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A Chapman-Layers Ionospheric Model for Mars

Xiaoqing Pi
Charles D. Edwards
George A. Hajj
Chi Ao
Larry J. Romans
John L. Callas
Anthony J. Mannucci
Sami W. Asmar
Daniel S. Kahan
Jet Propulsion Laboratory

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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Co-authors George A. Hajj and Larry J. Romans, now affiliated with JPMorgan Chase & Co., contributed to this research as JPL employees.

Abstract

A numerical model (CLIMM) is developed that adopts functions of two Chapman layers to compute Mars ionospheric electron densities at given local solar zenith angle and height. Electron density profiles derived from Mars Global Survey (MGS)-to-Earth radio occultation measurements collected during 1998 through 2005 are used to fit the model. The present model does not include variations with solar extreme ultralviolet (EUV) radiation cycles and seasons, and may have increased errors at lower latitudes. A more sophisticated model taking into account these variations is being developed and will be available in the future.

We have developed a Chapman-Layers Ionospheric Model for Mars (CLIMM) to estimate Mars ionospheric electron density as a function of height and solar zenith angle. The model has been applied to the prediction of horizontal gradient of the ionosphere, which is required in the simulations conducted at the Jet Propulsion Laboratory for radio occultation retrieval of Mars atmospheric parameters [*Edwards et al.*, 2006].

CLIMM applies the chemical equilibrium to Mars ionospheric state and adopts Chapman layers to model the altitude profile of ion production and electron density, while neglecting dynamical effects. In each Chapman layer, the equilibrium state is reached for daytime conditions as the ionization is balanced by the loss of ionized gas due to chemical processes. The state of equilibrium can be expressed as

$$\frac{\partial n_e}{\partial t} = P - L = 0, \tag{1}$$

or

$$P = L, \tag{2}$$

where P is the ionization production rate, L is the chemical loss rate determined by the processes of charge exchange between ions and neutrals and electron-ion recombination, and n_e is electron density.

To derive n_e as a function of altitude and solar zenith angle, a Chapman-α function [*Chapman*, 1931] is applied as follows to represent the production and loss rates:

$$P(z) = P_0 \exp\left(1 - z - e^{-z} \sec \chi\right), \tag{3}$$

and

$$L = \alpha n_e^2, \tag{4}$$

where

z $= \frac{h - h_0}{H}$, reduced height
h height
h_0 reference height
H atmospheric scale height
χ solar zenith angle
P_0 ion production rate at $\chi = 0$ and $h = h_0$
α recombination coefficient.

Combining equations (2) through (4) leads to

$$n_e(h, \chi) = n_{e0} \exp\left[\frac{1}{2}\left(1 - z - e^{-z} \sec \chi\right)\right], \tag{5}$$

where $n_{e0} = (P_0/\alpha)^{1/2}$. From equations (3) and (5), one can also derive the peak electron density as a function of solar zenith angle:

$$n_{e,\max} = (P_0/\alpha)^{1/2} (\cos \chi)^{1/2} . \tag{6}$$

To determine n_e using equation (5), three model parameters are required: h_0, H, and n_{e0}. To specify these parameters, CLIMM has been fitted to electron density (n_e) profiles obtained from the MGS-to-Earth radio occultation measurements (about 5600 occultations) made during 1998 through 2005. We found that two Chapman layers, primary (P) and secondary (S), with separate sets of h_0, H, and n_{e0} parameters for each layer, can fit the n_e profiles reasonably well.

In general, the values of these parameters can be functions of solar extreme ultraviolet (EUV) radiation flux that changes in cycles of 11 years, local solar zenith angle, solar longitude (seasons), and latitude at least for the P layer. For the first order of approximation, we select two groups of constants for these parameters; with which the CLIMM model roughly fits the MGS profiles spanning about eight years. Table 1 lists the parameters selected for the P- and S- layers, respectively. Figure 1 shows examples of CLIMM and MGS n_e profile comparisons for solar zenith angles at 78°±0.2°.

Table 1. Parameters for P- and S-layers

PARAMETER/LAYER	P-LAYER	S-LAYER
h_0 (km)	110	90
H (km)	13	8
$n_{e,0}$ (el/m^3)	1.7×10^{11}	6.0×10^{10}

Figures 2 though 4 show comparisons between three parameters of CLIMM and MGS n_e profiles, namely the peak density ($N_{\max}$), the height of peak density ($H_{\max}$), and total electron content (TEC, altitude integration of n_e). The comparisons include the MGS radio occultation data from 1998 through 2005. Note that the MGS-to-Earth radio occultation yielded data limited to a range of solar zenith angles (SZAs) from 71° to 90° and limited to latitudes above 60° (high latitudes). Some profiles are derived from data collected in the southern hemisphere in 1999, also limited to the high SZA and high latitudes. Thus the accuracy of CLIMM may become degraded at lower solar zenith angles and lower latitudes. It is also noticed that $H_{\max}$ decreases with SZA. Most of MGS profiles indicate that $H_{\max}$ becomes lower than 130 km at SZAs less than 80°. In addition, there are scatterings around the fitting curves, which indicate the solar cycle effect and possibly seasonal effect that are not modeled in this version.

