6.3 COMPARISONS OF SPACE-BASED GPS OCCULTATION IONOSPHERIC SCINTILLATION MEASUREMENTS WITH GROUND-BASED VHF MEASUREMENTS

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1. INTRODUCTION

Ionospheric irregularities are known to cause scintillation of transionospheric radio signals and will affect UHF/VHF communications, causing outages, and will degrade GPS precision. The most extreme scintillation occurs within a belt that is about ±15° of the earth's magnetic equator (Figure 1). Mitigation of the ill-effects of scintillation requires accurate and timely identification and forecast of the underlying ionospheric disturbances. Current capability for characterizing and predicting ionospheric scintillation is to use a network of ground-based receivers of geostationary satellite VHF transmissions (Groves et al. 1997) to detect scintillation and then extrapolate for short-term forecasts. A set of ground stations from the Air Force Research Laboratory's SCIntillation Network Decision Aid (SCINDA) has been deployed to carry out the observation portion of this effort. Figure 1 shows the location of the current stations supporting this effort. Obviously the practical limits on deploying the ground receivers limits the spatial resolution one can achieve in this approach. A way to increase the spatial resolution is to use a set of space-based radio occultation measurements. In 2006 a constellation of six satellites as part of the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC), was launched into low earth orbit to provide regular radio occultation measurements. The COSMIC satellites are equipped with L-band receivers that generate radio occultations with GPS satellites. Some preliminary results of the COSMIC mission can be seen in Anthes et al. (2008). With the six satellites, an example of the spatial coverage that can be achieved in one 24 hour period is seen in Figure 2. In this paper we examine the signal-to-noise values of the received L1 channel GPS signals on the COSMIC satellites to determine if we can identify ionospheric scintillation using computations of the S4 scintillation index. We try to validate the approach by comparing radio occultations in the vicinity of Kwajalein Atoll (9.4°N, 167.5°E) in the Marshall Islands (see Fig. 1) with near vertically pointing ground-based VHF signal to noise measurements from the Kwajalein SCINDA site.

2. RADIO OCCULATIONS

The geometry of the COSMIC radio occultations is presented in Figure 3. A typical occultation lasts only a few minutes. The most significant change in the geometry during the occultation is the occultation's tangent point height from the earth. Only when the tangent point height is below 120 km MSL is the signal to noise sent down via telemetry at 50 Hz (1 Hz at other times) thus limiting the useful part of the occultations for this study.

An example of the signal-to-noise plot for an occultation is shown in Fig. 4. As the tangent point height gets lower, terrestrial weather effects dominate the signal. To determine what tangent point heights are relevant for ionospheric scintillation computations

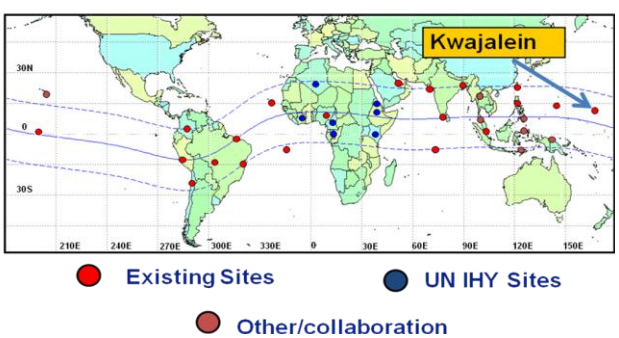

Figure 1. Magnetic equator (solid line), typical latitudinal extent of equatorial scintillation (dashed lines), and SCINDA ground station locations (dots).

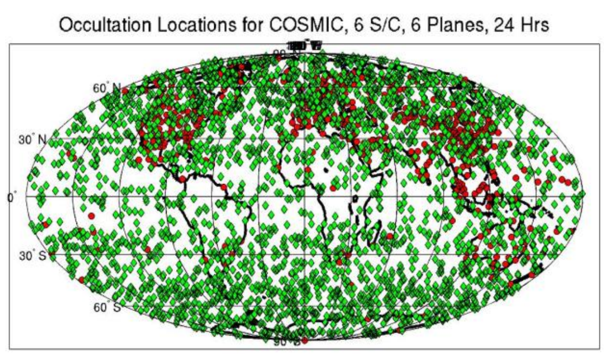

Figure 2. Occultation locations for six COSMIC satellites (green dots) in a typical 24 hour period.

