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Apparent precision of GPS radio occultation temperatures

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[1] The abundant atmospheric data provided by radio occultation (RO) via the Global Positioning System satellite network have improved short and long-term forecasts and have demonstrated the potential to provide a long-term, consistent, and independent climate dataset. Previous studies have already verified the consistency and reliability of the RO method, listing a range of precision estimates. Uncertainties arising during temperature retrievals, and confounding effects of atmospheric variability, have made the precision of RO temperature data difficult to determine. In this paper, we introduce the concept of *apparent* precision, and describe a simple, robust method for estimating the apparent temperature precision using data from the COSMIC project. We examine apparent RO temperature precision by latitude, and find it to be somewhat lower than previous estimates. We attribute this to apparent precision being a function of the true precision plus representativeness errors. **Citation:** Staten, P. W., and T. Reichler (2009), Apparent precision of GPS radio occultation temperatures, *Geophys. Res. Lett.*, *36*, L24806, doi:10.1029/2009GL041046.

1. Introduction

[2] Global Positioning System (GPS) radio occultation (RO) is an innovative new limb sounding technique, making use of radio signal delays to derive vertical profiles of atmospheric refractivity, temperature, and humidity data. Each GPS receiver can produce up to 650 consistent, globally distributed temperature measurements each day, at a cost per measurement only a fraction of that from radiosondes. RO instruments are effectively self-calibrating and free from instrument drift [*Anthes et al.*, 2000]. RO data inversion yields temperature profiles that are generally of the same order of precision as radiosondes [*Staten and Reichler*, 2008], and at a considerably higher vertical resolution than nadir-viewing remote sounders.

[3] The RO method involves precisely measuring the delay of a radio signal as it travels from a GPS transmitter to a receiver in low-earth orbit. As the receiver rises or sets behind Earth's atmosphere, this delay changes. This change can be used to calculate bending angle profiles, which can in turn be inverted to produce vertical profiles of refractivity. In the troposphere and stratosphere, this refractivity is a function of temperature, pressure, and water vapor, and these quantities can then be derived using basic assumptions and models for closure, including determining temperature (water vapor) from refractivity using ancillary estimates of water vapor (temperature) [*Anthes et al.*, 2000].

[4] The precision of an instrument or observing technique of the atmosphere may be described by the root-mean-square (RMS) difference between a large number of pairs of independent observations of a property (e.g. temperature) at the same point or averaged over the same volume of the atmosphere. However, measurements are generally separated in space and time. Thus a method of determining the precision is to estimate the limit as the space and time separation of independent pairs of observations tends toward zero. This is often done by extrapolating a best-fit curve of the observed differences to zero. For observing systems such as radiosondes, which sample the same points in the atmosphere as the separation distances approach zero, this method is straightforward. However, the situation is more complex for RO observations, which are observations that are weighted averages over a quasi-cylindrical volume of atmosphere with a horizontal length scale of 200–300 km; they are not point measurements [*Anthes et al.*, 2000], but they are often treated as such by assigning a point location in the atmosphere, which is the tangent point to Earth of the wave traveling from the GPS satellite to the receiver on the low-Earth orbiting (LEO) satellite. Independent RO observations that have the same tangent point may sample largely different volumes of the atmosphere, depending on the direction from the LEO to the GPS satellite. Therefore, differences in temperatures assigned to points that are derived from independent radio occultation observations depend on two factors: first, the precision of the observations themselves, and second, the representative errors that arise because RO observations are in general sampling different volumes of the atmosphere. We may define the *apparent* precision of RO temperatures, when treated as local observations, as the RMS differences of pairs of independent temperature estimates as the distance in space and time of the tangent points of the observation rays tends to zero. The apparent precision is lower than the true precision.

[5] Several previous studies have reported on the precision of RO measurements, but these studies often use relatively sparse data from early RO missions, or the results are theoretical or highly idealized. In addition, these studies say little or nothing about the seasonal and regional structure of RO precision. *Kursinski et al.* [1997] simulated RO measurements and estimated the precision to be in the sub-Kelvin range from 10 to 20 km altitude. *Ware et al.* [1996] and *Rocken et al.* [1997], examining actual profiles from the Global Positioning System for Meteorology (GPS/MET) experiment, confirmed that RO temperatures were precise to within 1 K at altitudes between 5 and 15 km. *Hajj et al.* [2004] compared collocated RO measurements from the CHAllenging Minisatellite Payload (CHAMP) mission, and used modeled atmospheric variability to place an approximate theoretical upper bound of ~0.5 K on the temperature precision of RO measurements between ~5 and 20 km.

