

Atmospheric GPS Radio Occultation Data Analysis: A Study

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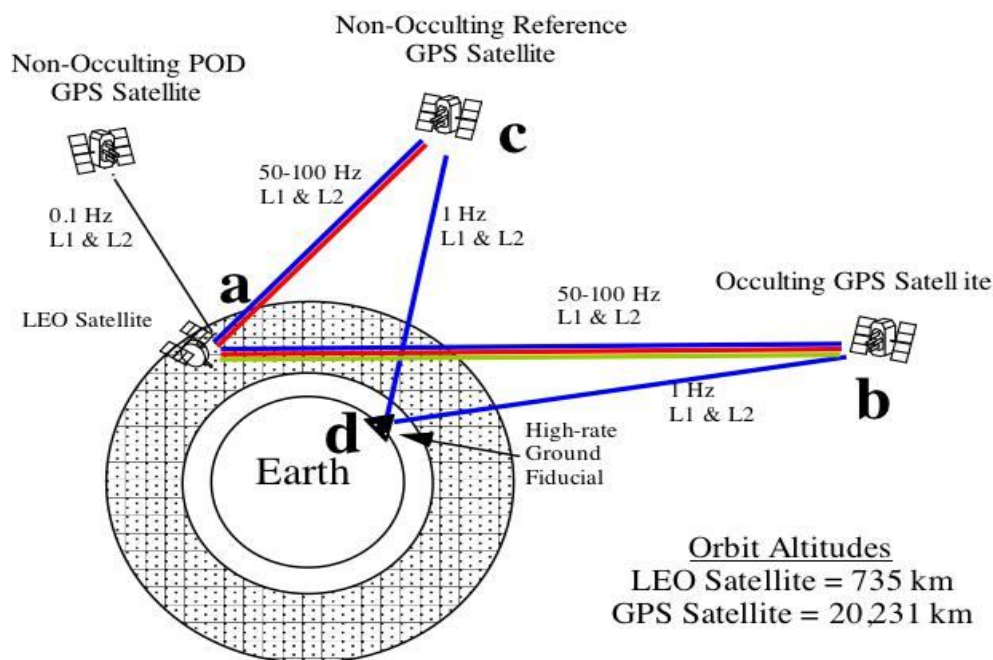
Abstract

In this paper, the study of noise level and point-to-point stability of Global Positioning System radio occultation (RO) neutral atmospheric bending angle data at the UCAR COSMIC Data Analysis and Archive Center (CDAAC). The Global Positioning System (GPS) radio occultation (GPS-RO) technique is an active limb sounding observation of the Earth's atmosphere using a GPS receiver onboard a low Earth orbit (LEO) satellite. Since the observation data taken by such technique have high accuracy and excellent height resolution, they are very useful for analyzing atmospheric structures including small-scale vertical fluctuations in the troposphere and stratosphere. Vertical resolution of (GO) method in stratosphere is 1.7 km due to Fresnel radius limitations, but full spectrum inversion (FSI) can provide superior resolutions. The archived GPS-RO data have been calculated applying FSI to COSMIC GPS-RO profiles in an altitude from ground level up to 30 km. The height resolution of archived data is 0.1 km and we averaged the original RISHANA data (refractivity, pressure, temperature, and tangential point of latitude and longitude) in a bin of 0.05 km for nominal height. Atmospheric radio occultation relies on the detection of a change in a radio signal as it passes through a planet's atmosphere, i.e. as it is occulted by the atmosphere. When electromagnetic radiation crosses through the atmosphere, it is refracted. The magnitude of the refraction depends on the gradient of refractivity normal to the path, which in turn depends on the density gradient. The effect is most marked when the radiation traverses a long atmospheric limb path. At radio frequencies the amount of bending cannot be measured directly; instead the bending can be calculated using the Doppler shift of the signal given the geometry of the emitter and receiver. The amount of curve can be related to the refractive index by using an Abel transform on the formula relating bending angle to refractivity. when the atmosphere is neutral (below the ionosphere) information on the atmosphere's temperature, pressure and water vapour content can be derived giving radio occultation data applications in meteorology. GNSS or GPS radio occultation (GNSS-RO, GPS-RO, GPSRO) is a type of radio occultation that relies on radio transmissions from GPS (Global Positioning System), or more generally from GNSS (Global Navigation Satellite System), satellites. This is a relatively new technique for performing atmospheric measurements. GNSS or GPS radio occultation as a weather forecasting tool, and could also be harnessed in monitoring climate change. The method involves a low-Earth orbit satellite receiving a signal from a GPS satellite. The signal has to pass through the atmosphere which has gases, dust and gets refracted along the way. The magnitude of the refraction depends on the temperature and water vapor concentration in the atmosphere when it observed.

