Multi-Constellation, Multi-Frequency Simulation of Ionospheric Scintillation along Radio Occultation Raypaths and Potential Impacts on Tropospheric Retrievals

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Abstract

In recent years, the need for improved global terrestrial and space weather specification and forecast has driven the development of new commercial satellite constellations to monitor radio occultations (RO) using Global Navigation Satellite System (GNSS) signals. These signals interact with irregularities in the ionosphere, causing radio wave scintillation that is known to degrade the performance of communication and navigation systems, and may also degrade the accuracy of RO tropospheric and stratospheric retrievals. This January, PlanetiQ will launch the first two of its planned 20 microsatellites commercial constellation (to be complete by 2022), focused on weather and space weather forecasting and climate. With this constellation, PlanetiQ intends to provide over 80 million global observations per day. The focus of this paper concerns a simulation study we conducted to assess possible impacts on tracking and tropospheric retreivals due to ionospheric scintillation. We constructed a 3D, time-dependent model for the strength, orientation, and spectral characteristics of the irregularities. Our methodology generates representative realizations of irregularity structure (space weather) rather than average conditions (climatology). We integrated through the model along each RO ray-path to determine the strength and location of an equivalent phase screen, which we used to generate realizations of intensity and phase scintillation at the receiver. The phase screen calculation is a generalization of our previous algorithm (Carrano et al., Radio Sci., 2011) which now admits propagation and scanning at arbitrary angles to the magnetic field. There were approximately 50,000 RO events between the 20 PlanetiQ microsatellites and the satellites of the GPS, GLONASS, Galileo, and BeiDou GNSS constellations each day. We simulated scintillation for each carrier frequency transmitted by each GNSS satellite for a total of 39 days. We discuss potential impacts of scintillation on satellite tracking and the accuracy of tropospheric retrievals as a function of season and solar activity. We compare the scintillation index (S4) along each RO raypath with a vertical propagation path through the same irregularities. These are compared with observations from the CORISS instrument onboard the C/NOFS satellite and ground based observations from the SCINDA network.

