Observing the moist troposphere with radio occultation signals from COSMIC

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New approaches for observing the moist troposphere using radio occultation (RO) signals transformed to impact parameter representation by radio-holographic (RH) methods are presented. Large changes in the RH bending angle are used as indicators of significant vertical refractivity gradients that often occur on top of the atmospheric boundary layer (ABL), convective cloud layers such as the trade-wind inversion, and other moist layers in the free troposphere. RH amplitude fluctuations are used as an indicator of turbulence in the moist troposphere. The approaches are demonstrated using RO data from the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) mission from September 2006. The global distributions of the ABL depths and tops of moist convective layers derived from COSMIC RO data correspond generally to the observed locations and structures of the Intertropical Convergence Zone and adjacent sub-tropical regions. The approaches are suitable for investigations of the temporal and spatial ABL variability. Citation: Sokolovskiy, S. V., C. Rocken, D. H. Lenschow, Y.-H. Kuo, R. A. Anthes, W. S. Schreiner, and D. C. Hunt (2007), Observing the moist troposphere with radio occultation signals from COSMIC, Geophys. Res. Lett., 34, L18802, doi:10.1029/2007GL030458.

1. Introduction

The six-satellite Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC), was launched on April 15, 2006. This system is primarily designed to produce GPS radio occultation (RO) observations of the neutral atmosphere and ionosphere [Cheng et al., 2006; R. A. Anthes et al., The COSMIC/FORMOSAT-3 mission: Early results, submitted to Bulletin of the American Meteorological Society, 2007, hereinafter referred to as Anthes et al., submitted manuscript, 2007]. The unprecedented large daily number of occultations provided by COSMIC is gradually increasing and, after full deployment and achieving a uniform 30-degree separation of the six orbit planes at the end of 2007, will provide ~2500 occultations per day, evenly distributed in local solar time. Another distinctive feature of COSMIC is routine tracking of RO signals in the lower troposphere (LT) in the open-loop (OL) mode (Anthes et al., submitted manuscript, 2007). This allows retrieval of the bending angle (BA) and refractivity (N) profiles almost down to the Earth’s surface by application of radio holographic (RH) inversion methods [Gorbunov, 2002; Jensen et al., 2003]. The retrieved BA and N profiles can be directly assimilated in models for weather forecasting [Healy et al., 2005] and other applications such as climate monitoring. In addition to the assimilation, OL RO signals can be used for observing the LT, e.g. determining the depth of the ABL, the height of inversion layers in the free troposphere, and regions of turbulence in the presence of moisture. Direct observations of the ABL, other inversion layers, and layers of turbulence have several important meteorological and climatological applications [Medeiros et al., 2005]. Observations of the ABL are useful in subjective weather forecasting, for example, in forecasting the development or suppression of convective clouds. Observations of turbulent regions are useful in aircraft operations [Cornmann et al., 2004]. In addition to these applications, knowing the height and structure of the ABL and inversion layers is useful for monitoring conditions of radio wave propagation [Rogers, 1998].

This paper presents and demonstrates the potential of these new approaches for observing the LT by RO. Section 2 briefly outlines the use of RH methods for inversions of RO signals by summarizing known results and referencing original publications for details. Section 3 introduces the use of bending angle for determining the top of the ABL or the height of other inversion layers. Section 4 introduces the use of the amplitude of an RO signal transformed to impact parameter representation by RH methods for identifying layers of moist convection and, in particular, their vertical extent. These methods are demonstrated with COSMIC RO data from September 2006. Section 5 is the summary and conclusions.

2. RH Inversions of RO Signals in the Troposphere

RO signals usually undergo strong fluctuations in the moist LT due to complicated structures of atmospheric refractivity N. The largest effect on the amplitude and phase of the RO signal, caused by focusing/defocusing and multipath propagation, occurs with horizontally extended N structures, such as inversion layers, although small-scale N variations such as turbulence also play a role. In the LT, the complex RO signals (phase and amplitude) are inverted by RH methods, such as the canonical transform (CT) [Gorbunov, 2002] or the full spectrum inversion (FSI) [Jensen et al., 2003]. The RH methods transform RO signal from time or space to impact parameter representation under the assumption of spherical symmetry of N. This allows...
solving for multiple rays that are uniquely defined by their impact parameters. The derivative of the phase of the complex transformed signal defines the arrival angle and thus the bending angle of a ray with a given impact parameter. The amplitude is not used except for measurements of the atmospheric transmissivity [Gorbunov and Kirchengast, 2005]. Using the principle of synthetic aperture, the RH methods allow sub-Fresnel resolution, estimated at ~60 m by Gorbunov et al. [2004].

