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Comparing reflection signatures in radio occultation measurements using the full spectrum inversion and phase matching methods

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ABSTRACT

Global Navigation Satellite System Radio Occultation (GNSS-RO) is an important technique used to sound the Earth's atmosphere and provide data products to numerical weather prediction (NWP) systems as well as to climate research. It provides a high vertical resolution and SI-traceability that are both valuable complements to other Earth observation systems. In addition to direct components refracted in the atmosphere, many received RO signals contain reflected components thanks to the specular and relatively smooth characteristics of the ocean. These reflected components can interfere the retrieval of the direct part of the signal, and can also contain meteorological information of their own, e.g., information about the refractivity at the Earth's surface. While the conventional method to detect such reflections is by using radio-holographic methods, it has been shown that it is possible to see reflections using wave optics inversion, specifically while inspecting the amplitude of the output of phase matching (PM). The primary objective of this paper is to analyze the appearance of these reflections in the amplitude output from another wave optics algorithm, namely the much faster full spectrum inversion (FSI). PM and FSI are closely related algorithms - they both use the method of stationary phase to derive the bending angle from a measured signal. We apply our own implementation of FSI to the same GNSS-RO measurements that PM was previously applied to and show that the amplitudes of the outputs again indicate reflection in the surface of the ocean. Our results show that the amplitudes output from the FSI and PM algorithms are practically identical and that the reflection signatures thus appear equally well.

Keywords: radio occultation, wave optics, reflections, full spectrum inversion

1. INTRODUCTION

GNSS Radio Occultation (GNSS-RO) is a technique for sounding the Earth's atmosphere. As GNSS signal rays pass through without reaching the Earth's surface, they are intercepted by low-Earth orbit (LEO) satellites. Due to the refractive properties of the atmosphere, the rays will bend as they are propagated through. For each point in the receiver's LEO, the bending angles of the rays can be computed as a function of their conserved impact parameter. Measuring their Doppler shift yields (under the assumption of spherical symmetry) vertical bending angle profiles, which in turn contains information about the refractive properties of the atmosphere. Knowing the chemical composition of the air subsequently allows for derivation of additional parameters such as humidity, temperature and pressure.¹ These measurements are of great value to numerical weather prediction (NWP) applications; the complementary geometry and the SI-traceable nature of the measurements make them useful for calibration and validation of other Earth-observing systems.

When the Earth's surface is reflective and smooth enough (i.e. over oceans), the receiver in LEO will record some reflected rays in addition to the direct ones. The identification and retrieval of reflected signal components can potentially contribute additional meteorological information, as Ref. 2 shows by means of a ray tracing comparison. At this point, however, it is unclear exactly what information in the signal is useful. Studying a data set from the Radio Occultation Meteorology Satellite Application Facility (ROM SAF), Ref. 3 concludes

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that a binary flag indicating the presence or absence of reflection is not sufficient for assimilation into NWP systems. Nevertheless, detection of events containing reflections remains an important task, to further study the phenomenon.

The most common way of identifying reflections is by time-frequency analysis, as they will appear as a Doppler delay in the spectrogram corresponding to a signal.⁴⁵⁶ Based on this approach a method of classifying spectrograms containing reflections using a support vector machine is presented in Ref. 7. The use of artificial neural networks to improve both the classification performance and the computational efficiency of detection is proposed in Ref. 8. Reference 9 shows that reflections can also be identified and retrieved using a Fourier integral operator (FIO) (originally intended for the retrieval of direct bending angles), specifically by a modification of the canonical transform.¹⁰ Reference 11 employs a different FIO, phase matching (PM),¹² and shows that by properly truncating the measured signal, a reflection signature will appear in the amplitude of the operator's output, corresponding to an impact parameter near the Earth's surface. This surface impact parameter is an important data point when trying to parametrically reconstruct super-refractive refractivity profiles.¹³ Reference 14 explores the correlations between the occurrence of reflections and several meteorological parameters, and suggests that reflected bending angle profiles could be assimilated into NWP models. The forward operator for reflected bending angles proposed in this study also depends on the surface impact parameter.

In this paper we revisit the idea of truncating RO signals and processing them with an FIO. The goal is to confirm that the Full Spectrum Inversion (FSI) operator¹⁵ admits reflected rays in the same way as the PM operator does. To accomplish this we replicate a part of the results presented in Ref. 11 using the FSI operator and compare them to the results yielded from PM. The paper is organized as follows: Section 2 describes the implementation details and differences between FSI and PM. In Sect. 3, we outline how the signals are processed and analyzed to match the previous study. Section 4 describes the results and in Sect. 5 we give the conclusion.

