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# O⁺ density profiles provided by the ultraviolet imagers onboard ICON: comparison with radio-based observations and role of the equatorial ionization anomaly

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## Abstract

The NASA-ICON mission was dedicated to the observation of the terrestrial equatorial ionosphere between November 2019 and November 2022 from a circular orbit at about 600 km altitude. The scientific payload encompasses two ultraviolet imagers: the Far Ultraviolet Imaging Spectrograph (FUV) and the Extreme Ultra Violet (EUV) spectrograph. FUV observes the emission of the atomic oxygen doublet at 135.6 nm as well as the Lyman-Birge-Hopfield (LBH) band of $N_2$ near 157 nm while the EUV spectrograph records daytime limb altitude profiles of terrestrial emissions in the extreme ultraviolet spectrum from 54 to 88 nm. Every 12s, based on the 135.6 nm emission for FUV and on the OII–61.7 nm and 83.4 nm emissions for EUV, both instruments provide $O^+$ density profiles for nighttime and daytime conditions, respectively.

Besides, the GNSS radio-occultation mission COSMIC-2 daily provides, since 2019, several thousands of electron density profiles above low and mid-latitudes, in addition to ground-based ionosondes delivering high-quality observations at a regular cadence. For FUV, the peak density and height are, on average, similar to radio-based observations by about 10% in density and 7 km in altitude. The EUV spectrograph provides peak density values smaller than that from other techniques by 50 to 60%, while the altitude of the peak is retrieved with a slight bias of 10 to 20 km on average. While the equatorial ionization anomaly does not have a significant influence on the EUV comparisons, it is found that the largest density differences between FUV and C2/ionosonde data are related to the ionization crests where their large density gradients and specific geometry break the spherical symmetry assumed by the inverse Abel transform to retrieve the $O^+$ density profile. We perform a dedicated analysis of these particular cases using GNSS-TEC maps to identify the problems arising when considering multi-sensor data fusion at low-latitudes.

## 1. Data and comparison methodology

### ICON data

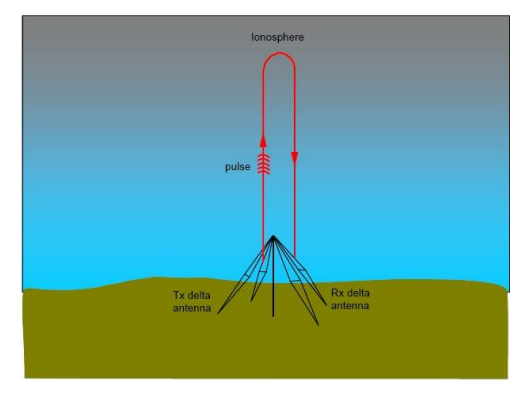
- Level-2 electron density ($N_e$) profiles (Data Product 2.5 for FUV and 2.6 for EUV)
- Latest file version/revision available at the time of the comparison

| | FUV | EUV |
|---|---|---|
| Number of vertical pixels in limb region for altitudes between 100 and 550 km | approx. 137<br>→ ~ 3km vertical resolution | approx. 92<br>→ ~ 5 km vertical resolution |
| Wavelengths [nm] / mode | 135.6 (nighttime) | 61.7 and 83.4 (daytime) |
| Time resolution | 12s | 12s |
| Horizontal « resolution » | 6 stripes (3° apart) | Single profile per epoch |

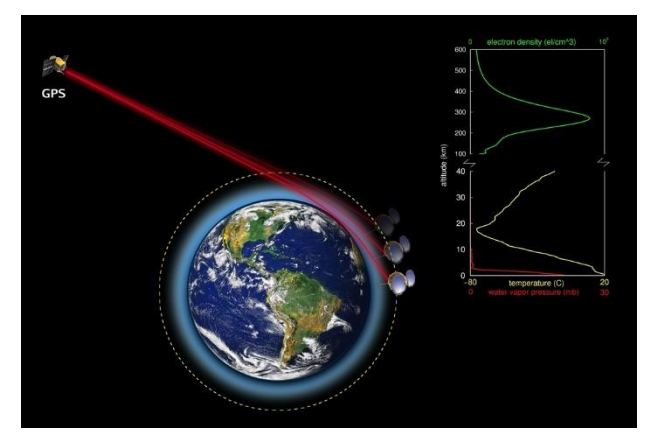
- Quality control
  - **FUV** quality check
    - Quality flag == 1 → reject all photoelectron effect and « doubtful » inversion
  - **EUV** quality check
    - Flag == 0 or 1 → we accept profiles that could have experienced some minor issues: low hmF2, low solar flux…
    - For flag == 1, all profiles corresponding to high values of Chi-square cases are excluded from the analysis

