Error Propagation from the Precise Orbit Determination and Clock Uncertainty Estimates to Bending Angle in the STAR's COSMIC-2 Processing System

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Abstract

Launched on June 25, 2019, the Constellation Observing System for Meteorology, Ionosphere, and Climate 2 mission and Formosa Satellite Mission 7 (COSMIC-2/FORMOSAT-7, hereafter COSMIC-2) is a-six satellite constellation mission with a 24-degree inclination orbit at 720 km altitude. COSMIC-2 mission is a partnering satellite program among US National Oceanic and Atmospheric Administration (NOAA), US Air Force (USAF), Taiwan's National Space Organization (NSPO), and the University Corporation for Atmospheric Research (UCAR). The UCAR COSMIC Data Analysis and Archive Center (CDAAC) is the COSMIC-2 operational data processing center, the National Environmental Satellite, Data, and Information Service (NESDIS) Center for Satellite Applications and Research (STAR) is the COSMIC-2 re-processing and quality monitoring center in NOAA.

To understand the COSMIC-2 data uncertainty induced in each step of the RO processing, the University of Maryland (UMD) and NESDIS/STAR developed an independent processing package to convert the COSMIC-2 pseudo-range and carrier phase observations to excess phases. We use the Bernese software to solve the LEO satellite clock bias and test the precise orbit determination (POD). The Radio Occultation Processing Package (ROPP) was used to convert the newly derived excess phase to bending angles.

This study examines the STAR COSMIC-2 POD results and explores the impact of different POD solutions on the bending angle retrievals. Multiple POD results of the same LEO satellite are available in the UCAR level1b dataset. However, only one is used for excess and bending angle calculation in operations. The POD from multiple solutions have uncertainty/difference ranges from centimeter levels to meter level. The POD solution change in time can impact the bending angle through derived additional Doppler in excess frequency. On the other hand, the COSMIC-2 single differencing clock bias correction is between observations from two antennas. The POD solution uncertainty can impact the clock bias removal in excess phase due to the POD uncertainty impact on the direct link removal in single differencing.

Unlike COSMIC-1, COSMIC-2 does not have a high-rate POD observation of reference GNSS satellite for single differencing. We will also evaluate the uncertainties in Clock bias (determined from using the single difference and zero difference) in the excess phase. We then use our excess phase package to quantify how the excess phase retrievals vary from different POD and clock bias estimates. Furthermore, the COSMIC-2 raw carrier phase displays a significant amount of cycle slips. Using of accurate excess phase model simulated from climatology is critical in cycle slip corrections. However, different excess phase simulated using a different model and forward operators can generate different excess phase profiles. How this model difference affects the excess phase and bending angle, refractivity, and dry temperature profiles, especially at the open-loop stage near lower 10 km near the surface, is also discussed.

1. COSMIC-2 Data Format and Conversion Flow Charts

- RO data processing
  - Decoding Level 0 data set to Pseudo range and carrier phase (Lv0 reader from UCAR).
  - Using Bernese software for Leo satellite clock bias solution and POD testing.
    - Orbital data in this study is still from UCAR, but clock bias is from Bernese solution.
  - Excess phase , antenna phase center position/velocity calculated with Matlab.
  - Modified ROPP for bending angle inversion from excess phase.
  - Fig. 1 shows the flow chart of the COSMIC-2 data conversion at STAR/UMD.
- One month of COSMIC-2 RO level1a data has been converted to L1B bending angle and compared with ERA-5 and UCAR for Oct. 2019.

