Determination of Vertical Refractivity Structure from Ground-Based GPS Observations

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Award #: N00014-00-C-0258

LONG-TERM GOAL

The goal of this multi-year project is to develop GPS remote sensing techniques for the determination of atmospheric signal delay, refractive bending, and refractivity structure to aid in sensing of the refractive environment of ships or land-based stations.

SCIENTIFIC OBJECTIVES

The primary scientific objective of this research is to develop GPS sounding techniques for ground based atmospheric refractivity sensing. 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 they provide direct measurements of microwave signal bending (Sokolovskiy *et al.,* 2001) and coarse refractivity structure information (Lowry *et al.,* 2002). Space based radio occultation data may also be useful for the detection of sharp refractivity gradients (Sokolovskiy, 2002).

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
  - (a) Determination of profile information & signal bending

(3) Develop a system for a mobile platform
  - (a) Evaluation and development of precise kinematic positioning
  - (b) Field tests – Flip-ship (FLIP) experiment
  - (c) Ocean ship-board experiment

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
30 SEP 2002		**00-00-2002 to 00-00-2002**

4. TITLE AND SUBTITLE **Determination of Vertical Refractivity Structure from Ground-Based GPS Observations**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **GPS Science and Technology ,University Corporation for Atmospheric Research,,Boulder,,CO, 80301**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The goal of this multi-year project is to develop GPS remote sensing techniques for the determination of atmospheric signal delay, refractive bending, and refractivity structure to aid in sensing of the refractive environment of ships or land-based stations.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Same as Report (SAR)**	**9**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

During the last year our efforts were focussed on ocean-based experiments. We processed the data collected during the Flip-ship experiment and prepared and conducted a new 7-day experiment aboard the Explorer of Seas (Explorer) in the Caribbean in July of 2002. We are now in the process of analyzing the rich data set collected aboard the Explorer and have initial results. High resolution vertical refractivity profiling is feasible from space with the GPS radio occultation technique. We are investigating the potential to detect sharp atmospheric gradients from satellite by use of this technique by simulating radio occultation data based on radiosonde observations and by processing real data from the GPS/MET CHAMP and SAC-C satellite missions.

WORK COMPLETED

Progress was made in:

(1) processing observations collected during the Flip experiment off the coast of Hawaii;

(2) preparation and carrying out of the sea-going experiment aboard Royal Caribbean's Explorer of the Seas;

(3) analysis of the data collected aboard the Explorer;

(4) continuation in the development of space based detection of ocean ducting layers. Highlights of the accomplished tasks are summarized below:

- **We have processed GPS data collected during the Flip-ship experiment off Hawaii.** The initial step requires precise positioning of the GPS antennas aboard Flip. This was achieved with precise carrier phase point positioning. The motion of Flip, especially in the horizontal was quite strong and irregular with oscillations of approximately 10-sec period and peak-to-peak amplitudes reaching 60 cm. Flip was much more stable in the vertical than in the horizontal position which is a disadvantage for refractivity profiling or bending angle determination since horizontal motion maps into the direction of setting satellites. The biggest challenge for the GPS data set from Flip was posed by the large number of data gaps and carrier phase cycle slips which were caused by the severe multipath environment and by obstruction from the ship's tower above the GPS antenna. Nevertheless we obtained some profiles of refractivity and of signal bending angle from the data collected aboard Flip.

