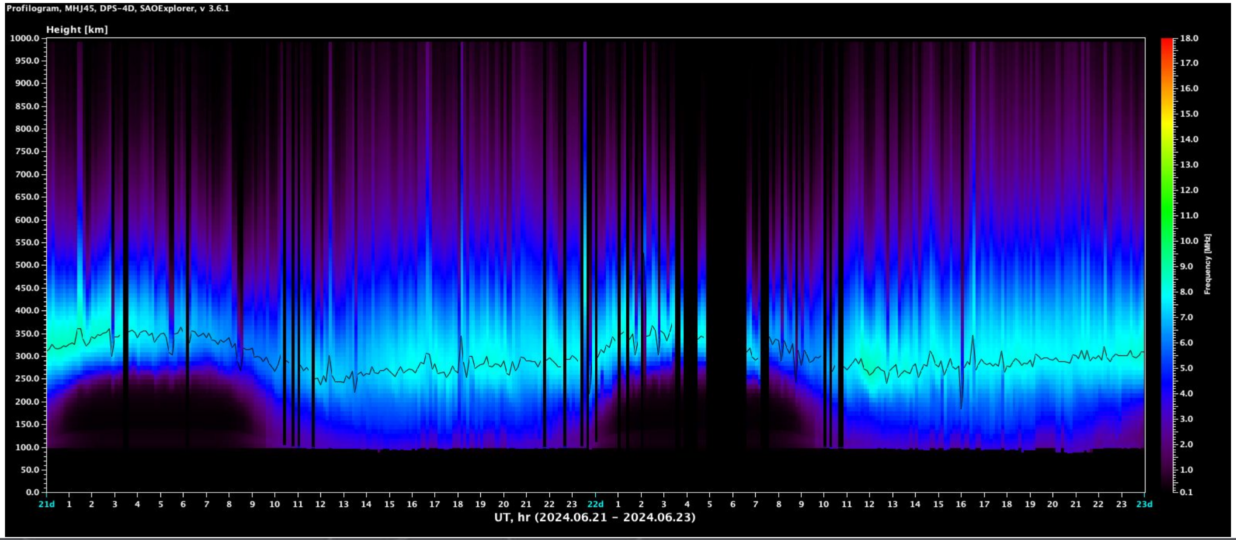
DIDBase Fast Station List

#	URSI	STATION NAME	LAT	LONG
1	AH223	AHMEDABAD	23.00	72.50
2	DH224	AL DHAFRA AFB	24.24	54.58
3	AL945	ALPENA	45.07	276.44
4	AN438	ANYANG	37.39	126.95
5	AS00Q	ASCENSION ISLAND	-7.95	345.60
6	AT138	ATHENS	38.00	23.50
7	AU930	AUSTIN	30.40	262.30
8	AW426	AWASE	26.32	127.84
9	BP440	BEIJING	40.30	116.20
10	BLJ03	BELEM	1.43	311.56
11	BJJ32	BERMUDA	32.40	295.30
12	BVJ03	BOA VISTA	2.80	299.30
13	BC840	BOULDER	40.00	254.70
14	BR52P	BRISBANE	-27.06	153.06
15	BV53Q	BUNDOORA	-37.70	145.05
16	CXM9B	CACHIMBO	-9.50	305.20
17	CAJ2M	CACHOEIRA PAULISTA	-22.70	315.00
18	CN53L	CAMDEN	-34.05	150.67

Global Ionosphere Radio Observatory (GIRO)