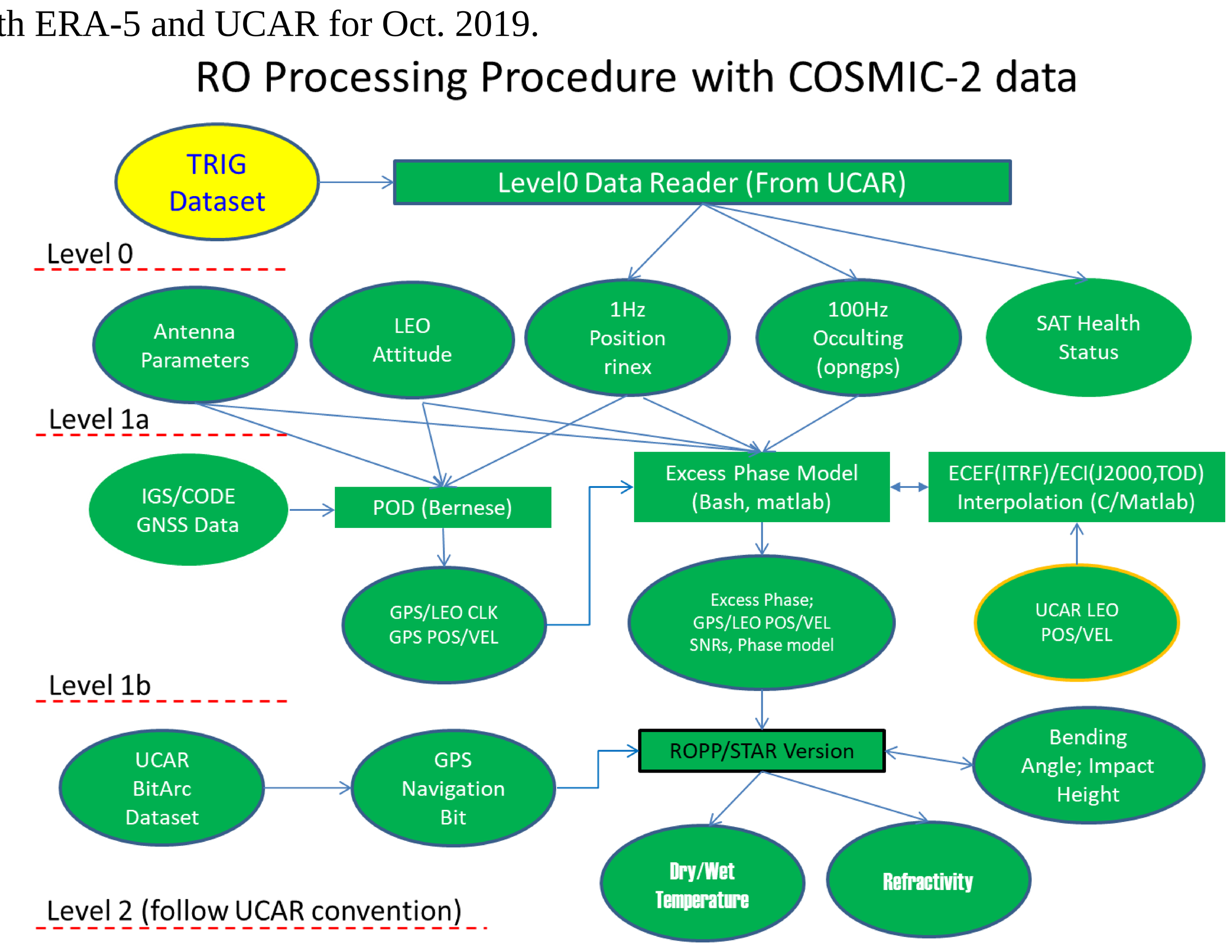

Fig. 1 Flow Chart of the Data Conversion from Level 0 to Level 2 at STAR/UMD

2. LEO Satellite POD and Clock Bias Solutions

- Bernese Software is used for testing satellite POD and Clock bias solutions
  - Using UCAR's COSMIC-2 POD products (SP3-C files) for orbital interpolation.
  - CODE GNSS orbital position/velocity and clock bias is interpolated using Bernese.
  - CLOCK bias is from Bernese kinetic solution for corrections mainly on the time tag for excess phase and coordinate transformation/interpolation.
  - Clock bias for COSMIC-2 (~ms) is generally larger than COSMIC-1 (~us) and clock adjustment is usually on a interval of a few days.

