EMPIRICAL MODELS OF THE PLASMA DENSITY IN THE PLASMASPHERE AND POLAR CAP[1]

Xueqin Huang(1)***, Bodo W. Reinisch***(2)***, Paul Song***(3)***, Gary S. Sales***(4)***, Patrick Nsumei***(5)***, James L. Green***(6)***, Robert F. Benson***(7)***, Shing Fung***(8)***, Dennis L. Gallagher***(9)***, Jiannan Tu***(10)***, James Horwitz***(11)

(1) Center for Atmospheric Research, University of Massachusetts Lowell, 600 Suffolk Street, Lowell, Ma 01854, USA, E-mail: Xueqin_Huang@uml.edu
(2) As (1) above, but E-mail: Bodo_Reinisch@uml.edu
(3)As (1) above, but E-mail: Paul_Song@uml.edu
(4)As (1) above, but E-mail: Gary_Sales@uml.edu
(5)As (1) above, but E-mail: Patrick_Nsumei@student.uml.edu
(6)NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA, green@bolero.gsfc.nasa.gov
(7)As (6) above, but E-mail: u2rfb@lepvax.gsfc.nasa.gov
(8)As (6) above, but E-mail: shing.fung@gsfc.nasa.gov
(9)NASA Marshal Space Flight Center, 320 Sparkman Drive, Huntsville, AL 35805, USA, Dennis.Gallagher@msfc.nasa.gov
(10) Center for Space Plasma and Aeronomic Research, University of Alabama in Huntsville, Huntsville, AL 35899, USA, tuj@cspar.uah.edu
(11) As (10) above, but E-mail: horwitzj@scpar.uah.edu

ABSTRACT

The radio plasma imager (RPI) on the IMAGE satellite performs radio sounding in the magnetosphere, transmitting coded signals stepping through the frequency range of interest and receiving the returned echoes. The measurements are displayed as plasmagrams showing the echo amplitude as a function of frequency and echo delay time. A newly developed technique inverts the traces on the plasmagrams to electron density profiles. Based on the profile data, empirical models are constructed that describe the density distribution inside the plasmasphere and in the polar region.

INTRODUCTION

The radio plasma imager (RPI) on the Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) satellite [1] performs sounding in the frequency range from 3 kHz to 3 MHz using three orthogonal antennas, 500-m long dipoles in the spin plane, and a 20-m dipole along the spin axis. IMAGE is on an elliptical polar orbit with an altitude of 7.2 R_E at apogee, and 1,200 km at perigee. When the RPI is sounding inside or close to the plasmapause there are often clear echo traces with virtual ranges of up to 7 R_E. Reinisch et al. [2] have shown that the waves producing these traces have propagated along the magnetic field lines. A newly developed profile inversion algorithm calculates the electron density distribution either along the direct path from the spacecraft down to some altitude in the polar cap, or in the plasmasphere along the magnetic field line through the spacecraft. The RPI sounding observations of the field aligned propagation echoes make it possible to measure the density profile in a large range along the field line on which the satellite is located. A single measurement is generally completed within two minutes. This paper first gives a brief description of the inversion technique. Based on the profile data, initial empirical models are developed describing the electron density structure in the plasmasphere and the polar region.

PLASMAGRAMS AND INVERSION TECHNIQUE

The coded signals are transmitted from the RPI into all directions, and they are reflected at places where the wave frequency equals the plasma cut-off frequency. The echo delay times are transformed into the so-called virtual ranges by multiplying them with half the speed of light, and the echo amplitudes are displayed in plasmagrams as function of virtual range in units of Earth radii R_E and frequency in kHz. Measurements are made about every 2 minutes during which time the satellite moves about 500 km along its trajectory. Fig. 1 shows two examples of RPI plasmagrams, the one on the left was recorded when IMAGE was inside the plasmasphere, and the one on the right when it was in the polar cap region.

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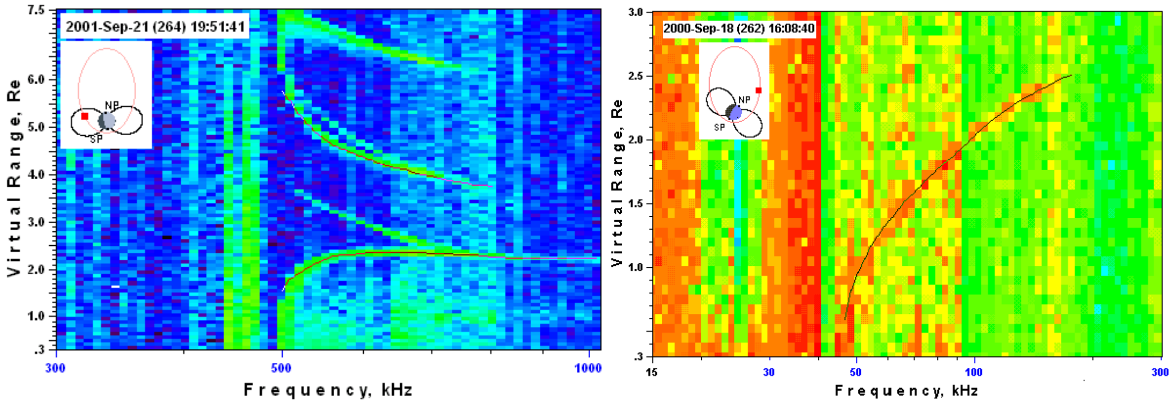


(a) (b)

Fig. 1. Plasmagrams recorded (a) inside the plasmasphere, and (b) in the polar cap. The red dot in the inserts shows the location of IMAGE at the time of the sounding.