Keywords: GPS, Earth-orbit, Satellite, Signals, Atmosphere, Radio-waves, Whether.

Introduction

Global Positioning System (GPS) Radio Occultation (RO) data are becoming a benchmark dataset of the international global observing system. The high vertical resolution, precision, and accuracy of retrieved atmospheric profiles make GPS RO ideal for weather and space weather specification and forecasting climate change research and detection and in-situ, ground-based and satellite instrument validation. With a GPS receiver on board a low-Earth orbiting (LEO) satellite, the amplitude and phase of the radio frequency (RF) signals transmitted from GPS satellites can be measured very precisely as the ray tangent point descends from ~100 km altitude to the surface when the GPS satellite is occulted by Earth's atmosphere. With proper algorithms and observational modeling, we can potentially derive vertical profiles of bending angle (Melbourne et al., 1994; Kursinski et al., 1997; Kuo et al., 2004) that are traceable to the international system of units (SI), i.e. the second (Ohring, 2007). Profiles of refractivity, and subsequently pressure, temperature and humidity can be derived with additional a priori information (Melbourne et al., 1994; Ware et al., 1996; Kursinski et al., 1997; Rocken et al., 1997), but the traceability of these products to SI is diminished.



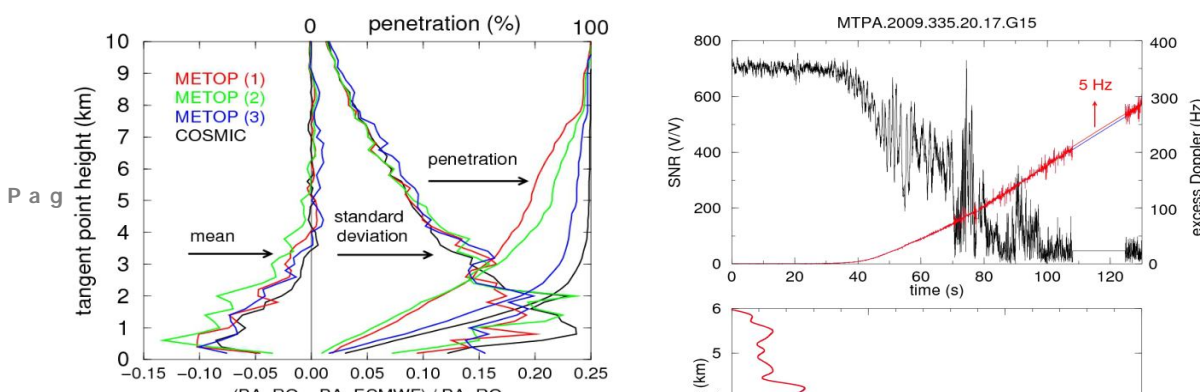
For GPS RO to be used as a benchmark dataset, especially for climate change research, an important initial step is to establish SI-traceability of the GPS RO bending angle data products through peer-reviewed theoretical and experimental validation studies. The GPS RO phase measurements fundamentally can be traced to the SI second, because the GPS transmitters use on-board atomic clocks that are linked to ground-based atomic clocks with a network of GPS ground fiducial receivers (e.g.

