Inversion of GPS Occultation Data
for Atmospheric Profiling

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1 Introduction

The GPS (Global Positioning System) radio occultation technique can provide valuable information about the atmospheric refractive index related to the temperature, pressure, and moisture, as well as the ionospheric electron density. Generally, the radio occultation method has been widely used in various planetary missions the last 30-35 years, and has given unique information about the atmospheres of the other planets in our solar system (e.g., Kliore et al. 1965; Fjeldbo et al. 1971; Tyler 1987). Just recently, with the launch of the American GPS/MET (GPS/Meteorology) experiment in April 1995, the technique has been successfully applied to the Earth's atmosphere as well (e.g., Ware et al. 1996; Kursinski et al. 1996; Rocken et al. 1997).

The basis of the GPS/MET occultation experiment is the GPS constellation, originally designed for precise positioning. The GPS constellation consists of 24 satellites in 6 orbital planes at a distance of about 20,200 km from the Earth's surface. These satellites continuously transmit electro-magnetic waves at two frequencies: \( f_1 = 1.57542 \) GHz and \( f_2 = 1.22760 \) GHz. In the GPS/MET experiment the signals are received at a Low Earth Orbit (LEO) satellite about 750 km above the surface. On their way the signals pass through the Earth’s ionosphere and neutral atmosphere (Fig. 1).

In the ionosphere and neutral atmosphere the signals are distorted because of the refractive index of the medium. In the geometrical optics approximation, the result is that a signal received at the LEO has been subject to a small bending. If we know the precise positions and velocities of the satellites (in principle obtained by simultaneous observations of different GPS satellites), we are able to measure the bending angle, \( \alpha \). Due to the satellite motions the whole atmosphere from top to surface is scanned, obtaining a set of bending angles related to different heights in the atmosphere. Using the Abel transform (e.g., Fjeldbo et al. 1971), the measured bending angles can be inverted to an atmospheric refractive index profile. In the case that one is only interested in the neutral atmosphere, the scanned region is restricted to the lowest ~ 100 km of the atmosphere. In this paper we shall concentrate on the neutral atmosphere occultation experiment.

The refractive index in the neutral atmosphere is related to the temperature, \( T \) [K], the total pressure, \( p \) [hPa], and the partial pressure of water vapor, \( p_w \)
Fig. 1. Illustration of the occultation geometry. Signals transmitted by a GPS satellite are refracted by the ionosphere and the neutral atmosphere. When received at a LEO satellite outside the main part of the ionosphere the signals have been subject to bending.

\[ \mu = 1 + 77.60 \cdot 10^{-6} \frac{P}{T} + 0.373 \frac{P_w}{T^2} \]  

The term related to the partial pressure of water vapor can sometimes be neglected, being a fair assumption at high latitudes. Generally, the water vapor in the lower troposphere can be neglected in regions colder than 250K (Kursinski et al. 1996). In the tropical troposphere the water vapor term can usually not be neglected and the derived temperature ignoring this term in (1) is therefore often denoted as the dry temperature.

In Sect. 2 we outline the inversion procedure, going from bending angles to the dry temperature profiles. This outline is only meant as an overview for the reader not familiar with the method, and does not take into account problems involving differentiation of noisy phase data to obtain the bending angles, ionospheric residual effects, diffraction effects, and model extrapolation dealing with infinite integration limits. For a closer inspection of these difficulties the reader is referred to (Syndergaard 1999b) and references therein. Section 3 is dedicated to a random error propagation analysis related to the Abel transform. In Sect. 4 some results of inverted data from the GPS/MET experiment are shown and compared to other data sources like radiosondes and numerical weather analyses. A case study, testing the spherical symmetry assumption is carried out in Sect. 5, and finally, conclusions and remarks are given in Sect. 6.
2 Data Processing Overview

The measured quantity is the GPS phase path, which upon differentiation gives a measured Doppler shift. This Doppler shift is not only due to the relative motion of the satellites but also due to the bending in the atmosphere which slightly modifies the emergent and incident angles of the signal to the satellite velocity vectors. From the occultation geometry, and assuming the atmosphere to be spherically symmetric, we are able to calculate the bending angle, $\alpha$, then related to an impact parameter, $a$, which is the asymptotic distance to the center of refraction (Fig. 2).

