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Simulation of liquid water and ice contributions to bending angle profiles in the radio occultation technique

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Abstract

Inversion of radio occultation profiles usually relies on the Abel transform in a spherically symmetric atmosphere. The main contribution to the refractive index comes from gaseous constituents such as pressure, temperature and water vapor. However, the impact of other particles in the troposphere, neglected in the retrieval, can become important during specific weather events causing the commonly applied assumptions to be invalid. In this study, Global Forecast System model is used to simulate the effect of cloud water on bending angle profiles. The information of solid and liquid fractions was assessed from the cloud mixing ratio based on a temperature-dependent separation. The signal was propagated between GPS satellite and low-Earth orbiter through tangent point placed in the vicinity of cloud water. The assumption of a spherically symmetric distribution for cloud refractivity fields is validated based on 2-dimensional simulations with multiple phase screen method. Using one year of forecast data for 2016, the most statistically probable examples were selected and analyzed as well as the uppermost impact of cloud significance was determined in terms of bending angle errors. Typical refractivity values induced by liquid clouds are within 2 ppm and result in single-spike profile structures. Corresponding fractional errors of the bending angle can reach −4% with respect to retrievals with zero clouds contributions. In the presence of unusual weather phenomena, simulations in a horizontally inhomogeneous atmosphere suggest a large dependency on propagation paths that should be considered in the modeling of cloud impact. Bending angles can be affected by −10% fractional error, which inverted with Abel transform corresponds to refractivity error of −2%. The highest fractional difference induced by the ice water is generally below −1% in the bending angle and −0.5% in the refractivity. The most significant cloud content was observed in the first 6 km above the Earth's surface, whereas ice clouds can affect radio occultation profiles up to the top height of 16 km.
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Keywords: Bending angle; Clouds; GPS; Radio occultation; RO; Simulation

1. Introduction

Amongst number of factors affecting the propagation of a microwave signal in Global Positioning System (GPS) radio occultation (RO) technique, major sources of noise in the retrieved atmospheric profiles come from the ionospheric correction (Zeng et al., 2016) and tropospheric multipath (Sokolovskiy, 2003). The signal received on low-Earth orbiter (LEO), in most atmospheric conditions, cannot be directly inverted using geometrical optics as more than one ray arrives at a given time leading to multivalued function of bending angle with respect to impact parameter. Number of methods based on Fourier integral operators (FIOs) has been developed for disentangling multiple rays with sub-Fresnel resolution (Gorbunov et al., 2004): with canonical transform (CT) (Gorbunov, 2002a) where the complex field is to back-propagated to a straight-line, the full spectrum inversion (FSI) (Jensen et al., 2003) numerically effective especially on circular orbits and the phase matching (PM) (Jensen et al., 2004)

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commonly applied for processing of real occultation data. The development in radio-holographic methods significantly improved the quality of tropospheric profiles under multipath propagation (Sokolovskiy et al., 2007). However, in the moist troposphere recorded radio occultation signals in the most recent Formosa Satellite Mission-3/Constellation Observing System for Meteorology, Ionosphere and Climate (FORMOSAT-3/COSMIC) can be still affected by systematic effects. The measurement uncertainty in the lower troposphere due to inversion biases is around 1% (Sokolovskiy et al., 2010). The retrieval accuracy partially arises from receiver-tracing errors (Beyerle et al., 2006) and strategies in processing software (Sokolovskiy et al., 2009).

