Scintillation Nowcasting with GNSS Radio Occultation Data

Keith Groves, Charles Carrano, Charles Rino and John Retterer
Institute for Scientific Research, Boston College

Paul Straus
Aerospace Corporation
Issues for GNSS RO scintillation* observations

Groud- and space-based RO scintillation comparison

Geometric considerations

Tools to Radio-Occulation Scintillation Simulation (ROSS)

Back-propagation techniques

Configuration space model

Summary

* Note that this presentation focuses on equatorial scintillation associated with plasma bubbles
GNSS RO Scintillation Mapping: What makes it so “special”?

Benefits
• Global access
• No ground stations required
• 24/7 wide area coverage

Concerns
• Accuracy
• Spatial and temporal resolution
• Latency

Six satellites in low inclination orbit provide good coverage
Multiple Structures Creates Complex Propagation Issues

- Observed signal is integrated over long slant path
- Potential for interaction with multiple turbulent plasma structures makes it difficult to adequately constrain inversion problem
- Other sources of information needed (and available)
Mapping RO Observations to Ground-based (User) Geometry

- Moving coordinate system at fixed altitude
- Structure intercepted across layers
- Path integrated structure maps onto two-dimensional plane at observation point

- Fixed coordinate system at minimum impact altitude
- Structure intercepted along layers
- Path integrated structure cannot be mapped in conventional ways
COSMIC OCCULTATION GEOMETRY
Parameter Variations Along Raypaths

- Varying magnetic field geometry
- Varying effective scan velocity

RED => GPS to COSMIC links <800 km
BLUE => Earth surface projection of links
CYAN => Magnetic field direction along links
  • => Link impact distance
### RO Geometries: Issues for Scintillation Mapping

#### Characteristic

- Long slant paths
  - Potential for multiple regions
  - Large density variance
  - Large range of relevant Fresnel scales
- Varying magnetic field geometry
- Varying effective scan velocity
- Quasi-parallel propagation paths relative to the magnetic field

#### Impact

**Geolocation**
- Distribution of irregularities
- Difficulty tracking phase
- Difficulty separating spatial/temporal scales

**Requires multiple complex serial calculations**

**Not described by existing models**
Quick-Look Study: Comparisons Near Kwajalein

- Used COSMIC occultation data from:
  - 12 July 2006 to 24 March 2007
  - 1 January to 8 August 2008
  - 0700 – 1700 UTC (~1930 – 0530 LT)

- Geographic window of comparison:
  - The occultation must transect the mid-level of the F-layer (300km) within
    - the latitudes of the equatorial magnetic belt
    - ± 5º longitude of the Kwajalein Atoll (AFRL VHF receiver)

1249 occultations used in the study
Typical COSMIC GPS radio occultation data for a setting occultation, using 50Hz data.

Ionospheric scintillation can be seen here, before lower atmosphere effects obscure it.

Analysis software automatically extracts relevant data segment.

Tropospheric effects become overwhelming as the ray path bends.

Significant ray path refraction occurs at lower altitudes. Straight line path is not valid.

Straight-line ray tangent height computations are valid at ionospheric heights.
COSMIC Comparison Results

Correlation Coefficient = 0.35

<table>
<thead>
<tr>
<th>VHF S4 ≥ 0.3</th>
<th>L-Band S4 ≥ 0.2</th>
<th>Yes</th>
<th>No</th>
</tr>
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<tbody>
<tr>
<td>Yes</td>
<td>19</td>
<td>54</td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>35</td>
<td>1141</td>
<td></td>
</tr>
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Probability of Detection = 0.35
False Alarm Rate = 0.74
Anatomy of a “False Alarm”

- **Time of Occultation**
- **F-peak Penetration Points**
- **VHF Scintillation 2 hours later**

Kwajalein
Inspection of Uncorrelated Cases Greatly Improves Statistics

- 34 geo-location issues
- 9 elevated L-Band S4 but < 0.2
- 7 elevated VHF S4 values but < 0.3
- 12 observed scintillation outside of ± 1.5 hour window
- 1 noise contaminated occultation
- 20 unexplained misses