National Institute for Standards and Technology (NIST) in Boulder, Colorado) as illustrated in Fig. The GPS atomic clocks have errors, but they are monitored and corrected with data from the GPS ground network. The LEO clock errors are estimated relative to GPS time along with the LEO satellite positions and velocities within pre-cise orbit determination (POD) data processing to maintain SI traceability (Hwang et al., 2008; Schreiner et al., 2009; Montenbruck et al., 2008; von Engeln et al., 2011). With the raw RO and ground-based GPS measurements and pre-cise positions, velocities, and clocks of GPS and LEO satel-lites, the fundamental RO observable, the atmospheric excess phase (in excess to vacuum) due to propagation through the atmosphere, can be computed. The atmospheric excess phases for both the L1 and L2 signals during an occultation can be computed accurately using either double-difference, single-difference, or zero (un)-difference processing strate-gies For altitudes above the moist troposphere where sin-gle path propagation allows application of geometric optics (GO), the time derivatives of the L1 and L2 atmospheric ex-cess phases, i.e. excess Dopplers, are noise filtered and used with the positions and velocities of the satellites to compute L1 and L2 bending angles as a function of impact parameter. An ionosphere-free bending angle profile is then traditionally obtained by a linear combination of the L1 and L2 bending angles taken at the same impact pa-rameter .Optimal filter-ing methods are also used to suppress the larger L2 bending angle noise as described in Sokolovskiy et al. (2009b). In the lower troposphere, where sharp vertical moisture gradients can cause multipath propagation, the L1 bending angle is de-rived from the raw phase and amplitude (complex signal) by wave optics (WO) methods. Both GO and WO methods use the assumption of local spherical symmetry of refractivity. Finally, the geometric optics and wave opticsbending angles are combined into one complete ionosphere-free bending angle profile.

Many theoretical and experimental validation studies have been published in an attempt to verify the high accuracy (i.e. degree of veracity) and high precision (i.e. degree of re-productibility, between satellites and between instruments) of GPS RO data. The first theoretical estimates of the accuracy of GPS RO in the Earth's neutral atmosphere were published by Yunck and Lindal (1988) and Hardy et al. (1993). A more detailed theoretical analysis of GPS RO accuracy was pub-lished by Kursinski et al. (1997). Experimental validation of GPS RO to ancillary data (such as radiosondes or atmo-spheric model analyses) is a difficult task due to the mea-surement and representativeness errors of both data sets. The first experimental estimates of the accuracy of GPS RO were obtained by Rocken et al. (1997) by comparing refractivi-ties and temperatures retrieved from GPS/MET data to ra-diosondes, atmospheric models and other satellite data avail-able at that time. The first experimental estimates of the precision of GPS RO temperatures were obtained by Hajj et al. (2004) by comparing collocated occultations observed by the CHAMP (CHALLENGING Minisatellite Payload) and SAC-C (Satelite´ de Aplicaciones Cientificas – C) satellites, where it was found that individual profiles agree to 0.86 K i.e. fractionally, to about 0.4 %, standard deviation between 5 and 15 km altitude. The initial deployment phase of the Constellation Observing System for Meteorology Ionosphere and Climate (COSMIC)/Formosa Satellite 3 (FORMOSAT-(hereafter F3C) RO mission when the six satellites were orbiting very close to each other offered a unique oppor-tunity to estimate the precision of F3C GPS RO

refractive indices and temperatures by analyzing the differences for collocated occultations (Schreiner et al., 2007; Staten and Reichler, 2009). Recently, structural uncertainties (the differences that depend on tracking depth, noise and processing) of GPS RO refractivity and bending angle in the lower troposphere were explained and quantified by Sokolovskiy et al. (2010). Another important study was recently performed using CHAMP data to quantify the structural uncertainty in CHAMP GPS RO-derived vertical profiles of refractivity and their temporal trends, related to different processing and inversion procedures (Ho et al., 2009a). An experimental validation of bending angles derived from different instruments and processing strategies has also been performed recently by comparing near real-time operational products from the F3C and the Metop/GRAS (GNSS Receiver for Atmospheric Sounding) missions. In this study we investigate the noise level and consistency of GPS RO bending angle data from the F3C and Metop/GRAS missions. These two missions use independently developed RO instruments: (1) F3C uses an IGOR (Integrated GPS Occultation Receiver) receiver developed at the Jet Propulsion Laboratory (JPL) and (2) Metop-A is flying the GRAS receiver developed by Ruag Space. This study uses six months (June–December 2009) of bending angle data that have been reprocessed with consistent software by one data processing center, the UCAR COSMIC Data Analysis and Archive Center (CDAAC). The consistent algorithms and data processing software (to the extent possible with account for differences in the data) used by the CDAAC allow this investigation to quantify bending angle uncertainties due to the instrument only (i.e. minimizes processing software induced structural uncertainty). Therefore, this study quantifies the precision (degree of reproducibility) in terms of random and systematic bending angle differences for different missions/instruments.

