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PROFILING THE ATMOSPHERE WITH AN AIRBORNE GPS RECEIVER SYSTEM

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ABSTRACT– Since the GPS/MET mission was launched in 1995, an extensive dataset of space-borne GPS radio occultation (RO) soundings have been derived and compared to in-situ measurements and numerical model analyses. The launch of the Constellation Observing System for Meteorology Ionosphere and Climate (COSMIC) introduces several thousand more profiles daily, which has attracted much wider attention in the atmospheric and space weather communities. However, due to the limited number of available satellites with GPS receivers and their fixed orbits, space-borne RO cannot provide dense sounding measurements in a specific region within a given time range on demand. With a GPS receiver onboard an airplane, the airborne GPS RO technique offers such an opportunity while retaining a high vertical resolution sounding capability. In July 2007, the GNSS Instrument System for Multistatic and Occultation Sensing (GISMOS), developed by Purdue University, was tested on the NCAR HIAPER (High-performance Instrumented Airborne Platform for Environmental Research) aircraft. Some preliminary observations were made. More measurements will be expected in the near future. A geometric optics retrieval system has been developed and a sensitivity analysis of the airborne occultation demonstrates that an overall accuracy of 1% for the retrieved refractivity could be achieved from the surface up to the altitude of the airplane at around 10 km, where the airplane velocity errors up to 5mm/sec restrict the accuracy. The sensitivity analysis and preliminary results from the first test flight will be presented. Such high-resolution targeted airborne RO measurements in the troposphere provide a new resource for regional weather and climate studies.

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1. INTRODUCTION

Global Positioning System (GPS) radio occultation (RO) is an active microwave limb sounding technique, which provides high vertical resolution and all-weather sounding capability and is an excellent complement to the existing passive infrared and microwave satellite soundings. Recognition for the potential of GPSRO to contribute to important issues in weather and climate has grown significantly. The recent National Research Council Decadal Survey identified GPSRO as a key element in the global climate observing system. The six-satellite Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) was launched in April 2006 and currently provides over 2000 daily RO profiles globally, which have created great interests to operational weather centers. Many NWP studies using actual GPSRO observations have yielded promising initial impact on weather forecasting in the upper troposphere and lower stratosphere (Healy and Thepaut 2006; Cucurull et al., 2006). However, a significant impact of RO data in the lower troposphere has yet to be demonstrated. Several features of the GPS RO technique, such as global coverage, high vertical resolution, high precision and accuracy, and the ability of GPS signals to penetrate clouds, have made the RO measurements an extremely valuable asset for global weather forecasting and climate modeling studies (Zou et al., 2004; Healy and Thepaut 2006; Cucurull et al., 2006). However, due to the relatively limited number of available low Earth orbit (LEO) satellites, the sampling in a region of specific interest is still rather sparse (only about 1 daily occultation per 167,000 km^{-2} at mid-latitudes and even fewer in the tropics), so it is difficult to acquire a series of profiles that are sequential in time for a desired period in a localized region of interest. RO measurements with a GPS receiver onboard an airplane offer the opportunity of rather dense sampling contiguous in space and time, while retaining a high vertical resolution sounding capability. This type of observation system could greatly facilitate studies of regional weather and climate. Section two of this paper presents an overview of the airborne and space-borne GPS RO geometry, and section three describes the state-of-art airborne GPS RO system developed by Purdue University and deployed on the National Science Foundation (NSF) High-performance Instrumented Airborne Platform for Environmental Research (HIAPER) aircraft. The post-processing software is summarized in section four. Some key simulation results of the airborne system are presented on section five. Finally, Some preliminary results and the future campaign plan for verifying the performance of the airborne GPS RO system will be outlined in section six.