2. IMPLEMENTATION

Throughout the description of the FSI and PM operators, we define a received GNSS-RO signal $V(t)$ as

$$V(t) = A(t) \exp(ik\varphi(t)), \quad (1)$$

where $A(t)$ is the real-valued amplitude, i is the imaginary number, k is the wave number related to the carrier frequency, and $\varphi(t)$ is the phase, or optical path length of the signal. Additional relevant parameters include the following ephemeris data: The distance from the Earth's center of curvature to transmitter and receiver $r_G(t)$ and $r_L(t)$ respectively, and the angle of separation $\theta(t)$ between the radius vectors. Applying either of these operators F to a signal will map it to impact parameter space:

$$F\{V(t)\} = \alpha(a), \quad (2)$$

where α denotes bending angle and a denotes impact parameter. Subtracting the local radius of curvature of the Earth r_E from a yields impact height.

We will not give a detailed account about the theoretical justifications for how these operators yield bending angle measurements. For this the reader is referred to Ref. 15 and Ref. 12, respectively. Instead we present summaries of the implemented algorithms, to give an idea of what computations are made.

Both FSI and PM require significant upsampling of the signal. Typically, an RO signal has a frequency of 50 or 100 Hz, but for these operators to be work it needs to be interpolated to approximately 2000 Hz. Additionally, a central step in both methods is the differentiation of a noisy phase. Since differentiation is sensitive to noise, some form of filtering is required to reach satisfactory results. In our implementations, we perform a polynomial least squares fit with a sliding window that can be analytically differentiated. The window lengths are not chosen with any sort of quality control in mind.

2.1 Full Spectrum Inversion

The main idea of FSI is to perform a Discrete Fourier Transform (DFT) to move the signal into the frequency domain, since a ray's corresponding frequency (ω) is proportional to its impact parameter. Differentiating the phase with regards to ω results in the arrival time of each frequency component, which is used to sample the ephemeris data and compute the bending angle for each impact parameter. Supposing that the radial velocities of transmitter and receiver are constant, the algorithm is straight-forward, as can be seen in Alg. 1.

Algorithm 1 Full spectrum inversion assuming constant radial velocities

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- 1: Subtract a linear phase from $V(t)$ based on the center frequency.
  - 2: Upsample $V(t)$.
  - 3: Let $\hat{V}(\omega) = \int_{t_0}^{t_{end}} V(t) \exp(-i\omega t) dt$.
  - 4: Add the center frequency to ω .
  - 5: Let $u(\omega) = \angle \hat{V}(\omega)$.
  - 6: Let $u_P(\omega)$ be a local polynomial fit of $u(\omega)$.
  - 7: $t(\omega) = -\frac{du_P}{d\omega}$.
  - 8: $a = \frac{\omega}{k \frac{d\theta}{dt}}$.
  - 9: $\alpha = \theta(\omega) + \arcsin(\frac{a}{r_L(\omega)}) + \arcsin(\frac{a}{r_G(\omega)}) - \pi$.
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However, in a real measurement there will be variations in the radial velocities. To address this, the signal is resampled with regards to θ and a corrective phase term φ_m is subtracted from the signal to remove the interference of radial variations. This phase term is derived from a model impact parameter, and for this we use the impact parameter yielded from the geometrical optics method applied on a smoothed signal phase. Ultimately the modified algorithm shown in Alg. 2 operates in a "pseudo frequency" domain, and includes some preprocessing of the signal as well as the iterative solution of another equation to find a .

The term "FSI amplitude" refers to $|\hat{V}_s(a)|$, i.e. the amplitude of $\hat{V}_s$ in impact parameter space. Since FSI makes use of the standard Fourier transform, the Fast Fourier Transform (FFT) can be employed to significantly reduce the computational complexity from $O(n^2)$ to $O(n \log n)$. The other operations are all made in approximately linear time.

2.2 Phase Matching

The core concept of PM is to construct a set of test rays where $S_t(t, a)$ describes their optical path length, and use as the kernel of the FIO. Since the test rays are defined in impact parameter space, so will the PM output $\hat{V}$ be. Thus, there is no intermediate step to map frequency to impact parameter. Finally the derivative of the phase of $\hat{V}$ is proportional to the bending angle. Compared to FSI, an implementation of PM will arguably look much more straight-forward, as shown in Alg. 3.

Similar to the FSI case, the term "PM amplitude" refers to $|\hat{V}(a)|$. Since PM does not make use of a standard Fourier transform, it does not benefit from the FFT. Thus, for every point in the impact parameter domain, every point in the time domain needs to be considered for the integral. This results in a computational complexity of $O(n^2)$.