Section 1 provides background information and an introduction of this study. Section 2 presents a mission overview and description of the CDAAC data processing used for F3C including POD and computation of atmospheric excess phases and bending angles. Section 3 presents an overview of the Metop/GRAS mission and a description of the CDAAC data processing used for Metop/GRAS including down-sampling the GRAS raw sampled data from 1000 Hz to 50 Hz and interpolation through data gaps. Section 4 presents statistical results of RO bending angle comparisons with climatology between 60 and 80 km altitude for each mission. Section 5 discusses results of an analysis of F3C collocated soundings in close proximity (tangent points within 10 km) from the beginning of the mission. Section 6 presents the bending angle differences at large heights observed between collocated F3C and Metop/GRAS profiles that occur within 2 h and 300 km of each other. Section 7 investigates differences between F3C and Metop/GRAS bending angles in the lower troposphere. The last section of the paper presents conclusions of the study.



Statistical comparison of Metop/GRAS and F3C with ECMWF bending angles. Different colors show different Metop/GRAS processing modes (for details see text).

2 F3C data processing

The COSMIC Data Analysis and Archival Center (CDAAC) at UCAR processes the raw F3C RO data into atmospheric profiles in near real time for use by operational weather centers, 2–3 months after real-time with currently developed algorithms and more accurate GPS orbits (i.e. post-processed solution), and also periodically re-processes all RO missions every 1–2 yr with consistent software to provide the most accurate and stable products for use in climate studies. CDAAC (v3.0) is currently publishing reprocessed data (product version 2010.2640) for F3C as well as other missions including GPS/MET, CHAMP, SAC-C, GRACE, TerraSAR-X, C/NOFS, and Metop/GRAS. The data processing tasks performed at CDAAC that are relevant to this study include: LEO POD and clock estimation, computation of L1 and L2 atmospheric excess phases, and finally calculation of neutral atmospheric bending angles for each LEO occultation event.

