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AURORAL IONOSPHERE MODEL (AIM-E) ADJUSTMENT FOR THE REGULAR E LAYER

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Abstract. The E-Region Auroral Ionosphere Model (AIM-E) was developed to determine the chemical composition and electron density in the auroral zone at E-layer heights (90–150 km). Solar and magnetic activity input parameters for AIM-E are the three-hour A_p index and the daily solar radio flux at a wavelength of 10.7 cm (index *F*10.7). In this paper, we compare AIM-E calculations of the electron density for the daytime with EUV radiation spectrum specified in two different ways: 1) the EUV spectrum theoretically calculated using the *F*10.7 index as an input parameter; 2) using TIMED satellite direct measurements of the EUV spectrum. We have corrected the EUVAC EUV radiation model to specify a photoionization source in AIM-E. Calculations of regular E-region critical frequencies show good agreement with the vertical sounding data from Russian high-latitude stations. Results we obtained make it possible to do a quick on-line assessment of the regular E layer, using the daily index *F*10.7 as an input parameter.

Keywords: high-latitude ionosphere, auroral oval, E layer, numerical simulation, EUV, photoionization, electron density.

INTRODUCTION

The E-region Auroral Ionosphere Model (AIM-E) provides temporal and spatial distribution of concentration of the main ionospheric ions O_2^+, NO^+, N_2^+, $O^+(4S)$, $O^+(2D)$, $O^+(2P)$, minor neutral components NO, N(4S) , N (2D) and electrons N_e in an altitude range from 90 to 150 km for different solar and geomagnetic activity levels.

AIM-E involves solving a system of nonstationary one-dimensional differential continuity equations for ten chemical components. Photoionization, ionization due to magnetospheric electron precipitation in the auroral zone, as well as production and loss of ions in chemical reactions are taken into account when calculating production and recombination rates. The numerical solution of continuity equations for neutrals and ions has been realized using the implicit Gear method [Gear, 1971] for numerical solution of ordinary differential equations (ODE). The Gear method for solving a stiff system of ODE (chemical reaction rates vary within 15 orders of magnitude) significantly reduces the computation time, as compared to widely-accepted methods, and makes it possible to calculate the global spatial distribution of ion content in the E layer.

Solar radiation is the main source of energy for most processes in Earth's atmosphere. During the daytime in the altitude range from 90 to 150 km, extreme ultraviolet (EUV) (from 10 to 105 nm) solar radiation is the main source of the atmosphere ionization. Neutral atmosphere parameters (concentrations of neutrals O, O_2, N_2 and temperatures at various altitudes) are specified according to the NRLMSISE-00 model [Picone et al., 2003].

The neutral gas *i*-th component photoionization rate (number of photoionization acts per unit volume per unit time) depends on many independent parameters: concentration of neutral gas *i*-th component, photoionization cross-section, and absorption of λ-wavelength radiation, and λ-wavelength photon flux at the atmosphere upper boundary. The photon flux at the atmosphere upper boundary is the number of photons arriving per unit time in a unit area, perpendicular to the direction of radiation. Stationary high-latitude ionosphere models do not require precise calculation of solar radiation, most of these models being designed for studying nighttime auroras. AIM-E is designed for continuous round-the-clock assessment of ionospheric parameters, hence the need for careful consideration of solar radiation.

AIM-E provides two different ways to calculate photoionization: 1) through direct satellite measurements of EUV radiation spectrum; 2) through empirical UV spectrum with the use of the *F*10.7 index.

Application of TIMED spectra

The TIMED (Thermosphere Ionosphere Mesosphere Energetics and Dynamics) satellite was commissioned in December 7, 2001 and operates to date. One of the scientific objectives of the TIMED mission is to explore the dynamics of the mesosphere and lower thermosphere induced by the solar UV radiation. The SEE (Solar EUV Experiment) device for the TIMED mission [Woodraska et al., 2004] was developed by the University of Colorado.

In this paper, for AIM-E calculations we have used SEE level 3A data being in the public domain [http://lasp.colorado.edu/home/see/data] and having a temporal resolution of 97 min, which corresponds to the frequency of satellite passage through the subsolar point. The SEE level 3A data is the solar radiation spectrum from 0.5 to 195 nm (X-rays, EUV and FUV radiation) with 1-nm channels.

