

A NOVEL APPROACH TO ATMOSPHERIC PROFILING WITH A MOUNTAIN-BASED OR AIR-BORNE GPS RECEIVER

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ABSTRACT

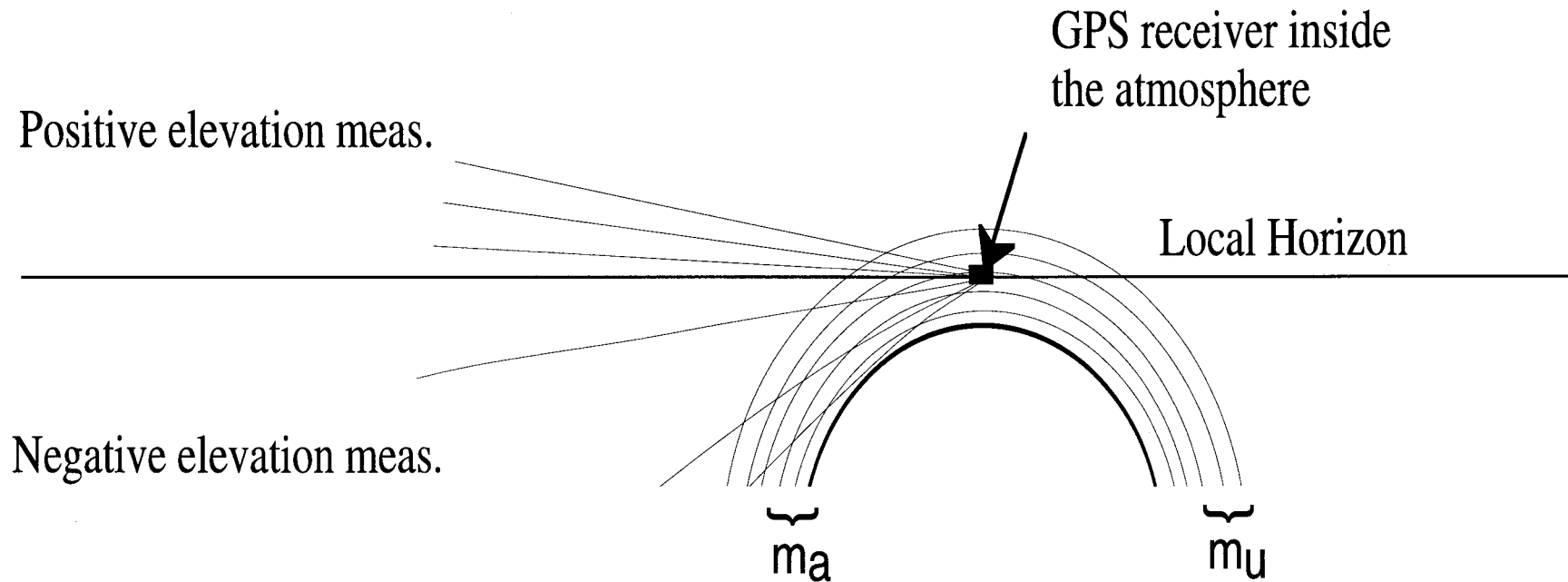
The delay induced by the Earth's atmosphere on the Global Positioning System (GPS) signal has been exploited in the last decade for atmospheric remote sensing. Ground-based GPS measurements are traditionally used to derive columnar water vapor content while space-based GPS measurements obtained by tracking GPS satellites occulting behind the Earth's atmosphere, as viewed by a receiver in a low-Earth orbit, have been demonstrated to yield very accurate high resolution profiles of refractivity, temperature and water vapor. A GPS receiver on a balloon, airplane or mountain top with a "downward-looking" field of view toward the Earth's limb is a novel concept which is presented here. This new remote sensing approach provides dense coverage of high vertical resolution profiles of refractivity in the region around the receiver, which yield much needed information on boundary layer structure and complement the columnar moisture data from upward looking receivers for regional hydrological research.

