Validation of STAR GNSS RO Bending Angle Conversion from COSMIC-2 Carrier Phase

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Outline

- COSMIC-2 and background
- Research Goals and approaches
- Flow chart for STAR/UMD RO data processing
- Calculation and validation of excess phase
- Calculation and validation of bending angle
- Summary

COSMIC-2 Mission

- Within one and half years after launch of COSMIC-2, validation and verification have proved:
  - High SNR with deeper penetration depth
  - Contribute additional daily RO profiles (>5000) into NWP (compared to <2600/day before).
  - Positive impact into NWP model and data into operations since March, 2020
  - Consistent with other RO observations (through inter-mission comparison
    - Shreiner et al, 2020; Cao et al.,2020; Ho et al., 2020
- COSMIC-2 are different from COSMIC-1.
  - Receiver (Trig vs IGOR); Clock, Antenna
  - More LC signals from GPS satellites
  - High rate Occultation rate (100 Hz vs 50Hz)
  - No high rate POD antenna observations (COSMIC-1 50HZ)
  - Early COSMIC-2 profiles from GPS L2P signals have some issues.
- To understand the data products errors and for better quality control monitoring, the procedure from raw observations to bending angles and higher level products needs to be understood.
  - Step by step inversion from carrier phase, time delays to bending angle
  - For better quality control and observation error assessments in NWP for data assimilation.

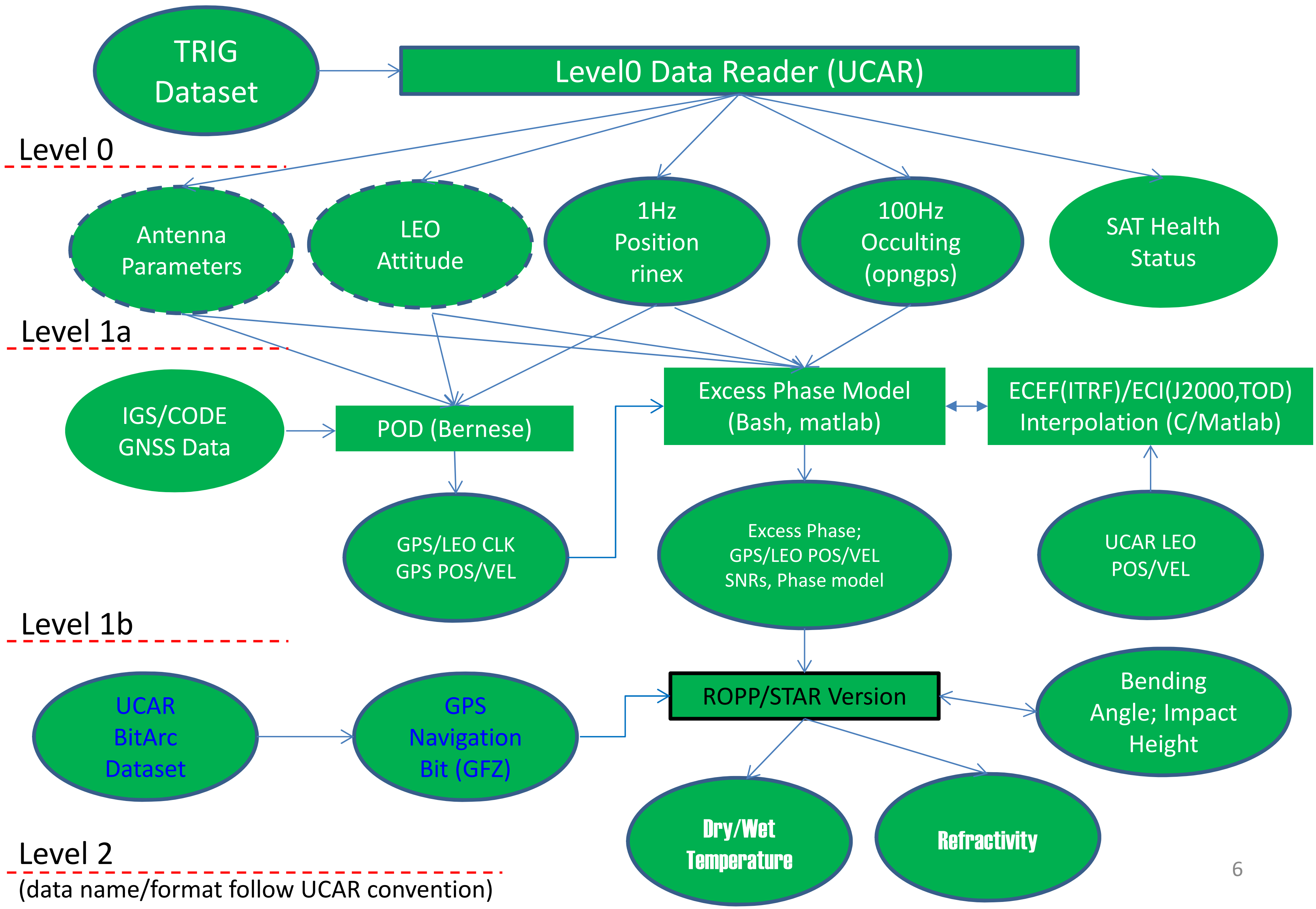
Research Goals

- NOAA/STAR recently developed RO Cal/Val System for monitoring the data quality of RO products for COSMIC-2, Metop-C and other RO missions.
- RO data processing from raw observations to Bending Angle is a new capability that needs to be developed onsite at NOAA.
- To establish the (Re)processing procedure from raw RO observations (carrier phase and time delay) to bending angle to understand processing steps.
- To understand the error source, magnitude, and their propagation model errors in the processing products.
- In this study, we process the COSMIC-2 data from carrier phase to bending angle to understand the error propagation and compare with weather model results and validate results from different centers.

