Space geodetic techniques for remote sensing the ionosphere

Mahdi ALIZADEH^{1}, Harald SCHUH^{1,2}, Jens WICKERT^{2}, Christina ARRAS^{2}

$^{1)}$ Technische Universität Berlin,

Strasse des 17.Juni 135, 10623 Berlin, Germany

$^{2)}$ German Research Centre for Geoscience (GFZ)

Telegrafenberg A17, 14473 Potsdam, Germany

ABSTRACT

Space geodetic techniques, such as Very Long Baseline Interferometry (VLBI), Global Navigation Satellite Systems (GNSS), satellite altimetry missions, and Low Earth Orbiting (LEO) satellites have contributed extensively to remote sensing and modeling of the ionosphere in the last decade. VLBI is a differential space geodetic technique which is capable of deriving absolute ionosphere parameters, i.e. Vertical Total Electron Content (VTEC) for each station. GNSS Dual-frequency observations have played a classical role for development of Global Ionosphere Maps (GIM). GIM are developed using the GNSS ionospheric observable L4 or the so-called geometry-free linear combination of simultaneous observations at two carriers L1 and L2. Nevertheless, when studying the ionosphere globally, the fact that GNSS stations are in-homogeneously distributed around the world, with large gaps particularly over the oceans should be taken into account; this fact reduces the precision and reliability of the GIM over these areas. On the other hand, dual-frequency satellite altimetry missions provide information about the ionosphere precisely above the oceans; and furthermore GNSS Radio Occultation (RO) measurements aboard LEO (Low Earth Orbiting) satellites provide great number of globally distributed information of the ionosphere. An important contribution of the GNSS RO data is the provision of vertical information on the electron density distribution. Therefore, this technique can also be used for the investigation of the layered structure of the ionosphere. Prominent examples are detailed studies of vertically thin ionospheric phenomena, like sporadic E layers. All in all, combining different space geodetic techniques for developing the ionospheric maps would significantly improve the accuracy and reliability of the developed model, as the combined model uses the advantages of each particular method and provides a more accurate result than the result from each single technique. This paper presents a general overview of the ionospheric investigations using the space geodetic techniques.

1. Introduction

Free electrons and ions within the ionosphere affect the propagation of the electromagnetic waves travelling through this medium. For space geodetic techniques, operating in microwave band, ionosphere is a dispersive medium; therefore in the first approximation signals are affected proportional to square of their frequencies. This effect is known as the ionospheric refraction. The ionosphere refraction can be determined in terms of Slant Total Electron Content (STEC), which is the integral of electron density along the signal path *s*.

$$STEC = \int N_e(s)ds \quad , \qquad (1)$$

Where N_e is the electron density along the line of sight (*ds*).

This quantity can be interpreted as the total amount of free electrons in a cylinder with a cross section of 1 m^2 and axis the signal path. Total Electron Content (TEC) is measured in Total Electron Content Units (TECU), with 1 TECU equivalent to 10^{16} electrons/m^2.Observing at two different radio frequencies allows the elimination of the ionospheric influence on the propagation of the signals of geodetic techniques. This on the other hand provides information about the ionosphere parameters. If the behavior of ionosphere is known, the ionospheric refraction can be computed via equation below

$$\vartheta = \frac{40.31 \cdot 10^{16}}{f^2} \qquad [\mathrm{m/TECU}] \quad . \qquad (2)$$

The ionospheric refraction can be used for development of regional and global models of the ionosphere. Different observation principles result in specific features of the ionosphere parameters derived by each of the techniques. Some of the space geodetic missions providing such information are briefly discussed in the following sections.

