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

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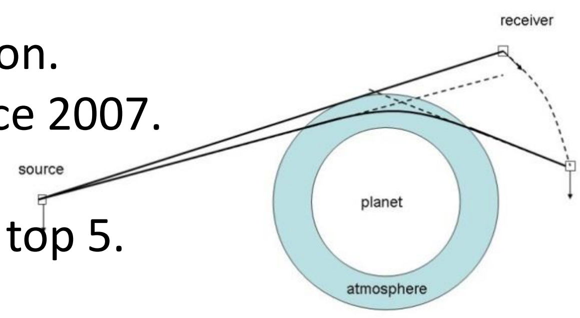
OUTLINE

- Radio Occultation background and research goal
- RO Excess Phase Calculation and error quantification
- RO Bending Angle Experiments using ROPP
- Summary

GNSS Radio Occultation Introduction

- GNSS RO Receivers
  - Slim designed, can be on the small satellites or legacy satellites.
  - Similar to car GPS receiver, with more bands (L1/L2 etc) and stable clocks.
  - Multiple receivers (POD (zenith view) vs. OCC (limb view))
  - Record GNSS Microwave signal phase and time delay.
- Radio Occultation Technique
  - Derive the GNSS signal path delay, the excess phase.
  - Derive the bending angle of the ray path
  - Inverse the atmosphere refractivity, temperature and water vapor
- RO derived bending angle/refractivity has been used in NWP as "bias anchor"
  - no need for bias correction before data assimilation.
  - COSMIC-1 data has been assimilated into GFS since 2007.
  - RO data have fine vertical resolution (~100m).
  - RO observations have observation impact among top 5.

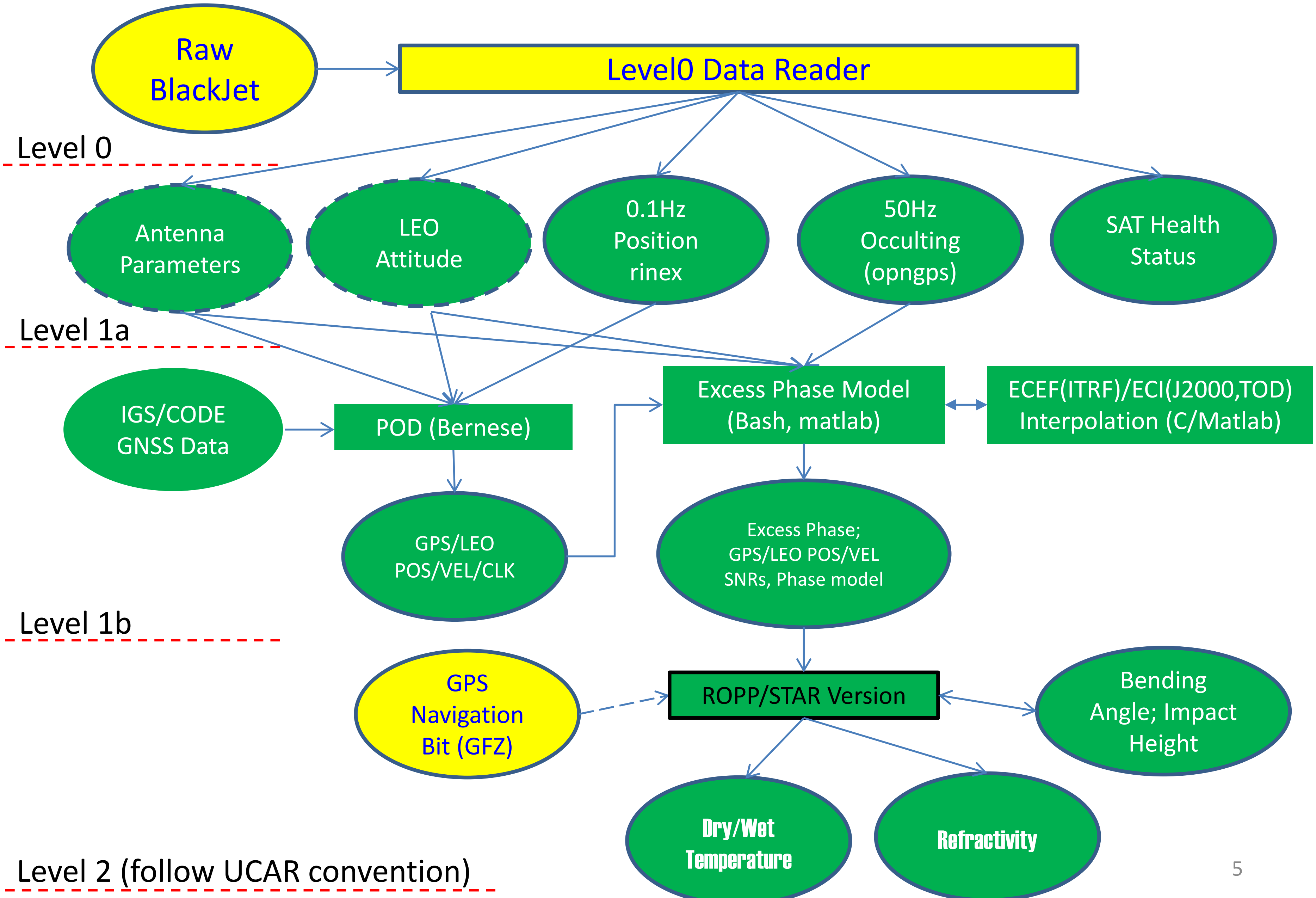


https://en.wikipedia.org/wiki/Radio_occultation

Research Goals

- NOAA/STAR recently developed RO Cal/Val System for monitoring the quality of data products for COSMIC-2, Metop-C and other RO missions.
- One of the important issues in data quality check is to understand the error sources in the data processing of different levels.
  - The RO derived bending angle profiles often have bias from different processing centers/different missions.
- RO data processing from raw observations to Bending Angle is a new capability that needs to be developed onsite.
- 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 reprocess the COSMIC-1 data and compare with UCAR results.

