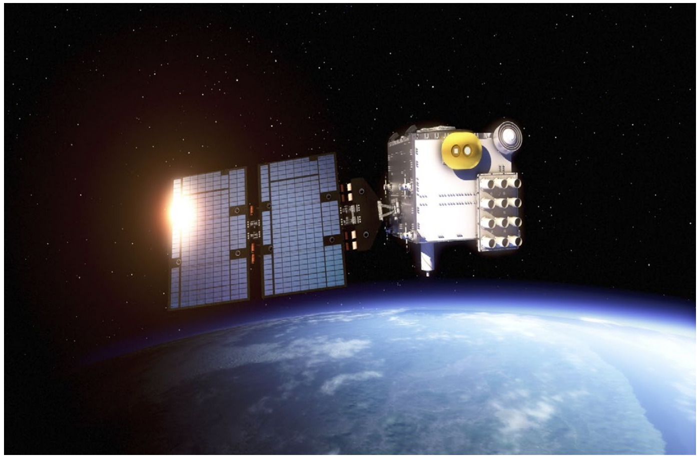
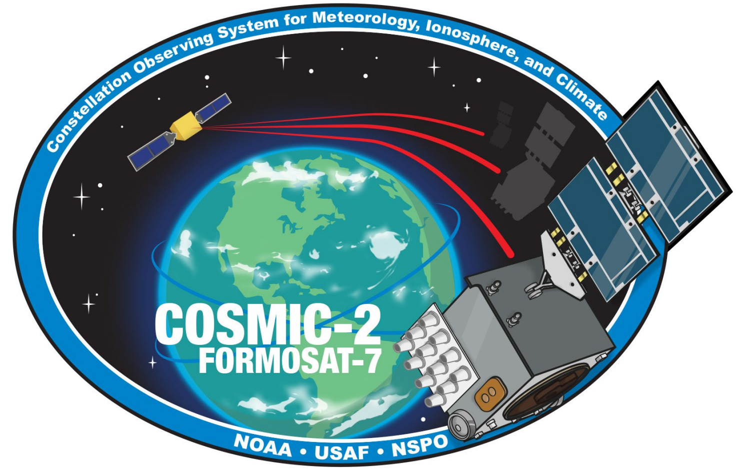
COSMIC

UCAR
UNIVERSITY CORPORATION FOR ATMOSPHERIC RESEARCH





(A Few) COSMIC-2: Highlights from 3 Years in Orbit

J. Weiss, R. Anthes, J. Braun, I. Cherniak, X. Feng, H. Huelsing, D. Hunt, N. Pedatella, M. Perrotta, J. Sjoberg, M. Sleziak-Sallee, S. Sokolovskiy, Q. Wu, I. Zakharenkova, Z. Zeng

September 8, 2022
Joint OPAC-7 and IROWG-9
Leibnitz, Austria

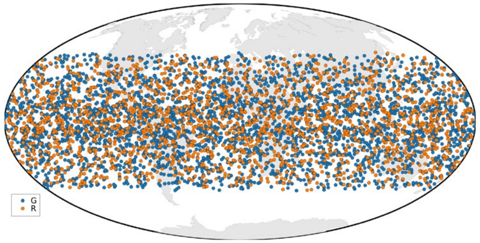
Outline

- Overview
- Neutral atmosphere
  - Product status
  - Bending angles compared to NWP
  - 3 cornered hat analysis
  - Super refraction detection
- Ionosphere
  - Product status
  - Total electron content
  - Scintillation geolocation, all-clear
- Data product latency
- Summary and plans

Overview

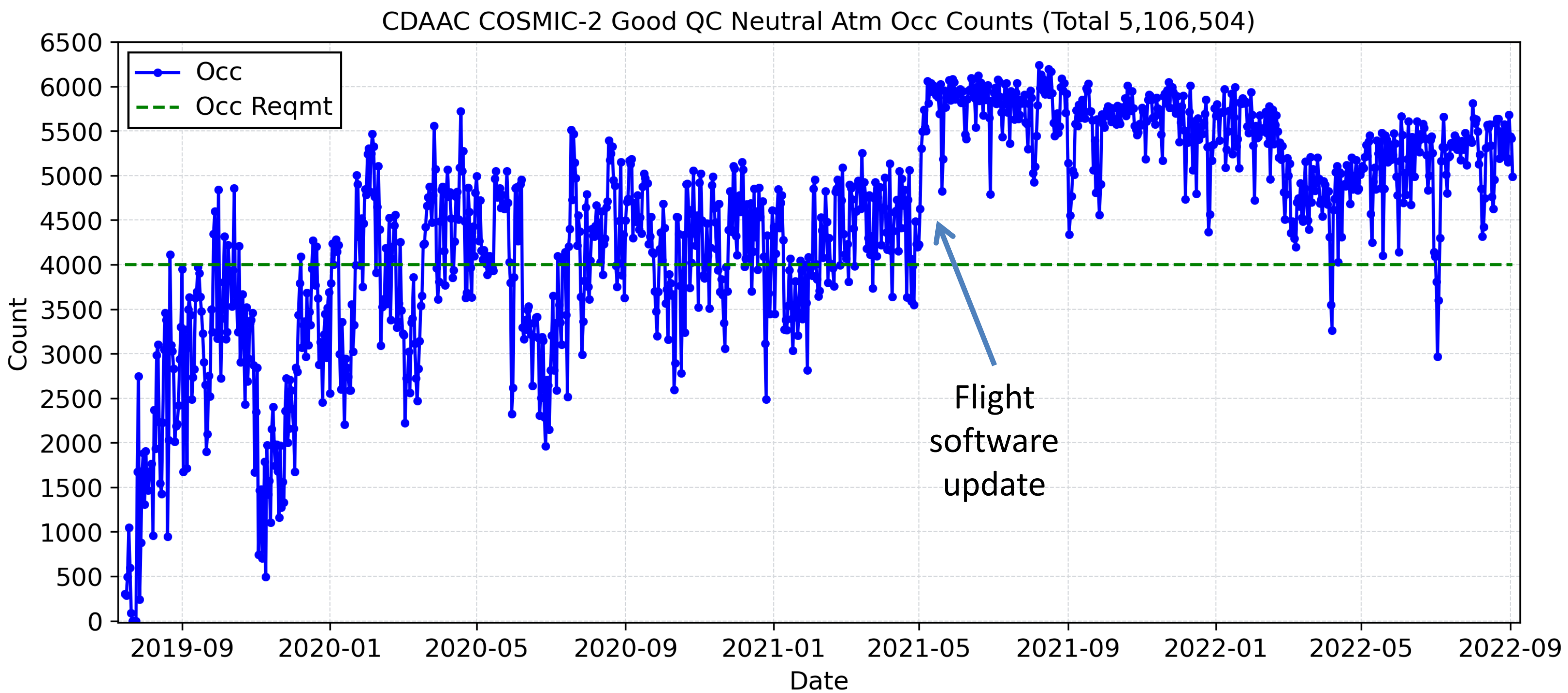
- COSMIC-2 is a US (NOAA, USSF) and Taiwan (NSPO) partnership
- Spacecraft constellation
  - Launched June 25, 2019
  - 6 satellites, orbit inclination 24 deg, altitude ~520 km
  - Final orbit configuration reached in March 2021

- Payloads
  - JPL/BRE GNSS payload is primary
    - GPS+GLONASS
    - 8 flight software updates since launch to improve performance
  - Secondary payloads are ion velocity meter (IVM), tri band RF beacon, laser retro reflector



- All neutral atm. and ionosphere products routinely produced, except IVM drifts
- Neutral atm. super refraction flag and additional ionosphere scintillation products planned