Although the methods are said to be virtually equivalent in literature, some small-scale differences in bending angle can occur. However, these differences occur at heights where the corresponding amplitude is low, indicating that the differences amount to noise rather than anything else. Figure 1 shows a measurement with a quite stable amplitude and thus quite small differences in bending angle, while Fig. 2 shows a measurement where the amplitude is noisier, and subsequently so are the differences in bending angle.

Algorithm 2 Full spectrum inversion for real measurements

- 1: Calculate a model impact parameter $a_m(\theta)$.
  - 2: Resample $V(t)$ with regards to θ .
  - 3: Let $\varphi_m(\theta) = \int_{\theta_0}^{\theta} \left(\frac{dr_L}{d\theta'} \sqrt{1 - \left(\frac{a_m}{r_L} \right)^2} + \frac{dr_G}{d\theta'} \sqrt{1 - \left(\frac{a_m}{r_G} \right)^2} \right) d\theta'$.
  - 4: Let $V_s(\theta) = V(\theta) \exp(-ik\varphi_m(\theta))$.
  - 5: Subtract a linear phase from $V_s(\theta)$ based on the center frequency.
  - 6: Upsample $V_s(\theta)$.
  - 7: Let $\hat{V}_s(\omega) = \int_{\theta_0}^{\theta_{end}} V_s(\theta) \exp(-i\omega\theta) d\theta$.
  - 8: Add the center frequency to ω .
  - 9: Let $u(\omega) = \angle \hat{V}_s(\omega)$.
  - 10: Let $u_P(\omega)$ be a local polynomial fit of $u(\omega)$.
  - 11: $\theta(\omega) = -\frac{du_P}{d\omega}$.
  - 12: Find a by solving $\omega + k \frac{d\varphi_m}{d\theta} = k \left(a + \frac{dr_L}{d\theta} \sqrt{1 - \left(\frac{a}{r_L} \right)^2} + \frac{dr_G}{d\theta} \sqrt{1 - \left(\frac{a}{r_G} \right)^2} \right)$ iteratively.
  - 13: $\alpha(a) = \theta(\omega) + \arcsin\left(\frac{a}{r_L(\omega)}\right) + \arcsin\left(\frac{a}{r_G(\omega)}\right) - \pi$.
-

Algorithm 3 Phase matching

- 1: Upsample $V(t)$.
  - 2: Define a as an independent variable with a desired resolution.
  - 3: Let $\phi_L = \arcsin\left(\frac{a}{r_L(t)}\right)$ and $\phi_G = \arcsin\left(\frac{a}{r_G(t)}\right)$.
  - 4: Let $\alpha_t = \theta(t) + \phi_L + \phi_G - \pi$.
  - 5: $S(t, a) = \sqrt{r_L(t)^2 - a^2} + \sqrt{r_G(t)^2 - a^2} + \alpha_t a$.
  - 6: $\hat{V}(a) = \int_{t_{start}}^{t_{end}} V(t) \exp(-ikS(t, a)) dt$.
  - 7: Let $u(a) = \angle \hat{V}(a)$.
  - 8: Let $u_P(a)$ be a local polynomial fit of $u(a)$.
  - 9: $\alpha(a) = -\frac{1}{k} \frac{du_P}{da}$.
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MTPA.2007.274.00.12.G13

Figure 1. An example of a retrieved bending angle (left) and its corresponding amplitude (right) of a measurement with a weak refractive gradient.

MTPA.2007.274.08.24.G07

Figure 2. An example of a retrieved bending angle (left) and its corresponding amplitude (right) of a measurement with a strong refractive gradient.

Figure 3. An event classified into category 1. $SLTA_{min}$ is at approximately -73 km, and the signal is truncated at $SLTA = -50$ km. The reflection spike is located at an impact height of 1919 m, and a_{min} is located at an impact height of 2017 m.

3. EXPERIMENTAL SETUP

The goal of this paper is to reproduce the results from Ref. 11, using FSI instead of PM. Thus, the same data and parameters will be used. RO measurements were downloaded from the COSMIC Data Analysis and Archive Center (CDAAC), specifically from the Metop-A mission on October 1st, 2007. Ten events over the ocean have been selected, such that their sharpest refractive gradient varies to cover a span of typical, realistic cases. The events have been classified into categories based on the maximum gradient of their co-located refractivity profile. These categories are defined for a reference dataset of refractivity profiles,¹⁶ where category 1 has the smallest gradients and category 4 the largest (super-refractive) ones. For each measurement, a suitable truncation point was set at hand-picked straight line tangent altitudes (SLTA) such that a reflection spike will be clearly visible. Using the same inputs for both PM and FSI, the signals are processed and the amplitudes of the outputs are plotted for comparison. No filtering is used for the amplitudes.