### External radio observations and IRI model

**Ionosondes**

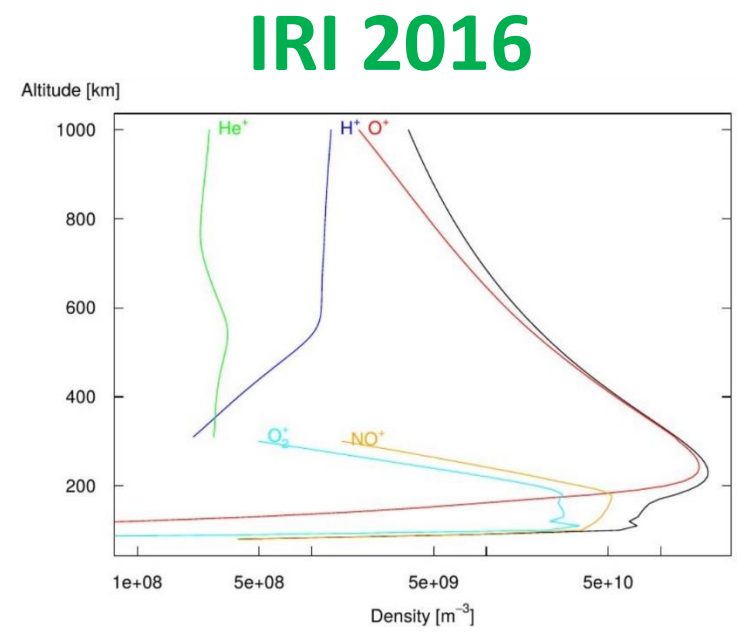


**COSMIC-2**



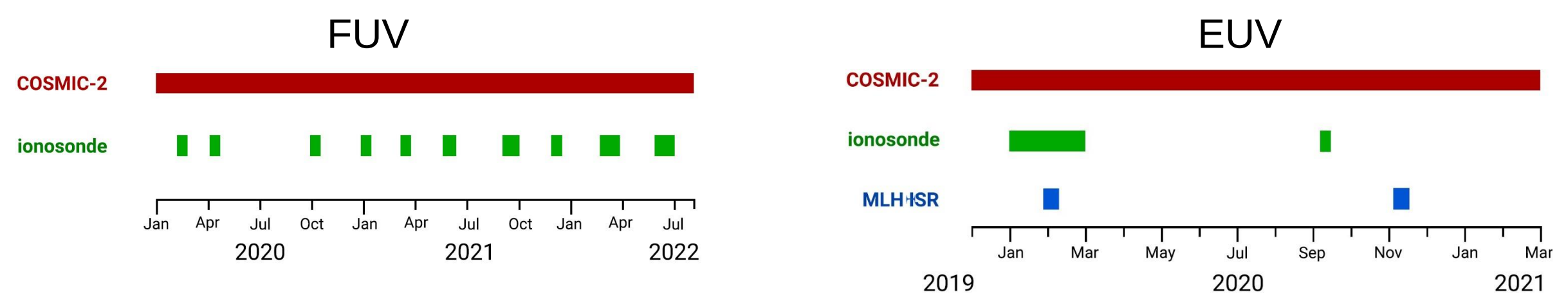
**Millstone Hill ISR**

**IRI 2016**



- Ionosonde quality check
  - Manual scaling of the ionogram sequence around the conjunction
  - Exclusion of doubtful ionograms: spread-F, forked traces at F heights, blanketing Es layers, tilts (TIDs), etc.
- COSMIC quality check
  - smear < 2200 km for FUV or < 1500 km for EUV
  - rejection of doubtful COSMIC profiles based on a Chapman fit of the electron density profile (H, α, ΔNmF2, ΔhmF2)
- ISR: two operating modes (plasma mode and ion-acoustic mode), used for EUV conjunctions only

### Time coverage for each radio-based data source



### Conjunction methodology and comparisons

- Conjunction definition : maximum distance = 500 km / Max. Δt = 15 min at 300 km altitude
- Computation of NmF2 and hmF2 differences: mean, standard deviation, median, IQR, etc.
- All density differences values are subtracted by **IRI differences** due to different LT/position
  → the different profiles are simultaneous et collocated at the IRI-level