2. AIRBORNE AND SPACE-BORNE RADIO OCCULTATION GEOMETRY

GPS RO senses the atmosphere using GPS radio signals that traverse the atmosphere as a moving receiver sets behind the horizon relative to the transmitting satellite. The radio wave is refracted (bent) and its travel time is delayed due to variations of atmospheric refractivity. A schematic plot of the space-borne (blue) and airborne (red) GPS RO geometry is shown in Fig. 1.

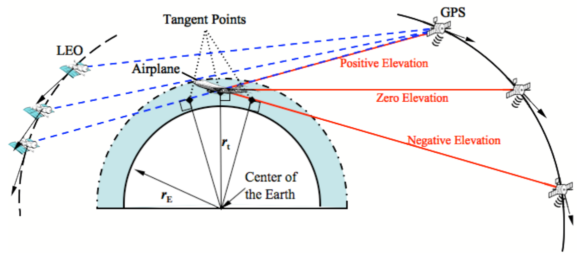

Fig. 1. Schematic diagram of radio occultation geometry with a receiver inside (airplane) and outside (LEO) the atmosphere (blue shadow), where r_E and r_t represent the radius of the Earth and the radius of the tangent points, respectively. The blue dashed and the red solid lines represent the raypaths at different tangent heights. Note that the bending of the raypaths is neglected and the relative scales of the plot are exaggerated for illustration purposes.

With a GPS receiver in low-earth-orbit (LEO), the GPS raypaths scan from the top of the atmosphere down to the earth surface. The bending angle and refractivity as a function of tangent point (the point of the ray's closest approach to the surface) altitude are derived from the sequentially recorded excess phase observations (Kursinski, et al., 1997). With a GPS receiver inside the atmosphere, e.g., onboard an airplane, it is possible to measure the bending of GPS rays that reach the receiver from above (positive elevation angle) and below (negative elevation angle) the local horizon. By assuming a locally spherically symmetric atmosphere, the refractivity below the airplane can be retrieved (Healy et al., 2002). The GISMOS (GNSS Instrument System for Multistatic and Occultation Sensing) (Garrision et al., 2006) was developed to make such observations. This airborne RO system offers dense occultation soundings for targeted observational studies, (Xie et al., 2007).

3. HIAPER GISMOS INSTRUMENT DESCRIPTION

The HIAPER is a Gulfstream V (GV) business jet modified for atmospheric research by the University Corporation for Atmospheric Research (UCAR). The GISMOS system on-board HIAPER is designed to use occulted and reflected GNSS signals to retrieve tropospheric water vapor, ocean surface roughness and soil moisture during long duration, high altitude, flights.

Five antennas are provided for the GISMOS instruments. One is placed on the top of the aircraft fuselage, to record the direct signal for navigation. Two high gain dual frequency antennas that are specifically designed for HIAPER with a gain pattern focused toward the horizon are mounted inside the windows on the side of the aircraft, for occultation measurements. Another two antennas, receiving both left-hand (LHCP) and right-hand (RHCP) circularly polarized signals, will be mounted on the bottom of the fuselage for the reflection measurements.

The GISMOS instrument includes four main components: (1) a pair of dual-–frequency survey-grade receivers for RO measurements, (2) a dedicated Applanix GPS/INS system for accurate aircraft velocity measurements (5 mm/s accuracy) which are critical for the inversion of RO profiles, (3) a Symmetricom GPS timing receiver used to provide a common 10 MHz frequency standard timing signal for all of the receivers, (4) a GNSS recording system (GRS) that is capable of continuous recording GNSS signals (sampled at 10 MHz) at both the L1 (1575.42 MHz) and L2 (1227.40 MHz) frequencies, (5) a patch panel that distributes different antenna signals to the receivers and GRS, and (6) a master control computer (MCC) that controls the recording of all receivers, and provides Ethernet communications to the network onboard HIAPER (Garrison et al., 2006). In the paper, we focus on the radio occultation (RO) component of GISMOS.

4. POST-PROCESSING SOFTWARE

Extraction of geophysical measurements from the GNSS data collected by GISMOS requires several stages of post-processing. The following sections describe the main steps for the post-processing.