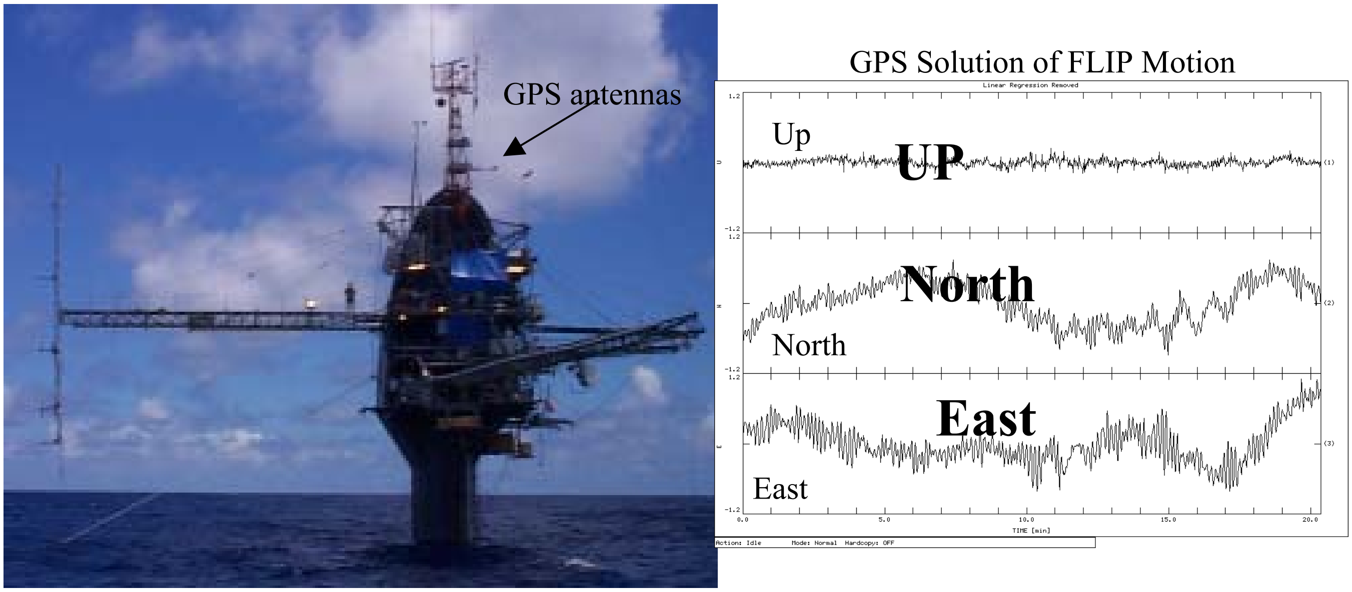
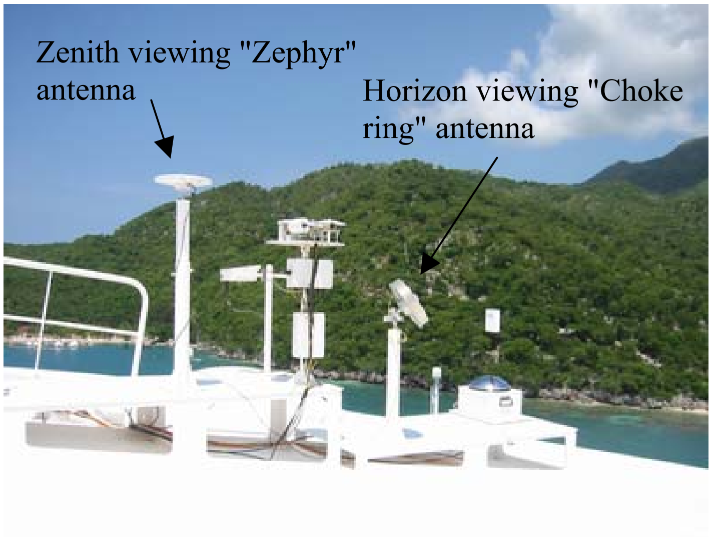


Figure 1 (left panel) shows the location of the GPS antennas on the Flip ship during the experiment. The right panel shows an example 20-minute segment of the GPS-determined motion of Flip after removal of a linear trend for the up, north and east motion components. The scale in each of the motion panels is +/- 1.2 m. The period of the primarily north and east motion is about 10-sec.

- **We prepared and conducted a second open-ocean experiment aboard the Explorer of Seas vessel.** Because of the limited data quality obtained aboard the Flip ship we organized a second experiment at sea. This experiment was carried out aboard the Explorer of the Seas - a very large cruise ship, owned and operated by the Royal Caribbean. The Rosenstiel School of the University of Miami manages scientific experiments that can be hosted aboard the Explorer using facilities that are sponsored jointly by Royal Caribbean, NSF and NOAA (http://www.rsmas.miami.edu/rccl/descrip.html). Our GPS experiment was accepted for a 7-day cruise out of Miami, starting Saturday, July 6, 2002. During the cruise we operated two dual frequency Trimble GPS receivers (one model 4700 and one model 5700 receiver) connected to antennas that were mounted near the front mast of the large ship. One of the antennas (a Trimble "Zephyr Geodetic") was mounted with boresight towards zenith, the second was tilted towards the horizon to track setting satellites with increased antenna gain. The GPS receivers were run during the entire cruise at 1-sec sampling rate.



