Empirical models of electron precipitations at the Earth’s ionosphere high latitudes: a review

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Abstract. This paper presents a review of the Earth’s ionosphere empirical models of high-latitude energetic electron precipitations. In total, the review includes twelve models. Those models represent the full spectra from the earliest to the most recently developed ones. The majority of models were derived from the DMSP mission data. Models by McDiarmid et al., Spiro et al., Zhang & Paxton, Kamp et al., and Wu et al. are the exceptions. The first two models were developed before the DMSP mission era. Most of considered models are based on a physical representation of precipitating electron fluxes. However, some models are utilizing the purely “technician” approach. Those models are constructed for each channel of the DMSP/SSJ4 detector separately. Nowadays, AFGL, Ovation Prime (OP), and OP-2013 are the most popular models. The AFGL model is the first one with reasonable accuracy being available for public use. However, OP/OP-2013 models are becoming more popular now. They provide the finer specification of the electron precipitations over the AFGL model but require the solar wind in situ observations as the input parameter.

1 Introduction

Energetic electrons precipitate into the Earth’s ionosphere along the geomagnetic field lines at high geomagnetic latitudes. The penetration intensity increases with geomagnetic activity. Energetic electron precipitations (EEPs) are an important ionization source in the high-latitude ionosphere. The interaction of the precipitations with the Earth’s ionosphere is clearly visible from the Earth as the polar lights, especially during storm periods.

The intensive EEPs-related processes have a significant influence on the radio-waves propagation (especially at the polar areas) and precision of the Global Positioning System (GPS) and Global Navigation Satellite System (GLONASS). As a result, the proper EEPs description is important for scientific (e.g., ionosphere modeling) as well as for applied (e.g., radio-waves propagation, ionospheric delay corrections) purposes.

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The EEPs measurements were collected for more than five decades. Early researches estimated EEPs’ characteristics using the balloon observations [1-3], the rocket launches [4-9], or the indirect methods [10-12]. Various satellite missions collected a huge dataset of in situ observations. One of them is the DMSP (Defense Meteorological Satellite Program) mission. It provides the EPPs data from the year 1974 until nowadays. According to the report [13], the estimated DMSP-observed EPPs’ uncertainties are approximately 20%.

In this paper, we review the general features of major empirical models of the Earth’s ionosphere high-latitude energetic electron precipitations.

2 Methods

This section presents a short description of the methods that we used to perform a review. A detailed description of the methods can be found in our previous paper [14].

A typical review process includes the following stages: (a) a scientific papers selection, (b) a duplicates removal, and (c) a manual evaluation of the selected publications. The manual evaluation stage includes the analysis and generalization of papers’ content as well as an investigation of references lists and the citing literature (citations and citing literature analysis). It usually extends the initial list of publications to consider.

We performed the initial search of scientific publications using (a) Web of Science and SCOPUS bibliographic databases, (b) ScienceDirect, Springer Link, Willey, ArXiv, Google Scholar, and Microsoft Academic search systems, as well as (c) ResearchGate and Academia scientific social networks. The search terms were ‘ionosphere’, ‘Earth’, ‘electron precipitation’, ‘energetic electron precipitations’, and ‘empirical model’. For manual evaluation, we considered peer-reviewed scientific publications only.

3 Results

3.1 McDiarmid et al. model

McDiarmid et al. [15] is one of the earliest papers providing the satellite-derived average patterns of the Earth’s ionosphere electron precipitations. They analyzed the data of International Satellites for Ionospheric Studies 2 (ISIS-2) for March 1971 – August 1972 with a geomagnetic activity index $k_p \leq 3$. Measurements were performed with one 8-channel detector for energies in the range 150 eV – 10 keV, and two additional detectors – for energies > 22 keV, and > 210 keV [15].

To the end-user, the model is provided as electron precipitation flux (average intensity) and energy maps in magnetic local time (MLT). The model uses invariant latitude coordinates. Average intensity maps are provided for the following energy values: 150 eV - 9.6 keV band, 150 eV, 1.3 keV, 9.6 keV, > 22 keV, and > 210 keV. Currently, this model is of primarily historical interest.