4.1 *Applanix Software for Velocity Determination*

The Applanix POS-AV inertial navigation system contains a dual frequency Trimble BD950 receiver card, an inertial measurement unit, and a recording system capable of continuous sampling of both L1 (1575.42 MHz) and L2 (1227.60 MHz) frequencies at 10 Hz and IMU measurements at 200 Hz (Garrison et al., 2006). The retrieval errors of this airborne system in particular will be assessed.

4.2 *Closed-Loop and Open-Loop Tracking*

The GRS provides two ways of tracking the direct signals with high-rate sampling. One is through the conventional delay-lock loop (DLL) and phase-lock loop mode and the other is the open-loop (OL) mode. RO measurements are limited by signal fading and multipath at low elevations, which can cause the tracking loops in receivers to lose lock. This limits the ability to obtain useful profiles. Therefore OL tracking (Sokolovskiy et al., 2006; Beyerle et al., 2006) will become necessary as a method to extract excess phase measurements from fading signals, through the use of a reference bending profile (Garrison et al., 2006).

4.3 *Inversion of RO Measurements*

The RO signals at both negative and positive elevations relative to the receiver's local horizon are collected. The excess phase is measured and differentiated with respect to time to give the excess Doppler shift, which in turn is used to derive the bending angle as a function of tangent altitude (Vorobev and Krasil'nikova 1994). The difference between the negative bending angle α_N and the positive bending angle α_P is called the "partial bending angle", i.e., $\alpha'(a)= \alpha_N(a) - \alpha_P(a)$. The refractive index ($n$) below the receiver can then be retrieved through the Abel inversion (Healy et al., 2002). The inversion technique is similar to the space-borne GPS occultation case but includes consideration for the refractivity at the receiver (n_R):

$$n(a) = n_R \exp\left[\frac{1}{\pi}\int_{x=a}^{n_R r_R} \frac{\alpha'(x)\mathrm{d}x}{\sqrt{x^2 - a^2}}\right], \quad (1)$$

where, *a* is the impact parameter, which is the asymptotic miss distance from the earth center to the tangent of the ray sent out from the GPS and *x*(*r*) is the impact parameter at the tangent radius of the ray path, *r*.

5. SENSITIVITY ANALYSIS

A sensitivity analysis of the airborne occultation retrieval process demonstrates an anticipated overall accuracy of better than 0.5% for the retrieved refractivity from the surface to about 1 km below the airplane, where the expected airplane velocity errors of up to 5mm/s limit the accuracy (Xie et al., 2007). Fig. 2 indicates the refractivity errors corresponding to a 5% error in humidity, a 10 % error in humidity, and a 1 K error in temperature. Comparing these with the altitude dependent error in the refractivity retrieval gives an indication of when the observations are accurate enough to provide an improvement in observation accuracy over currently available observations. Therefore, the retrieved profiles will be most useful in providing temperature information up to an altitude of about 9 km (or 1 km below the airplane) and humidity information up to about 5.5 km. Note that the current uncertainty in upper level humidity in weather prediction models may be as large as 20%, so it may be possible for occultation data to provide useful humidity information higher than 5.5 km. The accuracy of one-dimensional retrievals is further limited by the assumption that there is no lateral variation in atmospheric properties over the horizontal averaging length scale.