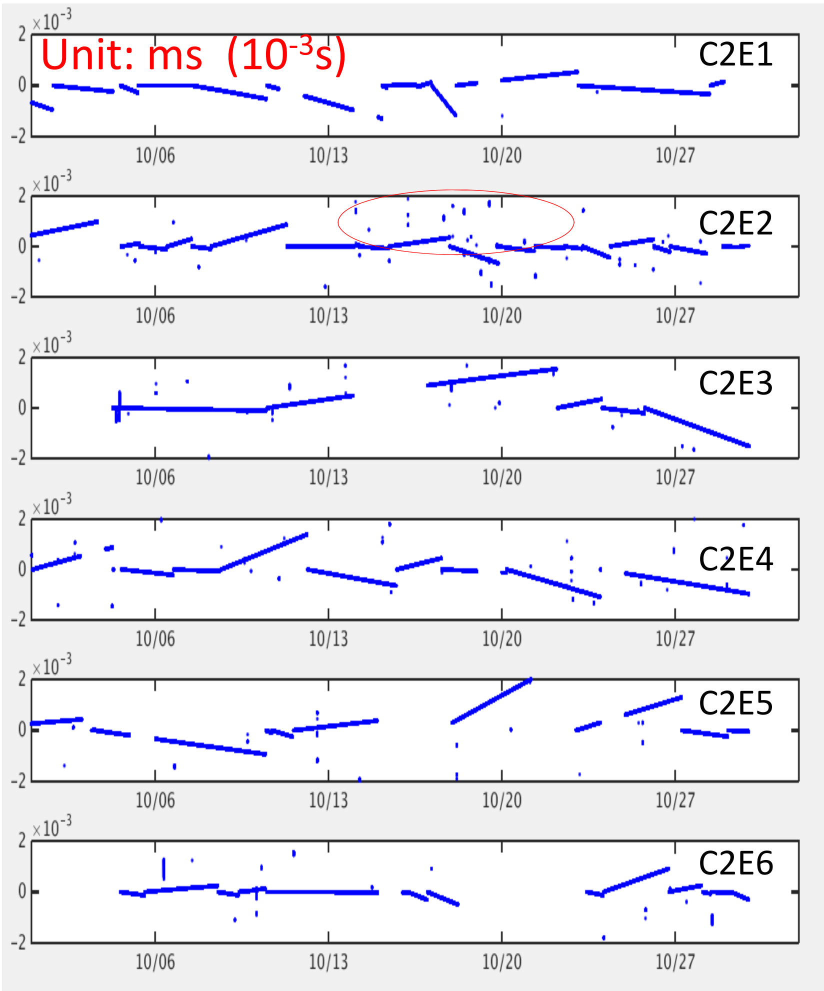
Approaches

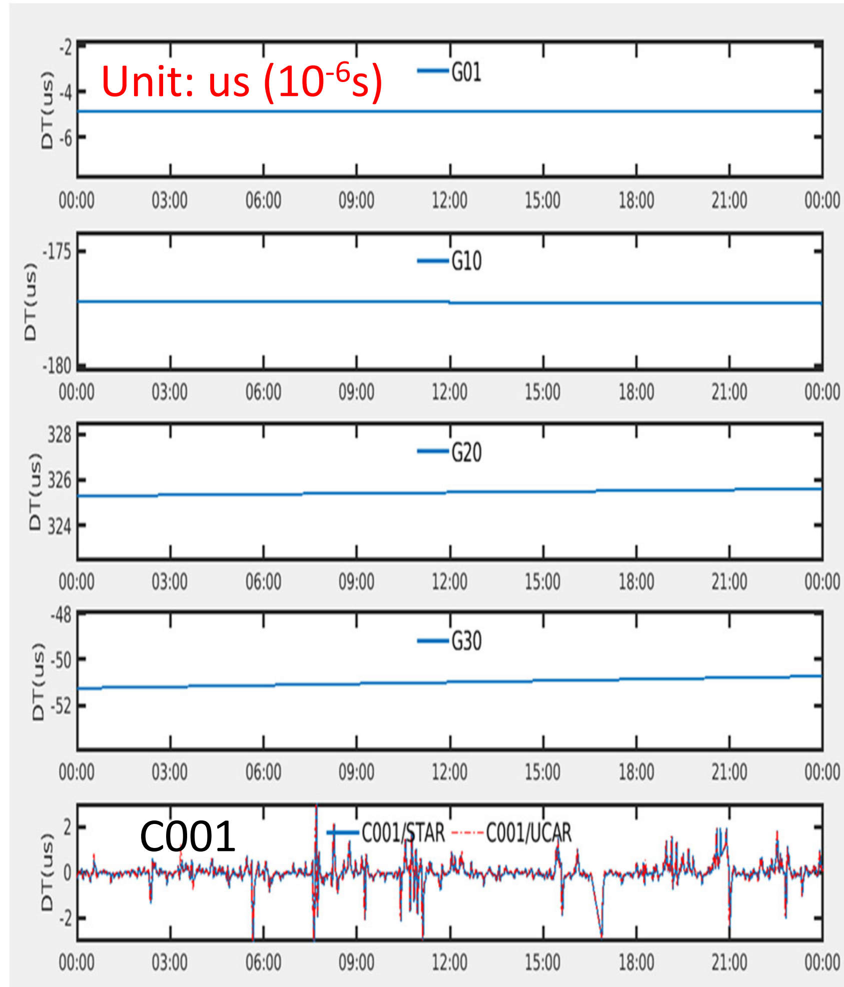
- Start from UCAR's Level 0 data and decoding script
- Use Bernese software for Clock solution and tested POD.
- Developed the excess phase code in Matlab to convert RENIX and high rate Occultation observations into excess phase
- Modified/adopted ROPP (9.0) to inverse the excess phase to bending angle, refractivity and dry temperature
- Compared the derived excess phase (and antenna positions) with UCAR results.
- Compared bending angle with ERA-5 simulated bending angle and UCAR results.

