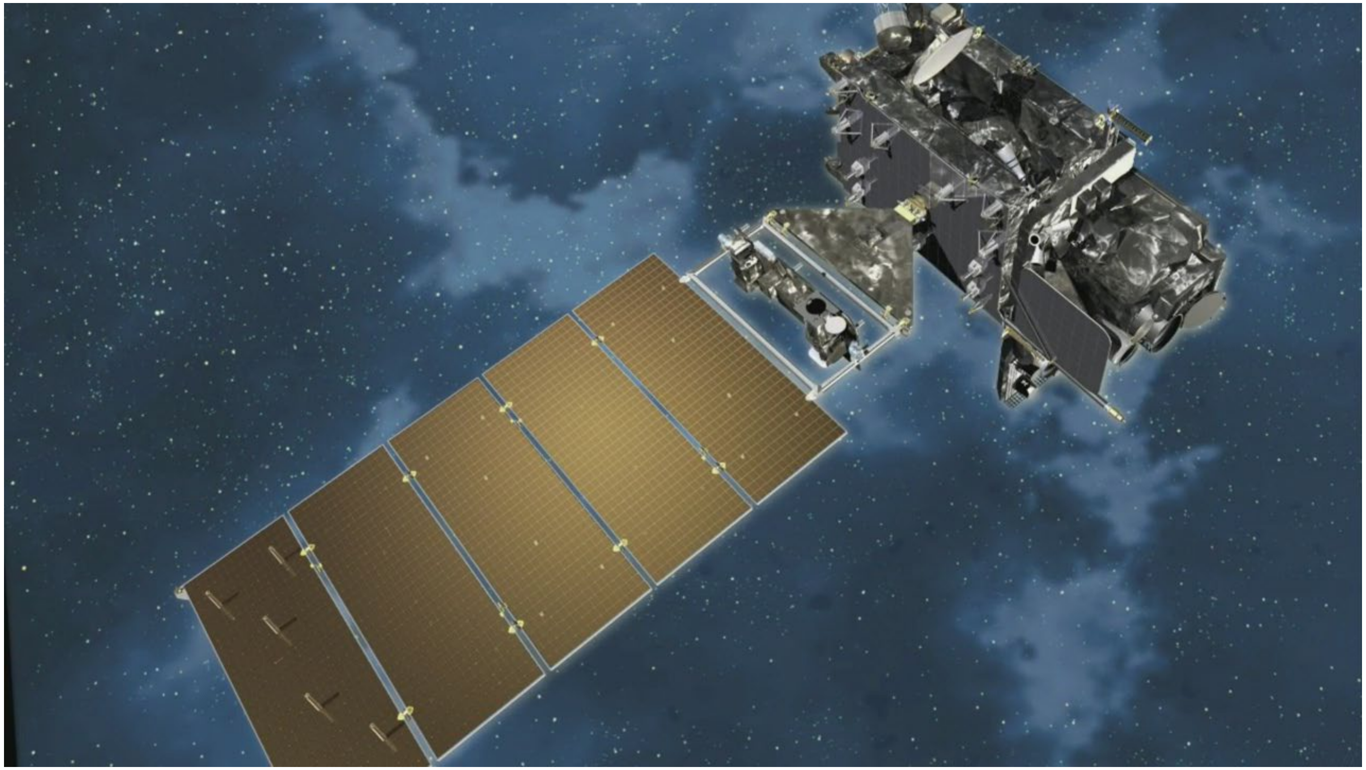


GOES Radio Occultation processing at UCAR

Doug Hunt, Scott Gleason, Irina Zakharenkova, Sergey Sokolovskiy, Iurii Cherniak (UCAR)
Doug Freesland, Alexander Krimchansky, Joel McCorkel (NASA GSFC)
Graeme Ramsey, Jim Chapel (Lockheed Martin Corporation)

9/08/2022

version 5

Overview

- Background
- Snapshot of the data
- GOES receiver geometry
- “Let’s just use the navigation solutions!”
- Processing details
  - Zero difference
  - Single difference
- Example profiles
- Statistics versus COSMIC-2 and the IRI model
- Conclusion

Background

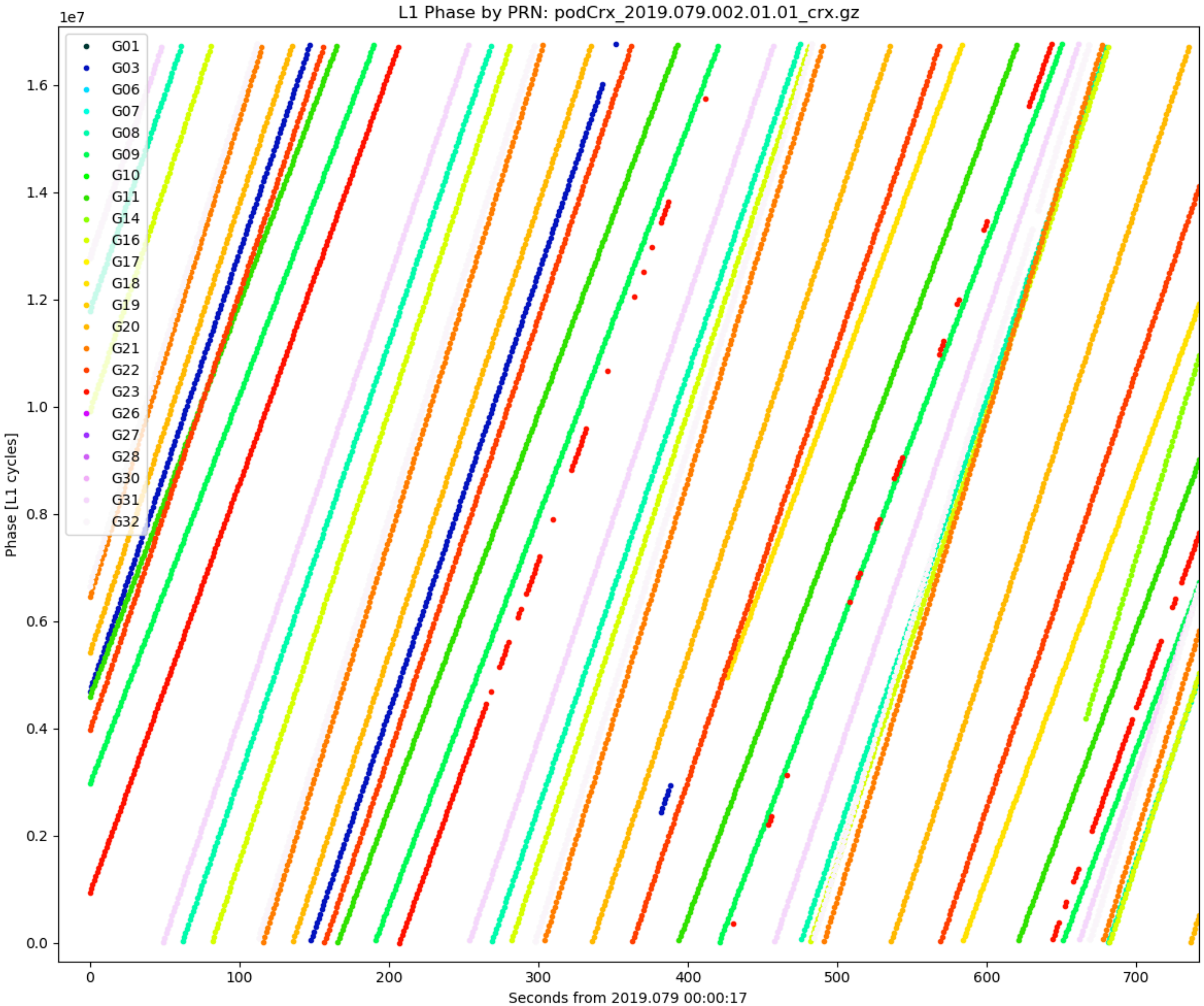
- Single frequency data from the GOES-R and GOES-S onboard GPS receiver made available for the UCAR GOES Radio Occultation project
- These data run from 2017.174 to 2022.120 (GOES-R) and from 2018.295 to 2022.120 (GOES-S)
- Originally supplied in binary 'APID 204' daily files from the NASA GOES team
- These data have been reformatted to CDAAC standards:
  - podCrx : RINEX 2 phase, code and SNR observations
  - gosOrb: SP3 format orbits from GOES navigation solutions
  - brnPol: Earth orientation information
  - leoClk: GOES clock offset data from navigation solutions
  - comClk: GPS clock offset data from MIT orbit analysis
- These are used to generate standard CDAAC 'ionPhs' files (ionospheric excess phase) and then 'ionPrf' files (ionospheric electron density profiles)
- These efforts are discussed in the recent paper:
  - S. Gleason et al., "The First Atmospheric Radio Occultation Profiles From a GPS Receiver in Geostationary Orbit," in IEEE Geoscience and Remote Sensing Letters, vol. 19, pp. 1-5, 2022, Art no. 1005605, doi: 10.1109/LGRS.2022.3185828.
- Project:
  - NASA ROSES 2019 GNSS Science Team, Grant Number 80NSSC20K1733, PI: Scott Gleason

Snapshot of GPS phase data

L1 phase data is spotty and suffers from rapid phase wraps every 200 or so seconds

Q: Can these be fixed other than manually?

A: Excess phase code described below contains an attempt to do so.