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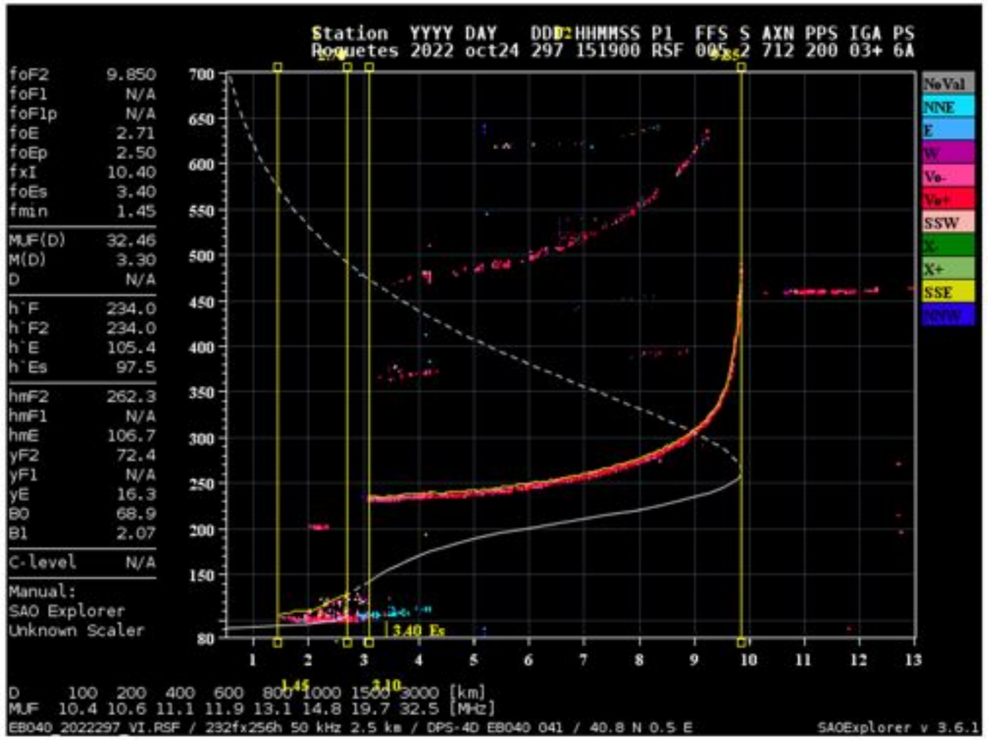
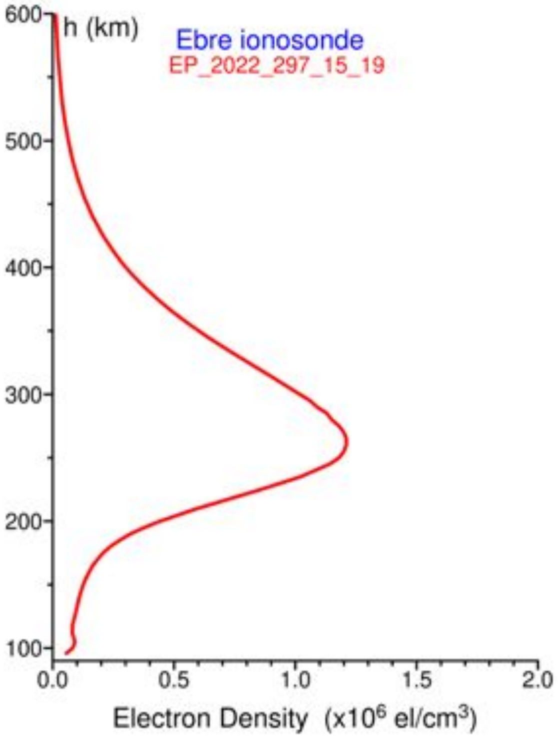
The expert-mode ionograms' analysis

Expert scaling of digital ionograms allows to get the precise virtual height - frequency inversion to the electron density profiles, along with accurate estimates of the major F2 peak parameters.

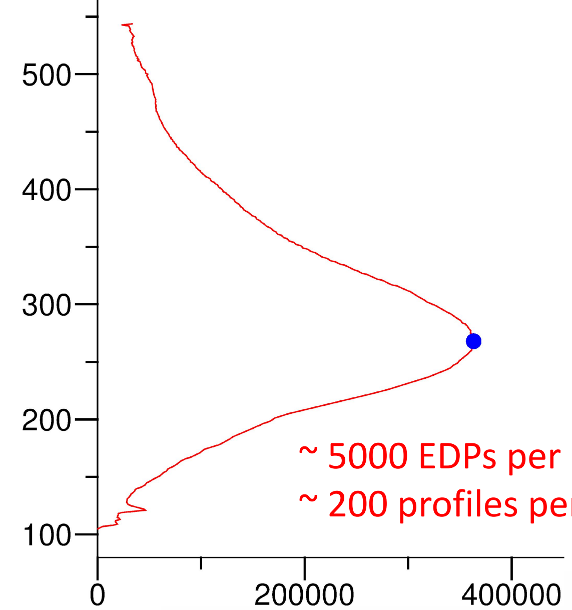




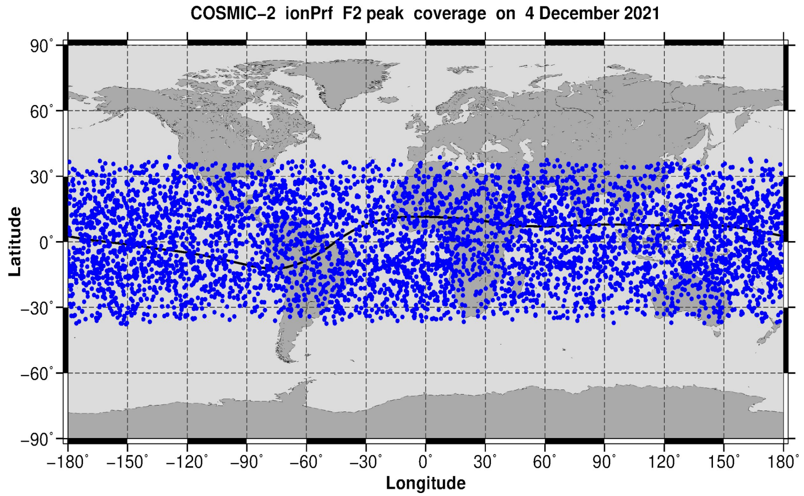
Example (from left to right) of the ground-based HF (ionosonde) sounding recording with results of the ionogram processing, and ionosonde-derived electron density profile Ne(h).

