Estimates of the precision of GPS radio occultations from the COSMIC/FORMOSAT-3 mission

W. Schreiner,[1] C. Rocken,[1] S. Sokolovskiy,[1] S. Syndergaard,[1] and D. Hunt[1]

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[1] The Constellation Observing System for Meteorology Ionosphere and Climate (COSMIC)/Formosa Satellite 3 (FORMOSAT-3) is a six-satellite radio occultation mission that was launched in mid-April, 2006. The close proximity of the COSMIC satellites provides a unique opportunity to estimate the precision of the radio occultation remote sensing technique from closely collocated occultations (<10 km separation of tangent points). The RMS difference of refractivity between 10 and 20 km altitude is less than 0.2%, which is approximately twice better than previous estimates obtained from CHAMP and SAC-C collocated occultations, apparently, due to smaller separation of the occultation pairs and due to parallel occultation planes. In the lower troposphere, the maximal RMS is ~0.8% at 2 km altitude and decreases abruptly to ~0.2% between 6 and 8 km altitude. The RMS difference of electron density in the ionosphere between 150 and 500 km altitude for collocated occultations is about 10^3 cm^{-3}. **Citation:** Schreiner, W., C. Rocken, S. Sokolovskiy, S. Syndergaard, and D. Hunt (2007), Estimates of the precision of GPS radio occultations from the COSMIC/FORMOSAT-3 mission, *Geophys. Res. Lett.*, *34*, L04808, doi:10.1029/2006GL027557.

1. Introduction

[2] The Constellation Observing System for Meteorology Ionosphere and Climate (COSMIC)/Formosa Satellite 3 (FORMOSAT-3) [*Rocken et al.*, 2000] was successfully launched into orbit by a US Air Force "Minotaur" rocket from Vandenberg at 1:40 UTC on April 15, 2006. COSMIC/FORMOSAT-3 is a joint US/Taiwan mission consisting of six identical micro-satellites designed by Orbital Sciences Corporation, integrated, tested, and operated by Taiwan's National Space Organization (NSPO), and payload-managed by the University Corporation for Atmospheric Research (UCAR). The primary instruments are Global Positioning System (GPS) radio occultation (RO) receivers developed by the Jet Propulsion Laboratory (JPL) and built by BroadReach Engineering (BRE). Each spacecraft utilizes 4 GPS antennas (built by Haigh-Farr): two 1×4 patch high-gain limb pointing occultation antennas for 50-Hz tracking for atmospheric profiling, and two single patch antennas (canted at +15 degree elevation) for 1-Hz tracking for precise orbit determination (POD) and ionospheric profiling, and 50-Hz tracking of reference satellites (for removal of GPS receiver oscillator drift) for atmospheric profiling.

[3] A distinctive feature of the COSMIC mission, compared to previous RO missions, is tracking both setting and rising neutral atmospheric occultations in the troposphere in an open-loop (OL) mode. The OL tracking technique has been tested by JPL with the GPS RO receiver on the Argentinean SAC-C (Satelite de Aplicaciones Cientificas – C) satellite in 2005. The OL tracking doubles the amount of occultations and allows tracking RO signals with complicated structure thus resulting in significant improvement of penetration of the retrieved refractivity profiles into the lower troposphere. Processing of the observed OL RO signals from SAC-C was briefly described by *Sokolovskiy et al.* [2006a]. A technical goal of COSMIC is to provide 2500 high quality GPS RO soundings per day from orbit altitude down to within 1 km of the surface.