## 2. Nighttime FUV results

### Comparison results

| | N | $\Delta N_mF_2$ $[m^{-3}]$ | $\Delta N_mF_2$ [%] | $\Delta h_mF_2$ [km] |
|---|---|---|---|---|
| FUV – COSMIC-2 | 339120 | $-3.7 \times 10^9$ $\pm 5.4 \times 10^{11}$ | 10 ± 48 | 6 ± 24 |
| FUV – ionosonde | 1169 | $9.0 \times 10^{10}$ $\pm 2.2 \times 10^{11}$ | 33 ± 80 | 4 ± 35 |

Wautelet *et al.* (2023), Space Science Reviews

- Very little bias for hmF2: similar to vertical resolution of FUV and about 1/10 of the ionospheric scale height at $F_2$ peak
- Slight positive bias for NmF2
- Large variability values, especially for NmF2

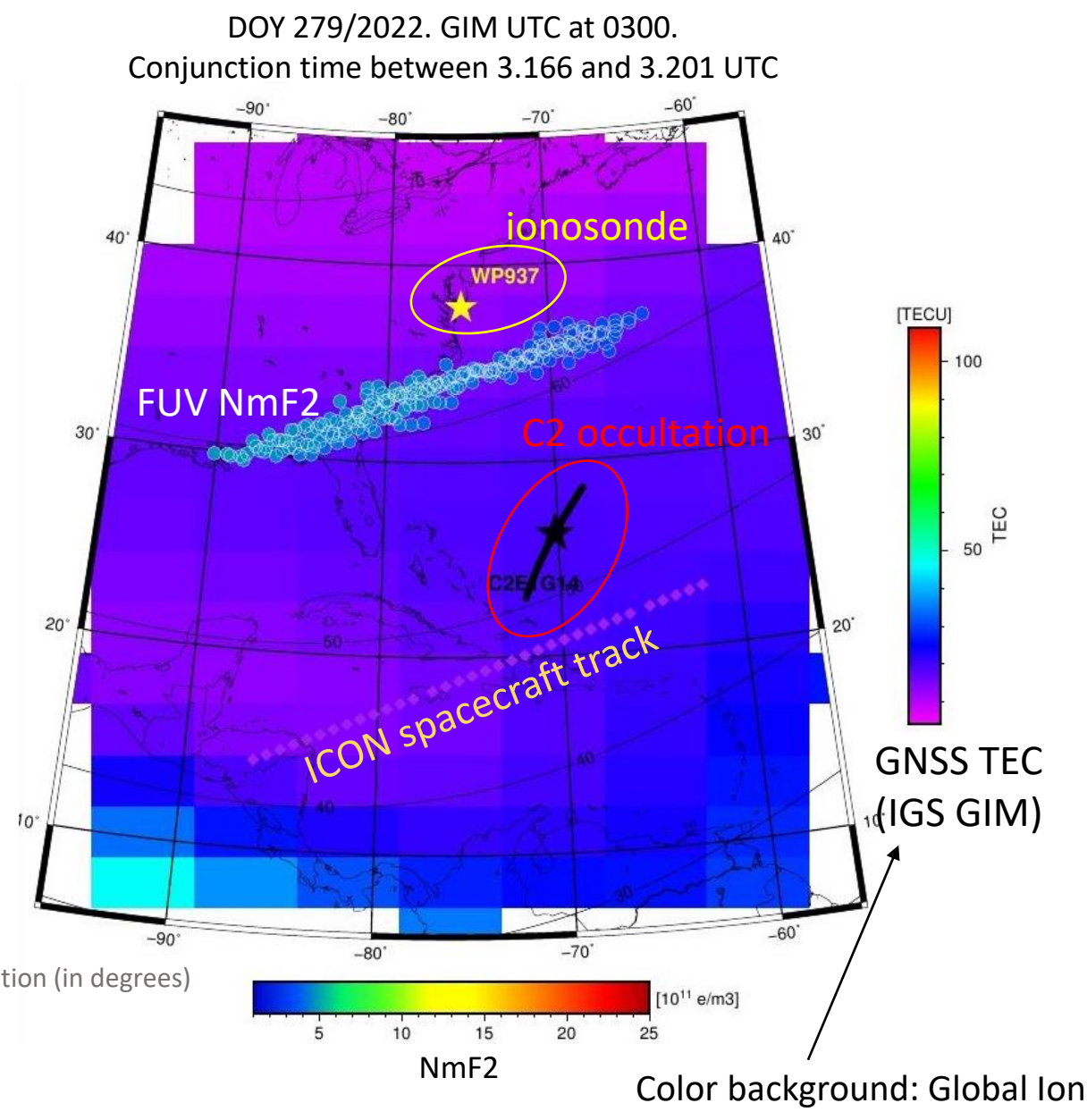
Good accuracy but poor precision → How to reduce the latter? In which cases does it occur ?