Applications: Global ionosonde network for COSMIC- 2 GNSS radio occultations EDPs validation

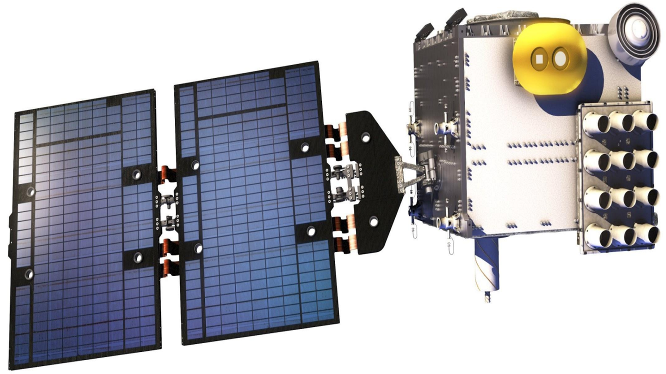
COSMIC-2 Ionospheric Electron Density Profiles Level 2 data product



~ 5000 EDPs per day
~ 200 profiles per 1 hr

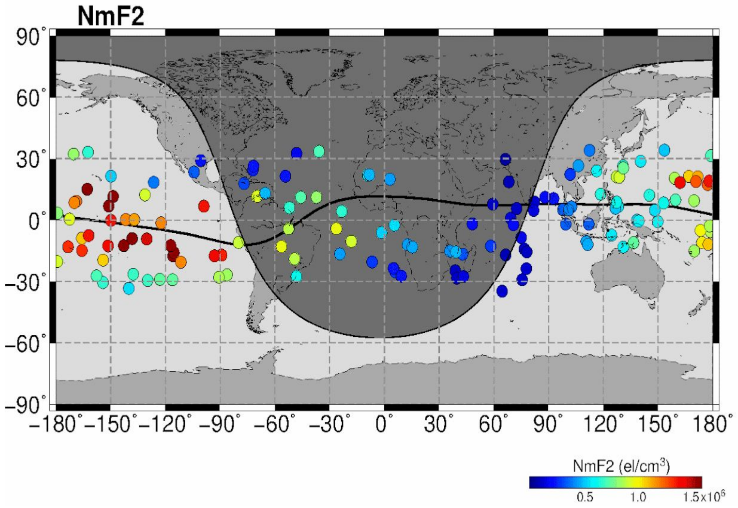


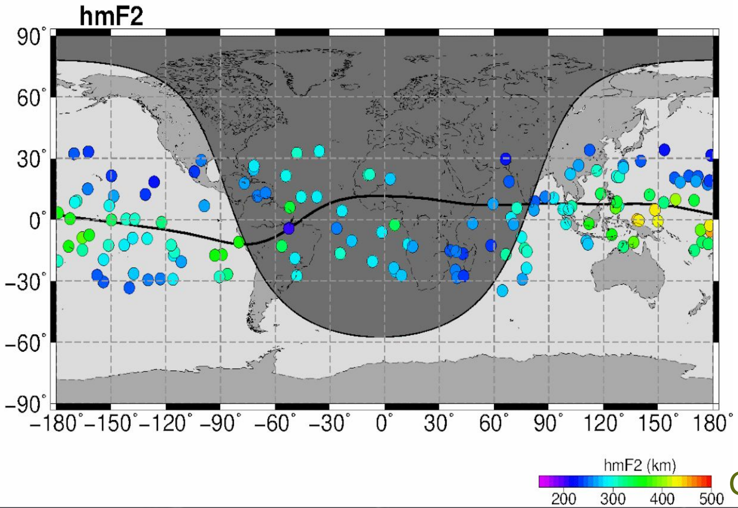
Available on COSMIC Data Analysis and Archive Center (CDAAC)

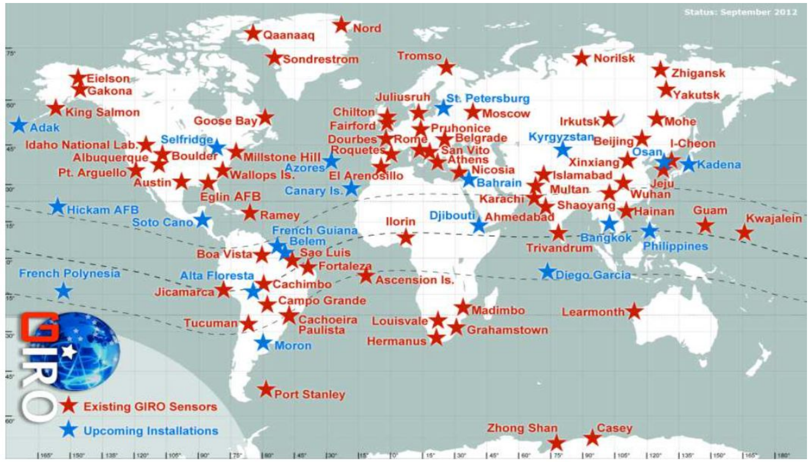


COSMIC-2 RO Tri-GNSS Radio Occultation Receiver System developed by JPL. RO with GPS and GLONASS signals

