Error Assessments in the GNSS Radio Occultation Excess Phase/Bending Angle Calculation

Bin Zhang[1], Shu-peng Ho[2],Xi Shao[1] and Changyong Cao[2]

[1]CISESS/ESSIC, University of Maryland, College Park, USA

[2] NOAA/STAR, College Park, USA

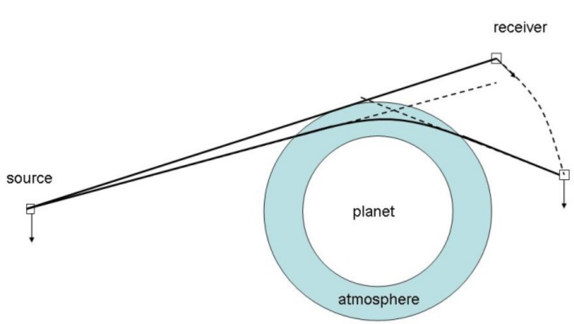
Nov. 12, 2019

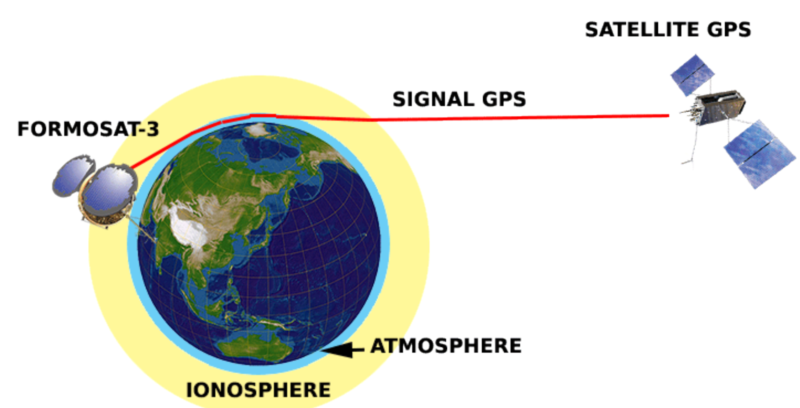
OUTLINE

- Introduction of GNSS Radio Occultation (RO)
- Global RO Profile Number monitoring in GDAS
- Recent COSMIC RO Data Quality issue
- RO Excess Phase Calculation
- RO Bending Angle Calculation
- Summary

What is radio Occultation

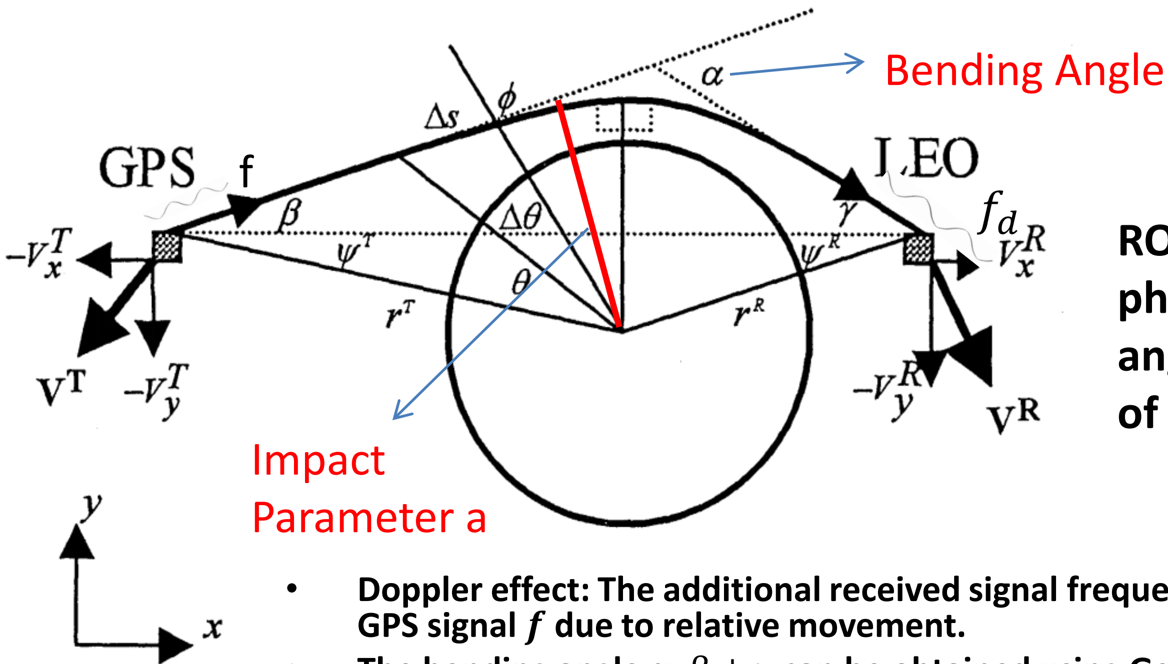
- **Radio occultation (RO)**
  - **a remote sensing technique used for measuring the physical properties of a planetary atmosphere or ring system.**
- **Atmospheric Radio Occultation**
  - **Atmospheric refractivity can change the path of a radio signal passing through.**
  - **Measuring a series of radio signal path changes can be used to derive the atmospheric refractivity index (related to temperature/humidity in troposphere or electron density in ionsphere).**
- **GNSS/GPS Radio Occultation**
  - **a type of radio occultation that relies on radio transmissions from GPS (Global Positioning System), or more generally from GNSS (Global Navigation Satellite System) satellites.**
  - **The technique involves a low-Earth orbit satellite receiving a signal from a GPS satellite. The signal has to pass through the atmosphere and gets refracted along the way**
  - **The relative position between the GPS satellite and the low-Earth orbit satellite changes over time, allowing for a vertical scanning of successive layers of the atmosphere for weather and climate study.**
  - **GPSRO observations can also be conducted from aircraft or on high mountaintops.**





https://en.wikipedia.org/wiki/Radio_occultation

How GNSS RO Works



RO: By measuring the wave phase change, the bending angle is derived as function of impact parameter.