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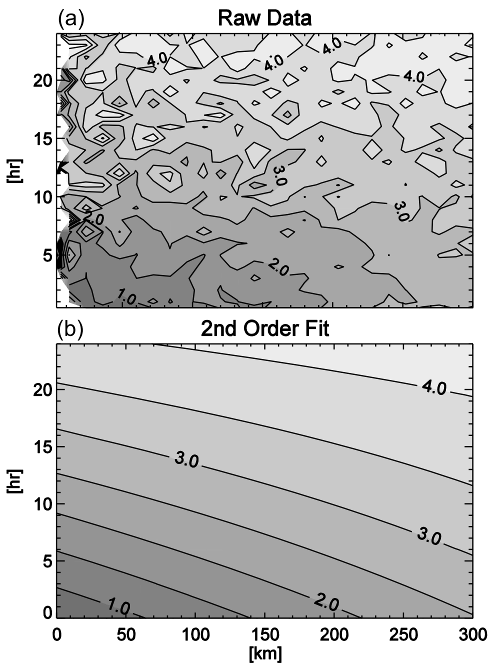

Figure 1. (a) RMS differences [K] between neighboring Year 2 COSMIC temperature measurements at 10 km altitude, for the northern hemisphere high latitudes, by separation time and distance, and (b) a second order polynomial fit of the RMS differences shown in Figure 1a.

[6] *Schreiner et al.* [2007] and *Anthes et al.* [2008] reported on the refractivity precision of the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) mission, and found refractivity measurements to be precise to within 0.2% and 0.1%, respectively, between 10 to 20 km altitude. This translates to ~0.5 K and ~0.25 K temperature precision across a wide range of altitudes. Whereas GPS/MET and CHAMP each include only one orbiting receiver, the COSMIC mission includes 6 receivers in low-earth orbit, and successfully tracks roughly 2000 occultations per day, yielding additional weight to the latter two studies. However, *Schreiner et al.* [2007] and *Anthes et al.* [2008] made use of early COSMIC data, when the satellites were very close together, before they reached their final orbits. Occultation paths during this time period were more often nearly aligned and likely produced relatively more similar profiles than can reasonably be expected now that the satellites have reached their final orbits. Precision estimates from just these first few months, while important, may not include the representativeness errors inherent in RO temperature data in general.

[7] Temperature precision also varies strongly by altitude, and is affected by residual ionospheric noise, the choice of processing method, and along-path horizontal atmospheric variability. Past studies examined RO precision as a function of height, and to some extent by latitude [*Anthes et al.*, 2008]. However, *Kursinski et al.* [1997] suggest that precision will vary by season as well, due to along-path horizontal variability.

[8] In this study, we seek to examine the apparent temperature precision of the RO method. We apply two types of estimation: first, averaging differences meeting specific collocation criteria, and second, extrapolating the differences to zero. The averaging method inherently underestimates the precision, as it allows temporal and spatial differences in temperature to contribute to the RMS difference. Tightening the collocation criterion generally reduces this problem, but at the cost of increased sampling uncertainty.

[9] In the following sections, we estimate the apparent precision of RO. We present our results as a function of height, latitude, and season for data from the COSMIC Data Analysis and Archival Center (CDAAC), processed using the Nov. 2007 software and a one-dimensional variational (1-DVAR) process to account for water vapor from analysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF).

2. Methods

[10] COSMIC has been operational for a number of years, but it was several months before the satellites were each maneuvered into their final, separated orbits. We examine COSMIC data from two years: Year 1, spanning (year/day) 2006/194–2007/193, and Year 2, covering 2008/061–2009/059. These were the earliest and latest years available to us. For Year 1, we include data only from satellites that have not been separated from their initial orbit. This should allow us to examine the effect of the initial close orbits on the apparent precision of the system.

[11] Measurements from COSMIC are dense enough that a substantial number of measurement pairs exist close together in space and time. Figure 1a shows the RMS differences between pairs of COSMIC temperature measurements from Year 2 between 60°N and 90°N, at an altitude of 10 km, as a function of temporal and spatial separation at that level. Immediately apparent is the noisiness of the data, particularly where the spatial separation is small, or along the left axis of Figure 1a. To a first order, RMS differences increase with increasing separation, as would be expected. The slope of this change is not constant, however. It appears to be steeper near the origin and shallower as distances increase. The decrease in slope with increasing distance likely represents the saturation of the difference as two observations become essentially unrelated.