3.2 Rice University electron precipitation model

Spiro et al. [16] developed the Rice University (William Marsh Rice University) electron precipitations model based on the electron detectors’ data from Atmosphere Explorer C (AE-C; January 1974 – October 1975 and February 1976 – April 1976) and AE-D (October 1975 – February 1976) satellites. These detectors had sixteen log-shifted channels and measured energies in the range of 200 eV – 27 keV.
To the end-user, the model is provided as a set of the following tables: (a) the precipitating electron energy flux, (b) the characteristic electron energy, (c) the Pedersen, and altitude-integrated Hall conductivities. The paper [16] also provides the analytical formulation of (a) the Pedersen conductivity linear regression against the characteristic energy of precipitating electrons, (b) the Hall to Pedersen conductivities ratio as a function of characteristic energy, and (c) the auroral zone total electron energy income.

Tabulated values are bin-averaged and ordered in MLT coordinates for four AE-index ranges: (a) $\text{AE}\leq 100$, (b) $100<\text{AE}\leq 300$, (c) $300<\text{AE}\leq 600$, and (d) $\text{AE}>600$. These AE ranges present 32%, 38%, 24%, and 6% of observations, respectively. The MLT has a 1-hour resolution, and 70% of observations are for the 0600MLT-1800MLT sector; the rest are for the night-time. The invariant latitude ($50 \leq \phi \leq 88$) has a 1-degree step in the $60 \leq \phi \leq 80$ range, and a 2-degree step in the $50 \leq \phi \leq 60$ and $80 \leq \phi \leq 88$ ranges. The model does not take into account such parameters as the hemisphere, season, longitude, and the solar cycle phase. The detectors’ peculiarities and data smoothing technique is applied. As a result, the model is not able to reproduce the “inverted V” electron precipitation pattern.

Authors of the original paper [16] did not expect significant errors in precipitating electron energy flux determination. However, some inconsistency is possible for the characteristic energy. Later, Robinson et al. [17] provided the corrections to the Pedersen and altitude-integrated Hall conductivities. The reason for corrections was that, given the characteristic energy of the electron precipitations followed the Maxwellian distribution should be equal to half of the average energy. Taking into account these corrections, Kamide et al. [18] modified the Rice University model's conductivities using the Dynamics Explorer 1 (DE-1) and DE-2 observations.

### 3.3 Air Force Geophysics Laboratory (AFGL) model

Hardy et al. [19] developed the Air Force Geophysics Laboratory (AFGL) model. This model is based on Defense Meteorological Satellite Program (DMSP) F2 (September 1977 – February 1980), DMSP F4 (April 1979 – August 1980), and Satellite Test Program P78-1 (February 1979 – January 1980) *in situ* measurements. Onboard satellites’ facilities were designed to register the precipitating electron energies in the range of 50 eV – 20 keV. DMSP satellites were equipped with one 8-channel detector for the 50 eV – 1 keV energy range, and another 8-channel detector for the 50 eV – 20 keV energy range. The P78-1 satellite had one 16-channel detector.

To construct the model, the data were organized in the corrected geomagnetic latitude (CGM Lat) vs MLT grid for seven levels of $k_p$-index. The latitudinal step is 1 degree at the $60 \leq \text{CGM Lat} \leq 80$ range, and 2 degrees outside of it, i.e. at the $50 \leq \text{CGM Lat} \leq 60$ and $80 \leq \text{CGM Lat} \leq 88$ ranges. The MLT step is 0.5 hours, thus, it corresponds to 48 intervals. The $k_p$-index values are grouped (binned) to integer numbers in the range $0 \leq k_p \leq 5$. All measurements for $k_p \geq 6$ are considered jointly without further binning on $k_p$-index values.

To the end-user, the model [19] is provided as the following graphical 2D maps: (a) the precipitating electron number flux density; (b) the precipitating electron energy flux density; (c) the precipitating electron average energy. All maps are log-scaled, provided for seven values of the $k_p$-index $(0,1,2,3,4,5, \geq 6)$, and performed in MLT grid using corrected geomagnetic latitude coordinates.