### Effect of the equatorial ionization anomaly (EIA) crests

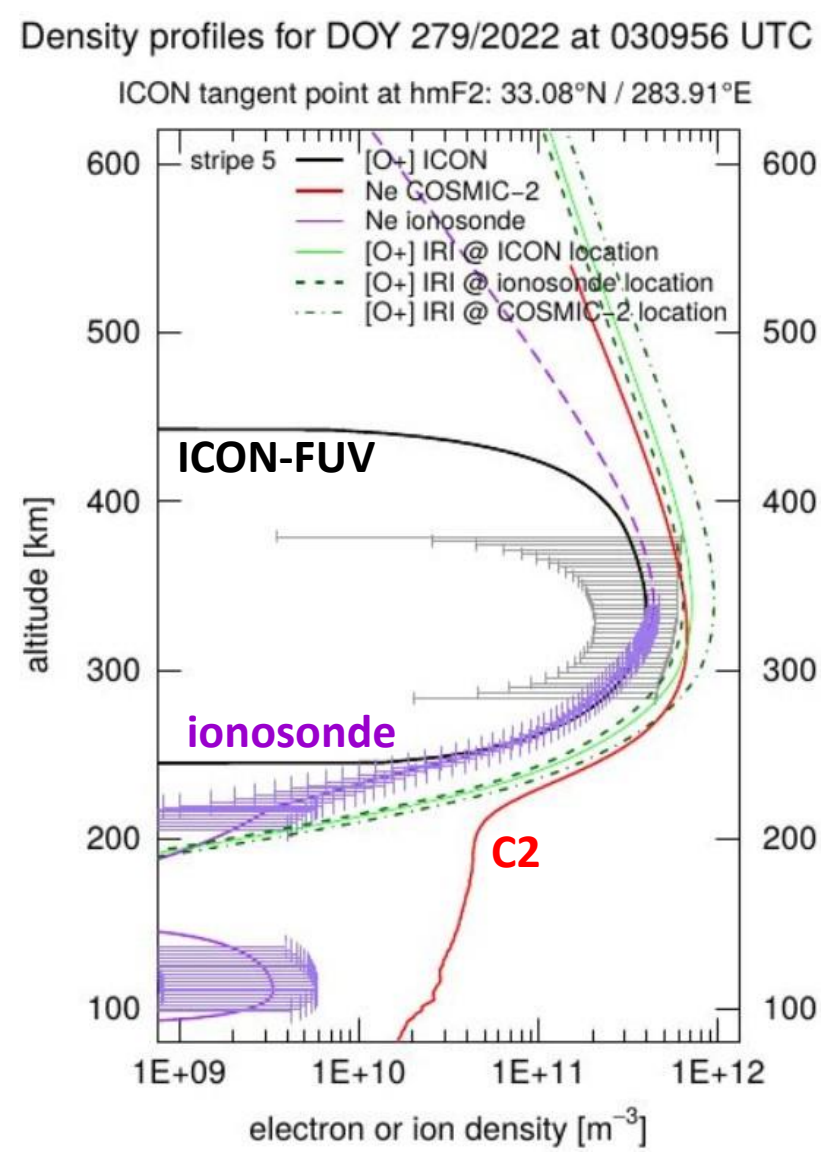
#### Example of a « nominal » conjunction

- Low TEC background (<10-15 TECUs)
- No significant TEC gradient
- ICON, C2 profile and ionosondes are observing a quiet ionosphere and the difference between techniques is the order of the expected accuracy (note the perfect agreement between FUV and the closely located ionosonde on the right figure)

DOY 279/2022. GIM UTC at 0300.
Conjunction time between 3.166 and 3.201 UTC



Density profiles for DOY 279/2022 at 030956 UTC
ICON tangent point at hmF2: 33.08°N / 283.91°E