RO Processing Procedure with COSMIC-2 data



COSMIC-2 Clock Bias





- Current results show the clock of E2-6 are more noisy than E1. Can be screened and smoothed.
- Different satellites (sub C2) have different Clock drift rate and adjustment schedules.
- Large errors (>100us) must be counted in the coordinate transformation, even using single differencing.

Excess Phase Modeling

Leo Clock Error — Range of GNSS/LEO

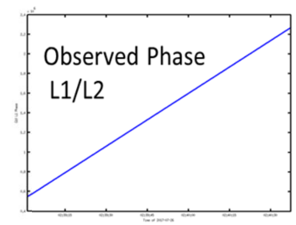
$$L1_r^s(t_r) = c \cdot \delta t_r(t_r) + c \cdot \delta t_{r,rel}(t_r) + \rho_r^s(t_r) + \delta\rho_{r,rel}^s(t_r) + c \cdot \delta t^s(t_r - \tau_r^s) + c \cdot \delta t_{rel}^s(t_r - \tau_r^s) + \delta\rho_{r,ion}^s(t_r) + \delta\rho_{r,trop}^s(t_r) + \lambda_1 \cdot N_{amb} + \varepsilon$$

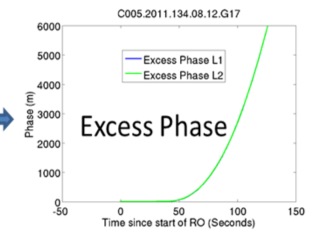
Carrier Phase Measured

Relativity Effects

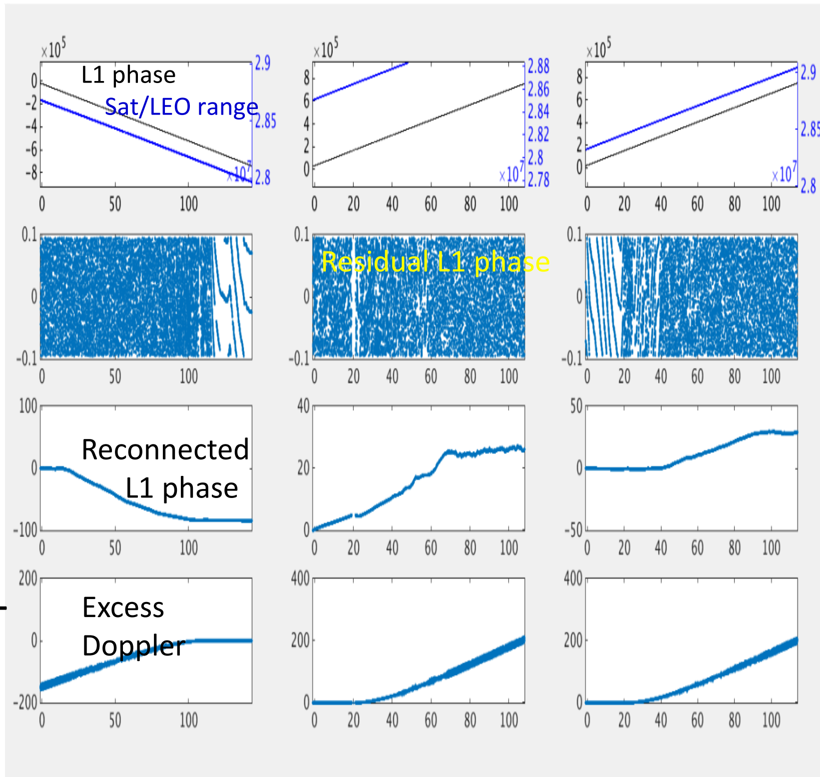
Schreiner et al., 2009

GNSS Clock Error — Excess Phase (ΔS) Wanted — Phase Ambiguity





INPUT



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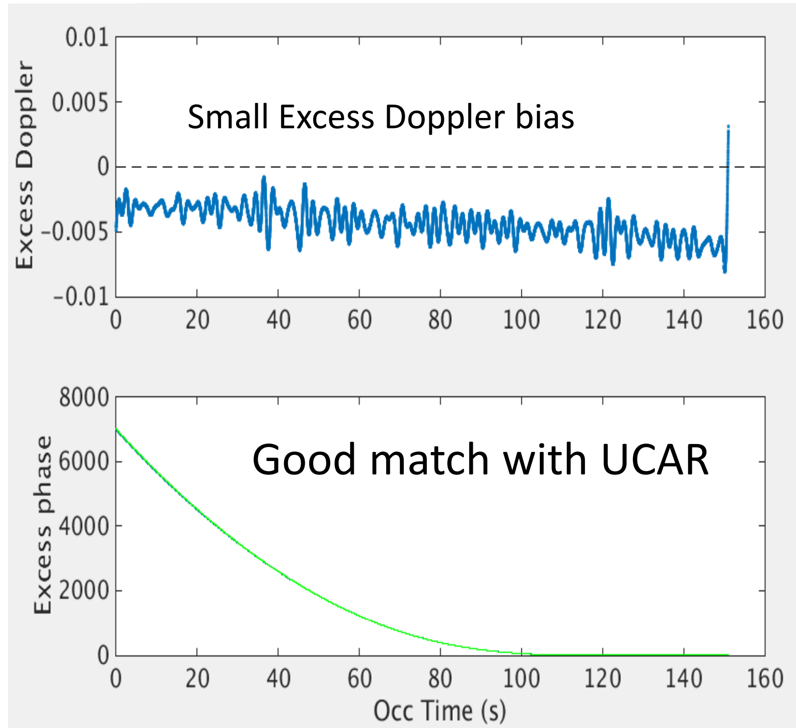
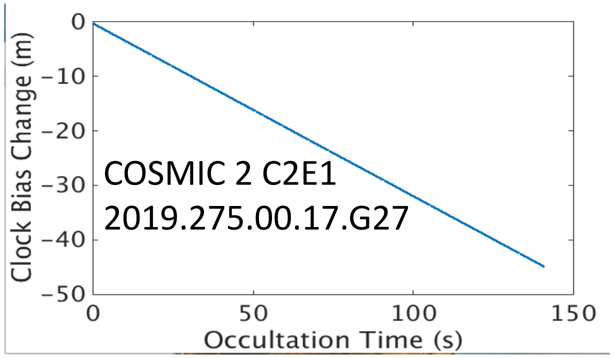
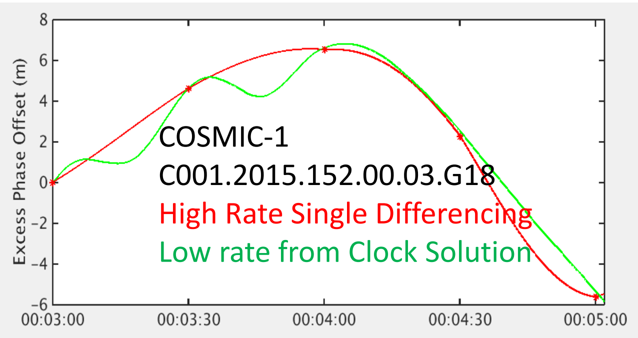