Application of empirical EUV parameterized by *F*10.7

Solar activity indices are widely used to parameterize the photon flux at the atmosphere upper boundary. AIM-E calculated the photoionization rate, taking into account the density of solar photon fluxes for different daily solar index *F*10.7 values. Solar radio emission at a wavelength of 10.7 cm (2800 MHz) is suitable for describing solar activity and forecasting space weather as it well correlates with UV and visible solar radiation and effectively monitors extreme ultraviolet flares. The series of *F*10.7 observations is one of the longest among solar activity indices. Measurements are made on a daily basis and are publicly available [Tapping, 2013].

In AIM-E, UV radiation at the atmosphere upper boundary for 37 wavelength intervals (20 5-nm spectral channels and 17 individual spectral lines) spanning the range from 5 to 105 nm was calculated using the Solar EUV Flux model for Aeronomic Calculations (EUVAC) [Richards et al., 1994] utilizing the *F*10.7 index as an input parameter.

EUVAC is based on data from Atmosphere Explorer E satellite for 1977–1981. Accuracy of the EUVAC model depends on *F*74113 reference spectrum errors [Richards, Torr, 1984] and on the degree of correspondence of solar EUV radiation to the normalization function $P=(F10.7A+F10.7)/2$, where *F*10.7 is the daily solar activity index and *F*10.7A is its mean over 81 days (the reference day is the central point for finding the mean). Because the data variation relative to the normalized function, the EUVAC error for each day varies from 15 to 30 % [Richards et al., 1994].

The launch of the TIMED satellite promoted further development of the model. TIMED data has been used to construct the HEUVAC model [Richards et al., 2006], which covers a wider range of wavelengths and has higher resolution. Girazian and Withers [2015] have expanded the range of data forming the basis of the model and have derived updated regression relationships for different wavelengths by analyzing more than 2800 SEE spectra from 2003 to 2010. Comparison of the HEUVAC model with satellite data has shown that the soft X-ray (0.1–10 nm) according to HEUVAC is underestimated by approximately 65 % during solar minimum, the flux in the Lyman-α continuum is underestimated by about 30 %; furthermore, the ionizing radiation according to HEUVAC is also lower than that measured by TIMED/SEE.

Despite the presence of more recent versions of the model, in this paper we use the original version of the EUVAC model for calculating UV radiation spectra as being freely available.

The purpose of this work is to adjust the AIM-E photoionization block, using two independent sources of solar EUV: 1) EUV spectrum theoretically calculated by the EUVAC model with the *F*10.7 index as an input parameter; 2) EUV spectra measured by TIMED/SEE level 3A. This adjustment will improve the accuracy of ionospheric parameter calculation for the entire auroral zone in quick on-line assessment of E-layer parameters.

DATA AND CALCULATION TECHNIQUE

Vertical sounding (VS) is the most widely used method of observation, which provides real-time ionospheric data. A VS ionospheric station is a kind of radar with combined transmitter and receiver capable of identifying signals reflected from the ionosphere in a wide frequency range, which allows us to determine the dependence of the reflection height on the gradually varying frequency of vertical wave. Normal scanning is performed in a frequency range from 1 to 10–25 MHz. This method is employed to find a critical frequency — a value corresponding to the maximum ionization of the ionospheric layer.

There is a direct relationship between sounding frequency and ionization of the layer that reflects the radio signal. Accordingly, the electron density calculated by the model at the E-layer maximum is uniquely converted into the critical frequency by the formula [Wright et al., 1957]:

$$f=\sqrt{\frac{N_e}{1.24\cdot 10^{10}}}, \qquad (1)$$

where f is the sounding frequency [MHz], N_e is the electron density [m^{-3}].

Since 2010, Russian high-latitude stations have been equipped with digital ionosondes CADI (Canadian Advanced Digital Ionosonde). Each station runs a sounding session every 15 min. Location of the Russian high-latitude ionospheric stations whose data we use is shown in Figure 1, and their geographic and corrected geomagnetic coordinates are listed in Table.