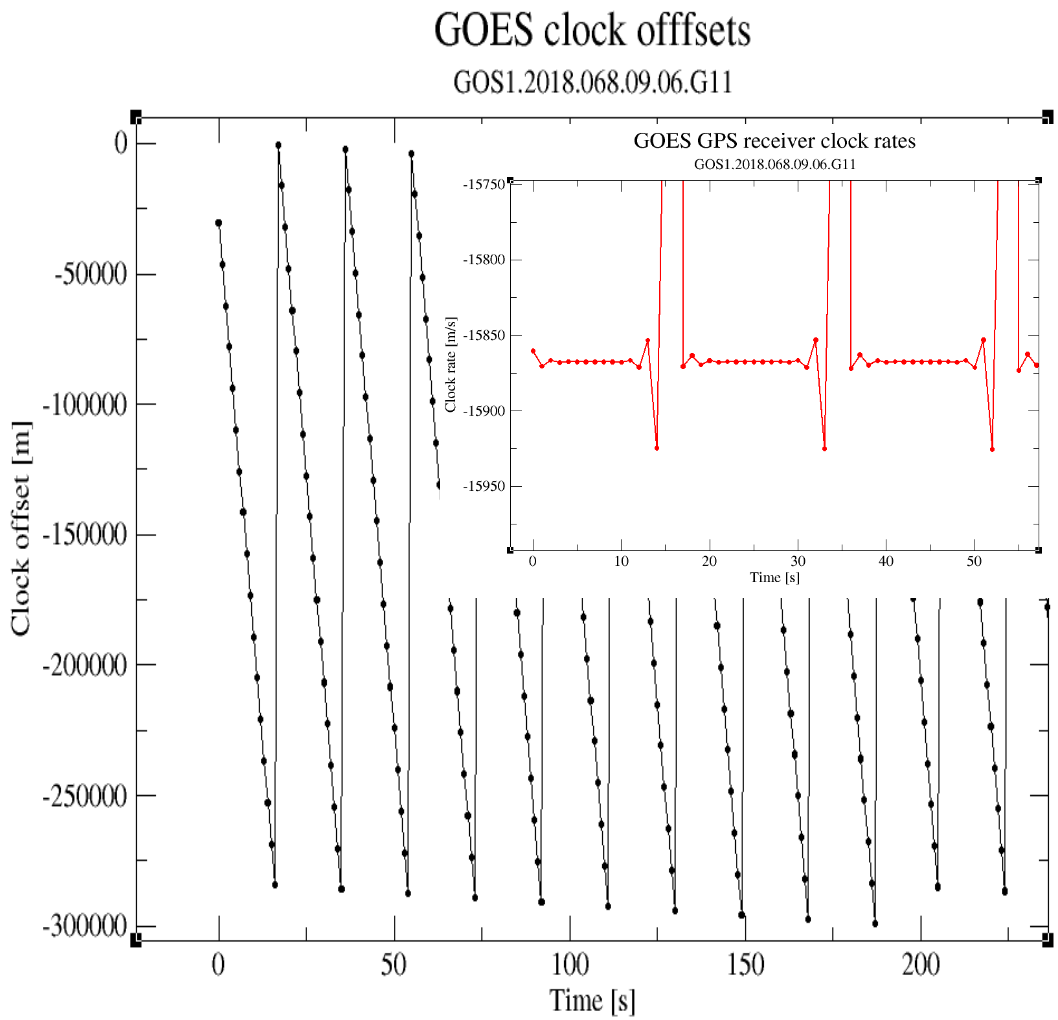
Snapshot of GPS data supplied

GOES clocks have an extremely high clock rate: a 1ms clock correction takes place once every 19 epochs or so.

This clock rate is from the internal oscillator of the General Dynamics Viceroy receiver, which is used on GOES. No more stable external frequency source is used.

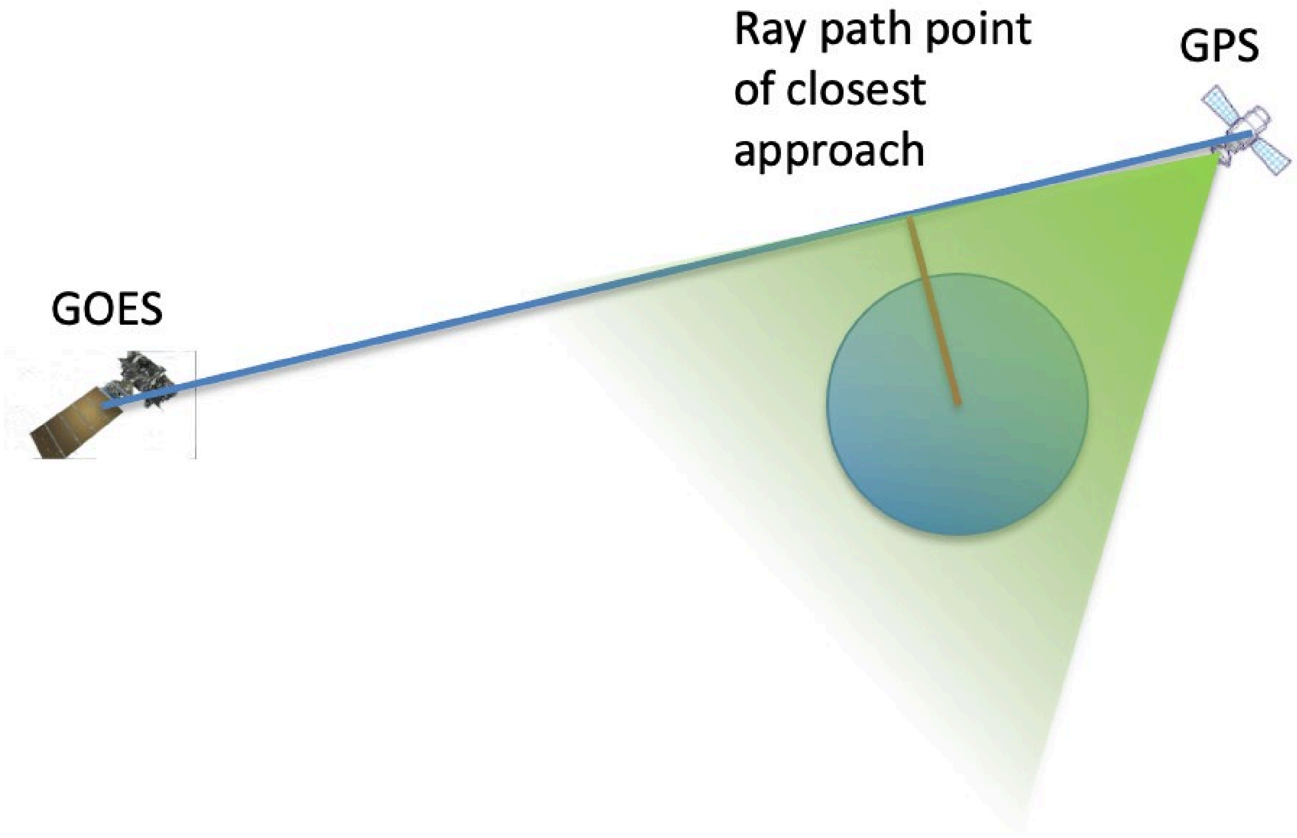
The high clock drift rate and the 1ms corrections must be handled in several ways:

- Apply GOES clock corrections to raw clocks
- Aggressive multi-pass filtering of phase to get rid of clock jumps and phase wraps
- Used of integrated GOES clock rates to get rid of most of the clock offset
- Linear calibration based on occultation data between 1000 and 2000 km SLH to get rid of the rest.



View of GPS satellites from GOES

Due to GPS antenna beam width limitations, all GPS visible from the GOES come from ‘behind the earth’, within a few degrees of the horizon.



View of GPS satellites from GOES

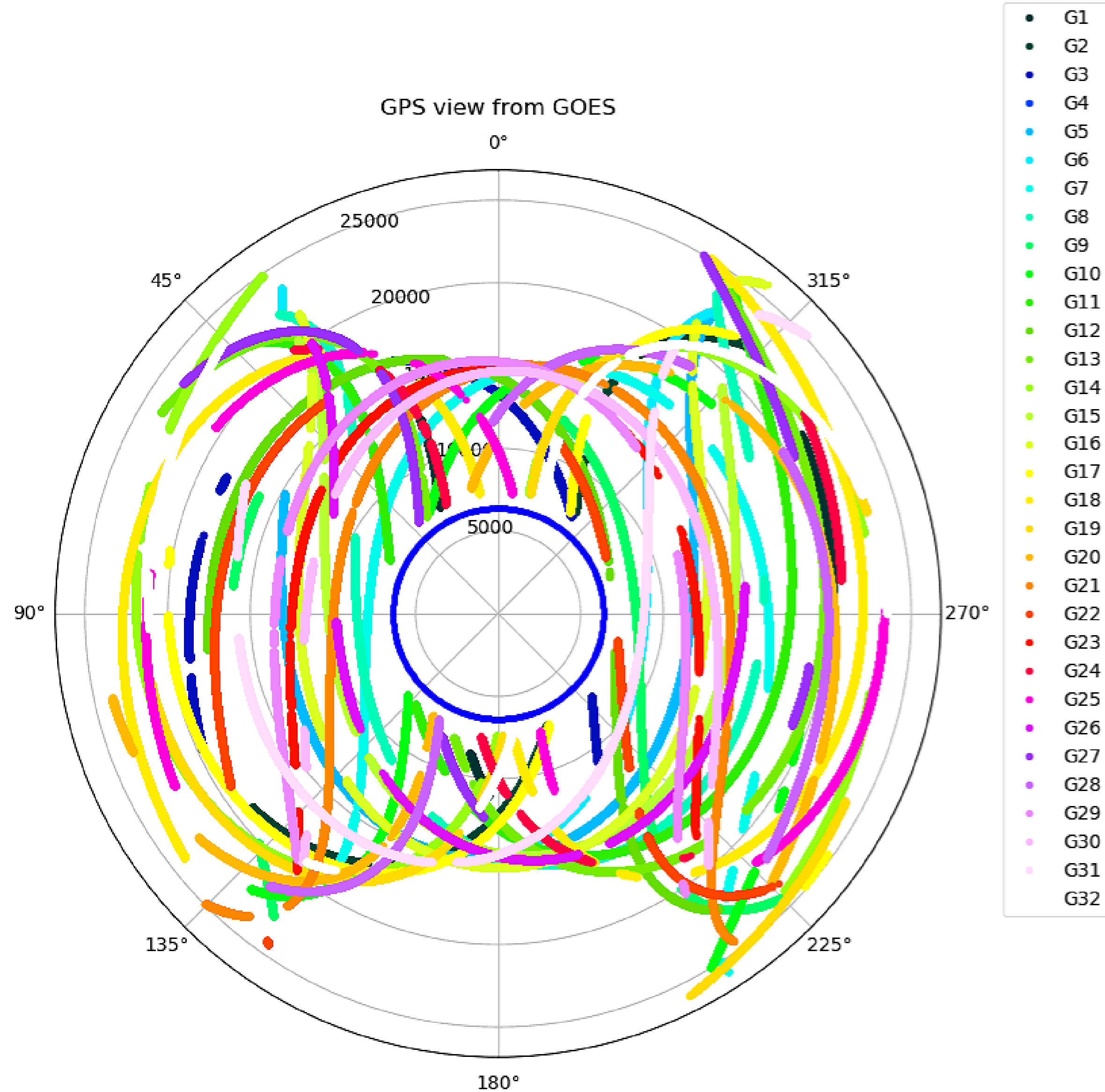
This plot shows the GPS satellite tracks from the point of view of the GOES.