[5] As opposed to the measured RO signal amplitude, the amplitude after RH transformation is nearly constant when the refractivity is spherically symmetric. However, non-spherically symmetric N-irregularities result in fluctuations of the RH-transformed amplitude. Thus the measured amplitude of the RO signal is most sensitive to the spherically symmetric structure of N, while the RH-transformed amplitude is most sensitive to the non-spherically symmetric structure of N as caused by turbulence. This effect is known from observations and simulations [Sokolovskiy, 2003; Gorbunov and Kirchengast, 2005], and is used for estimating errors in BA [Lohmann, 2006] and transmissivity [Gorbunov and Kirchengast, 2005]. This effect can also be used as an indicator of N irregularities in the moist troposphere. Such irregularities, in most cases, are associated with turbulence and moist convection in the troposphere. Turbulence in the upper troposphere – lower stratosphere has smaller effect on RO signals, but this effect has also been detected [Gurvich et al., 2004; Cornmann et al., 2004].

3. Observing of the ABL Depth From Bending Angle Profiles

[6] The ABL is the lowermost atmospheric layer. It is characterized by turbulent mixing generated by wind shear and convection, and is directly affected by the Earth’s surface on time scales of a few hours or less. The ABL is capped by a temperature inversion that separates it from the overlying stably-stratified free atmosphere [Garratt, 1994], and is usually accompanied by a significant decrease of water vapor and relative humidity. Strong inversions can also exist above the ABL, particularly at the top of moist layers such as trade-wind inversions. The ABL is more horizontally homogeneous over oceans than land. It should be noted that limb-viewing RO is well suited for observing horizontally extended N-structures. For example, if the depth $\Delta z$ of the transition layer on top of the ABL is 0.1 km, then this layer can be resolved by RO if its horizontal extent is $\geq 2\sqrt{2r_e\Delta z}$, where $r_e$ is the Earth’s radius [Kursinski et al., 1997]; i.e., ~70 km. Irregularities of this layer with smaller horizontal scales are averaged in the RO-retrieved vertical profiles.

[7] Figure 1 (left) shows an example of radiosonde temperature and water vapor profiles in the presence of a sharp ABL top. Figure 1 (right) shows the N and BA profiles computed from the profiles on the left. The transition layer at 1.8–2 km height manifests itself by step-like structures in N and BA, which are much more pronounced in BA (which is related to the N-gradient) than in N. We note that the N-gradient in Figure 1 exceeds the critical value $(-157 \text{ N/km})$ at ~1.9 km, which results in negative bias of the Abel-retrieved N below that height [Sokolovskiy, 2003]. Although the height of the transition layer, i.e., the ABL depth, is an important variable for predicting essential climatic quantities such as global cloudiness, precipitation, and surface winds [Medeiros et al., 2005], in many cases it is not well reproduced by atmospheric models [Zeng et al., 2004].

[8] A large N-gradient at the top of the ABL manifests itself clearly in the BA and N profiles retrieved from RO signals. Figure 2 shows examples of BA (red lines) and N (blue lines) profiles for several COSMIC RO soundings from September 2006 (crosses show collocated radiosonde data). Times and locations of RO and radiosondes are shown in Table 1. Profile A does not show evidence of a sharp ABL top, while profile B shows a very sharp ABL top. Other profiles that show pronounced ABL tops over the
ocean (C, D, E) and elevated inversion layers over land (F, G, H) will be discussed in conjunction with Figure 3.

Different approaches can be used for the automated detection of inversion layers in N and BA profiles (e.g. determining break point in N-profile, as suggested by Sokolovskiy et al. [2006]). In this study, we use the BA where the effect of strong N-gradient is more pronounced.