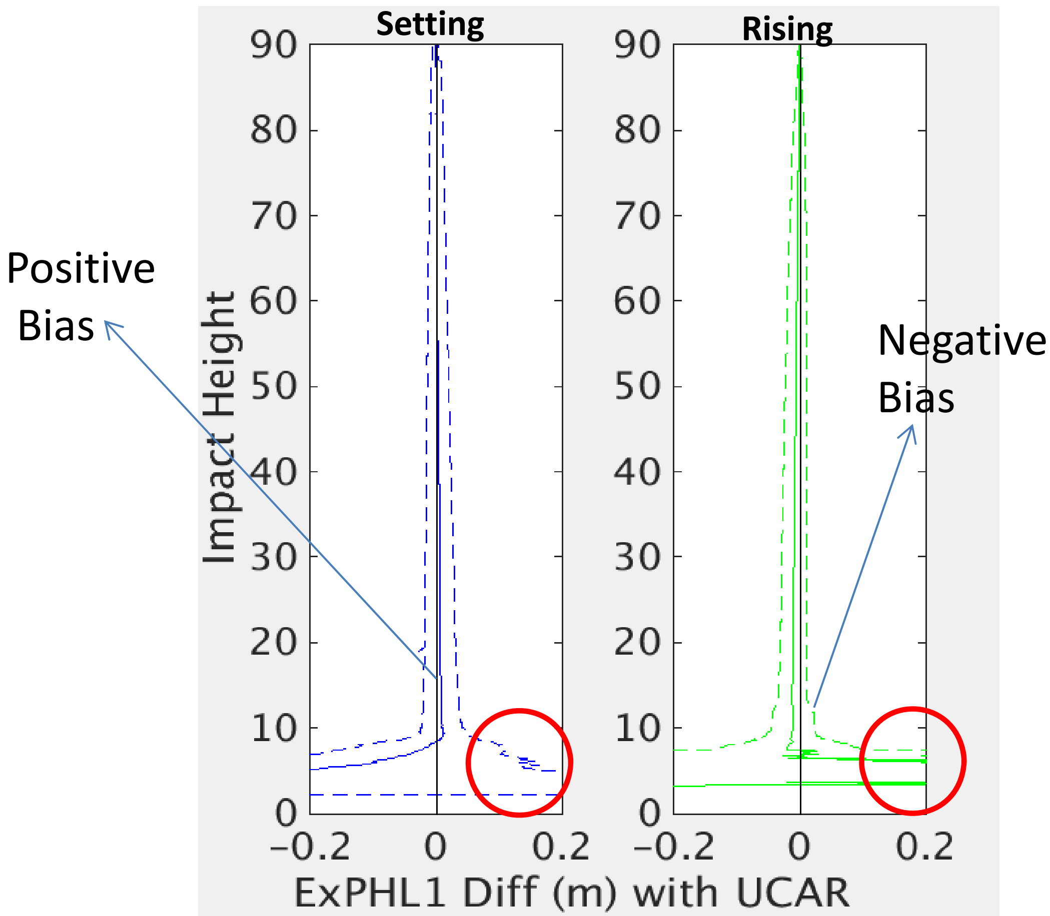
Receiver Clock Error Removal

- Receiver Single differencing Clock bias removal
  - 1HZ observation (POD) and 100Hz Observation(OCC)
  - Smoothing/filtering procedure.
  - Use the GPS satellites for differencing with high SNR values.
  - Slightly Different results using different GNSS satellites.
    - Atmospheric effects depending on the zenith angle
    - POD errors can take into effects
    - Mainly displays as excess phase trend.