04 Dec 2021 0000 UT

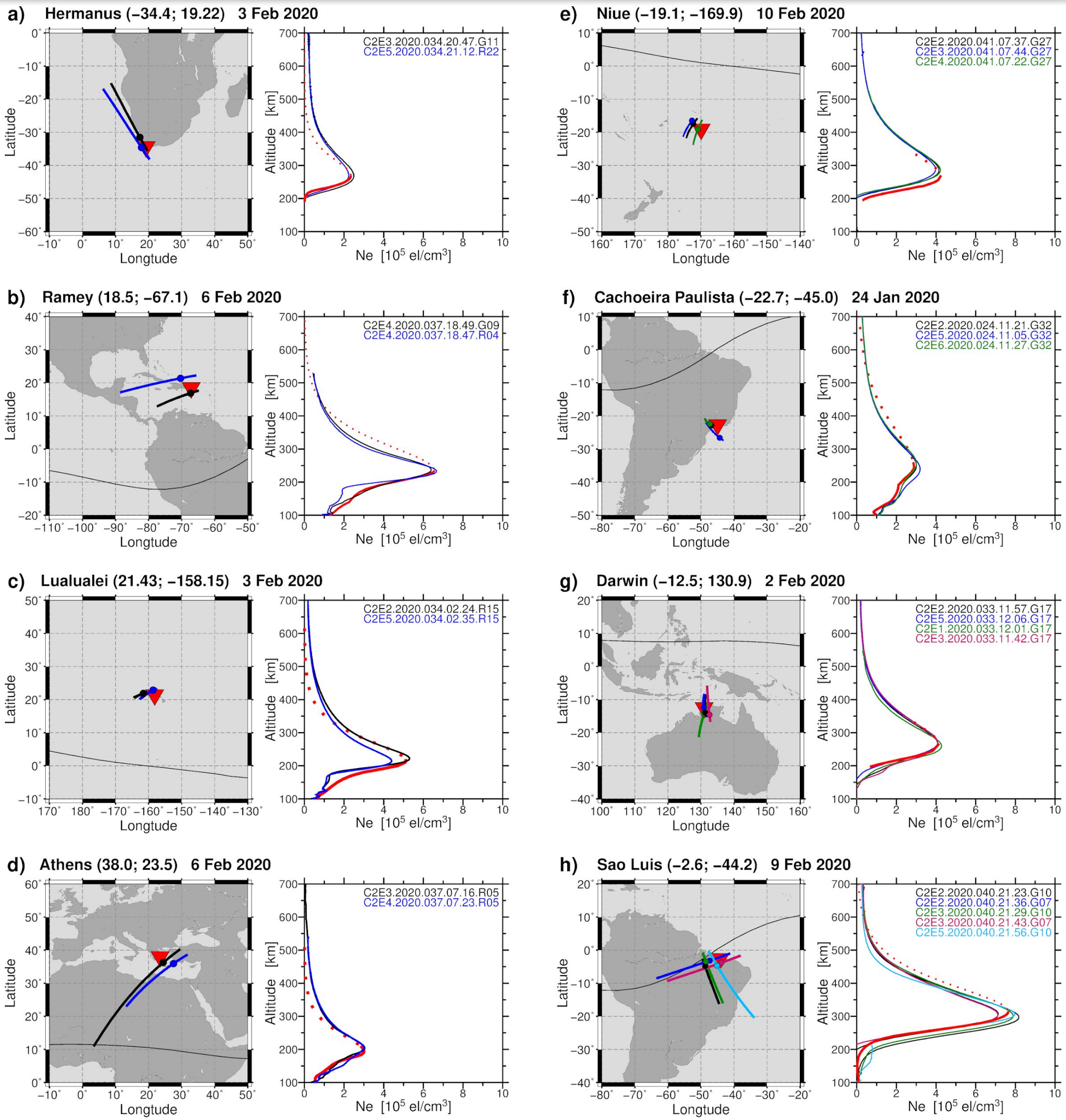




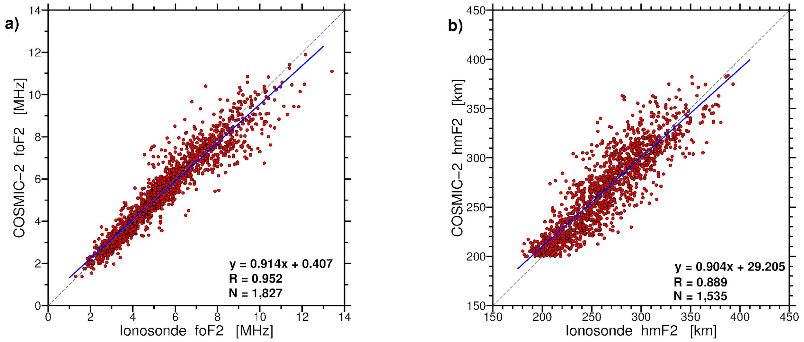


GIRO ionosondes locations vs COSMIC-2 operation area

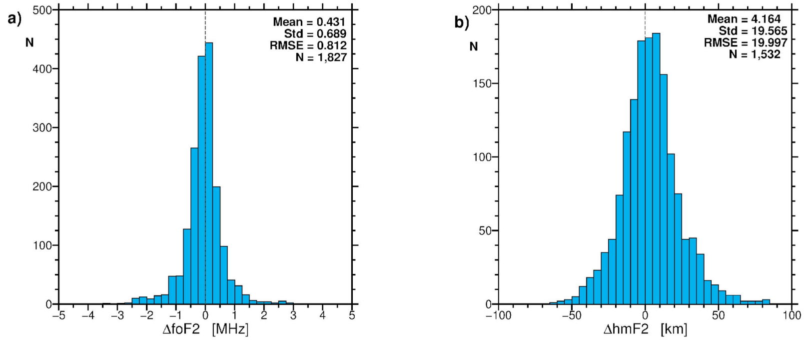
Applications: Global ionosonde network for COSMIC- 2 GNSS radio occultations EDPs validation