We present a generalized raytracing inversion scheme which can be used when occultation data is acquired with a receiver within (e.g., on mountain top) the atmosphere. In this scheme, spherical symmetry is assumed for the atmosphere and the refractivity is modeled as piecewise exponential, with scale height changing from one atmospheric layer to the next. Additional refractivity data derived from a model might be introduced at high altitude, and are treated as properly weighted measurements. The exponential scale heights and a normalizing value of refractivity are retrieved by minimizing the residuals between measured bending angles and refractivity and those calculated based on the exponential model. We first illustrate results comparing refractivity and temperature profiles obtained by this generalized raytracing scheme against those derived via the Abel inversion for the GPS/MET experiment. Additionally, we present results for a hypothetical situation where the receiver is placed within the atmosphere at a height of 5 km. For the last case we investigate the accuracy of the retrieval both below and above the receiver at a set of locations in the atmosphere ranging from mid to tropical latitudes. Our findings suggest that the GPS data collected from inside the atmosphere has enough strength to allow for quite accurate retrievals of refractivity at heights up to several km above the receiver locations.

ATMOSPHERIC SENSING WITH GPS RECEIVER OUTSIDE THE ATMOSPHERE

Radio occultation measurements using the Global Positioning System (GPS) and a receiver in low-Earth orbit (LEO) have recently been shown to provide accurate profiles of atmospheric refractivity, pressure, water vapor and temperature with high vertical resolution [e.g. **Hajj et al.**, *Proc. IAG Symp. G1, GPS Trends in Precise Terrestrial, Airborne, and Spaceborne Applications, IUGG XXI General Assy., Boulder, CO, 2-14 July 1995, Springer-Verlag, 1996*; **Kursinski et al.**, *Science*, 1996; **Ware et al.**, *Bull. Am. Meteorol. Soc.*, 1996; **Leroy**, *J. Geophys. Res.*, 1997; **Rocken et al.**, *J. Geophys. Res.*, 1997; **Kursinski and Hajj**, *J. Geophys. Res.*, 1998]. The high accuracy and resolution of atmospheric profiles obtained from GPS occultations at a relatively low cost, has created considerable interest in the atmospheric and climate research communities, because of the data's potential impact. For instance, several studies have investigated means of assimilating GPS occultation data into numerical weather predictions and the impact these data would have on the models [**Eyre**, *European Center for Medium-Range Weather Forecasts, Tech. Memo. No. 199*, 1994; **Kuo et al.**, *J. Dyn. Atmos. Ocean*, 1998; **Zou et al.**, *J. Geophys. Res.*, 1998], while others examined the climate information content of these data [**Yuan et al.**, *J. Geophys. Res.*, 1993; **Kursinski and Hajj**, *J. Geophys. Res.*, 1998; **Leroy**, *J. Climate*, 1998]. While GPS occultation data collected from space has the advantage of being global (one receiver in low-Earth orbit provides about 500 globally distributed occultations per day), the sampling in any particular region is relatively sparse without a large number of orbiting receivers. (For a review of the space-based GPS occultation technique see, e.g., **Kursinski et al.**, *J. Geophys. Res.*, 1997.)

ATMOSPHERIC SENSING WITH GPS RECEIVER INSIDE THE ATMOSPHERE



The viewing geometry of a “down-looking” GPS receiver located inside the atmosphere can be thought of as a hybrid between the space and ground viewing geometries . A mountain-based or air-borne receiver would track any GPS satellite as it sets or rises behind the Earth’s limb, therefore collecting data at both negative and positive elevations relative to the receiver’s local horizon . We have found that by combining both the negative and positive elevation data we obtain a high resolution profile of refractivity below the receiver’s height, and a coarser resolution profile extending a few kilometers above the receiver.

INVERSION SCHEME

In a spherically symmetric medium, a signal travels along a curve defined by $nr \sin(\phi) = \text{constant} \equiv a$ where r is the distance from the origin of symmetry to a point on the raypath, ϕ is the angle between the direction of r and the tangent to the raypath, n is the index of refraction at r . Based on this a signal traveling in a spherically symmetric medium will bend by an amount [*Born and Wolf*, 1980]

$$\alpha = a \int_{\text{raypath}} \frac{1}{n\sqrt{n^2 r^2 - a^2}} \frac{dn}{dr} dr$$

When the receiver is outside the atmosphere, a corresponds to the asymptote miss distance or impact parameter. In this case the equation can be inverted analytically via the Abel transform for $n(a)$. When the receiver is inside the atmosphere the transform cannot be applied because the bending is not known for impact parameters above the receiver location. A numerical inversion of the bending equation must be performed, based on raytracing.

