Bending angle retrieval algorithms using COSMIC mission observations

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1. Introduction

COSMIC Data Analysis & Archive Centre (CDAAC) provides post-processed and real time data and derived products such as, raw GPS and orbit determination data, and neutral atmosphere and ionosphere observation files. The scientific foundation of the Constellation Observing System for Meteorology, Ionosphere & Climate (COSMIC) is the Radio Occultation (RO) (limb sounding) technique used to study planetary atmospheres. RO involves tracking of L1 and L2 pseudo-range and carrier phase data transmitted from Global Positioning System (GPS) satellites using receivers on Low Earth Orbiting (LEO) satellites (e.g. CHAMP, GRACE and COSMIC). RO takes place in the occultation plane, which is defined by the two position vectors to GPS and LEO satellites with respect to a geocentric coordinate system. Satellite RO observation data are primarily used for retrieving atmospheric parameters such as, atmospheric temperature, pressure and relative humidity for weather, climate, and space weather research and forecasting, but also for applications in geodesy and gravity research (*Hajj, et al.,* 2002). The ultimate objective of this study is to investigate the impact of higher order ionosphere contributions to the retrieval of atmospheric refractivity. We employ COSMIC raw excess phase delays as well as GPS and COSMIC position and velocity vectors.

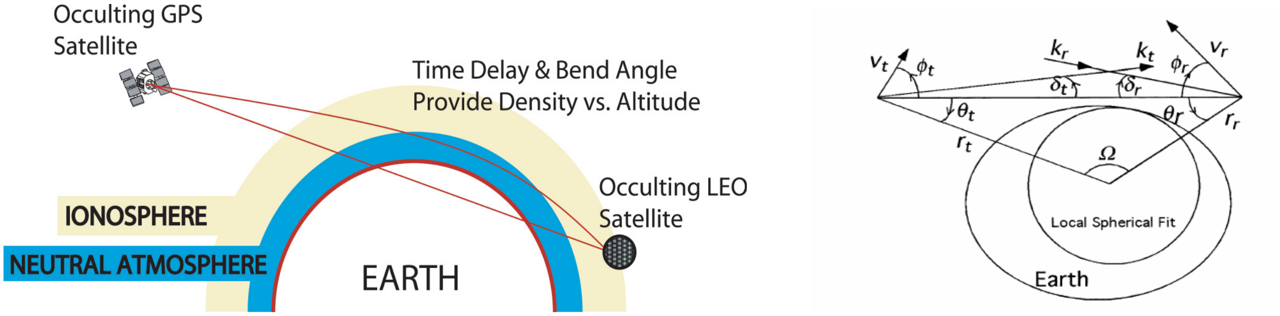


Fig. 1. *Schematic of radio occultation geometry. Signal (red line) transmitted by the occulting GPS and received by the LEO satellite is refracted by the neutral atmosphere (in blue) and the ionosphere (in yellow) (left graph) (courtesy of ©2008 UCAR). Occultation geometry defining the velocity and position vectors and the angles involved (right graph)*

2. Method

In previous work (e.g., *Hajj, et al.,* 2002), the GPS-LEO occultation technique has been described, from which bending angle profiles can be calculated. Figure 2 demonstrates step-by-step the procedure followed by the CDAAC team to calculate bending angle profiles. We adopt their approach to model and present preliminary results using near real-time observational data from the COSMIC mission in 2008. The first step is to understand how the RO works.

Initially, the L1 and L2 excess Doppler frequency shifts are obtained by differentiating consecutive measured excess phase delays divided by the time between the measurements (Fig. 2; left-side boxes). Next, the satellite elevation angles, and the velocity projections on the occultation plane of both LEO and GPS satellites are calculated given their velocity and position vector components in the X, Y and Z directions in the Geocentric Celestial Reference System (GCRS) (Fig. 2; middle boxes).