Later, the AFGL model was improved by Hardy et al. [20] in the following way. They (a) used a larger dataset to construct the model, (b) constructed the altitude-integrated Hall conductivities’ maps as well as (c) the Pedersen conductivities’ maps.
The maps had the same reference frame and $k_p$-index levels as the initial paper [19]. Additionally, they [20] provided the analytical formulations for the electron precipitations energy flux, number flux, and corresponding Hall and Pedersen conductivities. Those formulations are the Epstein-Fourier series expansions and corresponding tables of coefficients. Fourier expansions were used to reduce the number of Epstein coefficients. Researchers often reference the AFGL model as Hardy-85 or Hardy-87.

3.4 Hardy et al. model

Hardy et al. [21] investigated probability distributions of high-latitude precipitating electrons and published the model of total number flux $J_{TOT}$, total energy flux $J_{E_{TOT}}$, and average energy $E_{AVE}$. The model was based on nine DMSP satellites’ SSJ4 (Special Sensor for Precipitating Particles, version 4) detector data for the years 1983 – 2005.

To construct the model, the initial step data were corrected according to the SSJ4 detectors’ on-orbit degradation. In contrast, the AFGL model did not take into account such correction. As the next step, the corrected data were organized in spatial MLAT vs MLT grid for the integer values of the index $k_p$. Corresponding MLAT, MLT, and kp steps were 1 degree, 1 hour, and 1 unit, respectively.

To the end-user, the model [21] is provided as $J_{TOT}$, $J_{E_{TOT}}$, and $E_{AVE}$ maps in MLT – MLAT coordinates plotted for values 0, 3, and 5 of the $k_p$-index. The published maps have significantly lower $k_p$-index resolution in comparison with the AFGL model.

3.5 Zhang and Paxton model

Zhang & Paxton [22] constructed a model based on GUVI (Global Ultraviolet Imager) FUV (Far Ultraviolet) TIMED (Thermosphere – Ionosphere – Mesosphere – Energetics and Dynamics) mission observations for 2002-2005. They reconstructed the energy flux density and the average energy of precipitation electrons using the inverse problem solution. They used MSIS86 [23] as the neutral atmosphere model, Boltzman Three Constituent (B3C) [24] model as the ionosphere model, and calculated the airglow using the Atmospheric Ultraviolet Radiance Integrated Code (AURIC) [25]. An energy flux density distribution and an average energy were numerically estimated to fit the produced airglow to the GUVI FUV TIMED. Thus, in contrast to other models, this model was not based on in situ observations.

The model [22] uses MLT, MLAT, and the $k_p$-index ($0 \leq k_p \leq 9$) values as input parameters. The outputs are the precipitating electron energy flux density, the average energy, and the total hemispheric power. To the end-user, the model is provided as an Epstein-Fourier series expansion with the required coefficients supplied in the tabular form. Additionally, the paper [22] describes the algorithm for performing the calculations.

3.6 Auroral Precipitation Model (APM)

Vorobjev et al. [26-28] developed the Auroral Precipitation Model (APM) based on DMSP F6 and F7 observations for the year 1986. This model organizes observations of electron precipitations in three different zones according to the precipitation type: the diffuse auroral zone (DAZ), the auroral oval precipitation (AOP) zone, and the soft diffuse precipitation (SDP) zone. Each zone (borders and precipitations’ intensities) is modeled separately from the others. Analytical formulations for the APM model zones’ borders are provided for 21-24 MLT and 09–12 MLT in [26] and [27], respectively.
The APM model uses the $D_{st}$ and AL indexes as input parameters. It outputs maps of (a) the boundaries for DAZ, SDP, and AOP zones, (b) the precipitating electron energy flux density, and (c) the average energy. All maps are presented in the CGM MLAT – MLT coordinate system. The APM model is suitable for values of the AL and $D_{st}$ indexes in ranges $-1500 \text{ nT} \leq \text{AL} \leq 0 \text{ nT}$ and $-200 \text{ nT} \leq D_{st} \leq +10 \text{ nT}$, respectively.