- **Doppler effect: The additional received signal frequency f_d will be different from GPS signal f due to relative movement.**
- **The bending angle α=$\beta + \gamma$ can be obtained using Geometric Optical Method, following this two equations:**

$$f_d = \frac{1}{2\pi}\frac{ds}{dt}$$

S: Measured Wave phase

$$\left.\begin{aligned} f_d \;&=\; \frac{f}{c}(V_x^T(\cos\beta - 1) + V_y^T \sin\beta - \\ &\qquad V_x^R(\cos\gamma - 1) + V_y^R \sin\gamma), \\ r^T \sin(\beta + \Psi^T) &= \sin(\gamma + \Psi^R) = a \end{aligned}\right\}$$

Requires accurate Position and Velocity determination

with assumption: atmospheric spherically symmetric, single path propagation; good above UT.
For multiple path rays, Waver Optics methods are applied.

Healy, 2001

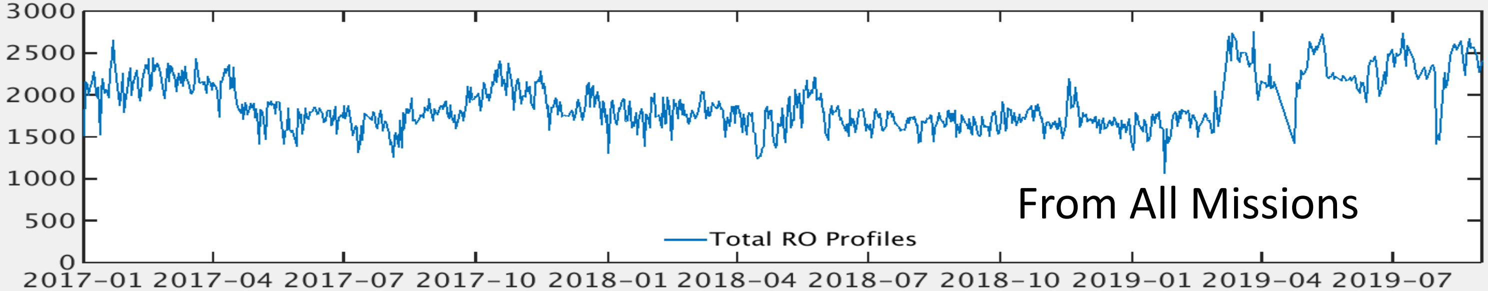
RO Observation Operationally Used in Numerical Weather Prediction

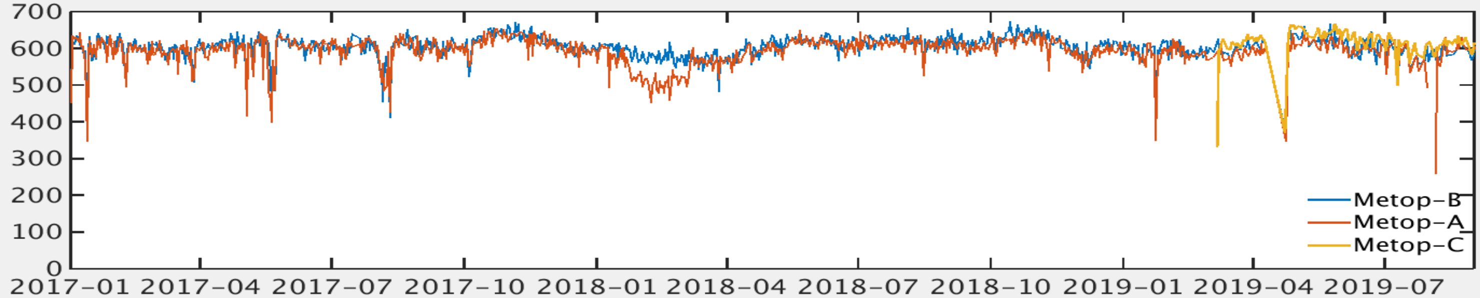
- RO derived bending angle/refractivity has been used in NWP as “bias anchor”, no need for bias correction before data assimilation.
  - Atmosphere refractivity is related to temperature and humidity
  - From bending angle and impact parameters, the refractivity can be derived under spherical assumption of atmosphere.
  - Proper design of forward operators in the NWP model can ingest the bending angle to inverse the refractivity, temperature or waver vapor profiles.
- RO observations have observation impact among top 5.
- RO data have fine vertical resolution (~100m).
- RO observations are relatively cheaper
  - GPS receivers mounted on the small satellites or legacy satellites.
  - Similar design as your car GPS receiver, but more channels
  - High rate data recording