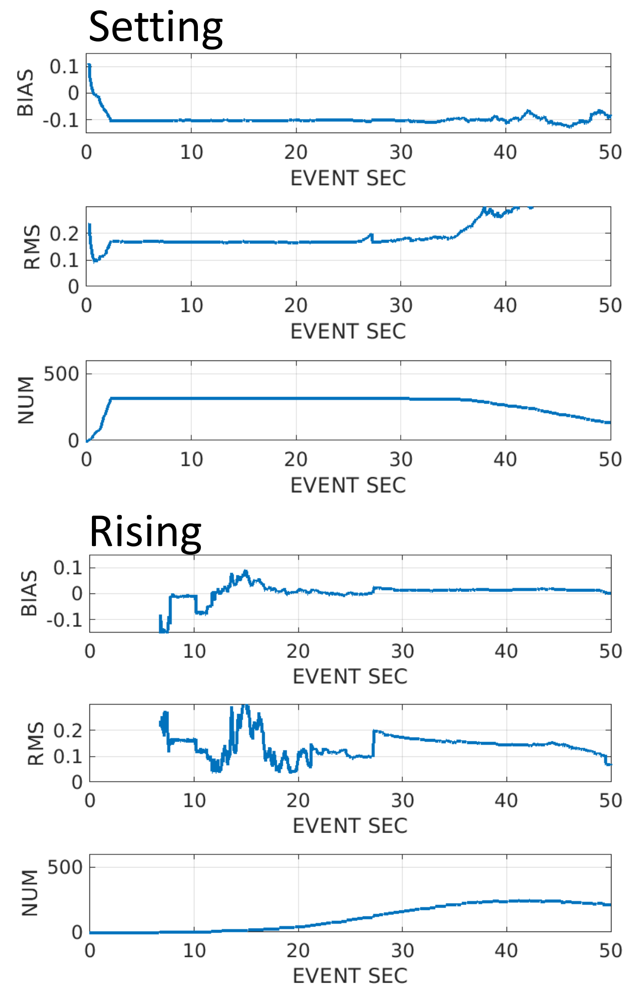




Excess Phase Comparison



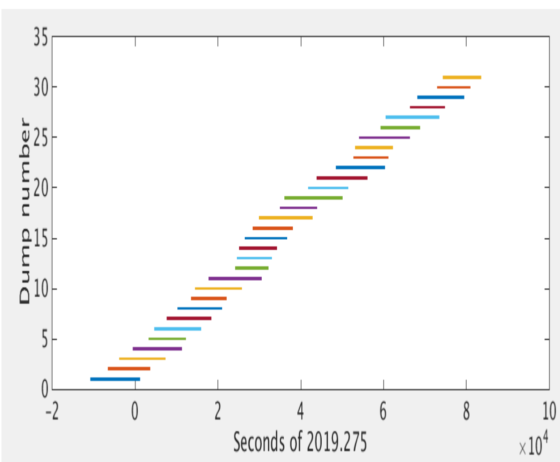
COSMIC-2 ExPhs Comparison with UCAR

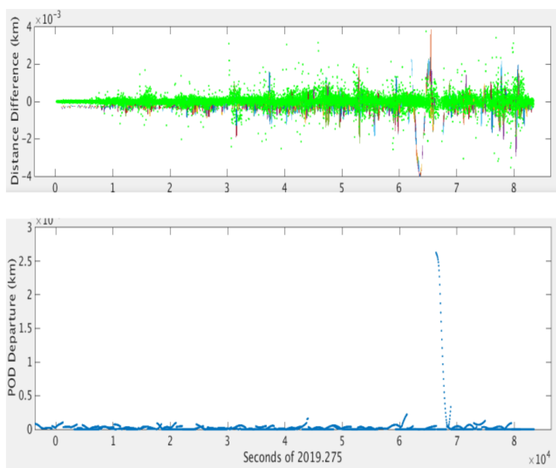


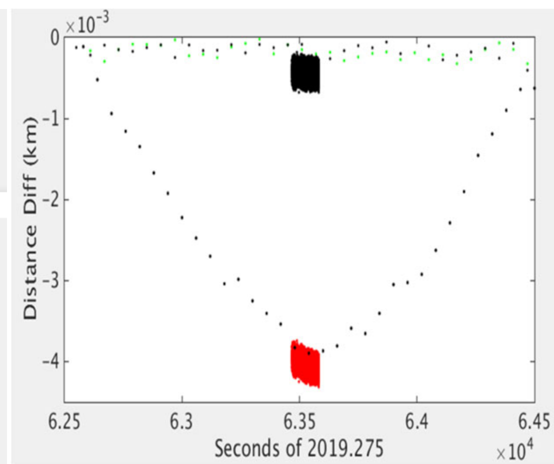
Metop-B ExPhs Comparison with UCAR

POD Solution Impact

- Multiple POD solutions from UCAR for different dumping segment (time)
- Overlap between POD epoch shows the POD differences.
- Using POD and OCC data from different dumping (but with same time range) can cause large departure from UCAR's Excess phase and bending angle profile. Also indicating the POD solution uncertainties.