According to the description (see Fig. 1), there are two options for running the model: (1) via the API – Application Programming Interface, and (2) via the online web service at the Polar Geophysical Institute (PGI) site at the URL http://apm.pgia.ru/. The service is available via the HTTP protocol only. It allows one to specify (see Fig. 2) AL and $D_{st}$
index values and the simulation mode: (a) “Zones CGM”, (b) “Energies CGM”, and (c) “Fluxes CGM”. Additional modes - “Zones (geographic)”, and “Zones (geographic, 24-hour animation)” – take AL, Dst, and UT as input parameters. Simulation results are provided as graphical images plotted on the canvas (see Fig. 3).

![Image of APM model simulations]

**Fig. 3.** An example of the APM model simulations

### 3.7 Ovation Prime model

Newell et al. [29-30] developed the Ovation Prime (Oval Variation, Assessment, Tracking, Intensity, and Online Nowcasting) model. It is a successor of the previous model published in [31]. The model’s principal features, stages of development, methodology, and electron precipitation classification techniques are described in [29]. The paper [29] introduces four types of precipitations which approximately correspond to the following polar aurora types: (a) the monoenergetic aurora, or the “inverted V” aurora, (b) the diffuse aurora, (c) the broadband aurora, and (d) the ions aurora. In this model, the ions aurora includes all of the auroras which are not classified into three previous classes. To classify observations into these four types, Newell et al. [29] designed special software algorithms. Thus, all the classifications were performed automatically.

The Ovation Prime model is based on SSJ/4 DMSP F8-F13 satellites’ data. It covers 11 years of observations from January 1, 1988, to December 31, 1998. The post-midnight sector observations are not available before the year 1992. To perform observations’ ordering, Newell et al. introduced the special function, namely, the coupling function $d\Phi_{MP}/dt = v^{4/3} B_T^{2/3} \sin^{8/3}(\Theta/2)$. Here $v$ is the Solar wind velocity; $B_T = (B_Y^2 + B_Z^2)^{1/2}$ is the Interplanetary Magnetic Field (IMF) intensity; $\Theta$ is the IMF Clock angle in the $B_Y$-$B_Z$ plane. $B_Y$ and $B_Z$ are the Y- and Z-component of the IMF, respectively. The coupling function contrasts the Ovation Prime model from earlier models that order observations according to a few geomagnetic indexes.

To the end-user, the Ovation Prime model is published as IDL v8 source codes. In addition, independent researchers ported the IDL code to Python and published it at the GitHub repository URL [https://github.com/lkilcommons/OvationPrime](https://github.com/lkilcommons/OvationPrime). Eventually, this Python implementation extended the original algorithms by adding extra filtering procedures. In other words, it is not identical to the original Ovation Prime model.

The model input parameters are the Solar wind velocity $V_{SW}$ (in GSM coordinates), the IMF $B_Y$ and $B_Z$, and the IMF Clock angle. For each precipitation type, it calculates
maps (AACGM MLAT – MLT coordinates) of (a) the precipitating particle number flux, (b) the energy flux, and (c) the auroral power. The integral flux can be obtained as a sum of these four maps.

### 3.8 Ovation Prime-2013 model

The Ovation Prime-2013 [32] is a further development of the Ovation Prime model. It extends the previous version by assimilation of TIMED mission GUVI data during high geomagnetic activity time periods. The activity levels are approximately corresponding to the $k_p$-index values ranging from 5+ or 6- to 8-. This uncertainty in the $k_p$-index values is due to the usage of the coupling function to organize observations. The model is appropriate for the coupling function $d\Phi_{MP}/dt$ values in the range $[0, 3.0]$ MWb · s⁻¹. The value 3.0 MWb · s⁻¹ approximately equals $k_p=8$.

The Ovation Prime-2013 model input parameters are the Solar wind velocity $V_{SW}$ (in GSM coordinates), the IMF $B_Y$ and $B_Z$, the IMF Clock angle, the AACGM MLAT, and the MLT. The AACGM MLAT and the MLT can be considered as coordinates for maps of parameters’ distributions. The outputs are (a) the precipitating particle number flux, (b) the energy flux density, and (c) the total inflowing power for both the Northern and Southern hemispheres.


![Fig. 4. A fragment of the webpage (https://bit.ly/op-in) with the Ovation Prime-2013 instant run example](https://bit.ly/op-in)

To run the IDL source codes, the model requires the IDL v8 or, at least, the IDL virtual machine. According to the official documentation, the IDL virtual machine can be obtained without fees, but it requires a user registration and an account approval by the IDL staff. The registration itself does not grant the IDL virtual machine license. The online service provides both the run-on-request and instant-run (see Fig 4) calculations.