Performance and accuracy of Electron Density Profiles Level 2 data product were evaluated by ionosonde observations.



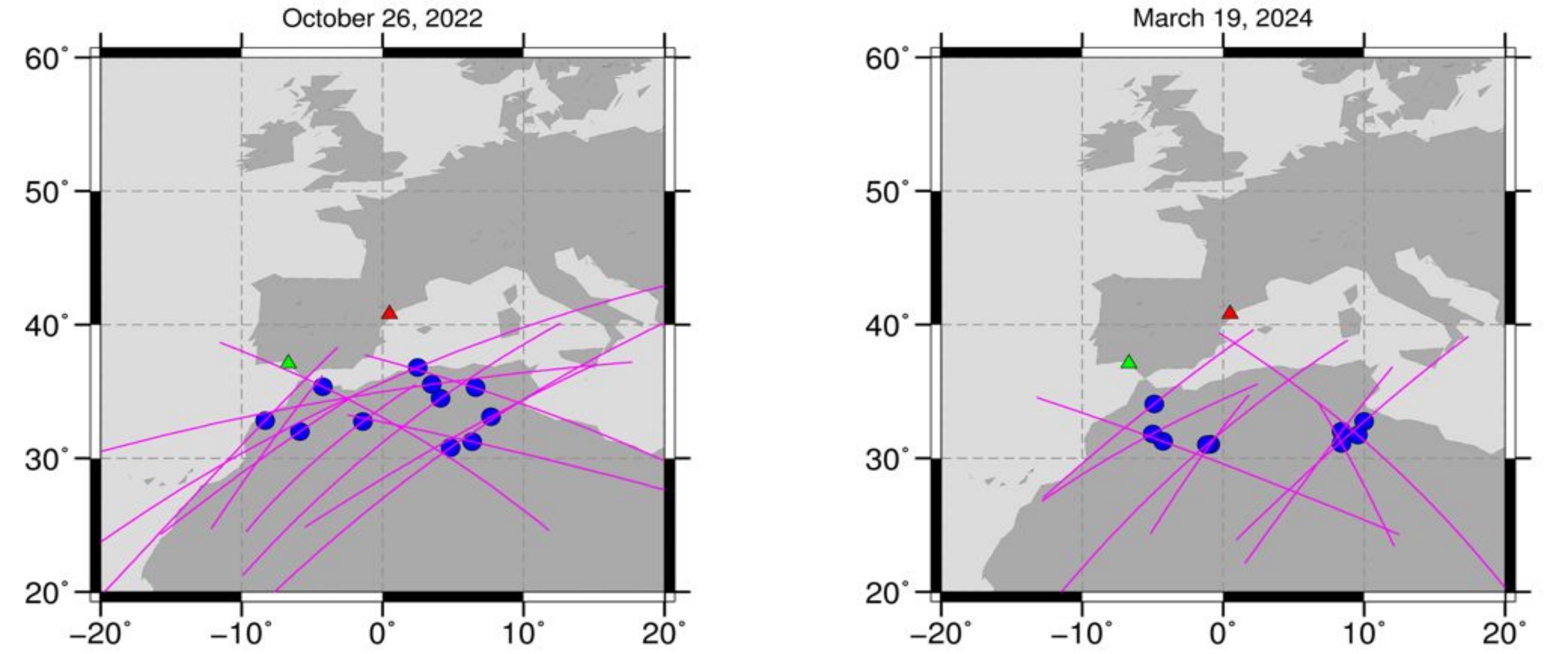
The scatter plots of the COSMIC-2 RO-based foF2 and hmF2 values against the corresponding ionosonde-derived ones.