In essence our raytracing technique models the atmosphere as a set of concentric layers of specified thickness, with refractivity varying exponentially as a function of radius with a fixed scale height for each layer. The inversion consists of finding the optimal set of scale heights and an overall normalization factor that best fit the measured bending angles and other given information or measurements. Since each bending measurement at negative elevation is heavily weighted by the atmospheric structure at the layer where the tangent point resides, the atmospheric structure below the receiver's height can, to some extent, be uniquely determined from these negative elevation measurements. In addition, we will demonstrate that refractivity at the receiver's height and immediately above it can be uniquely retrieved without the help of other information. As we start going to higher elevation, data becomes strongly correlated, and we must rely on other *a priori* information or measurements to be able to obtain a unique solution for the atmosphere at higher altitudes.

MATHEMATICAL FORMALISM

In representing the atmosphere as a layered medium, we assume refractivity to be changing exponentially with a constant scale height within each layer. Given these scale heights, a normalization value for the index of refraction, and constraining the refractivity (but not its derivative) to be continuous across the boundaries of different layers, we can write a functional form that describes refractivity everywhere in the atmosphere as a function of the radial distance from the earth's center. We can then calculate the bending by numerical integration of the bending equation. Because the problem is severely non-linear, it is advantageous to attenuate the non-linearity by solving for the logarithm of the refractivity and bending. However, since the reformulated problem is still not completely linear, a few iterations are required before a solution is reached. At each iteration, k , we use the set $\{ 1/H_i^k, \ln(N_{norm}^k) \}$, to calculate the bending and refractivity. Evolution of the solution from one iteration to the next is accomplished by Taylor expanding around $\{ 1/H_i^k, \ln(N_{norm}^k) \}$. To first order, this can be expressed as

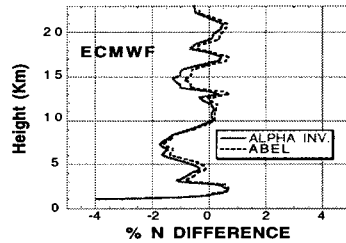
$$\ln(\alpha_m) = \ln(\alpha_c(H_i, N_{norm})) + \sum \frac{\partial}{\partial p} \ln(\alpha_c(1/H_i, \ln(N_{norm}))) \Delta p$$

$$\ln(N_m) = \ln(N_c(H_i, N_{norm})) + \sum \frac{\partial}{\partial p} \ln(N_c(1/H_i, \ln(N_{norm}))) \Delta p$$

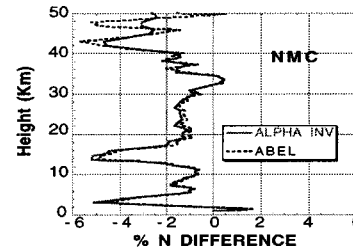
$$\text{where } p = \{1/H_i, \ln(N_{norm})\}$$

which is solved in a least-square sense. In the above equations a set of refractivities are introduced above the receiver locations to constrain the problem at heights where there are no bending measurements effects. Such values are obtained from an *a priori* model such as ECMWF or NMC.

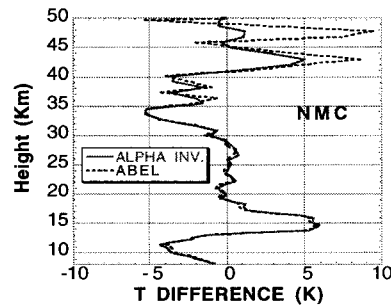
VALIDATION AGAINST ABEL TRANSFORM



(a)