[12] Basing precision on pairs of measurements within certain collocation criteria amounts to calculating the RMS error for all pairs in some rectangular region in the lower-left corner of Figure 1a. We refer to this method as the box method. Choosing sufficiently strict collocation criteria or a sufficiently small box should narrow down the differences, but the scarcity of measurement pairs that are very close in space and time will increase the sampling uncertainty.

[13] In order to ameliorate this problem, we apply a second order polynomial surface fit (Figure 1b) to the differences in Figure 1a. This fit appears to reasonably estimate the changes of the slope with separation in space and time. By using such a fit, we may be able to extrapolate the RMS differences to the origin and thereby determine a better estimate of the apparent RO temperature precision. The fit acts to filter noise, and extrapolating allows us to make use of 100–1000 times as many pairs as in the 36 km, 4 hr box average (~40,000 pair versus ~200 pairs is typical

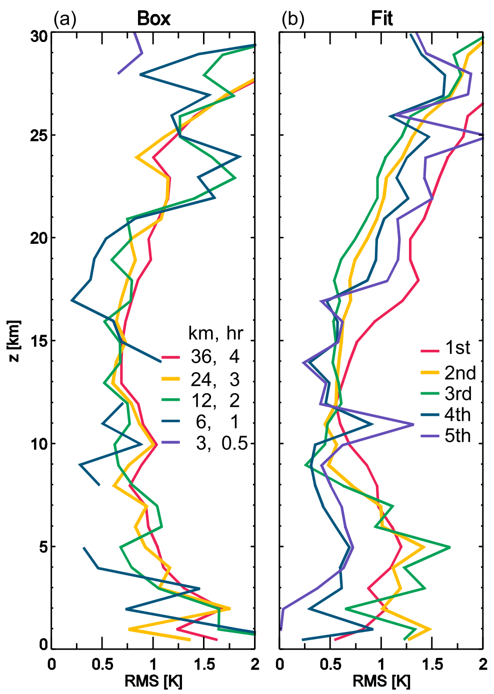

Figure 2. RMS temperature error [K] estimates for Year 2 COSMIC data from the northern hemisphere high latitudes, using the (a) box method and (b) polynomial fitting at each level with collocation criteria and polynomial orders shown. Gaps indicate missing data.

for a year of data from the midlatitudes), without overestimating the error as the box method does.

3. Results

[14] To compare the box and polynomial extrapolation methods, we apply both methods to data at 0.5 km altitude and at each kilometer from 1 to 30 km (Figure 2). Figure 2a shows profiles of RMS differences for Year 2 data from 60°N to 90°N for all seasons, produced by applying the box method with several different collocation criteria at each altitude. The loosest collocation requirement (4 hr/36 km) strongly overestimates error, as expected. As collocation requirements tighten, the error estimates generally tend to decrease, but sampling uncertainty becomes more pronounced, producing more jagged profiles.

[15] Polynomial extrapolation methods (Figure 2b) generally yield less jagged profiles than the box method. The first order extrapolation clearly overestimates the error, as this fit cannot account for the changing slope seen in Figure 1. Second and higher order extrapolations generally yield small errors, similar to the tightest box averages, but some of the higher order fits produce unrealistic values, and the estimates become less robust with increasing order. Results from different bands and from Year 1(not shown) are similar. Examining collocated analysis profiles, (ECMWF analysis data interpolated by CDAAC from an N400 reduced Gaussian Grid to points corresponding to individual RO profiles) the second-order method extrapolates very nearly to zero, as would be expected, while only the tightest collocation criteria can obtain differences below 0.2 K. Extrapolating model data to zero is desirable, as the model differences approximate atmospheric variability, and the goal of the extrapolation is to filter out this variability. For our subsequent results we use the second order extrapolation method, as this method appears to effectively filter at least the atmospheric variability depicted in model data, while still producing reasonable estimates.

[16] In this study, we define the tropics as 20°S–20°N, and the high latitudes as 90°S–60°S and 60°N–90°N. These definitions are intended to clearly isolate the effects of tropical and polar weather patterns on the apparent precision estimates. The broad latitude bands in between, which we call transition latitudes, are expected to demonstrate behavior from both the tropics and high latitudes.

[17] Figure 3 presents the error profiles from the second order extrapolation for Year 1 analysis data (gray lines), and for Year 1 (red lines) and Year 2 (green lines) COSMIC data. Profiles are shown for the entire year and selected latitude bands, and for the northern hemisphere high latitudes and selected seasons. Also shown are the 95% confidence intervals for the error estimates, obtained by applying the extrapolation method to a large number of random subsets of the data. Subsets included 50% of the data, chosen randomly without replacement.

