A Completed Simulation Tool to Explore the Optimal Configuration for the NOAA's Future GNSS RO Architecture Missions

Tung-Chang Liu[1], Shu-Peng Ho[2], Xi Shao[1], and Yong Chen[2]

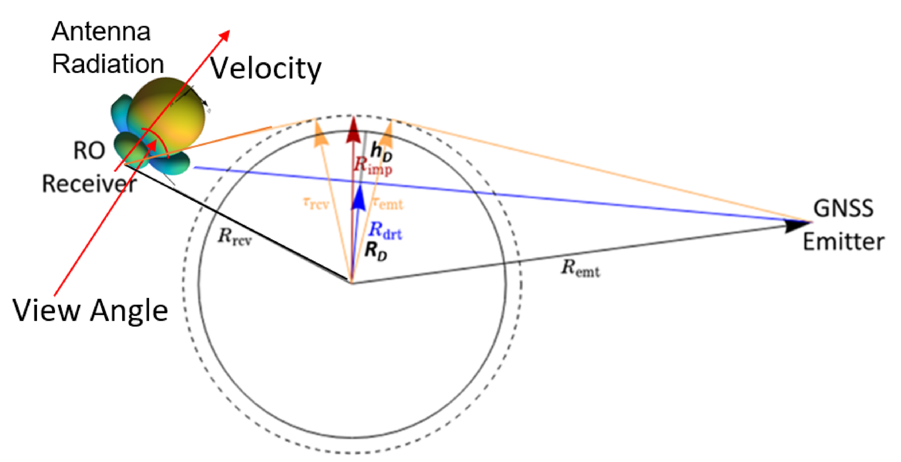
1. Cooperative Institute for Satellite Earth System Studies (CISESS), ESSIC, University of Maryland, USA

2. NOAA/NESDIS/STAR, USA

Introduction

- NOAA has included Global Navigation Satellite System (GNSS) Radio Occultation (RO) data as one of the crucial long-term observables for weather and climate applications. Currently, NOAA includes about 12K occultations per day from COSMIC-2, commercial cubesats, and partners' missions in its global weather forecast system. NOAA is also exploring optimal configurations for future RO architecture missions that will fulfill the need for climate study and weather forecasting. To fully explore the potential mission opportunities, we must carefully examine the optimal spatial and temporal coverage of the backbone RO observations (minimum RO constellation needed) with information on minimum latency for weather forecasts.
- With different receiver antenna designs, not all the data collected from different RO missions are of the same quality, especially in the lower troposphere. The signal-to-noise ratio (SNR) from various missions usually indicates the strength of RO signals penetrating the lower troposphere. The most dominant factors that affect the magnitude of SNRs and their spatial distribution include i) the GNSS emitter's signal power, ii) the receiver intermediate frequency bandwidth, iii) RO antenna design, iv) the antenna gain pattern related to the viewing geometry, and v) the azimuth angle (the angle between the occultation plane and the direction to the true North). We must also include information on the above factors in the optimal configurations for future RO architecture.
- This study reports the development of a simulation tool to explore the optimal configuration for future GNSS RO architecture missions for NOAA.
- ➢ Efficient algorithm for predicting RO limb-sounding events between GNSS transmitters and LEO RO receivers. Two Line Element (TLE) orbital data of GNSS and LEO Satellite for orbital tracking; Predict RO occurrences for their time, location (longitude and latitude), and occurrence of rising or setting RO limb-sounding events.
- ➢ Project temporal and spatial RO occurrences and SNR distributions for RO missions, accommodating different receiver antenna designs (single patch antenna vs. beam steering phased array antenna) and incorporating GNSS transmitters like GPS, GLONASS, Galileo, and BeiDou.
- Examine the RO occurrence coverage for existing missions such as NOAA JPSS, COSMIC-2, EUMETSET METOP, NASA CYGNSS with hypothetical GNSS receivers. The particular latitudinal distribution of COSMIC-2 SNR due to using the phased array antenna will be explained from the simulation.
- Simulate the hypothetical RO receiver constellations with different orbital inclination angles to explore the optimal spatial, temporal, coverage configurations.