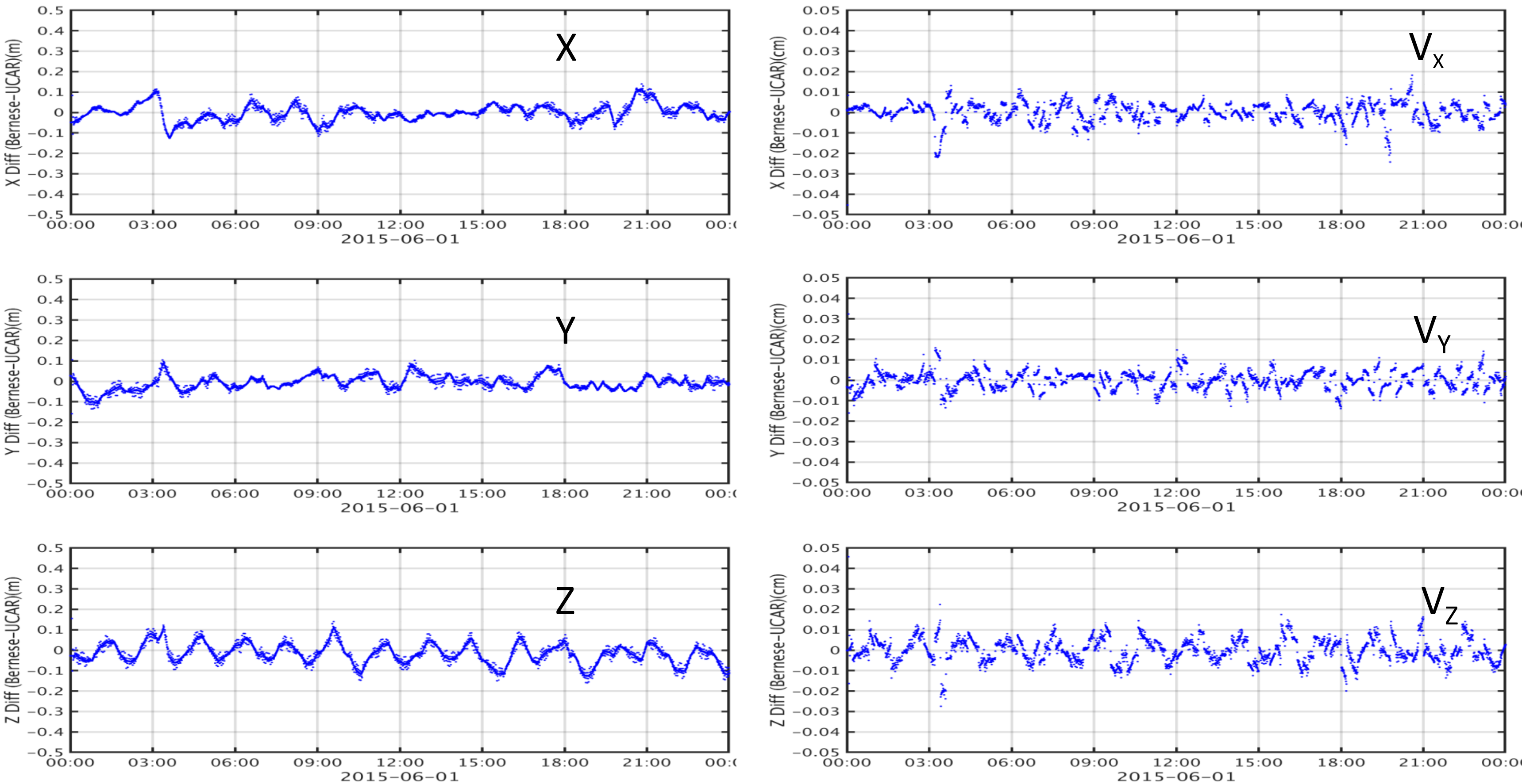
RO Processing Procedure with COSMIC-1 data



POD Error Quantification

- LEO Precise Orbit Determination is different from objects on ground
  - More affected by gravity anomaly than MEO satellites
  - Can not achieve high accuracy from kinematic solution
  - LEO mass center orbit determination needs (reduced) dynamic models for least square analysis.
  - Differencing with ground station receivers are more accurate but very computational cost.
  - Attitude control may introduce errors
- Bernese Software Configuration (test for COSMIC-1)
  - Antenna parameters are needed.
    - Offsets, PCVs, Boresight Vector etc (Cheinway Huang et al. 2009)
  - RINEX Observation files and attitude files (from UCAR/CDAAC)
  - IGS GNSS Orbit and Clock solution, Earth Orientation
- POD results
  - LEO mass center X/Y/Z in ECEF coordinates
  - 30 seconds (or high resolution) LEO/GNSS clock errors.

Bernese Output POD Compared with UCAR (COSMIC/FM-1)



- LEO POD X/Y/Z difference generally with 10cm difference, as LEO POD requirements for COSMIC is 10 cm.
- X/Y/Z Velocity difference generally within 0.1mm/s difference, as LEO POD Velocity uncertainty requirements: 0.1mm/s in 3D rms.

Calculation of Excess Phase

Leo Clock Error

Range of GNSS/LEO

$$\mathrm{L1}_r^{\mathrm{s}}(t_{\mathrm{r}}) = c \cdot \delta t_{\mathrm{r}}(t_{\mathrm{r}}) + c \cdot \delta t_{\mathrm{r,rel}}(t_{\mathrm{r}}) + \rho_{\mathrm{r}}^{\mathrm{s}}(t_{\mathrm{r}}) + \delta\rho_{\mathrm{r,rel}}^{\mathrm{s}}(t_{\mathrm{r}}) + c \cdot \delta t^{\mathrm{s}}(t_{\mathrm{r}} - \tau_{\mathrm{r}}^{\mathrm{s}}) + c \cdot \delta t_{\mathrm{rel}}^{\mathrm{s}}(t_{\mathrm{r}} - \tau_{\mathrm{r}}^{\mathrm{s}}) + \delta\rho_{\mathrm{r,ion}}^{\mathrm{s}}(t_{\mathrm{r}}) + \delta\rho_{\mathrm{r,trop}}^{\mathrm{s}}(\mathrm{t_r}) + \lambda_1 \cdot N_{\mathrm{amb}} + \varepsilon$$