2. Probing the ionosphere by means of VLBI

Very Long Baseline Interferometry (VLBI) is a unique technique for calculation of Celestial Reference Frame (CRF), Celestial Pole, UT1 and UTC. It is also a primary technique for estimating Earth Orientation Parameters (EOP) and Terrestrial Reference Frame (TRF). VLBI observations are currently carried out in two different frequency bands, X- and S-band. Therefore it is possible to derive absolute ionosphere parameters using VLBI technique, i.e. VTEC for each station. As shown by Hobiger et al. (2006) VTEC values can be determined similar as troposphere parameters. By taking advantage of the fact that the slant ionosphere delays are elevation dependent and can be described by an empirical mapping function. Thus VTEC values can be estimated for each station and constant instrumental delays can be separated from these parameters within the adjustment process. A drawback of using VLBI for the estimation of ionosphere parameters is the need of a mathematical relation between VTEC above the site and VTEC of each observation as described in *Hobiger [2005]* or *Hobiger et al. [2006]*. Moreover, as VLBI provides only a single scan per epoch and station, it is important that mapping function errors are reduced to a minimum in order to obtain unbiased VTEC estimates. *Dettmering et al. [2011a]* carried out a thorough investigation of systematic differences between VTEC obtained by different space-geodetic techniques including VLBI by applying the estimation strategy proposed by *Hobiger et al. [2006]*. Thereby it is concluded that VLBI derived ionosphere parameters are comparable to other space geodetic techniques, like GPS, DORIS, Jason and F3C concerning the accuracy of the estimation. Moreover, the mean biases found in that study are similar to those given in *Hobiger et al. [2006]* being in the range of a few TECU.

3. Combining various space geodetic techniques for global modeling of VTEC

Due to the fact that most of the space geodetic techniques operate in at least two different frequencies, they are capable of eliminating the influence of the ionosphere. This capability provides the ability to obtain information about the ionospheric parameters. Different observation principles result in specific features of the ionosphere parameters derived by each of the techniques. Some of these techniques are:

3.1. GNSS

Global Navigation Satellite Systems (GNSS) including the USA GPS, Russian GLONASS, Chinese COMPASS and the upcoming European GALILEO allow determination of station specific ionosphere parameters in terms of STEC values from carrier phase or code measurements. By applying the geometry-free linear combination *L4* on the double-frequency observations, the obtained data contains only the ionosphere refraction plus the ambiguity parameter in the phase case and the satellite and receiver hardware delays *[Schaer, 1999]*.

3.2. Satellite altimetry

Satellite altimetry missions with double-frequency radar altimeter on-board can derive information about the ionosphere. These missions operate at 13.6 GHz (Ku-band) and 5.3 GHz (C-band) simultaneously, and perform only over the sea surface. The main information is the altimeter height of the satellite above the sea (satellite range); the observations made at the two frequencies also allow gaining ionosphere correction *[Imel, 1994]*. As the measurements are normal to the sea surface, Vertical TEC (VTEC) is directly provided *[Todorova, 2008]*.

3.3. LEO satellites

Low Earth Orbiting (LEO) satellites operate at orbital altitudes between 500 and 2000 km and one of their primary science objectives is global sounding of the vertical layers of the neutral atmosphere and the ionosphere. Mission CHAMP (launched in 2000) and the follow-up missions GRACE (2001) and GOCE (2009) are equipped with ion drift meters and magnetometers, in order to study the solar terrestrial environment. However, the most important issue of the LEOs concerning ionosphere modeling is the opportunity for global monitoring of the electron density distribution by using GPS radio occultation [*Jakowski et al., 2004*]. One of the primary goals of the spacecraft SAC-C (2000) and Formosat3/COSMIC (F3/C) (2006) is obtaining vertical profiles in near real-time of the electron density through GPS radio occultation technique. The principle of the radio occultation is the measurement of the refractivity or bending of GPS signals slicing through the Earth's atmosphere and ionosphere, which provides information about the vertical variations through the entire ionosphere and gives the opportunity for developing four-dimensional ionosphere models - in latitude, longitude, time, and height.

3.4. Combination of different techniques

Although each of the above mentioned techniques is capable of providing information about the ionosphere, each technique has its pros and cons depending on its characteristics. The classical input data for development of Global Ionosphere Maps (GIM) are obtained from dual-frequency observations carried out at GNSS ground stations. However, GNSS stations are in-homogeneously distributed around the world, with large gaps particularly over the oceans; this fact reduces the precision of the GIM over these areas. On the other hand, dual-frequency satellite altimetry missions provide information about the ionosphere precisely above the oceans; and furthermore LEO satellites provide well-distributed information of ionosphere on globe. Combining different techniques for developing the ionospheric maps would significantly improve the accuracy and reliability of the developed model, as the combined model uses the advantages of each particular method and provides a more accurate result than from each single technique alone. To develop an integrated map of the ionosphere, the observation equation from each technique is formed and the combination is performed by stacking the normal equations of each individual technique. The developed maps are provided in 12 global maps per day, known as the GIM. The spatial resolution of the GIM is 2.5° in Latitude and 5° in Longitude and the temporal resolution is 2hours. In addition to the VTEC GIM, the corresponding Root Mean Square error (RMS) maps and daily values of the Differential Code Biases (DCB) for all the GNSS satellites and receivers are computed too. The final outputs are provided in the IONEX format [*Schaer et al. 1998*]. Figure 1 depicts 12 two-hourly maps of the GNSS-only solution for an example day, i.e. day 202 of 2007 [*Alizadeh et al. 2011*].