Color background: Global Ionospheric Map (GIM) provided by the International GNSS Service (IGS)

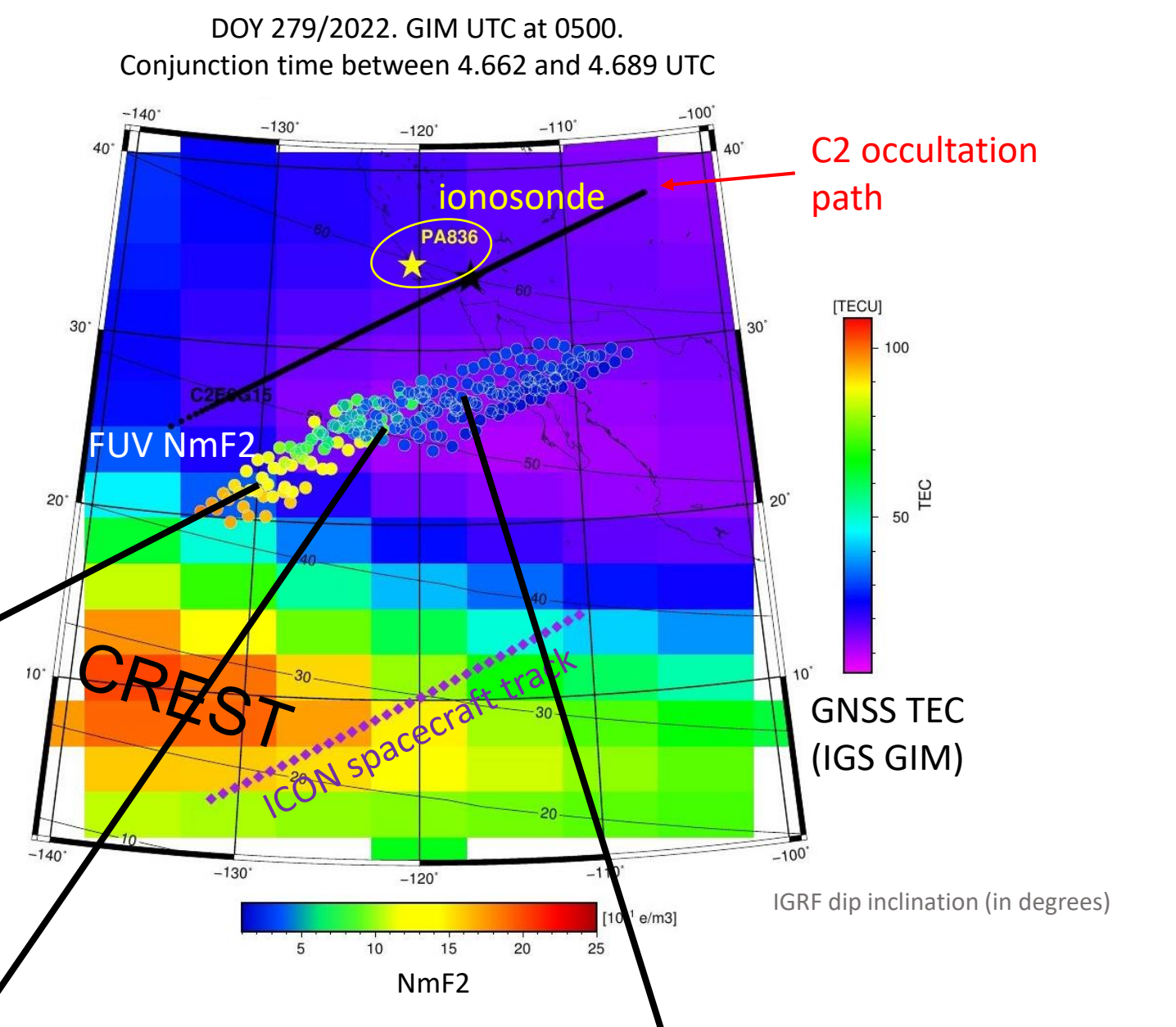
#### Example of a problematic conjunction (1 orbit later)