Caribbean track of the "Explorer of the Seas"
(GPS positions from 7-day cruise)

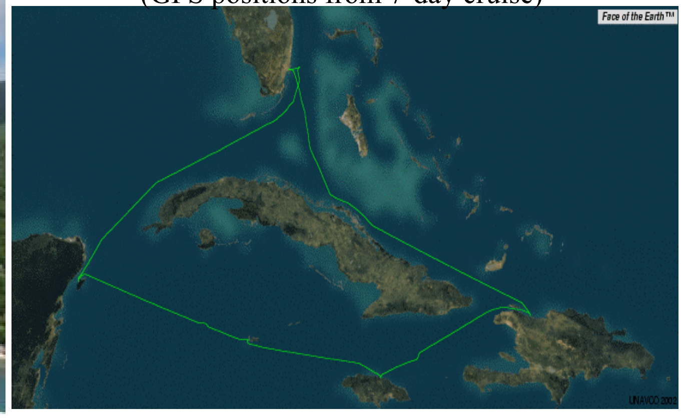


Figure 2 shows in the left panel the two GPS antennas mounted on the Explorer of the Seas. The view is toward the bow of the ship during anchorage off Haiti. The right panel shows the cruise track during the experiment. 1-sec GPS data was collected during the entire trip. Additional data collected aboard the Explorer of the Seas include ~2 daily radiosonde launches and surface pressure, temperature and humidity data. Additional photos and other plots of data from the cruise can be found at: http://www.cosmic.ucar.edu/~jjohnson/explorer/ .

- **Analysis of the data set collected during the cruise aboard the Explorer of the Seas is in progress.** The initial and maybe most challenging step is the precise positioning of the ship while under way in the open ocean at speeds of approximately 20 knots. Precise positioning and velocity determination of the GPS antennas is a prerequisite for succesful tropospheric estimation, and refractivity/bending angle profiling. So far our analysis from this experiment has focussed on estimating the ship's position at the several cm level (mm/sec veloicity determination) based on the analysis of dual frequency GPS carrier phase data. We are able to obtain positions associated with formal errors but validation of the position quality in the open ocean, where true position at the cm-level is not known, is a challenge. Figure 3 below shows (left panel results in colored 2-hour segments) the vertical WGS-84 ellipsoidal position of the ship from GPS ranging from 35 m to 22 m during day 193, 2002. Most of this ~13 m change is due to changes of the geoid along the ship's trajectory as inidcated by the curve at ~46 m height which was obtained after applying the OSU-91 geoid correction. The geoid-corrected curve still fluctuates in the range of approximately 1 meter during the day. Some of these fluctuation are due to errors in the GPS solutions - especially between 10-14 hours UTC when the GPS positions have larger uncertainties. However, we believe that most of these fulctuations are actual signal due to a combination of ocean tides, residual geoid error, and the ship's draft and speed. We also computed the amount of integrated precipitable water vapor (PWV) above the GPS antenna on the ship every 2 hours during day 193. The results are compared in the right panel of figure 3 with the water vapor determined from three radiosonde launches from the ship. The results indicate a bias of ~ 5 mm between the GPS and the radiosonde PWV. The source of this bias is still under investigation (i.e. no calibration was conducted for the Vaisala radiosondes). Even if we atribute all of this 5 mm error to an error in the vertical position of the ship this would indicate that the ship's poistion is known to better than 10 cm in the vertical.