Prediction and Modeling Algorithm for Radio Occultation Opportunity between GNSS and RO Receiver



Geometric relationships:

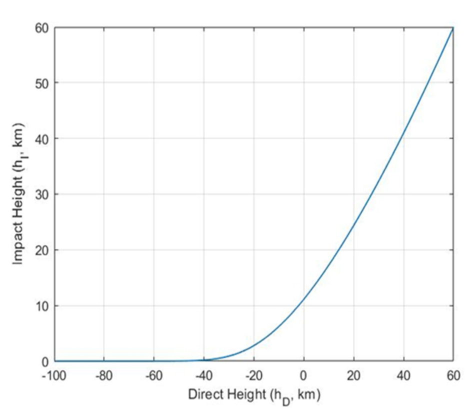
(1) $\|\mathbf{R}_{drt}\| = R_E + h_D = R_D$

(2) $\|\mathbf{R}_{imp}\| = \|\boldsymbol{\tau}_{rcv}\| = \|\boldsymbol{\tau}_{emt}\| = R_E + h_I = R_I$

(3) $\boldsymbol{\tau}_{rcv} \perp (\mathbf{R}_{rcv} - \boldsymbol{\tau}_{rcv})$

(4) $\boldsymbol{\tau}_{emt} \perp (\mathbf{R}_{emt} - \boldsymbol{\tau}_{emt})$

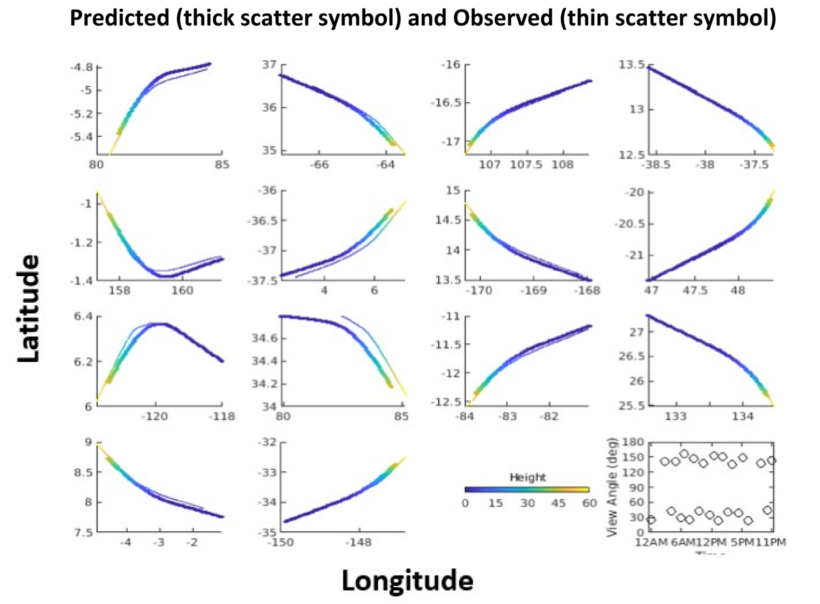
(5) $\mathbf{R}_{imp} // (\boldsymbol{\tau}_{emt} + \boldsymbol{\tau}_{rcv})$