[4] GPS RO is a space-borne remote sensing technique providing accurate, all-weather, high vertical resolution profiles of atmospheric parameters [*Melbourne et al.*, 1994; *Ware et al.*, 1996; *Kursinski et al.*, 1997; *Rocken et al.*, 1997; *Wickert et al.*, 2001; *Hajj et al.*, 2002]. The fundamental observable is the phase delay of the RO signal (related to propagation time between satellites). Since the time is calibrated very precisely by ultra stable atomic clocks, no additional satellite or inter-satellite calibration is needed contrary to passive thermal radiation measurements that require periodic calibration to account for the drift of sensitivity of the sensors, and thus also inter-satellite calibration. This makes GPS RO observations especially valuable for monitoring climate where both high accuracy (i.e. degree of veracity) and high precision (i.e. degree of reproducibility) measurements are desired, and monitoring climate trends which, generally, requires high precision measurements that are consistent from satellite to satellite. However, it is impossible to completely remove the ionospheric effect in the neutral atmospheric retrievals, and variability of the ionosphere will introduce errors regardless of how precise (i.e., reproducible for a given neutral atmospheric and ionospheric state) the measurements are. These errors increase with height, but their magnitude and long-term drift are not well understood and require additional study. The GPS RO amplitude, along with the phase, is used for radio-holographic (RH) retrievals of bending angles in the troposphere [*Jensen et al.*, 2003; *Gorbunov et al.*, 2004], but accurate calibration of the amplitude is not required. The fundamental retrieved (inverted) parameters are the bending angle of the ray and the refractivity of air. They both can be used for deriving meteorological parameters such as pressure, temperature and humidity under certain assumptions or via direct assimilation by atmospheric models [*Kuo et al.*, 2000].

[5] An important feature of the COSMIC constellation is that immediately after launch, the six satellites were clus-

[1]University Corporation for Atmospheric Research, Boulder, Colorado, USA.

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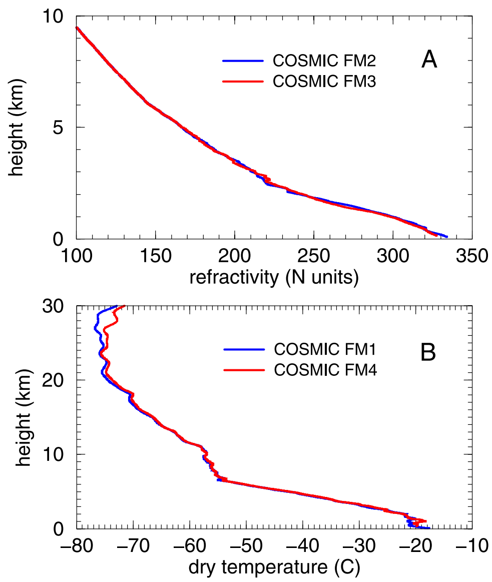

Figure 1. Inversions of pairs of collocated COSMIC occultations with horizontal separation of ray TP < 10 km. (a) Tropical soundings, 2006, DOY 154, 15:23 UTC, 22.7S, 102.9W. (b) Polar soundings: 2006, DOY 157, 13:14 UTC, 72.6S, 83.5W.

tered together in one orbit. Right after the launch the separation between each pair was about 1–2 s in time (about 10 km along the orbit) and is gradually increasing with time. This small separation allows for closely collocated occultations from one GPS satellite with almost parallel occultation planes. The horizontal separation of the ray tangent point (TP) at a given altitude depends mainly on the rotation of the Earth during the separation time. Thus, the COSMIC cluster mode gives a unique opportunity to estimate the precision of RO without the necessity of accounting for horizontal gradients with atmospheric models. It should be noted that collocated RO soundings only allow the precision of the technique to be estimated and not the accuracy because any systematic retrieval errors are eliminated when forming the difference. Due to different technical problems (orientation and stabilization of the satellites, limited GPS receiver operation, and receiver firmware bugs) a very limited number of collocated occultations were available during the period of the smallest horizontal separation of TPs (1–2 km). After fixing many of the problems, more data became available, but for most collocated soundings the separation of TPs increased to 10–20 km.

2. RO Accuracy and Precision in the Neutral Atmosphere

2.1. Previous Estimates

[6] The first theoretical estimates of the accuracy of GPS RO in the Earth's neutral atmosphere were published by *Yunck et al.* [1988] and *Hardy et al.* [1994]. Later, a more detailed theoretical analysis of GPS RO accuracy was published by *Kursinski et al.* [1997]. According to this analysis, under some mean conditions the refractivity retrieval error is about 1% at the surface, then approaches the minimum of about 0.2% at 20 km, then increases, by approaching 1% at 40 km. The dominant error source in the stratosphere is the ionospheric residual phase noise that passes through the dual frequency ionospheric calibration. The effect of horizontally-inhomogeneous refractivity irregularities and the ionospheric noise are most likely the dominant errors sources in the troposphere where RH retrieval methods are applied to the L1 GPS signal (prior to the development of the RH methods, multipath propagation was the dominant error source in geometric optical (GO) retrievals).