0 degrees is the North pole, the blue circle in the center is the earth.

The radial distance is the distance of the point of closest approach of the ray path between GPS and GOES to the earth's center

All GPS satellites are 'behind the earth' with rays passing at various altitudes from ~0km to ~20000 km from the earth's surface

This plot shows one day of data from GOES-S, day 2019.079



"Let's just use the nav solutions"

- The original plan had been to generate precise orbits for GOES using Bernese
- Bernese orbits generated from these data are of poor quality, due to these issues:
  - 1 ms clock jumps
  - Extremely fast clock rate
  - Poor geometry (orbit software tailored to LEO orbits)
  - Single frequency
- The APID104 data contains navigation orbits and clock solutions (offset and rate) in addition to the receiver phase and SNR data. These orbits are claimed to be good to 100 meters (pretty good for a geosynchronous satellite)
- Why not just use the GOES supplied orbit and clock solutions?

Excess phase: Zero difference

If the orbit problem is settled (use the nav solutions), the next issue is excess phase processing. The first cut was 'zero difference' processing.

Zero difference refers to the fact that no differences are computed between the occulting link/PRN and any other PRN to get a LEO clock solution.

Here are the steps:

1. Read in all necessary data: Orbits, GEO and GPS clock offsets, phase data.
2. Apply the GOES clock offsets directly to the input times read in from the RINEX. This usually gets rid of the 1ms time jumps and associated 'ringing', resulting in times that have jitter of less then 1 microsec/sec.
3. Generate quieter clock offsets by integrating the supplied clock rates
4. Extended fixing of raw phase values. First take the derivative, and work with Doppler:
    a. Large spike suppression: These values wrap about every 200 seconds: Detect spikes in Doppler and replace them with the average slope of the neighbors.
    b. Small spike suppression: These values suffer from smaller spikes with each 1ms clock jump (about every 19 seconds). Treat these similarly to 1, with different thresholds.
    c. Then use a novel filter I call the 'Bulldozer' is used to get rid of stubborn single or double point spikes not fixable by a Hample filter.

Zero difference (cont)

5. Integrate the cleaned up Doppler to obtain full clean phase.
6. Compute the excess phase:
   a. Read in all GOES and GPS orbits and clock information
   b. Form the combination:

$$\delta\rho_r^t = \phi - \rho_r^t \; - \; c\delta_r - c\delta^t$$

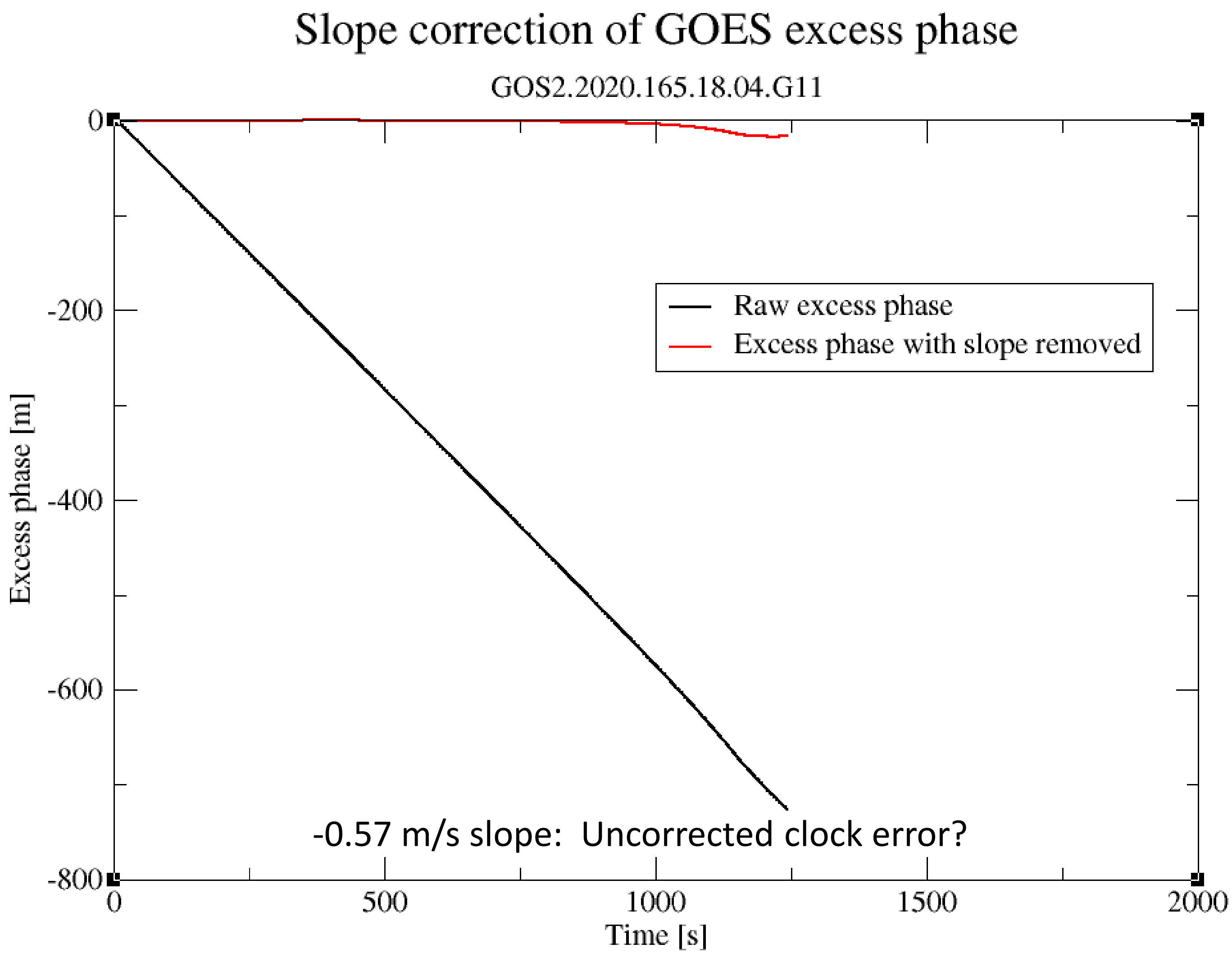
Where

- $\delta\rho_r^t$ – The excess phase (starts by convention at zero above the ionosphere)
- ϕ – The corrected phase
- ρ_r^t – Geometric distance between receiver and transmitter
- $c\delta_r, c\delta^t$ – Transmitter and receiver clock biases

The problem now is that the orbits and clocks are not *quite* good enough, in particular the clocks show a residual linear trend.

This can be removed if we assume that from 2000km – 1000km perigee path altitude the residual constant linear term is due to clock error and can be used to correct the rest of the occultation.

Still some residual clock error



Data start at 2000km straight line height. The section of data from 2000-1000km (about the first half of this track) is used to determine the slope: We don't expect any ionospheric or neutral atmospheric phase contribution here.

Doppler budget

Sources of Doppler (from the example)

Source	value [m/s]
Total measured Doppler, average between 1000-2000 km	-14934.44
Orbital motion (includes several second order effects)	-833.83
GPS clock	-0.0034
GOES clock (integrated clock rate from GOES data)	15767.71
Remaining linear trend (fixed manually)	**-0.57**

Usually, the measured Doppler is nearly offset by orbital motion, with the other terms small in comparison. Here the receiver clock dominates.

The LEO clock rate is extremely high for GOES. Normally, the LEO clock rate is closer to the GNSS clock rate, but here it is about 7 orders of magnitude worse! The remaining linear trend seems to be an error in the clock information from the GOES data.