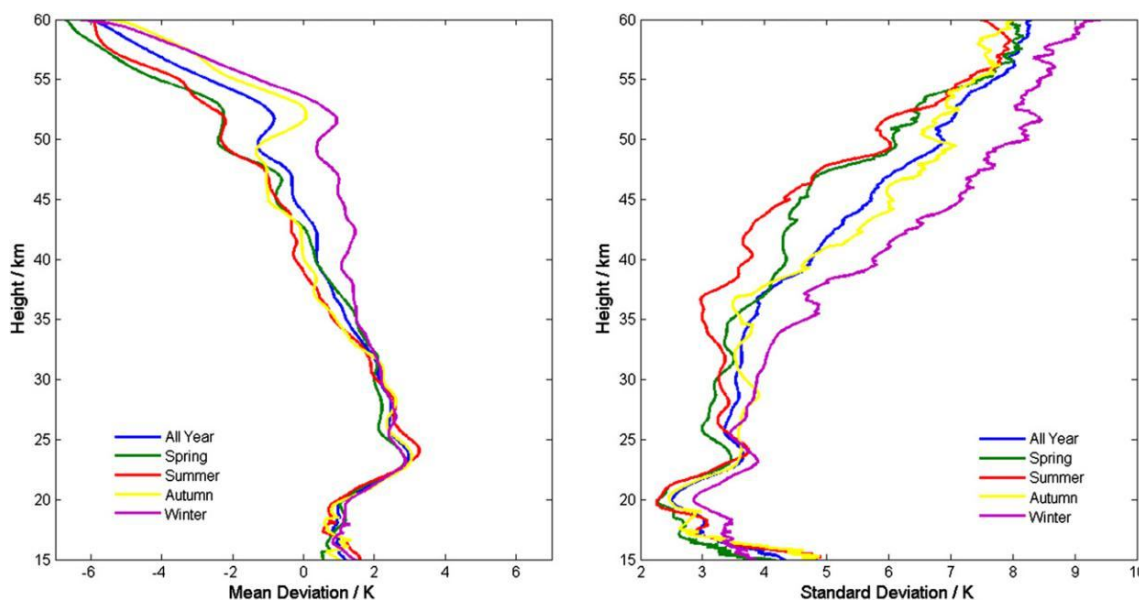
3 F3C IGOR instrument

The six-satellite F3C mission is a joint US/Taiwan mission that was successfully launched into orbit at 01:40 UTC on 15 April 2006 (Rocken et al., 2000). The primary instruments are IGOR (Integrated GPS Occultation Receiver) GPS RO receivers developed by the JPL and manufactured by Broad Reach Engineering. The IGOR is an advanced GPS receiver that tracks in both phase-locked loop (PLL) mode and in open-loop (OL) mode; the latter allows tracking of significantly fluctuating RO signals after propagation through the moist lower troposphere without tracking errors and loss of lock (Sokolovskiy, 2001, 2004) and, as the result, reduction of inversion errors and improved penetration of the retrieved profiles to surface (Anthes et al., 2008). Each COSMIC spacecraft utilizes two 1×4 microstrip patch high-gain limb pointing antennas for 50 Hz occulting satellite tracking for atmospheric profiling, and two single patch antennas (canted at +15 degree elevation) for 1 Hz POD (and ionospheric profiling) and 50 Hz clock reference satellite tracking for atmospheric profiling. The raw RO data output from the IGOR receiver is continuous and consists of receiver time, L1 and L2 pseudorange, carrier phase, and signal-to-noise ratio (SNR) measurements for PLL tracking, and the L1 I&Q (in-phase and quadrature) samples and Doppler and range models for OL tracking.

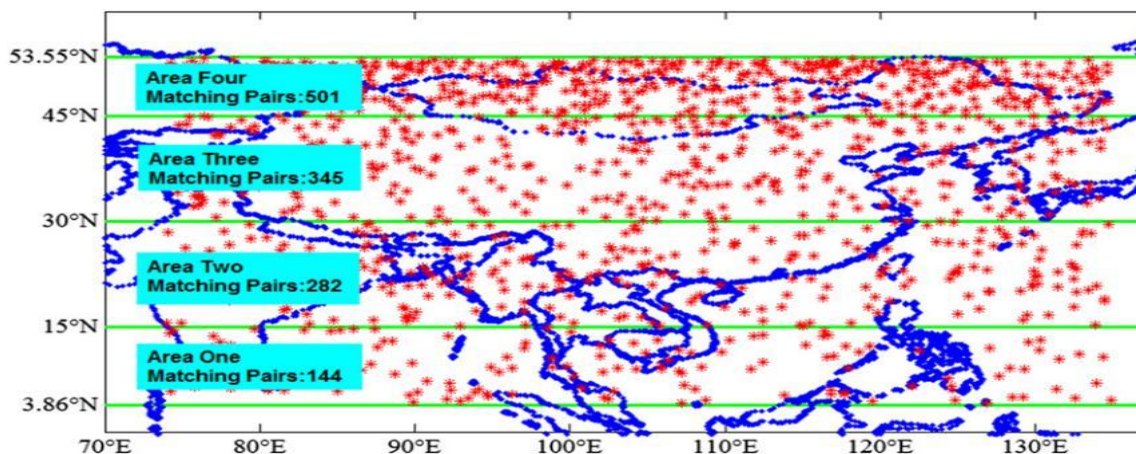
Atmospheric excess phase processing

The CDAAC atmospheric excess phase data for Metop/GRAS are generated with a zero-difference processing approach. This method of processing is possible due to an ultra-stable 28.25 MHz oscillator that produces an almost linear receiver clock offset in time (Montenbruck et al., 2008). Instead of having to eliminate the LEO clock errors from the occulting satellite data by subtracting reference satellite data as done in single-differencing, they can be removed with a low degree polynomial fit to the 30 s LEO clock offsets estimated in the POD solution. The CDAAC software applies a quadratic fit to the LEO POD clock offsets over a 5 min duration. The GPS satellite clock errors are removed from the occulting link data by interpolating the 30 s IGS Final clock offset estimates as is performed in single-difference processing.