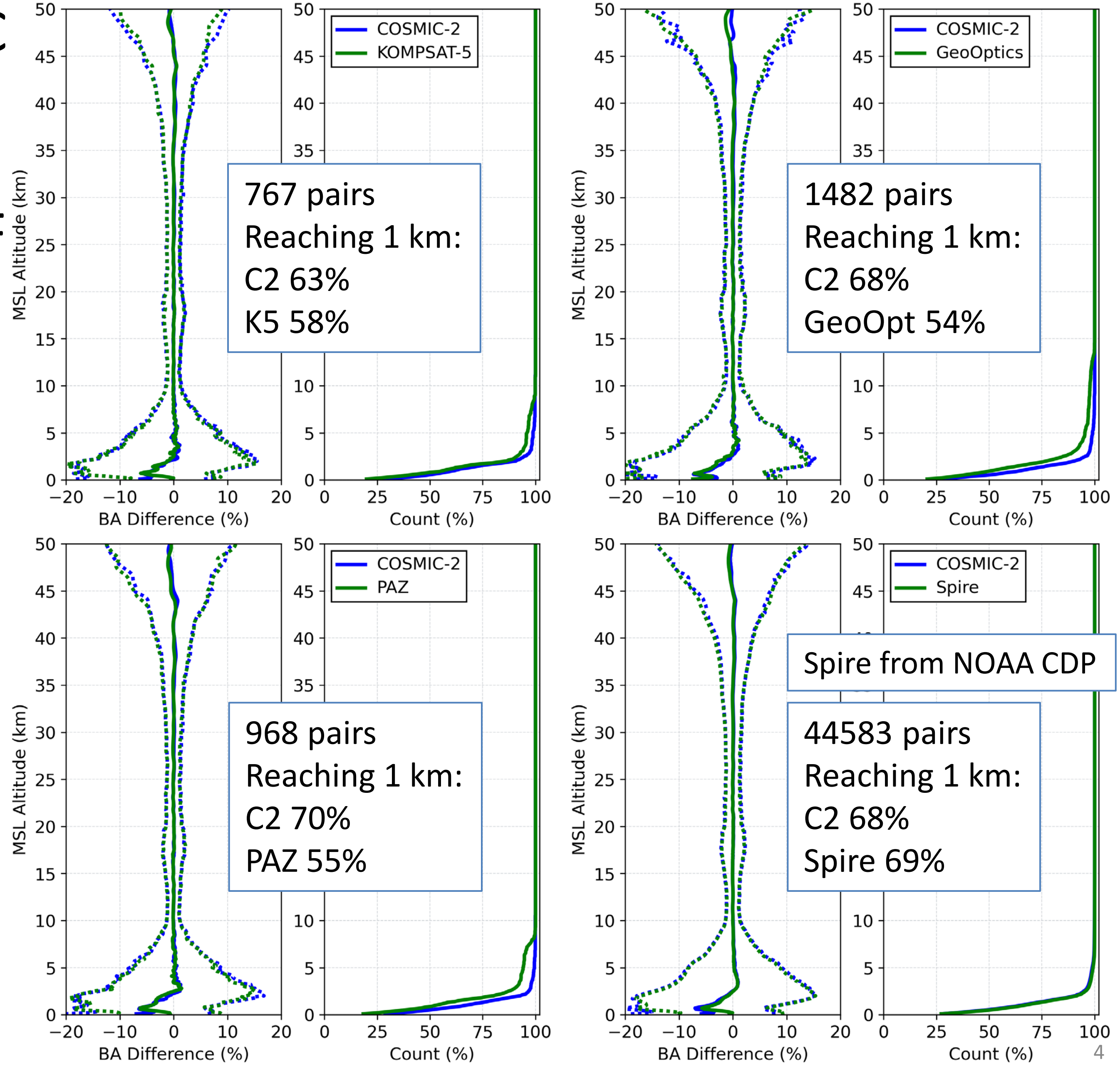
Neutral Atm Product Status



Metric	2021-06-01 to 2021-12-31	2022-01-01 to 2022-05-31	2022-06-01 to 2022-08-31
Total occs (daily mean)	6300	6155	6004
QC'd occs (daily mean)	5600	5148	5265
QC rate	90.5%	83.6%	87.7%

Bending Angle vs. NWP

- Showing CDAAC near real-time bending angle (BA) vs. ECMWF short term forecast statistics
- Collocated profiles (3 hr, 300 km) during Aug. 2022
- Generally very similar results across missions



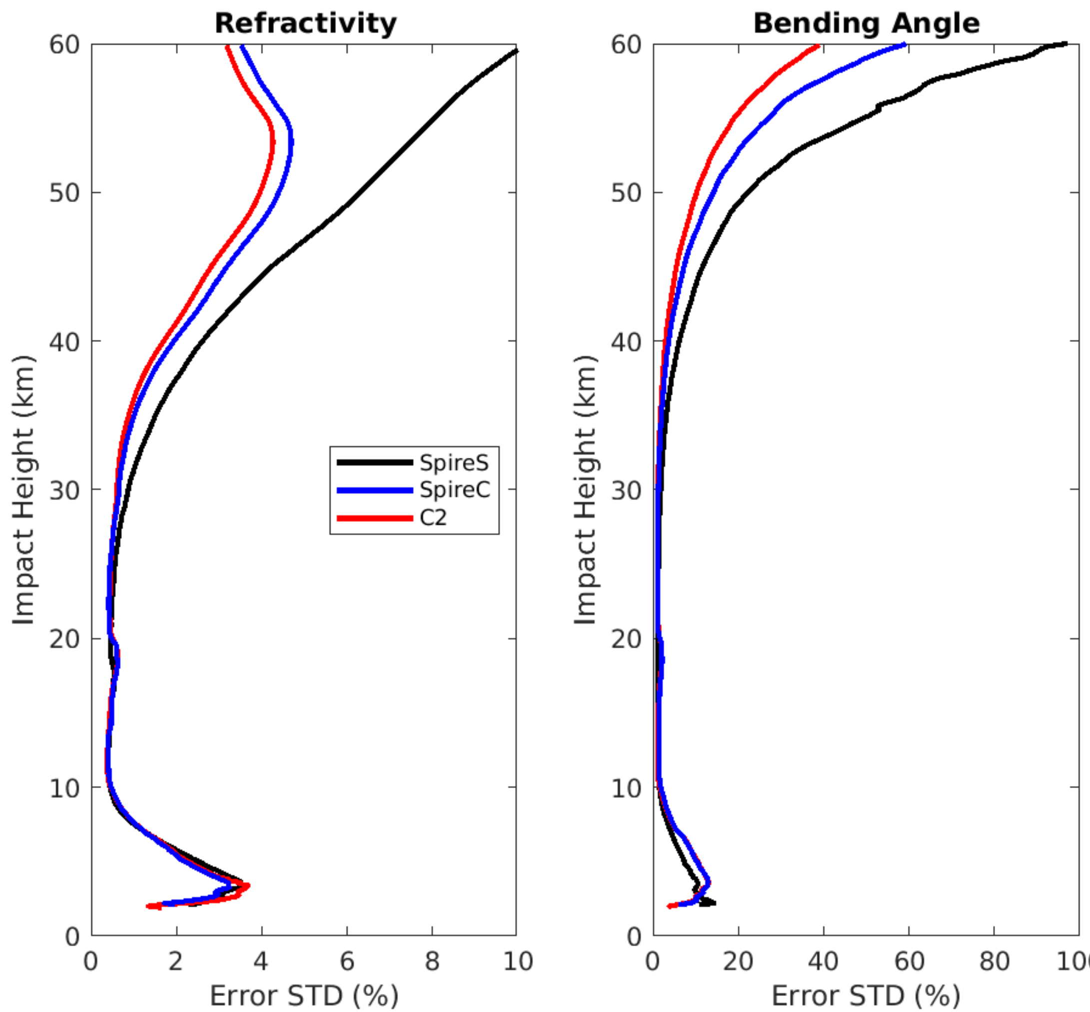
Courtesy Z. Zeng, UCAR

3CH Uncertainty for C2 & Spire

- Global bending angle and refractivity error for COSMIC-2 and Spire (from NASA CSDA) in January 2021
- Should include all Spire data (NOAA CDP should be subset)
- COSMIC-2 uncertainty at higher levels smaller than Spire
- COSMIC-2 and Spire similar below ~30 km
  - SpireS smaller due to vertical smoothing