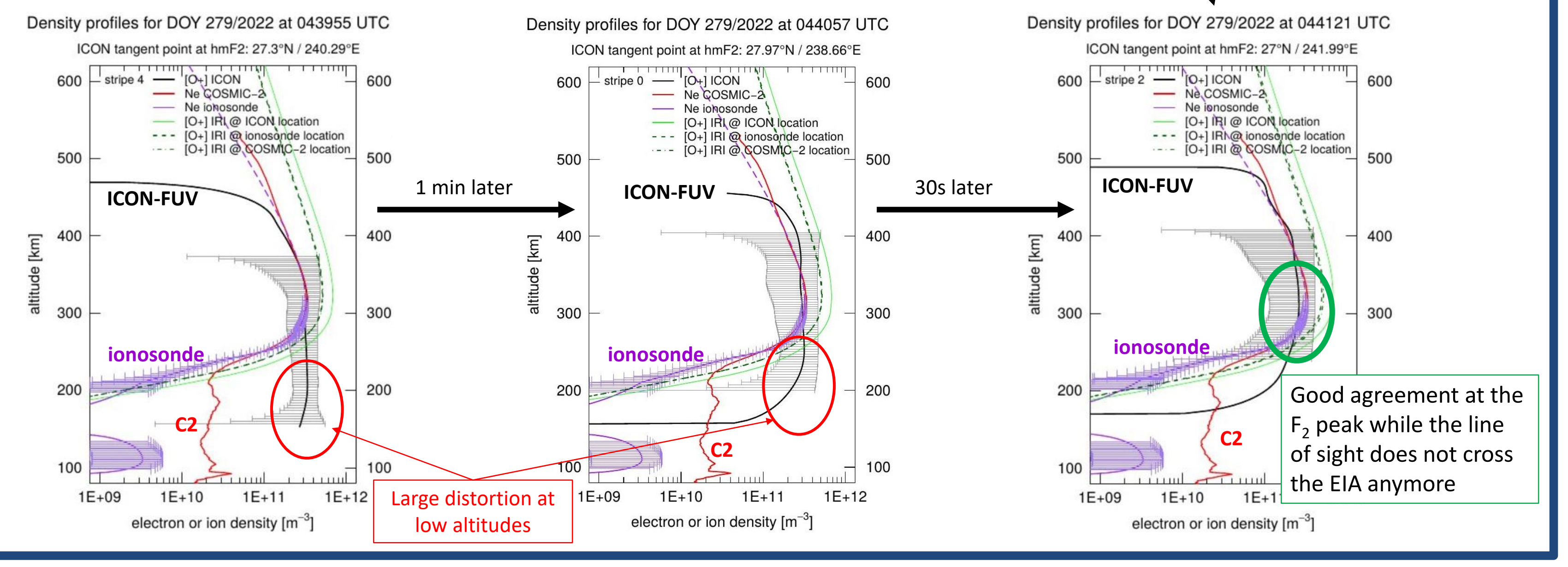
- The C2 radio-occultation profile and the ionosonde location are out of the EIA crest (TEC values > 100 TECUs)
  → perfect agreement between both profiles
- ICON-FUV: All the retrieved $F_2$ peak are located outside of the crest but the line-of-sight integration includes EIA crest contribution
  → breaking of the spherical symmetry assumption, resulting in distorted profiles
  → depending on the « amount » of the crest crossed, the inverted profile, hence NmF2 and hmF2, does not represent the actual profile located at peak location

→ **Distorted $N_e$ profiles, especially at low altitudes**

→ **Such profiles are not reliable for assimilation**

DOY 279/2022. GIM UTC at 0500.
Conjunction time between 4.662 and 4.689 UTC





Large distortion at low altitudes

Good agreement at the $F_2$ peak while the line of sight does not cross the EIA anymore

