The International Beacon Satellite Symposium *BSS2010*
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Campus Nord UPC, Barcelona, 2010

IMPROVEMENT AND VALIDATION OF RETRIEVED FORMOSAT-3/COSMIC ELECTRON DENSITIES USING JICAMARCA DPS

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Key words: FORMOSAT-3/COSMIC, radio occultation, Jicamarca DPS, ionosphere, electron density profile, topside.

Summary: In this study, the improved Abel transform inversion technique is used to analyze derived ionospheric electron density profiles for the whole year 2007 in a very ionospherically disturbed scenario: the neighbouring area of Jicamarca (79.9º*W*, 12º*S*, dip latitude: 1º*N*), Perú, located at very low latitude and close to the geomagnetic equator. Moreover, the comparison of different strategies to account for the topside electron content in the occultation data inversion are compared and discussed, talking advantage of the availability of FORMOSAT-3/COSMIC datasets and manually calibrated measurements from Jicamarca DPS.

1 INTRODUCTION

Inversion techniques applied to GPS-LEO radio occultation data allow the retrieval of accurate and worldwide-distributed refractivity profiles, which, in the case of ionosphere, can be converted into electron densities providing information regarding the electron content distribution in this atmospheric region. In order to guarantee the accuracy of the electron density retrievals, two key points should be taken into account, such as the horizontal gradients of the electronic distribution and, the topside electron content above the LEO orbit. This would allow improving the accuracy from 20 to 50%, depending on the latitude and the epoch regarding to the Solar cycle as reported in previous works.

The new work presented is focused in the analysis of previously studied occultation techniques based on FORMOSAT-3/COSMIC excess Doppler in a very hard ionospheric scenario: the neighbouring area of Jicamarca, located at (76.9ºW, 12ºS, dip latitude: 1ºN), hence exposed to fast variable ionospheric conditions due to its proximity to the geomagnetic equator.

2 INVERSION METHOD

In this paper, electron density profiles have been computed by precise refractivity values retrieved from measured bending angles derived from the observed excess Doppler frequency shifts in $L1$ (see [Hajj and Romans (1998)] and [Schreiner et $al.$(1999)]) in occulting scenarios. The basic observable needed is the phase change, called the Doppler shift:

$$f_d = \frac{d}{dt}(L - |\vec{r}_{LEO} - \vec{r}_{GPS}|) \qquad (1)$$

where L stands for $L1$ carrier phase observable, r_{LEO} and r_{GPS} for the LEO and GPS position respectively. The Doppler shift at both the transmitter and the receiver is produced by the atmospheric and ionospheric refraction index change, after subtracting the velocities of both, transmitter and receiver, projected along the actual signal propagation directions. In order to compute accurate radio occultation inversions, the clock drifts of the GPS transmitter and receiver clocks should be removed from the raw phase data in order to solve the bending angles derived from the Doppler $L1$ phase excess.

2.1 The classical Abel inversion

In a spherical symmetric medium, the bending of the signal can be related to the index of refraction by means of the following integral:

$$\alpha(a) = -2a\int_0^\infty \frac{1}{\sqrt{a'^2 - a^2}}\frac{dln(n)}{da'}da' \qquad (2)$$

where α stands for the bending angle, a for the impact parameter and n, the refractive index. By using an Able integral transform, Ep. 2 can be inverted (see [Tricomi(1985)]), obtaining the refraction index as a function of the impact parameter a:

$$\ln(n(a)) = -\frac{1}{\pi}\int_a^{\infty} \frac{\alpha(a^{'})}{\sqrt{a^{'2}-a^2}} da^{'} \quad (3)$$

The upper limit of the integral in Eq. 3 requires the knowledge of the bending α up to the furthest limits of the atmosphere. For practical reasons, the bending angles above the LEO position can either be neglected somehow extrapolated or replaced by a climatological model ([Schreiner et *al*.(1999)]). As a first approach, this integral is solved up to the LEO height, neglecting the contribution of the bendings angles above LEO orbit.

2.2 The improved Abel inversion

The classical Able inversion mainly presents two mismodelings, such as the *spherical symmetry* assumption and the neglection of the topside electron content contribution. The former can be mitigated by means of the *separabiliy concept*. The latter is going to be discussed in next section. It is believed that the dominant error is due to the spherical symmetry assumption imposed on the ionosphere.