Carrier Phase Measured

Relativity Effects

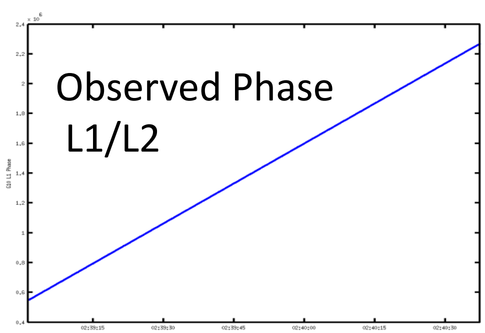
Schreiner et al., 2009

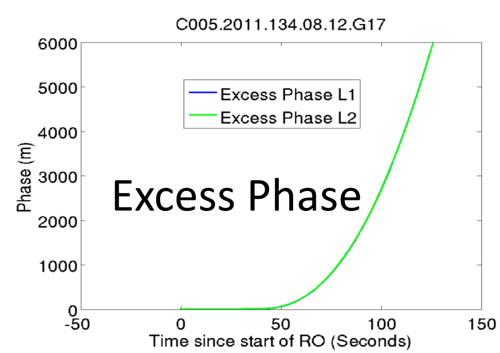
GNSS Clock Error

Excess Phase Wanted

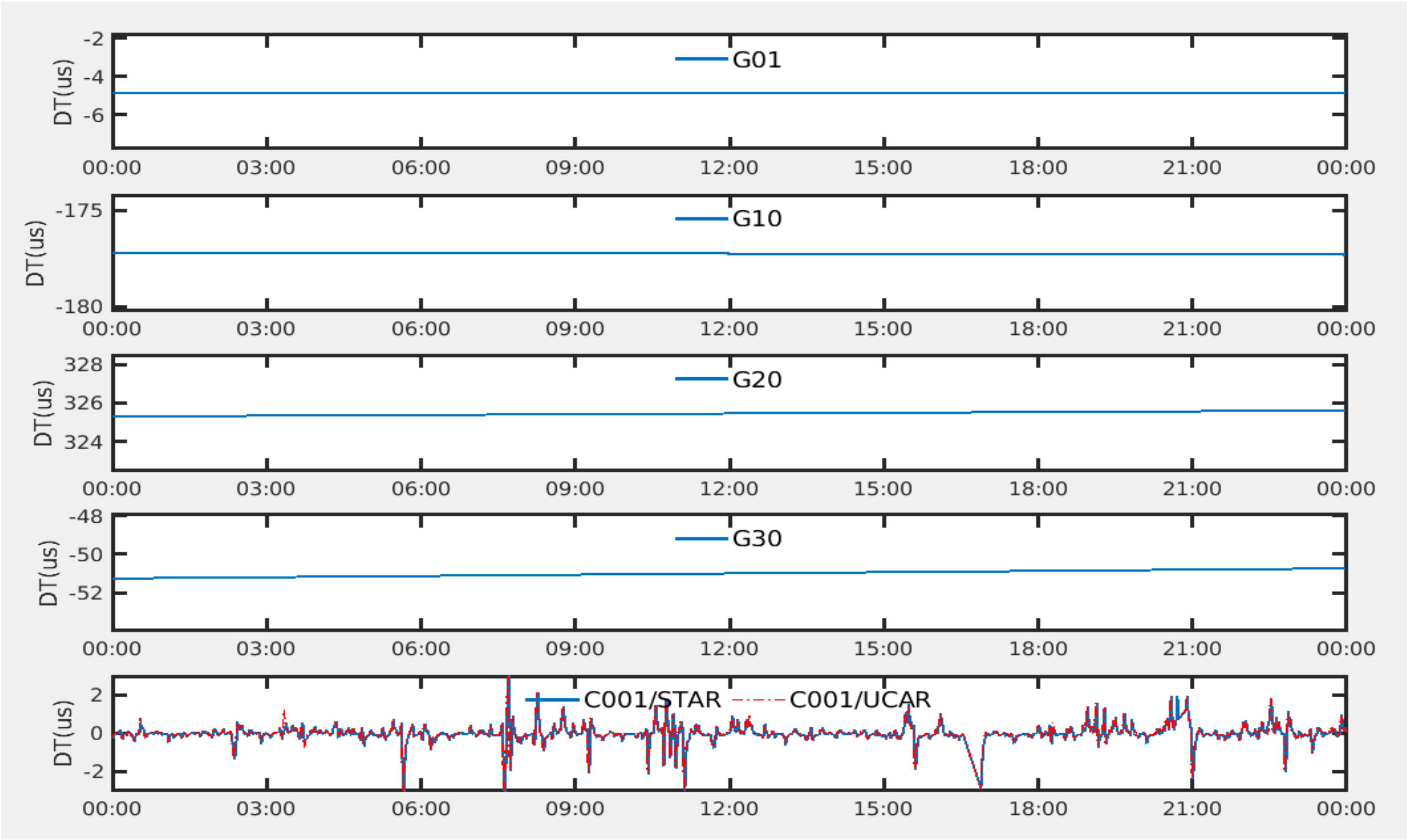
Phase Ambiguity

- Only time derivatives matter, constant offset has no effects!
- Error orders (large fluctuation to small changing during one occ events ~2 minutes).
  - LEO CLK Error >GNSS CLK ERROR >Range ERROR >Relativity Effects>Phase windup >other errors. Cycle slips can be removed using model or GPS bits.





