



METEOROLOGICAL INFORMATION IN GPS-RO REFLECTED SIGNALS

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Introduction

During the last decades several studies have assessed the geophysical content of Global Positioning System (GPS) signals reflected off the surface of the Earth. Vertical profiles of the atmosphere can be globally sensed thanks to radio-occultation technique. However, lowest layers of the atmosphere are biased due to strong vertical gradients of refractivity across the boundary layer over the oceans. Potential of GPS radio-occultation data has already been analyzed in several global data assimilation experiments.

We propose here to show how meteorological properties close to the surface can be extracted in case of reflected signals in GPS occultation. A relevant description of low layers is necessary to improve the initial conditions of the meteorological systems. Thus, the knowledge of such surface properties would be of great interest for future data assimilation experiments.

We use raytracing method which consists in analyzing electromagnetic waves propagation trajectories to extract three-dimensional information of the field of refractive index. First we will use a raytracing approach, next we describe the method of least squares and the inversion procedure used to extract the refractivity field.

Objectives and method

Several studies have shown the potential of GPS-RO data to retrieve accurately useful profiles of refractivity, geopotential and temperature. However, due to strong vertical gradients in the lowest layers systematic biases exist under super-refraction. The objective of the work is to assess the potential of GPS-RO signals especially for GPS signals that rebound off of the ocean surface.

First of all we present the potential of GPS-RO for reflected signals in comparison with the direct ones (Figure 1). Then we describe the raytracing procedure to obtain the propagation trajectories of the electromagnetic waves (Figure 2 and 3).

Reflected signals that cross the lowest troposphere through different geometry than the direct ones contain an additional information. We propose to emphasize that strong refractivity field exist close to the surface. Thus, after having detailed the raytracing procedure we will present the method of least squares we use to solve the system of normal equations.

Radio hologram derived from GPS observations

Signal to noise ratios and carrier phases measurements are combined to compute a complex electric field. This observed electric field is divided by a reference field to give the radio hologram (Hocke et al., 1999).

Figure 1 shows the temporal evolution of the hologram's power spectrum. The vertical axis represents the shifts in frequency with respect to the reference field. Time is measured since the beginning of the occultation.

As demonstrated in Beyerle et al., (2001), the radio hologram shows clearly the signature of GPS radio signals reflection at the Earth's surface. Analysis of frequency shift between direct and reflected signal can help determine atmospheric or surface properties. We propose to exploit this signal further to extract atmospheric refractive index field.

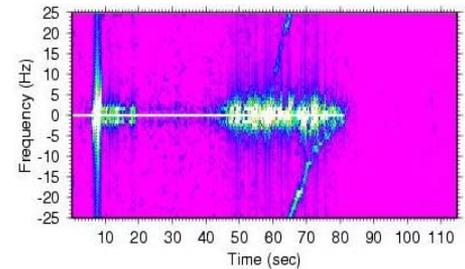


Fig.1: Temporal evolution of radio hologram power spectrum derived from GPS occultation on 10 April 2007. Courtesy E. Cardellach.

Raytracing procedure

A geometrical raytracing analysis has been performed to calculate optical path lengths of direct and reflected GPS signals. The raytracing is used to determine which region of the atmosphere is being probed by a given propagation beam. The tracing of the ray is a nonlinear problem since the refractivity field $N(\vec{x})$ related to the refraction index is not known in advance: $n(\vec{x}) = 1 + 10^{-6}N(\vec{x})$, where $n(\vec{x})$ is the refraction index.

We remind that the total optical path L of a given ray whose trajectory path is P can be expressed as: $L = \int_P n(\vec{x}) ds$ with s the geometric location along the path.

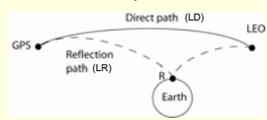


Fig.2: Schematic representation of the radio occultation geometry. Direct and reflected paths transmitted by the GPS satellite to the LEO satellite are represented. R is the reflection point.

Here we are interested on the difference between the direct propagation path and the reflection one (Figure 2).

Several paths going from the emitter (GPS) to the receiver (Low Earth Orbit satellite) may exist. Propagation is concentrated around extremal paths: $\frac{\delta L}{\delta P} = 0$

In our case we consider direct length path (LD) and reflected length path (LR).

a) Direct and reflected paths

In order to analyze the additional information of the reflected signal we represent here both direct and reflected length paths along an occultation event (Figure 3).