4. RESULTS

Figures 3 through 12 show FSI amplitudes on top of PM amplitudes. $SLTA_{min}$ refers to the SLTA where direct and reflected rays join, which is right at the Earth's surface. The surface impact parameter a_{min} is received from ECMWF's co-located refractivity profiles. These profiles stop a small distance above the surface, and this last bit is linearly extrapolated. It can clearly be seen that the respective amplitudes both give rise to the reflection signature, as the structures match very closely.

In all cases there is a offset in impact height between the reflection spike and a_{min} . The size of this offset depends on at which altitude the signal is truncated; for the reflection spike to occur at a_{min} , the signal would need to be truncated precisely at $SLTA_{min}$.

The level of noise is more dramatic in measurements corresponding with refractivity profiles of higher categories. Figure 5 and Fig. 6 in particular are examples of amplitudes with low levels of noise and distinct reflection spikes, while measurements from higher categories like Fig. 11 and Fig. 12 typically show more dramatic noise levels and more smeared out reflection spikes. Additionally, the occurrence of wildly oscillating structures that cannot just be attributed to noise is more common in the higher categories.

5. CONCLUSION

The goal of this study was to confirm that reflection spikes can be found in the FSI amplitude just as well as in the PM amplitude. An implementation of FSI was made, and ten RO signals with varying levels of noise were

Figure 4. An event classified into category 1. $SLTA_{min}$ is at approximately -73 km, and the signal is truncated at $SLTA = -60$ km. The reflection spike is 1881 m, and a_{min} is located at an impact height of 1992 m.

Figure 5. An event classified into category 1. $SLTA_{min}$ is at approximately -86 km, and the signal is truncated at $SLTA = -60$ km. The reflection spike is located at an impact height of 1948 m, and a_{min} is located at an impact height of 2008 m.

Figure 6. An event classified into category 1. $SLTA_{min}$ is at approximately -65 km, and the signal is truncated at $SLTA = -50$ km. The reflection spike is located at an impact height of 1849 m, and a_{min} is located at an impact height of 1888 m.

Figure 7. An event classified into category 1. $SLTA_{min}$ is at approximately -72 km, and the signal is truncated at $SLTA = -60$ km. The reflection spike is located at an impact height of 1940 m, and a_{min} is located at an impact height of 1993 m.

Figure 8. An event classified into category 3. $SLTA_{min}$ is at approximately -87 km, and the signal is truncated at $SLTA = -70$ km. The reflection spike is located at an impact height of 2075 m, and a_{min} is located at an impact height of 2204 m.

Figure 9. An event classified into category 3. $SLTA_{min}$ is at approximately -84 km, and the signal is truncated at $SLTA = -50$ km. The reflection spike is located at an impact height of 2057 m, and a_{min} is located at an impact height of 2182 m.

Figure 10. An event classified into category 3. $SLTA_{min}$ is at approximately -85 km, and the signal is truncated at $SLTA = -50$ km. The reflection spike is located at an impact height of 1928 m, and a_{min} is located at an impact height of 2200 m.

Figure 11. An event classified into category 3. $SLTA_{min}$ is at approximately -99 km, and the signal is truncated at $SLTA = -50$ km. The reflection spike is located at an impact height of 2363 m, and a_{min} is located at an impact height of 2301 m.

Figure 12. An event classified into category 4. $SLTA_{min}$ is at approximately -103 km, and the signal is truncated at $SLTA = -50$ km. The reflection spike is located at an impact height of 1994 m, and a_{min} is located at an impact height of 2232 m.

processed using a manual truncation. The results presented show that reflection spikes are apparent in the FSI amplitude. For cases with low refractive gradients, the spikes are often quite distinct, while sharper gradients tend to result in less clear signs of reflection. This matches well with the behavior of the PM amplitude. While the noise characteristics are not exactly the same, the structures of the respective amplitudes are very similar, including reflection signatures. There is no indication that one operator is able to more clearly depict an event containing reflection than the other. This is an expected result - both FSI and PM are FIOs, meaning they both rely on stationary phase approximations to process signals.

FSI allows for faster processing than PM, and it may be that useful information can be gained from the amplitude curves by varying the value for the truncation SLTA. In this way one can make the upper edge of the reflection spike move around, and by fitting a suitable model of the spike one can possibly retrieve the SLTA as a function of impact parameter for the reflected ray. This in turn could allow for the retrieval of such things as the value for a_{min} and $SLTA_{min}$.

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