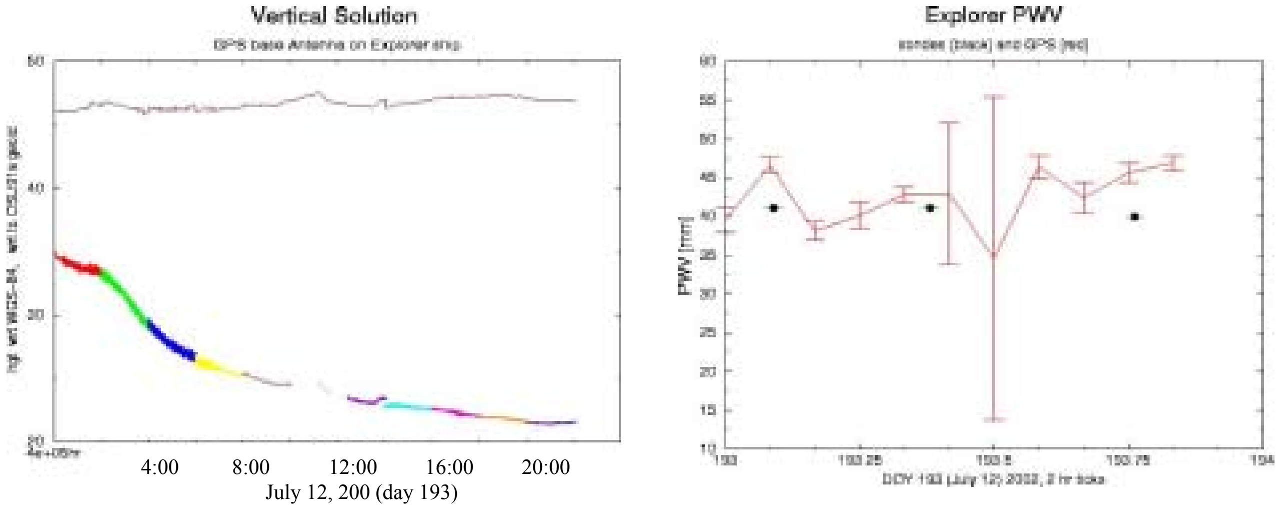


Figure 3 Left panel shows the ellipsoidal height of the ship during day 193. The top curve in the left panel shows the mean sea level height of the "Zephyr" GPS antenna after correction by use of the OSU-91 geoid. The right panel compares GPS estimates of precipitable water vapor (PWV) aboard the ship (red line with vertical error bars representing the formal error of the GPS PWV estimation) with PWV computed from ship-launched radiosondes. (See text for more details)

- **We continued to investigate the feasibility of ocean duct detection from space.** We applied the canonical transform method for calculation of signal bending angles to complex radio occultation (RO) signals in order to detect elevated super refraction (SR) layers. As an example, Figure 4 shows in the left panel the amplitude of the CHAMP RO signal (left), obtained on October 1, 001, 2:19 UTC, 37.2S, 127.8E, the bending angle (middle) which indicates a large increase at ~3.1 km ray asymptote height, and the retrieved refractivity (right) which apparently indicates the top of the moist boundary layer at ~1.7 km altitude over the MSL. This occultation, as well as some others with deep temporal fading of the signal amplitude, may indicate SR, however, the retrieved refractivity gradient remains below the critical value. This may be caused by the effect of large-scale horizontal inhomogeneity in the refractivity, as well as by the small-scale irregularities, which is the subject of further study. We are also looking into other physical parameters, which can potentially indicate large refractivity gradients and cases of SR. In particular, the sliding spectrograms of the simulated RO signals, plotted in coordinates of time (which is directly proportional to the straight-line altitude) and signal impact parameter show that in case of sharp refractivity gradients sub-signals may arrive under a constant impact parameter for an extended time. This corresponds to specific horizontal stripes in the spectrogram, which are not present when the refractivity gradients are well below the critical value. The colorful right panel in Figure 4 shows the sliding spectrogram of a simulated RO for one of the high-resolution radiosonde profiles collected at Point Loma by Kenn Anderson. The horizontal stripe at the height of ray asymptote of ~2.5 km corresponds to strong SR layer (duct) at ~0.2 km altitude. In real observations this effect may not be as obvious and can be smeared by horizontal inhomogeneity and small-scale irregularities in refractivity. Another indicator of large refractivity gradients is the amplitude of the RO signal after applying the canonical transform to the ray coordinates. Presently we believe that none of these parameters can reliably distinguish between critical and sub-critical refractivity gradients, but they can be used for indicating sharp gradients and for flagging the potential presence of super refraction.