![Diagram of occultation geometry](image)

**Fig. 2.** The geometry of the occultation is assumed to be spherically symmetric. The impact parameter, $a$, is defined as the perpendicular distance between either of the ray asymptotes and the center of refraction. At any point along the ray, $\psi$ is the angle between the wave normal and the radius vector. The tangent point is the closest approach of a ray to the Earth's surface.

When only interested in the contribution from the neutral atmosphere to the bending of the signal, the ionosphere contribution (overshadowing the contribution from the neutral atmosphere for rays with tangent points above some 45 km) has to be eliminated. This is possible, at least to a large extent, using a dual frequency combination. To eliminate most of the ionospheric effects a linear combination of the bending angles, $\alpha_1$ and $\alpha_2$, for each of the two GPS signals can be applied as

$$\alpha(a) = \frac{f_1^2\alpha_1(a) - f_2^2\alpha_2(a)}{f_1^2 - f_2^2}.$$  \hspace{1cm} (2)

This combination was first proposed by Vorob’ev and Krasil’nikova (1994) and has shown to give better results than the traditional combination of phases usually applied in ground based GPS measurements. A detailed theoretical analysis of the ionosphere calibration in GPS occultation measurements can be found in (Syndergaard 1999a).
In a spherically layered medium, Snell’s law of refraction results in Bouger’s law given by
\[ \mu(r) r \sin \psi = a, \]
where \( r \) is the radial distance and \( \psi \) is the angle between the wave normal and the radius vector at points along the ray (Fig. 2). The quantity \( \mu(r) r \sin \psi \) is an invariant along the ray. Based on Bouger’s law, Fjeldbo et al. (1971) derived an integral transform relating \( \alpha(a) \) and \( \mu(r_0) \):
\[ \alpha(a) = -2a \int_{r_0}^{\infty} \frac{d \ln \mu/dr}{\sqrt{\mu^2 r^2 - a^2}} \, dr, \]
and the inverse relation:
\[ \mu(r_0) = \exp \left( \frac{1}{\pi} \int_{a}^{\infty} \frac{\alpha(a')}{\sqrt{a'^2 - a^2}} \, da' \right). \]

In (5), \( r_0 \) is the radial distance from the center of refraction to the tangent point (Fig. 2). Equations (4) and (5) can be regarded as a special case of the Abel transform, first derived by the nineteenth century Norwegian mathematician, Niels Henrik Abel. These equations have been derived under the assumption of local spherical symmetry, and as we shall see later, this is a very good assumption for the neutral part of the atmosphere in most cases. Having calculated a set of bending angles as a function of impact parameters, (5) directly gives us the refractive index at the tangent point altitudes. The tangent point altitude for a given impact parameter can then be derived from Bouger’s law for \( \psi = 90^\circ \), giving
\[ r_0 = \frac{a}{\mu(r_0)}. \]

For convenience the refractivity, \( N \), is here defined as
\[ N = \mu - 1 = 77.60 \cdot 10^{-6} \frac{p}{T}, \]
ignoring the water vapor term. Close to the surface the refractivity reach a value of about \( 3 \cdot 10^{-4} \) under dry conditions. Under wet conditions the refractivity (including the water vapor term) may reach values of about \( 4.5 \cdot 10^{-4} \).

If we assume ideal gas behavior, it follows that the dry air density, \( \rho \), is proportional to the dry air refractivity given by (7). Therefore, applying (5) for a range of impact parameter values—and knowing the radius of the Earth—we obtain a dry air density profile. From the dry air density profile, pressure, \( p \), as a function of altitude, \( h \), is generated by applying the hydrostatic equilibrium assumption:
\[ p(h) = \int_{h'}^{\infty} g(h') \rho(h') \, dh', \]
where \( g(h) \) is the gravitational acceleration profile at the tangent point location. Finally the equation of state is applied once again to obtain the temperature:
\[ T(h) = \frac{p(h)}{R_d \rho(h)}, \]
$R_d$ being the gas constant for dry air.