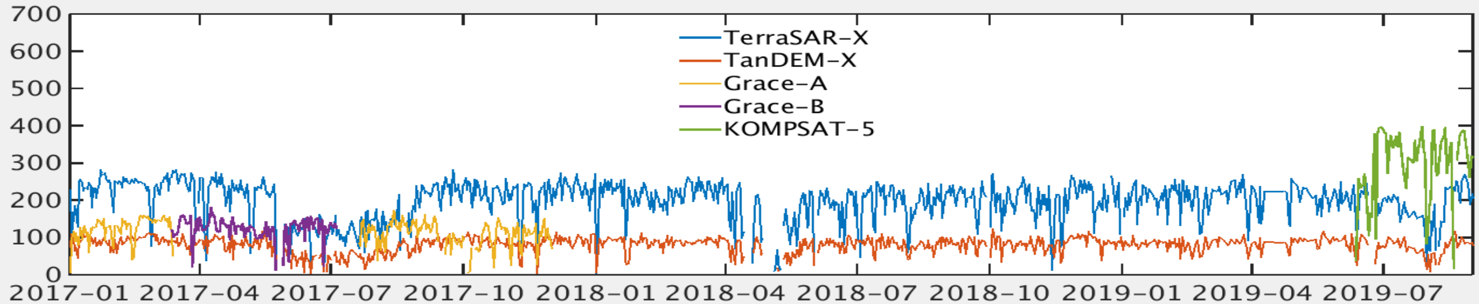
RO Missions and Receivers

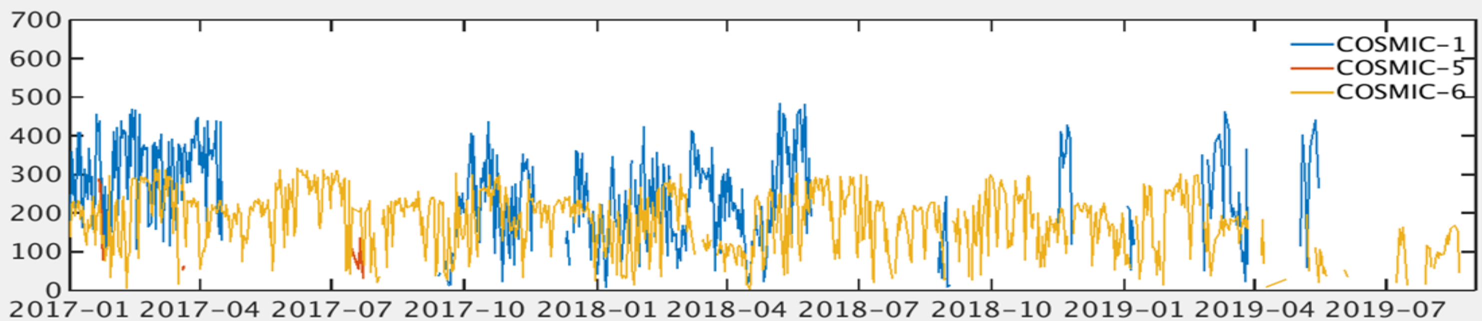
- Different GNSS missions with different GNSS RO Receivers
  - JPL BlackJak GPS receiver (CHAMP, GRACE).
  - IGOR/GOX on COSMIC, KOMPSAT-5
  - GRAS (MetOP), OMEGA4-G2(Novtel, Canada) PolarX2 (Septentrio, Belgium)
  - TriG (Tri-band GNSS Receiver, COSMIC-2), Polarimetric RO (PAZ)
  - Small SATs, Jason-CS, EPS-SG
- What information does the RO receiver provide?
  - High rate L1/L2 carrier phase Recording from occultation antenna.
    - 10-15 Hz for solving troposphere, 50Hz for COSMIC/KOMPSAT-5
  - Low rate data recording from POD antenna.
    - C/A pseudo range, L1/L2 carrier phases for orbit determination
  - GPS satellite broadcasting information (Position, clock)
  - LEO satellite navigation information (rough position, attitude)

