

Ground Based GPS Phase Measurements for Atmospheric Sounding

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LONG-TERM GOAL

The goal is to develop GPS remote sensing techniques to determine atmospheric signal delay and bending, and refractivity profiles to aid in the detection of oceanic boundary layers from a ship.

SCIENTIFIC OBJECTIVES

The primary scientific objective of this research is to develop GPS sounding techniques for ground based atmospheric profiling. Atmospheric profiling with GPS from space has been demonstrated (e.g. Rocken et al., 1997). Ground based receivers have been used to determine integrated atmospheric water vapor above a site but profiling techniques with ground-based GPS observations are still under development (Anderson 1982, 1994). Ground based observations of GPS tropospheric signal delay and bending cannot be inverted to high-resolution atmospheric profiles comparable to radiosondes, but may provide coarse profiling information. Direct assimilation of slant observations or bending angles into numerical weather models will most likely be the main meteorological application.

APPROACH

We are pursuing a three-step approach to reach the long-term goal of refractivity profiling with GPS from a ship.

- (1) Develop and test GPS single slant measurement techniques
- (2) Develop techniques to interpret these slant measurements
- (3) Develop a system for a mobile platform

We are working on (1) and (2). We are presently conducting a several month experiment to investigate the performance of the ground-based profiling techniques with a fixed antenna installed in San Diego, CA. The porting of the technique to a mobile platform shall begin after the feasibility of the proposed technique and its sensitivity to noise has been thoroughly investigated with GPS receivers from fixed sites.

WORK COMPLETED

Significant progress was made to develop the GPS slant observations technique. Tools were developed and tested to invert these slant observations in order to extract information on the atmospheric refractivity profile. The main tasks are summarized below:

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- Slant delay measurements based on the double difference approach have been implemented and tested with simulated and field data.
- Extensive tests of high quality clock oscillators were conducted in preparation for slant observations.
- Slant delay measurements with a zero-difference approach were implemented and tested.
- Comparisons between double difference and zero-difference results indicated that receiver clock errors are not the limiting error source for the ground-based static observations of GPS excess phases.
- Slant water vapor observations from double difference and point positioning techniques have been compared to pointed water vapor radiometer measurements to validate the technique.
- Slant delay observations with peak noise values of < 0.1 m were collected near Boulder, CO. ("Flagstaff" data set). We collected data on Flagstaff Mountain outside Boulder, and processed these observations with the point positioning technique. The tropospheric delays for one satellite that was tracked to below the horizon is shown in Figure 1.
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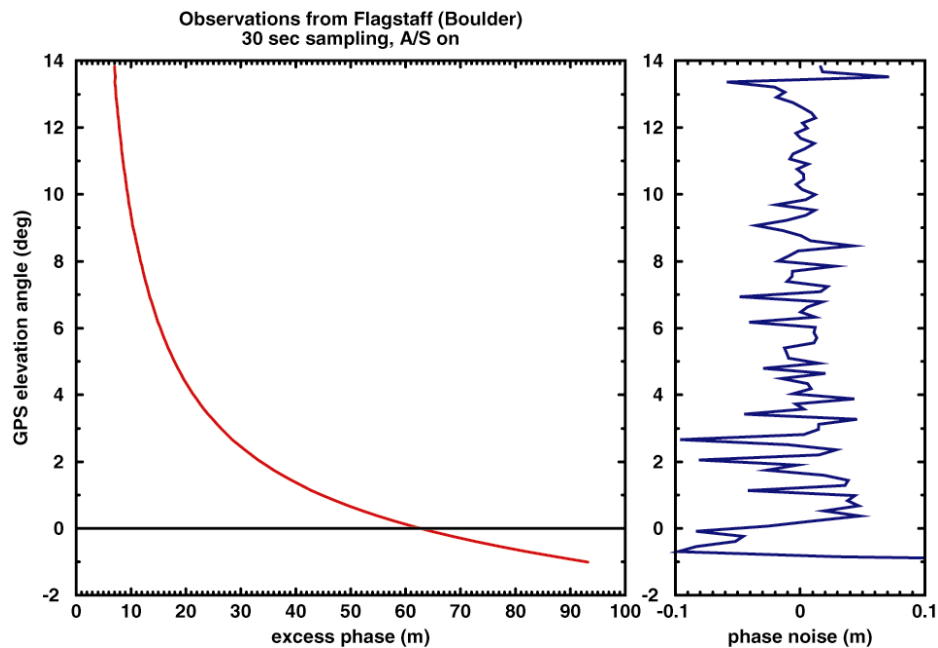