Arguably probability of detection could be as high as 0.74; false alarm rate could be as low as 0.16
Comparisons with ALTAIR
21 April -- 01 May 2009

- During a 10-day period a total of 49 GPS post-sunset occultations in the vicinity of Kwajalein were recorded by CORISS (nearly 5 occultations per evening!)
- On most evenings proximate occultations occurred nearly every orbit, a refresh rate of ~100 minutes
- Of 49 total occultations, 26 occurred within the effective field-of-view (FOV) of the ALTAIR radar while it was operating
  - In 15 cases both showed the presence of irregularities; the other cases correctly showed an absence of scintillations: 100% agreement!
- Geometric factors largely determine detection coverage region and mapping resolution in lat/lon
What about other geometries?

**Sweeping** Tangent Points

- Side-looking occultation sweeps across longitude as it progresses
- Provides better zonal resolution for geo-location than in-orbit occultations
- Apriori knowledge of bottomside height constrains spatial mapping
Mapping from higher magnetic latitudes

- Poleward occultations quickly map to higher apex altitudes; effective sampling altitude may be above irregularity regions
- Sub-ionospheric tangent point altitudes can map into F-region heights at magnetic equator while actual sampling region is below ionosphere
Both width and placement in good agreement with spectral analysis result
Locating the Scattering Region for an East-West Occultation

- Compute intensity PSD of scintillating signal

- If scatter is weak, mean distance to the scattering region along line of sight (LOS) is:

\[ d_s = \frac{1}{2\lambda} \left( \frac{V_{\text{scan}}}{f_b} \right)^2 \]

- If propagation is orthogonal to B, then \( V_{\text{scan}} \) is component of \( V_{\text{ipp}} \) perpendicular to the LOS:

\[ V_{\text{scan}} = V_{\perp C/NOFS} + \frac{d_s}{d} \left[ V_{\perp \text{GPS}} - V_{\perp C/NOFS} \right] \]

where \( d \) is the distance between the C/NOFS and GPS satellites.

- Solving these simultaneously gives the scan velocity and distance to scattering region.

Mean scattering distance: 627 km, location: (6.40°, 164.1°), intensity spectral index \( \approx 3 \)
Spawning a Bubble from CORISS Observations

- Tangent point track (blue)
- Apex altitude 300-400 km (cyan)
- SCINDA bubble from CORISS (green)
- C/NOFS orbital track (red)
- Mean Scatterer Location (black)
- Altitude 300-400 km (gray)
Inverse Diffraction Method: Back Propagation

Field Measurements

- 3D random medium
- L1
- GPS RX
  - Amplitude and phase on L1 carrier

Phase Screen Simulation

- L2
- Equivalent 1D screen (complex)
- Discard remaining amplitude fluctuations and scale phase to L2
- Back-propagate until amplitude fluctuations are minimized
- GPS RX
  - Amplitude and phase on L2 carrier
Example using actual GPS data

Note different axis range
2013 Day 052 – PRN 01

Black – measured, Red - Predicted

PRN 01

L1 Intensity (dB)
Relative amplitude error: 7.68%  Predicted from L2

L2 Intensity (dB)
Relative amplitude error: 10.10%  Predicted from L1

L5 Intensity (dB)
Relative amplitude error: 10.76%  Predicted from L5
In the case of propagation through a single bubble located at the tangent point, the apparent altitude of the intensity fluctuations is approximately the altitude of the bubble.
Since the bubble is thin (it was specified to have width of 100 km), Fresnel nulls in the intensity and phase spectra are clearly evident. The distance \( d \) to the bubble along the occultation raypath can be readily determined from the 1st Fresnel zone, \( k_F = 2\pi(\lambda d)^{-1/2} \).
In the case of propagation through multiple bubbles, the apparent altitude of the fluctuations in the received intensity is not the actual attitude of the bubbles. Instead, it is determined by the projections of the bubbles onto the observation plane.
We specify the background electron density as a Chapman layer. Irregularity strength (RMS $\Delta N/N$) throughout the volume is assumed to scale with the background density.