## 3. Daytime EUV results

### Comparison results

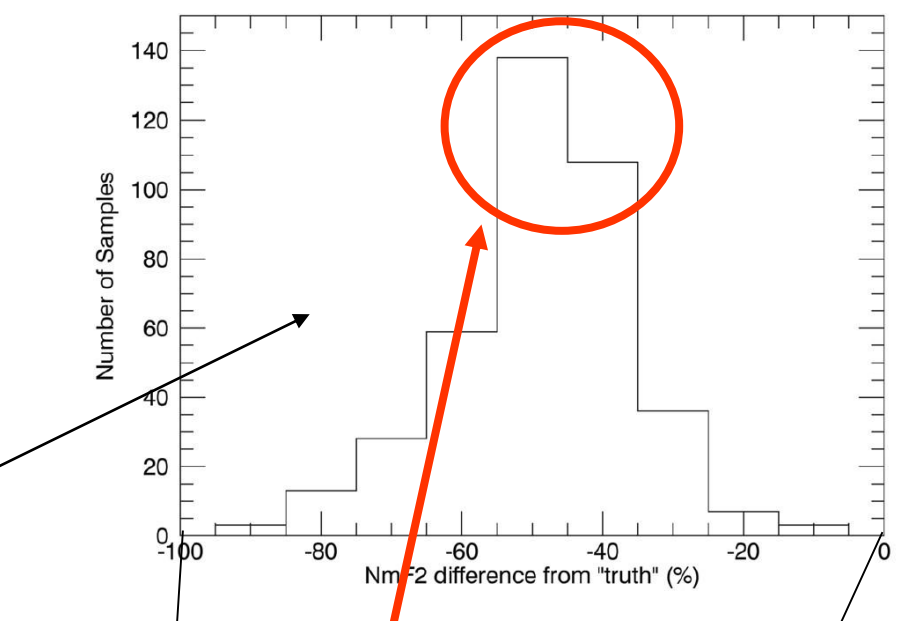
| | N | $\Delta N_mF_2$ $[m^{-3}]$ | $\Delta N_mF_2$ [%] | $\Delta h_mF_2$ [km] |
|---|---|---|---|---|
| EUV - COSMIC-2 | 38750 | $-3.9\times10^{11}$ | −56 | 20 |
| *(Dec 2019 - Mar 2021)* | | $+/- 2.6\times10^{11}$ | +/− 27 | +/− 42 |
| EUV - ionosonde | 674 | $-1.9\times10^{11}$ | −52 | 15 |
| *(Jan - Feb 2020)* | | $+/- 8.4\times10^{10}$ | +/− 17 | +/− 22 |
| EUV - ionosonde | 143 | $5.1\times10^{10}$ | 20 | 0 |
| *(Sep 2020)* | | $+/- 1.4\times10^{11}$ | +/− 33 | +/− 27 |
| EUV - MLH | 120 | $-1.6\times10^{11}$ | −52 | 8 |
| *(Jan - Feb 2020)* | | $+/- 4.1\times10^{10}$ | +/− 11 | +/− 19 |
| EUV - MLH | 141 | $-3.1\times10^{11}$ | −68 | 31 |
| *(Nov 2020)* | | $+/- 1\times10^{11}$ | +/− 15 | +/− 62 |

Wautelet *et al.* (2022), Space Science Reviews

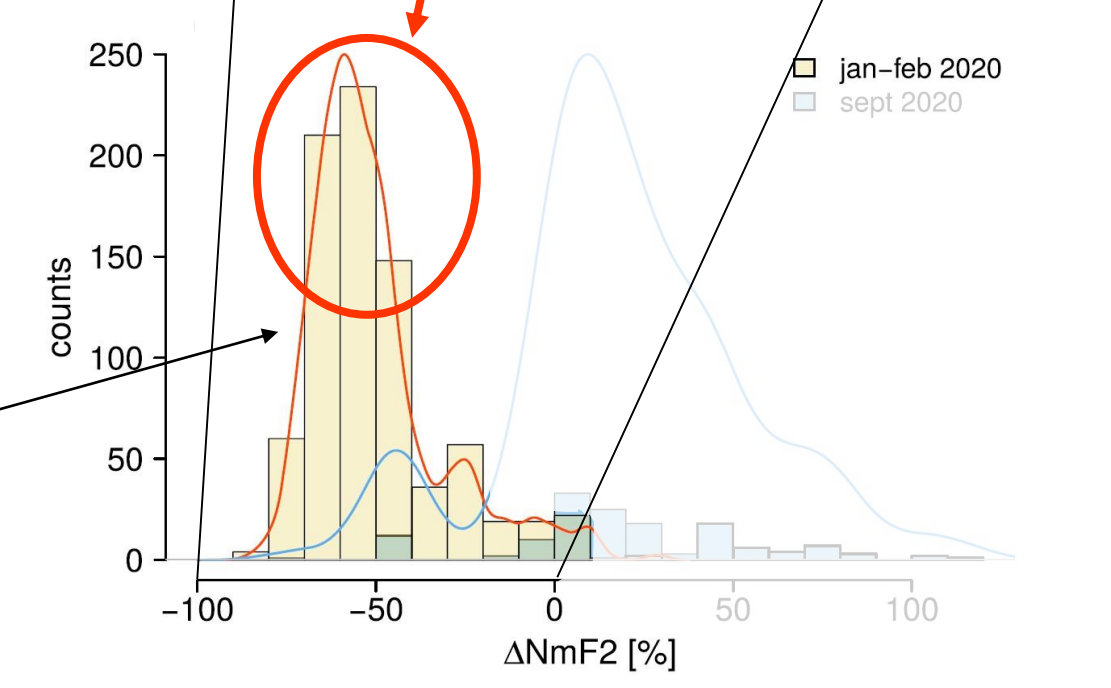
- Little positive bias for hmF2 between 0 and 30 km. Its magnitude depends on the comparison source
- Variability (std. dev.) of the NmF2 differences is about 15-25%
- **About 50-60% negative bias for NmF2** → Is there an issue in the calibration / some missing physics / other ???