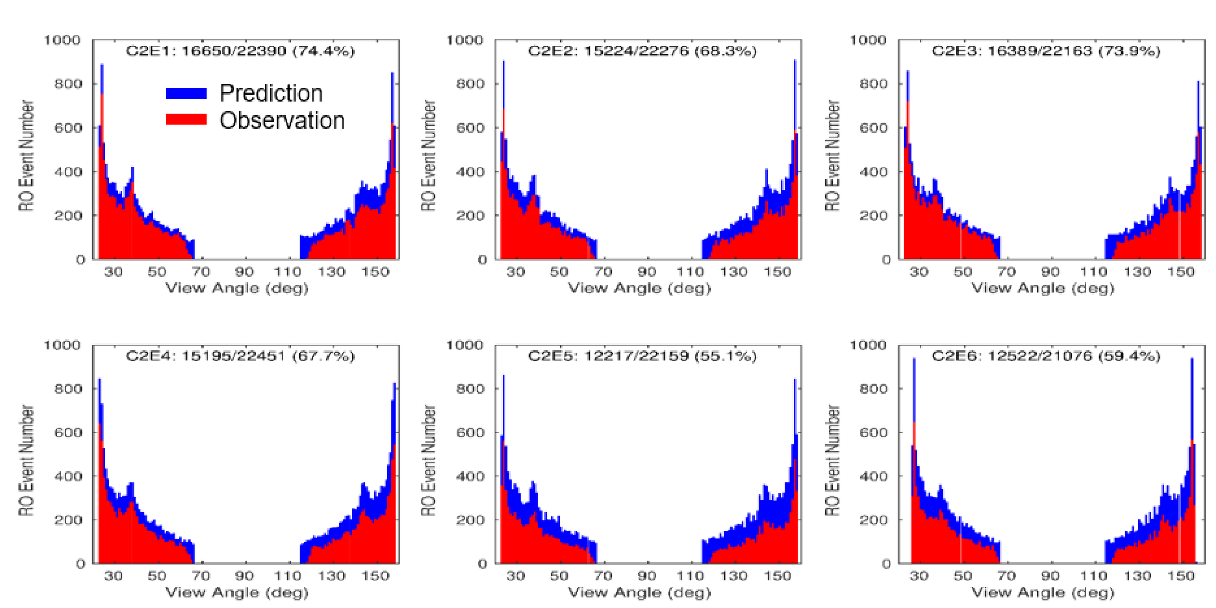
- Simplified orbital Perturbation Model (SGP4) with Two-Line Element (TLE) inputs to predict the positions and velocities of LEO and GNSS satellites
- Relation between R_{direct} and R_{impact} from learning
- Outputs: predicted time , location and viewing geometry of rising/setting RO profiles
- Modeling of antenna radiation pattern for a given antenna design and coupling with RO viewing geometry to simulate SNR distribution
- Chen, Y.; Shao, X.; Cao, C.; Ho, S.-p. Simultaneous Radio Occultation Predictions for Inter-Satellite Comparison of Bending Angle Profiles from COSMIC-2 and GeoOptics. *Remote Sens.* **2021**, *13*, 3644. https://doi.org/10.3390/rs13183644

Ground Track Comparison (Latitude, Longitude, and Distance)

Predicted (thick scatter symbol) and Observed (thin scatter symbol)



RO Event Distribution as a Function of Antenna View Angle



- Validation of predictions by comparing predicted COSMIC-2 RO events with the actual COSMIC-2 RO observations.
- The matched RO pairs (predicted vs. actually observed) are mostly consistent in latitude, longitude and height. For a given height, the distance between predicted and observed RO pair are mostly within 15 km.
- The distributions of the predicted potential RO events for C2E1 to C2E6 are very similar, with a maximum at 24° (View Angle) for the forward antenna and 157° for the backward antenna, almost symmetrical pattern between the forward and backward directions

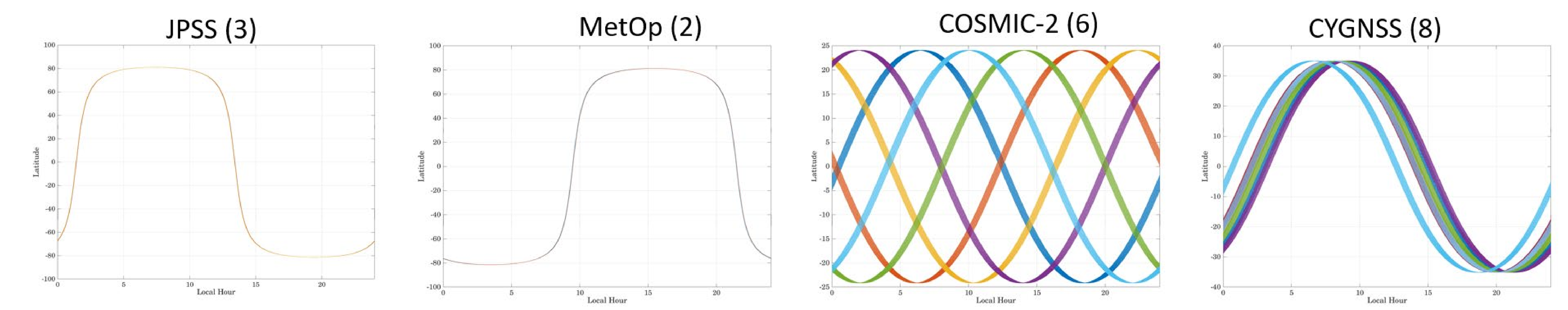
RO Opportunities with Current NOAA, NASA and EUMETSET Missions

