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How to process radio occultation data: 1. From time series of frequency residuals to vertical profiles of atmospheric and ionospheric properties

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ABSTRACT

Expertise in processing radio occultation observations, which provide vertical profiles of atmospheric and ionospheric properties from measurements of the frequency of radio signals, is not widespread amongst the planetary science community. In order to increase the population of radio occultation processing experts, which will have positive consequences for this field, here we provide detailed instructions for one critical aspect of radio occultation data processing: how to obtain a series of bending angles as a function of the ray impact parameter from a time series of frequency residuals. As developed, this tool is valid only for one-way, single frequency occultations at spherically symmetric objects, and is thus not immediately applicable to either two-way occultations, such as those of Mars Express, or occultations at oblate objects, such as Jupiter or Saturn. This tool is demonstrated successfully on frequency residuals from a Mars Global Surveyor occultation at Mars, and the resultant set of bending angles and impact parameters are used to obtain vertical profiles of ionospheric electron density, neutral atmospheric number density, mass density, pressure, and temperature via the usual Abel transform. The root-mean-square difference between electron densities in the ionospheric profile derived herein and archived electron densities is $7 \times 10^8\ \mathrm{m}^{-3}$. At the lowest altitudes, temperatures in the neutral atmospheric profile derived herein differ from archived neutral temperatures by less than 0.1 K. Software programs that implement these procedures accompany this paper and may be used to extract scientifically useful data products from lower-level data sets.

1. Introduction

Radio occultation investigations have been commonplace on planetary science flyby and orbital missions since Mariner 4 reached Mars in 1965 (Kliore et al., 1965), with dozens of spacecraft performing radio occultations at many planets, satellites, and a comet (Withers, 2010). The application of radio occultation investigations to planetary science has been described previously by several authors (e.g. Phinney and Anderson, 1968; Fjeldbo et al., 1971; Yakovlev, 2002; Kliore et al., 2004; Withers, 2010). These investigations transmit a radio signal such that it passes close to a solar system object (the "target object") during its journey from the transmitter to the receiver. Refraction of the radio signal in the neutral gas and ionospheric plasma around the target object affects the frequency of the radio signal. Vertical profiles of the number density of neutral gas and the electron density of ionospheric plasma can be obtained from time series measurements of the received radio frequency. Corresponding profiles of neutral mass density, pressure, and temperature can also be obtained. The resultant neutral atmospheric profiles offer better vertical resolution (sub-km) than most other techniques and are unaffected by instrument calibration issues. They are also referenced to an absolute altitude scale, unlike the pressure levels that are common to many infrared instruments, which provides deeper context for studies of atmospheric dynamics. In addition, compared to data sets from many other instruments, they have high accuracy at relatively high pressures, which enhances studies of tropospheric climate and, on objects whose surface pressure is not much greater than Earth's, atmosphere–surface interactions. Radio occultation investigations are even more valuable for planetary ionospheric studies than for planetary atmospheric studies—indeed, they have provided almost all measurements of planetary ionospheres.

However, the expertise necessary to obtain useful information about planetary environments from the recorded frequency measurements has not been widely disseminated across the scientific community in the 50 years since these skills were first developed.

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With one exception, merely two institutions, the NASA Jet Propulsion Laboratory (JPL) and Stanford, have provided the Principal Investigators or Team Leaders for every NASA planetary radio occultation investigation (see list of investigations and personnel at http://nssdc.gsfc.nasa.gov/planetary/ for each mission). The exception occurred when Dick French of Wellesley College replaced Arv Kliore of JPL as Principal Investigator of the Cassini Radio Science Subsystem some time after completion of Cassini's nominal mission. These two institutions have also provided most of the team members with instrumentation, operations, or data processing expertise (as opposed to scientific analysis of derived atmospheric and ionospheric properties). This localization of expertise was identified as a potential concern in the 1970s when Nicholson and Muhleman (1978) stated that "such an important experiment should be subject to independent confirmation, both to determine the reproducibility of the results and to check for systematic errors." They successfully reproduced the reported results of the Mariner 10 radio occultation investigation. Expertise also exists in Europe, where groups from Cologne and Munich lead radio science investigations on Rosetta, Mars Express, and Venus Express (Pätzold et al., 2004, 2007; Häusler et al., 2006); Japan, where the Sakigake, Nozomi, Selene, and Akatsuki spacecraft carried radio occultation investigations (Oyama et al., 2001; Noguchi et al., 2002; Imamura et al., 2011, 2012); and China (Hu et al., 2010). Several groups also possess related expertise concerning radio occultations of Earth's atmosphere and ionosphere (e.g. Kursinski et al., 1997, 2000; Anthes et al., 2008).