GNSS and LEO Clock Error



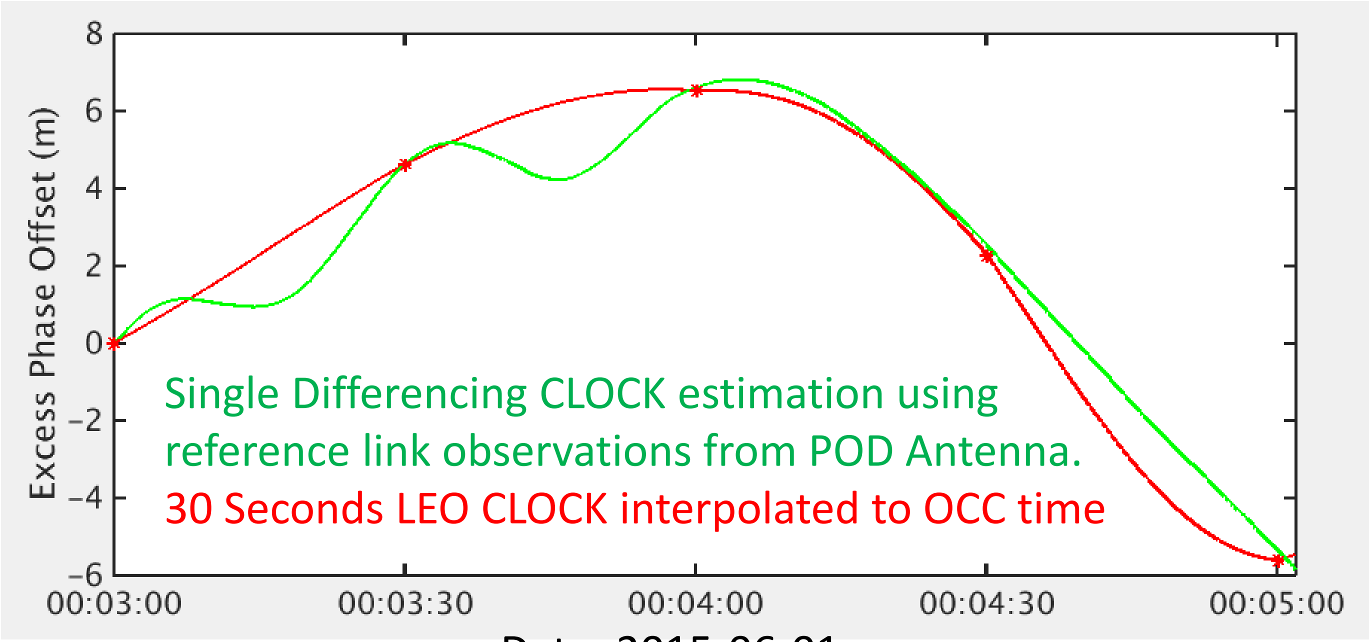
- GPS Clock
  - Using CODE 30 seconds product
  - Some GPS satellite bias may be large (0.5 ms), but relatively stable (<1us/day)
  - Zero differencing requires high rate clocks.
  - C*ΔT.

High rate estimation need ground stations.

- LEO Clock
  - Bernese Final Solution
  - Bias <1us, but not as stable as GPS
  - Interpolation problem.
  - -C*ΔT (significant effects on excess phase)

Single differencing is needed.

LEO Clock Error
(Zero versus Single Differencing)



Date: 2015-06-01

- Clock data out of Bernese usually with more than 1 second intervals.
- High rate observations on OCC requires interpolation for zero differencing.
- High rate reference link in POD antenna is necessary if the clock is not stable: interpolation errors can be large.

Antenna Offset and Phase Center Variations

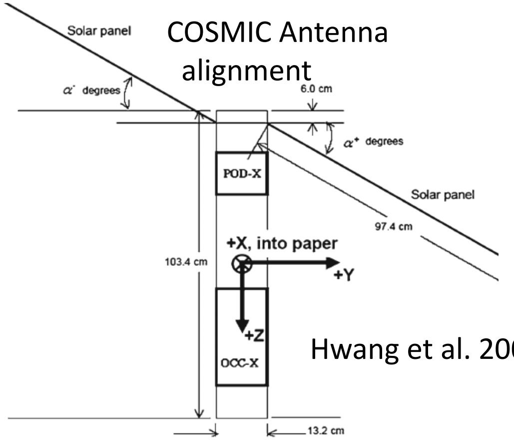
$$\rho_r^s = \sqrt{(x^s(t^s) - x^r(t^r))^2 + (y^s(t^s) - y^r(t^r))^2 + (z^s(t^s) - z^r(t^r))^2}$$

transmitter and receiver distance.
Different from mass center distance

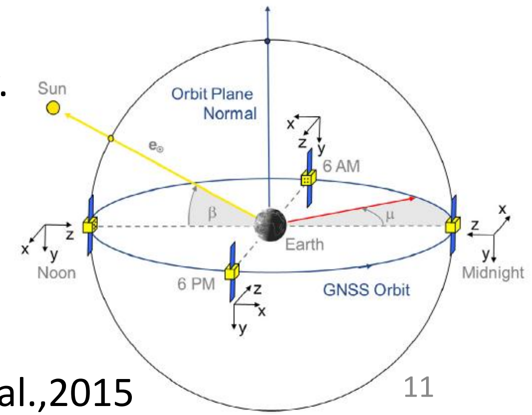
Transmittance time Can be determined
Only affect distance in this term!

- LEO Antenna Offsets and Antenna Phase center variation
  - Offset prelaunch determined. PCVs can update after launch.
  - Error can be present with Coordinate conversion (attitude).
  - Uncertainty can be more than few centimeter level from PCVs.
- GNSS Antenna Offsets/Phase Center Variations
  - Broadcast by IGS, can be on the order of 2m.
  - GNSS attitude control
    - Orbit normal mode (ON) vs Yaw Steering mode
    - Attitude can be obtained from Sun, Earth and LEO vectors.
    - GNSS antenna pointing to earth, but not to satellite directly.
    - GPS/GLONASS/Galileo/Beidou difference
- GNSS Antenna Phase Wind-up
  - Can be centimeter level due to
    Antenna rotating from attitude control.