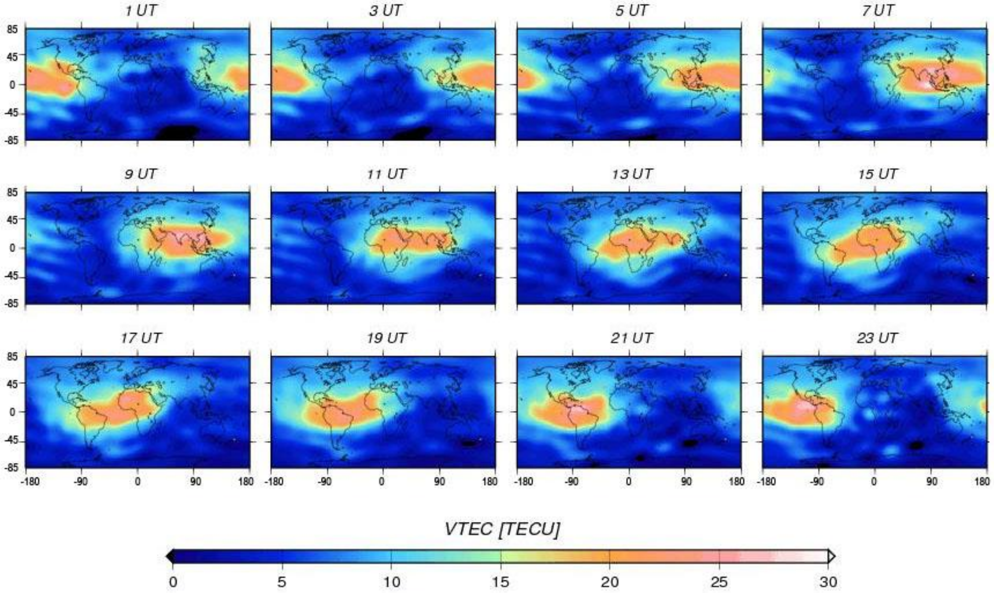

Figure 1 – GNSS-only VTEC map for the whole day 202, 2007 [*Alizadeh et al. 2011*]

Figure 2 depicts the VTEC and RMS map of GNSS and satellite altimetry combined GIM minus GNSS-only solution for day 188, 2006, 9:00 UT *[Todorova et al., 2007]*

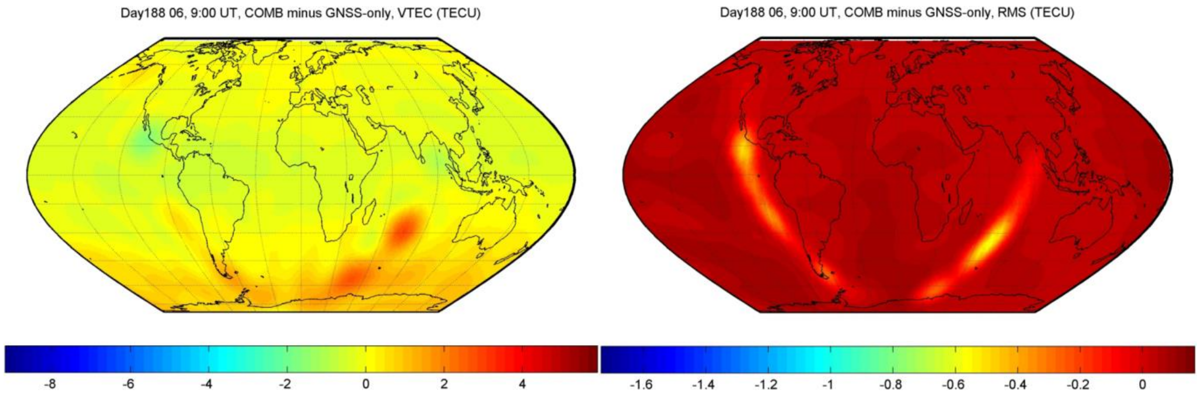

Figure 2 – (a) VTEC map **(b)** RMS map of GNSS and satellite altimetry combined <minus> GNSS-only solution, day 188, 2006, 9:00 UT *[Todorova et al., 2007]*