Daily RO Profile Numbers into GDAS From 01/2017 to 09/2019



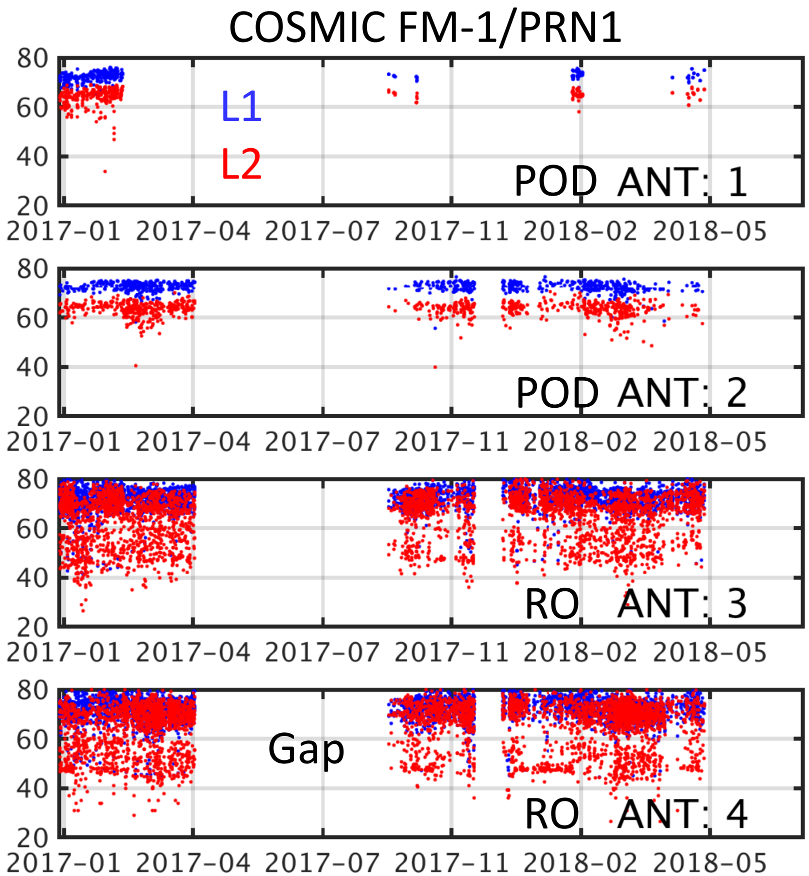


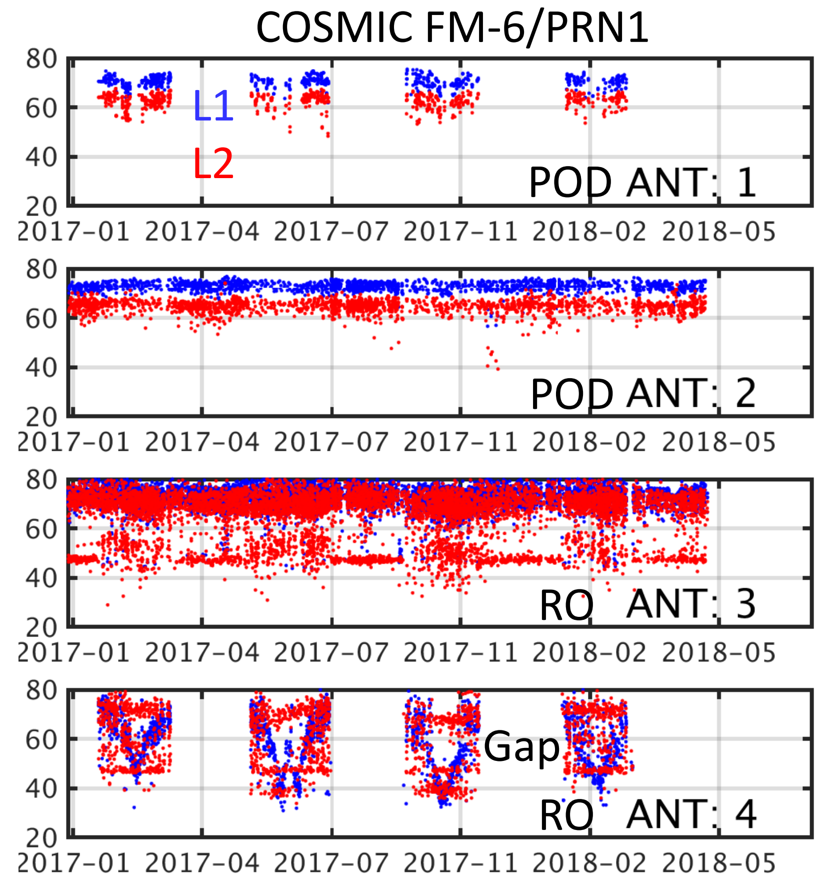


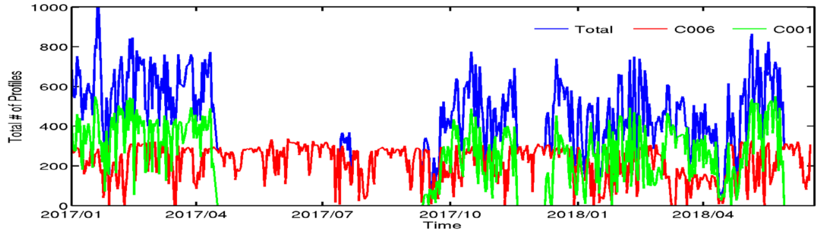


PAZ is not in GDAS yet

Antenna GPS Signal SNR monitoring

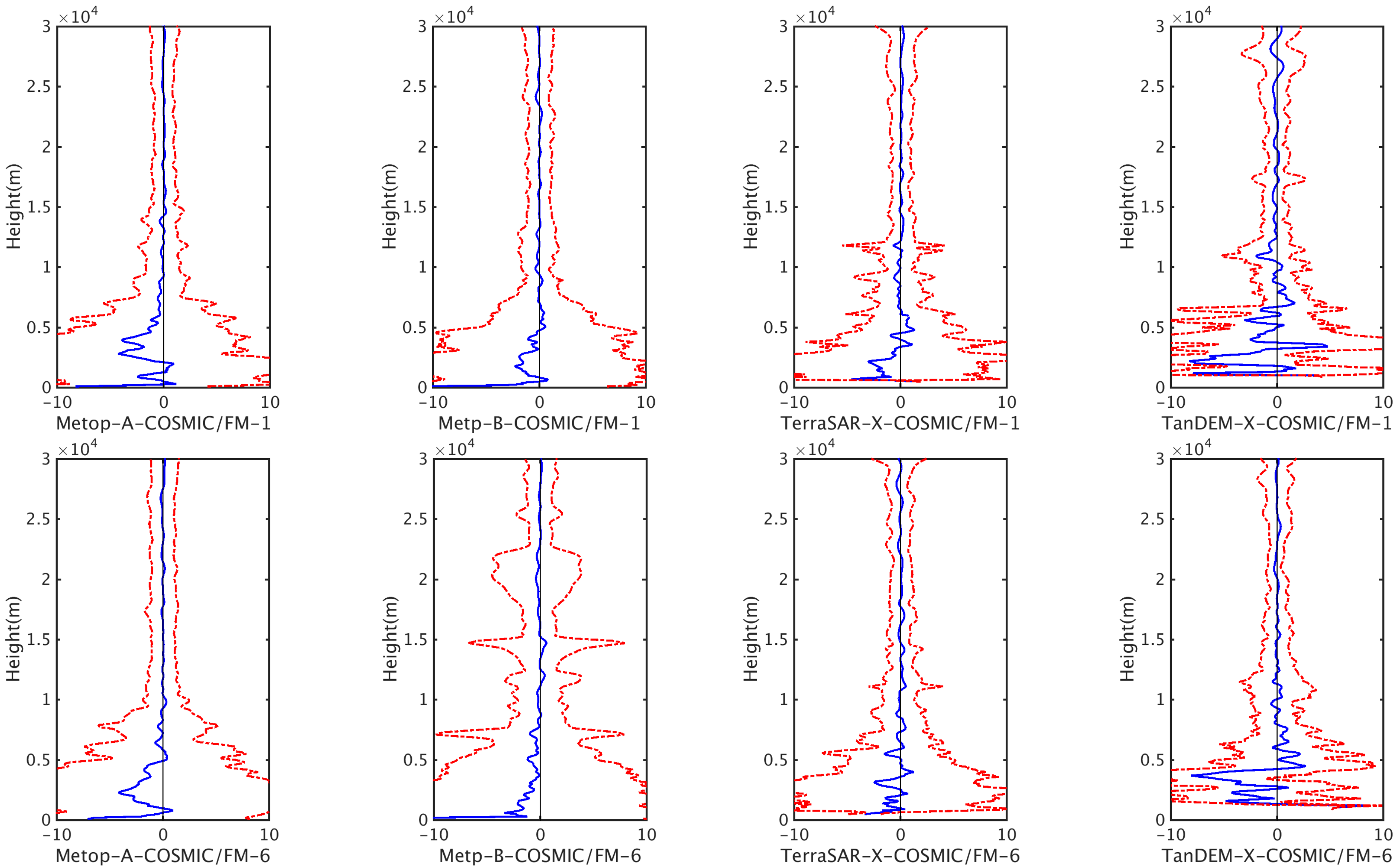






- Data from COSMIC opnGPS files, max SNR.
- Generally L1 has higher SNR than L2. FM-1 antenna SNR are ok, but sometime no data.
- FM-6 L1 SNR (ANT 4) has degradation (even below L2), only antenna ANT3 working normally