COSMIC Antenna alignment

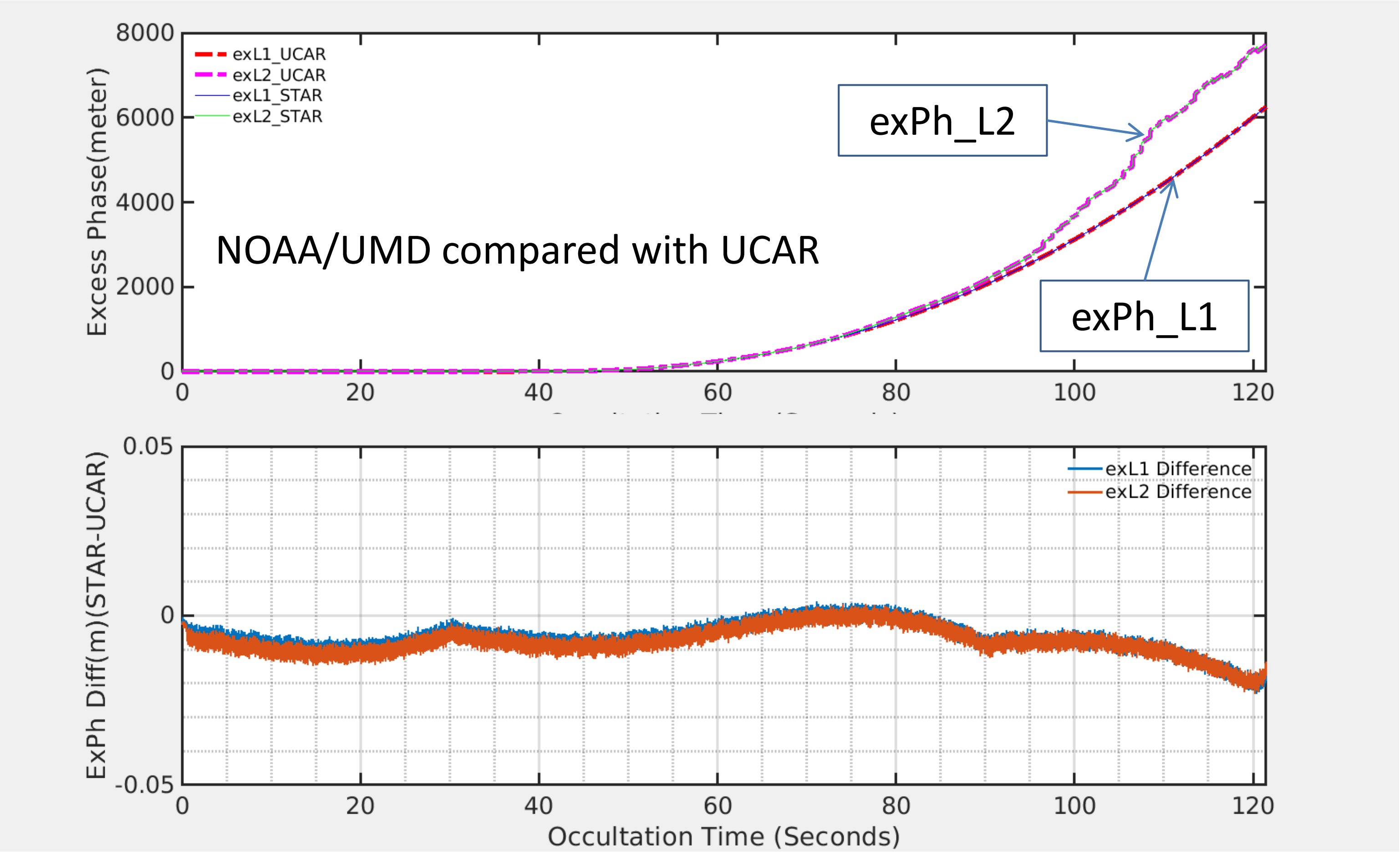


Hwang et al. 2009



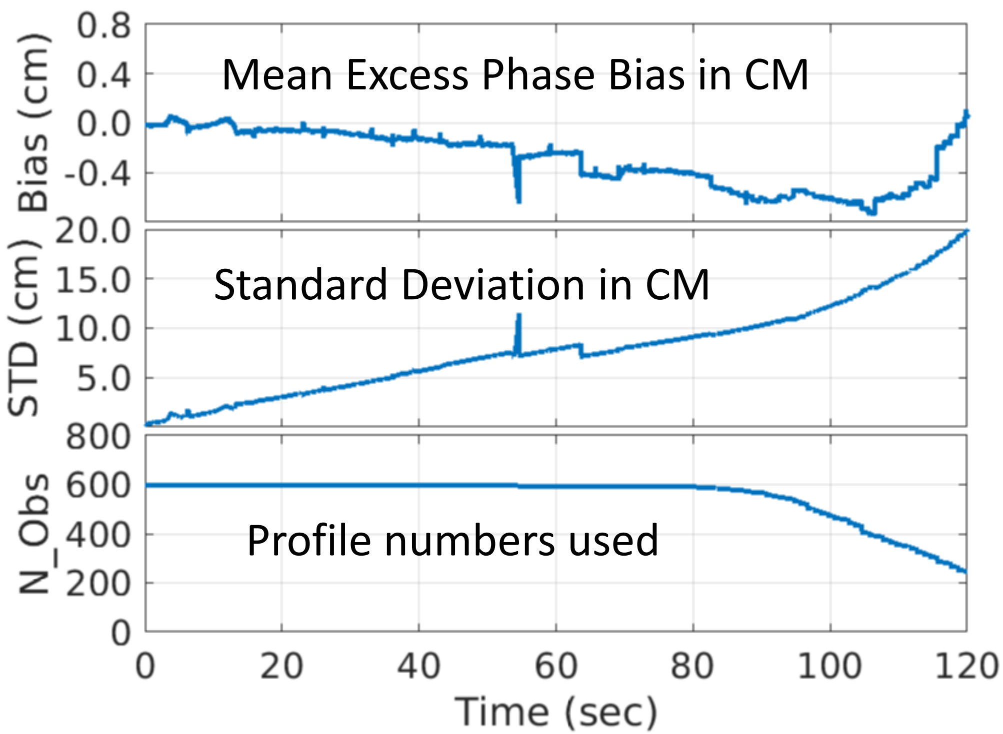
Montenbruck et. al.,2015

Calculation of Excess Phase (Example)



Calculated Excess Phase agrees well (<2cm) 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 613
- 598 in common
- 15 outlier profiles

The mean bias is small less than 0.5cm, the standard deviation is less than 20cm. Errors can be from different sources: clock error (low resolution GNSS CLK), interpolation algorithm, position/vel errors, model errors, round off errors, coordinate conversions.

