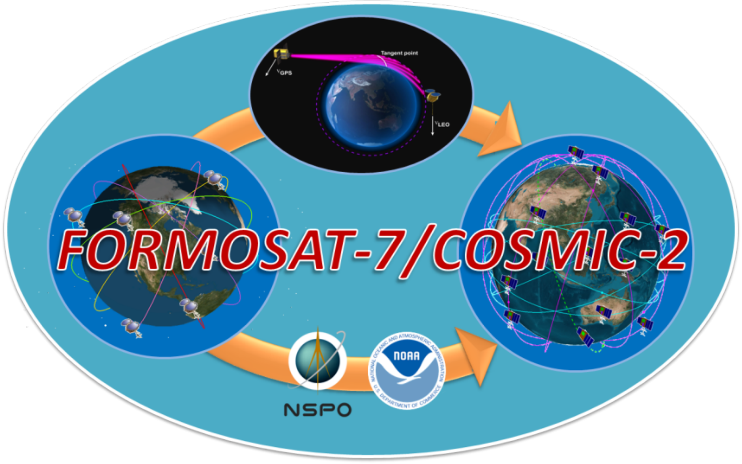
FORMOSAT-7/COSMIC-2 Program
Short Summary of the STAR Annual Report
2020/04



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NOAA/STAR

Main Activities 04/2019 - 4/2020
Submitted April 2018

1. Executive Summary

Radio Occultation (RO) is becoming a core NESDIS observation. Given its importance to NWP, NESDIS decided that radio Occultation (RO) will be a long-term core observable to be treated the same way we treat MW and IR radiances. The general goal for STAR is to build a long-term RO data processing center (PDC) to support all RO related operational and science applications as we do for Microwave and Infrared Sounders.

A COSMIC (Constellation Observing System for Meteorology, Ionosphere, and Climate) follow-on mission, COSMIC-2, has been successfully launched into low-inclination orbits in June 25, 2019. Starting in 2019, the NESDIS OPPA began funding NESDIS/STAR to execute COSMIC-2 related tasks.

Currently, one STAR federal employee leads L1b-L2 processing and validation. STAR is also in the process of hiring another federal employee who will focus on RO L0 – L1b data processing including Commercial Weather Data for RO (CWD-RO), COSMIC-2, and possible Sentinel-6.

There are a number of new projects / programs where STAR is significantly involved in the exploitation of their RO data: these are from partners' missions (KOMPSAT-5, PAZ, Metop, Metop 2nd Gen, Sentinel-6, etc). These projects also improve the STAR's capability in COSMIC-2 data processing and its science applications.

STAR has been developed as a GNSS RO processing and research center. Since Sep. 2019, we have developed the STAR GNSS RO Data Processing and Validation System for multiple RO missions.
In particular, we have dedicated our efforts on (1) RO data processing (both L1a-L1b processing, and L1b to L2 processing), (2) developing the Integrated calibration and validation (cal/val) system (ICVS) for data monitoring, (3) multi-sensor validation, and (4) data assimilation.

In this report we briefly summarize STAR's accomplishments for COSMIC-2 execution which include:

(1) the current status of the development of STAR RO DPC inversion and validation system (section 2),
(2) highlights of STAR's collaboration with national and international partners to serve NOAA and RO community to support science applications (section 3),
(3) the improvement of STAR COSMIC-2 inversion package (section 4),
(4) highlights of validation and application results (section 5).

2. Establishing STAR Long-term DPC system

2.1 Focus area for STAR RO data processing and validation system

STAR has been developed as a GNSS RO processing and research center. Since Sep. 2019, we have developed the STAR GNSS RO Data Processing and Validation System for multiple RO missions including COSMIC-2, CWDP, and other RO missions from partners.

Four major focus area of STAR RO data processing and validation are defined in **Figure 1.** In particular, we have dedicated our efforts on

(1) RO data processing (both L1a-L1b processing, and L1b to L2 processing),

(2) developing the Integrated calibration and validation (cal/val) system (ICVS) for data monitoring,
(3) multi-sensor validation, and
(4) data assimilation.

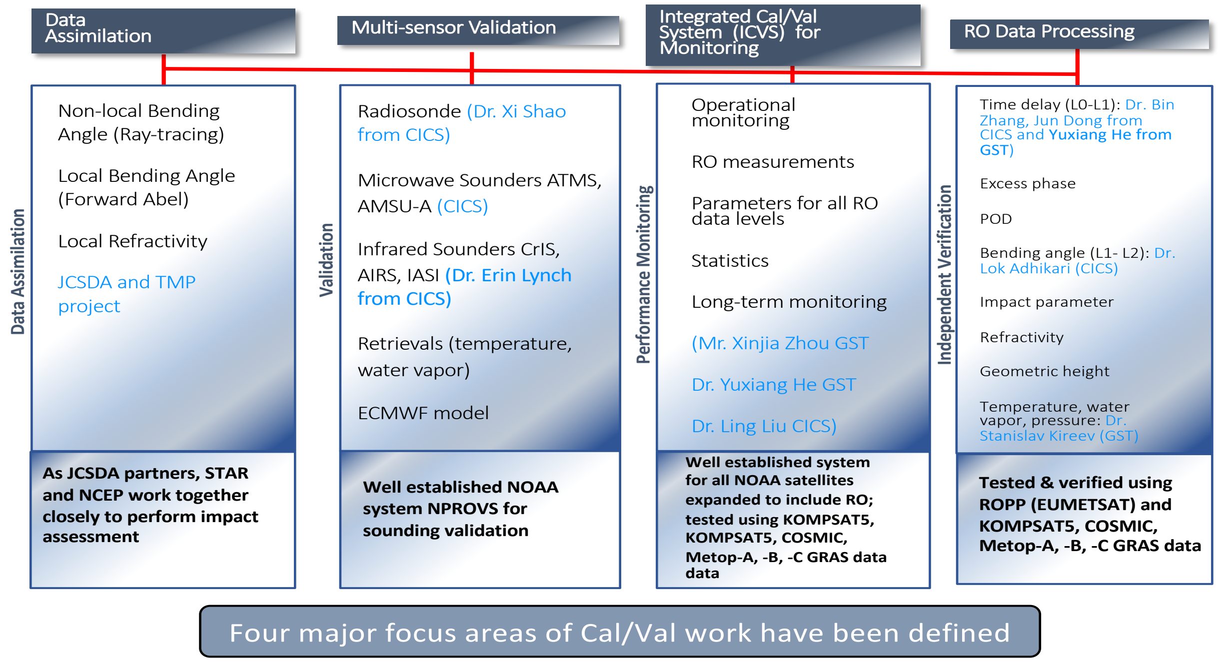


Figure 1. Four major focus areas of STAR COSMIC-2 RO processing and validation system.