Figure 3 depicts a snap shot of difference between VTEC and RMS of GNSS, satellite altimetry, and F3/C combined GIM and GNSS and satellite altimetry combined GIM at 9 UT of day 202, 2007 *[Alizadeh et al. 2011]*. As it can be seen in Fig. 3a, the VTEC values have slightly reduced over the ocean in southern latitudes by the amount of about 1 TECU. This is mainly in regions where no or few GNSS observations are available. The RMS of the combined solution (Fig. 3b) shows a general reduction of about 0.1 TECU in the whole globe. This reduction is specifically obvious in the low southern latitudes, over the southern ocean where a decrease of about 0.5 TECU can be detected, proving the fact that combining F3/C measurements with our GIMs can significantly improve the accuracy of the modeling techniques, especially when a high number of F3/C occultation measurements are available *[Alizadeh et al. 2011]*.

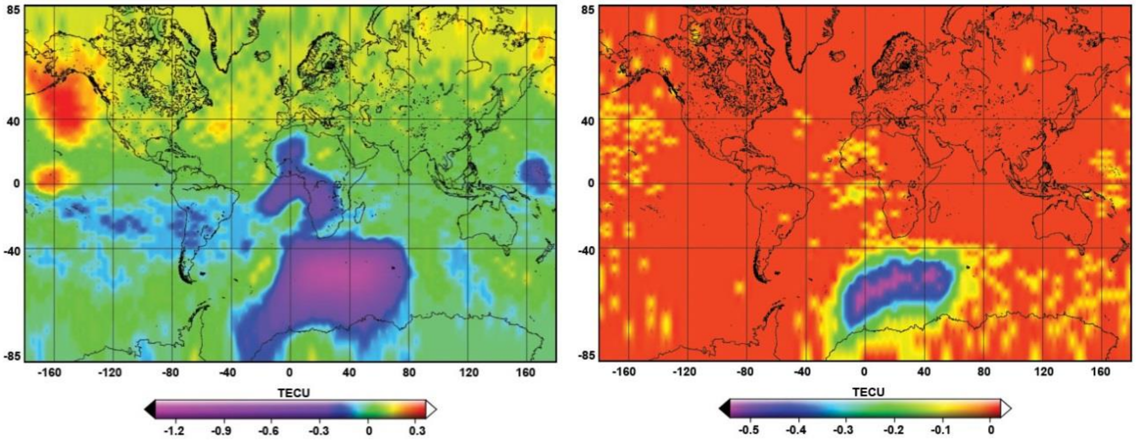

Figure 3 (a) VTEC and **(b)** RMS map of GNSS, satellite altimetry and COSMIC combined <minus> GNSS, satellite altimetry solution, day 202, 2007 - 9:00UT *[Alizadeh et al. 2011]*

4. Three-dimensional modeling of the ionosphere using GNSS

Due to the fact that 2D models of TEC provide information about the integral of the whole electron content along the vertical or slant ray-path, when information about the ionosphere at different altitudes is required, these maps are not useful; e.g. when electron density profile is required, or when satellite to satellite observation is being performed. Besides the geodetic applications, 3D modeling approach can include geophysical parameters like maximum electron density, and its corresponding height. High resolution modeling of these parameters, allow an improved geophysical interpretation. For these cases, a 3D modeling of the ionospheric parameters becomes necessary. To model the ionosphere in 3D we concentrate on modeling electron density in three dimensions, i.e. in longitude, latitude, and height. The classical GNSS TEC observable relates the electron density N_e to the smoothed code measurements

$$\tilde{P}_4 = \xi \int_R^S N_e(h)ds + c(\Delta b^S - \Delta b_R) + \varepsilon \quad . \tag{3}$$