No cycle-slip detection has been applied!
Cycle slip detection are done in ROPP before Bending Angle calculation.

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

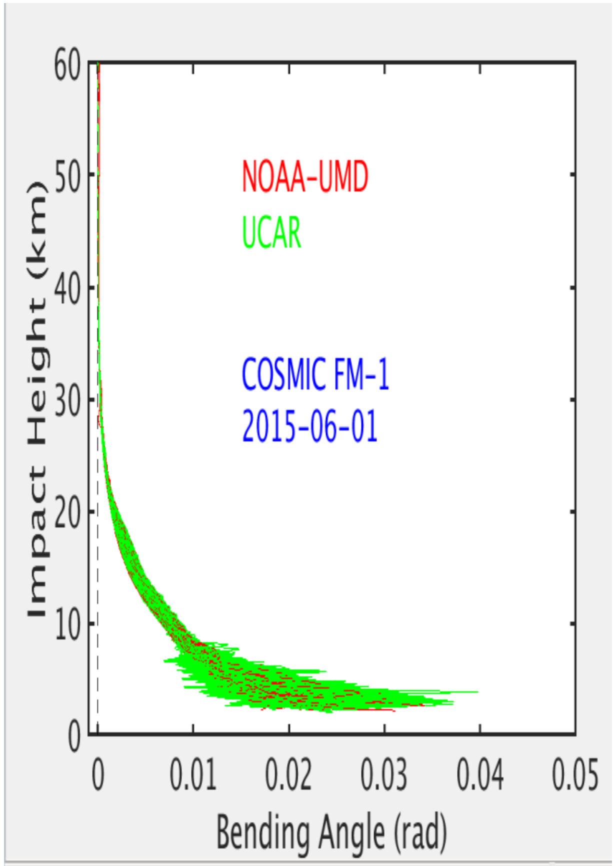
What matters in the inversion

- 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

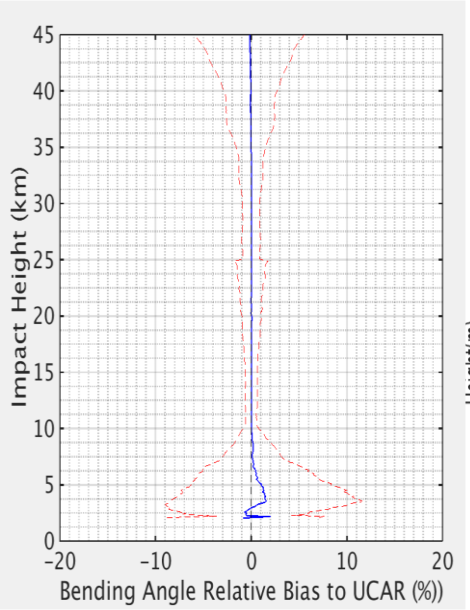
Radio Occultation Processing **Package** (ROPP, Culverwell et al., 2015) has been used in testing.

- Errors Propagation from Excess Phase/Pos/Vel to Bending Angle, time derivatives matter
- 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

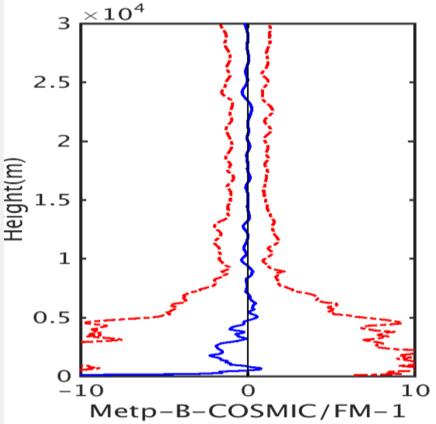
Bending Angle Comparison



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 Radio Occultation observations from low level to bending angle, which mainly serve for better Cal/Val activities and reprocessing at NOAA for COSMIS-2, CWDP and KOMPSAT-5 as well as future missions.
- Though RO observations are ‘bias anchor’ for NWP model, 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.
- We have illustrated all possible error sources in calculation of excess phase down to centimeter levels, however, correct each term is not trivial:
  - Position/velocity inaccuracy, attitude errors
  - Antenna offset/phase center variations
  - 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.
- Constant Errors not time related may not propagate into bending angle calculation, since only its time derivatives of excess phase are used in bending angle calculation.
- For COSMIC-2, work is in progress. In addition, the addition of GLONASS can introduce more complexity and challenges.

Acknowledgement

- We would like to thank the following organization and people for their help on training, discussion, analysis and data sharing:
  - EUMETSAT RO Team for RO on-site Training
    - Drs. Christian Marquardt, Axel Vonengeln, Yago Andres and Riccardo Notarpietro et al.
  - University of Bern, Astronomical Institute
    - For Bernese software training.
  - TAIWAN NSPO
  - UCAR/CDAAC
  - EUMET ROM SAF
  - Other NOAA STAR RO team members
    - Drs. Yuxiang He, Jun Dong, Wenhui Wang, Xinjia Zhou, and Erin Lynch etc.