The COSMIC-2 tasks performed by STAR are mainly based on studies from the first three focus areas.

The STAR FSI processing package is described in section 2.2 where the initial validation of COSMIC-2 bending angle retrieval processed by using the STAR FSI operational inversion package is shown in the same section. We will summarize the development of STAR 1D-var inersion package, Integrated calibration and validation system (ICVS), STAR Multi-sensor Validation approaches will be detailed in another report. The STAR ICVS system can be seen in section 2.3.

2.2 STAR RO data processing package

To derive bending angle and refractivity profile from RO occultation measurements, one must perform L0-L1 (from raw data to excess phase) and L1-L2 (converting excess phase to bending angle) processing. In the past year, STAR GNSS team has developed the capability to perform both L0-L1 and L1-L2 data processing. **Figure 2** depicts the flow chart of the STAR RO processing procedures.

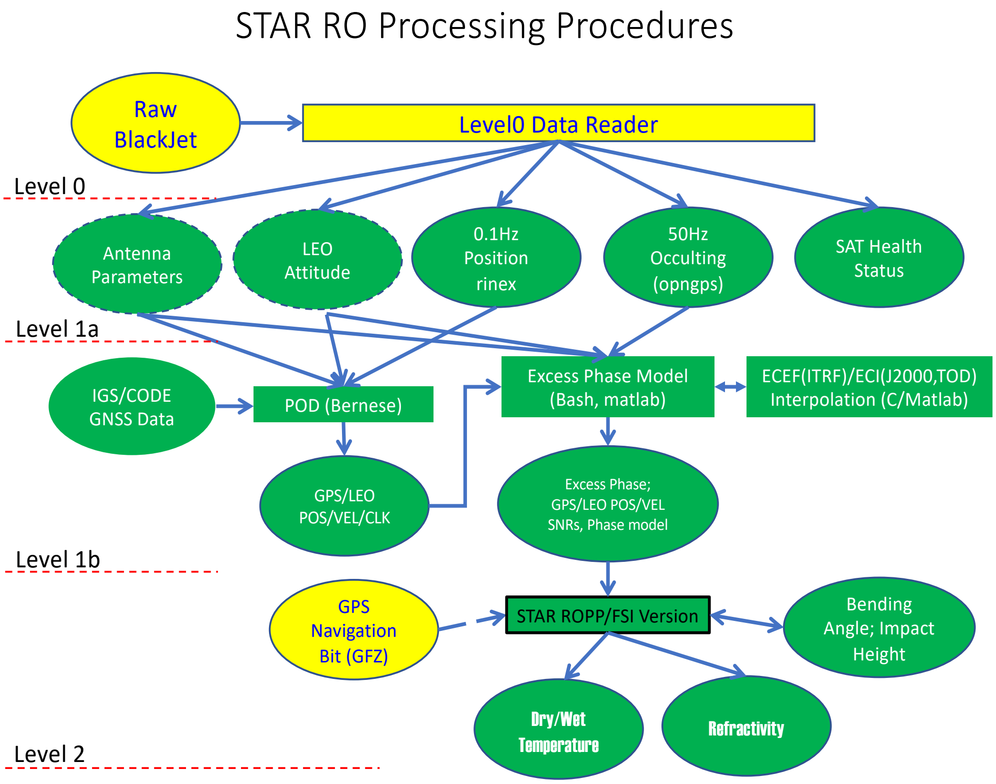


Fig. 2 The flow chart of the STAR RO processing procedures.

For L0-L1 processing, we are able to perform 1) precise orbit determination (POD) and clock synchronization to eliminate the effects of the geometric Doppler and of relative transmitter receiver oscillator drift, 2) bending angle calculation, 3) ionospheric corrections, 4) Abel integral inversion with upper boundary conditions, and 5) quality control (QC).

STAR processing algorithms include the following sequential processing modules:

a. ***I/O subroutine*** to read phase, amplitude and geometry data
b. ***Translation subroutine*** to change ECEF coordinates to local center of curvature and calculate the radius of curvature. The Flow chart to calculate the propagation of GPS and LEO orbits to circular orbits relative to a local center of curvature is described in **Fig. 3**.
c. ***Projection subroutine*** to project GNSS/LEO orbit to fixed radii from local center of curvature
d. ***FFT subroutine*** to get bending angle at each impact parameter: This is the core FSI/FFT subroutine.
e. ***Inverse Abel subroutine*** to compute refractivity from bending angle/impact parameter.

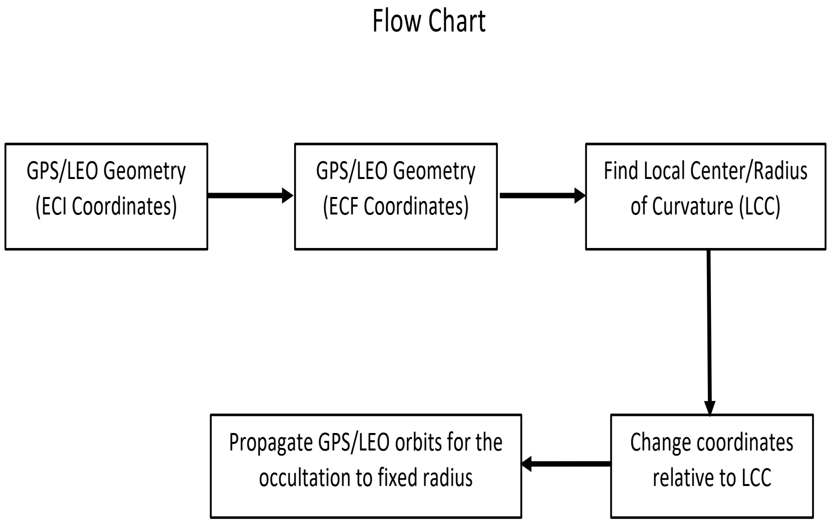


Fig. 3. Flow chart to calculate the propagation of GPS and LEO orbits to circular orbits relative to a local center of curvature.