Figure 1 The excess phase due to atmospheric delay and bending of the signal is shown in the left panel to increase from several meters at 14 degrees elevation to about 90 meters below the horizon. The right panel shows the residual of the measurements after cubic spline regression. This residual is caused by a combination of receiver measurement noise, site multipath, noise in the estimated receiver and satellite clocks, and atmospheric effects such as horizontal inhomogeneities. The observational noise level is about ± 10 cm peak value.

- A bending angle inversion technique was developed and tested with simulated and real data. While direct inversion of these bending angle profiles into refractivity profiles is too sensitive to measurement noise, we are now developing bending angle library search techniques, which should be more robust.

- We tested several slant delay library search techniques to map slant measurements as a function of the observation elevation angle into refractivity profiles. All of these techniques work in principle the same way. We establish a set of possible refractivity profiles. This set can be based on radiosondes or climatology. Next we compute the slant delay as a function of elevation angle (typically for the lowest 10 degrees) under the assumption of a perfectly homogenous atmosphere and for a given latitude. Now we have many functions of slant delays vs. elevation angles that map onto a set of refractivity profiles. These functions form our library. Next we can take real slant observations (or for testing purpose simulate them) and compare these to the slant delay functions in the library. That slant delay set from the library that agrees best with the observations in a least squares sense is selected. The corresponding refractivity profile is then selected.
- We tested this technique with the observations from Flagstaff Mountain. We also generated libraries and then generated slant delay sets from arbitrary test profiles and used the technique to recover the known profiles.
- An empirical orthogonal function (EOF) inversion technique for the Flagstaff observations was developed and tested
- For our first developed library search technique we built a library with 4 refractivity layers. In each layer we vary the refractivity in steps of 3 N units of refractivity with +/- 5 steps about the climatological mean. This parameterization results in $11^4 = 14,641$ possible profiles. For each of these profiles we compute the excess phase delay as a function of the elevation angle. These delays as a function of the elevation angle form our library. This library search technique is called LS1.
- EOF and LS1 techniques yielded similar looking profiles.
- Different more limited, library search techniques (LS2 and LS3) were developed for the detection of ocean boundary layer features in the bottom 1 km.
- These techniques were tested with radiosonde data and simulated observations for several ocean boundary layer cases.
- A very simple and fast 2-parameter library search technique LS4 was implemented and tested. Here, again, we computed observations from radiosonde profiles, provided by Kenn Anderson and inverted the excess path delay versus elevation angle data using the library search technique LS4. For LS4 we only vary two parameters: (1) The height of the breakpoint, or onset of the boundary layer and (2) the size of the refractivity step in the layer. We assume that surface refractivity is known, that the refractivity lapse rate below the break point is 10 N units/km and that the refractivity lapse rate in the layer is 160 N units / km (critical refraction conditions). Furthermore we assume that the profile is known above 5 km and we use log-linear interpolation between the upper break point and 5 km.