The temperature obtained in this way is a very good estimate of the real temperature in regions where the water vapor term has only little influence on the total refractivity. This is not generally the case in tropical regions at tropospheric heights. Then the dry temperature will underestimate the real temperature. As a consequence, in moist regions the water vapor pressure may be found if auxiliary information of the real temperature is available. From (1) it follows that

$$p_w = T^2 \frac{N - 77.6 \cdot 10^{-6} p / T}{0.373},$$

where $T$ denotes the auxiliary temperature while $N$ is the refractivity measured from the occultation data. The total pressure, $p$, may be obtained either from auxiliary sources also, or the hydrostatic equation may be invoked to get the relation between temperature, pressure and moisture. This latter approach becomes an iterative procedure, and a method for water vapor retrieval using such a scheme has been elaborated by Gorbunov et al. (1996). In this paper we shall consider dry air retrievals only.

3 Random Error Propagation Analysis

As seen in Sect. 2 we have an analytic formulation of the inverse problem. Nevertheless it is illuminating to take (4) and discretize it in order to do a random error propagation analysis using singular value decomposition. For this we choose to discretize the atmosphere into 100 layers, each of thickness 1 km. This is a representative value of the inherent vertical resolution of the method, which is limited by the first Fresnel diameter (cf Sect. 5).

We will first put (4) into a form ready for discretization. This can be done by a change of variable, $x = \mu r$, while at the same time using the approximation $\ln(\mu) \approx N$, to obtain

$$\alpha(a) = \int_{a_1}^b K(x, a) m(x) \, dx,$$

with

$$K(x, a) = \begin{cases} 0 & \text{for } x < a \\ \frac{2a}{\sqrt{x^2 - a^2}} & \text{for } x \geq a \end{cases}, \quad m(x) = -\frac{dN}{dx}.$$  

At $\sim 100$ km altitude and above we will assume the refractivity gradients to be negligible, so that the upper integration limit can be approximated by $b = a_1 + 100$ km, where $a_1 = 6371$ km is a representative value of the lowest impact parameter close to the Earth’s surface. Splitting up the integration into $n = 100$ sub-integrals in which $m(x) = m_j$ ($j = 1, \ldots, n$) are assumed to be constants, we get

$$\alpha(a) = \sum_{j=1}^n \int_{a_j}^{a_{j+1}} K(x, a_j) m_j \, dx.$$  

(13)
where \( a_{n+1} = b \) and \( a_{j+1} - a_j = \Delta a = 1 \text{ km} \). The integration of the kernel, \( K(x, a) \), can be evaluated analytically in each subinterval to give
\[
\int_{a_j}^{a_{j+1}} K(x, a) \, dx = 2a \ln \left( \frac{a_{j+1} + \sqrt{a_{j+1}^2 - a^2}}{a_j + \sqrt{a_j^2 - a^2}} \right), \quad a_j \geq a. \quad (14)
\]

Choosing \( \alpha_i = \alpha(a_i) \) \((i = 1, \ldots, n)\) to be \( n \) data points of bending angles with impact parameters \( a_i = a_1 + (i - 1) \Delta a \), we arrive at a discretized formulation of (11):
\[
\alpha = Km \quad (15)
\]
with
\[
K_{ij} = \begin{cases} 
0 & \text{for } j < i \\
2a_i \ln \left( \frac{a_{j+1} + \sqrt{a_{j+1}^2 - a_i^2}}{a_j + \sqrt{a_j^2 - a_i^2}} \right) & \text{for } j \geq i
\end{cases} \quad (16)
\]

In (15), \( \alpha \) is our data vector of bending angles and \( m \) our model vector of the refractivity gradients. Figure 3 is a plot of the resulting 100 \( \times \) 100 dimensional \( K \) matrix. It is an upper triangular matrix, and due to the shape of the kernel the diagonal elements are far the largest ones.