What error is important?

$$Excess\ Doppler\colon\ f_d = \frac{d\Delta S}{dt}$$

Only terms related to time changing is important.
Constant bias can be neglected.

$$\Delta S = \emptyset_r^s(t_r) - \rho_r^s + \mathrm{c}\cdot\delta t^r - \mathrm{c}\cdot\delta t^s + N + D + w + \varepsilon$$

$$\rho_r^s = \sqrt{(x^s(t^s) - x^r(t^r))^2 + (y^s(t^s) - y^r(t^r))^2 + (z^s(t^s) - z^r(t^r))^2}$$

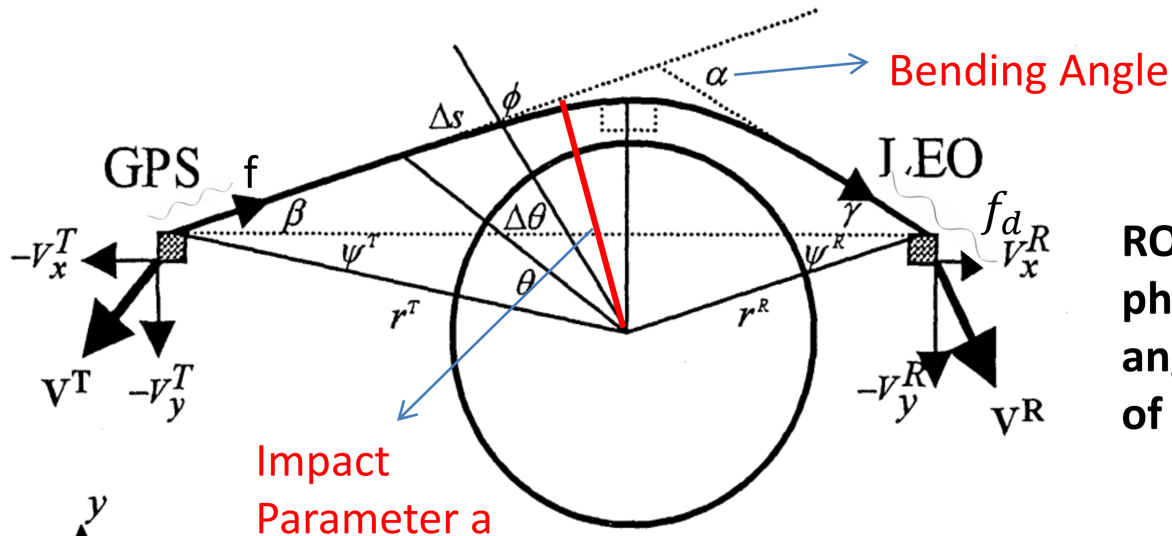
Depending on POD results for orbit and clock errors. Recursively depends on the carrier phase model in POD software, but different solutions can be set in different algorithm in POD procedure.

t^r *is receiver clock at the measurement.* t^s is unknown, need to calculate

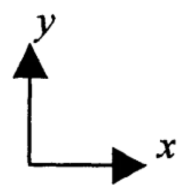
Error Sources in the excess Phase Model

- 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)
  - From Mass Center to Antenna Phase center
    - Satellite Attitude and Antenna Offset parameters, Phase center variations
- 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

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=β + γ can be obtained using Geometric Optical Method, following this two equations:**

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

S: Measured Wave phase

$$f_d = \frac{f}{c}(V_x^T(\cos\beta - 1) + V_y^T \sin\beta - V_x^R(\cos\gamma - 1) + V_y^R \sin\gamma),$$

$$r^T \sin(\beta + \Psi^T) = \sin(\gamma + \Psi^R) = a$$

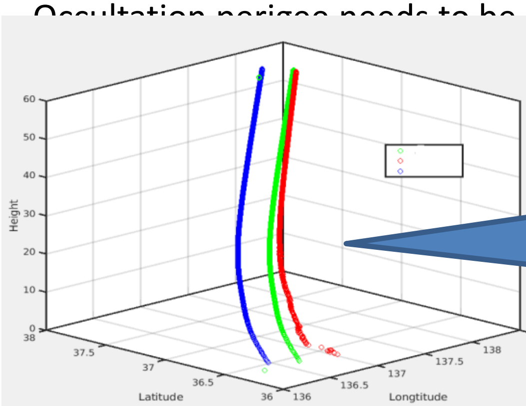
Requires accurate Position and Velocity determination

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

Healy, 2001

ECI/ECF Coordinate Transformation

- Relativity effects correction to excess phase needs inertial coordinate system, e.g Earth Centered Inertial (ECI) coordinate system. Attitude Quaternions are usually expressed as from spacecraft to ECI coordinate.
- Different ECI can cause confusion and misusage.
  - E.G. J2000 vs True of Date
  - Stick with one from start to end should be ok, but mixed usage can cause errors in Bending Angle inversion and profile geolocation.
- Consistency of ECI in attitude files and in Bernese (J2000)
  - Quaternions is defined as transformation from spacecraft to ECI.
  - J2000/TOD attitude file misused can cause additional error in POD (<cm level).
- ECI to ECEF transformation in bending angle determination
  - Antenna locations are in ECI
  - Occultation perigee needs to be represented as geodetic lon/lat in ECEF.



Using excess phase and associated satellite positions in a TOD ECI coordinates as J2000 can cause more than 15 km profile geolocation difference.

RO observations

GPS signal for POD

- GPS/GNSS on Zenith
  - Low rate (1Hz)
  - Pseudorange
    - C/A code, P1/P2
    - Time delay*speed of light
  - Carrier phase
    - Phase*wavelenghth (meters)
  - Doppler shift

```
     2.20           OBSERVATION DATA    M (MIXED)           RINEX VERSION / TYPE
kompsat5            COSMIC CDAAC        04-OCT-18 15:09     PGM / RUN BY / DATE
C001 L26 (OCCF)                                             MARKER NAME
SPACEBORNE                                                  MARKER TYPE
KOMPSAT5            KASI/KARI                               OBSERVER / AGENCY
                    IGOR                                    REC # / TYPE / VERS
                    KOM5 L45 (OCC1)                         ANT # / TYPE
       -0.4731        0.0036         0.2581                 ANTENNA: DELTA X/Y/Z
       -0.8883        0.0000         0.4593                 ANTENNA: B.SIGHT XYZ
        0.0000        0.0000         0.0000                 CENTER OF MASS: XYZ
     1     1                                                WAVELENGTH FACT L1/2
     8    L1    L2    C1    P1    P2    LA    SA    S2      # / TYPES OF OBSERV
  2017     6     1     6    55   17.0000000     GPS         TIME OF FIRST OBS
  2017     6     1    18    59    9.0000000     GPS         TIME OF LAST OBS
                                                            END OF HEADER
 17  6  1  6 55 17.0000000  0  2G04G23
   8353449.544     6509171.590    28250109.098    28250108.337    28250111.744
   8353449.292         487.000          88.000
   3826348.010     2981571.193    28439883.203    28439888.606    28439887.192
   3826348.739         262.000          15.000
 17  6  1  6 55 18.0000000  0  2G04G23
   8382997.654     6532196.083    28255731.724    28255731.448    28255734.209
   8382997.394         435.000          68.000
   3864133.947     3011014.464    28447073.634    28447079.762    28447079.059
   3864134.705         269.000          15.000
```