Histograms of the F2 peak parameters residuals ΔfoF2 ($\Delta foF2 = foF2_{RO} - foF2_{ionosonde}$) and ΔhmF2 ($\Delta hmF2 = hmF2_{RO} - hmF2_{ionosonde}$) between collocated COSMIC-2 and ionosonde measurements

More details in Cherniak et al, JSWSC, 2021

Applications: COSMIC-2 RO vs ionosonde combination



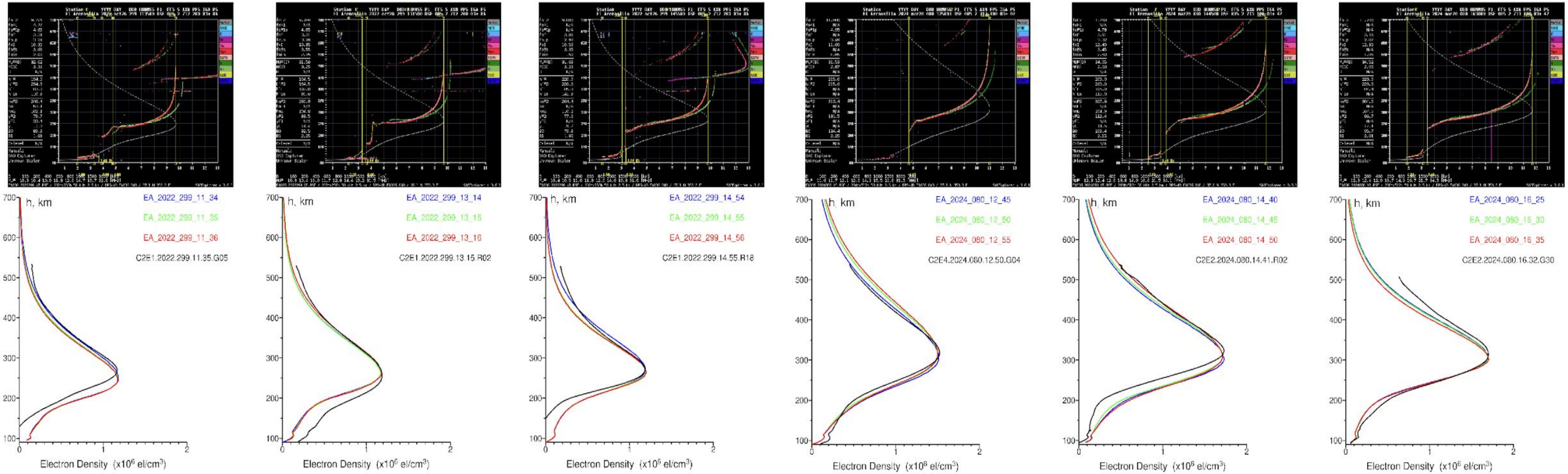
Example of COSMIC-2 RO observations with EDP tangent point projections (pink lines) for 26 October 2022 and 19 March 2024.

The blue dots corresponded to the F2 layer peak location derived from the COSMIC-2 RO profiles. Red and green triangles pinpoint the Ebre and El Arenosillo ionosondes locations.

Colocation criteria for the GNSS RO vs ionosonde measurements are based on the spatial correlation factor of ionospheric plasma density variability. For the quiet-time midlatitude ionosphere, the correlation distance (correlation coefficient r > 0.70) can be considered as approximately 1,500–3,000 km in an east-west direction and 1,000–1,800 km in a north-south direction.

Important advantage of high-rate ionosonde campaigns is that we can obtain more precise colocations in temporal domain.

Applications: COSMIC-2 RO vs ionosondes combination. El Arenosillo Observatory



Representative examples of EDP colocation events between COSMIC-2 RO and El Arenosillo ionosonde combining ionogram recording and EDP comparisons for the October 2022 (left) and the March 2024 (right) high-rate sounding campaigns.

Applications: Combined ionospheric EDPs as data source for validation of climatological models of the ionosphere

IRI

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

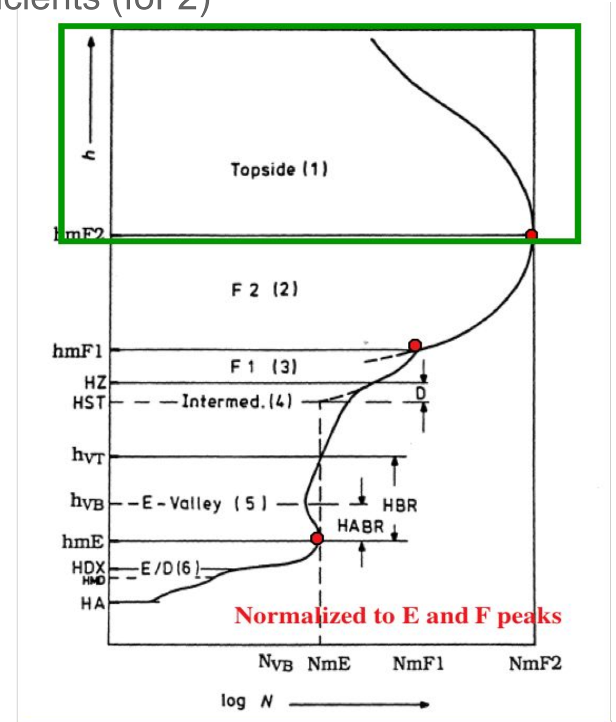
Model Input

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)