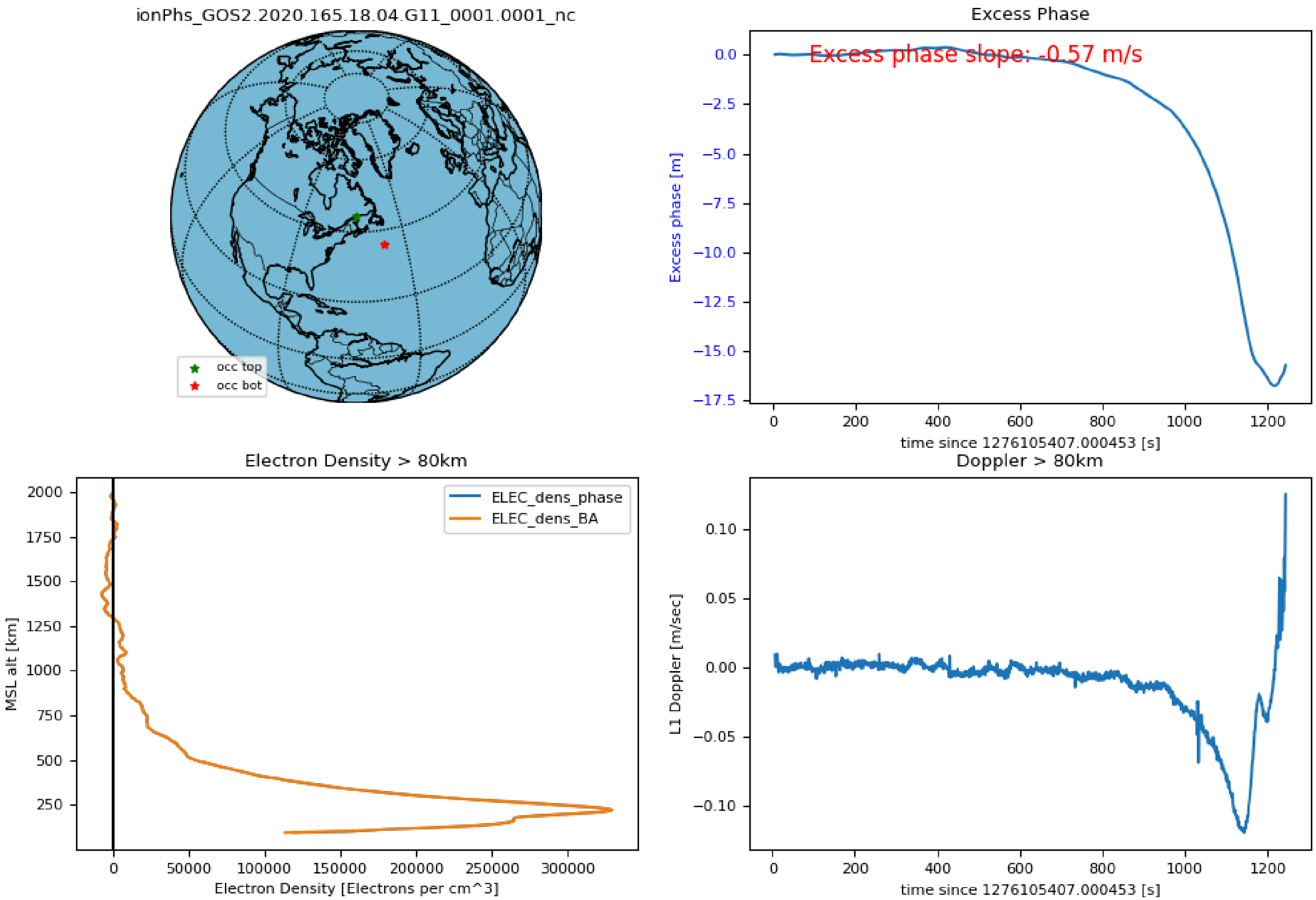
Ionospheric inversion

Once excess phase (ionPhs files) are computed, the next step is Abel inversion.

We use an ionospheric inversion code written by Sergey Sokolovskiy

- Based on early single frequency inversion code from GPS/MET (1994-1997)
- Two separate inversion algorithms: A simplified version assuming straight line propagation, and one which takes account of bending.
- These give very similar results

Final profile



The final corrected excess phase on on the top right. A linear trend of 0.57 m/s has been removed.

This plot shows the expected phase advance (negative excess phase) in the ionosphere and phase delay (positive excess phase) in the neutral atmosphere.

The inverted electron density profile (bottom left) looks reasonable.

Occultation coverage

- Illustration of geolocation of F2 peak coordinates generated from GOES-R and GOES-S electron density profiles over 2020.

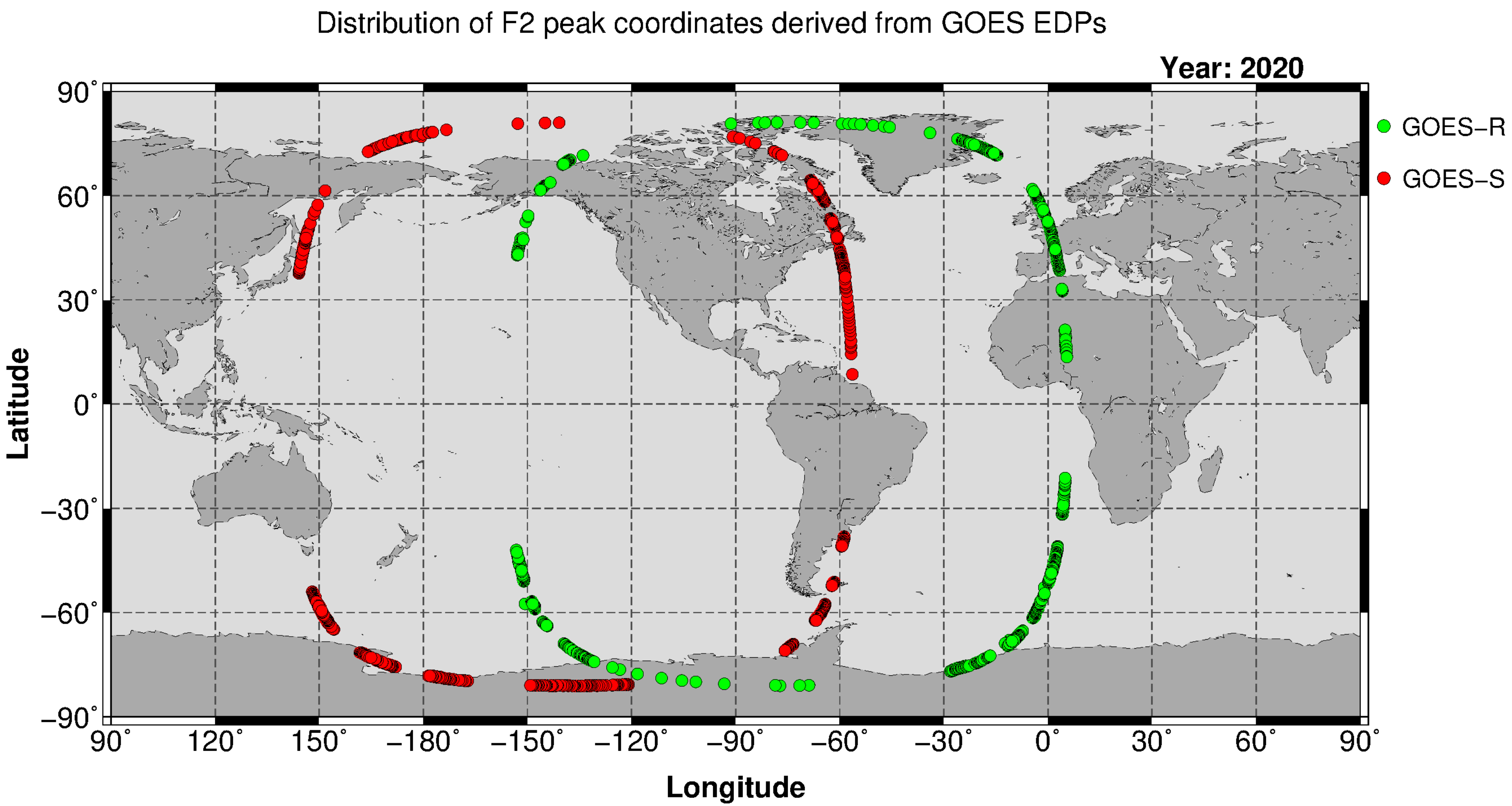


Figure courtesy IEEE GRSL submission

Two example profiles

- Two GOES Profile Examples were isolated for initial comparison with COSMIC-2 low Earth orbit observations and a ground based Ionosonde in Spain