Dataset	Penetration at 1 km (%)
C2	87.5
SpireC	83.5
SpireS	78.6

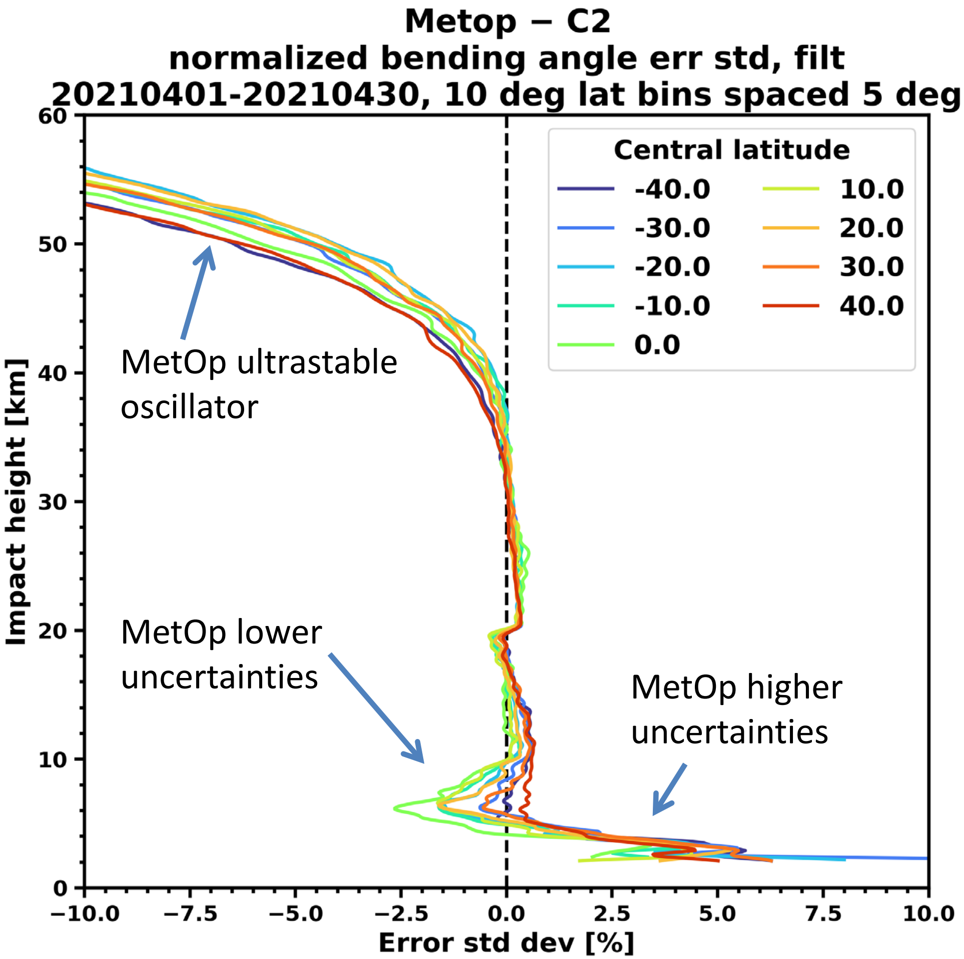
SpireS – Spire data processed by Spire
SpireC – Spire processed by CDAAC
C2 – COSMIC-2 processed by CDAAC

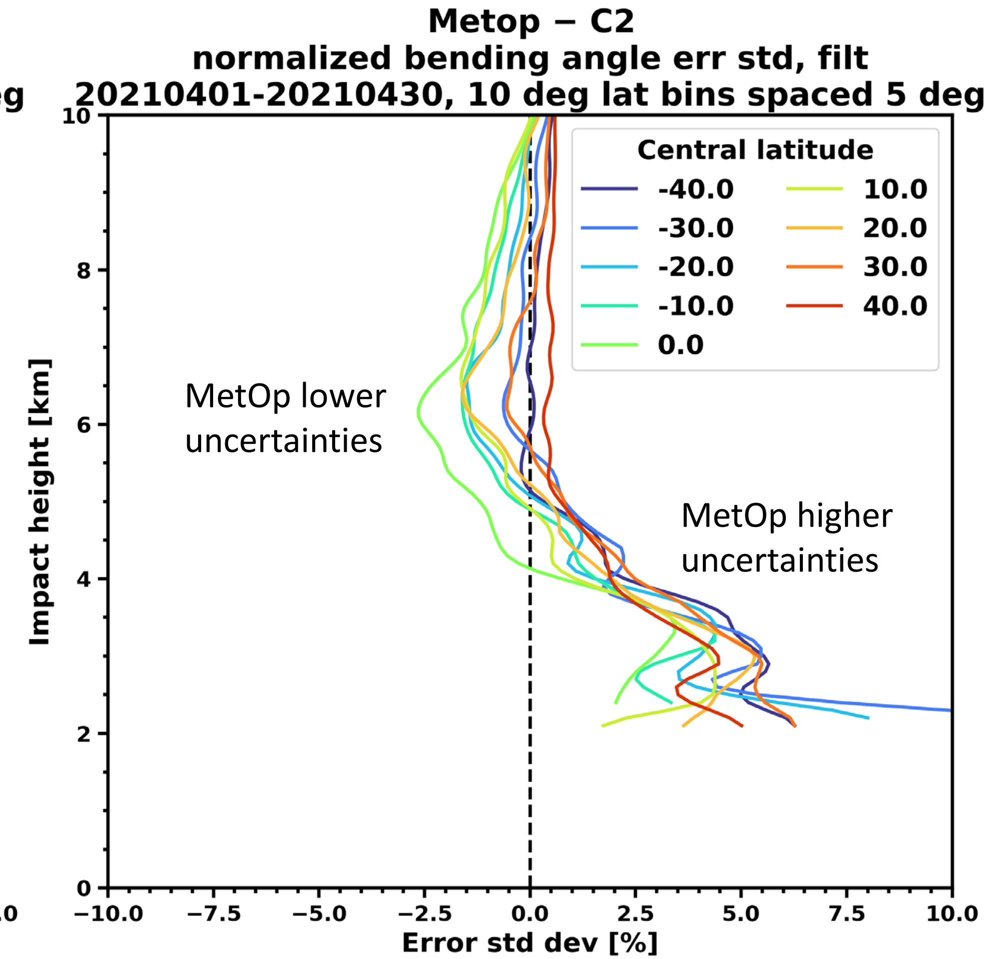


Courtesy R. Anthes, J. Sjoberg, X. Feng, UCAR

3CH Uncertainty for C2 & MetOp

- Global bending angle and refractivity error for C2 and MetOp in April 2021





Courtesy R. Anthes, J. Sjoberg, X. Feng, UCAR

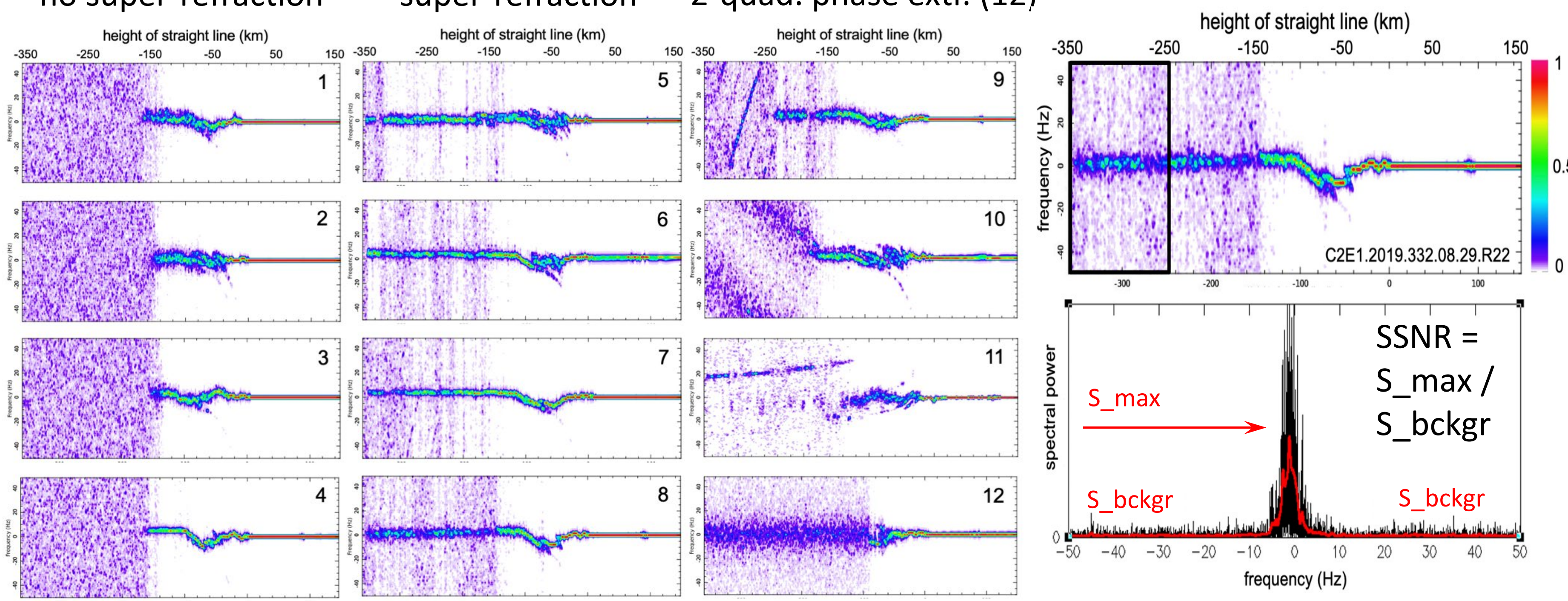
Detection of Super Refraction (SR)

- SR leads to problems including negative N-bias in inversions and uncertainty in data assimilation
- COSMIC-2 deep tracking down to -350 km HSL enables study of SR
- Sokolovskiy et al. recently submitted paper on detection of SR at the top of atmospheric boundary layer from C2 deep RO signals
- Definition of SR in this study: $dN/dz < -157\ km^{-1}$
  - SR cannot be detected from retrieved bending angle profiles (large BA is not a reliable proxy)
- SR at the ABL top (elevated ducts) results in weak diffracted signals observed at HSL < -200 km
- Detection of deep diffracted signals:
  - Frequency reduction by using the model based on GNSS and LEO orbits and N-climatology
  - Calculate power spectrum S(f) in large window, from -250km to -350km HSL; smoothing (Hann's window)
  - Calculate Spectral Signal-to-Noise Ratio
    - SSNR = S_max / S_background (see next slide)
- Large window increases the SSNR and discriminates from some types of interfering signals.