A thin black line marks the traces used for the calculation of the electron density profiles. These traces where identified as X mode echoes [2]. The virtual range, *P*, for a trace point can be represented as an integral

$$P(f)=\int_{\Gamma}\frac{cds}{V_g}, \tag{1}$$

where c is the speed of light in the free space, and V_g is the group velocity of the wave with frequency f, traveling from the spacecraft along the path Γ to the reflection point and back to the spacecraft. With the cold plasma and geometric optics approximations we can write

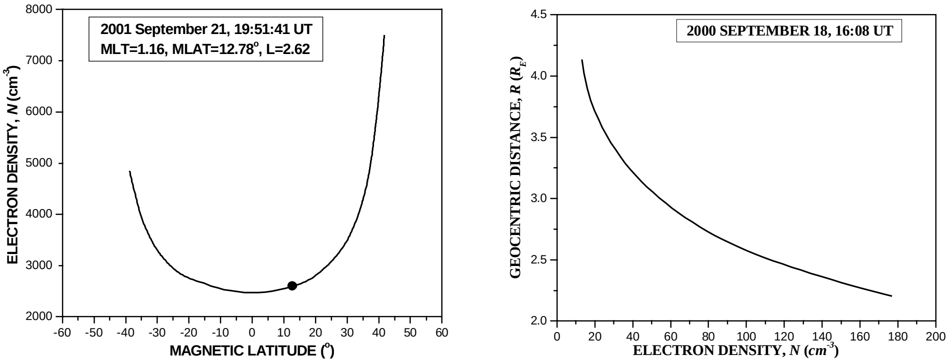
$$P(f)=\int_{\Gamma}\frac{n'}{\cos\alpha}ds \text{ with } n'=\frac{\partial(nf)}{\partial f} \tag{2}$$

where n is the refractive index, n' the so-called group refractive index, and α the deviation angle between the group velocity and the wave normal. In an earlier paper Muldrew [3] suggested that the echoes are traveling along the magnetic field line intersecting the spacecraft. The multiple echo traces on the left plasmagram are the result of waves propagating to the local and conjugate hemispheres. The echoes from the local (northern) hemisphere produce the trace with smaller virtual ranges, while the longer virtual ranges result from reflections in the conjugate hemisphere. The trace at ~7 R_E (not used for the inversion) propagates first to the local hemisphere, then to the conjugate one, and then back to the spacecraft. For propagation along the field line, the deviation angle α becomes zero, and the wave normal is parallel to the group velocity. Then (2) simplifies to

$$P(f)=\int_{\Gamma} n'(f,f_P,f_B)ds \tag{3}$$

The group refractive index n' is a function of the wave frequency f, the electron plasma frequency f_P, and the gyro-frequency f_B. A new algorithm, based on the method used to invert the topside ionograms [4], was developed to solve the integral equation (3) numerically for the true reflection distance. The integration is carried out along the field line using a global magnetic field model [5].

The X mode traces in Fig. 1a extend from f = 500 kHz to higher frequencies with virtual ranges increasing from 0 to ~2 R_E for the local trace, and ~4 R_E for the conjugate trace. The local trace determines the electron density distribution along the field line (L=2.62) from the satellite position (MLAT=12.78^o) to higher latitudes. The conjugate trace with echoes reflected in the southern hemisphere does not start at 0 range. The waves must propagate across the low density equator region before it is reflected at the point approximately conjugate to the spacecraft location. For f close to and slightly above 500 KHz, the group velocities are small producing large virtual ranges of ~6 R_E. Higher frequencies have higher group velocities reducing the virtual range even though the actual range increases when the wave propagates into higher densities until reflection occurs at the cut-off location. No echoes return from the equatorial section of the path from the spacecraft to its conjugate point and the densities can be deduced only indirectly by extrapolation and symmetry considerations. The contributions of the ionization around the equator to the virtual ranges of conjugate echoes is subtracted from the left side in (3), and the inversion procedure is applied to the adjusted conjugate trace. In the polar cap plasmagrams in Fig. 1b, the observed trace starts at zero and (3) is solved directly to determine the profile. The inversion results for the two plasmagrams are shown in Fig. 2.