IRI is a ISO standard



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

NeQuick

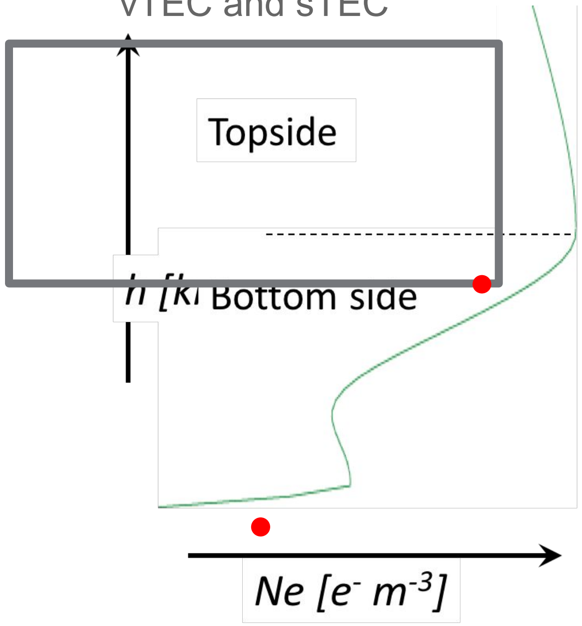
Model Developers: S. Radicella, B. Nava, ICTP

Model Input

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

Model Output

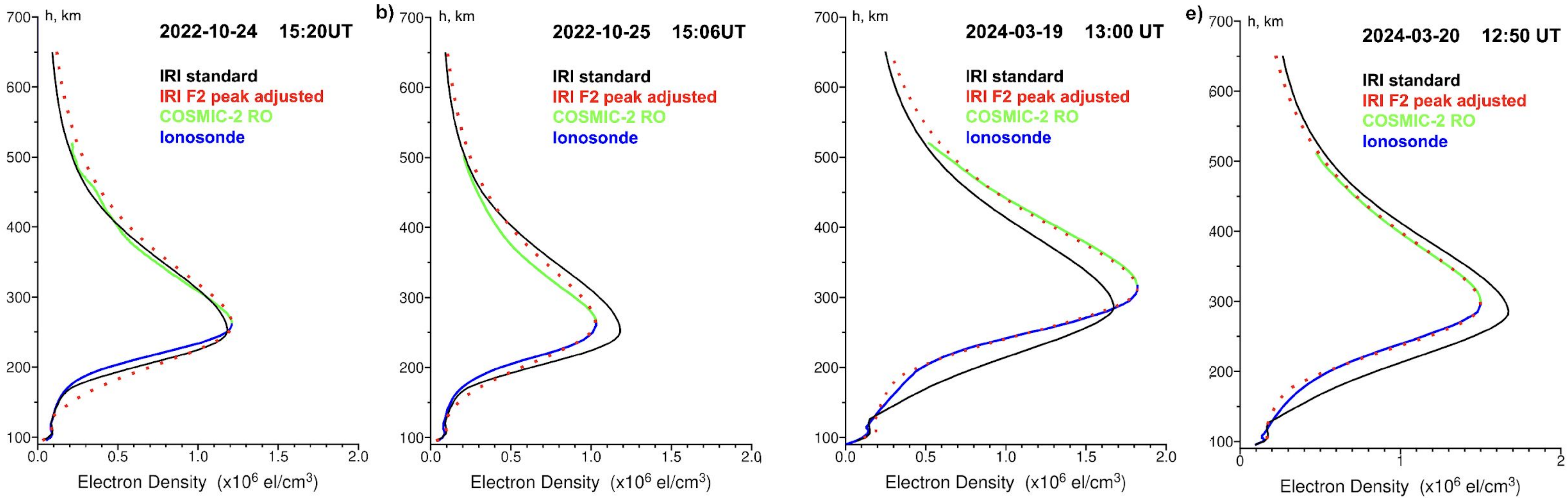
Electron density
Height range: 80 – 20,000 km
Ionospheric total electron content (TEC): vTEC and sTEC



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.

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

Applications: Combined ionospheric EDPs as data source for validation of climatological models of the ionosphere

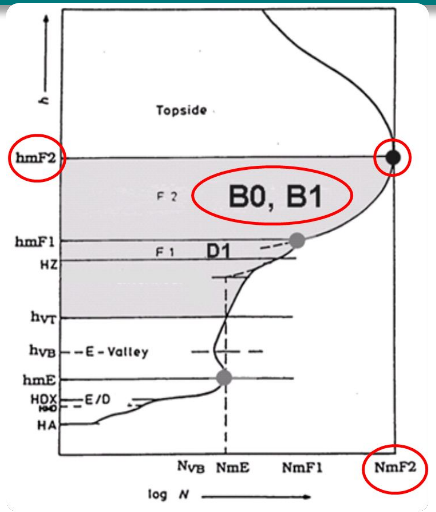


Comparison of the IRI-2020 adjusted EDPs (red dots) with reference combined EDPs (blue-green line).
The standard IRI output is shown as a black line.