Detection of Super Refraction

- Examples of spectrograms of deep RO signals

Standard RO signals, no super-refraction | Deep RO signals, super-refraction | Interfering signals (9-11), 2-quad. phase extr. (12)



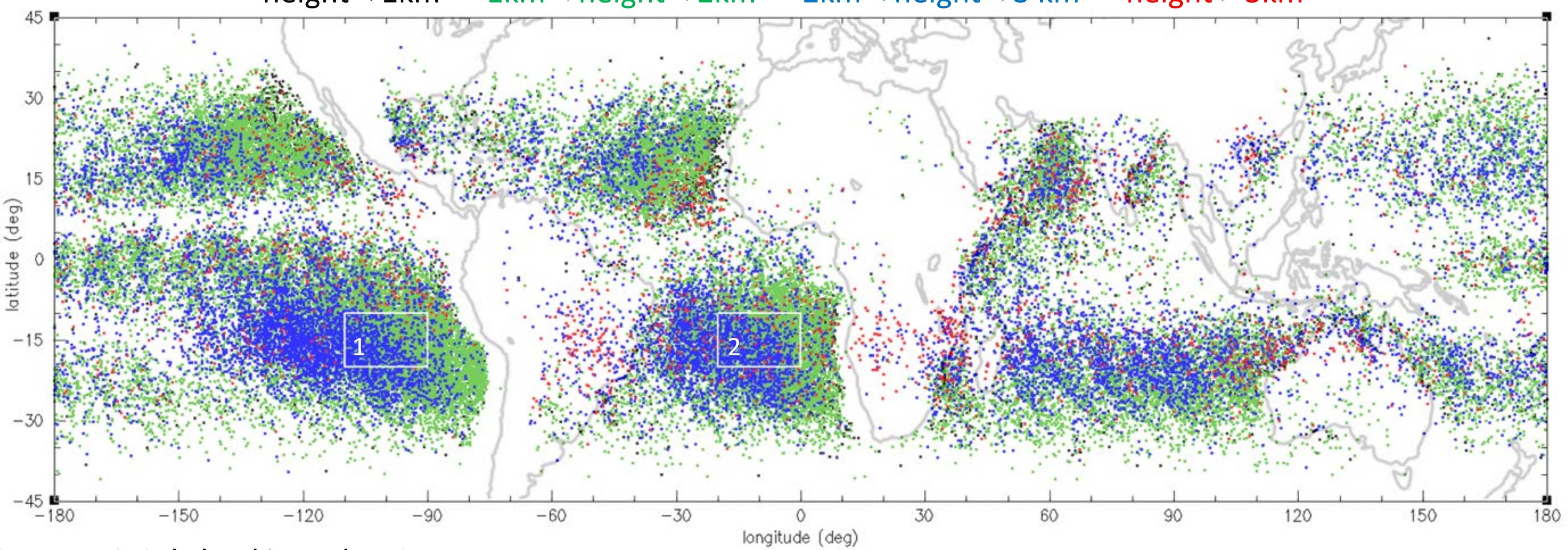
- Metric for detection of SR:
  - (1) SSNR > 10;
  - (2) max. retrieved BA lapse > 0.01 rad, a proxy for sharp inversion layer (ABL top)
- (2) helps to further discriminate from deep signals not induced by strong inversion layers
- Estimation of impact heights of deep signals by geometric and wave optics is under testing

Courtesy S. Sokolovskiy et al., UCAR

Detection of Super Refraction

- Global distribution of super-refraction detected from COSMIC-2 occultations from 2020.181-2022.180, setting occultations, OL tracking down to -350km HSL
- ~60,000 cases of detected SR, ~3% of all setting occultations
- Strong dependence of the SR detection rate on the SNR
- Wavy structures are correlated with the distribution of the occultations with SNR > 2000 V/V
- Most of SR occurs over the sub-tropical ocean (23% and 21% in regions 1 and 2).
- SR detected over the continents: S. America, S. Africa (SR height often > 3 km), Australia
- SR not detected close to west coasts (though it may exist)
  - ABL top is known to be low; surface ducts are not detectable by RO; penetration of retrieved BA profiles may be insufficient to detect large BA lapse.

height < 1km   1km < height < 2km   2km < height < 3 km   height > 3km

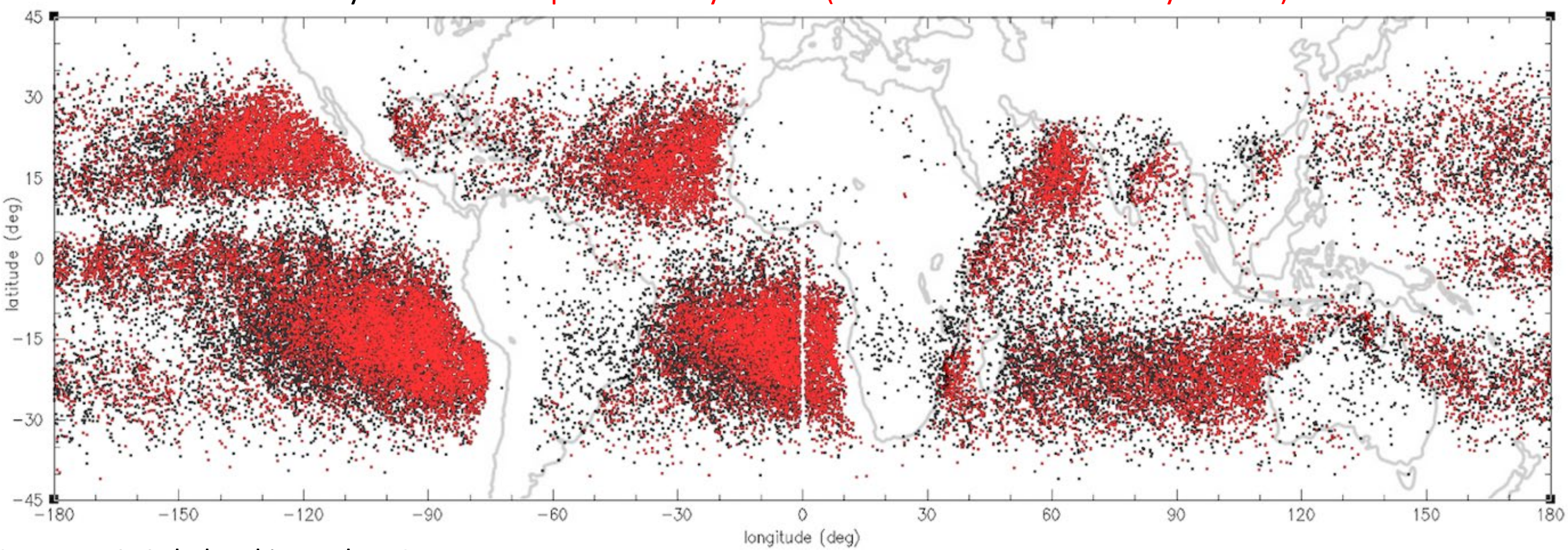


Courtesy S. Sokolovskiy et al., UCAR

Detection of Super Refraction

- Comparison of super-refraction cases detected from COSMIC-2 with cases predicted by ECMWF analysis (137 levels)
  - SR from RO is based on measurement (underestimates the SR occurrence)
  - SR from model is prediction (may underestimate or overestimate the SR occurrence)
- For the set of occultations with SR detected from COSMIC-2 RO, the ECMWF model predicts SR in 52% of cases
  - This percentage is significantly lower over the continents (S. America, S. Africa, Australia)
- The set of occultations with SR predicted by model is not shown because if SR is not detected by RO, this does not mean that SR does not exist
- Detection of SR by RO is complementary to model prediction and may be used as an additional QC flag in data assimilation

SR detected by C-2 RO   SR predicted by model (for the cases detected by C-2 RO)