[18] Differences above 20 km (Figure 3) are generally large (>1 K) due to a combination of thermal noise, residual ionospheric error, errors due to orbit determination and clock offset uncertainty, and possibly error due to boundary conditions used in data inversion[*Kursinski et al.*, 1997]. RMS errors generally reach a minimum at about 10–15 km altitude, where the effects of residual ionospheric noise and along-path atmospheric variability are small. Here, the values drop to as low as 0.25 K in some cases. Errors increase once more towards the surface. This is expected, as water vapor at low altitudes becomes the dominate term in the refractivity equation. We see a small decrease in errors in the lowest 1 km, but temperature data at this level are suspect [*Sokolovskiy*, 2003]. Errors in the tropics (Figure 3c) reach a local maximum at ~5 km, while in the high latitudes (Figures 3a and 3e) the errors peak between 2–3 km. Transition altitudes (Figures 3b and 3d) show no clear maxima, as these profiles exhibit a mixed tropical-polar behavior. These latitudinal variations are further modulated by season. Errors in the high latitudes are largest during the summer season.

[19] Corresponding COSMIC temperature difference profiles from the two years show a general decrease in apparent precision from Year 1 to Year 2, in particular over the northern hemisphere and the tropics. This is likely to be related to the separation of orbits, and the increased likelihood of collocated occultation points with very different occultation paths. Why the precision doesn't clearly decrease from Year 1 to Year 2 in the southern hemisphere is not understood at this time.

4. Summary and Discussion

[20] Although it is not immediately obvious that RO apparent precision should vary by season and latitude, our results show that to be the case. *Kursinski et al.* [1997] suggest that even a single RO mission will experience varying apparent precision by latitude due to the differing