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Abstract

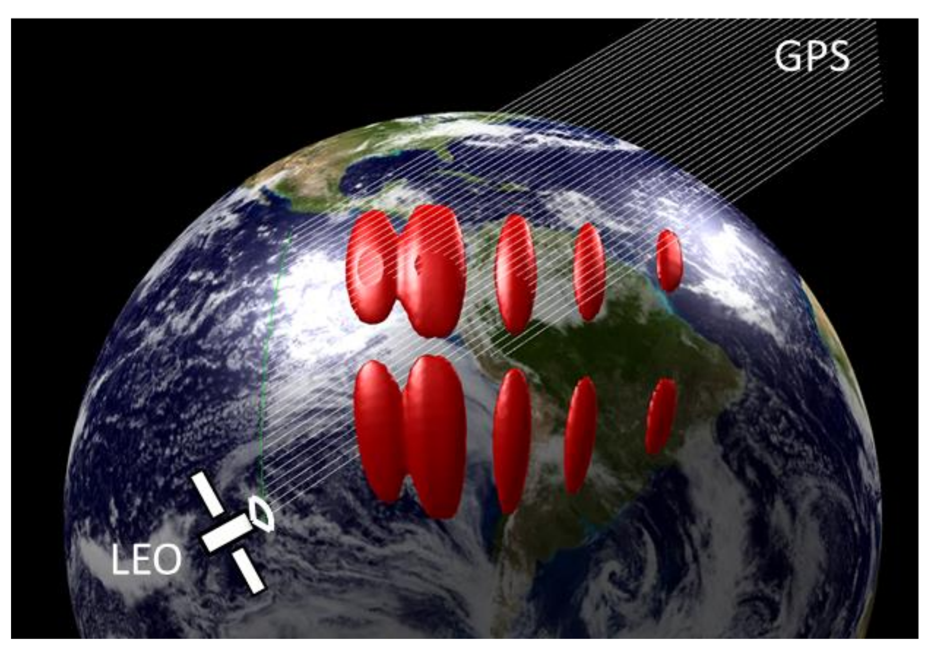
In recent years, the need for improved global terrestrial and space weather specification and forecast has driven the development of new commercial satellite constellations to monitor radio occultations (RO) using Global Navigation Satellite System (GNSS) signals. These signals interact with irregularities in the ionosphere, causing radio wave scintillation that is known to degrade the performance of communication and navigation systems, and may also degrade the accuracy of RO tropospheric and stratospheric retrievals. This January, PlanetiQ will launch the first two of its planned 20 microsatellites commercial constellation (to be complete by 2022), focused on weather and space weather forecasting and climate. With this constellation, PlanetiQ intends to provide over 80 million global observations per day. The focus of this paper concerns a simulation study we conducted to assess possible impacts on tracking and tropospheric retrievals due to ionospheric scintillation. We constructed a 3D, time-dependent model for the strength, orientation, and spectral characteristics of the irregularities. Our methodology generates representative realizations of irregularity structure (space weather) rather than average conditions (climatology). We integrated through the model along each RO ray-path to determine the strength and location of an equivalent phase screen, which we used to generate realizations of intensity and phase scintillation at the receiver. The phase screen calculation is a generalization of our previous algorithm (Carrano et al., Radio Sci., 2011) which now admits propagation and scanning at arbitrary angles to the magnetic field. There were approximately 50,000 RO events between the 20 PlanetiQ microsatellites and the satellites of the GPS, GLONASS, Galileo, and BeiDou GNSS constellations each day. We simulated scintillation for each carrier frequency transmitted by each GNSS satellite for a total of 39 days. We discuss potential impacts of scintillation on satellite tracking and the accuracy of tropospheric retrievals as a function of season and solar activity. We compare the scintillation index (S4) along each RO raypath with a vertical propagation path through the same irregularities. These are compared with observations from the CORISS instrument onboard the C/NOFS satellite and ground based observations from the SCINDA network.

Generation of 3D Irregularity Structure

Our intent was to construct representative realizations of ionospheric structure for use in these simulations, rather than average conditions (climatology). We used the High Fidelity Ionospheric Scintillation Simulation Algorithm (IONSCINT-G) to produce global maps of the scintillation intensity index S4 along vertical (nadir) propagation paths (McNeil 2003). These S4 maps were converted to vertically integrated turbulence strength C_kL using the Rino power law phase screen scintillation theory (Rino, 1979). Assuming that $\Delta N/N$ is invariant with altitude, we constructed a simple model to extend the turbulence strength to three-dimensions:

$$C_k(\lambda,\varphi,z) = C_k L(\lambda,\varphi)\,\frac{\int_0^z N^2(\lambda,\varphi,z')\,dz}{\int_0^\infty N^2(\lambda,\varphi,z')\,dz},$$

where N is the electron density at a given latitude (λ), longitude (φ), and height (z). We used the IRI Real-Time Assimilative Modelling (IRTAM) system developed by Galkin et al. [2012] to provide the 3D distribution of electron density in the ionosphere. The figure below shows isocontours of the 3D turbulent intensity constructed in this fashion, along with the raypaths through these structures for a radio occultation between satellite piq01 and GPS PRN15 on 1 Mar 2014.