Doing the singular value decomposition (e.g., Scales and Smith 1996),
\[
K = U \Sigma V^T, \quad (17)
\]
we find, not surprisingly, that the condition number is relatively low \((\approx 9.67)\), meaning that this is a very well-posed problem. Assuming uncorrelated errors on
Fig. 4. Standard deviation on retrieved refractivity. a) In N-units ($1\,\text{N-unit} = 10^{-6}$). b) Relative to a background refractivity taken as $N = 3 \times 10^{-4} \exp(-(a_k - a_1)/8\,\text{km})$.

the bending angles$^1$, with a constant standard deviation $\sigma_\alpha$, the error covariance matrix for the refractivity gradients becomes

$$C_m = \sigma_\alpha^2 V \Sigma^{-2} V^T.$$  \hspace{1cm} (18)

From the error covariance matrix of the refractivity gradients we obtain the resulting standard deviation on the refractivity, $N_k = N(a_k)$ ($k = 1, \ldots, n$), at different heights:

$$\sigma_{N_k}^2 = (\Delta a)^2 \sum_{i,j \geq k} C_{ij}. \hspace{1cm} (19)$$

For $\sigma_\alpha = 10^{-6}\,\text{rad}$ (which is not so far from what can be obtained from the GPS/MET data with this technique), Fig. 4a shows how the refractivity standard deviation decreases slightly with altitude in the atmosphere. However, since the atmospheric refractivity is decreasing almost exponentially with altitude, the relative errors in refractivity increases with altitude (Fig. 4b). At altitudes above $\sim 70\,\text{km}$ the air is so thin that the bending angle signal becomes less than the

$^1$ Since the bending angles are derived from the phase measurements, involving numerical differentiation, the bending angle errors will not be perfectly uncorrelated. A more elaborate random error propagation analysis for the whole problem going from phase to temperature can be found in (Syndergaard 1999b).
bending angle noise. For the retrieved refractivity the relative error exceeds 20 % above 70 km. The error behavior seen in Fig. 4b maps into a similar behavior on the temperature standard deviation, which is the main reason that this method is only capable of providing good temperature estimates (better than 1–2 °C) below some 30–40 km altitude. In the estimations above we have made a small approximation, equalizing the impact height with the altitude. In fact the impact height and the actual tangent height differs by a few kilometers at the lowest altitudes.

The result in Fig. 4b is similar to earlier results given by Kursinski et al. (1997). However, it should be emphasized that the resulting standard deviation of the refractivity—besides the standard deviation of the bending angle—depends on the number of discretization levels and the spacing between them as well as the vertical correlation between the bending angle errors (Syndergaard 1999b).

4 Results

The method outlined in Sect. 2 has been used to obtain the dry temperature from the GPS/MET phase data in a few cases. Figure 5 and 6 compares inversion results with nearby radiosonde data and numerical analyses from the European Centre for Medium-range Weather Forecasts (ECMWF) and the U. S. National Centers for Environmental Prediction (NCEP).

In Fig. 5 we see a good agreement between the GPS/MET and the radiosonde temperature. Both measurement methods catch some of the same temperature variations in the tropopause and stratosphere up to the altitude where the radiosonde stops giving data. The differences are only a few °C. The inversion result also agrees quite well with the numerical analyses up to an altitude where we expect the inversion accuracy to become poor (above 35 km). Below some 4 km the results are not good because of increasing moisture in the lower troposphere. Generally, it should be noted that the correlative data (radiosonde data and the analyses data) are separated in time and space from the occultation data, since the correlative data are only available at fixed times and locations while the temporal and spatial distribution of the occultation events is almost random. This fact may also account for some of the discrepancies between the occultation measurements and the correlative data.

In the lower troposphere moisture may cause sharp vertical gradients in the refractivity which influences the signal tracking performance of the receiver. If the defocusing of the signal becomes to large, the signal becomes so weak that the receiver loses the signal. In extreme cases super-refraction may occur, which is the situation when the bending at the tangent point becomes larger than the Earth’s curvature (Kursinski et al. 1997). In such cases the signal will never reach the receiver. Even if the signal is tracked correctly, atmospheric multi-path propagation, which will occur in regions of sharp vertical gradients, makes it more difficult to retrieve the refractivity correctly. In such situations there is no unique value of the bending angle connected to the Doppler shift at the LEO satellite. Instead, more advanced methods like back-propagating the electro-magnetic field
Fig. 5. GPS/MET sounding (occ. no. 665, day 46, 1997) compared with a nearby radiosonde measurement and numerical analyses from ECMWF and NCEP.