6. FIELD CAMPAIGN MEASUREMENTS

A preliminary test of the HIAPER GISMOS system was flown in July 2007. Data were collected from a soil moisture test flight over Oklahoma, an ocean wind speed flight in the Gulf of Mexico and an

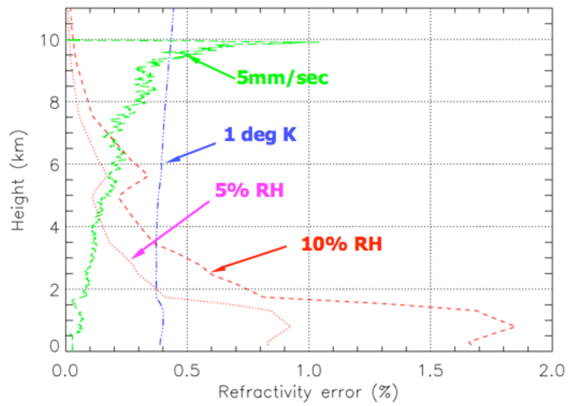

Fig. 2. Comparison between the standard deviation (green) of refractivity retrieval errors due to 5mm/s Doppler error with the equivalent refractivity errors to current observational accuracy of 1 K temperature error (blue dash-dotted), and 5% (red dotted) and 10% (red dashed) relative humidity errors.

occultation test flight over South Dakota. Three hours of data were collected 2007.07.19 to test operation. Six hours of data were collected on 2007.07.24 while flying over the Little Washita and Fort Cobb watersheds in Oklahoma. Land surface reflection data were successfully recorded by the GRS. These watersheds are currently monitored with in-situ soil moisture sensors. One overflight over an inland lake was included at the beginning of the flight to calibrate the amplitude of the reflected signal. Two hours of occultation data were collected on 2007.07.27 around the time of a radiosonde launch in Amarillo Texas. The remainder of this flight was dedicated to ocean reflection as the aircraft flew cloverleaf patterns over three National Data Buoy Center buoys off the Texas coast. The final flight on 2007.07.30 was dedicated to occultation recording for four hours as the aircraft flew a pattern near the radiosonde launch at Rapid City, SD. Despite problems with the side-looking antenna installation on the aircraft, high quality data was recorded by the zenith antenna, which made possible a study of the precision of the GPS navigation solutions. The zenith antenna successfully recorded below horizontal on two flights, indicating it will be possible to extract some information on the profiles, though the signal noise ratio will be lower than that which should be collected with the high-gain side-looking antennas.

The red line in Fig. 3 shows the navigation solution (flight track on 2007.07.30) from the GPS/INS system, which has a specified accuracy of 5 mm/sec velocity. This is possible by post-processing the data for relative positioning relative to a known reference site, and by incorporating the high accuracy data from the inertial measurement unit. In order to confirm the quality of the solution, we processed the data using several different reference sites (blue star in Fig. 3) to compare different solutions to reveal any long term drift in velocity potentially linked to uncorrelated GPS inaccuracies. These results (Fig. 4) show that the solutions are consistent with the specified accuracy, which should allow retrieval of refractivity profiles with the accuracy expected from the simulations in section 5.

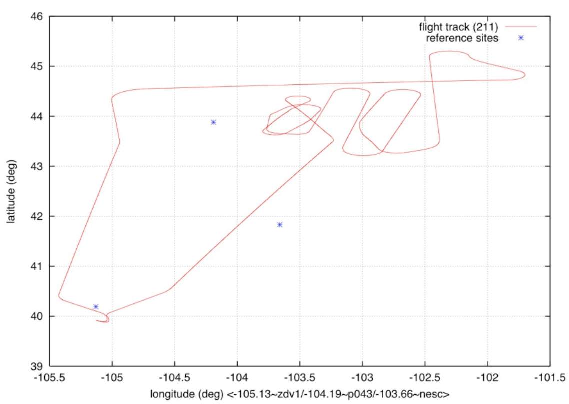

Fig. 3 The flight track on 2007.07.30 (red line) and the three ground reference sites: from left to right, zdv1 (Denver, CO, 1-sec); p043 (Newcastle, WY, 15-sec); and nesc (Gering, NE, 5-sec).