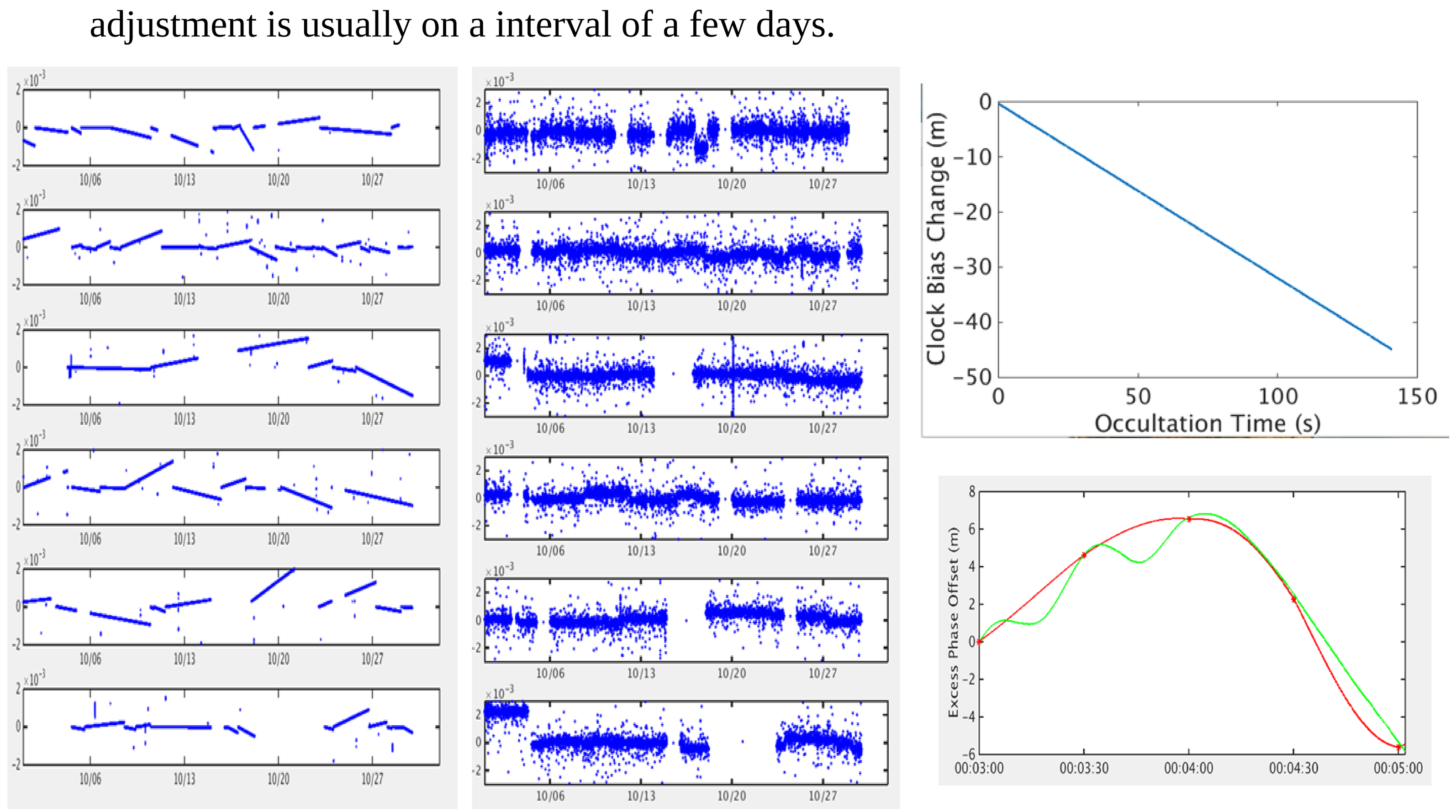

Fig. 2 COSMIC-2 Clock bias and drift. Left panel is for COSMIC-2 Clock Bias (Unit: seconds) and middle panel shows the clock drift rate (Unit: seconds/day) of C2E1-C2E6 on Oct.2019; Right two panels show two cases of the clock bias contribution to excess phase (meter) for COSMIC-2 and COSMIC-1respectively using the single differencing.

3. Excess Phase Calculation

- Time tag is corrected using Bernese clock solution.
- Signal time delay between GNSS and LEO receiver is calculated using relaxation method.
- Direct range between the GNSS transmitter and LEO receiver phase center is removed from carrier phase. Other terms (relativity effects etc.) are also removed.
- Reference satellite (for SD) is selected with best SNRs. Low pass filter is used for ionosphere-free L3.
- MSIS simulated phase model is used for correction the open-loop stage excess phase. Different phase model used can affect the cycle slip correction results.
- Excess phase comparison with UCAR shows good agreement above 10 km (0.3cm±3cm after QC) and gradually departure toward surface.