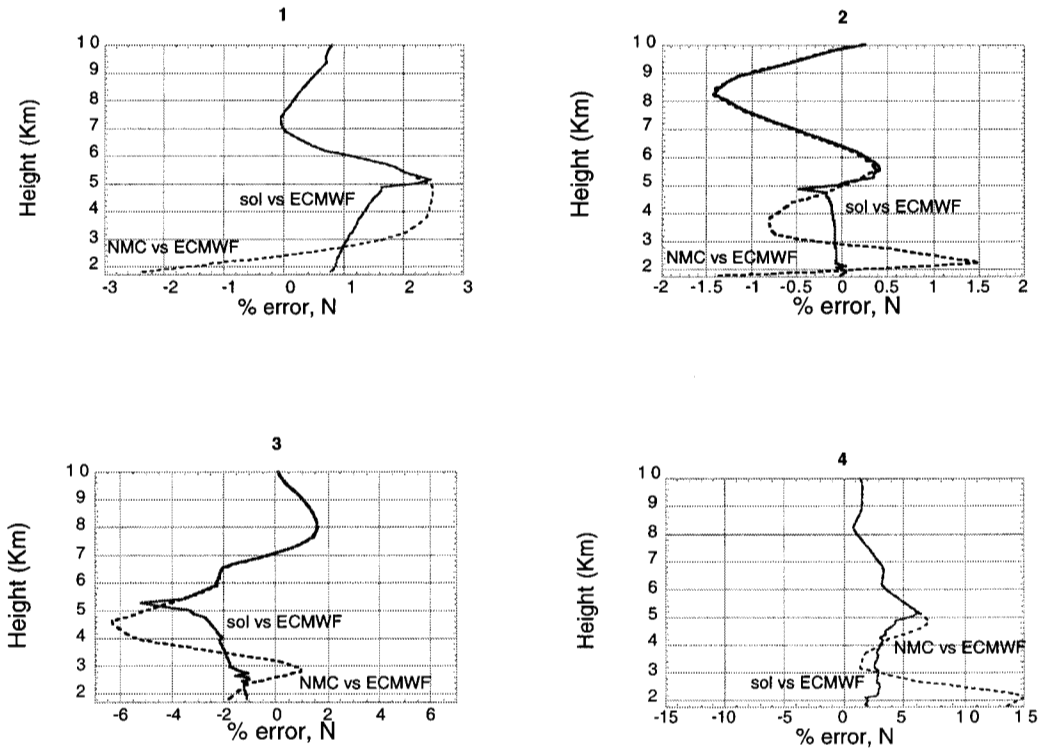
(b)



(c)

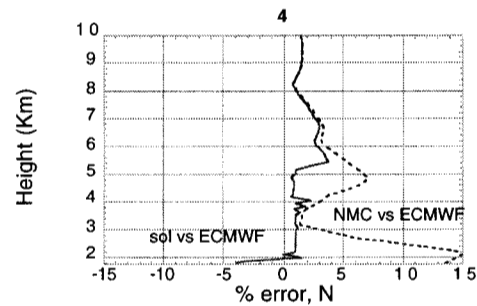
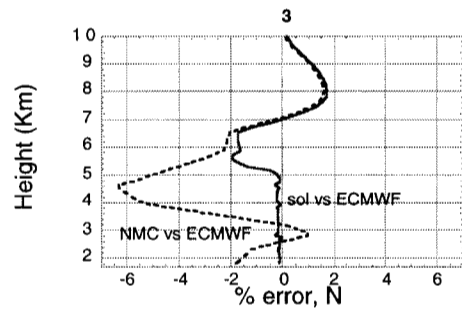
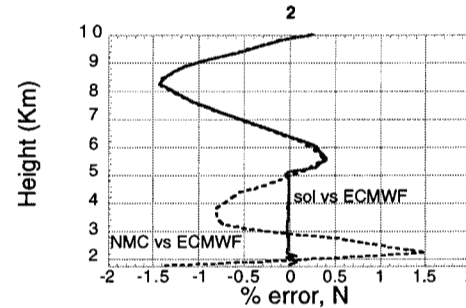
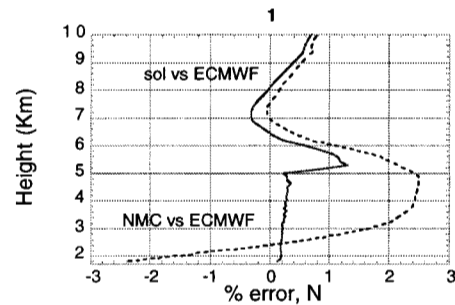
(a) Fractional refractivity difference between ECMWF model and GPS/MET (receiver is outside the atmosphere) data inverted with the Abel and our technique (on the figure referred to as ALPHA); (b) same as in (a) but for the NMC model; (c) same as (b) but for temperature.