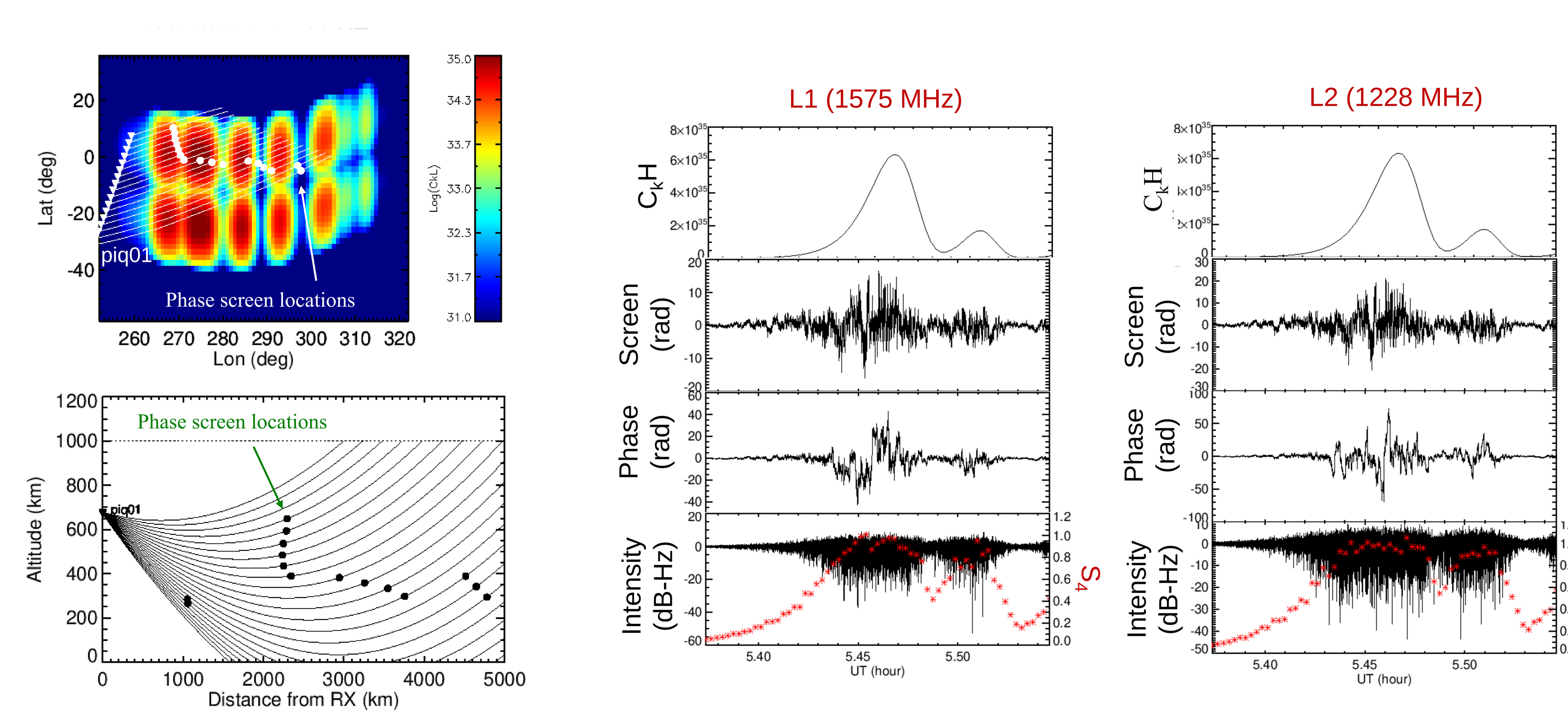
Constructing the Phase Screens

Subdivided each RO event into 10 second intervals. We constructed a phase screen to simulate the signal in each 10 second interval. A phase screen was located along each ray path at the distance (d) from the receiver that captures 50% of the integrated turbulence along that ray:

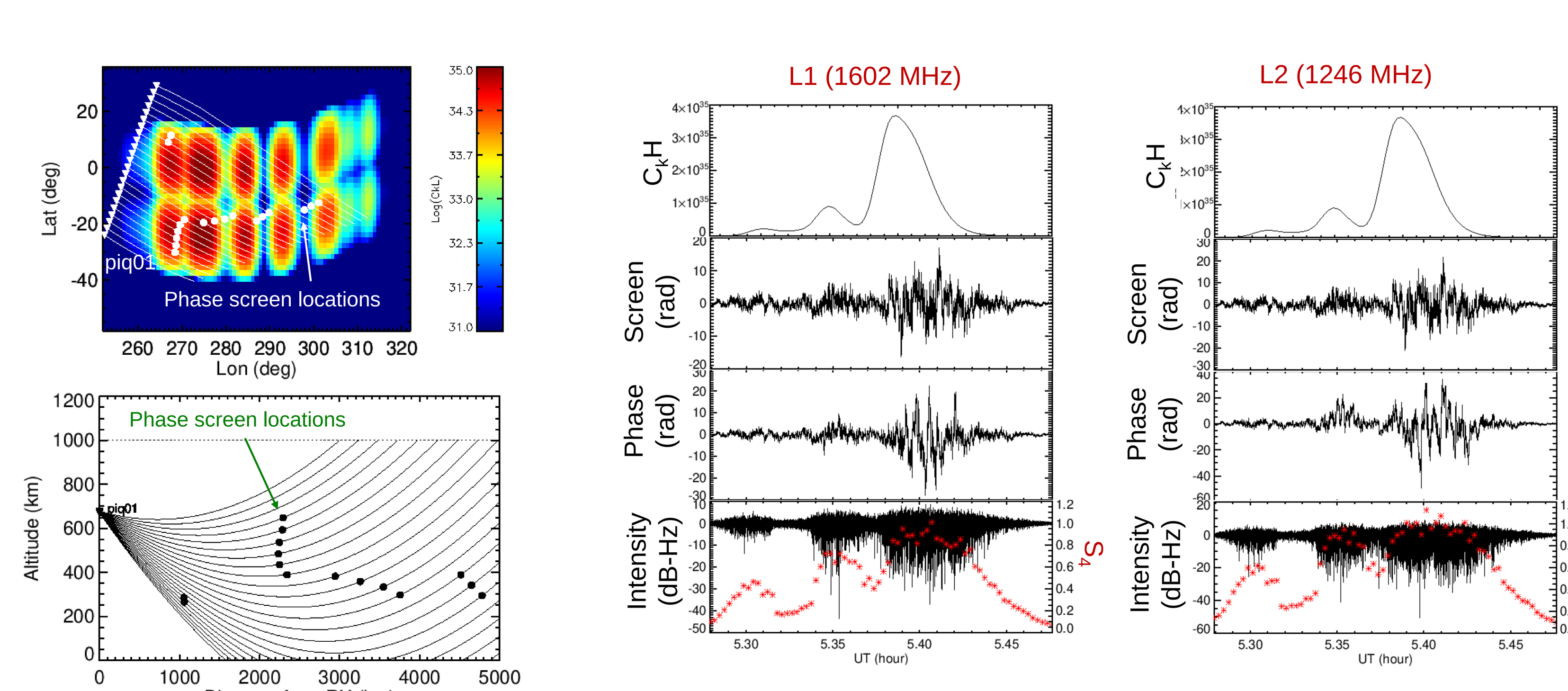
$$\int_0^d C_k(d)\,ds = 0.5\int_0^{d_T} C_k(d)\,ds,$$ where d_T is the distance from the receiver to the transmitter.

We then proceeded to simulate scintillation at multiple carrier frequencies for each of the GNSS satellite constellations using the thin phase screen propagation method. The plots below show the contours of vertically integrated turbulence strength, the locations of the phase screens (filled circles) and the RO raypaths. Also shown are the integrated turbulence strength along these (largely horizontal) raypaths, C_kH, and the, for each carrier, the phase screen and the simulated intensity and phase.