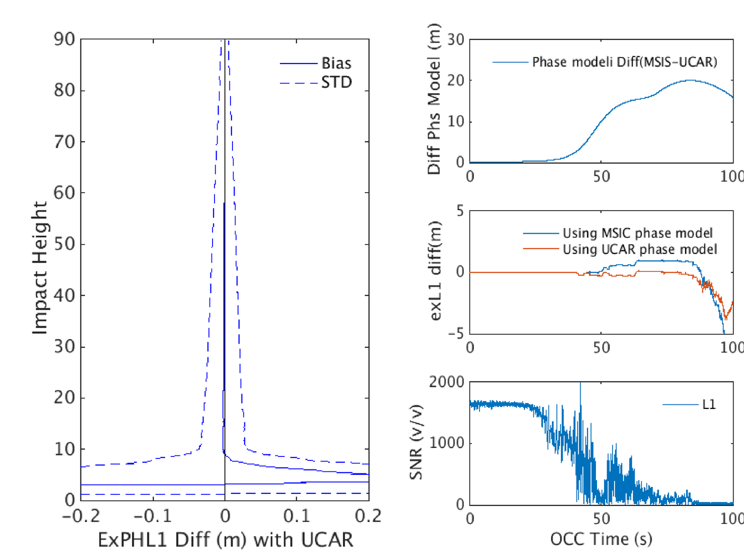

Fig. 3 Excess Phase comparison Left) with UCAR and different phase model impacts on cycle slip detection

4. Bending Angle Comparison

- ROPP-9.0 is modified to convert COSMIC-2 excess phase, SNR and antenna position to bending angle.
- The bending angle can be different from different bending angle inversion methods (ROPP and UCAR method) even excess phase bears very similar structure (Fig. 4)
- One month data are produced from RINEX/opnGns to excess phase to bending angle.
- Good agreement with ERA-5 and UCAR at height between 10km and 35 km using one month data at Oct. 2019 (Fig. 5).