RECEIVER INSIDE THE ATMOSPHERE AT 5 Km



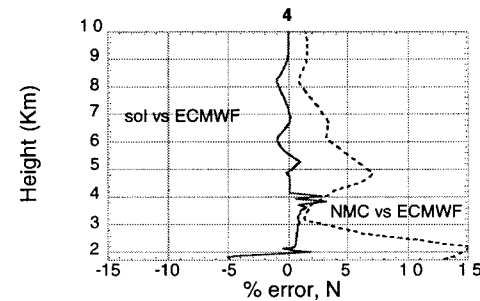
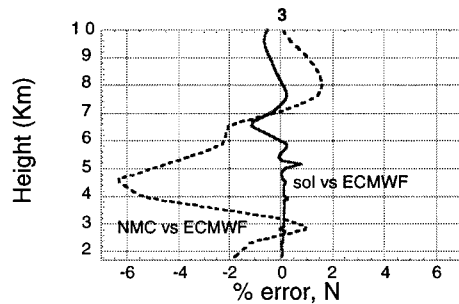
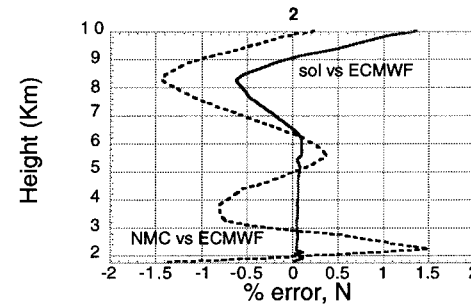
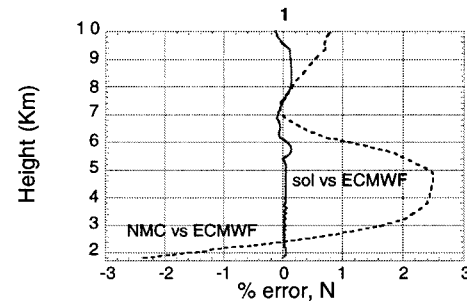
Fractional error in retrieved refractivity when **positive elevation** measurements are **not** included.
LOCATIONS (lat , lon): (1) - 40,180 (2) - 34, -120 (3) 20, -160 (4) -10,40

RECEIVER INSIDE THE ATMOSPHERE AT 5 Km



Fractional error in retrieved refractivity when **positive elevation measurements are included** as well as **refractivities above the receiver**. LOCATIONS (lat , lon): (1) - 40,180 (2) - 34, -120 (3) 20, -160 (4) - 10,40

RECEIVER INSIDE THE ATMOSPHERE AT 5 Km



Fractional error in retrieved refractivity when **positive elevation** measurements are included and **no refractivity below 25 km** is used. LOCATIONS (lat , lon): (1) - 40,180 (2) - 34, -120 (3) 20, -160 (4) - 10,40

SUMMARY AND CONCLUSIONS

We have described and demonstrated a technique appropriate for inverting GPS occultation data to retrieve vertical profiles of refractivity, which could be used in assimilating the data into numerical weather models. Close agreement with the Abel results, in the applicable cases, confirms the correctness of the approach and implementation. Results presented for a simulated receiver fixed at 5 km indicate that the accuracy of the retrieved refractivity below the receiver is good at and above the receiver location. Inclusion of positive elevation bending data significantly improved the retrieved structure at most altitudes. In fact, inclusion of positive elevation bending data and simultaneous removal of *a priori* model refractivity below 25 km actually improved the accuracy of the results, clearly indicating that the model values were weighted too strongly relative to the data. More importantly, the results using positive elevation bending data means the retrieved vertical refractivity structure does not depend much on the accuracy of the model values to at least 5 km above the receiver altitude. The inclusion of positive elevation data, which enables us to retrieve refractivity up to a few kilometers above the receiver's height, implies that any mountain at the height of, or taller than, the boundary layer can be used as a vantage point to characterize the boundary layer structure.

Accuracy and independence at and above the receiver location also mean that airplane results derived near the height of the airplane (defined as the altitude of interest) will be quite accurate and independent of *a priori* first guesses and may therefore significantly impact weather forecasting in the region. Although the conclusions drawn above are based on the examination of synthetically generated bending data, we feel encouraged by our very promising preliminary results and will pursue a validation with real data in the near future. Finally, it is important to note that even though we have validated this technique assuming a layered exponential model for the atmosphere, the approach can easily be generalized to include some horizontal variation of the gradient of refractivity.