(a) (b)

Fig. 2. Inverted density profiles for the plasmagrams in Fig. 1

EMPIRCAL MODELS

Since the launch of IMAGE in March 2000, RPI has continuously recorded plasmagrams in the plasmasphere and the polar cap region. The inversion technique described above has been applied to process plasmagrams with good quality echo traces. The profile inverted from a single plasmagram gives the density distribution along the field line, and it can be regarded as an instant measurement over a large region. Combing the profiles along different L shell it is possible to construct an empirical model showing the two-dimensional density distribution.

For the plasmasphere density distribution, we made a case study using a time sequence of RPI plasmagrams for a morning pass on June 8, 2001 when IMAGE changed positions from L = 2.22 to L = 3.23 during 20 minutes. The inverted seven profiles in Fig. 3 provide the density structure in one magnetic meridian plane.

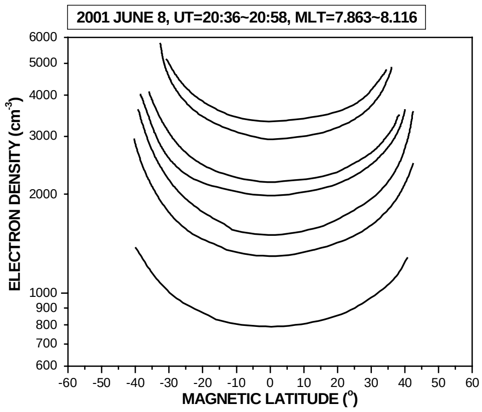


Fig 3. Density profiles on June 8, 2001.

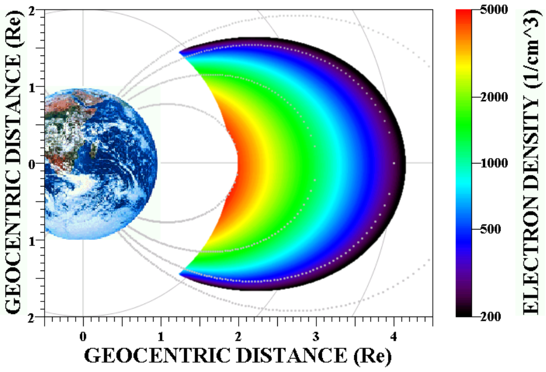


Fig. 4. Modeled two-dimensional density distribution.

The seven profiles as functions of latitude λ and L-value are well represented by:

$$
\begin{aligned}
&N(L,\lambda) = N_0(L)\cdot(1+\gamma\frac{\lambda}{\lambda_{INV}})\cdot\sec^{\beta(L)}\left[\frac{\pi}{2}\cdot\frac{1.25\lambda}{\lambda_{INV}}\right] \\
&N_0(L) = C_0 + C_1\exp(-L/C_2) \qquad (4)\\
&\beta(L) = C_3 + C_4 L
\end{aligned}
$$

Here λ_{inv} is the invariant latitude of the L shell. The parameter γ describes the asymmetry of the north-south distribution around the equator, $\gamma < 0$ meaning that the density in the southern hemisphere increases faster with λ. $N_0(L)$ is the density at the equator. The index $\beta(L)$ defines the steepness of the variation with latitude. The values of the relevant coefficients are

$$C_0 = -157\,(cm^{-3}), \quad C_1 = 49309\,(cm^{-3}), \quad C_2 = 0.841, \quad C_3 = 0.207, \quad C_4 = 0.0347, \quad \gamma = -0.114 \qquad (5)$$

Equations (4) and (5) specify the two-dimensional distribution of density in the magnetic meridian plane (Fig. 4). A similar model was used to describe the refilling process after the March 31, 2001 storm [6]. For the equinox period, the asymmetry factor γ equals zero.

Using polar cap plasmagrams from May to December 2000, an empirical density model for invariant latitudes greater than 70° was derived. In this model, a power law describes the density variation with geocentric distance (in units of R_E), and an exponential function the Kp dependence.

$$\begin{aligned} &N(R, Kp) = N_0 R^{\gamma} \exp(\beta Kp) \\ &N_0 = 4552.0(cm^{-3}), \quad \gamma = -5.47, \quad \beta = 0.19 \end{aligned} \qquad (6)$$

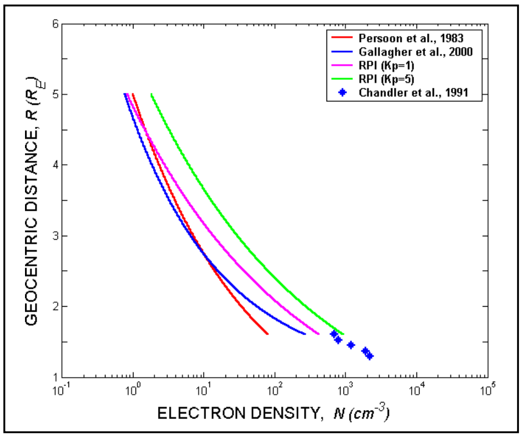


Fig. 5. Empirical polar cap model and comparisons with other models.

Comparisons with other models [7, 8] show good agreement for low Kp values. Persoon's and Gallagher's models are based on periods of quite conditions while our empirical model (6) covers levels of different magnetic activity.

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