### The answer: updated ionization cross-sections

- EUV $N_e$ retrieval method uses the emission ratio between the **83.4** and the **61.7 nm** wavelengths
- The value of this ratio is **set to 10** in the ICON-EUV inversion procedure but recent advances, based on high-resolution definition of the partial cross sections for the photoionization rate of O into many $O^+$ energy levels, suggest that the ratio should be **raised to 12.0** at solar maximum ($F_{10.7}$ = 250) and **up to 13.5** at solar minimum ($F_{10.7}$ = 70)
  → see Meier *et al.* (2023)
- According to their authors, this study shows that adjusting the emission ratio in the inversion would **remove the 50-60% negative bias** we have observed in our NmF2 differences
- For a single day (2020-01-22), the figure shows the difference between NmF2 values using the current inversion algorithm and that obtained using the updated cross-section values. This **perfectly matches the NmF2 differences observed** in the result table (here above), also shown in histograms (see Wautelet *et al.* 2022)
- A **full reprocessing** of the EUV data set (level-1 to level-2) is therefore needed to confirm this very encouraging result



*A histogram of the errors in NmF2 values derived from 400 profiles measured by the ICON EUV for 22 January 2020, assuming that retrievals with the theoretical emission ratio derived here is the « true » NmF2 (from Meier et al., 2023)*



*Histograms (yellow) and their related kernel density estimation (red) of NmF2 between EUV and ionosondes for Jan-Feb 2020 and Sept. 2020 (blue) periods. (from Wautelet et al. 2022)*

## Summary and future work

- In the context of data assimilation, merging airglow $N_e$ profiles with existing datasets like COSMIC-2 (C2) and ionosondes is a convenient way to provide both excellent vertical precision and time resolution.
- We perform $N_e$ comparison of ICON ultraviolet imagers (FUV and EUV) with C2, ionosondes and ISR and the results show discrepancies, depending on the considered instrument.
- For FUV, comparisons allow to identify problematic inversion due to the **crossing of the EIA** and pave the way towards mitigation techniques and flagging of situations in which the spherical symmetry hypothesis is not fulfilled.
- For EUV, our comparisons allowed to shed the light on the inaccuracy of a the **physical constant** used for the inversion (i.e. the 83.4/61.7 nm emission ratio). Updated values would remove the observed discrepancies while implementing the changes to the whole EUV dataset.

**Future work and investigation** include but are not limited to:

- Find a convenient way of identifying the strong gradients induced by the ionization crests to warn the inversion software that brightness profiles may include contribution of non-symmetric layers. At least, flagging resulting level-2 data as “unreliable” for data assimilation.
- As being observed in brightness profiles, the EIA crests and in particular their vertical extension and dynamics would be studied in detail using FUV nighttime 135.6 nm emission.
- Applying for a complete reprocessing of EUV dataset, including updated 83.4/61.7 emission ratio values.
- If successful, testing data merging of EUV and FUV on a regular grid → daytime and nighttime single product.

**References** **Wautelet** et al. (2022). Comparison of ICON-EUV F-peak characteristic parameters with external data sources, *Space Sci. Rev.*, 218:62
**Wautelet** et al. (2023). Update of ICON-FUV hmF2 and NmF2 comparison with external radio observations, *Space Sci. Rev.*, 219:21
**Meier** et al. (2023). New O Partial Photoionization Cross Sections Resolve Ionospheric EUV Remote Sensing Issues, *J. Geophys. Res. Space Phys.*, 128, e2023JA031533

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