...to a region nearer the tangent point, by means of wave theory, should be applied (Karayel and Hinson 1997; Gorbunov and Gurvich 1998). The back-propagation method also corrects for diffraction effects, theoretically improving the vertical resolution in the troposphere by a factor of about 2–5, depending on the altitude (Mortensen et al. 1999). In any case, the moist and the dry contribution to the refractivity in the lower troposphere cannot be distinguished without auxiliary information of either temperature or water vapor (Kursinski et al. 1995; Ware et al. 1996).

In Fig. 6 the radiosonde and the GPS/MET sounding match extremely well. This is a high latitude occultation where the air is mostly dry all the way down to the altitude where the receiver loses track of the signal. Also the numerical analyses data agree well with the GPS/MET sounding up to about 20 km where they suggest a warmer stratosphere than the inversion result. However, it should be noticed that the ECMWF and NCEP analyses are more or less driven by radiosonde data, and in this case the nearest radiosonde stops giving data at 17–18 km altitude. Therefore it is most likely that the GPS/MET sounding in this case is closer to the truth than the NCEP results in the range 20–35 km.

At present, serious efforts are made to develop techniques for assimilation of the occultation data, either bending angle or refractivity, into numerical weather prediction models (e.g., Zou et al. 1999).
5 Testing the Spherical Symmetry Assumption

It should be remembered that the measurement is an integrated effect over the entire path from the GPS satellite to the LEO satellite. However, most of the bending occurs over approximately 700 km of the path, centered at the tangent point (Høeg et al. 1996). Taking into account the sphericity of the atmosphere, the first Fresnel diameter, $z_F$, can be used to define a horizontal resolution at the tangent point as

$$D_F = 2\sqrt{2r_0 z_F} \quad \text{(20)}$$

If $z_F \ll r_0$, $D_F$ is approximately the horizontal width of a spherical shell having the thickness equal to the first Fresnel diameter. The first Fresnel diameter is the inherent vertical resolution limit when using the geometrical optics approximation, and for a GPS receiver in LEO it varies from about 1.5 km in the stratosphere to about 0.5 km in the lower troposphere (Melbourne et al. 1994). Roughly speaking, components of all rays that pass through the first Fresnel diameter zone will add constructively to some degree, while the contributions of those outside this zone will cancel (Kursinski 1994). For $z_F = 1$ km we get $D_F \approx 220$ km. During the occultation the tangent points are drifting horizontally due to the satellite motion, giving different tangent point locations at different
Fig. 7. Cross section of a model temperature field of a severe frontal system. The slope of the front is 1%, and the maximum gradient at the surface is 5°C/100 km. Isotherms are in °C.

heights. This horizontal drift may become as large as 300 km during the lowest 60 km of ray path descend (Kursinski et al. 1997).

The inversion described in Sect. 2 is based on the assumption of local spherical symmetry, which, if being true, would make our concerns about the horizontal resolution superfluous. However, as we know, the atmosphere is not spherically symmetric, and larger errors than the ones in Fig. 4 are expected below some 40 km, and especially in regions of severe horizontal gradients. To assess this, a small case study has been carried out, including 3D ray tracing through a frontal system to obtain synthetic phase data.

Figure 7 is the cross section of the model temperature field of a severe frontal system. For simplicity, in the simulations the front is directed so that the temperature gradient lies in a meridian plane. To simulate a worst case scenario, the difference between the warm and the cold sides of the front at the surface has been set to about 25 °C. Such differences might be found at mid latitudes over continents during the winter (Hardy et al. 1994). The model has been constructed from an analytical expression of the refractivity given by Syndergaard (1999b). The model is based on calculations excluding the water vapor contribution. Hardy et al. (1994) performed a similar case study using a more realistic model including the water vapor, but only presenting a single result. Here we shall go a bit further and look at different cases. Excluding the water vapor is no serious violation in favor of the method. On the contrary, in a real frontal system the refractivity may not vary much across the front because the dry and the moist refractivity terms tend to cancel, understood in the way that the cold side
**Fig. 8.** Left) Ray paths in a longitude-latitude plot. The simulation of rays are based on a real set of GPS/MET orbit ephemerides. Only a few rays out of about 3000 are shown. The left most ray corresponds to a ray tangent altitude of about 100 km, and the right most ray has its tangent point close to the surface. The drift of the tangent points are shown as diamonds. The three cases of placing the base of the front are indicated as lines with triangles. Right) Each of the three cases in a latitude-height plot, with rays (every 50th ray) superimposed on the temperature fields.

is denser but contains less water vapor than the warm side (Hardy et al. 1994). In Fig. 7 the temperature gradients are produced solely by the dry refractivity term (7).