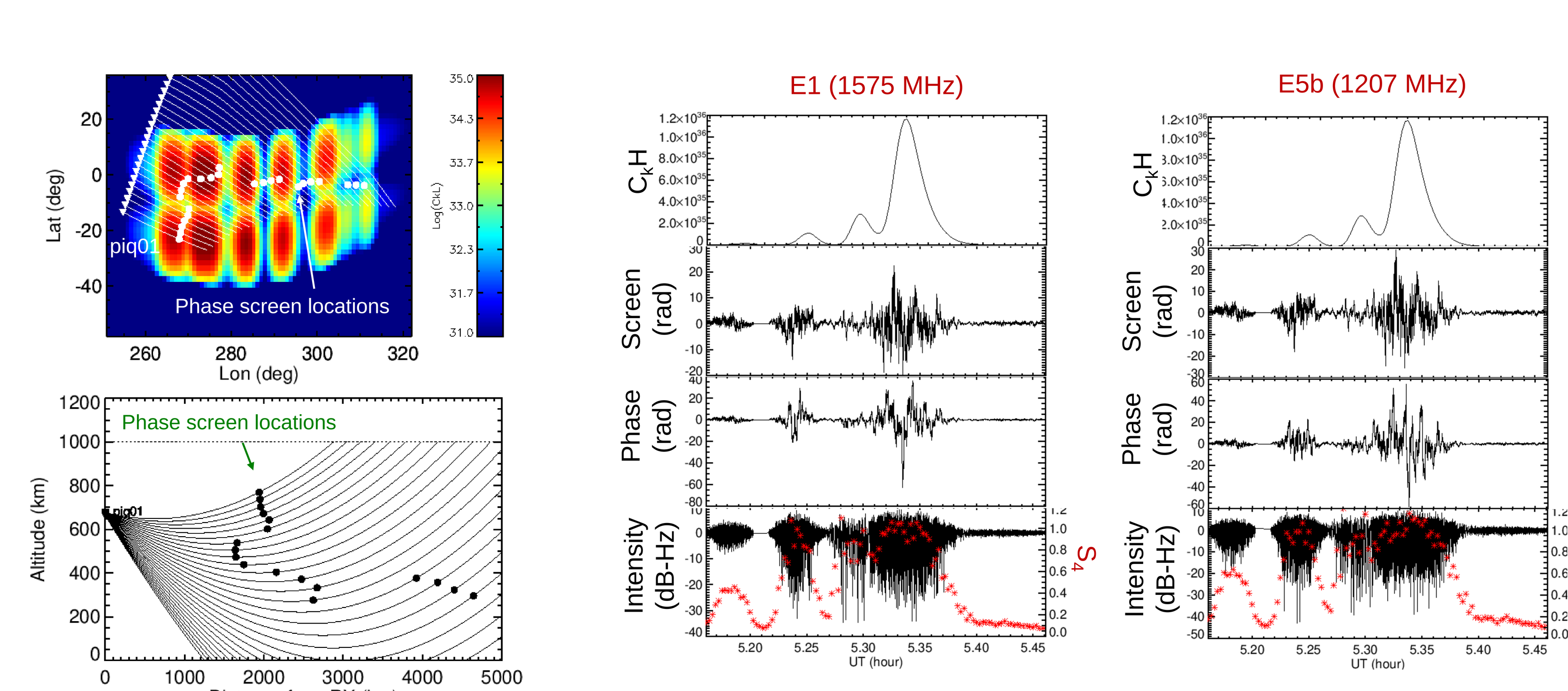
GPS



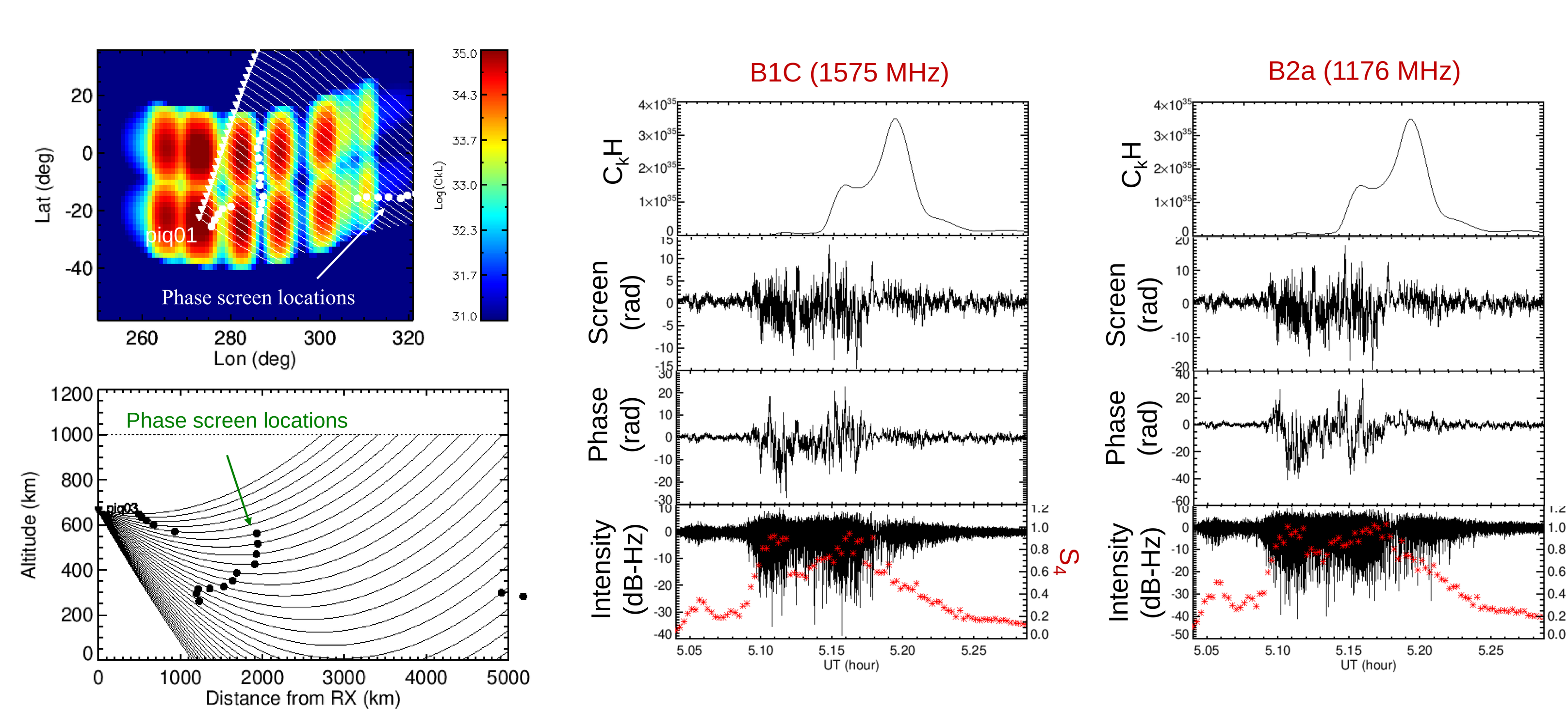
GLONASS



GALILEO

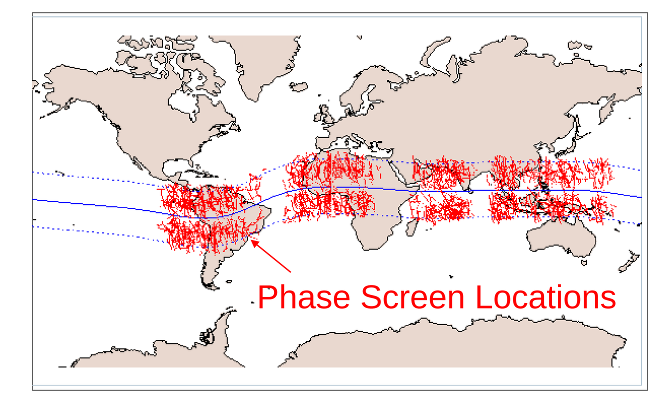


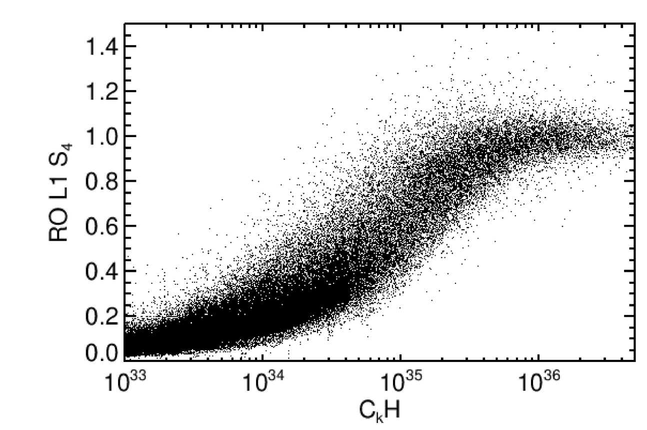
BEIDOU



Simulation Summary for a Single Day

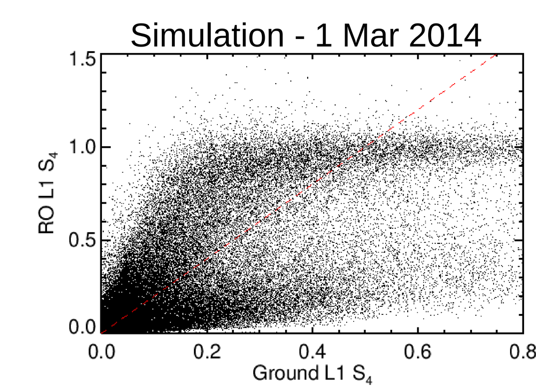
Here we show a map of the phase screen locations for all simulated GPS occultation events on 1 Mar 2014 and a plot of S4 vs turbulent strength integrated along the ray (C_kH) for each phase screen.

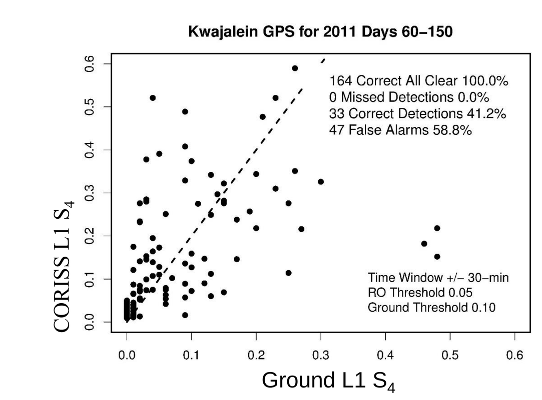




Comparing RO and Ground-Based S4

We compared the simulated scintillation index along each RO raypath with a vertical propagation path through the same irregularities at the location of each screen (left plot). This compares favorably with observations from the CORISS instrument onboard the C/NOFS satellite and ground based observations from the SCINDA network (right plot).





Summary

- We simulated RO scintillation for each carrier frequency transmitted by GPS, GLONASS, Galileo, and BeiDou constellations each day for a total of 39 days during solar minimum and solar maximum periods.
- Our methodology generates representative realizations of irregularity structure (space weather) rather than average conditions (climatology).
- Assumption that $\Delta N/N$ is invariant in altitude within bubbles yields similar ratio of RO to ground S4 as we observed with CORISS and ground-based GPS at Kwajalein.
- For computational efficiency, we placed a single phase screen along each ray. When multiple bubbles are present, it may be preferable to use a new screen for each bubble or multiple phase screens (MPS) distributed along the ray path. However, one must evaluate the magnetic field orientation at each screen location and this does increase the computational cost.
- Work continues to assess the impact of ionospheric scintillation on tropospheric retrievals.

References

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Acknowledgements

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