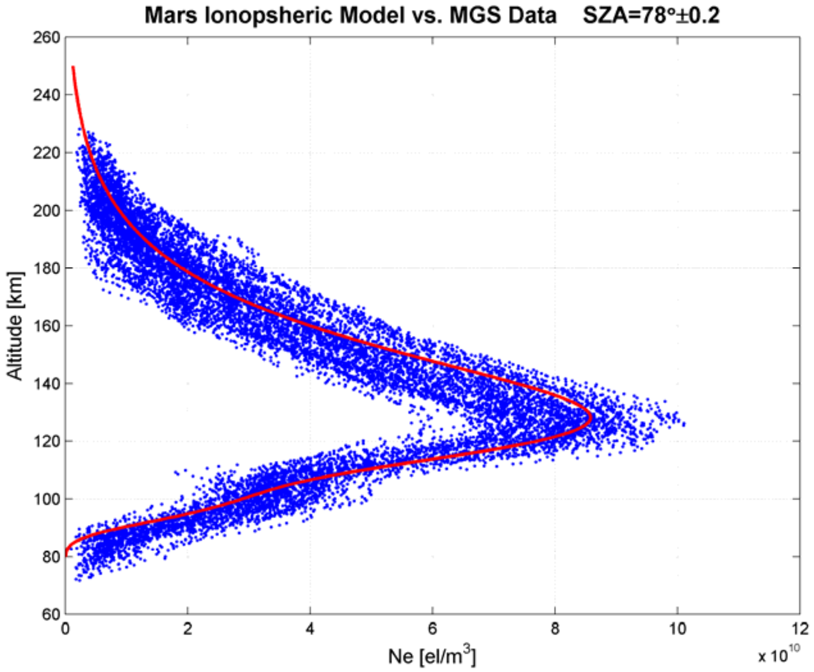

Figure 1. Comparisons between CLIMM (red) and MGS (blue) n_e profiles for solar zenith angles at 78°±0.2. The model profile is composted of P- and S-layers.

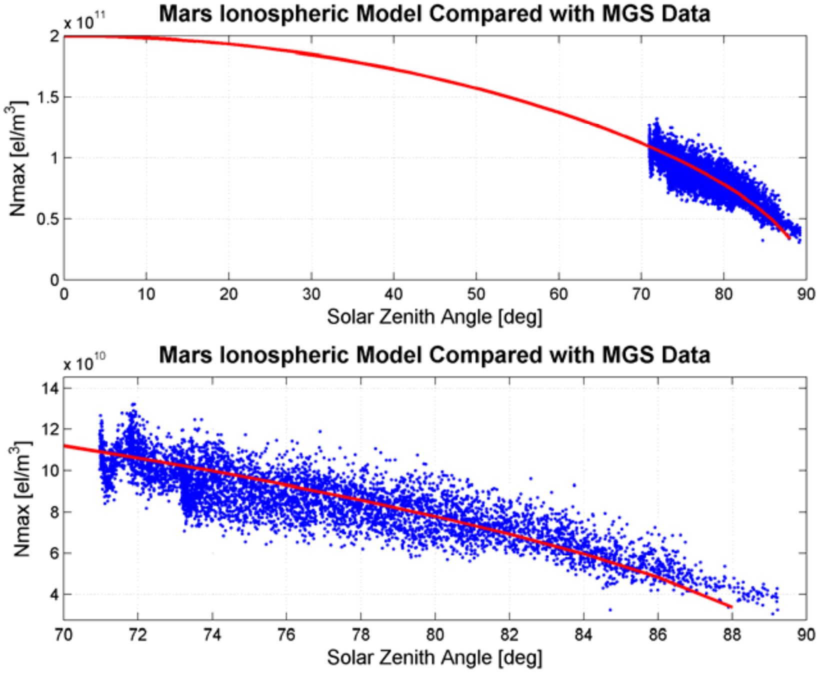

Figure 2. Comparisons between CLIMM and MGS measurements for peak electron density vs. solar zenith angle for 5600 profiles derived from the occultation data collected during 1998 through 2005. The upper panel shows model results at extended SZA where data are not available.