In the forward ray-tracing modeling, three different cases of occultations going through the frontal system have been simulated, aligning the rays approximately along the meridian: Case 1, where the base of the front has been placed right in front of the tangent points. Case 2, where the base of the front has been placed 5 degrees north of the tangent points. Case 3, where the base of the front has been placed 10 degrees north of the tangent points. In Fig. 8 the placements of the front in each of these three cases are illustrated. The left figure shows the ray paths and the frontal bases in a longitude-latitude plot. The three figures at the right show the situations in latitude-height plots. Because of the Earth’s curvature, the almost straight rays (the bending angle close to the surface is about 1 degree and bending towards the Earth) become convex curves in the three small
Fig. 9. Retrieval errors for each of the three cases as described in the text.

panels to the right in Fig. 8. Such figures are also an excellent illustration of the spatial resolution of the method. In principle, the horizontal resolution defined by (20) corresponds to twice the horizontal distance between the lowest point on a ray and the neighboring ray, except that the vertical distance between rays in Fig. 8 is not exactly the same as the first Fresnel diameter (see also (Kursinski et al. 1997)).

For each of the three cases, about 3000 samples of synthetic phase data (50Hz sampling rate) where calculated, covering the altitude range 0-100km. Bending angles and the corresponding impact parameters were obtained, and the procedure outlined in Sect. 2 was then used to calculate a retrieved temperature profile. A model temperature profile was extracted from the corresponding model field of Fig. 8. The location of the model profile was taken as the latitude and longitude of the point closest to the Earth’s center on that line connecting the GPS- and the LEO satellite which was tangent to the Earth’s surface. This gives a profile close to the set of tangent points shown in the left part of Fig. 8. The retrieved temperature profile and the model temperature profile was compared and the differences in each of the three cases are plotted in Fig. 9. It is seen that the errors are of the order of 0.5 °C, and in the worst case, which turned out to be case 1, the error is still less than 2 °C.

The retrieved temperature profiles were also compared with profiles extracted from the model field at the exact positions of the tangent points. The observed
differences were of the same order as those shown in Fig. 9, although case 2 showed an error as large as case 1, being about 1.5°C. In the above numerical experiments the frontal slope was 1% which is a typical value in the real atmosphere. However, close to the surface the slope may become larger (Gurvich and Sokolovskiy 1985). Increasing the frontal slope to 5% in case 1 resulted in somewhat larger errors (mostly above 4 km, though still less than 2°C), confirming similar results by Gurvich and Sokolovskiy (1985).

Since the temperature profiles are derived via the hydrostatic integration of the refractivity, errors in refractivity, pressure, and temperature do not map as a one to one relationship. There will be differences in the error behavior as a function of height. Also, in a weather front the strict assumption of hydrostatic equilibrium may be questionable. Here we have only concentrated on the temperature errors, though pressure and refractivity errors may be of equal relevance. The order of magnitude of the relative errors, however, is generally the same.

6 Conclusive Remarks

In this paper the inverse problem for the radio occultation method has been presented to which there exist a unique solution connecting measured bending angles to the atmospheric refractive index through an Abel integral transform. Nevertheless, the problem was discretized to investigate the random error propagation using the singular value decomposition. For a constant value of the bending angle error of 1 μrad, relative errors in refractivity increase nearly exponentially with height, exceeding 1% above 50km altitude.

The inversion method was applied to real data to obtain temperature profiles, and the results were validated against radiosonde measurements and numerical analyses results. The agreements were within a few °C.

A case study was carried out testing the method in situations of horizontal inhomogeneities such as a severe frontal system. Errors obtained were less than 2 °C.

Other important retrieval errors are due to residual ionospheric effects and uncertainties in upper boundary conditions in the Abel and hydrostatic integrations.

In the future it is the plan that the occultation method shall provide data to be assimilated into numerical weather prediction models, hopefully improving the initial conditions, and thereby the predictions.

The occultation technique can also be applied to the ionosphere, then obtaining electron density profiles (Hajj and Romans 1998).

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