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Analysis of the IMAGE RPI electron density data and CHAMP plasmasphere electron density reconstructions with focus on plasmasphere modelling

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Abstract

The electron density of the topside ionosphere and the plasmasphere contributes essentially to the overall Total Electron Content (TEC) budget affecting Global Navigation Satellite Systems (GNSS) signals. The plasmasphere can cause half or even more of the GNSS range error budget due to ionospheric propagation errors. This paper presents a comparative study of different plasmasphere and topside ionosphere data aiming at establishing an appropriate database for plasmasphere modelling. We analyze electron density profiles along the geomagnetic field lines derived from the Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) satellite/Radio Plasma Imager (RPI) records of remote plasma sounding with radio waves. We compare these RPI profiles with 2D reconstructions of the topside ionosphere and plasmasphere electron density derived from GNSS based TEC measurements onboard the Challenging Minisatellite Payload (CHAMP) satellite. Most of the coincidences between IMAGE profiles and CHAMP reconstructions are detected in the region with L-shell between 2 and 5. In general the CHAMP reconstructed electron densities are below the IMAGE profile densities, with median of the CHAMP minus IMAGE residuals around $-588\ cm^{-3}$. Additionally, a comparison is made with electron densities derived from passive radio wave RPI measurements onboard the IMAGE satellite. Over the available 2001–2005 period of IMAGE measurements, the considered combined data from the active and passive RPI operations cover the region within a latitude range of ±60°N, all longitudes, and an L-shell ranging from 1.2 to 15. In the coincidence regions (mainly $2 \leqslant L \leqslant 4$), we check the agreement between available active and passive RPI data. The comparison shows that the measurements are well correlated, with a median residual of $\sim 52\ cm^{-3}$. The RMS and STD values of the relative residuals are around 22% and 21% respectively. In summary, the results encourage the application of IMAGE RPI data for plasmasphere and plasmapause modeling.

Keywords: Plasmasphere; Ionosphere; IMAGE RPI profiles; CHAMP; Electron density; Total Electron Content

1. Introduction

The ionosphere is the ionized part of the upper atmosphere extending from about 50 up to 1000 km height. The plasma is mainly generated by ionizing solar radiation at wave lengths <130 nm. According to a suggestion by Appleton (1947) the vertical ionization profile may be considered as being composed of different layers (D, E, F1 and

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F2) depending on major height depending processes and resulting ionization level. The most ionized region of the ionosphere is the F2 layer. The topside ionosphere above the height of the F2 layer peak density changes smoothly into the plasmasphere at a transition height of about 1000 km height where the atomic oxygen and lighter proton densities are equal. The cold plasma of the plasmasphere consisting mainly of light protons, co-rotates with the Earth up the plasmapause height. Here a sharp plasma density gradient separates the dense co-rotating torus-like plasmasphere from the outer magnetosphere (e.g. Davies (1990) and Lemaire et al. (1998)).

Only limited data sources are available for studying the plasmasphere, and especially the plasmapause location. Low-power space-borne sounders traversing the whole plasmasphere region, such as the Radio Plasma Imager (RPI) instrument on the Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) satellite, are rare. During the 2001–2005 period of the IMAGE mission, the RPI instrument measured both close to spacecraft location and remotely sensed electron densities in the Earth's plasmasphere and magnetosphere by (a) observing the natural radio emissions along the orbit, (b) stimulating resonances in the ambient plasma at the spacecraft location, and (c) transmitting and receiving radar signals.

The field-aligned electron density profiles derived by means of radio sounding are of particular interest to our present study. The RPI instrument was the first instrument to observe radar echoes from remote plasma locations at distances up to 7 Earth radii (R_E) from the spacecraft where conditions for the specular signal reflection could be met (cf. Reinisch et al. (2001a); Benson et al. (2003, 2013); Section 2). In the RPI plasmagram mode operation, radio pulses with varying frequencies were transmitted and the signal travel times $\tau(f)$ were measured. From these measurements the virtual radar ranges $r'(f)$ to location the reflecting are calculated ($r' = 0.5\,c \cdot \tau$, where c is the speed of light). A computational procedure inverts the $r'(f)$ functions into the electron density functions along the magnetic field line intersecting the spacecraft (cf. Reinisch et al. (2001b), Huang et al. (2004)).

In addition to the remote sensing operation, the RPI conducted highly accurate plasma density measurements along the IMAGE satellite orbit, using a passive mode observation (cf. Webb et al. (2007), Denton et al. (2012), Gerzen et al. (2014)), and the relaxation sounding mode measuring characteristic resonance frequencies (cf. Benson et al. (2003)). The "sub-pixel" resolution analysis of the relaxation sounding data yields uncertainty of measured plasma frequency as low as 0.1 kHz. Both active and passive techniques determine in-situ plasma density values, though based on slightly different considerations: while the passive method detects the frequency band of the ambient thermal noise bound by the local upper hybrid resonance frequency, the active method triggers the plasma frequency f_{pe} resonance directly.

Dual-frequency Global Navigation Satellite Systems (GNSS) receivers on board of Low Earth Orbiting (LEO) satellites offer additional opportunity of ionospheric sounding, especially of the topside ionosphere and plasmasphere. The Global Positioning System (GPS) is one of these GNSS systems, and its signals were tracked onboard the LEO Challenging Minisatellite Payload (CHAMP), 2000–2010 (cf. Reigber et al. (2000)). At the German Aerospace Center (DLR), Neustrelitz, Germany, the GPS measurements recorded by CHAMP with its navigation antenna (looking from CHAMP up to the GPS satellites) were used to reconstruct the topside electron density distribution (ionosphere and plasmasphere) from CHAMP up to GPS altitude (cf. Heise et al. (2002)). To prove the suitability of these CHAMP topside reconstructions for advanced plasmasphere modelling and for analyzing space weather related changes in the geo-plasma, the accuracy of these data was closely investigated by Gerzen et al. (2014), focusing on the comparison of the CHAMP reconstruction results with the above mentioned electron density data derived from passive radio wave observations of the IMAGE RPI instrument for the years 2001–2005.

With the goal of establishing an appropriate database for topside ionosphere, plasmasphere, and plasmapause modelling, we have extended the evaluations performed in Gerzen et al. (2014). In the present paper a comparative study of all above mentioned sources of plasmasphere and topside ionosphere data is conducted. We analyzed the IMAGE electron density profiles and compared them with the CHAMP GPS data derived reconstructions and with in-situ IMAGE electron densities for the years 2001–2005. In addition, the availability and data coverage provided by the IMAGE RPI active and passive data are briefly discussed.

The current paper is set up as follows: Details about the IMAGE data are described in Section 2. For details about the CHAMP electron density reconstructions and passive IMAGE data, reference is made to Gerzen et al. (2014). Section 3 explains the data comparison technique. Explicitly addressed are our approach on how to make this different data types comparable, the coincidence criteria, and an approach for the coincidence analysis. Section 4 presents the results and is divided into three parts: The first part investigates the comparison of the IMAGE profiles with the CHAMP reconstructions, the second part the comparison of the IMAGE active with IMAGE passive data, and the third part the analysis of both IMAGE active and passive data in terms of availability, data coverage and dependencies. Section 5 summarizes the main conclusions of this study. Finally, Appendix A shows a computation time optimized variant of algorithms used in Section 3.1, which might be helpful for similar applications.