GPS signal for Occultation

- GPS/GNSS on limb
  - High Rate (50/100 Hz)
  - time/Prn/track-status
  - Carrier Phase (L1/L2), Pseudo Range , open-loop model phase

prn	time	datalen	ant	trkstatus	flystatus	carange	l1	l2	snr1	snr2	ca_model	dfaz	p2_model	dfaz2
1	1180293551.5035	len000	ant03	trk33	fly00	28026245.017	-3347.761	-3347.867	7114	2040	-999.000	-999.00000	-999.000	-999.00000
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1	1180293551.5435	len000	ant03	trk33	fly00	28026245.017	-3078.049	-3078.154	7097	2040	-999.000	-999.00000	-999.000	-999.00000
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1	1180293551.5835	len000	ant03	trk33	fly00	28026245.017	-2808.340	-2808.448	6892	2040	-999.000	-999.00000	-999.000	-999.00000
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1	1180293551.8035	len000	ant03	trk33	fly00	28026245.017	-1324.989	-1325.086	7010	2040	-999.000	-999.00000	-999.000	-999.00000
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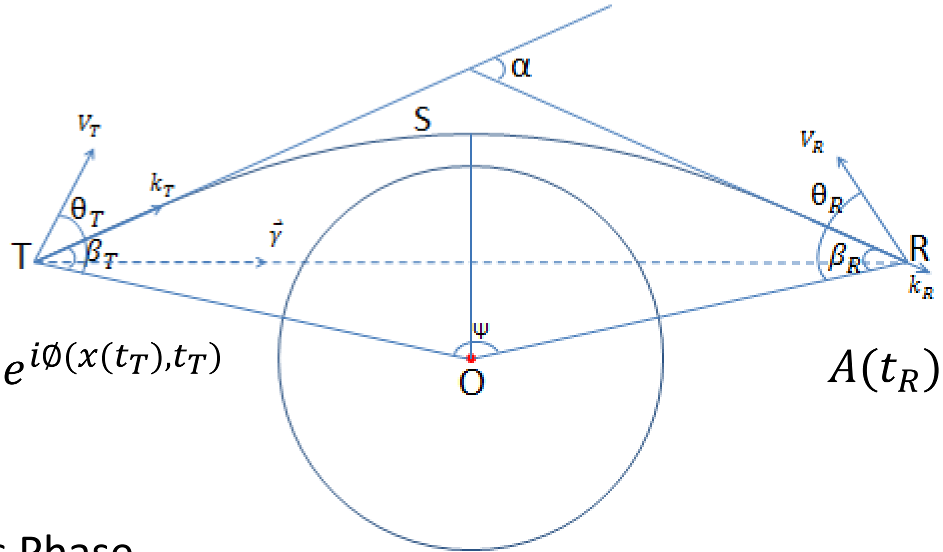
1	1180293551.9235	len000	ant03	trk33	fly00	28026245.017	-515.928	-516.022	7114	2040	-999.000	-999.00000	-999.000	-999.00000
1	1180293551.9435	len000	ant03	trk33	fly00	28026245.017	-381.086	-381.186	7034	2040	-999.000	-999.00000	-999.000	-999.00000
1	1180293551.9635	len000	ant03	trk33	fly00	28026245.017	-246.247	-246.336	7043	2040	-999.000	-999.00000	-999.000	-999.00000
1	1180293551.9835	len000	ant03	trk33	fly00	28026245.017	-111.408	-111.506	7022	2040	-999.000	-999.00000	-999.000	-999.00000

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

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

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

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

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

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

Observed Carrier Phase

Clock Corrections

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

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

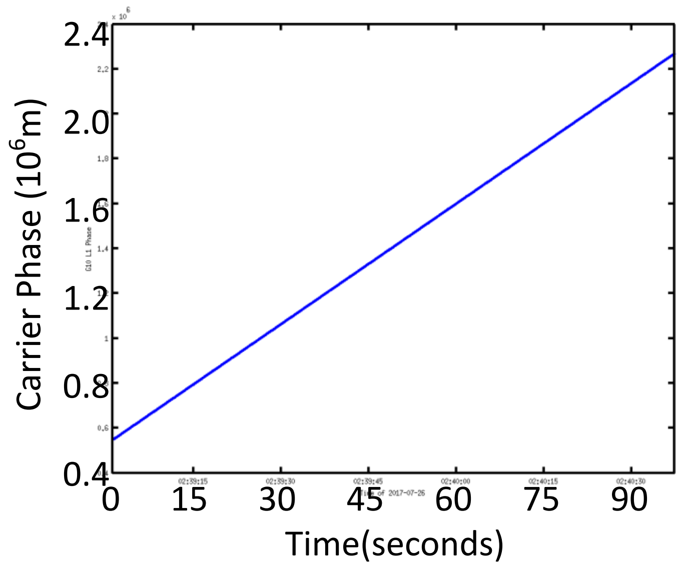
$$= \frac{f}{c}(v_T\cos(\theta_T - \beta_T) - v_R\cos(\theta_R - \beta_R) - (V_T - V_R)\cdot\vec{\gamma})$$

Only time derivative matters. Phase measurements needs locked.

Relativity Effects

- In Earth Centered Inertial Coordinate system
- Range Correction
  - Contribute to excess phase (order~ 0.2m)
  - Contribute to transmittance time determination.
    - 0.2m/C~<1ns
- GPS Clock Correction (proper time and coordinate time)
  - Generally proportional to GPS clock error.
- LEO Clock Correction (proper time and coordinate time)
  - Single differencing, removed both
  - Zero differencing, can be modeled, but very small.

Excess Phase Example



Raw Measurements: Carrier Phase

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