The *separabitity concept* can be integrated in the inversion procedure by considering not only the radial component dependence but also longitude and latitude in the density calculation [Hernández-Pajares et *al*.(2000)]. Indeed, when considering the latitudinal and longitudinal variation of VTEC into the electron density, the quality of the retrieved electron density profiles is improved. The benefits of implementing the separability hypothesis to bending angles were already stated with respect to actual ionosonde data (see [Aragon-Angel et *al*.(2009)]). These comparisons confirmed a global improvement in the critical frequency estimations of the *F*2 peak of 45% in Solar Minimum. Whereas in the E layer, the improvement in electron density estimates reaches up to 32%.

3 UPPER IONOSPHERIC CONTRIBUTION

In this section, the contribution of the electron content above the LEO orbit in the inversion process is tackled. One first approximation to the problem is to consider that there is no significant electron content above the LEO orbit. For the case of working with the excess Doppler observable as main input, this implies that the gradient of the refractive index above the LEO position remains constant and, we equals to one at the LEO and GPS heights. Although this issue may not be critical for LEOs with nominal orbits above 700 km, it is a crucial point to be considered with lower earth orbiters. For instance, within the FORMOSAT-3/COSMIC constellation, not all six satellites have been at the same nominal altitude at all times, since, after the launching, some of them remained in a parking orbit while the others were reaching their final destination orbit at about 800 km. Thus the lower the LEO altitude, the bigger the mismodeling error introduced. In the followings sections, two approaches to overcome this issue are going to be proposed: firstly, the usage of climatological model, and secondly, an exponential decay.

Considering the actual geometry and epoch of the occultations (i.e. real line-of-sights), the NeQuick model is run for the upper observation (the one corresponding to the high-test impact parameter) and the electron density for such point is obtained. Once this initial value is calculated, the inversion is performed by means of both, classical Abel and Improved Abel inversions and the global profile of electron density is retrieved. The peak of the electron density (i.e. N_mF2) and its corresponding height (i.e. h_mF2) are extracted from these new preofiles and compared with the co-located values provided by Jicamarca. Another approach would be performing an exponential extrapolation of the profile as done in [Hernández-Pajares et *al*.(2000)] or, alternatively, in the data as in [Hajj and Romans, (1998)]. According to [Schreiner et *al*.(1999)] this approach of exponential extrapolation is more appropriate than the use of a climatological model.

4 EXPERIMENT

In order to assess the accuracy of the FORMOSAT-3/COSMIC electron density retrieval by means of the proposed extrapolation schemes, the critical frequency estimates of the *F*2 peak, *foF*2, and their corresponding heights, h_mF2, from FORMOSAT-3/COSMIC occultation observations are going to be compared with a low-latitude digisonde located at Jicamarca, Perú (76.9º*W*, 12º*S*, dip latitude: 1º*N*). In previous works, it has been shown that ionosonde measurements can become a reliable source of accurate estimates of the critical plasma frequency from ionogram analysis ([Paul and Mackinson (1981)]). In this sense, consistently scaled and well-calibrated Digisonde Portable Sounder (DPS) measurements at Jicamarca were available for the whole year 2007 with a sample rate of fifteen minutes. This high quality real data offers a valuable possibility to perform the proof of concept and the comparison of the inverted electron density profiles using the presented approaches for the upper ionosphere estimation. Moreover, there is a small co-location error with respect location since the ionospheric profiles from Jicamarca DPS have been compared with extremely close co-located FORMOSAT-3/COSMIC profiles: only when the tangent point of the FORMOSAT-3/COSMIC profiles is located in the range of 9 – 15º*S* and 73.9 – 79.9º*W*, then the FORMOSAT-3/COSMIC profiles is selected to be compared with the corresponding digisonde profile. Regarding temporal co-location, a time span of 15 minutes has been considered around the RO time of occurrence to allow comparisons with Jicamarca DPS measurements. The experiment data correspond to one whole year period: 2007. Radio occultation data from GPS-FORMOSAT-3/COSMIC satellites were processed with classical

Abel and Improved Abel inversions, the latter with the aid of the global VTEC maps computed and distributed by the Technical University of Catalonia (UPC) is IONEX format.

5 CONCLUSIONS

Under very stric co-location criteria around Jicamarca DPS location, an exhaustive comparision in a difficult ionospheric scenario of the classical Abel and the Improved Abel inversion has been carried out, showing that the separability concept can help to correct the error due to the spherical symmetry assumption used in the classical Abel inversion by assuming the horizontal inhomogeneity of the electron densities being dependent on longitude and latitude similarly to VTEC. Two schemes to account for the upper electron content have been implemented to both, classical and improved Able inversions.

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