Courtesy S. Sokolovskiy et al., UCAR

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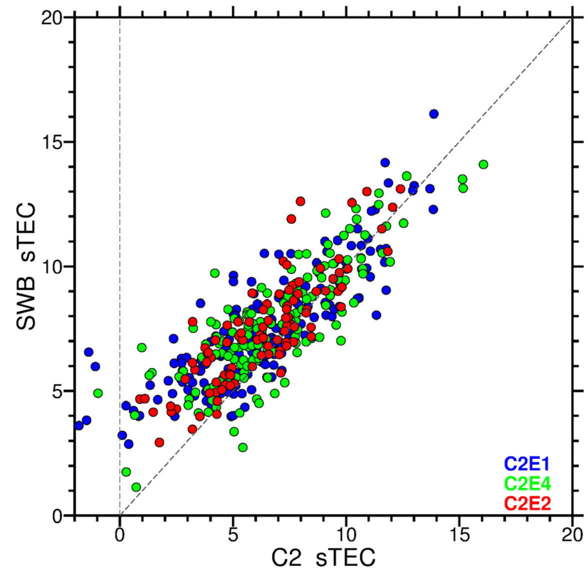
C2 GNSS Space Weather Products

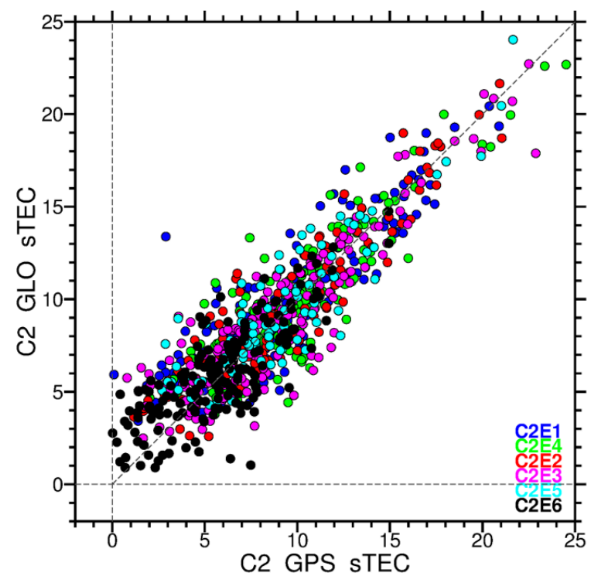
- Total electron content (TEC)
  - TEC arc data data above s/c altitude
  - TEC occultation data from s/c altitude to 90 km altitude
  - TGRS scheduler slightly prioritizes occultations over arcs
- Scintillation
  - Record high rate phase and amplitude data for entire occultation when onboard S4 measurement exceeds a specified threshold
  - Enables detailed investigation of scintillation (using ground computed S4 and sigma-phi)
  - Boston College and UCAR developed advanced methods to geo-locate ionosphere irregularity regions causing scintillation
- Ion velocity meter
  - In-situ plasma density, composition, and temperature (all times and FMS) and drifts (partial times and FMs)

Total Electron Content (TEC)

- Absolute TEC validated and released to ops and science users
  - GPS, July 2020
  - GLONASS, January 2021
- GPS TEC validated through collocation comparison with SWARM-B mission
  - C2 and Swarm-B collocations based on following
    - Same time, same transmitter, angle between Swarm-B and C2 less than 2 degrees
  - See Pedatella et al (2021)
- GLONASS TEC validated through comparison to GPS TEC

GPS TEC error ~2.5 TECU
GLO TEC error ~2.6 TECU

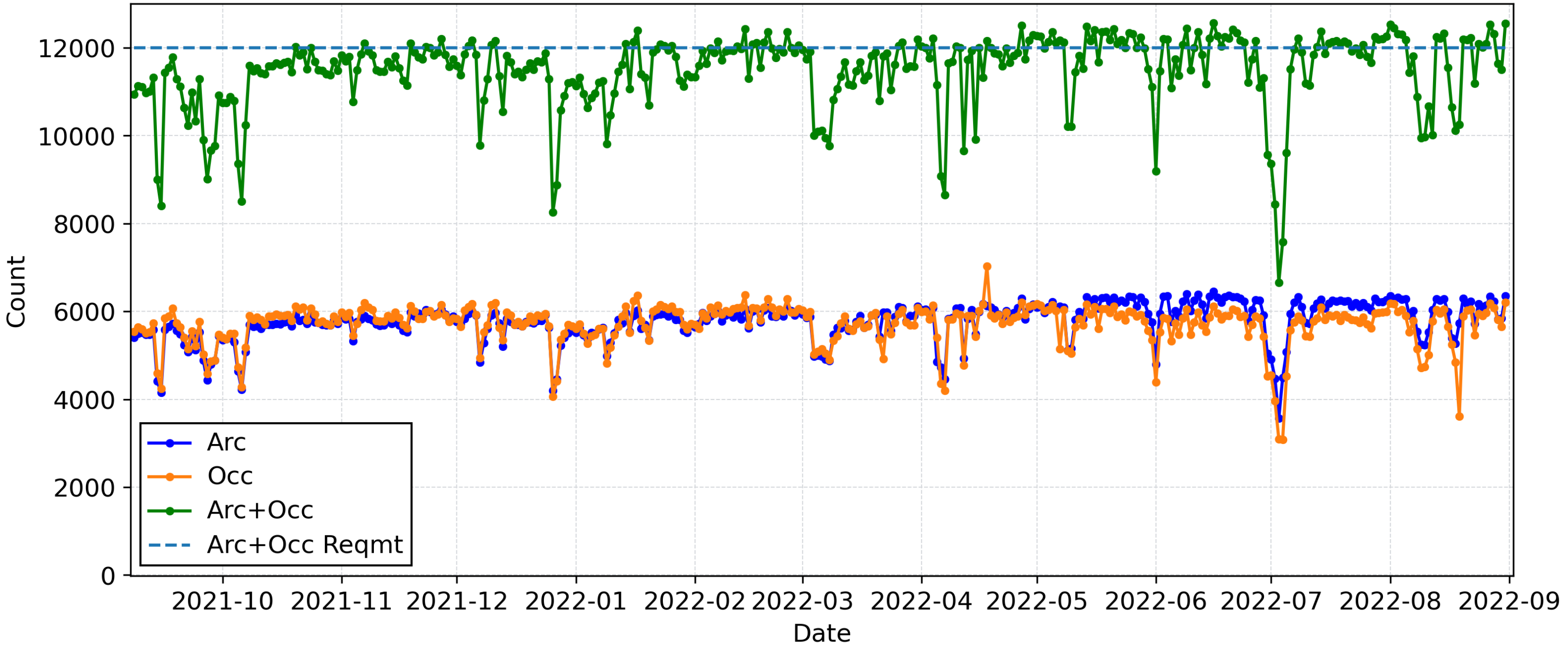




Courtesy I. Zakharenkova & space weather team, UCAR

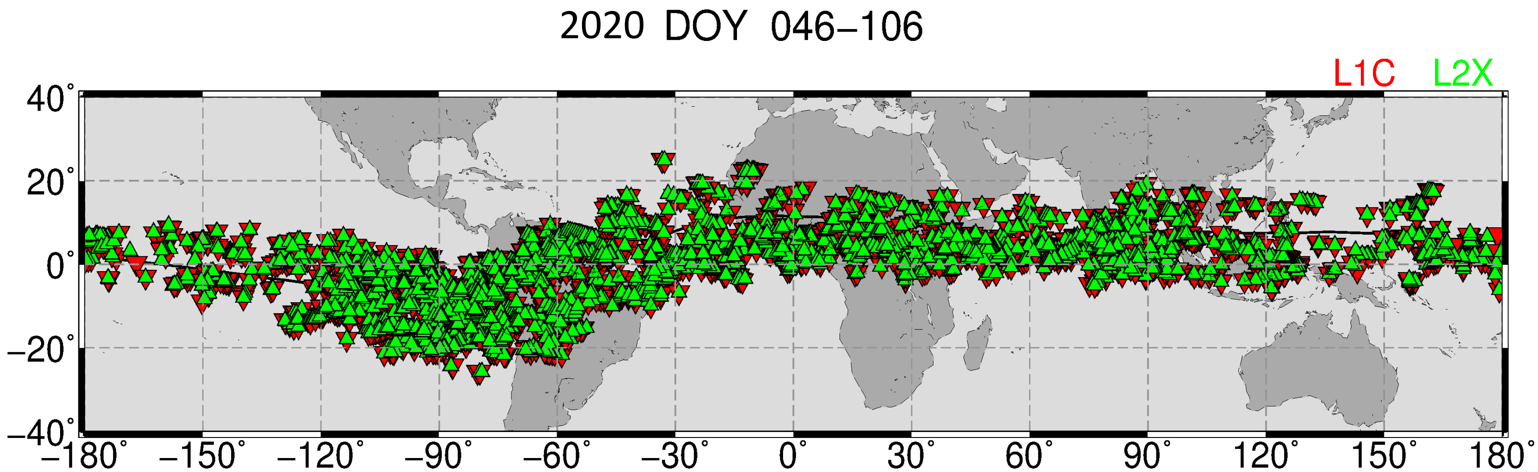
Total Electron Content (TEC)