For the COSMIC-2 data operation, we input the Phase/SNR (signal noise ratio) data purchased and processed by the commercial providers into our inversion algorithms and output the bending angle profiles. We further perform Abel integral transform which converts atmospheric bending angles to profiles of refractivity.

Accurate bending angle processed from the raw GNSS signals received from the RO receivers are critical for numerical weather prediction (NWP) through data assimilation (DA). Using STAR inversion package described above, we have successfully inversed the raw phase, amplitude and geometry data provided from GeoOptics to bending angle profiles (i.e., STAR bending angle profiles).

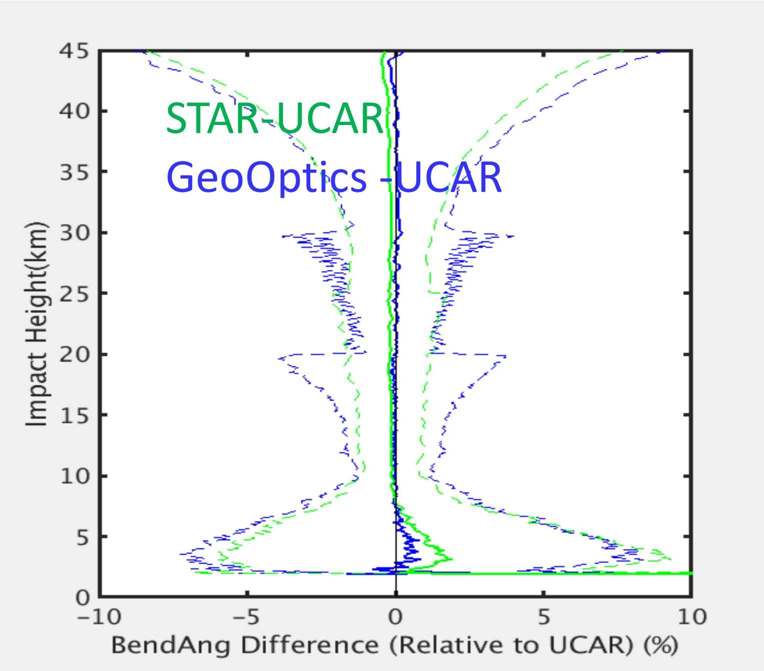


Figure 4. Bending angle profiles difference between STAR and UCAR pairs (in green) and between GeoOptics and UCAR pairs (in blue). The standard deviation of the mean differences are in dashed lines.

Figure 4 depicts the STAR bending angle profiles compared to the exactly the same profiles generated by UCAR (the green line). The bending angle difference between those provided by GeoOptics and UCAR are in blue. GeoOptics data collected for the whole month of December 2018 are used in this comparison where more than 2300 profiles are compared in **Fig. 4. Fig. 4** shows that the STAR bending angle are very close to those of UCAR with less than 0.1% of fractional difference. The standard deviation of the mean difference (the dashed lines) for STAR-UCAR pairs and smaller than those of GeoOptics-UCAR pairs especially at the impact height between 10 km and 30 km.

Figure 4 demonstrate the feasibility of STAR RO inversion package to process the raw RO phase, amplitude and geometry data and generate reasonable RO bending angle profiles which are of the same quality of those UCAR processed bending angle profiles.

2.3 STAR ICVS Tool Development

NOAA/NESDIS/STAR plays an important role in the Commercial Weather Data Pilot (COSMIC-2) studies. A STAR testbed center was established to routinely process the COSMIC-2 data. An Integrated calibration and validation system (ICVS) was also developed to routinely monitor the quality of the derived RO data.

A STAR operational inversion package was developed to process COSMIC, Metop-C, and COSMIC-2 2 data. COSMIC-2 R2 data were obtained from both GeoOptics and Spire Global. An interface page of the STAR GNSS RO ICVS is shown in **Fig. 5**.

STAR RO ICVS system can be seen under
https://ncc.nesdis.noaa.gov/GNSSRO/ICVS/index.php

The references used in the RO ICVS include weather model outputs, reanalysis, data from various RO missions, and radiosonde measurements. The functions of the STAR GNSS RO ICVS include:

- Near real time and long-term instrument status, performance monitoring, and anomaly diagnosis
- Near real time and long-term level 1 data product quality monitoring
- Provide real time support for sensor calibration activities
- Provide rapid and preliminary estimate of satellite data impact in NWP applications
- Ensure the integrity of the climate data records from all satellite instruments
- Currently, RO data from 12 publicly available missions are included, from GPSMET collected in 1995 to COSMIC2 data in 2019.
- RO data producer: UCAR, ROMSAF, ROPP and STAR (under testing). Monitoring RO product parameters and instrument performance at all levels.
- Routine comparison of atmospheric profiles with other satellite observations and retrievals including microwave, and infrared.
- Routine comparison of profiles with those from Radiosondes.
- Dynamic web interface with many capabilities.
- Long-term monitoring of the parameters.