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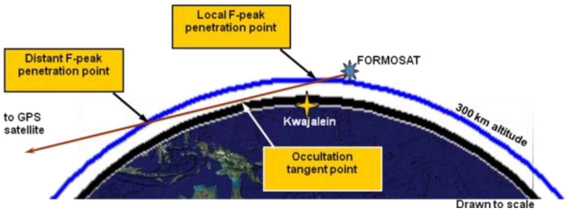

Figure 3. Radio occultation geometry between COSMIC (FORMOSAT) and GPS satellites.

an automated procedure was employed. The procedure computes a reference signal-to-noise at a mean height well above where any terrestrial weather effects would occur (110-120 km) and compares that with a running mean of signal-to-noise values as the occultation progresses. Once the running mean deviates by > 30% from the reference mean, the ionospheric portion of the occultation is terminated. As a hard stop no data below 35 km is used for the ionospheric study.

For the ionospheric portion of the occultation the S4 index is computed,

$$S4 = \sqrt{\frac{\overline{I^2} - \overline{I}^2}{\overline{I}^2}}$$

where *I* is the signal-to-noise value in 0.1*volts/volts.

Examination of the resulting S4 computations and signal-to-noise plots revealed that some preprocessing was needed prior to comparing with the ground-based measurements. In particular two different types of cases needed to be addressed. The first case was obviously spurious data because the signal-to-noise showed high speed frequency noise with constant amplitude. We suspect that this is radio frequency interference caused when the tri-band beacon on the satellites is turned on although we have to yet to try to prove it conclusively. These cases were removed by computing the energy spectra on the ionospheric portion of the occultation and looking for situations where there was substantial energy at the higher frequencies. These cases were thrown out. The second situation was cases where there were significant but isolated spikes in the occultation signal-to-noise ratios from the GPS satellites. An example is shown in Fig. 5. These spikes will elevate the S4 value for the occultation. We don't doubt that there a physical phenomena causing these signals, most likely E-layer structures; however they are not cases of ionospheric scintillation and should not cause any significant effect on radio signals. To account for these situations, a running S4 is computed every for 2 sec of data (100 points) during the ionospheric portion of the occultation. If a running S4 value is 3.5 times the standard deviation of all the running S4s, that section of the occultation is replaced by a linearly interpolated value of the signal-to-noise ratio from before and after the spurious section. By doing this we are still able to use these occultations in our study.

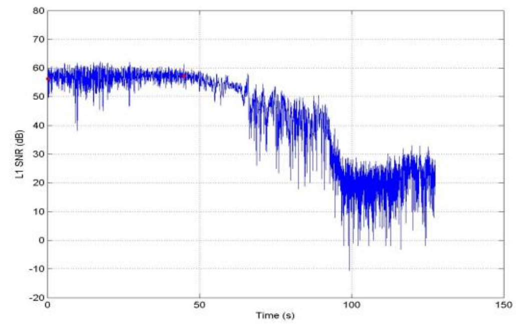

Figure 4. Example of GPS received signal-to-noise plot displaying effects of ionospheric scintillation. The area between the red dots indicate the ionosphere-only portion of the occultation.

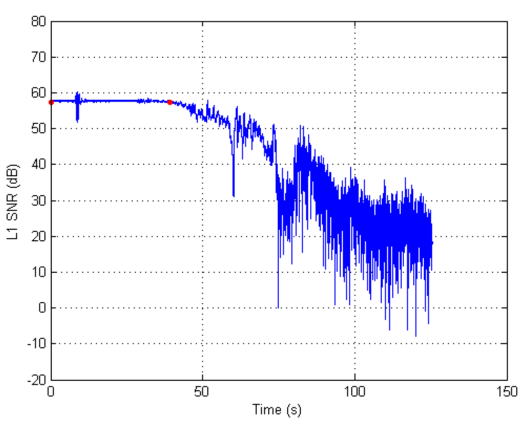

Figure 5. Example of COSMIC received signal-to-noise plot displaying a singular event.