LEO and GNSS Satellites used in the analysis

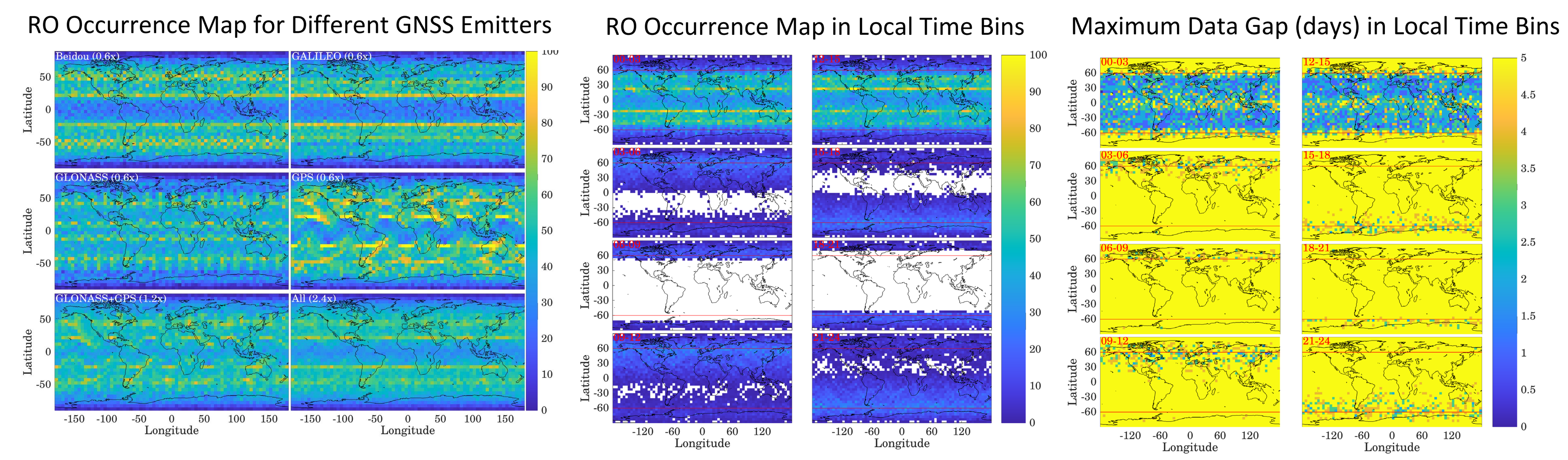
GNSS	GPS	GLONASS	Galileo	Beidou
# of Satellites	31	24	28	40 (GEO Excluded)

LEO	JPSS	METOP	COSMIC-2	CYGNSS
# of Satellites	3	2	6	8
Orbital Inclination	98.79°	98.7°	24°	35°
Altitude	833 km	817 km	520-550 km	536 km
Note	Sun-Sync LTAN: 13:30	LTAN: 9:30		