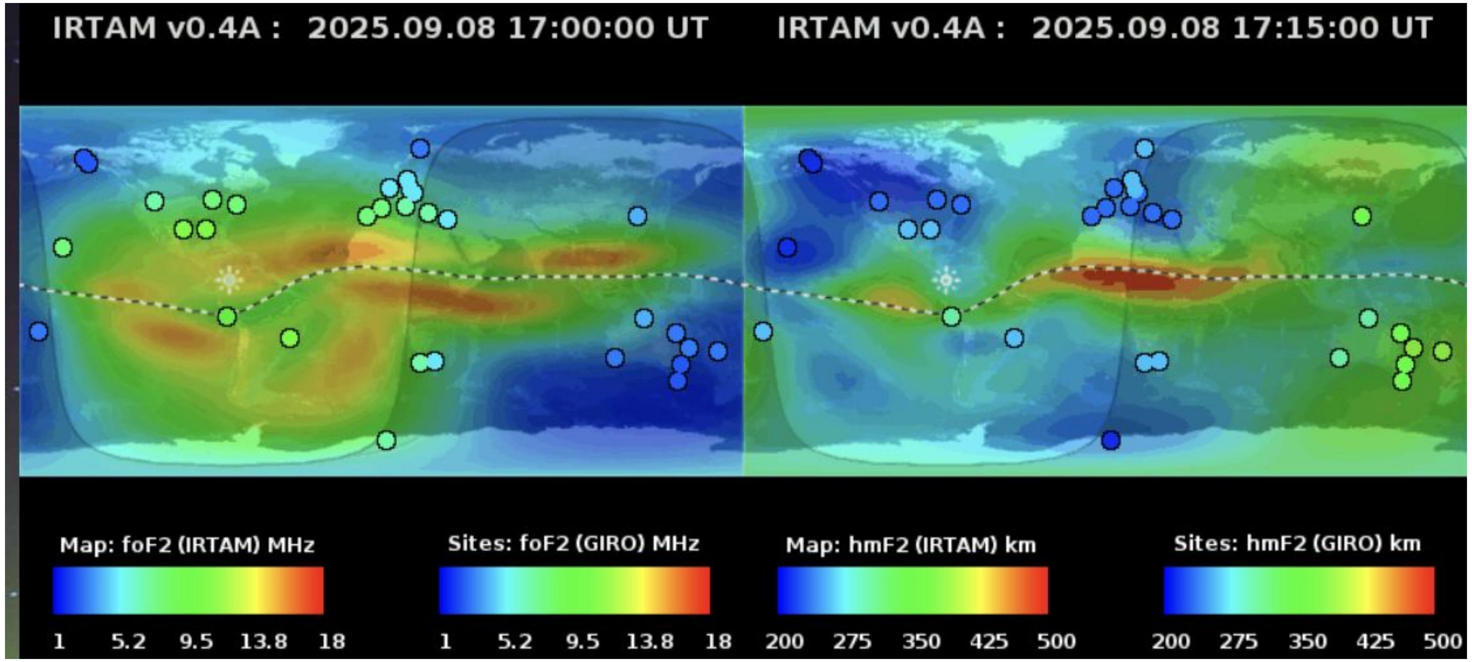
Applications: Data assimilation. IRI rea-time (IRTAM)

REAL TIME IRI
Assimilative Mapping
IRTAM

Galkin et al. (2012) developed the IRTAM (http://giro.uml.edu/IRTAM) system, which extracts four parameters (which are $foF2$, $hmF2$, $B0$, and $B1$) from the GIRO ionosonde data and assimilates them into the IRI model.



- Real-time IRI
- Empirical assimilative nowcast model
  - Data-driven empirical model, driven by new data
  - Massively "4DDA": assimilation of <u>24-hour history</u> to extract and manipulate diurnal harmonics separately
- Manipulates IRI climate coefficients into the best match to GIRO measurements
  - IRTAM <u>is</u> IRI with updated coefficients
    - Smooth ionosphere, good for raytracing
    - Sharper features are not represented



Summary

- High frequency (HF) ionosphere soundings technique with ground-based ionosondes provides unbiased measurement of electron density in the ionosphere and precise characterictics of plasma distribution in the bottomside ionosphere below F2 peak.

- Global Ionosphere Radio Observatory (GIRO) is an international collaboration project for data sharing from a network of ionosondes whose data collections are represented in the GIRO database. The quasi-realtime and low latency data are avaliable for GIRO users.

- Ionosonde observations represent an effective benchmark dataset for other techniques for probing ionosphere including GNSS-based radio occultation.

- Combination of ionosonde observations with collocated COSMIC-2 RO measurements provides possibilities to develop a new experimental data source for specification of ionosphere plasma density vertical distribution - combined ionospheric EDPs based solely on real high-quality observations from both the bottomside and topside parts of the ionosphere. Such profiles offer a valuable data source for validating and further improvement of empirical, first principle, and assimilative ionospheric models.

- Empirical assimilative nowcast model IRTAM demonstrates effectiveness of quasi-realtime ionosonde observations for global ionosphere specification.

Acknowledgements

Raw ionograms, profilogramms and scaling parameters are available through the GIRO database (http://giro.uml.edu/)

We acknowledge COSMIC CDAAC for providing RO electron density profiles from COSMIC-2 mission (UCAR COSMIC Program, https://doi.org/10.5065/t353-c093)

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Thank you for your attention!