To adjust the photoionization unit, calculations by AIM-E with different input parameters (UV spectra measured by TIMED or calculated by EUVAC) have been compared with VS data from all existing Russian arctic stations. We have employed E-layer critical frequencies (f_oE) obtained by ionosondes at seven high-latitude stations located in auroral and subauroral regions: Gorkovskaya (GRK), Salekhard (SAH), Lovozero (LOZ), Pevek (PBK), Amderma (AMD), Tiksi (TIK), and Dikson (DIK).

We have considered two periods with quiet solar and geomagnetic conditions: June 1–3, 2014 (solar maximum), and June 4–6, 2019 (solar minimum), characterized by the almost complete absence of sporadic layer E_s at all the stations. We have processed 936 VS hour ionograms, from which we have obtained 281 values of f_oE. For each station and moment of observations with AIM-E we calculated vertical electron density profiles in an altitude range 90–130 km with 1 km step size. The electron density at the E-layer maximum was recalculated into the critical frequency by Formula (1).

The midday solar indices *F*10.7 we used to calculate *F*10.7A and *P* were taken from the open database OMNI [https://omniweb.gsfc.nasa.gov/ow.html]. In view of the temporal resolution of the *F*10.7 index, in the AIM-E calculations with the EUVAC model the UV flux was constant for each day. With TIMED satellite data having higher time resolution, the UV flux was updated every 1.5 hrs. The actual flux for the calculations is a flux in the measurement moment preceding the estimated time.

To calculate the photoionization profile in AIM-E, we converted the energy flux spectra [W·m^{-2}·nm^{-1}] measured by TIMED/SEE to photon flux spectra [m^{2}·s^{-1}·nm^{-1}], by dividing the flux by photon energy *hc*/λ in each channel of the instrument, where *h* is the Planck constant; *c* is the speed of light; λ is the wavelength corresponding to the center of each measuring channel.

By using the satellite EUV radiation spectra as an input AIM-E parameter, we got good agreement between the calculated values and VS ionosonde data (Figure 2) for both solar maximum and minimum. Nonetheless, when using the EUV spectrum, calculated by the EUVAC