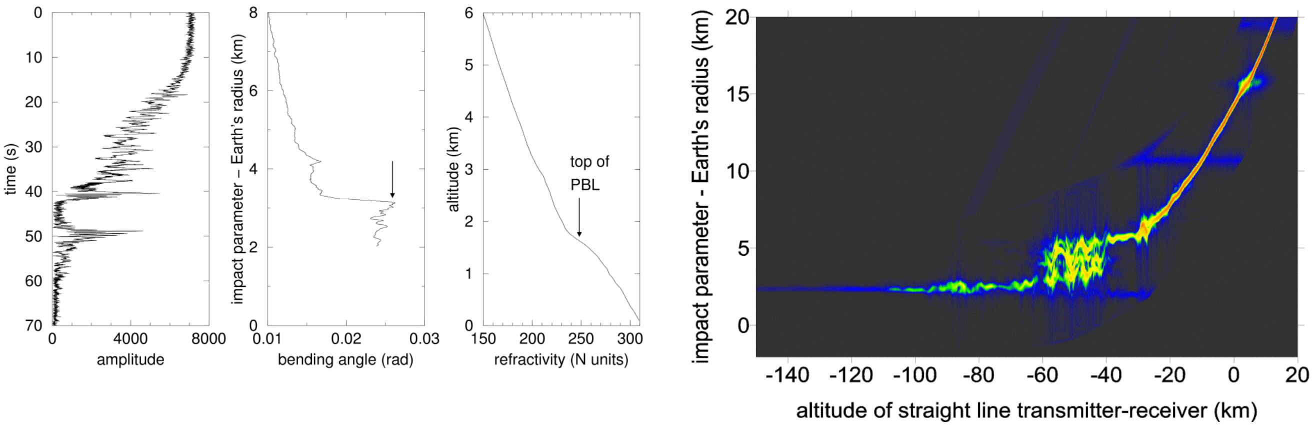


Figure 4 . The three small panels on the left show signal amplitude (left), signal bending (middle), and retrieved refractivity for a RO occultation from the CHAMP satellite. A sharp refractivity gradient indicating the PBL can be seen at ~ 1.7 km. The right panel is a sliding spectrogram of a simulated RO signal based on a high-resolution radiosonde, which indicated super refraction layers. The horizontal lines of constant ray asymptote (which is the same as impact parameter minus Earth radius) can be used to identify the super refraction layers. The lowest one in these simulations is at 200 meters above the surface. (See text for more details)

IMPACT/APPLICATION

Remote sensing of atmospheric features and refractivity profiles with GPS promises to impact Navy communication and sensing capabilities and to provide a new data set for improved numerical weather prediction. Ground based determination of bending angles using GPS has the potential for aiding in locating exo-atmospheric targets. Precise kinematic point positioning to conduct these activities from a moving platform (ship) seems feasible and may also lead to precise timing on ships. Precise kinematic point positioning from ships may also provide additional data for Geoid improvements in the oceans. Estimation of precipitable water vapor from ships seems feasible and may aid in weather forecasting.

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 described here may work best in combination.

2) The Department of Energy is continuing to fund 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, NOAA and scientists in Europe and Japan are working on assimilation of PWV and 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. Ship-based PWV may also be of value for weather models.

4) Georgia Tech. has prepared a first draft of the joint patent application for determination of GPS bending based on ground based observations.

SUMMARY

Results from last year's effort can be summarized as: (1) The quality of the GPS data collected on Flip during RED required the development of new software to deal with the combination of significant wave motion and frequent cycle slips in the GPS data; (2) A new GPS experiment was prepared and we conducted a 7-day science experiment cruise in the Caribbean; (3) Preliminary processing of the data from the latest experiment in July, 2002 shows that: (a) precise carrier phase positioning of a ship on the open ocean with GPS is feasible; (b) the vertical component of the ship's GPS antenna is estimated to 10 cm or better; (c) it is possible to compute reasonable tropospheric delay and precipitable water vapor values from the ship's data; (d) reliable low-elevation tracking of the signals of setting GPS satellites remains a challenge with GPS receivers which are developed for geodetic applications; (4) Space based detection of elevated sharp gradients in refractivity is feasible and was shown in real data - however the distinction between critical and sub-critical refractivity gradients remains difficult; (5) Peer-reviewed papers have been published/submitted and a first draft of a joint patent with GATech has been prepared.

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