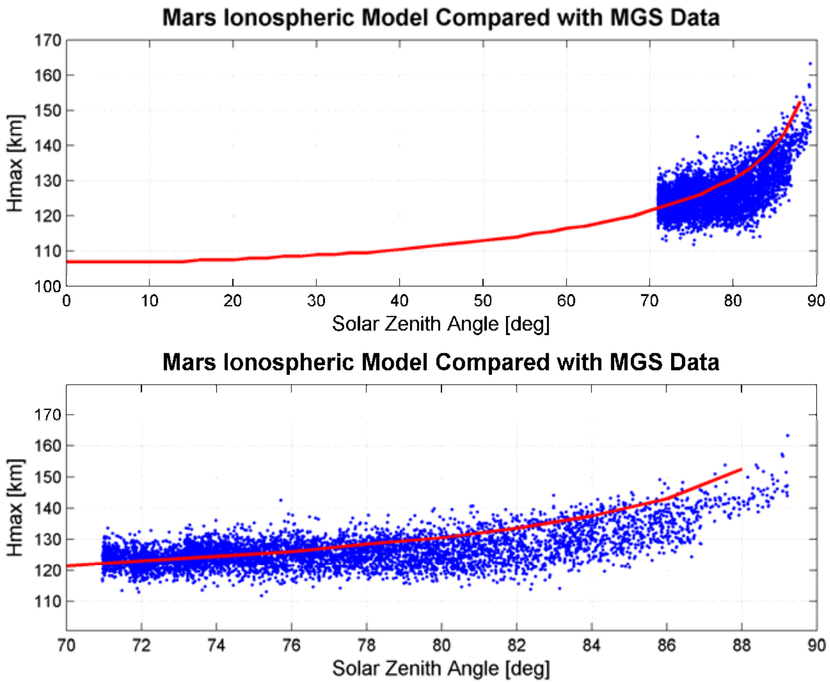

Figure 3. Comparisons between CLIMM and MGS measurements for the height of peak density vs. solar zenith angle for the same data as shown in Figure 2.

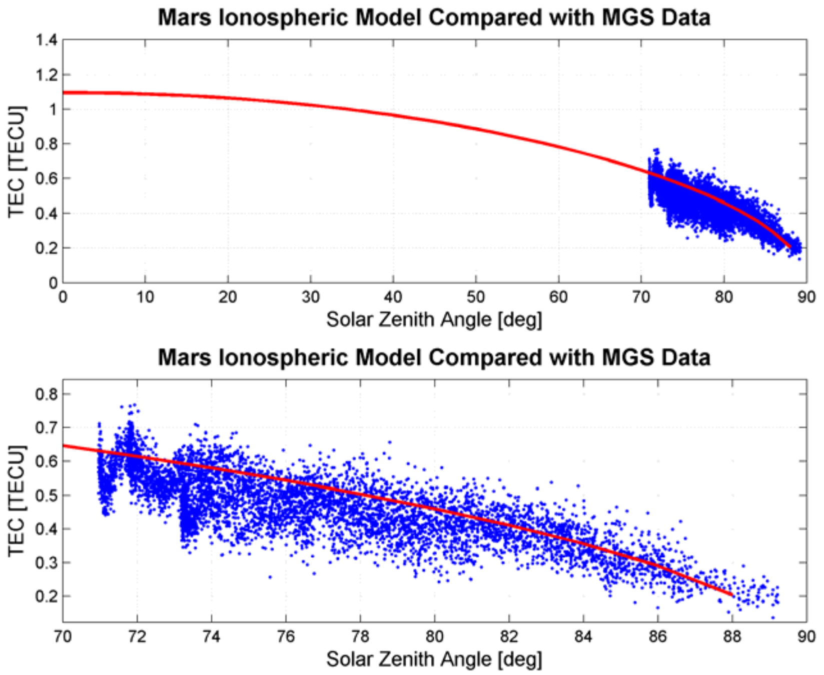

Figure 4. Comparisons between CLIMM and MGS measurements for vertical TEC, obtained by height-integration of n_e vs. solar zenith angle for the same data as shown in Figures 2 and 3.

Nighttime electron density can be solved for through its continuity equation neglecting dynamics as follows:

$$\frac{\partial n_e}{\partial t} = -\alpha n_e^2 . \tag{7}$$

Its time integration leads to

$$n_e(t) = \frac{n_e(t_0)}{1 + \alpha n_e(t_0)(t - t_0)} , \tag{8}$$

and α can be obtained by fitting equation (6) to measured n_e profiles.

As mentioned above, the present model (CLIMM v1.0) does not take into account the effects of solar EUV radiation cycle, season, and full latitude extension. A development of a more sophisticated model that includes variations with these effects is currently undertaken by the authors at JPL.

References

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Author Contact

Email: Xiaoqing.Pi@jpl.nasa.gov
Phone: +1-818-354-4257