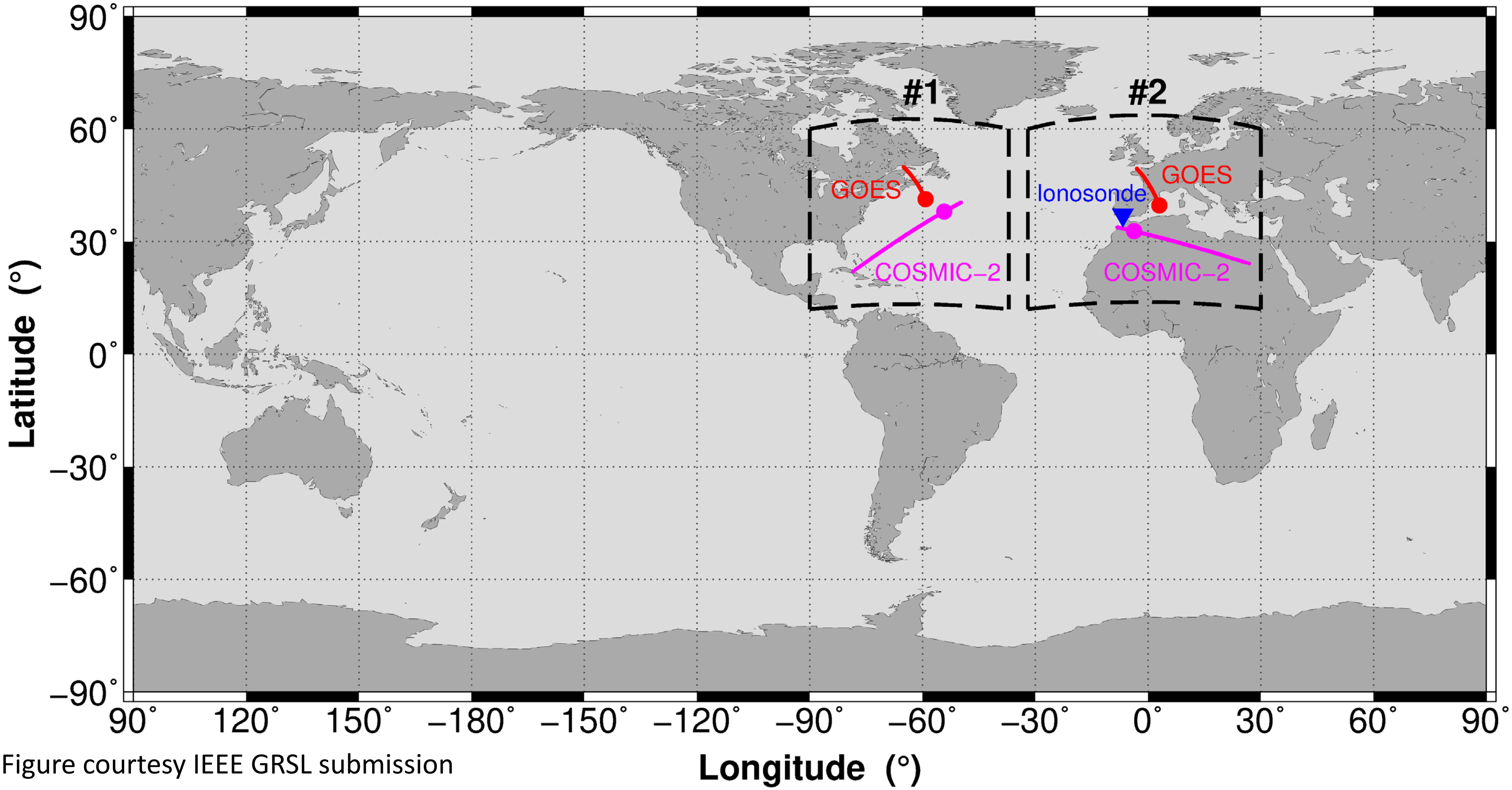


Figure courtesy IEEE GRSL submission

GOES RO Profile Comparison: Example 1

- Example #1 GOES profile in the Eastern Atlantic Ocean region with a good co-location to a COSMIC-2 profile.

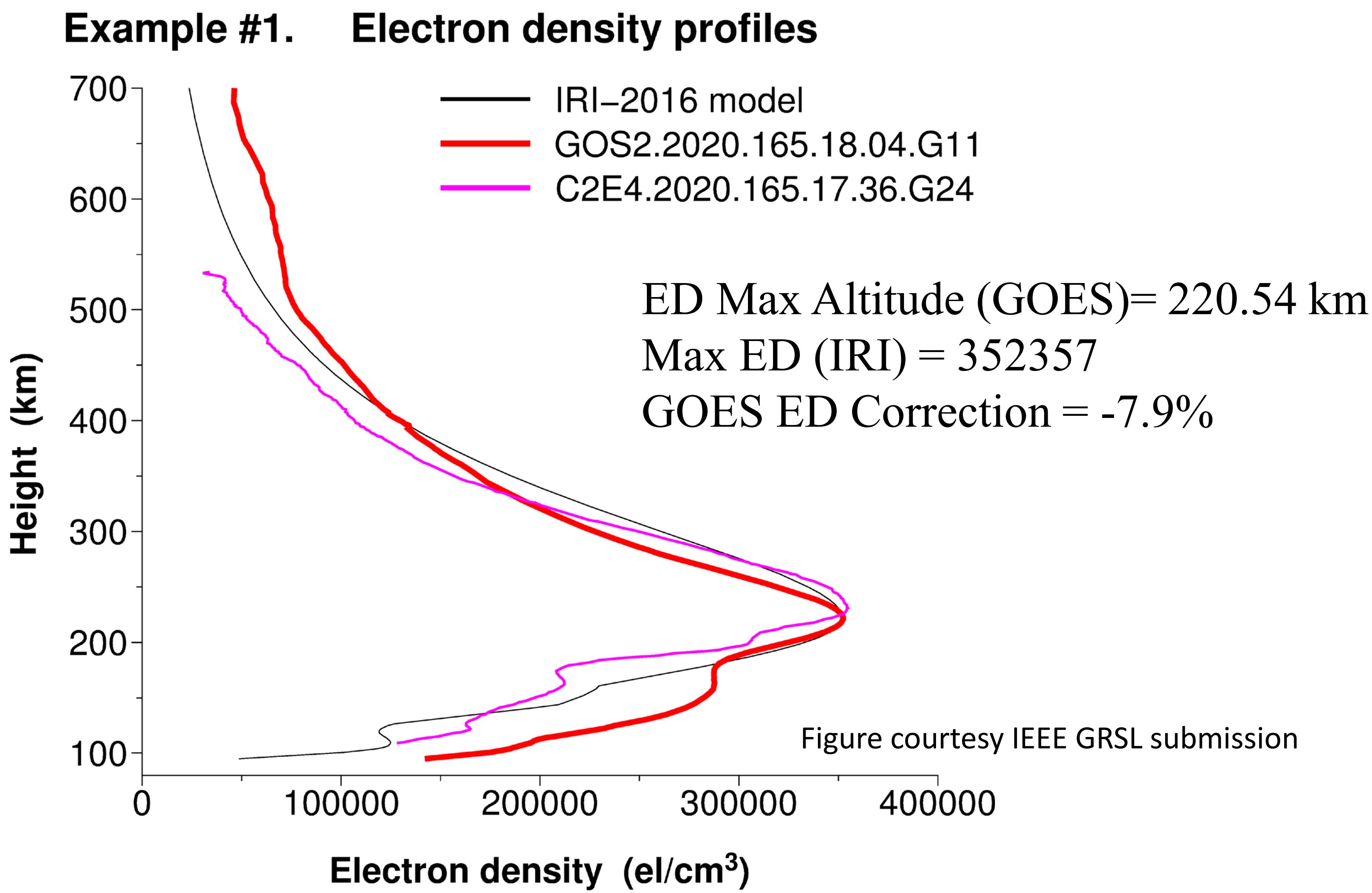


Figure courtesy IEEE GRSL submission

GOES RO Profile Comparison: Example 2

- Example #2 GOES profile in the regions of Western Europe with a good co-location to a COSMIC-2 profile and a nearby Ionosonde reference.