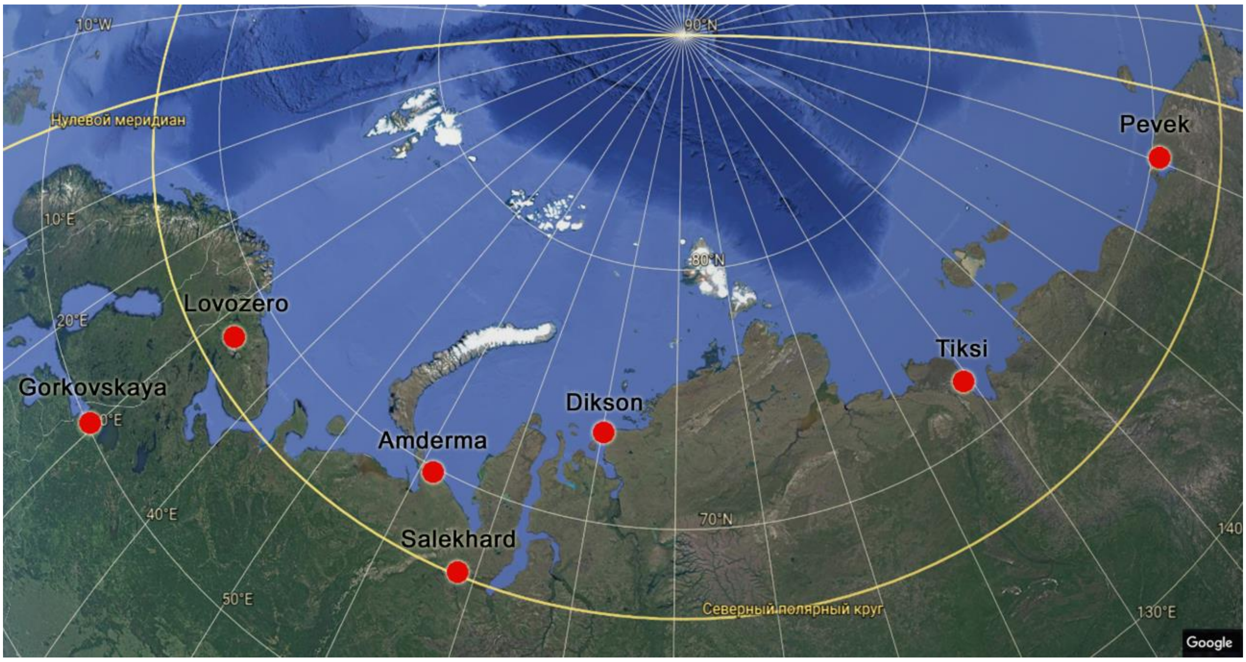

Figure 1. Map of Russian high-latitude vertical sounding stations

Geographic and corrected geomagnetic coordinates of Russian high-latitude vertical sounding stations

Station number station	Code	Observation station observations	Geographic		Corrected geomagnetic	
			latitude	longitude	latitude	longitude
1	GRK	Gorkovskaya	60.27° N	29.38° E	56.74° N	105.55° E
2	SAH	Salekhard	66.52° N	66.67° E	63.04° N	141.69° E
3	LOZ	Lovozero	68.00° N	35.02° E	64.67° N	113.47° E
4	PBK	Pevek	70.03° N	170.92° E	65.83° N	126.77° W
5	AMD	Amderma	69.60° N	60.20° E	66.04° N	136.48° E
6	TIK	Tiksi	71.35° N	128.54° E	66.65° N	160.40° W
7	DIK	Dikson	73.52° N	80.68° E	69.59° N	156.42° E

model, we can see a systematic discrepancy between model critical frequencies and measured ones by ~15 %, which indicates an inconsistency between model EUV spectra and real ones.

To evaluate the discrepancy between the EUVAC calculations and measured spectra, we have analyzed a large amount of the TIMED/SEE level 3A EUV radiation flux data. The analysis covered the period from 2009 to 2019 including the whole solar cycle 24. For each satellite passage at the subsolar point, we found the integral radiation flux in the spectrum range from 5 to 105 nm with 1 nm resolution and its daily average value for each day. Similar values were obtained by the EUVAC model (Figure 3, *a*).

It has been shown that the EUVAC model photon flux is systematically underestimated by approximately 40 % (Figure 3, *b*), which is consistent with the results received in [Girazian, Withers, 2015].

The degree of the discrepancy between satellite and model data depends on the solar radiation intensity. Figure 4 shows the *F*107A dependence of the ratio between integral photon fluxes according to TIMED and EUVAC data. We can see that, despite the wide spread of the data, the variance depends on *F*107A: the discrepancy between model calculations and real data decreases with increasing solar activity.