Bending Angle Difference (percent) between COSMIC and other RO Missions in GDAS

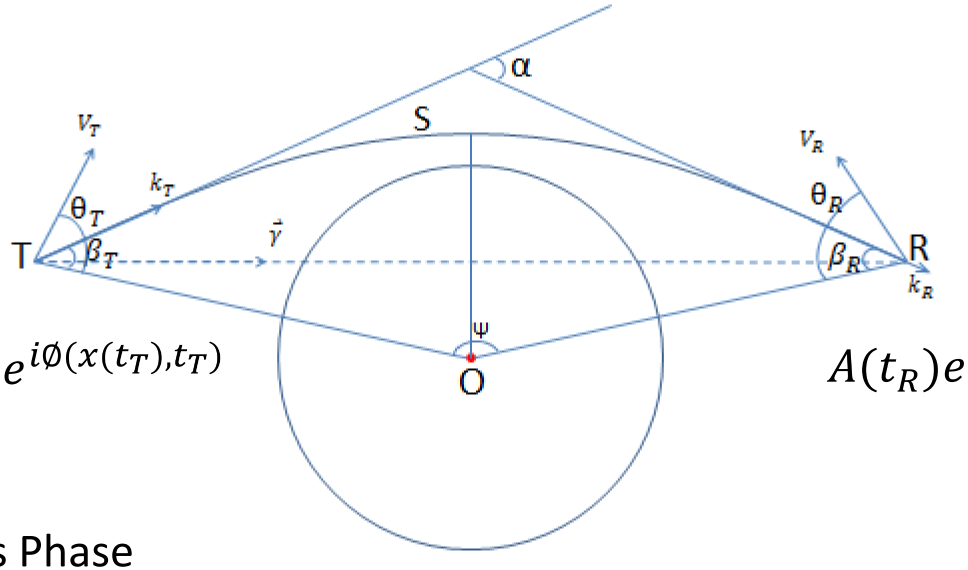


Percentage Difference between COSMIC FM-1(FM-6) and Other Satellites. Between height 10-30 km, mean BA difference <0.1%, oscillating between ±0.4% (metopA/B on the order of 0.02%, in a range ±0.2%). Negative bias (referred to COSMIC) exists below 5km but with larger uncertainty.

Research Goals

- NOAA/STAR recently launches Radio Occultation Cal/Val System for monitoring the quality of RO observation from different missions.
- One of the important issues is data quality check on various levels and understand its error source.
- The RO derived bending angle profiles from different processing centers/different missions always have bias.
- However, RO data processing from observations to Bending Angle are missing on site.
- This research is to establish the processing procedure from RO observations (carrier phase and time delay) to bending angle to understand different steps and identify possible error sources.

Explanation of Carrier Phase



$A(t_T)e^{i\emptyset(x(t_T),t_T)}$

$A(t_R)e^{i\emptyset(x(t_R),t_R)}$

Excess Phase

Full Phase

$$\Delta s = \int ndr - \overline{TR}$$

$$\boxed{\emptyset(x(t_R),t_R) - \emptyset(x(t_T),t_T) = S = \Delta s + \overline{TR}}$$

$$\emptyset(x(t_R),t_R) = \varphi + c\delta t_R + N_R(t_0)$$

$$\emptyset(x(t_T),t_T) = 2\pi f(t_T - t_1) + N_T(t_1) + c\delta t_T$$

$$\Delta s = \varphi - 2\pi f(t_T - t_1) + N_R(t_0) - N_T(t_1) + c\delta t_R - c\delta t_T - \overline{TR} + \varepsilon$$

Observed Carrier Phase Clock Corrections

Excess Doppler shift: $f_d = \frac{d\Delta s}{dt}$

$$f_d = \frac{f}{c}(V_T \cdot k_T - V_R \cdot k_R - (V_T - V_R) \cdot \vec{\gamma})$$

$$= \frac{f}{c}(v_T \cos(\theta_T - \beta_T) - v_R \cos(\theta_R - \beta_R) - (V_T - V_R) \cdot \vec{\gamma})$$

Only time derivative matters. Phase measurements needs locked.

Calculation of Excess Phase

Leo Clock Error

Range of GNSS/LEO

$$
\begin{aligned}
\mathrm{L1}_r^{\mathrm{s}}(t_{\mathrm{r}}) = {} & c \cdot \delta t_{\mathrm{r}}(t_{\mathrm{r}}) + c \cdot \delta t_{\mathrm{r,rel}}(t_{\mathrm{r}}) + \rho_{\mathrm{r}}^{\mathrm{s}}(t_{\mathrm{r}}) + \delta\rho_{\mathrm{r,rel}}^{\mathrm{s}}(t_{\mathrm{r}}) \\
& + c \cdot \delta t^{\mathrm{s}}\left(t_{\mathrm{r}} - \tau_{\mathrm{r}}^{\mathrm{s}}\right) + c \cdot \delta t_{\mathrm{rel}}^{\mathrm{s}}\left(t_{\mathrm{r}} - \tau_{\mathrm{r}}^{\mathrm{s}}\right) \\
& + \delta\rho_{\mathrm{r,ion}}^{\mathrm{s}}(t_{\mathrm{r}}) + \delta\rho_{\mathrm{r,trop}}^{\mathrm{s}}(\mathrm{t}_{\mathrm{r}}) + \lambda_1 \cdot N_{\mathrm{amb}} + \varepsilon
\end{aligned}
$$