### 3.9 McIntosh et al. model

McIntosh et al. [33] evaluated precipitating electron spectra against different statistical distribution functions to find the best fit. They analyzed data fits against
(a) the Maxwellian, (b) the Kappa, as well as (c) the monoenergetic, and (d) the broadband distributions for the period 1996-2003 of DMSP F1 – F15 SSJ observations. To perform the analysis, McIntosh et al. [33] organized precipitating electron data as a function of MLAT (50 ≤ MLAT < 90), MLT (0000 ≤ MLT < 24), and the kp-index. The kp-index bins are [0, 0+], [1-, 1+], [2-, 2+], [3-, 3+], [4-, 4+], [5-, 5+], and kp ≥ 6. MLAT and MLT steps are 1 degree and 15 minutes, respectively.

For each of the four distribution laws, the paper [33] presents the number (quantity) of best-fitted spectra in the form of MLAT-MLT maps for different kp-index values. However, the paper [33] does not provide spectra at all, and interested parties should email requests to phillip.anderson1@utdallas.edu.

### 3.10 Kamp et al. model

Kamp et al. [34-35] presented analytical approximations of precipitating electrons with energies in the range of 30 keV – 1000 keV. The formulations are derived with [34] and without [35] accounting for the zonal (longitudinal) variation.

The model describes the spectra density and the electron number flux as a function of (a) the a_e- or Dst index, (b) the L-parameter, and (c) the MLT (when zonal variation is taken into account). The model is based on observations provided by the National Oceanic and Atmospheric Administration (NOAA) -15, -16, -17, -18, and -19 Polar Orbiting Environmental Satellites (POES) Space Environment Monitor (SEM-2) / Medium-Energy Proton and Electron Detector (MEPED), as well as the Meteorological Operational (MetOp2) satellite. It covers the years 1998-2012. Usage of the a_p and Dst indexes allows application of the model for the pre-satellite era. These indexes are derived since the year 1932 and 1957 for a_p and Dst index, respectively.

### 3.11 Auroral energy Spectrum and High-Latitude Electric field variability (ASHLEY) model

The Auroral Energy Spectrum and High-Latitude Electric field variability (ASHLEY) model [36] was based on SSJ/5 DMSP F16-F18 (years 2010-2015) and SSIES/3 DMSP F15-F18 (years 2010-2018) satellite data. SSJ detectors provided precipitating electron data. SSIES were used for ions’ measurements. In contrast with other models, the ASHLEY model constructed an independent regression model for each of the nineteen spectral lines (bands) of the SSJ/5 detector.

The model input parameters are (a) the IMF intensity {B_T = (B_Y^2 + B_Z^2)^1/2}, where B_Y and B_Z are components of the IMF, (b) the solar wind velocity in GSM coordinates, and (c) the solar wind protons number density. The model output is presented using a spatial grid (map) in MLAT – MLT coordinates. The outputs are (a) the MLAT-MLT numerical grid, (b) the differential energy fluxes for the each of nineteen DMSP SSJ/5 channels, (c) the electric potential, and (d) the electric field.

The model sources are published at the GitHub URL https://bit.ly/ashley-github, as well as the Zenodo URL https://zenodo.org/record/4157718. Unfortunately, both links provide the sources without the required coefficients. Thus, it is impossible to run the published code. Additionally, the model’s license prohibits any modifications of the code without the permission of the Physical Department of the University of TEXAS, Arlington, USA.

### 3.12 Feature Tracking Empirical Model of Auroral Precipitation (FTA)

Wu et al. [37] developed the Feature Tracking Empirical Model of Auroral Precipitation (FTA). It was based on on-board Far Ultraviolet (FUV) observations provided by the Polar
satellite, specifically, Lyman–Birge–Hopfield small (LBHS, 140.0–150.0 nm) and Lyman–Birge–Hopfield long (LBHL, 165.0–180.0 nm) emissions. It allowed derivation of the energy flux and the average energy from LBHL and LBHL/ LBHS ratio, respectively.