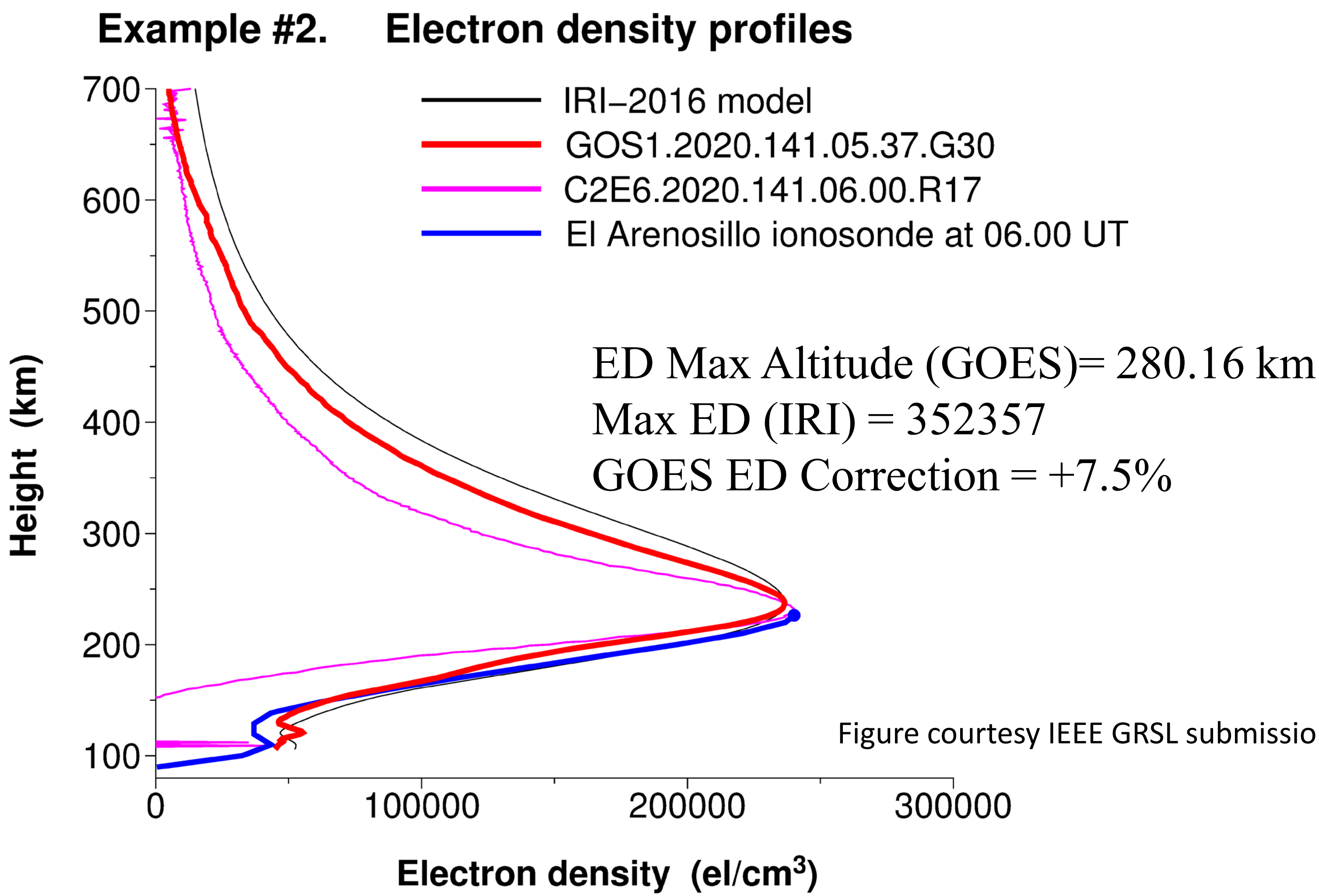
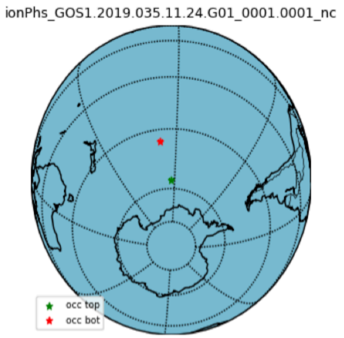
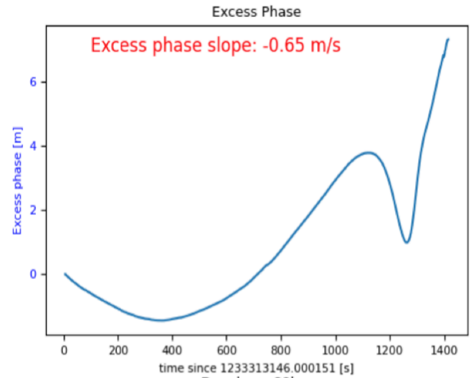
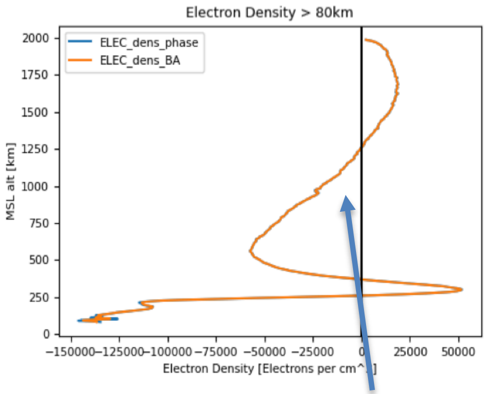


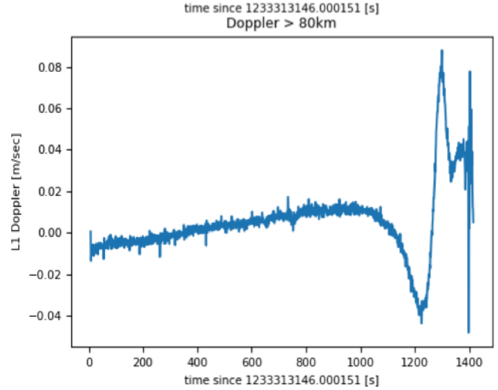
Figure courtesy IEEE GRSL submission

What can go wrong?









Since the receiver clock term so dominates the other excess phase terms, I assume this is an error in the receiver clock correction.

How to fix this if the navigation solution clock is found wanting?

Sometimes, even after linear correction of the the clock offset, there is residual signal that shows up as a non-physical shape in the election density curve between 1000 and 2000km.

Alternative Clock Correction

Standard practice for many years in LEO RO has been to use a higher elevation 'reference' GNSS satellite for LEO clock correction. Data from this reference satellite shares the same LEO clock errors that the occulting link does, but is not contaminated by the ionosphere. The links can be differenced to get rid of LEO clock errors:

$$\delta\rho_r^t = (\phi_{occ} - \phi_{ref}) - [(\rho_{occ}^t - c\delta_{occ}^t) - (\rho_{ref}^t - c\delta_{ref}^t)]$$

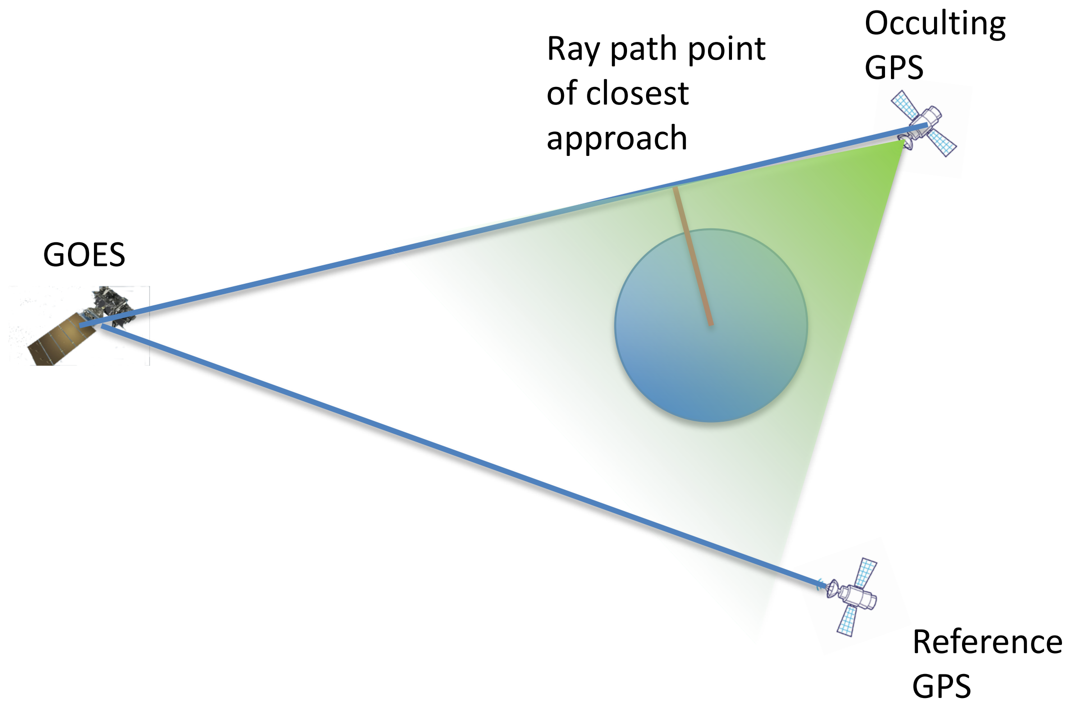
Alternatively, the reference link LEO clock can be solved for by combining the zero-difference equation shown earlier:

$$\delta\rho_r^t = \phi_{occ} - \rho_r^t - c\delta_r - c\delta^t$$

with the above single-difference equation to get:

$$\delta_r = (\phi_{ref} - \rho_r^t - c\delta^t)/c$$

and applied later as if it were a LEO clock solution.
Further, several clock solutions can be found, one from each of many reference GNSS satellites.