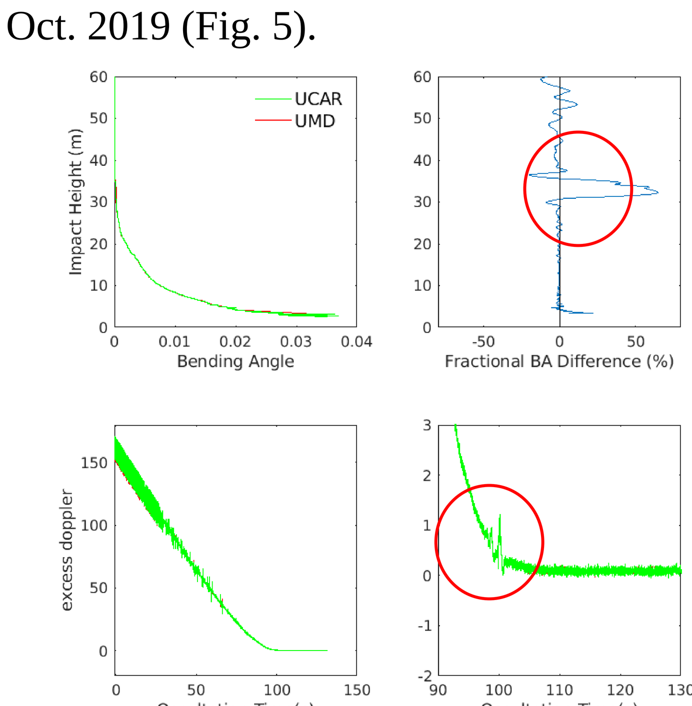

Fig. 4 Error propagation from excess phase to BA

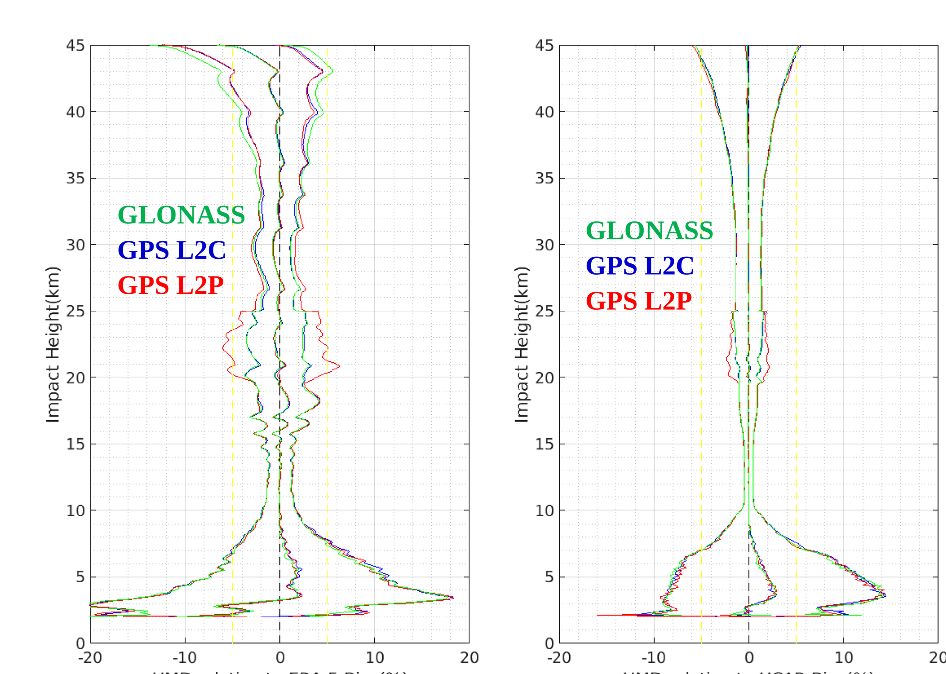

Fig. 5 Relative BA (Bias and STD) with ERA-5 and UCAR

5. POD difference to Bending Angle Difference

- Operational UCAR POD has multiple solutions (POD overlapping from different segments).
- Different POD solutions have differences from few centimeters up to meter level (Fig. 6).
- The POD uncertainties can introduce errors in estimation of the SD clock bias and direct distance removal in excess phase and hence errors in bending angle (Fig. 6).

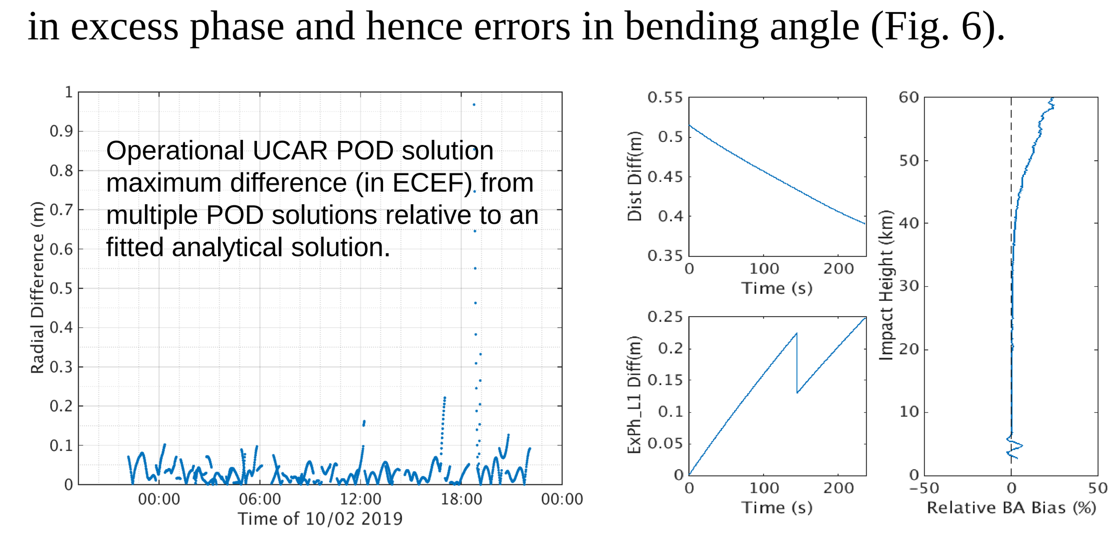

Fig. 6 Using different POD solutions can yield different bending angle profiles. The POD difference is up to 50 cm different and changing with time for case: Oct. 2nd, 2019, 18:46UTC for G15 of C2E1. The jump in the excess phase is due to the cycle slip removal difference.

6. Summary:

- We have developed a COSMIC-2 data processing package to convert the COSMIC-2 carrier phase and pseudo-range to excess phase and then to bending angle. The Results show good agreement in excess phase and bending angle with ERA-5 simulated and UCAR results between 10km and 35 km.
- The processing package facilitates our understanding for RO error propagation in the data conversion and it will help for NOAA/STAR's RO calibration/validation activities.
- Further improvements will be needed including reprocessed POD with daily solution and corrected excess phase model to reduce standard deviation above 35 km and below 10 km. These results will be reported in a journal paper.

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8. References:

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