Characterizing Irregularities and Scintillation with GNSS Radio Occultations

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Outline

• Motivation
• Complications of Radio Occultations
• Tangent Point Analyses
• Parameterized Constraints Analysis
• Irregularity Parameter Estimation
• Back Propagation
• Summary
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

Single Orbit Global Coverage with C/NOFS

Ionospheric Occultations

Single Orbit

Scintillation Regions

Six satellites in low inclination orbit provide good coverage
COSMIC-2

Global Occultation Coverage for two one-hour periods with COSMIC-2 (includes GLONASS)

**COSMIC-2**
- 6 satellites
- Multi-GNSS capabilities
- Fore & Aft sensors
- ~Early 2018 launch

**Significant expansion of coverage compared with single sat mission**
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)
A number of studies have demonstrated the use of GPS RO measurements from LEO satellites to map the global distribution of scintillation.

Typically, these studies associate the scintillating regions with the occultation Tangent Point.

Often a single value for the TP at a specific altitude (350km) is used to characterize the event.

Comparisons with ionospheric models, *in-situ* measurements, and/or ground-based observations have shown that these techniques represent the climatological global distribution of scintillation reasonably well.
The RO Data Set for 2011

- C/NOMS RO data was obtained from Aerospace for two 90 day periods.
- The plot below shows the 350 km Tangent Point (TP) for all occultations from the March through May 2011 data set.

- The blue and red dots indicate quiet and active RO’s based on an $S_4$ threshold of 0.05.
- For this period the SSN is 74 (solar moderate conditions).
The VHF Ground Data

- This plot shows a measure of the scintillation as a function of day for seven stations.
- These are some stations for which we have corresponding RO’s.
- We note here the seasonal behavior of scintillation, which is different at different longitudes.
- Except for Cape Verde, the bulk of the scintillation comes in March.
SAMPLE RESULTS

• $S_4$ Scatter Plots
  Ground-vs-Space

• Grouped into several categories
  ✓ Correct All Clear
  ✓ Missed Detections
  ✓ Correct Detections
  ✓ False Alarms

• Comparison with two SCINDA GPS stations (top)
• Comparison with two SCINDA VHF stations (bottom)
  ✓ Top panels: RO Threshold high
    (strong scintillation only)
  ✓ Bottom panels: RO Threshold low
TPA Summary for 2011 Period

<table>
<thead>
<tr>
<th>Station</th>
<th>Mag Lat</th>
<th>Missed Detections</th>
<th>False Alarms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>VHF</td>
<td>GPS</td>
</tr>
<tr>
<td>Ancon</td>
<td>0.3°</td>
<td>5%</td>
<td>4%</td>
</tr>
<tr>
<td>Bahir Dar</td>
<td>3.4°</td>
<td>12%</td>
<td>6%</td>
</tr>
<tr>
<td>Kwajalein</td>
<td>4.2°</td>
<td>9%</td>
<td>3%</td>
</tr>
<tr>
<td>Guam</td>
<td>6.0°</td>
<td>6%</td>
<td>6%</td>
</tr>
<tr>
<td>Bangkok</td>
<td>6.2°</td>
<td>12%</td>
<td>6%</td>
</tr>
<tr>
<td>Cuiaba</td>
<td>8.0°</td>
<td>3%</td>
<td>1%</td>
</tr>
<tr>
<td>Nairobi</td>
<td>9.4°</td>
<td>5%</td>
<td>4%</td>
</tr>
<tr>
<td>Antofagasta</td>
<td>12.0°</td>
<td>6%</td>
<td>2%</td>
</tr>
<tr>
<td>Ascension Island</td>
<td>16.5°</td>
<td>3%</td>
<td>3%</td>
</tr>
</tbody>
</table>

- Criteria are ± 30 minutes and ± 5° in longitude from 350 km tangent point
- Missed detections refer to TPA not detecting scintillation observed on ground
- False alarms refer to TPA detecting scintillation not observed on the ground
- For most locations TPA provides 80-90% correct detection within 1-hr/10° boundaries from the tangent point; no quantitative equivalent S4 information
Parameter Constraint Analysis (PCA)

- PCA is essentially an attempt to define within an RO FOV where we would detect scintillation if it were present.
- We do this by applying apriori knowledge of bubble dynamics and radio wave propagation that allow us to define simple probabilities for detection based on plasma density and apex altitude.
- This results in a “percentage” which delineates regions where scintillation can be detected by an RO and where detection is unlikely.
We have puzzled over what PCA threshold to pick for defining an “all clear” area.

To investigate this, we have made a scatter plot of the $S_4$ measured in the RO against the peak PCA calculated along the ray path corresponding to the $S_4$.

Our results show that about 90% of the scintillating ray paths have PCA levels above 0.75.

So, we have tentatively selected the 0.75 PCA level as “all clear”.