- Figure shows TEC arc, occ scores since Sep. 2021
  - Arc is topside portion of track, occ is s/c altitude to 90 km HSL
  - Average arc+occ score in 2022 is 11618
  - Program has waived 12K arc+occ requirement



Scintillation Geolocation

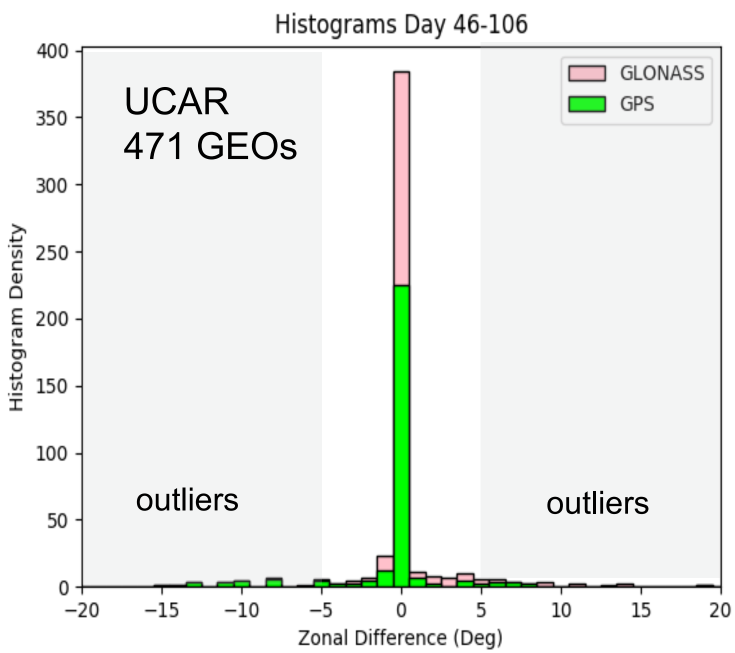
- Boston College (BC) and UCAR developed algorithms to geolocate phase scintillation using TGRS high rate data
- UCAR algorithm based on back propagation method (Sokolovskiy et al., 2002) with further modifications and enhancements
  - Geolocation can be done with both L1C and L2X observations
  - Global distribution of geolocations for 2020 scintillation season illustrates potential to monitor scintillation on a global scale

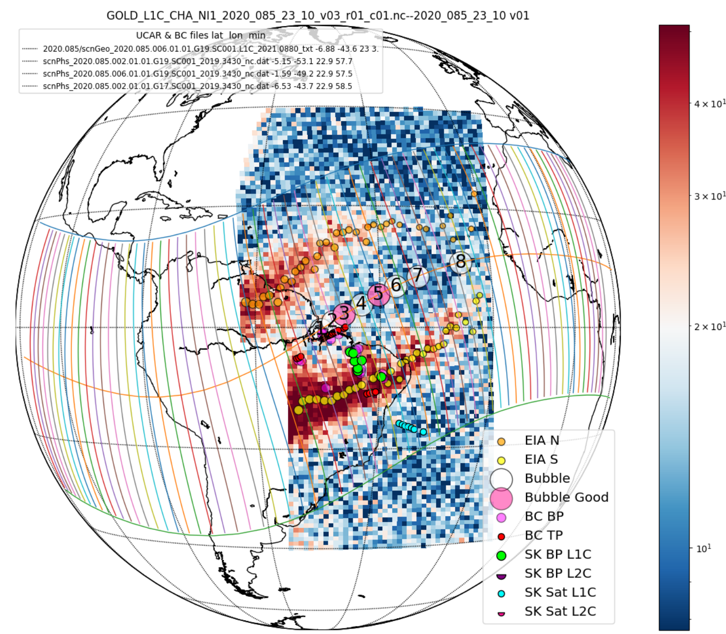


Courtesy I. Zakharenkova & space weather team, UCAR

Scint. Geolocation Validation with GOLD

- GOLD is NASA UV instrument on geosynchronous (SES-14)
  - Observes Oxygen 135.5 nm UV emission, proportional to square of electron density
- Algorithm developed to identify ionosphere depletions related to equatorial plasma bubbles
  - Bubbles often contain irregularities that produce scintillation
- BC geolocation validated against locations of GOLD bubbles & ground VHF sites
- UCAR geolocation algorithm validation with GOLD
- Figures show histogram of zonal differences between bubbles and TGRS geolocations (left) and example GOLD image (right)

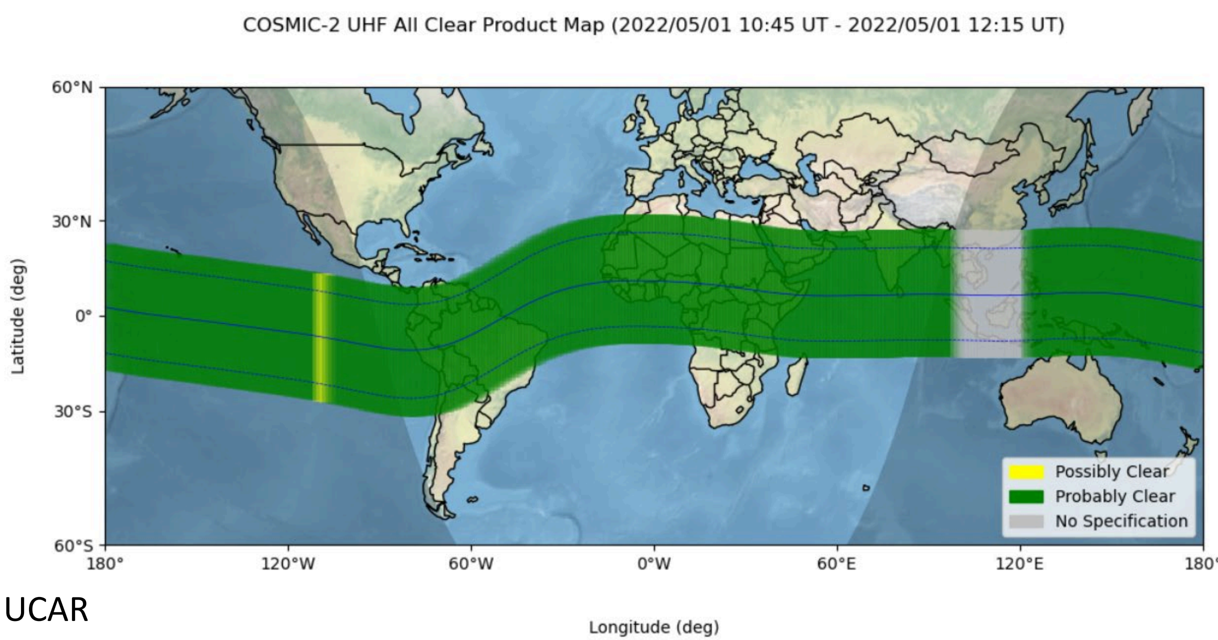




Courtesy Q. Wu, UCAR

Scintillation All-Clear

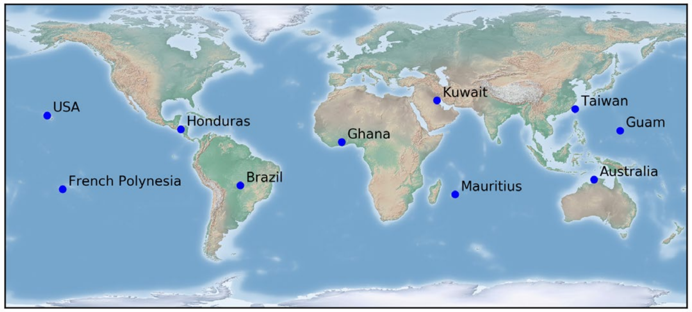
- Boston College developed algorithm utilizing 1 Hz POD antenna L1 SNR observations to estimate when scintillation is not likely along a signal path
  - Validated by comparisons to ground-based S4
- Maps generated by modeling extension of observations along magnetic field lines
- UCAR implementing operational all-clear processing
  - Expect to run every 15-30 min using data from past 90-120 min (TBD)
  - Output data product and web dashboard for use by operational space weather centers