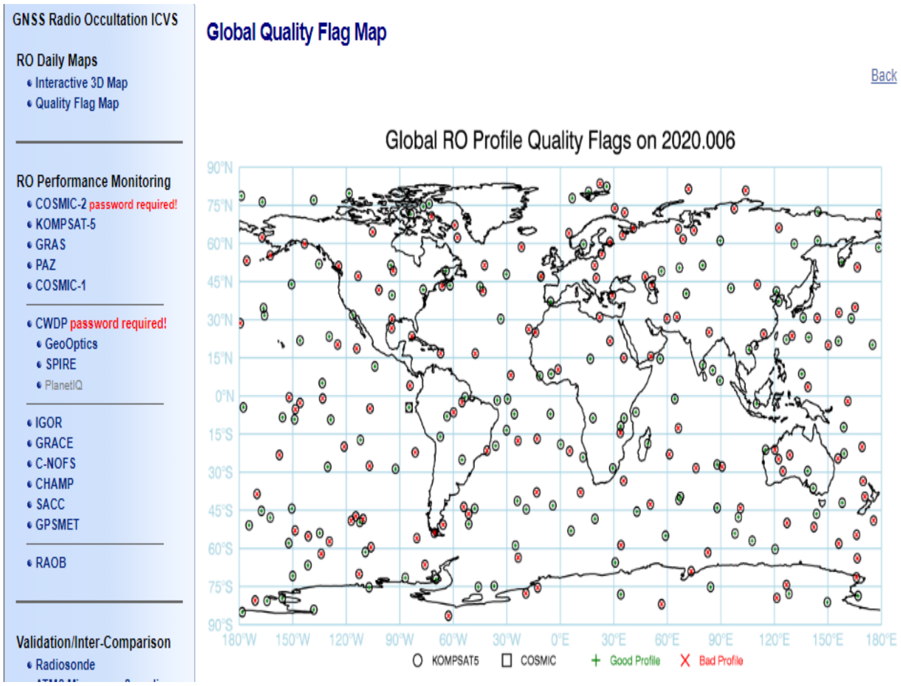


Figure 5. An interface page of the STAR GNSS RO ICVS.

3. Highlights of STAR's collaboration with national and international partners and community Service

There are a number of new projects / programs where STAR is significantly involved in the exploitation of their RO data: these are from partners' missions (KOMPSAT-5, PAZ, Metop, Metop 2nd Gen, Sentinel-6, etc).

STAR is also leading the effort to further explore the optimal approaches for using RO data in the operational Data Assimilation (DA) environment through a Technology Maturation Project (TMP) RO project.

We have established an internal NOAA website to summarize activities, publication, and
The current development on RO inversion package in

https://www.star.nesdis.noaa.gov/smcd/ncc/GNSSRO/GNSSRO_Publications/index.php

The login name is "cosmic", the password is also "cosmic"

The National and international collaborations and Community Service since April 2019 conducted by STAR lead and team members are listed below.

- Work closely with OPPA on organizing the IROWG GNSS RO conference EUMETSAT on CWDP data evaluation
- Work closely with IROWG, G-VAP, SPARC, GCICS MW team, etc to promote interagency/international collaboration
- AMS 2020 special GNSS RO section chair
- AGU 2019 special GNSS RO section chair (working with JPL, UCAR and other agencies to organize this special section)
- Remote Sensing Guess editor
- SPARCS STAR lead
- G-VAP co-chair
- AMS GNSS RO section co-chair
- AGU GNSS RO co-chair
- GCISC RO lead in STAR
- G3 RO lead in STAR
- IROWG STAR lead
- TAO editor for COSMIC-2 special issue
- Co-chair of the WCRP (World Climate Research Program) SPARC global temperature profile climate record assessment.
- Member of the IROWG ROtrend working group: participate the ROtrend tele-conference meetings and work with other ROtrend members to quantify the structural uncertainty for RO data.
- Co-Principal Investigator for SCOPE-CM project: Sustained generations of upper tropospheric humidity (UTH) from multi-sensors with multi-agency cooperation, SCOPE-CM (Sustained and coordinated processing of Environmental Satellite data for Climate Monitoring).
- Member of the WCRP (World Climate Research Program) SPARC global temperature profile climate record assessment group.
- Provided text/presentation material on COSMIC, KOMPSAT-5, and RO water vapor sensing to Jack Kaye for CGMS meeting.

- Journal paper review: review RO-related journal papers from JGR, IEEE remote sensing, AMT, ACP, Journal of Radio science, etc.
- NOAA climate contact for COSMIC
- NASA atmospheric sounding Instrument and Science Team, Member
- NCAR SOARS steering committee: review panel members to select SOARS summer students for 2016.
- Member of the WCRP (World Climate Research Program) SPARC global temperature profile climate record assessment. Working with all the membrs and complete the GEWEX water vapor assessment (G-VAP) Final Report. Also participate the strategical planning for the G-VAP and future research goals.
- Member of international working groups, the World Climate Research Programme (WCRP) Global Energy and Water Cycle Experiment (GEWEX).
- Member of the IROWG ROtrend working group: participate the ROtrend tele-conference meetings and work with other ROtrend members to quantify the structural uncertainty for RO data. Attending the IROWG ROtrend group meeting and participating the draft writing to WMO.
- Working with JPL scientists to propose/organize a special GNSS RO section in AGU.
- Working with NSPO scientist to propose/organize a special COSMIC-2/F7 section in AGU.
- Guest editor of the special GNSS RO issue of “remote sensing”

4. GNSS RO Inversion Algorithm Improvements

In the past year we have been coordinating with domestic and international partners from RO data operational centers including EUMETSAT, NSPO, UCAR, JPL, WegC, ROM-SAF, NSPO, UCAR, JPL to develop the optimal STAR RO processing algorithms for both COSMIC-2 and CWDP data. CWD-RO and COSMIC-2 projects are planned to take advantage of the existence of these other projects and the national and international collaborations among the world-leading RO processing centers and operational NWP centers.

In this section, we summarize our efforts on not only perform L1b-L2 inversion development (see section 2) but also the development of L1a – L1b COSMIC-2 processing package to prepare STAR as RO data processing center (DPC).

In this section, we provide the steps converting the phase observation (opnGns files) to bending angle (cicPhs files) and compare our solution with GeoOptics and UCAR to understand the differences and errors in excess phase and bending angle products.