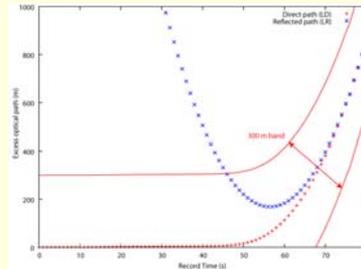


Fig.3: Direct and reflected excess optical paths (m). The 300 m band represents the range of delays where the reflected signal will be captured by the correlator that tracks the direct signal, and interfere with it.

b) Comparison between direct and reflected paths

We present here a comparison between "measured" and evaluated path difference. The "measured" path difference is obtained using the unwrapped phase. Evaluation is made over a refractivity field (we choose several):

1. Standard atmosphere (STD) that is a coarse exponential atmosphere $N = 300 \exp^{(-h/H)}$, with $H = 15 \text{ km} / \log(10)$ without ionosphere.
2. Standard atmosphere (STD) using ionosphere model from COSMIC estimation.
3. ECMWF model without ionosphere.
4. ECMWF with COSMIC ionosphere.
5. A reference vacuum raytracing (straight lines) is also shown.

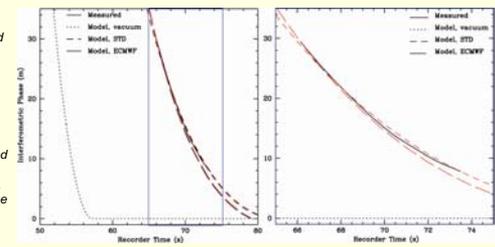


Fig.4: Path difference between direct/reflected signals over sea using interferometric phases. Black curves do not use ionosphere correction. Red curves use ionosphere correction.

The method of least squares

We describe the inversion procedure used to extract the refractivity field. We have seen that raytracing procedure is able to extract 3D information. However a full 3D solution requires massive amounts of data which generally will not be available.

Inversion procedure

We must determine from the obtained ray trajectories which regions of the atmosphere, divided in finite elements, are participating in the propagation of every ray (Aparicio, J.M., and A. Rius (2004)). To do that, we compare the predicted and the observed delays. The raytracing delivers a prediction for the observable delay L^p . Then we attribute a weight w to each finite element, proportional to its contribution to the excess optical length.

Knowing the weight matrix and the phase observation difference it is possible to deduce the refraction index correction (linear least squares) that bring the difference between measured and evaluated delays.

We want to calculate: $\Delta\varphi = \Delta L_{measured} - \Delta L_{estimate}$

with $\Delta L_{measured} = (LD_{measured} - LR_{measured})$ which is the unwrapped phase

and $\Delta L_{estimate} = (LD_{estimate} - LR_{estimate})$

The ray tracing method allows to estimate raytracing function such as:

$$f(n) = L, \text{ applying the derivative: } f'(n) = f'_0(n_0) + W(n - n_0)$$

with n_0 as a reference field. Then we have to solve the following equation

$$\text{to deduce the refractivity correction coefficients: } W\Delta n = \Delta\varphi$$

To find the solution we use the least square method and solve this final

$$\text{equation: } \Delta n = (W^T W)^{-1} W^T \Delta\varphi$$

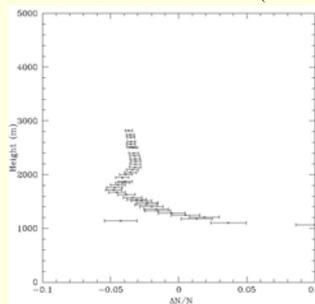


Fig.5: Refraction index correction coefficients ($\Delta n / n$)

Perspectives and conclusions

We have shown that it is possible to do realistic raytracing thanks to the comparison between measured unwrapped phase and over realistic refractivity models, including ionosphere corrections. The non-vacuum raytracing methods are reasonable close to the unwrapped reflected phase.

A least squares inversion allows the extraction of useful meteorological information.

One major perspective of the work is to determine the ability of such a measurement to qualify the properties of the low atmosphere (refractivity profile within the boundary layer).

If the determination of such properties is feasible then the Numerical Weather Forecast system of Environment Canada could take advantage of the RO-observations.

References

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