To construct the model, Wu et al. [37] ordered datasets according to the AE-index, MLT, MLAT, and the cumulative energy distribution. Then the latitude-integrated intensity of the emission was calculated for each MLT sector. In total, there were 21 bins for the cumulative energy distribution (which corresponds to a 5% step in the range of 0–100%), 96 sectors for MLT (it corresponds to 15 min step), and 20 bins for the AE-index (it corresponds to 50 nT step for the 0 – 1000 nT interval).

Internally, the FTA model uses machine-learning techniques (k-means clustering) to determine the oval's equatorial and polar boundaries during the increased activity levels. To the end-user, the model is available as the Python code under the GNU GPL v3 license at the GitHub URL https://github.com/FTAModel/FTA/tree/v1.0. Additionally, this repository mentions the AU/AL-driven versions of the model, while the paper [37] does not describe it. A further publication on the AU/AL-driven model is planned.

4 Discussion

In total, we selected twelve models of precipitating electrons to consider their principle features (see Table 1). Table 1 shows that the majority of researchers uses the DMSP mission data to build the models. Exceptions are McDiarmid et al. [15], the Rice University model [16], Zhang & Paxton [22], Kamp et al. [34-35], and the FTA model [37].

The papers [15–16] represent pioneering studies performed before the DMSP mission data became available. McDiarmid et al. [15] mapped average intensities and energies of precipitating electrons for kp ≤ 3 conditions. Due to the accuracy limitations, this model is of historical interest nowadays. At the same time, it still can be used as a common pattern of electron precipitations. The Rice University model [16] is a further attempt to define the specification of the precipitating electron energy flux, the characteristic electron energy, and the auroral zone of the electrical conductivity for different levels of the geomagnetic activity characterized by the AE-index values. Subsequent publications [17-18] report that this model has a few inaccuracies in the specification of the characteristic electron energy and the ionospheric conductivities. Robinson et al. [17] provided corresponding corrections of the altitude-integrated Pedersen and Hall conductivities, and the corrections still can be used.

Zhang & Paxton [22] used ultra-violet (UV) spectrum observations to reconstruct the energy flux and the average energy. On the one hand, the use of global UV images allows for analyzing a “global snapshots” of precipitating electrons, while the DMSP mission provides in situ electron precipitation data at two points for any given moment of time. Only a few periods had more than two satellites operating simultaneously. On the other hand, this [22] approach introduces some uncertainties related to the neutral atmosphere model (MSIS86), the ionosphere model (B3C), and the airglow model (AURIC).

Wu et al. [37] built the FTA model based on the Polar satellite far-ultraviolet data. They derived the precipitating electron energy flux and the average energy from the LBHL and LBHL/ LBHS ratio, respectively. To recalculate LBHL values to an equivalent energy flux, Wu et al. used the scaling factors and techniques described in [38-39]. Due to this, the above discussion on the use of UV data vs DMSP data is generally applicable to the FTA model as well.

The paper by Kamp et al. [34-35] initially addressed precipitating electrons with energies in the range of 30 keV – 1000 keV. These energies significantly exceed
the energy range targeted by other models. Due to this, the direct comparison is inappropriate. The remaining models [17-18, 21, 26-30, 32, 33, 36] rely on the DMSP mission data. Among them, the AFGL [17-18], the Ovation Prime [29-30] (OP), and the Ovation Prime-2013 [32] (OP-2013) models are the most popular ones. The AFGL model is referenced to as Hardy-85 or Hardy-87. This is the first model, which provided the electron energy and the number flux density maps for the geomagnetic conditions characterized by the index $k_p$ values with resolution step 1, i.e. for 0, 1, 2, 3, 4, 5, and $\geq 6$ $k_p$-index bins. Previous models did not provide such a level of granularity. Eventually, Hardy et al. [20] published analytical formulations in the form of Epstein-Fourier series with corresponding tables of coefficients. It allows to use their model directly (without graphical image digitization). In addition, the FORTRAN-77 code of the AFGL model is published (that url is not currently available). All these factors lead to the wide use of the AFGL model. The OP and OP-2013 models are becoming more and more popular nowadays. The OP-2013 model is the extended version of the OP model. The model can be used for geomagnetically disturbed situations. It is achieved by the inclusion of TIMED GUVI observations into the model database. Both OP and OP-2013 models provide a finer specification in comparison with the AFGL model, but they require satellite observations as inputs (solar wind speed, IMF $B_y$ & $B_z$ components). Due to this, the AFGL model may be preferred when the satellite data is not available.