4.1 Extracting the opnGns phase and Rinex file phase

The OpnGns of GeoOptics has 100 HZ observations, approximately 0.02 seconds intervals. Usually the file provides the observations (pseudo range: C1C, L1 Phase: L1C, L2 Phase: L2L, and SNR: S1C,S2C) and modeled phase data (L1C(M) and L2L(M)). One important step in this opnGNS processing is to extract all the information and concatenate into one formatted file (easily readable into matlab) and determine each Radio Occultation events and their associated start and end time. Based on the each RO event start and end time, we look into the same day RINEX observations from POD antennas. For each continuous of a single GNSS observation by the POD antenna, we called them a reference link event. The pair between the RO event and an reference link event are determined by looking at the reference link data SNR and its time range covering the RO event.

4.2 Orbital Determination for LOE/GNSS position and velocity

The LEO (Geoptics) POD has been provided as SP3-D format with 1HZ interval. At this time, due to the lengthy processing in Bernese, we decided to use the GeoOptics provided L1a POD information. We extract the GPS time, Position and velocity in ECEF and Clock bias from all the SP3-D files in one day and forms a formatted data file into matlab. This step is relatively easy since it only involves the format change. However, we found that the SP3-D orbit has large clock bias. The bias in the time derivatives of the positioning can cause wavy structure in the bending angle profiles. We also looked into the level-2 POD file, cicPOD, which has complete 1HZ POD information. However, the POD position of the LEO satellite is given in ECI coordinate system and we have to do the coordinate transformation.

To derive the GNSS position/velocity and clock information, we have to reply on the CODE/IGS products. The 15 minutes CODE GNSS solution and Earth Orientation Parameters are downloaded/reformatted and feed into the Bernese software. The orbit and clock are reproduced into 30 seconds products using SP3-C format. The SP3-C formats are then used to form formatted inputs to excess phase model to provide the GNSS pos/vel/clk data. For both LEO and GNSS orbit, a high order polynomial interpolation (9th order) has been used in the interpolation of orbital time to observational time.

4.3 Extracting the Attitude Information

The GeoOptics attitude file adopts the Champ convention. The quaternions are defined from space craft coordinate to ECI (J2000). We extract the GPS time and the Quaternions into formatted file ready into matlab. Also, the GeoOptics attitude files include the POD and antenna offset information. From here we can derive the antenna offset for POD and excess phase calculation. Together with the SP3/cicPOD file provided GNSS/LEO mass center position, the antenna offset and attitude information can be used to derive the LEO antenna position/velocity in ECI coordinate system.

4.4 Earth Coordinate System Conversion

The GNSS/LEO satellite positions are given in ECEF coordinate system with the IGS convention. However, the excess phase calculation involves terms must be corrected in ECI coordinate system. Thus we need convert the Pos/Vel data sets from ECEF to ECI. While the general coordinate transformation can be done using a generalized matrix considering the earth rotation, the accurate conversion from ECEF to ECI (vice versa) needs a well defined equatorial plane and an earth's pole, where the earth's rotation, , precession, nutation and Polar wander must be considered. Here, we use True of Date coordinate system, one of the ECI, the same as UCAR used for our processing. Before doing the temporal interpolation from POD time (30 seconds interval) to the high rate phase observation time (100 Hz), we carried out the coordinate transformation first, which means the interpolation is done in ECI coordinate system.

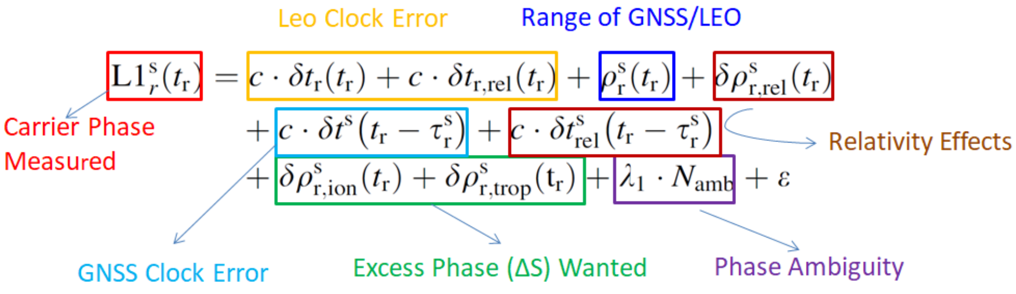
4.5 Cycle Slip Detection

The cycle slip happens when connecting the observed phase in a range of $[-\pi,+\pi]$ to a continuous, unwrapped phase time series. In the discontinuity, an integer number of the (half) wave lengths must be added into the time series; otherwise the time derivative will be changed abruptly and hence affects the bending angle calculation. Generally, the residual phase between the observed L1/L2 phase and phase model are looked. During the phase-locked loop (close) stage, the difference can be easily identified since the change of residual phase between two observational point s are close to zero, hardly exceed quarter of wave length (0.19cm for L1). The integer number of π can be added by minimizing the difference between the previous observation and current. However, during open loop stage, we may also need to reply on the navigation bit time series or an internal NDM correction. Once the phase has been reconnected, it will be added back to the phase model and then provided for excess phase calculation.

4.6 Calculation of Excess Phase

We designed an excess phase model (mainly in matlab) to incorporate all steps from coordinate conversion, polynomial interpolation, excess phase calculation and netCDF data output.

The excess phase model can be expressed as the following equation (Figure 6):



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

Figure 6. The calculation of excess phase involves different types of phase corrections

From the equation, the dominate part is the LEO clock error. For COSMIC-1, the high rate POD observations can be paired with OCC high rate observations to remove this clock error completely (only increase noise level due to smoothing procedure of L1/L2 phases). For the GNSS clock error, since the GNSS clock is usually very stable (or drift rate is very stable), the error from polynomial interpolation from 30 seconds (or 1HZ GNSS ground station observations) is negligible, a zero differencing can be applied to these part usually within a few millimeter difference in excess phase. However, we need to estimate the time propagation τ_r^s from the transmitter to receiver. This can be roughly calculated using the direct distance divided by speed of light and recursively calculated using the GNSS orbit and LEO receive position in ECI coordinate system. The range between transmitter and receiver, $\rho_r^s(t^r)$, refers to the antenna phase center position. Thus it combines the POD mass center position, the antenna offset and the antenna phase center variation. However, to connect these three, the attitude information must be taken into accounts since the antenna offset and PCVs are given in instrument coordinate system.