As we examine more validations, this number may be adjusted.
PCA Visualization Maps

Color-code shows quantitative probability value (e.g., red > 0.9, yellow > 0.75, green > 0.5)

The extent of each ray path below 1,500 km altitude

PCA quantifies the meaningful sampling region for a given RO

The white bar shows the tangent point; red area shows region of enhanced RO S4 while blue indicates no S4 data.

The probability for detecting irregularities outside the PCA region is low
PCA for a Quiet Occultation

- It follows that, for an RO where we do not detect scintillation, the region defined by some PCA level will likely be free from scintillation.
- In the quiet RO illustrated here, if we pick “yellow” as our PCA threshold, we would predict that scintillation should be absent over the Atlantic.
- So, this is the simple idea of PCA.
- We ask in what region scintillation would be detected and, if none is in fact detected, we declare this region “all clear”.

![PCA Map for Occultation 0078 PRN 30 on 2011/060 21:07 UT](image)
A PCA Validation Case Study

- We have carried out a validation of PCA on 10 in-season nights.
- Success rate is about 90%; much better than 50-70% results from tangent point analysis.
- Here we trace field lines from the boundaries of the PCA regions to the equator and compare these to the station apex longitude.
- This plot shows the results of the RO predictions compared to the ground data for one day.
- Irregularity geolocation needs further refinement.
Validation Results for Our 10 Nights

- This table shows the results of our “all clear” predictions for the 10 nights considered.
- As indicated earlier, these nights were selected from the in-season data for the South American and Atlantic sectors.
- We can see that we correctly predicted “all clear” regions in excess of 90% of the time.
- This compares favorably with the 50% or at most 75% correct using the simple tangent point analysis.

<table>
<thead>
<tr>
<th>Case</th>
<th>Night</th>
<th>Total</th>
<th>Correct</th>
<th>Percent</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>60/61</td>
<td>192</td>
<td>180</td>
<td>93.8%</td>
</tr>
<tr>
<td>2</td>
<td>63/64</td>
<td>48</td>
<td>39</td>
<td>81.2%</td>
</tr>
<tr>
<td>3</td>
<td>65/66</td>
<td>68</td>
<td>58</td>
<td>85.3%</td>
</tr>
<tr>
<td>4</td>
<td>96/97</td>
<td>224</td>
<td>224</td>
<td>100.0%</td>
</tr>
<tr>
<td>5</td>
<td>72/73</td>
<td>42</td>
<td>40</td>
<td>95.2%</td>
</tr>
<tr>
<td>6</td>
<td>71/72</td>
<td>104</td>
<td>100</td>
<td>96.2%</td>
</tr>
<tr>
<td>7</td>
<td>92/93</td>
<td>152</td>
<td>128</td>
<td>84.2%</td>
</tr>
<tr>
<td>8</td>
<td>93/94</td>
<td>132</td>
<td>118</td>
<td>89.4%</td>
</tr>
<tr>
<td>9</td>
<td>66/67</td>
<td>106</td>
<td>96</td>
<td>90.6%</td>
</tr>
<tr>
<td>10</td>
<td>95/96</td>
<td>144</td>
<td>127</td>
<td>88.2%</td>
</tr>
<tr>
<td>Combined</td>
<td>1212</td>
<td>1110</td>
<td>91.6%</td>
<td></td>
</tr>
</tbody>
</table>
Irregularity Parameter Estimation

- PCA helps localize the action along the ray path better than tangent point analysis, but we need to do better.
- For further refinement we explore more sophisticated propagation techniques.
- Irregularity Parameter Estimation (IPE): Minimization technique to fit observations to model spectra to deduce irregularity amplitude and effective drift velocity.
  - Requires only amplitude data.
  - Model based on phase screen theory; geometry impacts accuracy.
  - Applied to case studies; initial results promising but routine performance characteristics currently unknown.
Theoretical Model for Fitting Scintillation Spectra

• Temporal frequencies in the observed scintillation spectra are related to spatial wavenumbers via the so-called effective scan velocity $V_{\text{eff}}$ as $\mu = 2\pi f \rho_F / V_{\text{eff}}$.

• Using this we can express the temporal spectrum of intensity fluctuations as a function of phase screen parameters $p_1$, $p_2$, $\mu_b$, and $U$, and Fresnel frequency $f_F = V_{\text{eff}} / \rho_F$:

$$I(f;U,p_1,p_2,\mu_b,f_F) = 2 \int_0^\infty \exp \left[ -\gamma \left( \frac{2\pi f}{f_F};U,p_1,p_2,\mu_b \right) \right] \cos \left( \frac{2\pi f \eta}{f_F} \right) d\eta$$

where $\gamma$ is the so-called structure interaction function (see Carrano et al., 2016).

• This theoretical model lacks a direct dependence on the propagation geometry and even on Fresnel scale! In particular, data can be fit without knowing distance to the screen.

• Model is valid in weak and strong scatter conditions for transverse scans to the extent that a 1D phase screen model adequately describes the propagation physics.