Where $P^{\sim}_4$ is the smoothed code measurement, Ne(h) is the height-dependent electron density, Δb^S and Δb_R are the satellite and receiver DCBs respectively, and ε is the random noise. In this study we apply a combination of two different models for representation of Ne. A multi-layer Chapman function for the bottom-side and topside ionosphere and the TIP model *[Jakowski et al., 2002]* for the plasmasphere:

$$N_e(h) = NmF2.e^{\alpha(1-z-e^{-z})} + NmF2.e^{\beta(1-z-e^{-z})} + N_{P_0}.e^{-h/H_P} \quad , \qquad (4)$$

where

$$z(h, hmF2) = \frac{h - hmF2}{H_{TS}} \quad . \qquad (5)$$

In Eq. (4) and (5) NmF2 and hmF2 are the F2 maximum electron density and its corresponding height. H_{TS} is the ionosphere scale height. N_{P0} and H_P are the plasmasphere basis density and scale height; and α and β are constants. Substituting Eq. (4) and (5) into Eq. (3) yields our observation equation.

$$\begin{aligned} \tilde{P}_4 = \xi\Bigg(\int_R^{h_mF2} N_mF2 \;\, e^{(1 - z - e^{-z})} ds + \int_{h_mF2}^{h_{IonoTop}} N_mF2 \;\, e^{0.5(1 - z - e^{-z})} ds \\ + \int_{h_{IonoTop}}^{S} N_{P0} \;\, e^{(-h/H_P)} ds \Bigg) + c(\Delta b^S - \Delta b_R) + \varepsilon \; . \end{aligned} \qquad (6)$$

In Eq. (6) NmF2, hmF2, H_{TS}, N_{P0}, and H_P are our unknowns. Within this study, we concentrate only on the ionospheric parameters NmF2, hmF2, assuming H_{TS} and the plasmaspheric parameters as known.

To estimate NmF2 and hmF2 in globe, two sets of spherical harmonic expansions with a degree and order 15 are implemented; one for NmF2 and the other for hmF2. To estimate the coefficients of spherical harmonic expansions, ray-tracing technique is implemented in the upper atmosphere. Ray-tracing estimates the propagation of an electromagnetic wave through a medium. In contrary to the mapping function method, ray-tracing estimates the delays for any arbitrary slant direction. In the estimation procedure, due to the fact that GNSS observations are relatively insensitive to height variations, some constraints should be applied to avoid obtaining unrealistic large residuals. Figure 4 depicts the estimated NmF2 and hmF2 for a snapshot of [0-2]UT, day 182 of 2010 *[Alizadeh, 2013].*

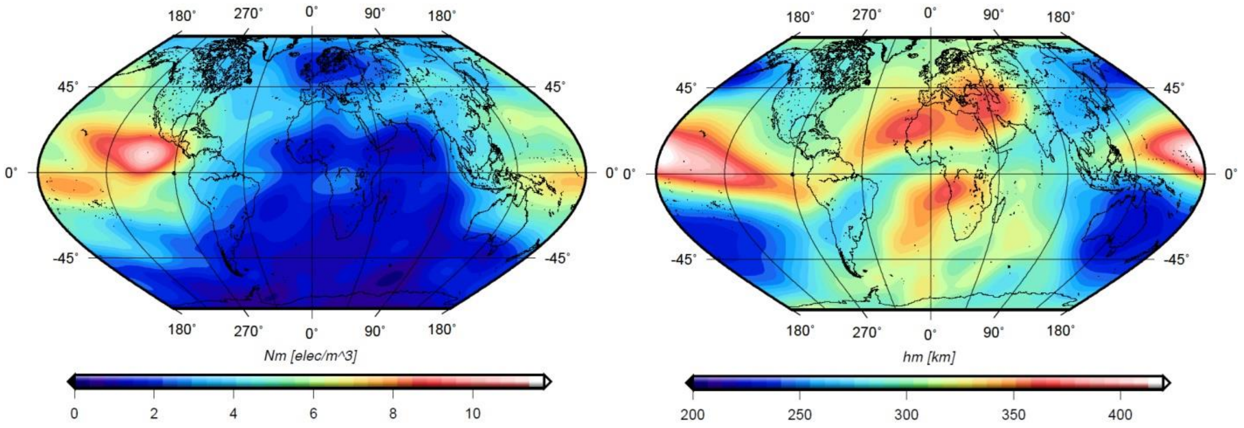

Figure 5 - (a) Estimated maximum electron density ($\times 10^{11}$ *elec/m*^{3}) and **(b)** estimated maximum electron density height (*km*) GNSS estimated model, doy 182, 2010 – [0,2]UT *[Alizadeh, 2013]*