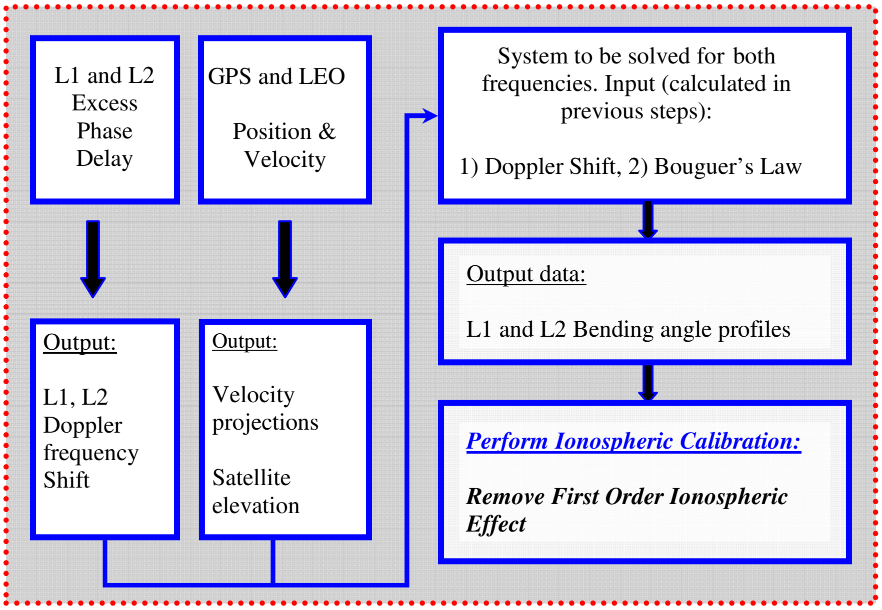


Fig. 2. *Methodology followed for the calculation of L1 and L2 bending angle profiles. Blue-Italic-bold text indicates the research area of our focus.*

The output products of the previous steps are used as input parameters in a non-homogeneous, non-linear system of equations given in Hajj et. al., (2002) for the estimation of L1 and L2 bending angle profiles. The system to be solved consists of two equations: a) the Doppler frequency shift and b) Snell's Law for spherical media (Bouguer's formula) (Fig. 2; top, right-side box), as shown below:

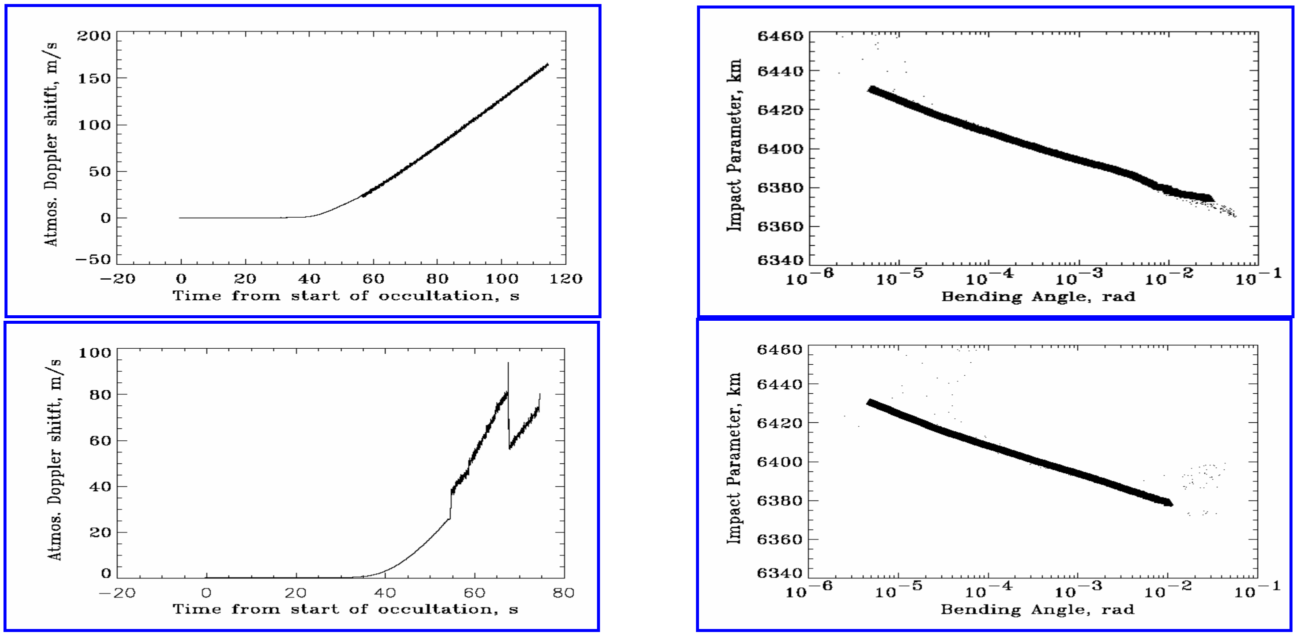
$$\frac{d\gamma}{dt} = \left(v_t \cos(\varphi_t - \delta_t) - v_r \cos(\varphi_r - \delta_r)\right) - \left(v_t \cos\varphi_t - v_r \cos\varphi_r\right),$$