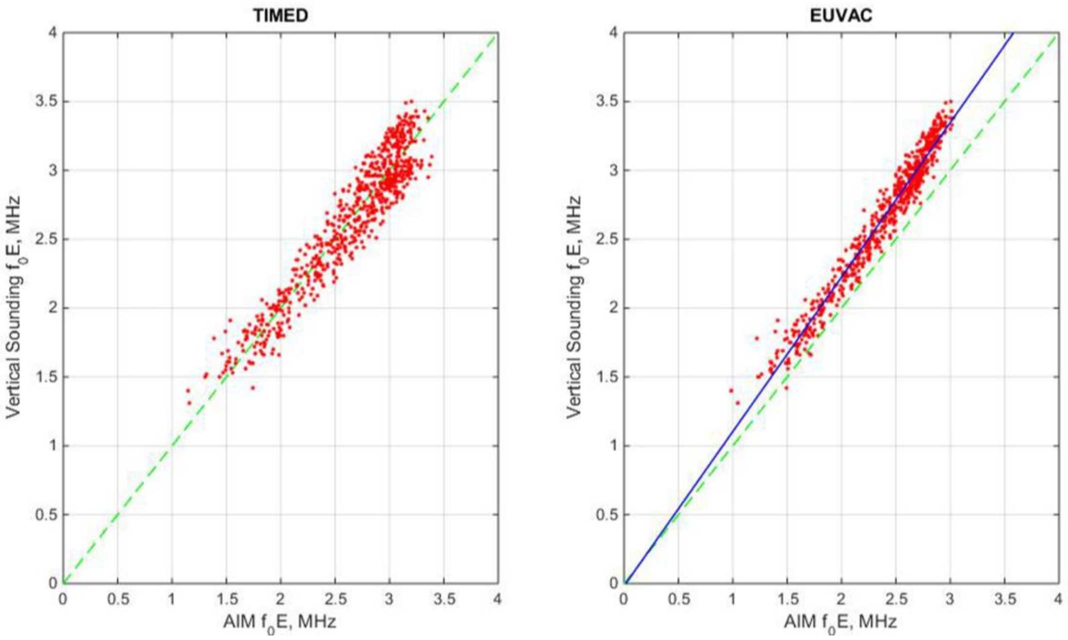

Figure 2. Comparison of vertical sounding data (stations Gorkovskaya, Salekhard, Lovozero, Pevek, Amderma, Tiksi, and Dikson) with AIM-E calculations from measured TIMED spectra (left panel) and model EUVAC spectra (right panel) for June 1–3, 2014 and June 4–6, 2019: the blue solid line indicates a linear relationship between real and calculated critical frequencies; the green dashed line is the straight line $y=x$ (complete data fit); for calculations from TIMED data, these two lines coincide

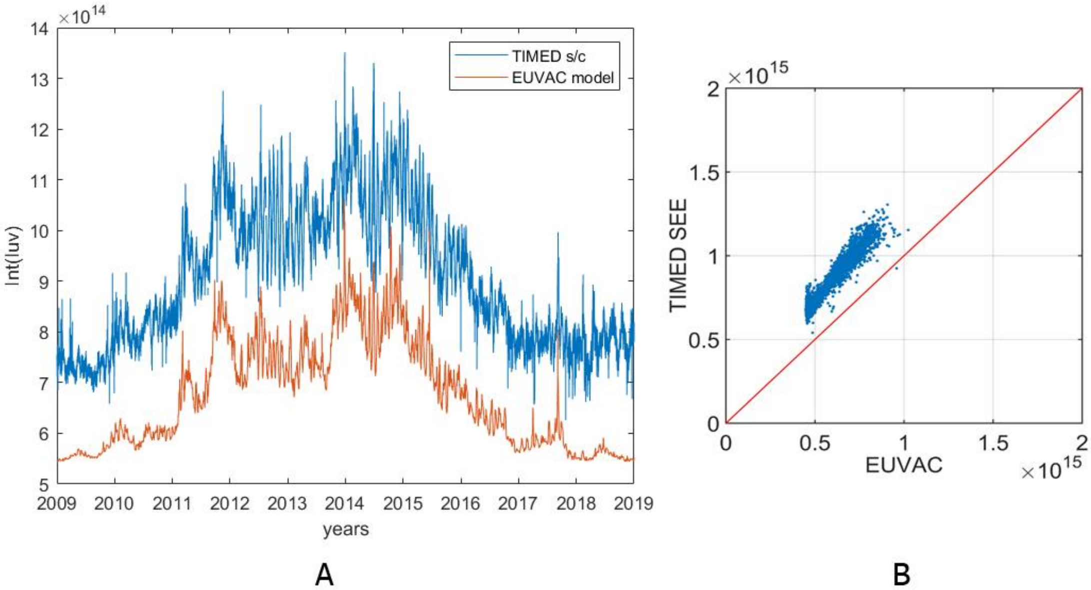

Figure 3. Time variation of the integral photon flux for TIMED and EUVAC in 2009–2019 (*a*); plot of spread of values for this period (*b*)

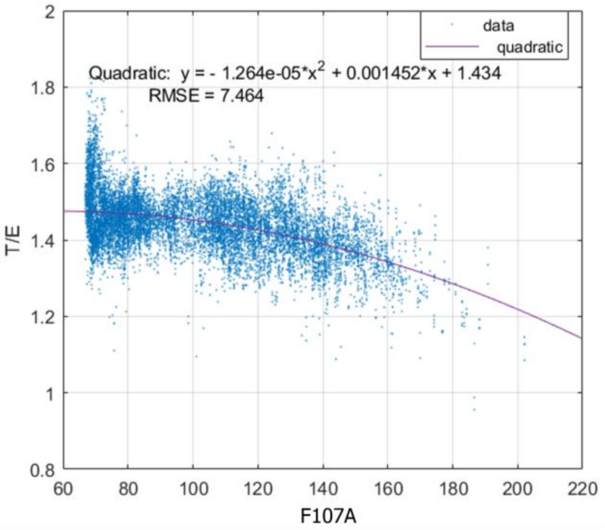

Figure 4. Relationship between integral photon fluxes according to TIMED and EUVAC as function of F107A