5. Sporiadic E-layer from Radio Occultation

Sporiadic E-layers (E_s) are known as layered structures of enhanced electron density which appear sporadically in the altitude range between 90 and 120 km. They consist of a considerable amount of long-lived metallic ions *[Kopp, 1997; Williams et al., 2006]*, which are transported by wind fields, e.g., tides in the upper atmosphere. In the past decades E_s observations exist mostly from ground-based ionosonde and incoherent scatter radar measurements e.g. *[Whitehead, 1989; Mathews, 1998]*. In this study GPS radio occultation measurements from CHAMP, GRACE-A and F3/C are used to derive global information on small-scale ionospheric irregularities such as sporadic E layers between January 2002 and December 2007 *[Arras et al. 2013]*. The investigations are based on the analysis of amplitude variations of the GPS radio occultation signals. The global distribution of ionospheric irregularities shows strong seasonal variations with highest occurrence rates during summer in the middle latitudes. The long-term data set of CHAMP allows for first climatological studies, while the data coverage increases significantly with the combination of CHAMP, GRACE and F3/C measurements.

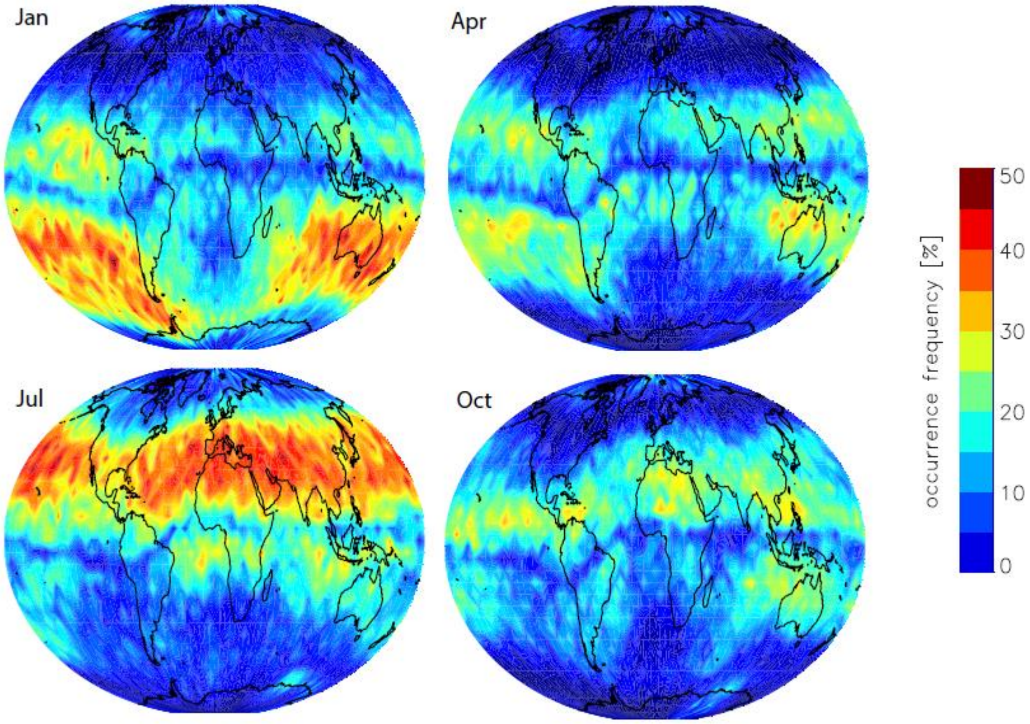

Figure 6 - Seasonal occurrence of E_s detected with CHAMP, GRACE and FORMOSAT-3/COSMIC with a resolution of 5° × 5°. Plots for the (top left) autumn (September, October, November) 2006 and (top right) winter (December, January, February) 2006/2007. Data from (bottom left) spring (March, April, May) 2007 and (bottom right) summer (June, July, August) 2007 *[Arras et al., 2013]*

6. References

Alizadeh M.M., Schuh H., Todorova S., Schmidt M., Global Ionosphere Maps of VTEC from GNSS, Satellite Altimetry and Formosat-3/COSMIC Data, Journal of Geodesy 85(12), 975-987, doi:10.1007/s00190-011-0449-z, 2011.