Changes of deviation with latitude To investigate the effects of latitude variation, we divided the China region (3.868–53.558N, 73.668–1358E) into four areas according to latitude and analyzed the temperature deviations in the different areas. gives the partition results, and it shows that the number of matching pairs increases with increasing latitude. givesthe statistical results for the change interperature deviation with latitude. As can be seen from, the difference in the mean temperature deviation between the different areas is small at height of 17–32 km, but it is larger in lower and higher regions. Figure 1 showsthat the standard deviation decreaseswith increasing latitude at heights of 15–20 km: the de-viation is larger at lower latitude in this region, with a maximum of ;7.5 K at 15 km, and is smaller at higher latitudes. The effect of latitude is very small, and the standard deviations of the four different areas are close at heights of 20–24 km. In the range 25–55 km, the standard deviation is greatest in area 4, of higher lati-tude, and is smaller in areas 1 and 2. In the range 55–60 km,



Mean temperature and standard deviation for different seasons and annually (colors).



The temperature deviations in four areas partitioned by latitude with matching pairs indicated.

In the south of China, cloud-top altitudes frequently are higher than 10 km. Infrared limb emissions are very sensitive to thin ice clouds, while COSMIC observations are insensitive to thin clouds. Given that SABER has a vertical field of view of 2 km, the increasing standard deviations below 20 km may indicate cloud contamination of SABER retrievals. In northern China in winter GWs were detected by a various instruments. Since these are unlikely to be viewed exactly at the same location and in the same observation geometry (horizontal viewing direction) GW activity in winter at northern China may explain these increased standard deviations.

Conclusions

This study has attempted to quantify the precision (degree of reproducibility) of GPS RO bending angles in terms of random and systematic differences for different satellites and instruments. We used six months (June–December 2009) of data from the F3C and Metop/GRAS missions that were processed by the UCAR CDAAC to analyze bending angle profile differences from climatology and differences between collocated profiles. Between 60 and 80 km the standard deviation of the Metop/GRAS bending angle differences from climatology are smaller (1.13 μ rad) than those from F3C (1.78 μ rad), because the Metop/GRAS data use zero-difference processing that does not include phase noise from the reference satellite observations. The F3C standard deviation reduces significantly to 1.44 μ rad when single-difference processing uses GPS satellites on the same side of the spacecraft. The reason for smaller noise of same-side occultations is not understood and is under investigation. The F3C mean bending angles differences relative to climatology are smaller than those for Metop/GRAS by approximately 0.03 μ rad and may be due to large-scale ionospheric residuals that are expected to

be negative and should have more impact on F3C since it samples the full diurnal cycle. This difference is quite small and illustrates the high degree of re-produceability and mission independence of the GPS RO data at high altitudes. In the LT, especially in the tropics, insufficient straight-line tracking depth limits the re-construction of the true bending angle profile. For example, collocated bending angles between two F3C satellites from early in the mission differ on average by up to 0.5 % near the surface due to systematically lower signal-to-noise ratio for one of the satellites that affects its cutoff depth. The difference between F3C and Metop/GRAS bending angles in the lower troposphere depends on the Metop/GRAS processing mode. On average, Metop/GRAS bending angles are negatively biased compared to F3C with a maximum of several percents in tropical regions. This bias is related to a higher observed RO signal cutoff height for Metop/GRAS that is due to the receiver being configured to track signals down to an insufficient height. The differences between different processing modes are related to data gaps. This increases the structural uncertainty of Metop/GRAS inversions compared to F3C. This uncertainty may be reduced in the future with changes of the Metop/GRAS receiver firmware (Bonnedal et al., 2010b). The results of processing of Metop/GRAS raw-sampled data with different down-samplings suggest the use of 100 Hz sampling in the LT in future RO receivers.

Acknowledgements. This material is based upon work supported by the National Science Foundation under Cooperative Agreement No. AGS-0918398/CSA No. AGS-0939962 and work supported by the EUMETSAT under Award No. EUM/CO/09/4600000677/AVE. The authors are grateful to Jay Fein for support of the CDAAC, to the JPL receiver team for implementing and debugging the COSMIC receiver firmware, and to EUMETSAT for assistance in decoding the GRAS data, and GRAS precise orbits used for comparison.

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