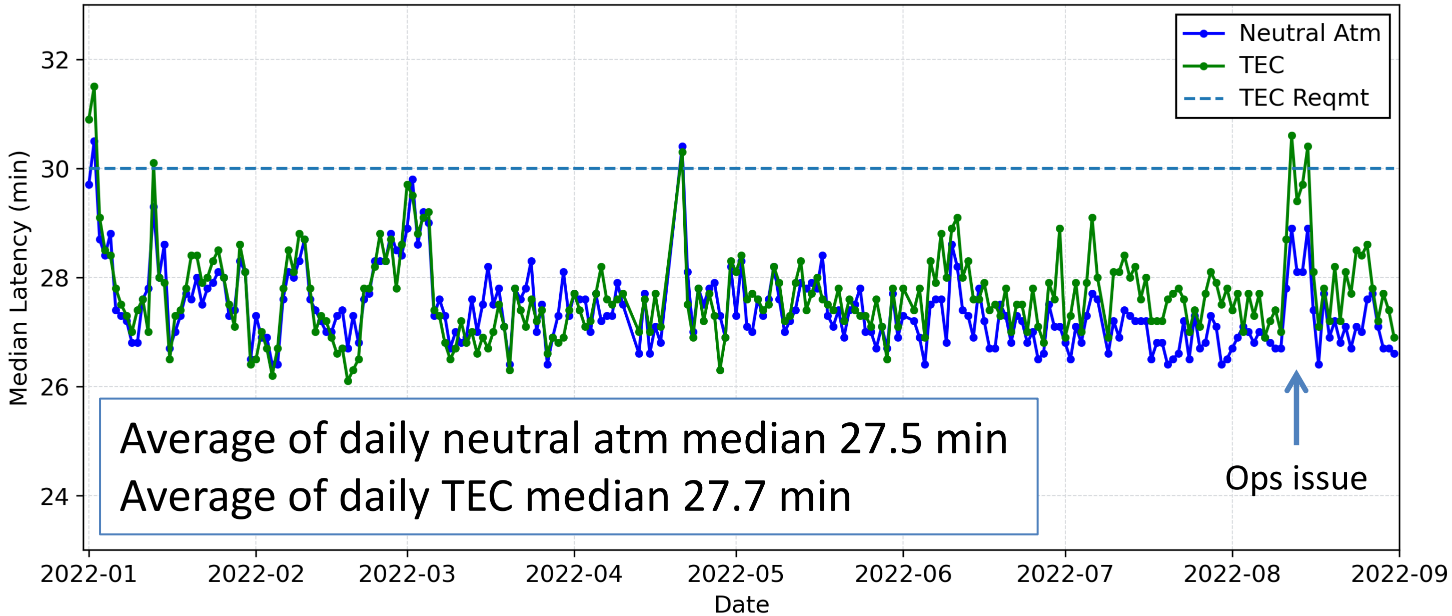
Courtesy H. Huelsing, UCAR

Latency

- 10 downlink stations enable rapid acquisition and processing of low level data
- 10th station became operational on January 3, 2022



- Since then C2 has met its 30 min median TEC latency requirement (45 min median neutral atmosphere requirement was already met)



Summary and Plans

- COSMIC-2 mission has accomplished significant milestones and data product releases since the last in-person IROWG in 2019
- Mission operations, processing, product utilization, and science going well
- Neutral atm and ionosphere products validated and of high quality, with several "firsts" accomplished (e.g. SR detection, GLO TEC, scintillation geolocation)
- Planned products include SR flag, Galileo occultations, scintillation geolocation and all-clear, bubble map, additional IVM drifts

Acknowledgements

- Thanks to the FORMOSAT-7/COSMIC-2 Program partners!

Backup

3-Cornered Hat (3CH) Analysis

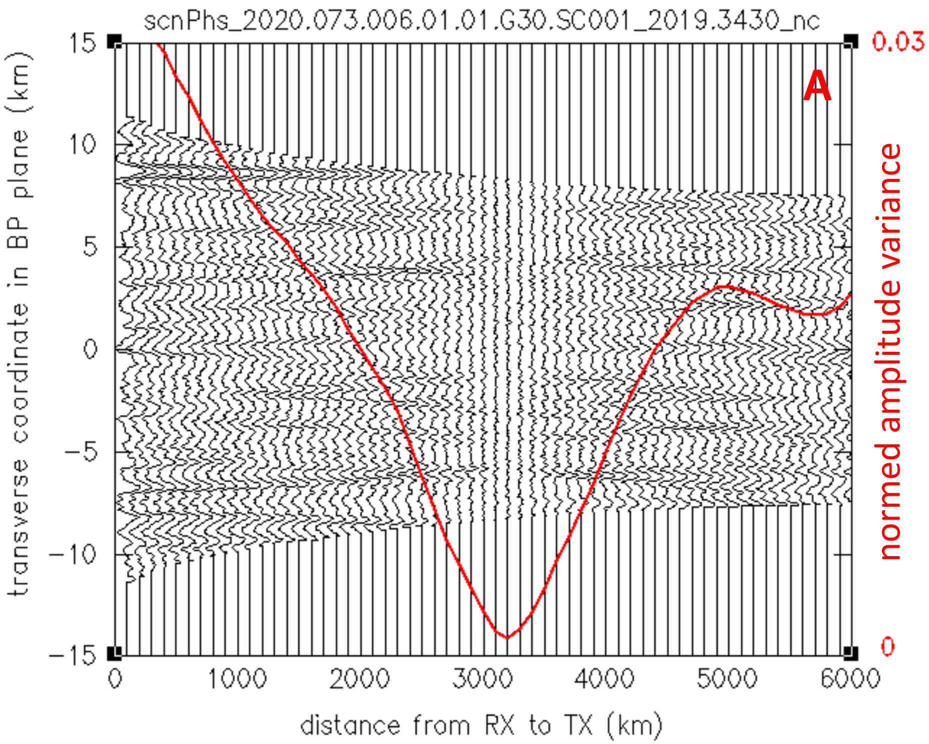
- Assume a set of observations X can be written
$$X = T + \beta_X + \varepsilon_X$$
where T is Truth (set of values), β_X is the mean bias, ε_X are random errors

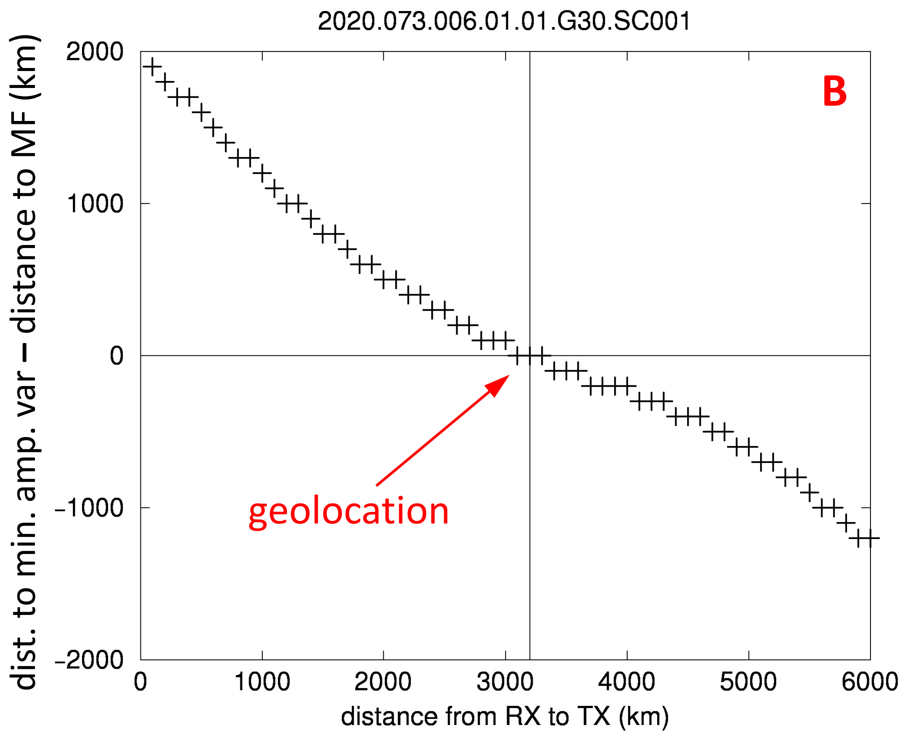
- With two more data sets Y and Z, we can write the error variance as
$$\mathrm{Var}[\varepsilon_X] = \frac{1}{2}(\mathrm{Var}[X - Y] + \mathrm{Var}[X - Z] - \mathrm{Var}[Y - Z])$$
$$+\mathrm{Cov}[\varepsilon_X, \varepsilon_Y] + \mathrm{Cov}[\varepsilon_X, \varepsilon_Z] - \mathrm{Cov}[\varepsilon_Y, \varepsilon_Z]$$
with similar equations for Y and Z