A reliable automated search algorithm for inversion layers cannot be based on local maxima of the BA gradient because these often correspond to small-scale structures in BA profiles. It is possible to search for a maximal BA lapse $\Delta \alpha$ within a sliding height interval of a fixed length $Dz$ corresponding to an approximate mean depth of the transition layer at the ABL top. However, this depth may vary from tens to hundreds of meters [Garratt, 1994] depending on region, season, local time, etc. In this study we search for the maximum of $P = \Delta \alpha / (\Delta \alpha / Dz)$ which is a trade-off between the maximal lapse and the maximal gradient. This results in searching for three parameters: $\Delta \alpha$, $\Delta z$, and $z_i$ which is the median height of the interval $Dz$.

To illustrate our approach we use COSMIC RO data from September 2006. By selecting occultations that meet different criteria i.e., by restricting the values of $D\alpha$, $z$ and $Dz$ to specific intervals, it is possible to reveal different structures in the global distribution of the ABL depth and other inversion layers.

For example, Figure 3 (top) shows the global distribution of RO soundings that penetrated to at least 0.5 km above mean sea level and met the following criteria: $D\alpha < 1.2 \cdot 10^{-2}$ rad, $z < 3$ km. These criteria reveal the ABL depth, in the case of a sharp ABL top, mainly over the oceans (the color scale shows the estimated $z$). We see a sharp ABL top mainly in the sub-tropics and mid-latitudes, and rarely in the Inter-Tropical Convergence Zone (ITCZ). In particular, the West Pacific tropical region, known for its deep convection and intense cyclogenesis, does not show sharp ABL tops. Decreasing ABL depth towards the West coasts of North and South America, and South Africa is obvious [Neiburger et al., 1961]. Profile A in Figure 2 is from the ITCZ while profile B is from the region with a sharp ABL top. Profiles C, D, E in Figure 2 are from the South Pacific. Comparison to collocated radiosondes (from islands) shows overall reasonable agreement; the differences can be explained by the differences between RO and radiosonde locations and by horizontal averaging of RO (mentioned above).

As another example, Figure 3 (bottom), shows the global distribution of COSMIC RO soundings meeting the criteria $6 \text{ km} < z < 8$ km and $D\alpha > 6 \cdot 10^{-3}$ rad (further relaxing the criteria on $D\alpha$ would not allow reliable determination of single inversion layers as can be seen in Figure 2). Profiles that meet these criteria reveal elevated inversion layers over the oceans and continents. In addition to scattered RO soundings, Figure 3 (bottom) clearly shows three clusters of RO soundings over the continents in September 2006: central South America, Australia and the Arabian Peninsula. Profiles F, G, H give examples of RO

![Figure 2. Bending angle (red lines) and refractivity profiles (blue lines) retrieved from COSMIC RO signals. Each successive profile is offset in height by +5 km. Observations of N from collocated radiosondes are indicated by +. For details see text.](image)

| Table 1. Times and Locations of Radio Occultations and Radiosondes$^a$ |
|-------------------|---------|--------|---------|---------|---------|---------|---------|
| RO Day          | RO UTC  | RO Latitude | RO Longitude | RS UTC  | RS Latitude | RS Longitude |
| A               | 12.09.06 | 21:36   | 17.1      | 158.8   | -         | -         |
| B               | 11.09.06 | 11:01   | -31.9     | -13.9   | 24:00     | -23.35    | -149.48  |
| C               | 07.09.06 | 20:33   | -25.5     | -151.5  | 24:00     | -27.62    | -144.33  |
| D               | 08.09.06 | 20:20   | -26.3     | -141.4  | 24:00     | -27.62    | -144.33  |
| E               | 24.09.06 | 19:07   | -28.2     | -144.8  | 24:00     | -27.62    | -144.33  |
| F               | 13.09.06 | 00:00   | -15.2     | -52.6   | 00:00     | -15.65    | -56.10   |
| G               | 05.09.06 | 04:01   | -25.3     | 135.6   | 00:00     | -23.80    | 133.90   |
| H               | 29.09.06 | 01:26   | 18.7      | 42.1    | 00:00     | 18.23     | 42.65    |

$^a$RO is radio occultations and RS is radiosondes.
Figure 3. Global distribution of COSMIC RO profiles showing (top) a sharp ABL top and (bottom) elevated (4–6 km) inversion layers for September 2006.