Carrier Phase Measured

Relativity Effects

GNSS Clock Error

Excess Phase Wanted

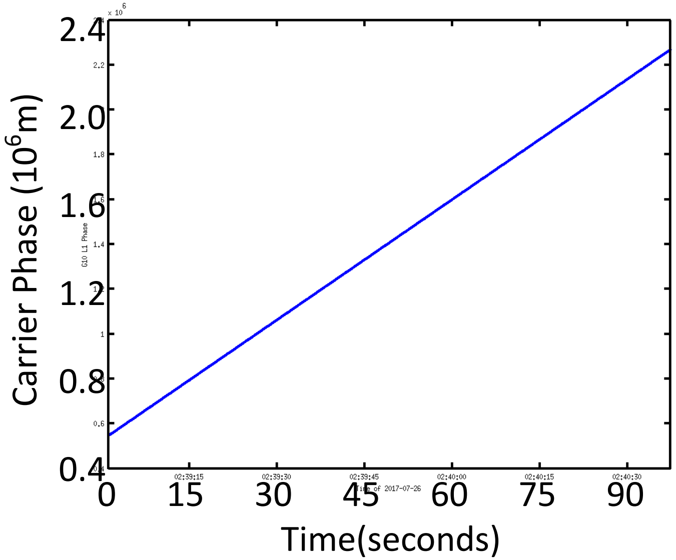
Phase Ambiguity

Dealing with Clock/time offsets:

- Zero Differencing (needs very stable clocks):
  Using GNSS and LEO satellite Clock offset
- Single Differencing (needs second antenna):
  Need second antenna to remove LEO clock error, noise increases
- Double differencing to remove GNSS clock error (needs multiple ground stations):
  Using ground station to remove GNSS clock error, noise increase