- Necessity for reprocessing of POD using a longer time arc (such as one day observations).

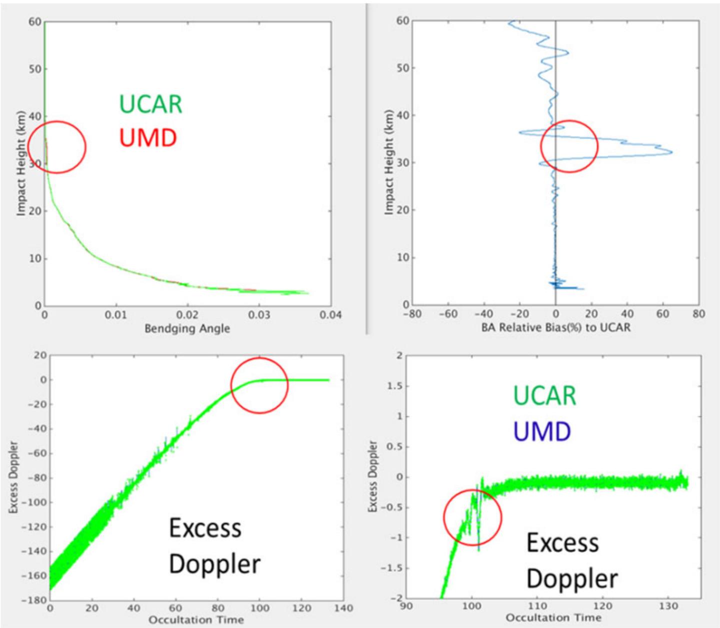






ROPP for Bending Angle

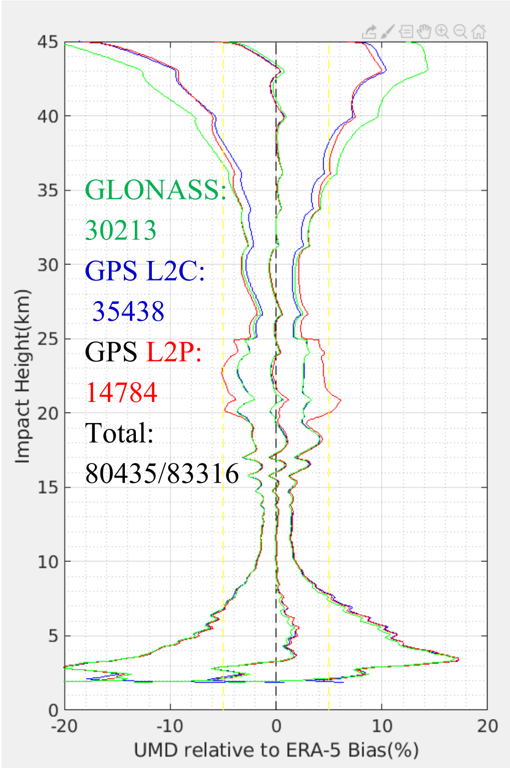
- Modified Radio Occultation Processing Package(ROPP) to accommodate COSMIC2 data
  - 100Hz data
  - GLONASS profiles
  - Mission names/data format.
- Important parameters:
  - Wave Optics below 25km
  - Vertical Resolution 100m
  - Excess Phase/BA smoothing
- Datasets
  - 6 satellites , Oct. 2019 for 30 days.
- Parallel computing
  - Distributed CPU based on daily process per LEO
  - Separate Excess Phase and Bending Angle Calculation