It recognized that the POD with accuracy of 10 cm level does not have significant impact on the bending angle calculations, such as COSMIC-1. By examining the POD error in the GeoOptics POD netCDF file, the uncertainty of the POD is on the order of 0.5 cm level (as 1 σ value). Similar to the CLOCK drift, the position error can be easily more than centimeter level. To reduce error, a 10th order polynomial interpolation scheme has been applied to the position and velocity interpolation. The general relativity effects consider time and distance difference when referencing different clocks on different satellites. Those corrections are small but must be done in a inertial system, that's why the excess phase is always associated with position/velocity in the ECI coordinate system.

The basic steps in calculation of excess phase:

- Determine the high rate OCC time, in 0.01 second interval.
- NDM removal for residual phase and added back to phase model.
- Calculate the phase center position/velocity of the LEO satellite receiver and GNSS transmitter at OCC time 10th order polynomial interpolation.
- Calculate the range of the transmitter and receiver.
- Subtract the range from both L1/L2 phase.
- Calculate general relativity terms and subtract these corrections from phase.
- Calculate the referenced link 1HZ L1/L2 observations from RENIX file and pair with the opn

- Remove the GNSS clock bias using zero differencing (4th order polynomial interpolation).
- Apply the same algorithm to 1HZ POD observations and interpolate the results into OCC observation time.
- Linearly combine L1 and L2 phase from 7) to form L3, the single differencing clock error.
- Subtract L3 in 6) from residual phase in 4.) and subtract a constant to make the first excess phase value as zero.
- Format the datasets and output as netcdf as function of GPS time (with bias corrected). The netCDF variables include excess phase, phase model, position and velocity of transmitter and receiver, SNR as function of the GPS time (with bias corrected).

While the steps look straight forward, there are many caveats and subtle steps needing additional care. Such as dealing with the LEO receiver POD/OCC antenna offsets needs the LEO attitude information, dealing with GNSS antenna offsets needs the GNSS attitude information. The accuracy of observational time is also important. With receiver clock bias on the order of ~0.1ms, the range error between transmitter and receiver can be 10 centimeters difference (think of the LEO/GNSS relative movements) if not subtracted from the receiving time.

4.7 Calculation of Bending Angle

Once the excess phase and SNR as well as associated position/velocity in ECI have been determined out of excess phase model, we can use the Radio Occultation Processing Package for next step, bending angle conversion. The inputs are solely a netCDF file containing all the excess phase related information and a parameter control file. **Figure 7** shows one case of the bending angle profiles using the SP3-D and cicPOD files. We notice that the SP3-D files can cause large errors in the BA, while using cicPOD can result in better solution in bending angle, which is very close to GeoOptics bending angle.

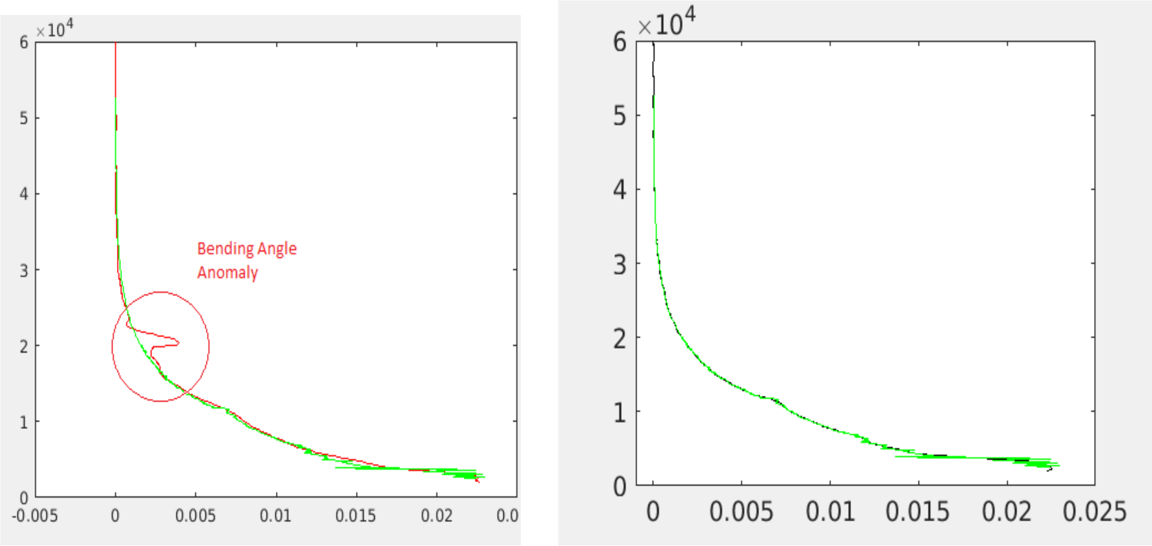


Figure 7. Bending Angle Profiles using GeoOptics SP3-D (left) and cicPOD orbit products.

5. Recent STAR RO validation and application highlights

With in-house experts of radiosonde data (NPROVS), IR data (NUCAP), and MW data (MiSR), STAR GNSS RO team has demonstrated the CWDP RO validation using available in house developed CrIS, AMT, and RAOB data. Significant contributions by STAR to the Commercial Weather Data Pilot projects in the past two years has provided the foundation for continued work for the next phase of the CWD-RO, especially in the in-house expertise to perform satellite (IR/MW) and in situ (radiosonde) inter-comparison to validate the CWD RO data, which is essential for the success of NOAA's CWD program.