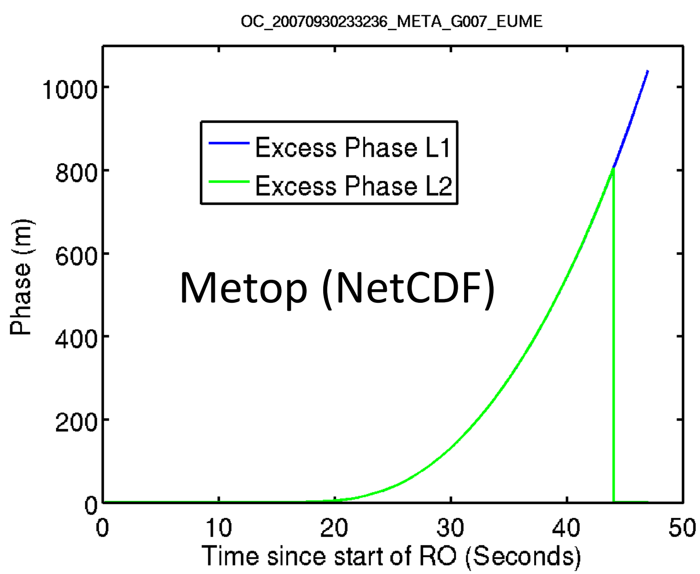
References: Schreiner et al., 2009

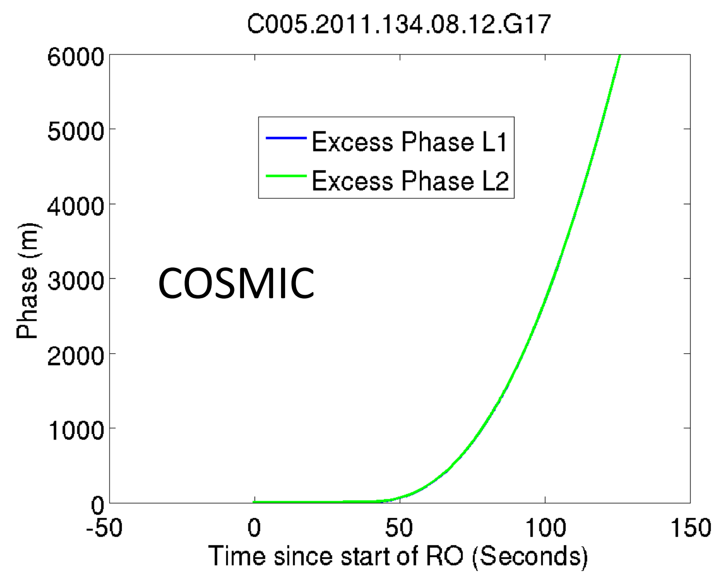
Excess Phase Example



Raw Measurements: Carrier Phase

Processed Excess Phase: path delay passing atmosphere as function of time

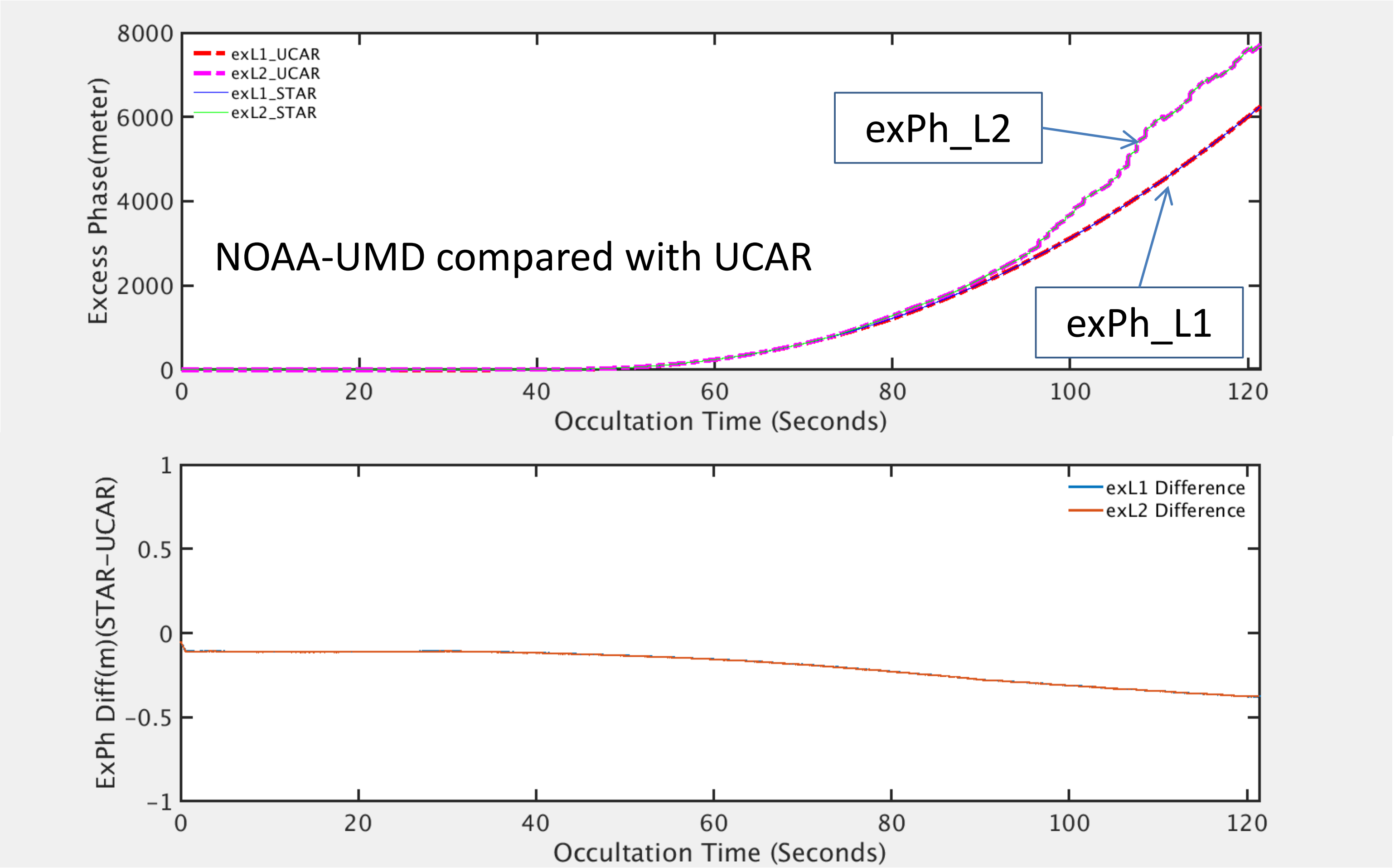




Error Sources in the excess Phase Model

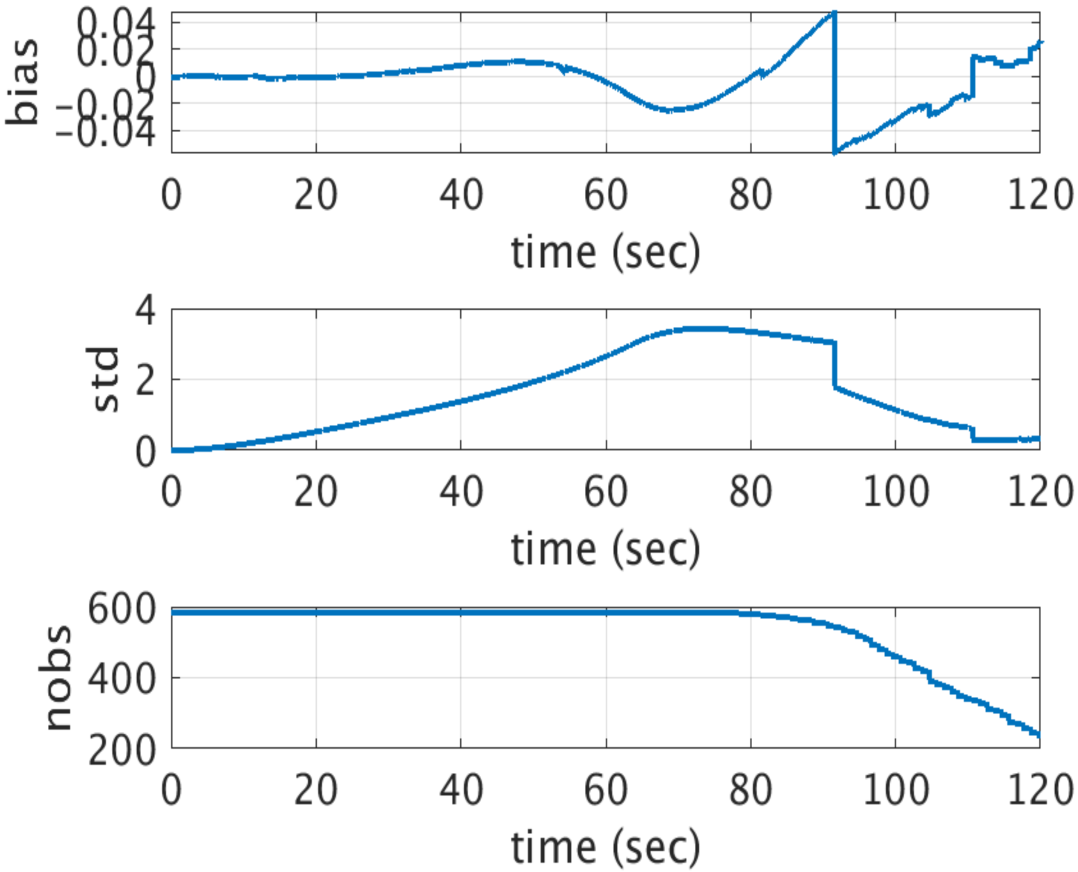
- Accuracy of Position and Velocity of the satellite (transmitting and receiving antenna).
  - Cosmic generally about 10cm level (post processing).
  - Metop-A/B 5 cm level
  - IGS GNSS Orbit Products
    - Final(2.5cm, ~two weeks delay), Rapid(3.5 cm, ~1-2 days), Ultra-rapid (5cm,3-9hours), broadcast (1m)
- GNSS/Leo satellite clock errors.
  - A few to hundred nano seconds, but very stable. (thinking of light speed).
  - Can affect the accurate determination of position/velocity
- Cycle slips in the time series, especially near surface
  - GPS signals are waves, the phase can be determined using replica oscillator on-board GPS receiver.
  - Using navigation bit series, time series demodulation and open-loop phase model
- Coordinate transformation Errors
  - Attitude error, ECEF/ECI transformation inconsistency
- Excess Phase Model
  - L1/L2 time series noise level
  - Numerical Scheme/Round off errors
  - L1/L2 ionosphere delay correction

Calculation of Excess Phase (Example)



Calculated Excess Phase agrees well (<0.5m) with UCAR!
(Example: COSMIC-C001, G18, 2015-06-01 00: 02
Using Single differencing with reference link: G21)

Excess Phase Difference Statistics



- UCAR 637
- UMD 612
- 588 in common
- 9 outlier profiles

Although the mean bias is small, the standard deviation is still a bit bigger. Further improvements are needed. Errors can be from different sources: clock error, interpolation algorithm, position/vel errors, model errors, round off errors, coordinate conversions.