[7] Experimental validation of theoretical error estimates by comparing GPS RO to ancillary data (such as radiosondes or atmospheric model analyses) is a difficult task since it is affected by the measurement and representativeness errors of both data sets. Such validation was undertaken by *Kuo et al.* [2004]. It resulted in error estimates comparable to, but slightly larger than the theoretical estimates obtained by *Kursinski et al.* [1997].

[8] The first experimental estimates of the precision of GPS RO were obtained by *Hajj et al.* [2004] by comparing collocated occultations observed by the CHAMP and SAC-C satellites. They examined 212 pairs of occultations that occurred within 30 min and 200 km (horizontal distance between ray tangent points) of each other. They compared temperatures by using an atmospheric model to initialize the temperature retrieval and for correcting for the horizontal variability of the atmosphere at lower altitudes. After such a correction, they found that individual profiles agree to 0.86K i.e., fractionally, to about 0.4%, standard deviation between 5 and 15 km altitude.

2.2. COSMIC Data

[9] The RO observation and its retrieval (retrieval algorithms used in this study were described by *Kuo et al.* [2004]) contain a number of steps affected by different error sources that impact the accuracy and/or precision of retrieved profiles. Here we briefly discuss the effect of these errors. Additive (thermal) noise is un-correlated for any two occultations, thus affecting both accuracy and precision. The horizontally-inhomogeneous irregularities in the neutral atmosphere and the small-scale irregularities in the ionosphere (whose effect is not completely eliminated by the ionospheric calibration) affect the accuracy and the precision estimated from pairs of closely collocated occultations when the separation of the occultation planes is larger than the correlation radii of the irregularities. The errors of calibration of the excess atmospheric phase that includes POD and uses data from a reference GPS satellite, generally, affect both accuracy and precision. However, they affect the precision to a lesser extent when the same reference GPS is used for both collocated occultations. Issues related to receiver tracking also impact accuracy and precision of retrieved profiles. For example, RH methods, applied in the troposphere under conditions of multipath propagation, use the principle of synthetic aperture. Insufficient tracking depth, i.e. the size of the aperture, results in errors of the retrieved profile above the cut-off altitude [*Sokolovskiy*, 2003]. Thus, the estimate of precision is also affected when the tracking depths are different for a pair of collocated occultations.

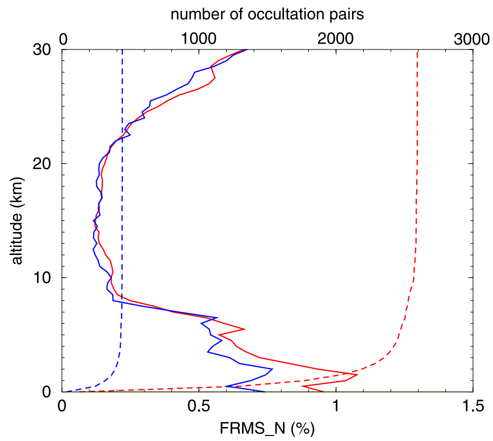

Figure 2. Statistics of comparison of refractivities for pairs of collocated occultations (for details see text).

[10] Figure 1 shows retrieval results for two pairs of collocated occultations. Figure 1a shows retrieved refractivity for two tropical occultations. Both profiles penetrate close to the ocean surface and have elbows at heights of 2–2.5 km that apparently trace the top of the boundary layer [*Sokolovskiy et al.*, 2006b]. Figure 1b shows "dry" temperature (retrieved from refractivity under the assumption of hydrostatic equilibrium and dry air) for two polar occultations. Possible causes of the difference between the retrievals (i.e. 3–4 C) above 25 km are the fraction of residual ionospheric calibration errors that are uncorrelated between the two occultations, orbit determination and clock calibration uncertainties, and local spacecraft multipath.