The STAR processed COSMIC-2 retrievals are used to understand the quality of the RO raw phase delay data and to quantify the structural uncertainty of the derived bending angel profiles and refractivity profiles when different inversion methods and initialization approaches are implemented. The related COSMIC-2 tasks and their corresponding completion rate are:

- Participate in the COSMIC-2 "Neutral Atmosphere cal/val plan" (100% completion);
- Perform inter-comparisons of RO measurements among RO satellites and other sources (100% completion);
- Develop tools to support the COSMIC-2, KOMPSAT-5, PAZ and MetOP activities (85% completion);
- Perform Operational monitoring of RO instruments and derived data with the Integrated Calibration/Validation System (ICVS) (85% completion);
- Develop web interface for the ICVS monitoring to include identification of RO-derived data quality trending correlated with source, time and geolocation (90% completion);
- Develop bias monitoring regime including calculation of observed to model background (O-B) bias (90% completion);
- Perform RO observation impact assessments (working with JCSDA, AMOL, and EMC, 85% completion);

Recent STAR RO validation and application highlights can be seen in the following conference papers and journal papers.

We have given more than 15 presentations to summarize our C2 retrieval and validation results in national and international WS and conference since April 2019.

2020 (AMS)

- Shu-pen Ben Ho & Xinjia Zhou. (2020). COSMIC-2 Product Validation at NESDIS/STAR Using Global Radiosonde Observations. *American Meteorological Society*, Boston, MA, January 12-16, 2020
- Bin Zhang & Shu-pen Ben Ho. (2020). Error Assessments in the GNSS Radio Occultation Excess Phase/Bending Angle Calculation. *American Meteorological Society*, Boston, MA, January 12-16, 2020
- Changyong Cao & Shu-pen Ben Ho. (2020). The Significant Roles of COSMIC2 GNSS RO in NOAA Integrated Calibration/Validation System for NWP. *American Meteorological Society*, Boston, MA, January 12-16, 2020
- Erin Lynch & Flavio Iturbide-Sanchez. (2020). Intercomparison of Hyperspectral Infrared Sounders with Simulated Radiances from GNSS-RO Inputs *American Meteorological Society*, Boston, MA, January 12-16, 2020
- Xinjia Zhou & Shu-peng Ben Ho. (2020). NOAA Integrated Cal/Val System (ICVS) for Radio Occultation Performance Monitoring and Data Quality Assurance *American Meteorological Society*, Boston, MA, January 12-16, 2020

2019 (IROWG)

- Shu-pen Ben Ho & STAR GNSS Team NOAA/STAR. (2019). Inter-comparison between GNSS RO and hyperspectral infrared soundings and Combined Retrieval Results. *International Radio Occultation Working Group(IROWG)*, Konventum, Helsingør (Elsinore), Denmark, September 19-25, 2019
- Shu-pen Ben Ho & Xinjia Zhou. (2019). NESDIS RO Science Studies and Quality Assurance through the STAR Integrated Cal/Val System: Initial Validation of COSMIC-2 Data. *International Radio Occultation Working Group(IROWG)*, Konventum, Helsingør (Elsinore), Denmark, September 19-25, 2019
- Joint Center for Satellite Data Assimilation and CDAAC, STAR, OPPA. (2019). Commercial Weather Data Products Evaluation preliminary results. *International Radio Occultation Working Group(IROWG)*, Konventum, Helsingør (Elsinore), Denmark, September 19-25, 2019
- Xinjia Zhou & Shu-pen Ho. (2019). Construction of Temperature Climate Data Records using Multiple RO Missions. *International Radio Occultation Working Group(IROWG)*, Konventum, Helsingør (Elsinore), Denmark, September 19-25, 2019
- Bin Zhang & Shu-peng Ho, Xi Shao, Changyong Cao. (2019). Using Radio Occultation Profiles to Detect Microwave Sensor Bias for Climate Studies. *International Radio Occultation Working Group(IROWG)*, Konventum, Helsingør (Elsinore), Denmark, September 19-25, 2019
- Francois Vandenberghe& Suryakanti Dutta, Hailing Zhang, Hui Shao and James Yoe. (2019). Recent and New GNSS-RO missions: Quality Assessment and Comparative Data Assimilation. *International Radio Occultation Working Group(IROWG)*, Konventum, Helsingør (Elsinore), Denmark, September 19-25, 2019
- Stanislav Kireev & Shu-peng Ho. (2019). NOAA/STAR 1D-Var Retrieval Algorithm to Process Radio Occultation Data. *International Radio Occultation Working Group(IROWG)*, Konventum, Helsingør (Elsinore), Denmark, September 19-25, 2019

2019 (AGU)

- Shu-peng Ho & Xinjia Zhou. (2019). Climate Correction of Radiosonde Temperature Biases in the Lower Stratosphere using GPS RO data. *American Geophysical Union(AGU)*, San Francisco, CA, USA, December 9-13, 2019

Presentations in COSMIC-2 cal/val meetings:

- Ho, S.-P., et al., COSMIC-2 RO Products Validation using Satellite and In Situ Data, College Park, Sep. 10-11, 2019.
- Ho, S.-P., et al., Validation of COSMIC-2 Neutral Atmospheric Data Products using Measurements from Multiple Satellite Sensors and In situ Data, College Park, Taipei, Oct. 18-20, 2019.
- Ho, S.-P., et al., Validation of COSMIC-2 Neutral Atmospheric Data Products using In situ Data, San Francisco, CA, USA, Dec. 8, 2019.
- Ho, S.-P., et al., COSMIC-2 Product Validation at NESDIS/STAR Using Global Radiosonde Observations. *American Meteorological Society*, Boston, MA, January 12-16, 2020.

NOAA STAR team have published about 15 papers in world famous journals to summarize our inversion and validation results to demonstrate the maturity of our algorithms using other RO missions (i.e., COSMIC) as COSMIC-2 proxy data. We are preparing another four or five papers to summarize our COSMIC-2 results.