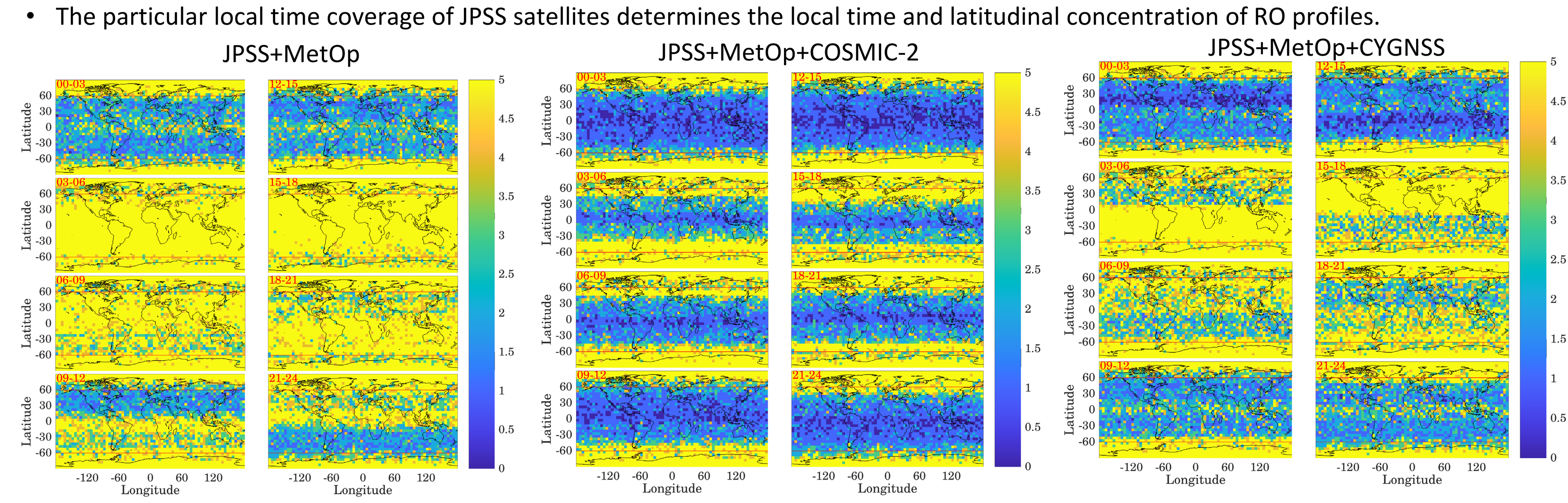
Orbital Local Time Map



JPSS (NOAA-21/NOAA-20/SNPP) (Sun-Synchronous Polar-Orbit) with GNSS Receivers (Hypothetical)