From Excess Phase to Bending Angle

What matters from observation

- Excess Doppler Shift
  - L1/L2 excess phase
  - Time derivative
  - Open loop/close loop
- SNR
  - Quality
- LEO/GNSS position/velocity
  - Antenna pos/vel

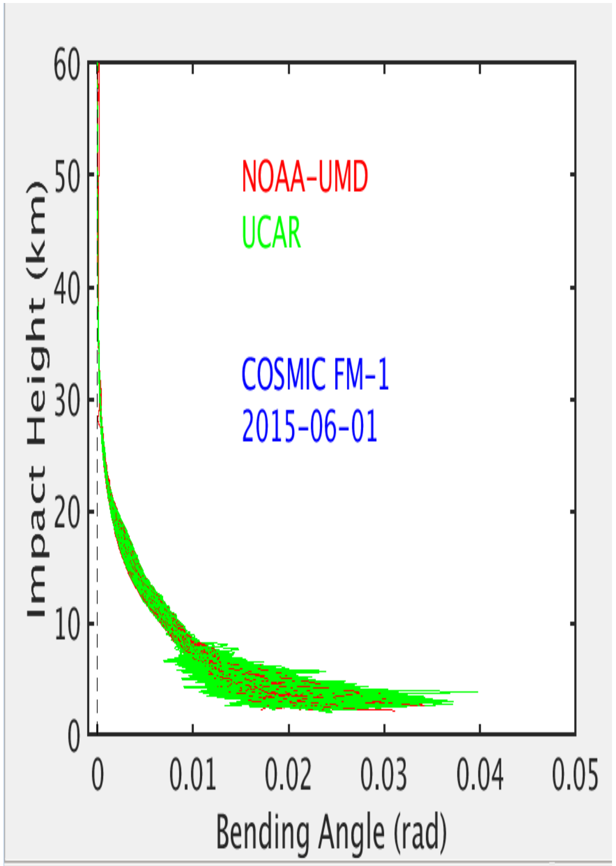
What matters in the inversion

- Geometric optical determination
  - Single path assumption
  - parameterization
- Wave optical determination
  - Atmospheric Multiple path
  - Open loop
  - From [time, phase] space to [bending angle, Height] space
  - parameterization

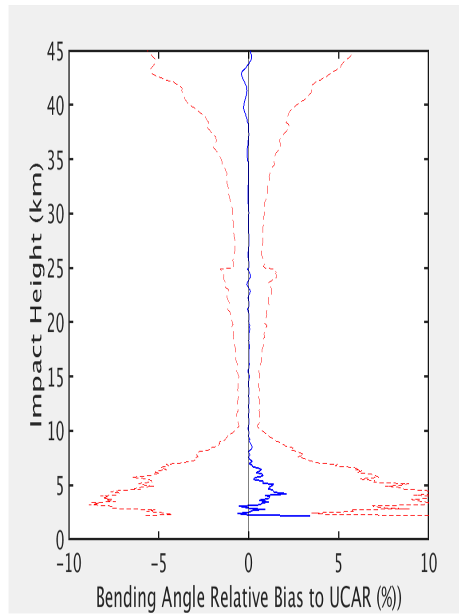
Radio Occultation Processing **Package** (ROPP, Culverwell et al., 2015) has been used in testing.

- Errors Propagation from Excess Phase/Pos/Vel to Bending Angle
- Spherical symmetric assumption
- L1/L2 ionosphere correction (first order approximation)
- ECI coordinate transformation from ECEF (more artificial mistakes), Geolocation mismatch.
- Wave optics inversion algorithm(s) CT2 versus Full Spectrum Inversion
- Atmosphere multiple path effects
  - SNR cut off arbitrary

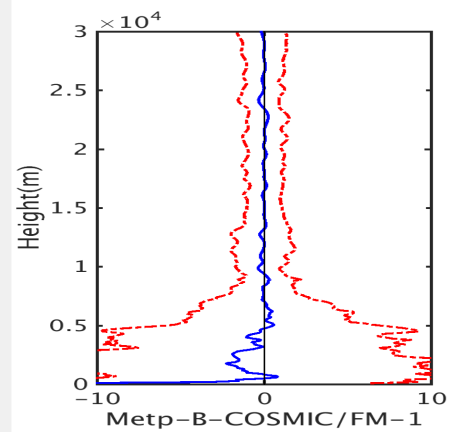
Bending Angle Comparison



Bending Angle Profiles Comparison (UMD vs UCAR)



NOAA-UMD/ROPP compared with UCAR



Metop-B compared with COSMIC in GDAS

Results are good but need improvements!

Summary

- We have demonstrated the capability of processing of Radio Occultation observations from low level to bending angle, which mainly serve for better Cal/Val activities at NOAA for COSMIS-2, CWDP and KOMPSAT-5 as well as future missions.
- Though RO observations are 'bias anchor' for NWP model. However, products from different centers do have inter-mission, inter-center bias, especially on the lower troposphere. Only through understanding the processing procedure, we can understand the causes of the differences.
- These bias could be related to the following sources:
  - Position/velocity inaccuracy, attitude errors
  - Antenna offset /phase center specification
  - Cycle slip detection (esp. in the open loop stage).
  - Clock error from both Leo and GNSS satellites
  - Interpolation schemes, coordinate conversion
  - Operational versus reprocessing
    - Different accuracy in the IGS GNSS Orbit products, Earth Orientation Products
    - Not enough observations for accurate representation of the satellite orbits.
  - Each error term is evaluated in the processing procedure.