We applied this dependence to the AIM-E input parameters adjustment in order to eliminate the systematic error in the photoionization rate calculation, associated with the EUVAC model.

DISCUSSION

In order to verify the correctness of normalization of EUV radiation flux by the EUVAC model, we compared AIM-E calculations of regular E-layer parameters for quiet geomagnetic conditions on June 2–5, 2015 (not involved in adjusting the model) with VS data.

Figure 5 shows the diurnal variation of E-layer critical frequencies according to ionosonde data from Gorkovskaya, Pevek, Lovozero, Amderma, and Dikson stations and f_oE calculated using the photon flux obtained by the EUVAC model before and after correction.

We can see that before introducing the normalization function the diurnal variation of f_oE calculated by AIM-E for all the stations gives the low values. However, after correction of EUV flux in the EUVAC model, the f_o values calculated by AIM-E almost completely coincide with the measured f_oE values (correlation coefficient R=0.986), indicating that the radiation flux has been specified precisely. The E-layer critical frequencies obtained by AIM-E can be used to describe daytime ionospheric conditions.

Unlike the AIM-E results obtained using the empirical model EUVAC, the AIM-E results received using TIMED/SEE spectra (temporal resolution of 1.5 hr) might demonstrate smaller-scale variations in simulated parameters due to higher temporal resolution of solar flux, which is essential to describing ionospheric parameters during sporadic events such as solar UV flares. That said, TIMED data is available in open access with a considerable time delay that makes it impossible to do quick on-line calculations, which can be performed using the EUVAC model. Using the adjusted EUVAC model in AIM-E, we can calculate the vertical distribution of ionospheric parameters in real time and obtain electron density spatial distribution maps for on-line monitoring of the entire high-latitude ionosphere (Figure 6).

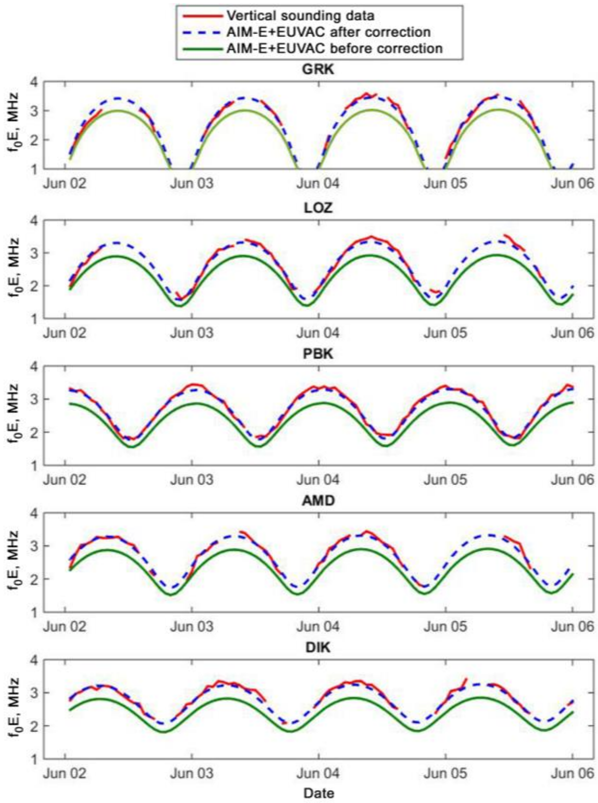

Figure 5. Diurnal variation of regular E-layer critical frequencies (f_oE) on June 2–5, 2015: red lines are observations at GRK, LOZ, PBK, AMD, and DIK; solid green and blue dashed lines indicate results of AIM-E calculations from the EUVAC photon flux before and after correction respectively

RESULTS

- We have found a significant systematic error in the EUVAC model when calculating the EUV photon flux, which is 20–40 % depending on solar activity.
- We have corrected the photon flux in the EUVAC model, using TIMED/SEE satellite data covering the entire solar cycle 24. We have established that model calculations diverge from satellite data depending on solar activity.
- Comparison of critical frequencies obtained by ionosondes in Russian Arctic and calculated by AIM-E has shown high accuracy of model calculations after correction of photoionization input parameters. Depending on modeling tasks, AIM-E can use both direct satellite measurements of photon flux spectrum and EUVAC model spectra.