[11] For statistical evaluation of the precision of RO we use the retrieved refractivity rather than the temperature because the refractivity is less affected by initialization. We use the collocated pairs of setting occultations only (receiver tracking firmware for rising occultations was tested and modified frequently during this period) from DOYs 111–277, 2006, with the horizontal separation of ray TPs less than 10 km between the pairs. All of the occultations used in this study were subjected to the same quality control procedure. One outlier occultation pair that passed the quality control procedure was removed from this study due to erroneous L1 tracking data in phase-locked loop mode. The solid lines in Figure 2 show fractional Root Mean Square (RMS) differences of refractivity, FRMS_N, versus altitude for collocated pairs and correspond to the bottom x-axis. The mean differences and RMS deviations are not shown, because the mean is not well defined (since differences involving more than two satellites are used) and it is very close to zero. The dashed lines show the number of occultation pairs that penetrated to a given altitude and correspond to the top x-axis. The red lines in Figure 2 correspond to all collocated occultation pairs (~2,600) from the entire date range. The blue lines in Figure 2 correspond to collocated occultations (~400) for which the minimal straight-line heights (i.e. height of straight-line between GPS and COSMIC satellites) down to which the RO signals were used for RH retrievals differ by less than 1 km. The FRMS_N for both red and blue lines is better than 0.2% between 10 and 20 km altitude and increases to about 0.7% at 30 km. The estimates of precision of refractivity between 10 and 20 km and shown in Figure 2 are, fractionally, significantly better than those obtained for temperature by *Hajj et al.* [2004], apparently, due to smaller separation of the occultation pairs and due to parallel occultation planes. In the lower troposphere, the maximal FRMS_N for collocated occultations that are restricted to the use of RO signals down to nearly equal (within 1 km) straight-line heights is ~0.8%, which is significantly better than for all occultation pairs, ~1.1%. This result demonstrates the necessity for GPS RO receivers to track RO signals in the lower troposphere to a sufficient (i.e. −150 km) straight-line depth [*Sokolovskiy et al.*, 2006a].

3. RO Accuracy and Precision in the Ionosphere

3.1. Previous Estimates

[12] Validation of ionospheric electron density profiles from GPS RO measurements was first reported by *Hajj and Romans* [1998]. They compared retrieved profiles from the GPS/MET experiment with the parameterized ionospheric model (PIM) and incoherent scatter radar measurements and found very good agreement in selected cases. Statistical comparisons of derived electron density maximum values (NmF2) with nearby ionosonde measurements indicated agreement within about 20%. *Schreiner et al.* [1999] also compared GPS/MET derived NmF2 to ionosonde measurements and found a mean difference of a few percent and an RMS difference of 26%. Comparisons of nearly 4200 GPS/MET measurements with nearby ionosonde data [*Hajj et al.*, 2000] showed a NmF2 RMS difference of about 1.5×10^5 cm^{-3}. The electron density near the orbit altitude derived from CHAMP RO measurements (assisted by model data) have been compared to CHAMP Langmuir probe data [*Jakowski et al.*, 2002], resulting in an RMS difference of about 0.9×10^5 cm^{-3}.

[13] The largest error in the GPS RO retrieved electron density profiles is due to strong horizontal gradients disrupting the assumption of spherical symmetry. This assumption, in cases with large NmF2 values, can result in either positive or negative errors larger than 10^5 cm^{-3} at the bottom of the retrieved profiles [*Syndergaard et al.*, 2006]. Several studies have attempted to mitigate the errors induced by horizontal gradients using different approaches [e.g., *Hajj and Romans*, 1998; *Schreiner et al.*, 1999; *Hernandez-Pajares et al.*, 2000; *Tsai and Tsai*, 2004], but with moderate statistical improvements. Thus, retrieved electron density profiles are expected to have rather poor accuracy when interpreted as actual vertical profiles, whereas the precision (or repeatability of measurements from different platforms) is expected to be much better.