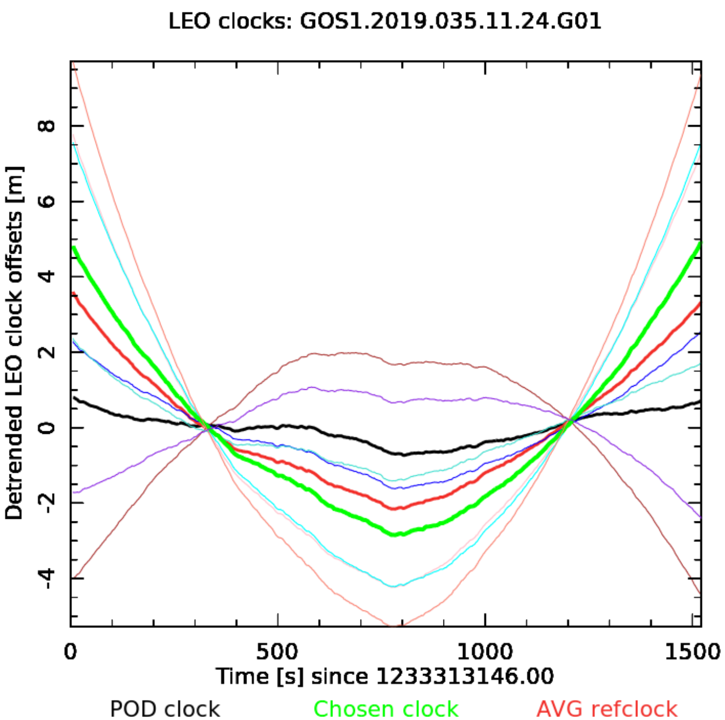
Key

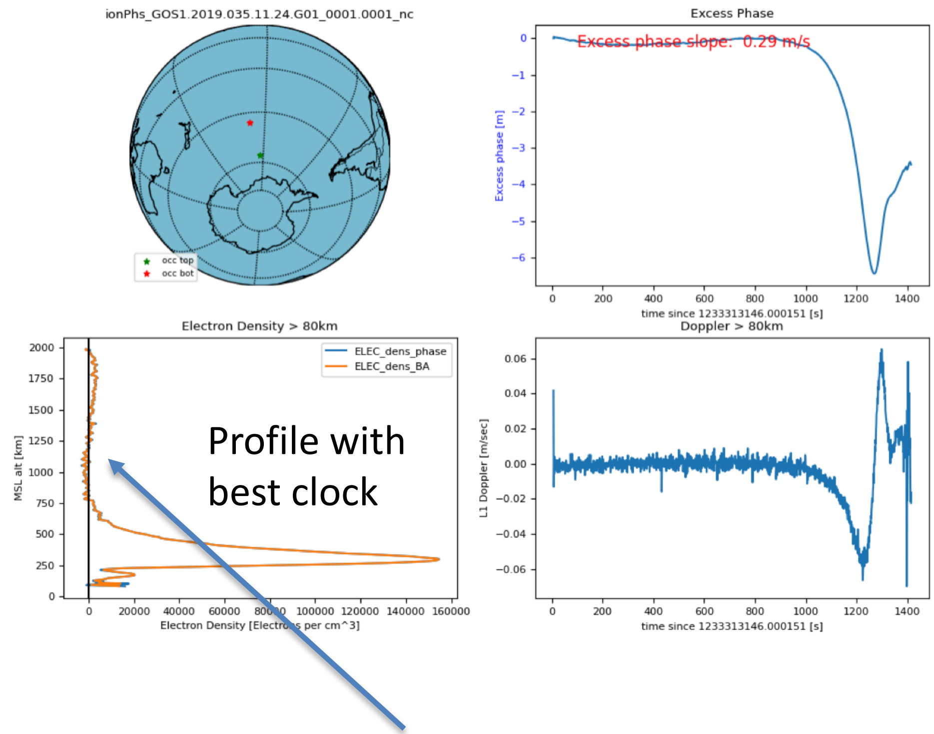
$\delta\rho_r^t$ – The excess phase
ϕ_{occ} – The measured occultation link phase
ϕ_{ref} – The measured reference link phase
ρ_{occ}^t – Geometric distance between receiver and occulting GPS
ρ_{ref}^t – Geometric distance between receiver and reference GPS
$c\delta_r, c\delta^t$ – Transmitter and receiver clock biases

Using multiple clock solutions

Since the GOES receiver tracks up to 12 PRNs at a time, we can solve for several different clock solutions.

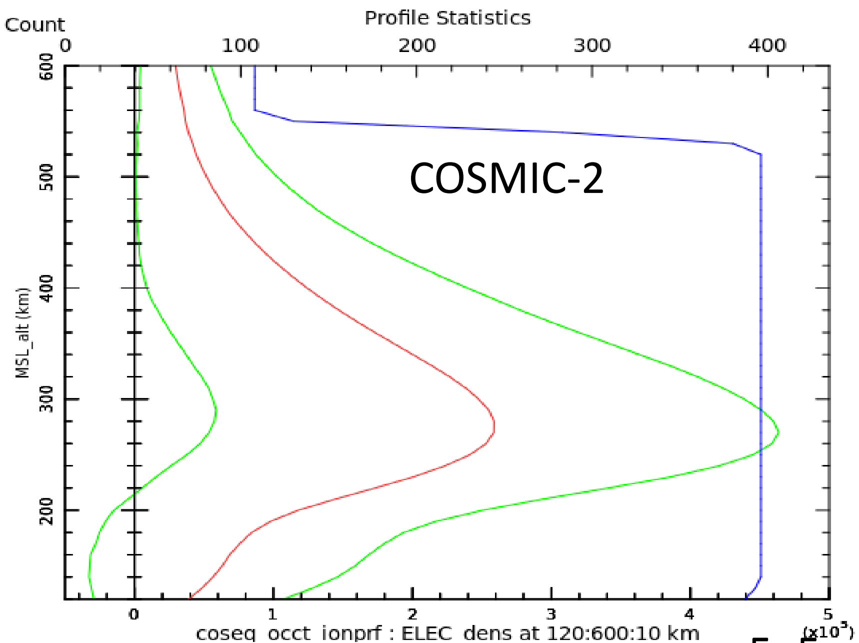
Below are all the detrended clock solutions for the previous occultation, including the navigation solution clock (in black) and the average of all reference link clocks (in red).



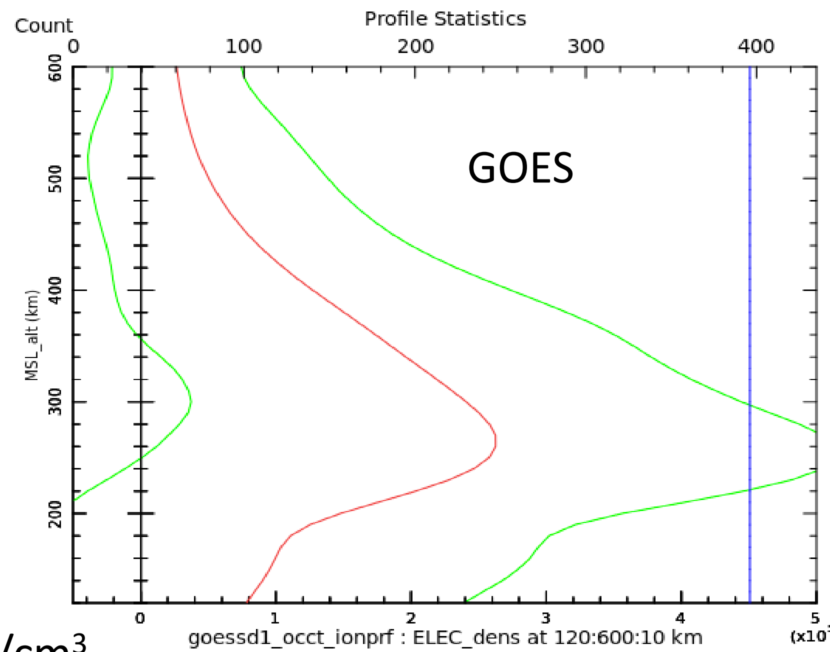


When the clock is carefully chosen, a much more physical slope can be obtained between 1000 and 2000km, as shown above.

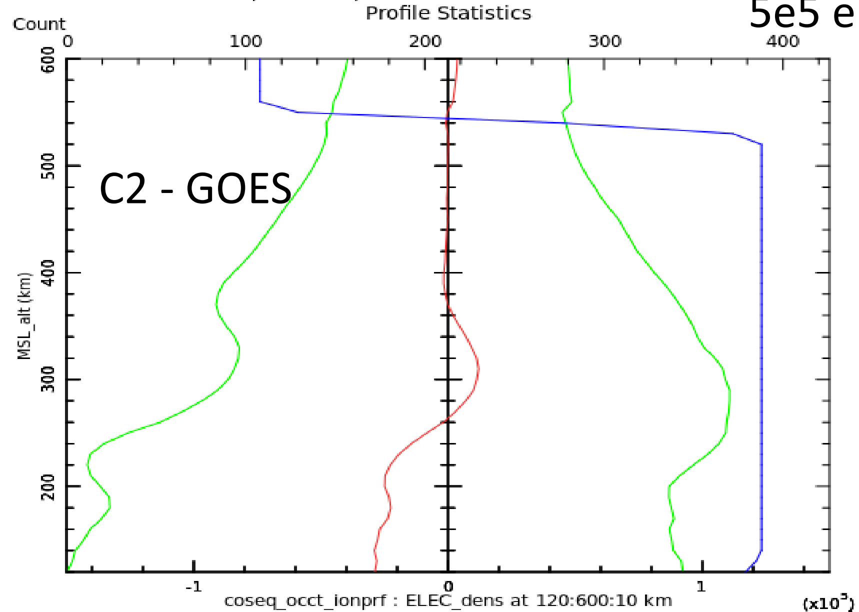
Statistics vs. COSMIC-2



5e5 el/cm^3



5e5 el/cm^3



1e5 el/cm^3

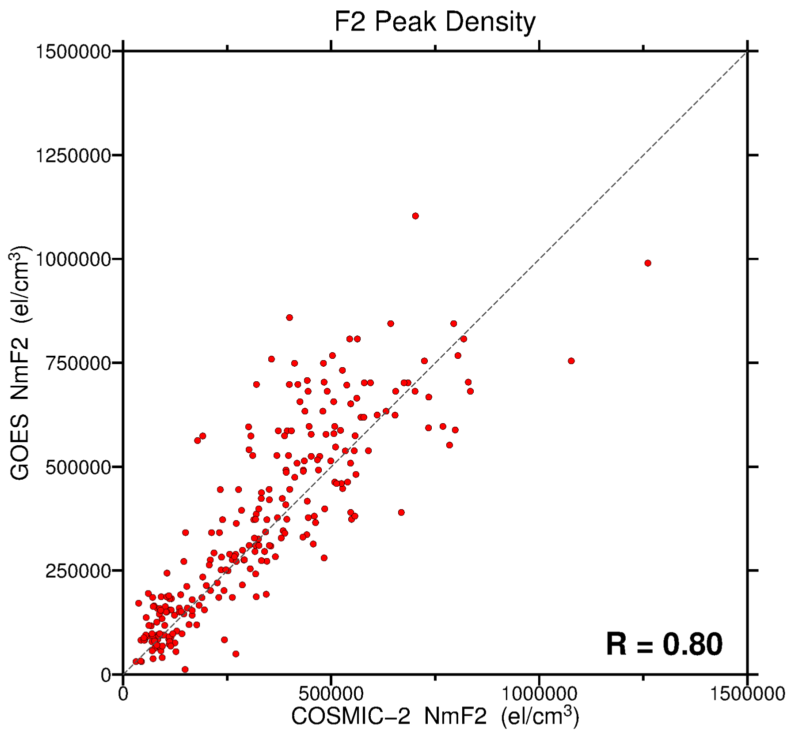
Electron density comparison with COSMIC-2 for 2020 and 2021.