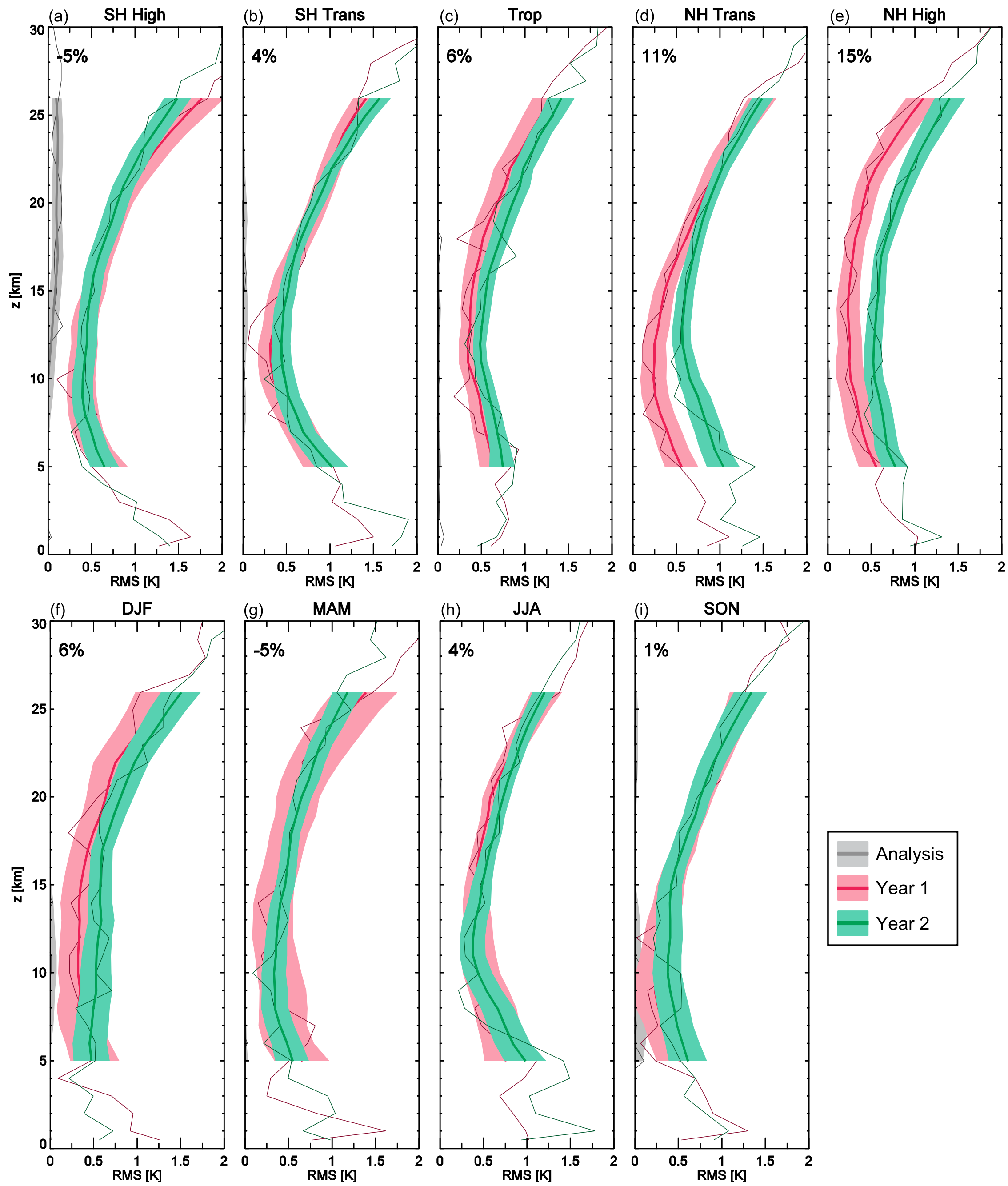

Figure 3. Profiles of COSMIC RMS temperature error [K] on the second order polynomial fit for Year 1 (red), Year 2 (green), and for collocated analysis data (gray) as described in Section 2. Note that analysis profiles are close to zero and therefore nearly invisible. Thin lines show actual results, thick lines are vertically averaged, and shading indicates 95% confidence intervals (shaded regions) of the vertically averaged RMS error. (a–e) The profiles for the entire years for the latitude bands and (f–i) profiles by season for the northern hemisphere high latitudes are shown. Year 1 spans (year/day) 2006/194–2007/193, and Year 2 spans 2008/061–2009/059. The fractional change in error from Year 1 to Year 2, vertically-averaged over 1–30 km altitude, is indicated in the top left of each panel.

character of along-path atmospheric variability. *Chou et al.* [2009] give an example of an occultation path crossing a strong horizontal moisture gradient, resulting in several poor moisture retrievals in the tropics from 3 to 9 km. As long as occultation paths are not constrained to be parallel, nearby measurements can be significantly different (representativeness error). Since the average frequency and severity of horizontal atmospheric temperature and moisture gradients differ by latitude and season, so too does the apparent RO precision. This may explain why we find latitudinal and seasonal apparent precision differences in the troposphere, where the spatial temperature and moisture gradients are largest.

[21] Water vapor gradients likely provide a large contribution to this type of error in the lower troposphere, as refractivity at RO wavelengths is a stronger function of

water vapor pressure than of the dry temperature term. This hypothesis is substantiated by the seasonal apparent precision differences in the northern hemisphere high latitudes (Figure 3). While midlatitude instability is largest in the wintertime, RO errors are largest during the summertime, when the water vapor pressure and the corresponding horizontal water vapor gradients increase. The overall low precision in the lower troposphere can also be attributed to the effect of water vapor on the temperature retrieval.

[22] In some cases, our error profiles reach values as small as 0.25 K, but we do not find such small values across broad height bands, such as the 10–20 km range reported by *Anthes et al.* [2008], except for northern hemisphere high latitude data from Year 1. Year 2 precision profiles generally do not approach 0.25 K. Our lower apparent precision values for both years may be in part due to errors introduced by processing refractivity data into moisture and temperature data; *Anthes et al.* [2008] base their temperature precision estimation on their work on refractivity data, while we use temperature profiles derived through a 1-DVAR process using water vapor from ECMWF analyses.

5. Conclusion

[23] Previous studies have presented RO precision as a function of altitude, but the apparent precision in the troposphere is affected by horizontal moisture and temperature variability along the occultation path as well. Thus, precision estimates which ignore the influence of along-path horizontal atmospheric variability, either by focusing on aligned occultation paths, or by reporting a global average precision for a given altitude, may not be representative for some applications.

[24] Our results apply to RO temperature data, but can be extended to RO point or profile data in general, which require a spherical atmosphere assumption. Bending angle and refractivity data can, however, be assimilated into forecast systems as non-local data [*Ringer and Healy*, 2008], and the horizontal atmospheric variability – the likely source of our latitudinal and seasonal differences – can be accounted for by the model itself.

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