3.2. COSMIC Data

[14] The electron density profiles from COSMIC are processed as described by *Schreiner et al.* [1999] and *Syndergaard et al.* [2006]. Figure 3a shows two collocated ionospheric occultations from FM2 and FM4 on April 22, 2006. In this case FM2 is about 4 seconds behind FM4 and the horizontal distance between TPs at a given altitude is about 4 km. The difference in electron density in this case (black curve in Figure 3b) is most likely due to thermal noise. This noise can vary from comparison to comparison depending on SNR. The impact of thermal noise has been verified by independent simulations where random noise,

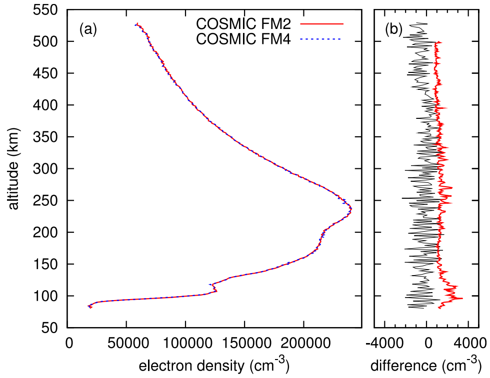

Figure 3. (a) Electron density as a function of altitude for two collocated occultations on DOY 112, 2006, 9:22 UTC (10:34 LT), 62N, 18E. (b) Electron density difference between these two profiles (black curve), and the RMS (red curve) for 183 pairs of profiles with TP difference less than 5 km.

according to the actual SNRs, was added to smoothed RO L1 and L2 data. Horizontal variations in the ionosphere and local spacecraft multipath can also contribute to differences and may be the cause of the large-scale fluctuation seen near 400 km altitude. The red curve in Figure 3b shows the RMS difference taken over 183 collocated pairs of profiles with tangent point distance less than 5 km from DOYs 111–148, 2006. Between 150 and 500 km altitude the RMS is $\sim 10^3$ cm^{-3}, whereas below 150 km the RMS increases to a maximum of $\sim 3 \cdot 10^3$ cm^{-3} at $\sim$100 km. The increased RMS near 100 km is most likely a combination of effects. The 1-Hz sampling of the observations used in the retrievals and the vertical descent rate of the occultation ray paths ($\sim$2–3 km/sec) do not allow a full sampling of the sharp vertical structures of the E-layer. Additionally, horizontal variations due to sporadic E-layers is also a likely cause of the increased RMS near 100 km. For example, going beyond 5 km in TP distances, we found that electron density differences generally increased and in many cases overshadowed the differences due to thermal noise. Even with TP distances less than 5 km we identified cases where the electron density differences look as if they arise from natural variations. Another possible cause for the increased RMS near 100 km is lower SNR due to signal defocusing resulting from large E-layer gradients. However, the increased RMS near 100 km in Figure 3b is probably more due to data sampling limitations and natural variations than to thermal noise.

4. Conclusions

[15] The six COSMIC satellites will produce about 2500 globally distributed occultations daily after resolving all technical problems and achieving full deployment to their final equally separated orbits at $\sim$800 km altitude. Shortly after launch, closely spaced satellites in one circular orbit provided a unique opportunity to estimate the precision of RO. The RMS difference of refractivity between collocated occultations with horizontal distance between TPs <10 km is less than 0.2% between 10 and 20 km altitude, increasing to about 0.7% at 30 km altitude. In the lower troposphere, the maximal RMS is about 0.8% at 2 km altitude and decreases abruptly to about 0.2% between 6 and 8 km altitude. The RMS difference of electron density in the ionosphere between 150 and 500 km altitude for collocated occultations with TP distance <5 km was found to be about 10^3 cm^{-3}.

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D. Hunt, C. Rocken, W. Schreiner, S. Sokolovskiy, and S. Syndergaard, University Corporation for Atmospheric Research, PO Box 3000, Boulder, CO 80307-3000, USA. (schrein@ucar.edu)