$$r_t n_t \sin(\theta_t + \delta_t) = r_r n_r \sin(\theta_r + \delta_r),$$

where $d\gamma/dt$ is the excess atmospheric Doppler shift derived by differencing the Doppler shift observed in the presence of the atmosphere and the Doppler shift that would be observed for the same transmitter-receiver geometry in the absence of the atmosphere. The velocity and position vectors of both GPS and LEO satellites as well as the angles involved are shown in Fig. 1 (right-graph). The angles δ_t, δ_r are determined by simultaneously solving the system of the two equations above using Newton's method, and the bending angle is $\alpha = \delta_t + \delta_r$. The first order ionospheric correction can be realized through a linear combination of the derived bending angle profiles (e.g. *Kursinski, et al.,* 2000, *Hajj, et al.,* 2002). Although first order ionospheric corrections can account for the major part of the ionosphere, residual terms of higher order still affect the results and their significance is mentioned briefly in the conclusions.

3. Preliminary results and discussion

The excess atmospheric Doppler shift on the occulted signals between COSMIC – GPS16 starting at 2008/03/06 – 00:04 UT and COSMIC – GPS03 starting at 2006/04/21 – 19:19 UT are shown in Fig. 3. Figure 3 (left graphs) demonstrates the linear relationship between atmospheric Doppler and occultation time, peaking at about 160 m/s and 65 m/s, respectively. These case studies aim at demonstrating the effect of Doppler shift "jump" which sometimes is observed in the COSMIC measurement datasets. Figure 3 (left graphs; bottom) presents a case of a 25m/s "jump" in the Doppler shift during the 55 and 65s of the occultation (case of COSMIC – GPS03), which may be attributed to GPS signal loss (*Hajj et. al.,* 2002). The COSMIC – GPS16 case study appears to be following a linear relationship from the beginning until the end of the occultation. Figure 3 (right graphs) shows the comparison between the derived bending angles (dots) and the observation data (solid line). The asymptotic miss distance - defined as the closest distance of the signal-ray from the centre of the Earth - is plotted against the bending angle (*rad*) in a linear-log graph to demonstrate their exponential relationship. Our calculations show very good agreement with the observations below the 6,430km asymptotic miss distance. Above 6,430km, (upper stratosphere/lower mesosphere) the GPS signal has to be corrected for higher order ionospheric terms to achieve better agreement. The small perturbations on the atmospheric Doppler (Fig. 3, left graph) after 55s, are responsible for the scattered behaviour of the bending angle profile.



***<u>Fig. 3</u>**. Atmospheric Doppler shift (left graphs). Bending angle profile as a function of the asymptote miss distance (right graphs); the thick-solid-black line represents COSMIC observational data, and the dotted-grey line shows the retrieved bending angles.*

It is worth mentioning that the retrieved bending angle profiles examined in this paper show a "jump" in the lower part of the atmosphere (below ~6,385km) similar to the "jump" shown in the Doppler shift. However, this behaviour is not shown in the results presented by the CDAAC team. Instead, the CDAAC bending angle profile seems to follow a rather exponential behaviour. Numerous COSMIC observational datasets (not shown here) have been processed showing a slight disagreement both, in the altitude and the number of observation points (see Fig. 3; left panel) The altitude difference may be attributed to a coordinate transformation from the Geocentric Celestial Reference System (GCRS) to the Earth Fixed reference frame, and to the ellipsoidal shape of the Earth, which still need to be implemented in our method. The difference, however, in the number of the observation points can be attributed to the CDAAC using constraints on the bending angle profiles to an exponential climatological model rejecting those observations that do not meet certain criteria; a speculation which seems to be supported by the results presented in Fig. 3 (bottom left).

4. Conclusions

It has been suggested that higher order ionospheric terms can enable more accurate positioning of LEO using line-of-sight carrier-phase measurements (e.g. *Hoque and Jakowski,* 2007) and hence, more accurate bending angle estimation. On these grounds, focus is currently being placed on developing a technique for the removal of second order ionospheric effects. The Earth's magnetic field is being introduced into the mathematical formalism of higher order ionospheric terms, which we now have to account for. The results produced with our technique will be compared against COSMIC observational data for validation purposes. Upon achieving higher precision by accounting second order ionospheric terms, this research will provide the basis for a new data set of atmospheric parameters.

References

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