Consequently, radio occultation investigations are often viewed by the planetary science community as an esoteric speciality. Hands-on analysis of all radio occultation data products that precede the final vertical profiles of neutral atmospheric and ionospheric properties has been conducted by only a small subset of those using these final products. It is clearly detrimental to the advancement of planetary science for the vast majority of the users of these data sets to have such limited awareness of the preceding data processing steps. For instance, such users are hard-pressed to critically evaluate whether an unusual feature in the final data products is an exciting scientific discovery or an instrumental glitch. Another consequence is that atmospheric and ionospheric profiles that were not comprehensively archived by the original investigators are effectively lost, since barely any scientists interested in analyzing these profiles have the skills necessary to recover them. This is not merely a hypothetical concern: the atmospheric and ionospheric profiles acquired by missions as significant as Pioneer Venus Orbiter, the Voyagers, and the Viking Orbiters are not archived. Images of some of these profiles may be present, in cramped and cropped formats, in published articles, but today's scientists are unable to work meaningfully with these profiles. If the size of the community capable of obtaining such profiles from raw radio occultation data were to increase, then some of these past data sets could be regenerated and the chances of current and future data sets suffering a similar fate would diminish.

Our aim in this paper is to make this arcane skill more readily accessible to the broader scientific community. Although the theory of how to process radio occultation data has been presented in several publications, it is exceedingly challenging to create a functional radio occultation processing tool from the scientific literature without mentoring from an expert. Many issues important for practical implementation are stated either implicitly or not at all. Here we describe how to implement one of the key steps in the processing of radio occultation data: the determination of vertical profiles of atmospheric properties from time series of "frequency residuals". As will be explained in more detail in Section 3, the frequency residual is the difference between the frequency of the received radio signal and the frequency it would have had in the absence of refraction in the atmosphere and ionosphere of the solar system object that is the target of the occultation. The frequency residual is intimately associated with the number densities of neutral gas and ionospheric plasma around the target object. The software programs that were developed in the course of writing this paper accompany this publication, and we hope these programs in the IDL programming language will encourage many readers to work more closely with radio occultation data sets.

There are many types of radio occultation experiments and here we focus on the simplest example: a one-way, single frequency downlink experiment with a transmitter that has a stable frequency source and a target object whose atmosphere and ionosphere can be assumed to be spherically symmetric. Mars Global Surveyor is representative of this type of radio occultation experiment. We focus on this simple type because it offers the clearest possible framework for establishing and illustrating the practical principles of a radio occultation experiment. We discuss the numerous limitations that arise from this decision in Section 5. It is hoped that this will be the first of a series of papers concerning how to process radio occultation data in which the future papers will present more sophisticated tools developed from the present work that are suitable for more complex radio occultation experiments.

Detailed knowledge of the positions and velocities of solar system objects, both natural and artificial, as functions of time is required for the interpretation of radio occultation observations. The JPL SPICE system provides a remarkably straightforward, yet powerful, tool for obtaining and manipulating such information (http://naif.jpl.nasa.gov). Our software makes extensive use of SPICE and it is painful to imagine how radio occultation data processing would be accomplished without a tool like SPICE.

Section 2 explains why the angle by which a radio ray is bent is useful. Section 3 describes how to derive vertical profiles of ray bending angles from time series of frequency residuals. It presents the basic requirements (Section 3.1), explains how the relativistic Doppler shift alters the radio frequency (Section 3.2), introduces the concept of the frequency residual (Section 3.3), and links the frequency residual to the bending angle (Sections 3.4–3.7). Section 4 applies this method to a sample of Mars Global Surveyor data from Mars, including the transformation of bending angles into vertical profiles of refractive index, ionospheric electron density, neutral density, pressure, and temperature. These results are validated against archived results. Section 5 discusses the many limitations of our method, which is less sophisticated than the state-of-the-art tools used by active flight missions. Section 6 presents the conclusions of this work.

2. Why bending angles are useful

The objective of a radio occultation is to obtain scientifically useful information about the environment through which a radio signal has propagated by analysis of properties of that radio signal. The primary environmental property that is usually determined is the refractive index. In geometric optics, the direction of propagation of a ray depends on the refractive index, n, as follows (Born and Wolf, 1959):

$$\frac{d}{dl}(n\underline{\hat{l}}) = \underline{\nabla} n \quad (1)$$

Here unit vector $\underline{\hat{l}}$ is the direction of propagation of the ray. Consequently, the path of a radio ray bends as it passes through an atmosphere or ionosphere, except for the unlikely case of radio transmission through a medium in which the gradient of refractive index is parallel to the direction of propagation. The total angle by