As one can see in Table 1, the electron precipitation models use different parametrizations (input parameters). The general trend is to use space-borne measurements such as the solar wind velocity and the IMF characteristics instead of input parameters like $k_p$, AE, or $D_{st}$ indexes (which are derived from on-the-ground observations). Another trend is to provide a model in a ‘runnable’ form. Recent models including the most popular ones are provided as sources, an online service, or both. However, a few models are formally published, but their usage is complicated or requires explicit permission from the authors.

Most models are based on a physical representation of precipitating electron fluxes. For example, the OP and OP-2013 models consider precipitations as approximately corresponding to the monoenergetic, diffuse, broadband, and ions auroras. The last category just collects all unclassified precipitations. The APM model introduces the diffuse auroral zone, the auroral oval precipitation zone, and the soft diffuse precipitation zone. This zone-based classification corresponds to the used one in the OP/OP-2013 models. At the same time, there are models that utilize purely the ‘technician’ approach and construct separate models for each channel of the DMSP/SSJ4 detector. We expect that such models will eventually adopt some kind of physical representation because the ‘channel-like’ representation could lead to unexpected results. For example, the DMSP F16-F18/SSJ5 detectors do not have channel 11 (central energy 949 eV), but the corresponding data files contain channel #11 records for the (binary) file format compatibility issues. Moreover, for the flight missions up to F15 channels #10 and #11 measure the same energy band. In other words, a simple summation will produce the overestimated total values.