Alizadeh M.M., Multi-Dimensional modeling of the ionospheric parameters, using space geodetic techniques. PhD thesis, Vienna University of Technology, February 2013. Geowissenchaftliche Mitteilungen Heft Nr. 93, 2013, ISSN 1811-8380.

Alizadeh M.M., Schuh H., Schmidt M., Ray-tracing technique for global 3D modeling of ionospheric electron density, using GNSS measurements, paper submitted to Radio Science, April 2015.

Arras, C., Wickert, J., Jacobi, C., Heise, S., Beyerle, G., and Schmidt, T.: A global climatology of ionospheric irregularities derived from GPS radio occultation, Geophys. Res. Lett., 35, L14 809, doi:10.1029/2008GL034158, 2008.

Arras, C., Wickert, J., Jacobi, C., Beyerle, G., Heise, S., Schmidt, T. (2013): Global Sporadic E Layer Characteristics Obtained from GPS Radio Occultation Measurements. - In: Lübken, F.-J. (Ed.), Climate and weather of the sun-earth system (CAWSES): highlights from a priority program, (Springer Atmospheric Sciences), Springer, p. 207-222.

Dettmering D., R. Heinkelmann, and M. Schmidt. Systematic differences between VTEC obtained by different space-geodetic techniques during CONT08. J. Geod., 85:443–451, 2011a.

Hobiger T. VLBI as tool to probe the ionosphere. PhD thesis, Vienna University of Technology, Austria, 2005.

Hobiger T., Kondo T., Schuh H.: Very long baseline interferometry as a tool to probe the ionosphere. Radio Science, 41(1): RS1006, 2006. doi:10.1029/2005RS003297, 2006.
Imel D.A., Evaluation of the TOPEX/POSEIDON dual-frequency ionosphere correction. J. Geophys. Res., 99(12):24895 – 24906, 1994.

Jakowski N., I.S. Kutiev, S. Heise, and A. Wehrenpfennig, A topside ionosphere plasmasphere model for operational applications. In Proceeding of URSI XXVII General Assembly, pages 2174-2177, 2002.

Jakowski, N., Leitinger, R. and Angling, M. (2004). Radio occultation techniques for probing the ionosphere. Annals Of Geophysics, Supplement to Vol. 47, 1049 - 1066.

Kopp, E.*,* On the abundance of metal ions in the lower ionosphere*,* J. Geophys. Res.*,* 102*,* 9667–9674*,* 1997

Mathews, J. D.*,* Sporadic E: Current views and recent progress*,* J. Atmos. Sol. Terr. Phys.*,* 60*,* 413–435*, 1998.*

Schaer S., W. Gunter, and J. Feltens, Ionex: The ionosphere map exchange format version 1. In In J. M. Dow, J. Kouba, and T. Springer (Eds.), pages 233 - 247, Darmstadt, Germany, 1998. Proceeding of the IGS AC Workshop.

Schaer S., Mapping and predicting the Earth’s ionosphere using the Global Positioning System. PhD thesis, Bern University, Switzerland, 1999.

Todorova S., Schuh H., Hobiger T., Using the Global Navigation Satellite Systems and satellite altimetry for combined Global Ionosphere Maps. Advances in Space Research 42:727–736, 2007.

Todorova S., Combination of space geodetic techniques for global mapping of the ionosphere. PhD thesis, Vienna University of Technology, Austria, 2008.

Whitehead J., Recent work on mid-latitude and equatorial sporadic-E, J. Atmos. Terr. Phys., 51, 401–424, 1989.

Williams, B., C. Croskey, C. She, J. Mitchell, *and* R. Goldberg, Sporadic sodium and E layers observed during the summer 2002 MaCWAVE/MIDAS rocket campaign, Ann. Geophys., 24, 1257–1266, 2006.