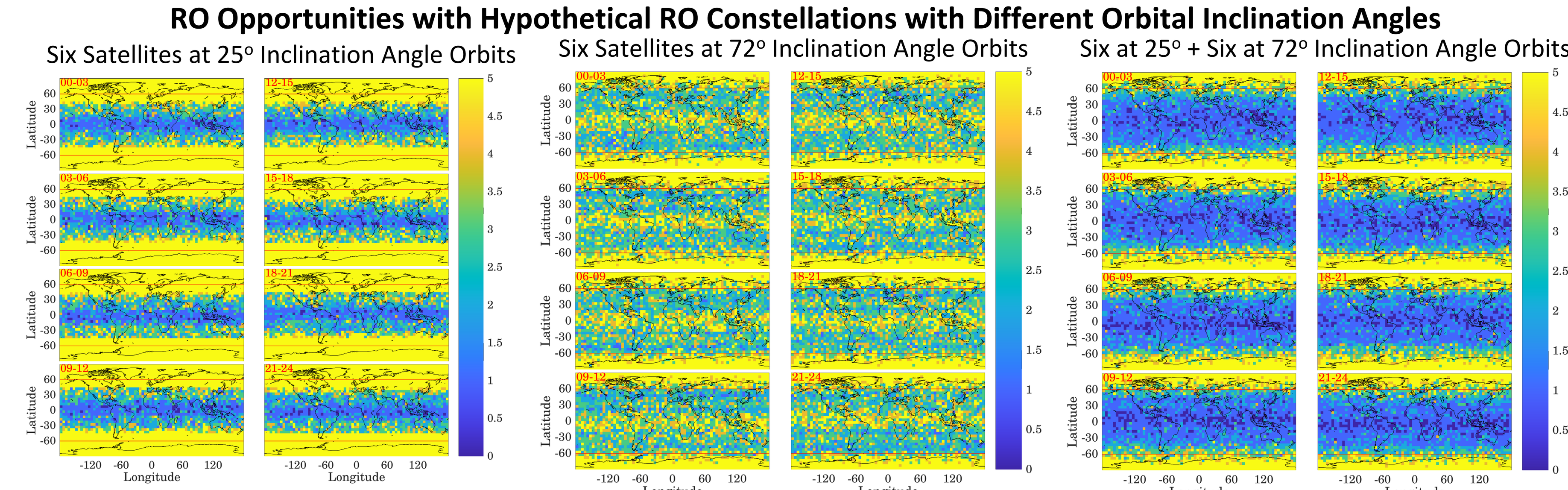


- Maximum Data Gap (days) map is defined as the gap between days with the occurrence of a minimum of 1 RO profile in a given 5°x5° grid.
- Max. Data-Gap Map at different local time bins can reveal the gaps in the coverage for a give RO sensor constellations.
- The particular local time coverage of JPSS satellites determines the local time and latitudinal concentration of RO profiles.



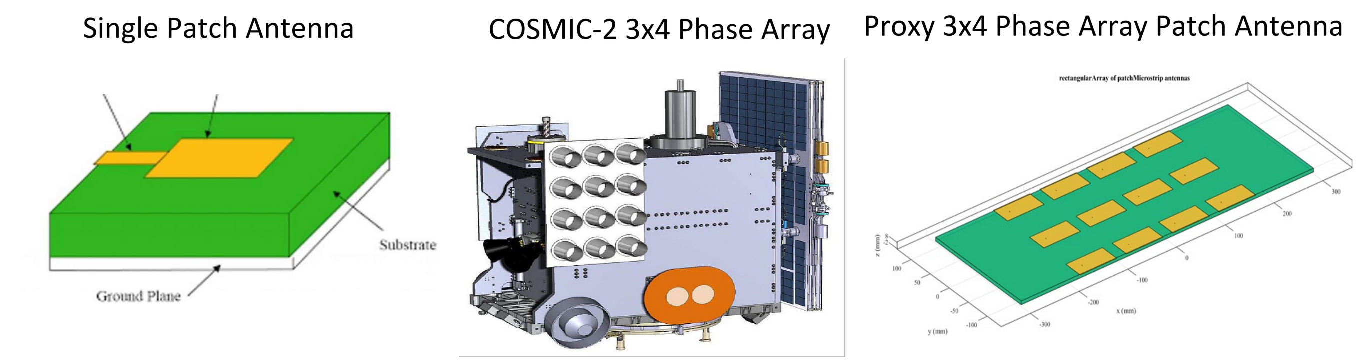
- By leveraging the existing missions such as JPSS (afternoon orbit) and MetOp (morning orbit), about 4 local time bins can be covered.
- JPSS+MetOp+COSMIC-2 provides better local time and latitude coverage than other combinations such as JPSS+MetOp+CYGNSS.

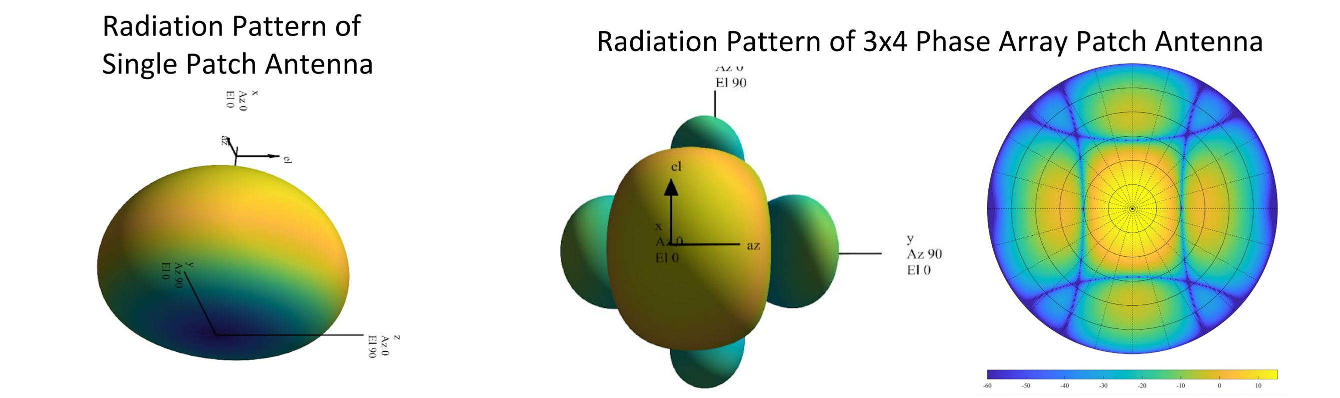
RO Opportunities with Hypothetical RO Constellations with Different Orbital Inclination Angles