Table 1. General features of high-latitude electron precipitations’ models

<table>
<thead>
<tr>
<th>No.</th>
<th>Model / Refs. / Year</th>
<th>Features</th>
</tr>
</thead>
</table>
| 1   | McDiarmid et al., Ref. [15], 1975 | Data: ISIS-2  
Parameters: electron energy (one of six bands) to choose a map  
Output: maps (invariant latitude vs MLT) of precipitating electron flux average intensity and energy  
Form: printed contour maps and 1D variations |
| 2   | Rice University model / | Data: AE-C, AE-D  
Parameters: MLT, invariant latitude, AE-index |
<table>
<thead>
<tr>
<th>Model</th>
<th>Output</th>
<th>Parameters</th>
<th>Form</th>
</tr>
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<tbody>
<tr>
<td>Spiro-1982, Ref. [16], 1982</td>
<td>Output: precipitating electron energy flux, characteristic electron energy, Pedersen, and altitude-integrated Hall conductivities</td>
<td></td>
<td>Form: analytical formulations with tables of coefficients</td>
</tr>
<tr>
<td>AFGL model / Hardy-1985, Refs. [17-18], 1985</td>
<td>Data: DMSP F2, F4; Satellite Test Program P78-1</td>
<td>Parameters: MLT, MLAT, k&lt;sub&gt;p&lt;/sub&gt;-index</td>
<td>Output: precipitating electron number flux density, energy flux density, and average energy.</td>
</tr>
<tr>
<td>Zhang &amp; Paxton, Ref. [22], 2008</td>
<td>Data: GUVI FUV TIMED (2002-2005)</td>
<td>Parameters: MLT, MLAT, k&lt;sub&gt;p&lt;/sub&gt;-index</td>
<td>Output: energy flux, average energy, and total hemispheric power</td>
</tr>
<tr>
<td>APM model, Refs. [26-28], 2005</td>
<td>Data: DMSP F6, F7 (1986)</td>
<td>Parameters: indexes D&lt;sub&gt;as&lt;/sub&gt; and AE</td>
<td>Output: maps (MLT vs MLAT) of boundaries for DAZ, SDP, and AOP zones; energy flux density and average energy for each zone (independently)</td>
</tr>
<tr>
<td>Ovation Prime, Ref. [32], 2014</td>
<td>Data: DMSP F8-F13 (1988–1998)</td>
<td>Parameters: Solar wind velocity V&lt;sub&gt;SW&lt;/sub&gt; in GSM coordinates, IMF By and Bz, and the IMF Clock angle</td>
<td>Output: digital values – for the each type of precipitations, maps (AACGM MLAT – MLT coordinates) of precipitating particle number flux, energy flux, and auroral power</td>
</tr>
<tr>
<td>McIntosh et al., Ref. [33], 2014</td>
<td>Data: DMSP F1 – F15</td>
<td>Parameters: k&lt;sub&gt;p&lt;/sub&gt;-index</td>
<td>Output: graphical MLAT-MLT maps</td>
</tr>
<tr>
<td>Kamp et al., Refs. [34-35], 2016</td>
<td>Data: SEM-2 / MEPED NOAA POES -15, -16, -17, -18, and -19</td>
<td>Parameters: a&lt;sub&gt;p&lt;/sub&gt;- or D&lt;sub&gt;s&lt;/sub&gt; index, L-parameter, and MLT if zonal variation is accounted for</td>
<td>Output: digital values – spectra density and electron number flux of precipitating electrons with energies in the range of 30 keV – 1000 keV</td>
</tr>
<tr>
<td>ASHLEY model, Ref. [36],</td>
<td>Data: SSJ/5 DMSP F16-F18 (years 2010-2015)</td>
<td>Parameters: IMF intensity B&lt;sub&gt;T&lt;/sub&gt;, Solar wind velocity V&lt;sub&gt;SW&lt;/sub&gt; in</td>
<td></td>
</tr>
<tr>
<td>Year</td>
<td>Models and Sources</td>
<td>Description</td>
<td></td>
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<tr>
<td>2021</td>
<td>GSM coordinates, and Solar wind number density</td>
<td>Output: digital values – MLAT-MLT numerical grid, maps of differential energy fluxes for each of nineteen DMSP SSJ/5 channels, the electric potential, and the electric field</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Form: Python3 code; the required dependencies / coefficients are not provided</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>FTA, Ref. [37], 2021</td>
<td>Data: FUV Polar Parameters: AE-index; AU/AL-driven version as well (the paper [37] describes AE-index version only) Output: digital values – CGM MLAT vs MLT maps Form: Python3 code under the GNU GPL v3 license</td>
<td></td>
</tr>
</tbody>
</table>

## 5 Conclusions

In this paper, we present a review of scientific publications devoted to the research area of empirical modeling of the Earth’s ionosphere precipitating electrons. In total, the review observes twelve models. These models represent the full spectra from the earliest ones till the most recent models (see Table 1). The majority of models (nine of twelve) is derived from the DMSP mission data. McDiarmid et al. [15], the Rice University model [16], Zhang & Paxton [22], Kamp et al. [34-35], and the FTA [37] models are exceptions. However, these models [15-16] were developed before the DMSP mission era. The model by Kamp et al. [34-35] targets energy bands exceeding the registered ones by the onboard DMSP detectors.

Nowadays, the AFGL (also known as Hardy-85 or Hardy-87), the Ovation Prime (OP), and the Ovation Prime-2013 (OP-2013) models are the most popular. The AFGL model gained its favor in the scientific community due to the reasonable resolution, accuracy, and availability of both graphical maps and analytical formulations. Additionally, the model is provided using the FORTRAN-77 codes. However, the Ovation Prime family is gaining popularity nowadays. Both the OP and the OP-2013 models are published in source codes. They provide finer specifications in comparison with the AFGL model, but they require satellite observations as input parameters. As a result, users might still prefer the AFGL model.

Most of the considered models are based on a physical representation of precipitating electron fluxes. However, some other models use the ‘technician’ approach only. For example, some of them are constructed for each channel of the DMSP/SSJ4 detector. As a result, a model user should take into account specific features related to apparatus design.

## Acknowledgements

The reported study was performed within the independent research and development project "Computer modeling of the current system in the Earth's ionosphere". Authors express a special acknowledgement to Alexander A. Namgaladze, Dr. Sci. (Phys. & Math.), Prof., former Head of Near-Earth Environment Computer Modelling Laboratory, Murmansk Arctic University (now retired).

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