- In practice, we assume error covariance ≡ 0, and take steps to increase this likelihood

- 3CH method is accurate and easy to implement

Localization of the ionospheric irregularities by back propagation (BP) of complex RO signal. **1)** Defining MF at a distance from RX to TX (use IGRF-13 model). **2)** Defining BP plane ⊥ to MF. **3)** Projecting TX and RX trajectories onto BP plane. **4)** Correcting TX and RX trajectories for TX motion (stationarization). **5)** Correcting sphericity of wavefront at RX (account for projection). **6)** BP of the complex RO signal from RX to TX **(A)**. **7)** Calculating dist. to global local minimum of the normed amplitude variance **(A)**. **8)** Return to step **1** by defining MF at another distance. **The location of minimum amplitude variance which corresponds to the location of MF used to obtain that minimum is the estimated location of irregularities (geolocation) (B).**





Courtesy S. Sokolovskiy & space weather team, UCAR

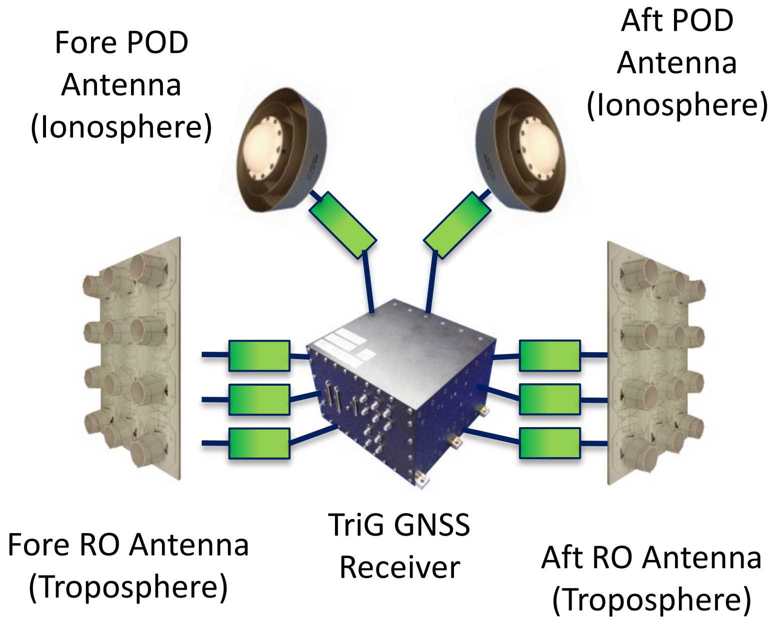
COSMIC-2 Product Types

Type	Available	Notes
Precise orbits	Yes	podCrx
Excess phase	Yes	conPhs
Neutral atm retrieval	Yes	atmPrf
1D var retrieval	Yes	wetPf2
Neutral atm BUFR	Yes	bfrPrf, sent to NOAA PDA and WMO GTS
Electron density profiles	Yes	ionPrf
GPS abs TEC	Yes	podTc2
GLONASS rel TEC	Yes	podTc2
GLONASS abs TEC	Yes	podTc2
Scintillation amplitude and phase indices	Yes	scn1c2, scnLv2
IVM in-situ plasma density, composition, temp	Yes	ivmLv2

Data and Support Links

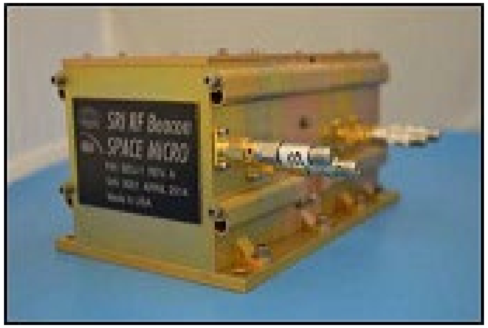
- CDAAC data information page
  - https://www.cosmic.ucar.edu/what-we-do/data-processing-center/data
- COSMIC-2 data
  - https://www.cosmic.ucar.edu/what-we-do/cosmic-2/data
  - https://tacc.cwb.gov.tw/v2/download.html
- Data download server
  - https://data.cosmic.ucar.edu/
- Support provided via web forum (signup link)

COSMIC-2 Instruments



TGRS

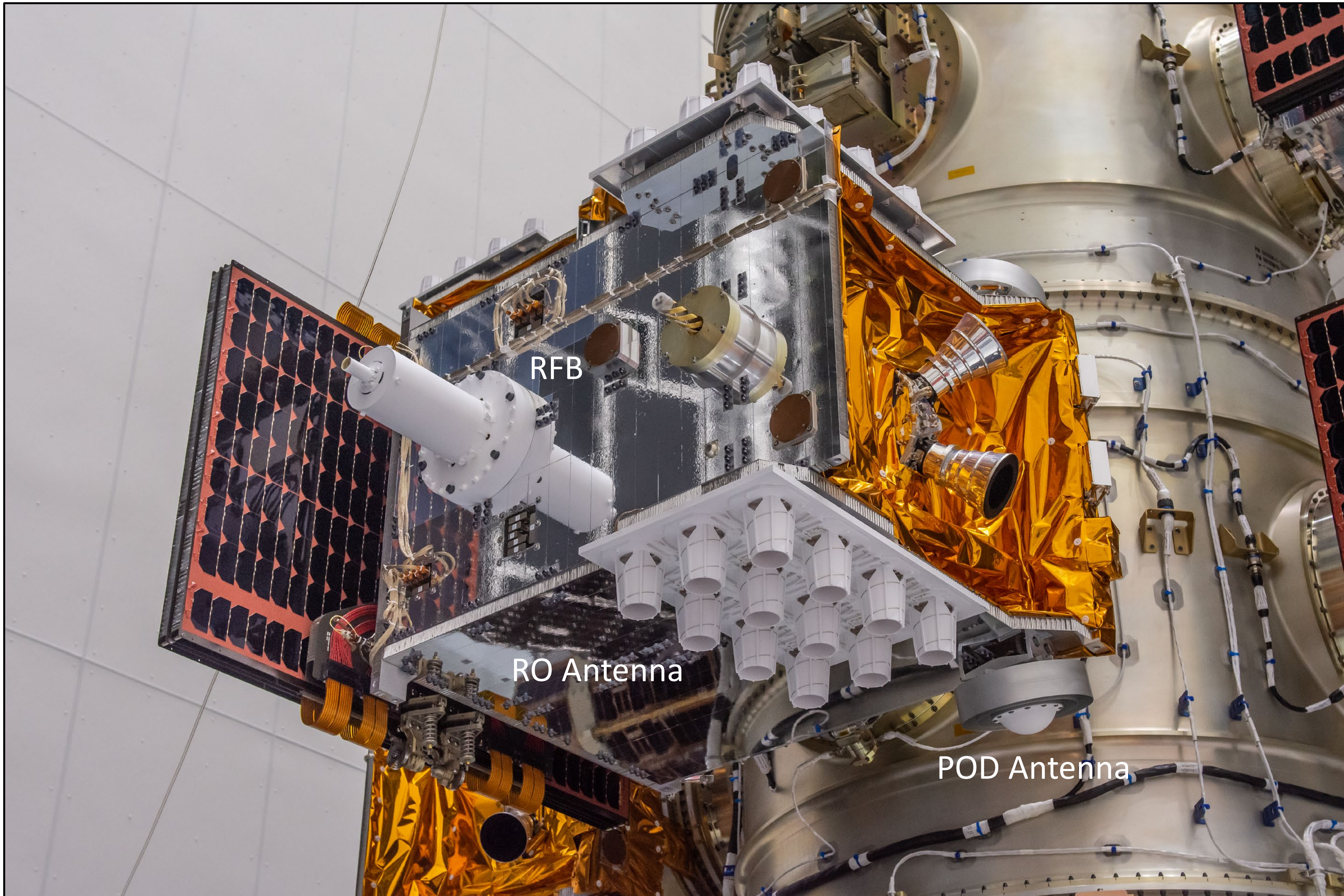
IVM



RFB

Mission Payload	**TGRS (Tri-GNSS Radio occultation System)**	**To measure the amplitude and phase/group delay of GNSS signals**
Science Payload	**IVM (Ion Velocity Meter)**	**To measure in-situ ion density, drifts (Electric fields), temperature & composition**
	RFB (Radio Frequency Beacon)	**To measure total electron content and ionospheric scintillation.**

COSMIC-2 on STP-2 Stack



[Photo courtesy of SpaceX]