3. RESULTS

We examined COSMIC radio ocultations that had at least one F-peak penetration point (estimated at 350 km) within 15° of Kwajalein from the period 12 July 2006 to 24 March 2007. There where a total of 223 occultations available during this time. It should be noted that six COSMIC satellites did not achieve their final orbits and separations until near the end of our data collection period. Some of the 223 occultations were discarded due to the high-frequency noise problem identified above or the fact that there were no coincident ground measurements available at Kwajalein at the time of the occultation. This resulted in 146 occultations being used for comparisons in this study.

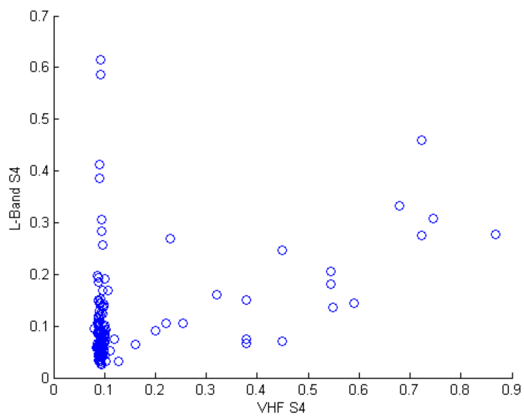

Figure 6. Scatter plot of COSMIC occultation S4 values versus ground-based VHF S4 values at Kwajalein

A scatter chart showing the S4 values observed from the fixed-point VHF receiver at Kwajalein with L-band S4 values from the COSMIC occultation is shown in Fig. 6. Ignoring for the moment the large number of points along the 0.1 VHF S4 axis, you can see that for VHF S4s > 0.15 the relation between the VHF S4s at Kwajalein and the L-band S4s from the COSMIC occultations is about what one would expect given the S4 frequency dependence found by Fremouw et al (1978). Given the GPS L1 frequency of 1.573 GHz and VHF frequency of 244 MHz you would expect an approximate 1:5 relationship between their respective S4 values below 0.6. Above 0.6 as noted by Fremouw et al (1978) both sets of values trend towards unity.

While the above relationship is a hopeful sign of the utility of using the space-based GPS occultations for identifying scintillation, the number of cases where the COSMIC occultations registered a S4 above 0.2 and the ground-based measurement was 0.1 (essentially the measurement floor) is distressing. To gauge the magnitude of the problem we created the contingency shown in Table 1 that relates the prediction of VHF S4 > 0.3 based on the observation of L-band S4 > 0.2. From this we can compute the Probability of Detection (PoD--fraction of cases where VHF S4 >0.3 is correctly predicted by L-band > 0.2) and the False Alarm Rate (FAR--fraction of cases where VHF S4 >0.3 is incorrectly predicted by L-band > 0.2). The resulting PoD and FAR are 0.47 and 0.53 respectively. This is not indicative of a procedure with much skill.

We looked into the most egregious false alarm cases where the L-band S4 was >0.2 while the VHF S4 were ≤ 0.1. We found that some of these cases were occurrences where at the time of the occultation the VHF S4 at Kwajalein was relatively benign but that at a later time enhanced values were seen. An example is shown in Fig. 7. The signal-to-noise ratio in 7a shows scintillation while at the same time the Kwajalein S4

	VHF S4 > 0.3	
L-Band S4 > 0.2	**YES**	**NO**
YES	**7**	**8**
NO	**8**	**123**

Table 1. Contingency table of the prediction of scintillation by COSMIC L-band S4 verified by SCINDA VHF S4.

receiver was quiet. However approximately 2 hours later the Kwajalein receiver was experiencing significant scintillation as seen in 7b. Panel 7d shows the geographical locations of the F-peak penetration points relative to Kwajalein. Based on longitudinal difference between the Kwajalein and the closest F-peak penetration point an approximate drift velocity of approximately 30 m/s would be needed for an ionospheric irregularity to migrate to Kwajalein. Given the time of night (20:00-01:00 LT) this is a reasonable drift velocity. We did attempt to automate a process to account for drift velocity in order to identify cases like this, however the variability of the drift velocities made this difficult.