Signal intensity at the observation plane is computed by propagating through multiple phase screens oriented normal to the raypath. The phase in each screen (shown in red) is computed by integrating the density fluctuations between adjacent blue dashed lines.

Scattering is strongest at the ionospheric peak height ($H_{mF2}$), but also occurs at much lower apparent altitudes due to Earth curvature effects.
As compared to the radio occultation case, a radio wave propagating from space to ground encounters a thinner layer of irregularities, and propagate a shorter distance after them to the receiver.

These effects cause the received intensity fluctuations to be weaker for space-to-ground propagation than radio occultation propagation.

In this simulation, the occultation raypath encounters 20 times more TEC than along the space to ground (zenith) raypath, and the scintillation intensity index is 7.5 times greater.
Multiple Phase Screen Simulation of CORISS Scintillation

**Density Background**

**Density Fluctuations (Absolute)**

**Simulation Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_k L$</td>
<td>$1.1 \times 10^{34}$ (SCINDA)</td>
<td></td>
</tr>
<tr>
<td>$\nu$</td>
<td>$3/2$ (CORISS)</td>
<td></td>
</tr>
<tr>
<td>$q_0$</td>
<td>$2\pi/10$ km</td>
<td></td>
</tr>
<tr>
<td>$L$</td>
<td>61 km (ALTAIR)</td>
<td></td>
</tr>
<tr>
<td>$L_{RO}$</td>
<td>232 km (CORISS)</td>
<td></td>
</tr>
<tr>
<td>$d_s$</td>
<td>627 km (CORISS)</td>
<td></td>
</tr>
<tr>
<td>$N_{mF2}$</td>
<td>$8.81 \times 10^{11}$ m$^{-3}$ (ALTAIR)</td>
<td></td>
</tr>
<tr>
<td>$H_{mF2}$</td>
<td>288.5 km (ALTAIR)</td>
<td></td>
</tr>
<tr>
<td>Scale Height</td>
<td>31 km (ALTAIR)</td>
<td></td>
</tr>
</tbody>
</table>
MPS Simulation of CORISS Scintillation

• Results shown thus far assume propagation geometry is perpendicular to the magnetic field

• Under these conditions classic phase screen theory may be applied treating irregularity spectra as power-law

• In the real world the irregularities occur along striations; when looking along B (or nearly so) the correlation lengths are much longer and the spectra do not obey power laws

• A new modeling approach is needed for such quasi-parallel propagation

• Such propagation occurs frequently in RO geometries

Planar cut of electron density variations perpendicular to B from a configuration space model under development by Rino
Summary

• Mapping equatorial scintillation using RO techniques poses numerous technical challenges
  – Defining spatial distribution of structures over large slant paths potentially transecting multiple contributing structures
  – Varying magnetic aspect angle and scan velocity
  – Regimes where existing phase screen theory is invalid

• Accuracy of results will depend on specifics of geometry, distribution of contributing structures, magnetic field mapping, etc.

• Ancillary information must be applied whenever available
  – In situ density observations to map boundaries
  – Apriori knowledge of bubble morphology
  – Other ground- and space-based observations
Summary

- Sophisticated tools have been developed to address the complex propagation issues
  - Ionospheric Parameter Estimation (IPE) extracts ionospheric quantities from observed spectra using multi-parameter fitting technique
  - Inverse propagation techniques (Back Propagation)
  - Radio Occultation Scintillation Simulation (ROSS) models occultation geometries with multiple phase screens
  - Configuration-space model under development to address quasi-parallel propagation limits of existing theory

The limits of how well this can be done have not yet been fully determined, but preliminary results suggest that high rate RO data can provide meaningful scintillation detection and characterization