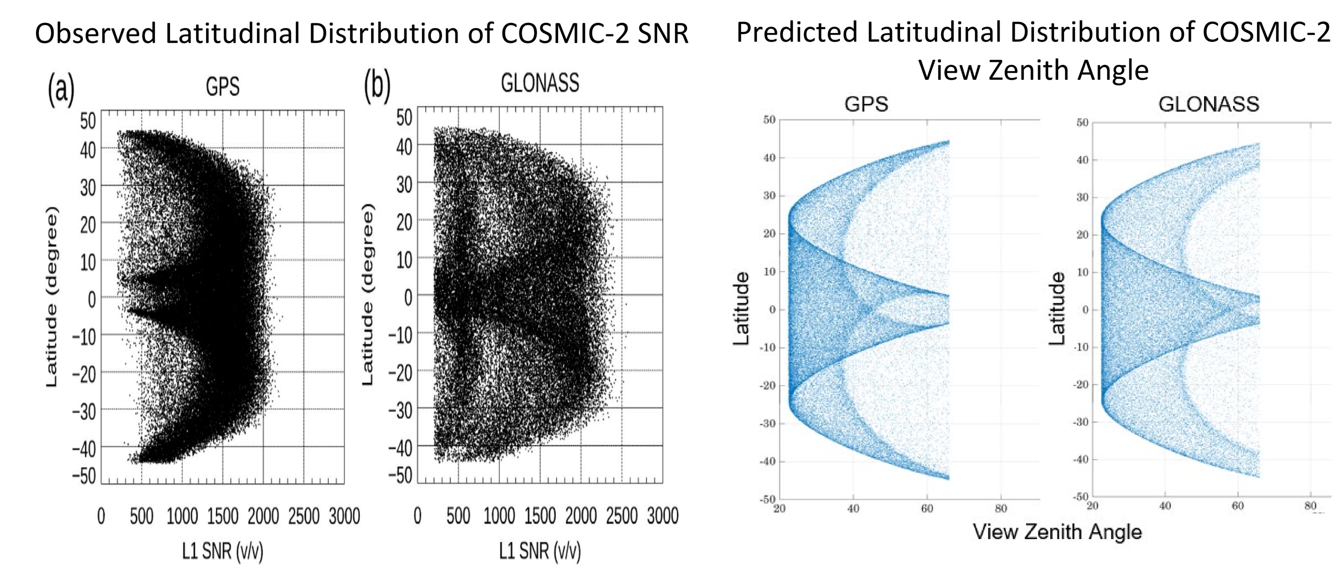


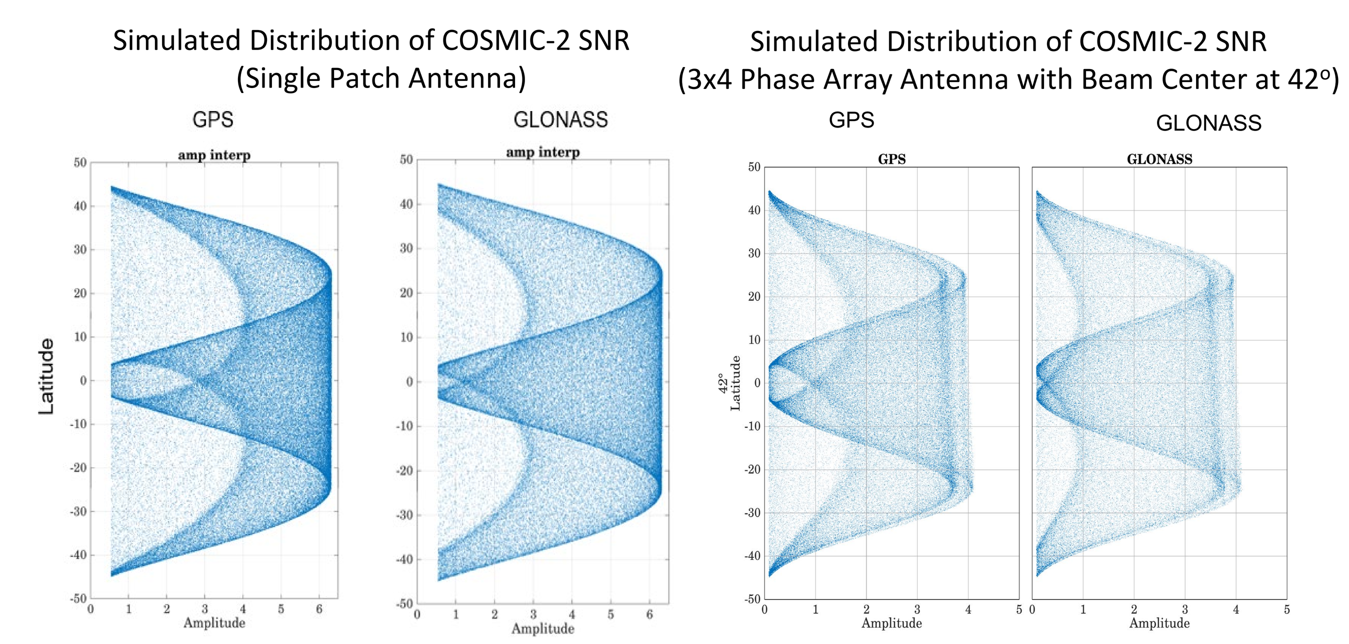
- One RO constellation (6 satellites) with low inclination angle orbits + one RO constellation (6 satellites) with high inclination orbits can provide mostly < 1 day data gap in the global 5°x5° grids over -60 to 60 degree latitude region; Further optimizations can be performed with varying number of satellites and orbital inclination angles.

Antenna–Coupled Modeling of RO SNR Distribution



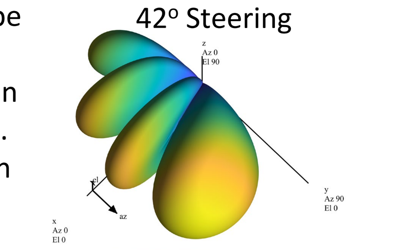






- By coupling antenna radiation pattern modeling with RO opportunity prediction, the SNR distribution of RO mission can be predicted and assessed.
- The tool can be used to assess the SNR distribution of RO mission with different antenna designs and coupled with different GNSS.
- The difference of latitudinal COSMIC-2 SNR distribution between GPS and GLONASS can be predicted with the tool.

3x4 Phase Array with 42° Steering



Summary

- Presented an efficient tool to predict potential RO events from the TLEs of GNSS and LEO satellite, and coupled with antenna radiation pattern modeling to predict SNR distributions.
- COSMIC-2 RO observations are used to validate the method in terms of ground track, RO event distribution as a function of view angle, and SNR distributions.
- Performed RO occurrence perditions for future RO missions by
- ➢ Leveraging existing NOAA JPSS and ESA MetOp missions with COSMIC-2-like constellation
- ➢ Simulating hypothetical constellations with different orbital inclination angles.
- ➢ Combination of low inclination + high inclination angle RO constellations can provide minimum global data gap over the -60 to 60 degree latitude region.
- The simulation tool is extremely useful for exploring optimal RO coverage tailored to the weather forecasting needs regarding global and local time and SNR coverage with a combination of planned NOAA missions and additional RO constellations.

Acknowledgements

The scientific results and conclusions, as well as any views or opinions expressed herein, are those of the author(s) and do not necessarily reflect those of NOAA or the Department of Commerce.