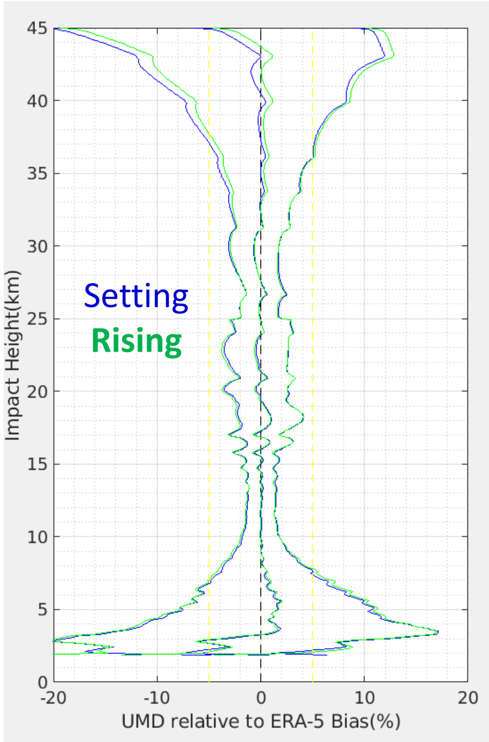


ROPP: Culverwell, et al., 2015

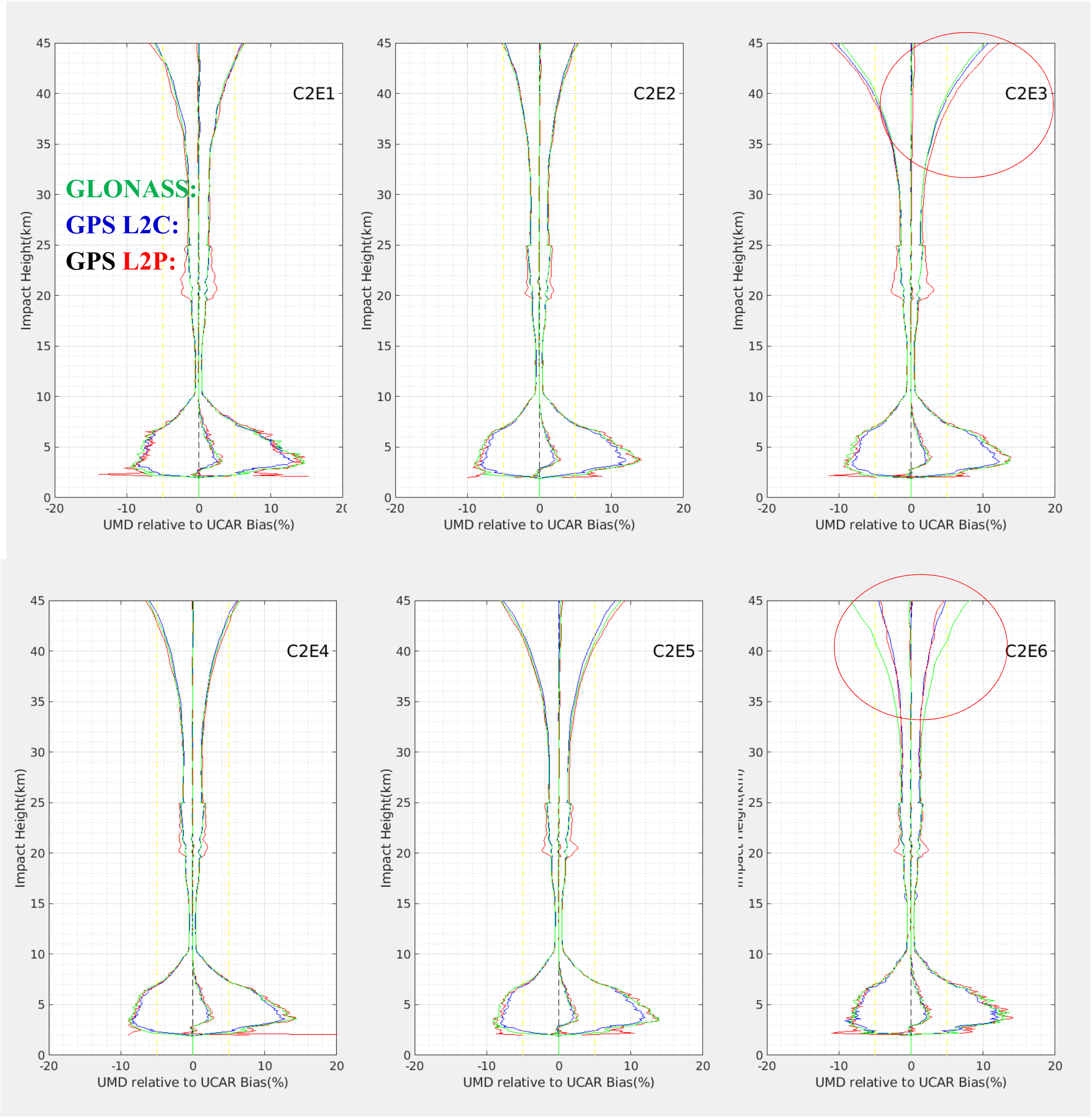
Bending Angle Compared with ERA-5

- ERA-5 data are used to derive background bending angle profiles for comparison.
- Simple QC
  - 15 sigma.
- Results:
  - Good agreement between 10-35km.
  - Larger STD above 35km and below 10km.
  - Consistent with other studies
    Shreiner et al. 2020; Cao et al. 2020;
  - Setting/Rising bias
    - Different POD solutions
    - Clock bias residual