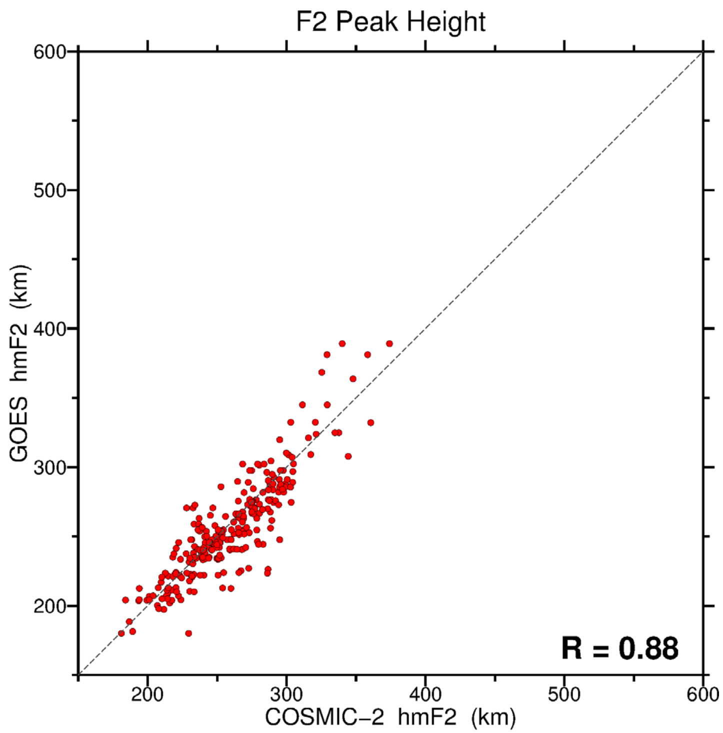
There are few matches since the match window is tight (1 hour/500 km) and since C2 tracks only in the tropics and mid-latitudes whereas GOES tracks predominantly in the upper latitudes.

Statistics vs. COSMIC-2: HmF2 and NmF2

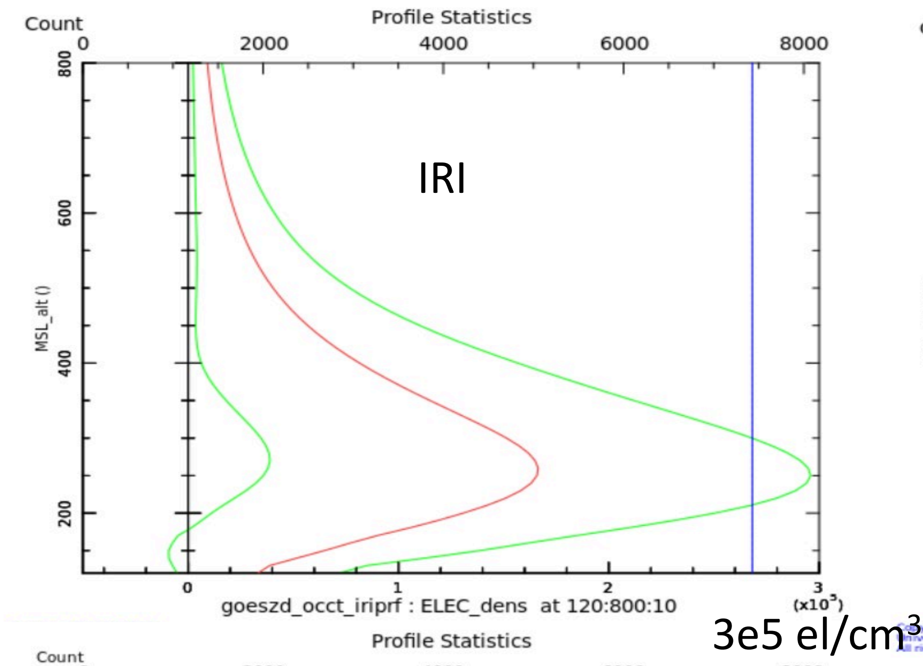
GOES vs COSMIC-2

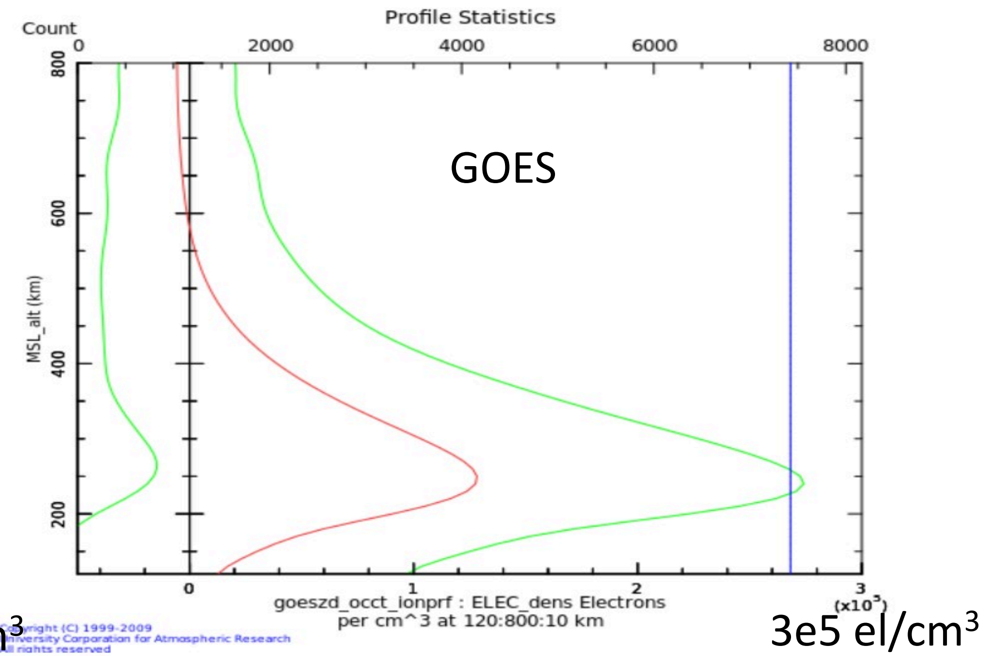
Time : 2020-2021
Collocation in F2 peak: 5 degree X 1 hour

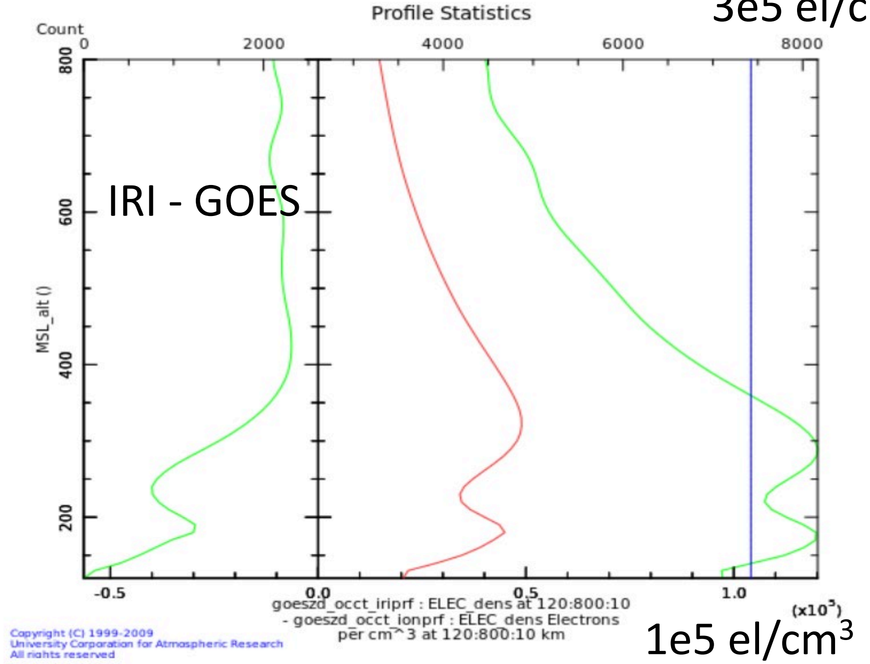




Statistics vs. IRI







Electron density comparison with the IRI-2021 model (release 2021) for 2020 and 2021.

The positive bias between IRI and GOES (IRI greater than GOES) is likely due to:

1. GOES clock correction problems
2. IRI is known to overestimate density at low solar activity periods like 2020-21

Conclusion

- The first RO ionospheric processing from a geostationary satellite has been done with data from the GOES weather satellites.
  - This GPS instrument on the GOES was not intended for remote sensing use, just for satellite positioning and station keeping.
  - Nonetheless, reasonable profiles have been generated by the use of innovative data filtering and processing strategies.
  - A new single-differencing strategy can help overcome limitations in the receiver clocks supplied by the instrument.
- Data from GOESR and GOESS from 2017 to 2022 have been processed to electron density profiles.
- This is an interesting technical exercise, but beyond that:
  - It demonstrates the feasibility of Geosynchronous RO
  - The different geometry and repeatable nature of the observations make this an interesting dataset.
- In the final year of the project we will continue to optimize the quality of the RO profiles as well as study the potential of detecting atmospheric scintillation events using magnitude and phase based algorithms.
- We are working with the NASA GOES team to perform an instrument optimization study to optimize the GNSS-RO receiver performance on future Geosynchronous satellites.

Backup slides