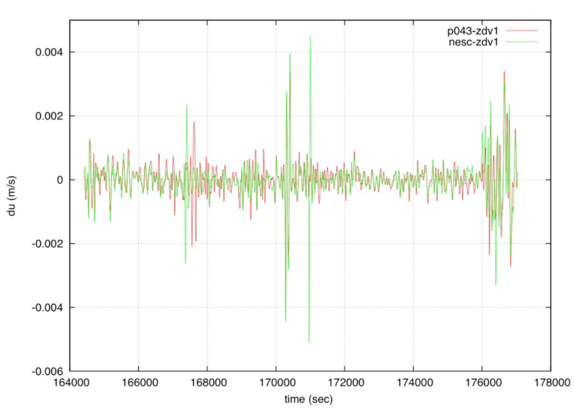

Fig. 4 Comparison of the eastern velocity solutions among three different reference sites during the flight on 2007.07.30.

A second experiment is planned for February 2-22, 2008 as part of the HIAPER Airborne Instrumentation Solicitaiton Experimental Flight Tests (HEFT-08). This experiment will target a more thorough exploration of occultation profile validation in the presence of laterally heterogeneous structure. The antenna installation has been upgraded with modifications made to the windows on which the antennas are mounted to assure high quality signal reception, and additional lower gain backup antennas have been mounted externally. There are 6 flights planned: 2 days of occultation flights with dropsondes, 2 days of flights over radiosonde sites with additional launches planned, and 2 days of flights over the gulf for ocean surface reflection data collection. North-south flight paths are planned over the ocean for the dropsonde validation. An example of the flight paths are shown in Fig. 5, by running a simulation with real orbits, to provide a typical set of occultations. For the actual flight planning, the simulations will be run a day in advance of the flights. The setting occultations are indicated by the path followed by the tangent point, which starts near the aircraft at the top of the profile and drifts away from the aircraft as the satellite sets in the east because of the inclination of the orbits. Optimal recording geometries have the shortest drift, on the order of 250 km. After the satellite sets the aircraft will circle back to fly along the occultation plane and deploy dropsondes to sample the horizontal variation in the profiles for later comparison with the airborne occultation retrievals. An example of east-west flights over the Louisiana/Florida coast is shown, along with the corresponding occultations recorded from this geometry. Typical tangent point drifts are longer with this flight direction. Additional radiosonde launches at 18:00 and 21:00 UTC will supplement the 00:00 UTC soundings at 3 of the radionsone sites near the flight paths to provide more validation data. Finally, the ocean reflection flights will overfly some subset of the NDBC buoys indicated by the black star pattern in Fig. 5, depending on the restrictions of airspace. This data collection effort is the most significant campaign validation of occultation to take place. It should have great utility in interpreting the effects of lateral heterogeneity on space borne occultation observations as well, for which it is impossible to plan such a campaign.

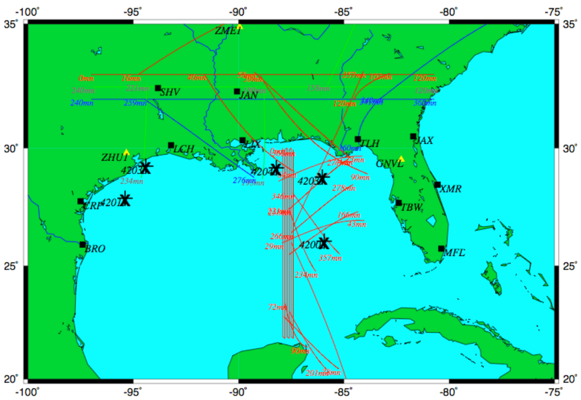

Fig. 5 Test plan for GISMOS in February 2008. The six red lines (North-South direction) show the flight tracks of six one-hour flights at 12 km (00Z~06Z) and the segments with one end connecting to the flight track are the simulated occultation tangent point positions, the numbers on both ends are the start and end time for each occultation. The two East-West direction lines (red and blue) demonstrate another two flights over the radiosonde sites (black block). Note that the flights over buoys (black stars) for reflection measurements are not shown.

7. ACKNOWLEDGEMENTS

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