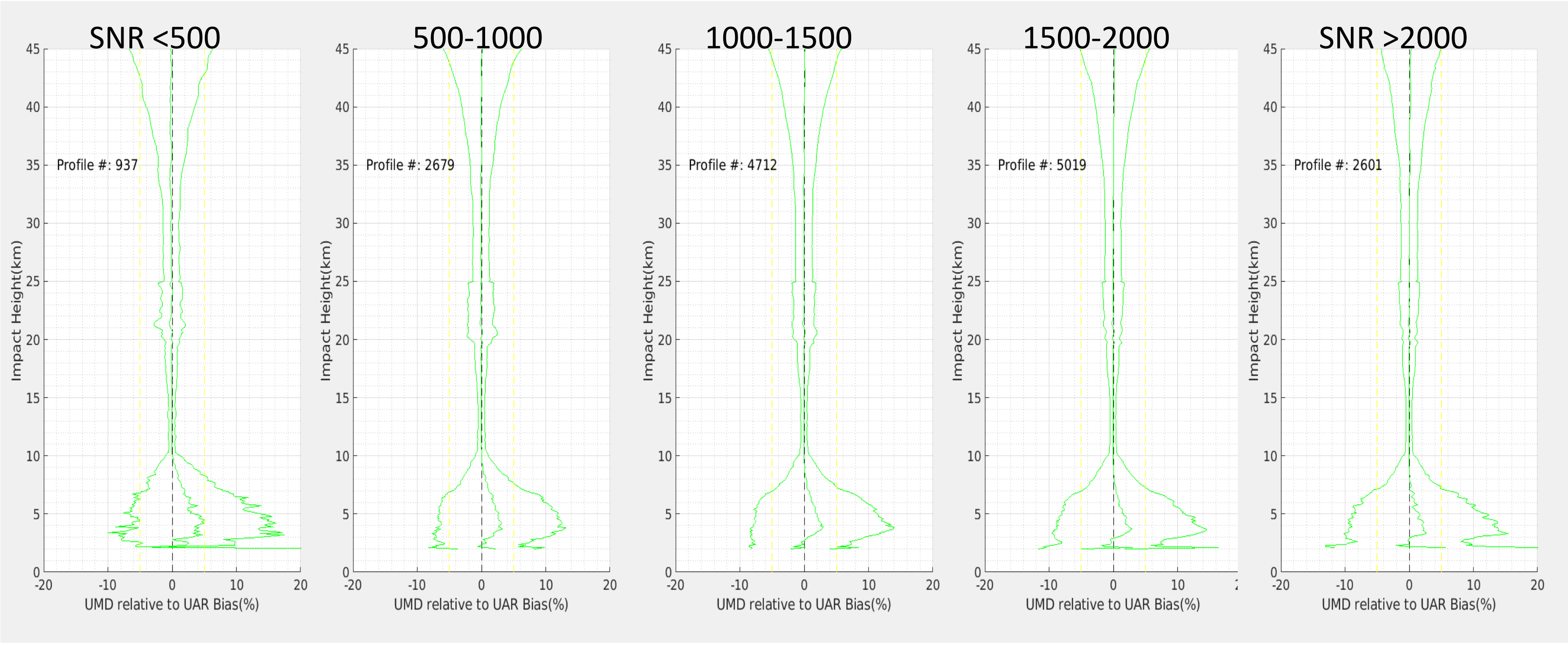
Bending Angle Compared with UCAR



- Simple QC flag
  - 15 Sigma for all levels
  - In addition to UCAR QC flag.
- C2E3 has larger STD
  - QC?.
  - Clock adjust
- General L2P problems.
- C2E6 large GLONASS errors
  - QC?
- Large STD/bias below 10km
  - Open–loop cycle slip vs excess phase model.
- Needs further investigation

SNR Effects on the Results

- L1 SNR at 80km is used to group bending angles for BA comparison with UCAR results (C2E1 only).
- Profiles with larger SNR values tend to more close to UCAR regarding the standard deviation in 20-25 km (GPS LC) and bias below 10 km.



Fractional Bending Angle Bias (with UCAR)

Summary

- We have developed package for converting carrier phase to bending angle for understanding the RO processing and Cal/Val.
  - Bernese + Matlab + Bash Script + ROPP
  - Tested one month datasets on Oct. 2019 for all six satellites.
  - Bending Angle results generally agree well between 10-35 km with UCAR and ERA-5 derived bending angle.
  - Standard deviation increases toward high altitude and surface below 10 km
  - SNR values at 80km are correlated to bending angle standard deviation.
  - The processing procedure helps us to understand the error sources in the bending angle profiles.
- Near Future work
  - Keep working on Bernese software for POD.
  - Resolve issues near surface (open loop phase model).
  - Reduce overall standard deviations with high rate GNSS clocks (ground).
  - Further improvement using ROPP;
  - Automate/Expand the work to CWDP, KOMPSAT-5 and other missions.

Acknowledgement

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