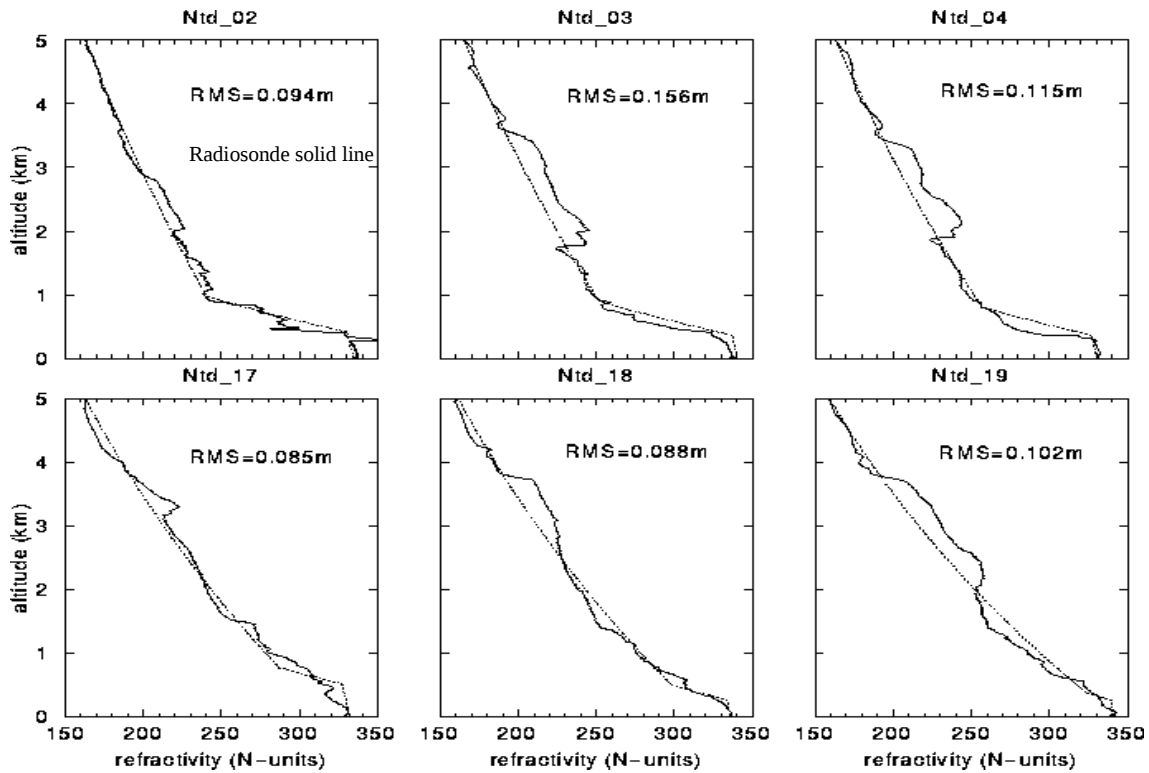


Figure 2 shows example refractivity profile results from the LS4 search technique. The height of the boundary layer is generally well detected, and the size of the step appears to be an indication whether a significant duct is present or not.

- In preparation for a larger scale test of the technique a new GPS receiver was purchased for more reliable tracking of low-elevation observations. We also acquired a ground-based meteorological sensor for measuring refractivity at the GPS receiver site. The meteorological sensor package, the GPS receiver, a stable external oscillator, and a high-gain GPS antenna were all configured to be run remotely in San Diego from Boulder through the Internet for a several month test. During this test we plan to compare profiles from GPS with radiosonde profiles and other "ground truth" data.



Figure 3. GPS antennas at Point Loma to measure the slant tropospheric delay.

Ground based profiling with GPS is challenging. Our research has shown some promising results and additional field tests are now being conducted to test the reliability of the developed techniques and their sensitivity to noise sources. Of particular concern are site multipath and horizontal atmospheric inhomogeneities. If the technique can be shown to provide useful atmospheric profile information we will study its robustness in the context of additional noise in a kinematic environment.

IMPACT/APPLICATION

Remote sensing of atmospheric features and refractivity profiles with GPS promises to impact Navy communication and sensing capabilities and provide a new data set for improved numerical weather prediction. Some applications also require the direct determination of atmospheric bending for locating distant radar targets.

RELATED PROJECTS

- 1) Dr. Kenn Anderson is developing techniques that use amplitude measurements for the detection of specific refractivity profiles. Dr. Anderson's amplitude approach and the phase approach under development may work best in combination.
- 2) The Department of Energy has funded UCAR to develop low-cost L1-only GPS systems for tropospheric tomography. This study requires the measurement of single transmitter - receiver slant ranges, the same GPS observable required for refractivity profiling.
- 3) NCAR and NOAA scientists are working on assimilation of single GPS slant measurements into numerical weather models. The slant measurement techniques that we are developing with this study can then be applied to numerical weather forecasting.
- 4) We have been contacted by groups at Boeing and at Georgia Tech. for information and potential collaboration on the determination of atmospheric bending angles from ground-based GPS observations for the correction of radar observations.

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