Figure 4. Normalized FSI amplitude (black lines) and local spectral width of the FSI amplitude (red lines) for COSMIC RO soundings shown in Figure 2. Each successive profile is offset in amplitude by +2 (in local spectral width by 50 km$^{-1}$). For details see text.
soundings from each of those regions that agree fairly well with the collocated radiosondes. Naturally, the distributions shown in Figure 3 shall change with the season; this will be the subject of future study.

4. Observing Layers of Moist Convection From RH Amplitude Profiles

[13] Figure 4 (black lines) shows amplitudes of the FSI-transformed RO signals for the RO profiles used in Figure 2 plotted as functions of impact height \( h \) (impact parameter minus local Earth curvature radius). It is seen that the structure of FSI amplitude, and the magnitude and frequency of scintillations vary significantly with impact height and are substantially different for different occultations.

[14] The effect of FSI amplitude scintillations can be described by the local scintillation index \( Gorbunov and Kirchengast, 2005 \). Additional simulations (not discussed here), similar to those performed by Sokolovskiy [2003], show that the frequency of scintillations more than the scintillation index is sensitive to the strength of the N-irregularities that cause the scintillations. In this study we characterize scintillations by the width of the local spectrum of the FSI amplitude, by calculating the spectrum in a \( 0.5 \) km sliding window. We arbitrarily define the width \( w \) of the spectrum as \( \int_0^w s(k)dk \approx 0.5 \) where \( s(k) \) is the normalized spectral amplitude and \( k \) is the vertical wavenumber.

[15] Figure 4 (red lines) shows vertical profiles of \( w(h) \) for the FSI amplitudes. In case A, \( w(h) \) gradually decreases from a maximum around 3 km to zero at almost 10 km. This indicates strong moist convection up to large heights in the ITCZ. In other cases (B – H) with pronounced inversion layers \( w(h) \) shows local maxima around the heights of the inversion layers (note that the impact height in Figure 4 differs from the geometric height in Figure 2) and rapidly decrease above. This suggests that the moist air turbulence is mainly confined to the regions around the inversion layers [Wyngaard and LeMone, 1980]. We found significant correlation between the inversion heights and the heights of maxima of \( w(h) \) up to 4–6 km.

[16] For revealing regions with strong moist convection, we arbitrarily define the top of the convective layer \( h_{top} \) as the largest height where \( w(h) > 10 \) km\(^{-1} \). Figure 5 shows the global distribution of RO soundings satisfying the criterion \( 6 \) km < \( z_{top} < 8 \) km. The distribution in Figure 5 resembles the structure of the ITCZ, which includes, in particular, the South Pacific Convergence Zone extending southeastward from the equator at the dateline and the South Atlantic Convergence Zone extending southeastward from equatorial South America [Tian and Ramanathan, 2002; Carvalho et al., 2004]. Expansion of the regions of strong convection into the North Atlantic and Northeast Pacific also is observed. The pattern shown in Figure 5 is somewhat complementary to that in Figure 3 (top); i.e., the regions with strong convection do not show a sharp ABL top and vice versa (except some overlapping regions, such as the North Atlantic and Northeast Pacific).

5. Summary

[17] This study introduced new approaches for observing the moist LT by use of RO signals recorded in OL mode and inverted by RH. Their feasibility is demonstrated with COSMIC RO data from September 2006. A large lapse in the bending angle profile, which indicates strong vertical moisture gradients, is used for estimating the ABL depth or the height of other inversion layers in the free troposphere. Amplitude scintillation of the RH-transformed RO signal, which indicates turbulence in moist air, is used to estimate the height of moist convection in the troposphere. The feasibility of both approaches is illustrated by calculating global distributions of the ABL depth and the height of moist convection. The calculated distributions agree generally with observed climatological features; e.g. the absence of well-defined ABL tops in tropical regions of deep convection, well-defined ABL tops in the subsiding subtropical high-pressure regions, and decreasing ABL depth towards west coasts of continents in the subtropics.
formation about the ABL and moist convective layers is useful for numerical weather prediction, diffusion, and climate studies. Inversion heights are also useful for observing conditions important to radio wave propagation. Application of these approaches to seasonal, regional and diurnal studies will be addressed in future publications.

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