Determination of Model Parameters
$C_kL$, $p$, and $V_D$
The Spectral Ratio and its Distribution

- Consider $R_i = I^m(f_i) / I(f_i; \theta)$ as a random variable where $\theta = (U, p_1, p_2, \mu_b, f_F)$.
- For a perfect model $R_i$ will follow a chi-squared distribution of order $d$
  \[ R_i \sim \chi^2_d \text{ / } d, \quad \text{where } d \text{ is number of periodograms averaged together} \]
- This assumption looks quite good for simulated scintillation data.
100 Monte Carlo Simulations ($p=3.0$)

Dashed lines indicate Truth

90% Confidence Intervals

Realization

90% Confidence Intervals

Realization

90% Confidence Region

Solid curve is covariance ellipse of Monte Carlo results; dashed is ellipse from MLE
Inferring the Distance from a Phase Screen

• For space-to-ground propagation, we have an a-priori estimate for Fresnel scale $\rho_F$ (using slant distance to irregularities presumed to be near F-region peak). *Irregularity Parameter Estimation* (IPE), can determine $C_p$, $p$ and $V_{\text{eff}}$ by fitting the intensity spectrum with a model.

• For space-to-space propagation, IPE provides $U$, $p$, and $V_{\text{eff}}/\rho_F$. $V_{\text{eff}}$ itself depends on the distance to the irregularities along the LOS.

• If we model $V_{\text{eff}}$ using knowledge of the scan and magnetic field geometries, we can infer this distance following application of IPE.

• Method will not be accurate in all cases but we have a technique to estimate the error as a function of the geometry.
IPE Case Study

• Case Study: FALSE ALARM

• Example:

  ✓ Scintillation detected on RO event over South Am.
  ✓ Scatterer at any location along RO path link (red)
  ✓ Tangent Point (gray) maps to longitude of ANC
  ✓ Comparison with in-situ densities from PLP sensor indicate irregularities > 10° to the west
  ✓ Test using IPE Technique confirms
  ✓ 25 cases with PLP validation to examine

> 1,000 km error in geolocation with TP
Deconvolving Range & Intensity

• With amplitude measurements only it is not possible to unambiguously separate space and irregularity amplitude effects

• In some cases PCA and/or effective scan velocity will constrain the likely scintillation regions adequately

• Fundamental propagation techniques (inverse diffraction AKA back-propagation) can potentially resolve this dilemma, as well as improve the overall characterization of the horizontal spatial distribution (VERY important for estimating propagation effects on overhead geometries of interest to most users)
Inverse Diffraction Method: Back Propagation

Requires high rate amplitude AND phase

3D random medium

Discard remaining amplitude fluctuations and scale phase to L2

Back-propagate until amplitude fluctuations are minimized

GPS RX

Amplitude and phase on L1 carrier

GPS RX

Amplitude and phase on L2 carrier
Example using actual GPS data
2013 Day 052 – PRN 01

Note different axis range
Predicting Complex Signals
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

UT (hours)
Spatial Distribution Characterization

- Given knowledge of the horizontal distribution of irregularity strength (e.g., CkL, not S4) in a given region, calculating scintillation parameters on other geometries is trivial.
- Multiple tools are useful for addressing this challenge:
  - Back-propagation
  - Ancillary sensors (beacon, IVM)
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.
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.
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. Scattering is strongest at the ionospheric peak height ($H_mF_2$), but also occurs at much lower apparent altitudes due to Earth curvature effects.
Space-to-Ground Propagation through Uniformly Distributed Irregularities

As compared to the radio occultation case, a radio wave propagating from space to ground encounters a thinner layer of irregularities, and propagates 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.
Other COSMIC-2 Capabilities

• The use of IVM data to identify longitudinal boundaries is a critical capability
  – Initial simulation estimates suggest that IVM data will be relevant ≤ 50%; valuable coverage with six satellites

• Beacons also provide valuable data unavailable elsewhere (require ground-based receivers):
  – Spatial structure of irregularity regions
  – Validation/confirmation of scintillation strength (S4) on space-to-ground geometry of greatest interest to users

These sensors will be integrated into a fused irregularity specification algorithm
Examples from C/NOFS

PLP Density Data

Beacon irregularities
Summary

• Radio occultations offer tremendous potential for characterizing the global occurrence of irregularities.

• Applying empirical constraints to extended RO raypaths provides significant benefit in determining where irregularities are located along the paths.

• More complex propagation techniques based on robust phase screen theory are utilized to further refine irregularity characteristics.

• More issues to address but the future of this work looks very promising for extracting irregularity characteristics from RO in a meaningful way.

• The fidelity of these approaches depends on the quality and type of input data available, e.g., high rate phase & amplitude, amplitude only, etc.
Thanks for your attention.
COSMIC-2 Simulation Results

- We have carried out PCA calculations using simulated COSMIC-2 occultations.
- These plots show results for solar minimum (top) and solar moderate (bottom) conditions.
- We see that there is a “hole” in the PCA coverage at solar min.
- We find that this will limit the PCA coverage after about 0200 LT.
- This is not too limiting as this local time has less scintillation.
- We should have no problem predicting all night at solar max.