In the forward modeling of radio occultation profiles, the highest contribution to the signal bending in the neutral atmosphere comes from dry atmospheric pressure and water vapor, while the effects induced by aerosols or hydrometeors are considered negligible (Kursinski et al., 1997). The structure of observed radio occultation refractivity profiles within Numerical Weather Prediction (NWP) models is commonly represented by the fundamental meteorological variables in two-term (Smith and Weintraub, 1953) or three-term expression (Thayer, 1974). Usually, in the variational assimilation (Cucurull et al., 2013), the model-based counterpart of the bending angle profile is retrieved in the assumption of spherically symmetric atmosphere. Hence, the refractivity can be inverted to the bending angle by the Abel transform (Fjeldbo et al., 1971). An observation error covariance matrix is required in a forward model, which can consider the fractional refractivity errors to vary linearly with height from 1.1% at 4 km to 0.25% at 10 km (Healy et al., 2005). The percentage error for the bending angle is assumed to be 10% at the surface decreasing linearly to 1% at 10 km (Healy and Thépaut, 2006). The Abel transform provides an explicit method to solve the radio occultation problem by imposing horizontally homogenous case of the atmosphere (Rodgers, 2000). As such, differential equations reduce and the refractive index n is a function of distance r only, since $\partial n/\partial r = dn/dr$ that gives the formula of Bouguer (Born and Wolf, 2000). However, the information about horizontal inhomogeneity is lost which in average introduces uncertainty of 3% in bending angles near the surface and can reach over 20% in a frontal case (Healy, 2001). The more sophisticated and computationally-demanding variational assimilation methods use two-dimensional (Liu and Zou, 2003; Healy et al., 2007) or three-dimensional approach (Zou et al., 2000) in order to more accurately reconstruct observed occultation profiles. The impact of ignored terms in atmospheric refractivity, namely liquid and solid water, on the bending angle profile remains unknown. The along ray-path length of traversing signals between GPS transmitter and LEO receiver in the radio occultation technique is relatively large comparing to ground-based GNSS observations. Hence, the contributions have a potential to reach a non-negligible order in cloudy conditions.

Solheim et al. (1999) estimated radio propagation delays in GPS limb sounding technique by semi-empirical approach. The highest contribution from non-gaseous constituents of refractivity is expected to be induced by clouds and is generally under 3% of the largest delays associated with dry air and water vapor. Zou et al. (2012) found the GPS RO refractivity in deep convective clouds to be systematically larger than a refractivity derived from European Centre for Medium-Range Weather Forecasts (ECMWF) analysis, whereas in clear-sky conditions observations were unbiased. Results based on CloudSat ice water content (IWC) collocated with radio occultation profiles at locations of tangent points showed that the fractional bias can be as high as 1.8% with the maxima located at about 7.5 km of altitude. Similar methodology was applied to assess the impact of cloud liquid water on RO refractivity with a separation on different cloud types (Yang and Zou, 2012). In the tropical regions, the observed liquid water content (LWC) and associated N-bias were the largest at 6 km altitude. The highest fractional bias reached 1.2% of total refractivity within cumulus clouds. However, the authors expect the liquid water content in severe weather conditions to be a magnitude higher than that values retrieved from CloudSat data. The along-track dependence of positive refractivity bias showed the cloud contribution can vary between 1% and 2% for fractions of the sky obscured by deep convective clouds in 90% or higher (Yang and Zou, 2017).

Difficulties in parametrization of clouds in weather models and assessment of cloud information from remote sensing platforms result in very limited knowledge about cloud-induced effects on radio occultations. While most of processing centers operationally assimilate bending angle profiles to NWP models (Healy and Thépaut, 2006; Poli et al., 2010), the uncertainty introduced by neglected cloud refractivity terms has not been investigated. Because the accuracy of modeled clouds is very difficult to estimate (Stephens, 2005), the following study does not attempt to assess the uncertainty associated with mismodeling of cloud variables (Yoo and Li, 2012). Instead, the expected magnitude of cloud refractivities is determined based on distribution of cloud mixing ratio. The effect of the cloud liquid water and ice crystals on radio occultation bending angle profiles is analyzed and explained by means of wave optics simulations. Simulations in a spherically symmetric atmosphere provide the upper-limit of cloud contributions, whereas the 2-dimensional approach allows to estimate the impact of horizontal inhomogeneities. The accumulated bending due to cloud refractivity fields along propagation ray-paths is modeled and a vertical distribution of retrieved occultation profiles is discussed in details on a representative sample of cloud fractions.

2. Simulations with multiple phase screen

Simulations of radio occultation profiles are performed with multiple phase screen (MPS) method (Knepp, 1983;

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