CONCLUSION

One advantage of AIM-E is flexibility in specifying input parameters of the photoionization source. The solar EUV radiation spectrum can be set in two ways: 1) through direct measurements of the photon flux spectrum by the TIMED satellite; 2) using EUVAC model spectra parameterized by daily F10.7.

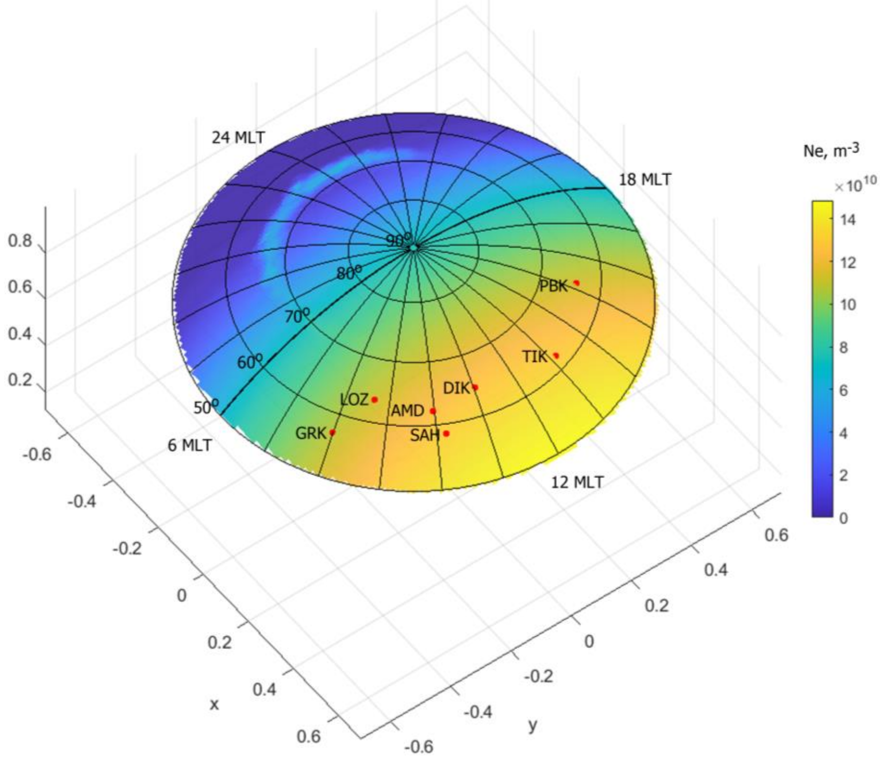

Figure 6. A map of electron density spatial distribution at the E-layer maximum for June 04, 2015, 05:00 UT. The coordinate system is solar magnetic (SM)

Direct measurements of the photon energy spectrum made by TIMED every 97 min can be used for studying ionospheric effects of space weather extreme events such as solar flares. Delay of data does not, however, allow us to use it for diagnosing ionospheric conditions in real time.

The adjustment of the AIM-E photoionization unit will ensure high accuracy of calculations in quick online assessment of regular E-layer parameters with the daily *F*10.7 index as an input parameter. Due to the fact that a continuous series of daily radio flux *F*10.7 measurements is available since 1947 (for seven solar cycles), this AIM-E mode can be applied to the ionosphere climatological studies.

With a reliable *F*10.7 forecast, AIM-E can predict parameters of the regular E-layer at high latitudes.

In addition, due to its fast operation and accuracy AIM-E can serve as an ionospheric module in larger-scale models to calculate the spatial distribution of ionospheric parameters at high latitudes, the electric conductivity, fields, and currents.

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