4. DISCUSSION

If we consider the fixed-point VHF scintillation measurements as our "ground truth" for verifying the COSMIC occultation simulations, then based on the results presented above one might not think that the space-based approach is very useful. However we did identify cases where we saw scintillation with the VHF receiver within a few hours of the occultation which accounting for plausible drift velocities would verify the scintillation observed by the COSMIC occultation. For other cases where the COSMIC occultation has significant scintillation but no scintillation is observed by the VHF receiver during the night there also may be a physical solution. We have observed cases using the ARPA Long-Range Tracking and Instrumentation Radar **(**ALTAIR**)** at the Ronald Reagan Test Site on Kwajalein where ionospheric irregularities develop to the west or east of the site but never advect over it. Therefore unless the occultation and ground receiver are nearly geographically co-located we cannot be absolutely certain that a case is truly a false alarm or a missed detection.

While we need to examine more cases than what are presented here we feel confident that the additional data will reinforce our preliminary conclusion that space-based occultations can be a viable and accurate source of radio scintillation information, providing substantially more spatial resolution than what is available from ground networks such as SCINDA. However it is important to realize that ground networks still are an important component to scintillation detection and forecasting because they still provide a temporal resolution that could only be matched by a prohibitively large constellation of GPS receivers.

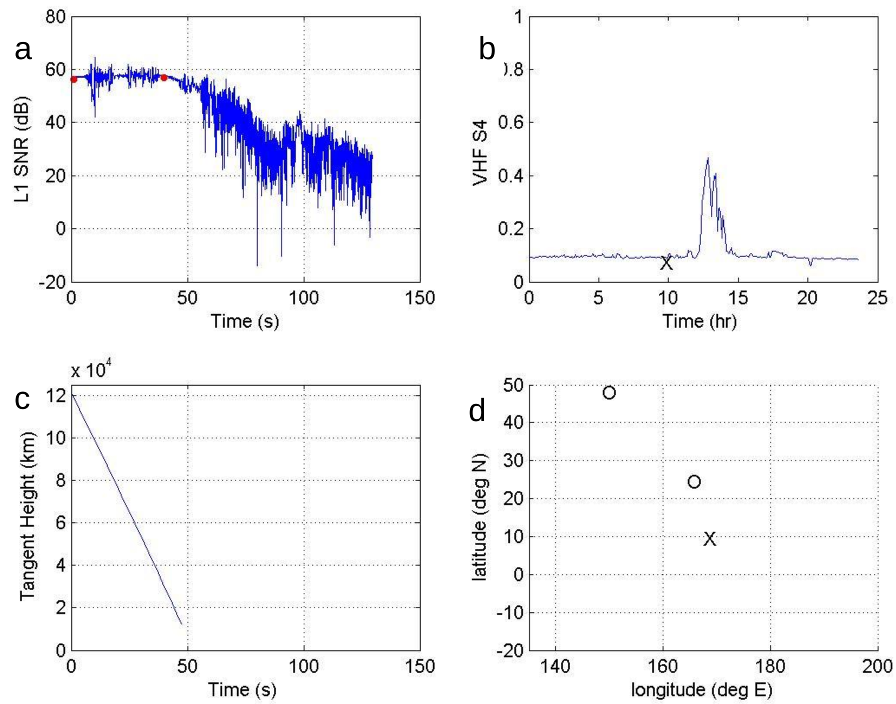

Figure 7. Signal-to-noise ratio during an occultation occurring at 9:24 UTC on 25 July 2006 (a), S4 index for Kwajalein SCINDA station for 25 July 2006 (b), tangent heights during ionospheric only portion of occultation (c), and location of Kwajalein ground site relative to occultation F-layer pierce points (d).

5. FUTURE WORK

In order to verify our preliminary conclusions we need to analyze additional cases. Since the end our first data analysis period another year and a half of COSMIC occultations have been collected. We will compare the additional occultations with ground-based measurements at Kwajalein as well as several equatorial fixed point VHF receivers at other locations. In addition we will run comparisons of our COSMIC occultation S4 computations with those generated on board the COSMIC satellites. We hope to be able to validate the on board S4 calculations because they are down linked at 50 Hz for all tangent point heights whereas the L1 signal-to-noise is only down linked at 50 Hz at tangent point heights < 120 km.

We would also like to apply this approach to the Communication/Navigation Outage Forecast System (C/NOFS) Occultation Receiver for Ionospheric Sensing and Specification (CORISS) sensor which was launched in April 2008. This sensor is capable of computing S4 at 50 Hz regardless of tangent point height. The C/NOFS mission will also include focused field campaigns with ground sensors such as tri-band beacon receivers and radars that would prove useful to positively determine the cause of false alarms or missed detections.

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