Journal papers have been published or under review:

1) Cao, Changyong, Wenhui Wang, Erin Lynch, Yan Bai, **S.-P. Ho**, 2020: Simultaneous Radio Occultation for Inter-satellite Comparison of Bending Angles towards More Accurate Atmospheric Sounding, Remote Sensing.
2) Steiner, A. K., F. Ladstädter, **S.-P. Ho**, 2020: Observed temperature changes in the troposphere and stratosphere from 1979 to 2018, J. of Climate.
3) Schröder, M., R. Bennartz, **S.-P. Ho,** 2020: Using GPS RO data as on-orbit references to calibrate Temperature in the Lower Stratosphere obtained from Satellite Microwave Sounders: Recent Results, GEWEX News letter.
4) Von Engeln, X., H. Gleisner, **S.-P. Ho**, A. Stanier, H. 2020: IPCC AR5 GPS RO section. (submitted).
5) Mears C., **S.-P. Ho**, J. Wang, H. Huelsing, and L. Peng, 2020: Total Column Water Vapor, [In "States of the Climate in 2018]. *Bul. Amer. Meteor. Sci.*, **98** (8), S24-S25, doi:10.1175/2019BAMSStateoftheClimate.1 State of the Climate.
6) Vinay Kumar; S. B. Surendra Prasad; K. Krishna Reddy; S. K. Dhaka; R. K. Choudhary; M. Venkatarami Reddy; **Shu-Peng Ho**, 2020: Temperature perturbations in the troposphere and lower stratosphere over a semi-arid region during the 2010 solar eclipse, PAAG-D-19-00515.
7) Li, ying, G. Kirchengast, B. Scherllin-Pirscher, M. Schwaerz, J. K. Nielsen, T.-K Wee, **S.-P. Ho**, and Y.-B. Yuan, 2019: new algorithm for the retrieval of atmospheric profiles from GNSS radio occultation data in moist air and cross-evaluation among processing centers, *Remote Sens.* **2019**, *11*(23), 2729; doi:10.3390/rs11232729
8) A. K. Steiner, F. Ladstädter, C. O. Ao, H. Gleisner, **S.-P. Ho**, D. Hunt, T. Schmidt, U. Foelsche, G. Kirchengast, Y.-H. Kuo, K. B. Lauritsen, A. J. Mannucci, C. Marquardt, J. K. Nielsen, W. Schreiner, M. Schwärz, S. Sokolovskyi, S. Syndergaard, A. von Engeln, J. Wickert, Consistency and structural uncertainty of multi-mission GPS radio occultation records, Atmos. Meas. Tech. Discuss., doi:10.5194/amt-2019-358
9) Mears C., **S.-P. Ho**, J. Wang, H. Huelsing, and L. Peng, 2019: Total Column Water Vapor, [In "States of the Climate in 2019]. *Bul. Amer. Meteor. Sci.*, **98** (8), S24-S25,doi:10.1175/2017BAMS State of the Climate
10) **Ho, S.-P.**, Achieving interoperability between Global Navigation Satellite System (GNSS) and GSICS: using GPS-RO as an on -orbit reference for Microwave Satellite sounders, GSICS News letter, doi: 10.25923/j01d-g110, Vol.13 No 1, 2019.
11) Yunheng Xue, Jun Li, W. Menzel Paul, Eva Borbas, **Shu-Peng Ho**, and Zhenglong Li, 2018: Impact of Sampling Biases on the Global Trend of Total Precipitable Water Derived from the Latest 10-Year Data of COSMIC, SSMIS and HIRS Observations, JGR (accepted).
12) **Ho, S.-P.**, R. A. Anthes, C. O. Ao, S. Healy, A. Horanyi, D. Hunt, A. J. Mannucci, N. Pedatella, W. J. Randel, A. Simmons, A. Steiner, F. Xie, X. Yue, Z. Zeng, 2019: The COSMIC/FORMOSAT-3 Radio Occultation Mission after 12 years: Accomplishments, Remaining Challenges, and Potential Impacts of COSMIC-2, *Bul. Amer. Meteor. Sci.,* DOI: 10.1175/BAMS-D-18-0290.1
13) **Ho, S.-P.**, Anthes, R. A., Zhang, H., Chen, S., 2019: Improving the Impact of Radio Occultation Observations on Numerical Forecasts of Tropical Cyclones, JCSDA Quarterly Newsletter, No. 62, Winter 2019, pp11-17. doi:10.25923/w2dh-ep66.
14) Vandenberghe, F., Shao, H., Dutta, S., Zhang, H., Ruston, B., McCarty, W., Ho, S., Cucurull, L., Yoe, G. J., 2019: Global Navigation Satellite Systems Radio Occultation Data Assimilation at JCSDA, JCSDA Quarterly Newsletter, No. 62, Winter 2019, pp7 -11. doi:10.25923/w2dh-ep66.
15) Mears C., **S.-P. Ho**, J. Wang, H. Huelsing, and L. Peng, 2019: Total Column Water Vapor, [In "States of the Climate in 2018]. *Bul. Amer. Meteor. Sci.*, **98** (8), S24-S25, doi:10.1175/2017BAMS State of the Climate.

Papers are in preparation:

1) Shao. S., S.-P. Ho, COSMIC-2 Radio Occultation data quality evaluation through collocation-based and O-B inter-comparison

2) Shao. S., S.-P. Ho, Inter-calibration between COSMIC-2 Radio Occultation and SNPP and NOAA-20 CrIS through Radiative Transfer Modeling.

3) Shao. S., S.-P. Ho, Inter-comparison of COSMIC-2 Radio Occultation Retrieval Data with SNPP and NOAA-20 ATMS Measurements through Radiative Transfer Modeling

4) Kireev, S., and S.-P. Ho, COSMIC-2 1D Var inversion algorithm Water Vapor Retrievals in Tropical Moisture troposphere, Remote Sensing.

5) Adhikari, L. and S.-P. Ho, Inverting COSMIC-2 Phase Data to Bending Angle and Refractivity Profiles using the Full Spectrum Inversion Method, Remote Sensing (ready to submit).