Complex analysis of the ionosphere variations during the geomagnetic storm at January, 20, 2010 performed by DIA software and DEMETER satellite data

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Abstract. The DIA software was developed and used for ionosphere research in the Institute of Space Techniques and Technologies of the National Center of Space Research and Technology (Almaty, Republic of Kazakhstan). The software was designed for ionosphere anomalies detection, identifying and analyzing from satellite spectral and wave data from scientific payload installed on the DEMETER satellite. The main task of DIA software is to provide the researcher with a convenient package for detection and identifying of the sources of electromagnetic radiation, variations of the ionic and electronic component of the ionosphere, and other ionosphere parameters from satellite data. Using this software, a complex research of the state of the medium-latitude ionosphere during a geomagnetic storm on January 20, 2010 was done.Electric and magnetic components of the field in ULF, ELF and VLF band is processed and analyzed; as well as temperature, velocity and density of ionic and electronic plasma components and fluxes of energetic electrons at satellite altitude during a storm.

1 Introduction

One of the most informative way of ionosphere research is the spacecraft onboard measurements. Such measurements has a number of advantages and disadvantages. The main advantage of satellite experiments is the possibility of measurements directly inside of studied object. Using a set of measuring instruments on a satellite, a number of ionosphere parameters can be obtained to study its connection with the atmosphere, lithosphere, solar activity, etc. If the satellite at the solar-synchronous orbit (altitude of 600-700 km), it makes about 15 orbit passes around the Earth per day, which provides the opportunity to explore the ionosphere over almost the entire Earth surface. However, this is also a problem, since the possibility of monitoring of short-term variations over certain regions of the Earth surface is practically excluded. Also, due to the fact that the satellite passes over the different parts of the Earth, it is impossible to take into account the diurnal variation of ionospheric parameters over some particular point of observation. The last is rather important when searching for the irregular parameter behaviour.

Artificial Earth's satellites (one or constellation), depending on the payload, accumulate and transmit to ground a huge amount of data in its different form: raw data; partially processed data (waveform, spectrograms), etc. The amount of this data can reach tens of Gigabytes. Satellite scientific mission developers are often provide scientists with data in a raw form, for example, only time, coordinates and parameter value. Therefore, further research requires a great deal of time for scientific data processing by various software, especially if it concerns complex research.

The one of the interesting satellite projects for the study of the ionosphere and ionosphere-lithosphere coupling was the French satellite DEMETER (Cussac et al., 2006), which active period was more than 6 years (2004-2010).In the of Scientific Space Systems Laboratory of the Institute of Space Techniques and Technologies (ISTT) of the National Center for Space Research and Technologies (Almaty, Republic of Kazakhstan) the development of a software for complex analysis of ionosphere parameters from satellite data was initiated. This acitivity was started within the framework of the project of creation a Kazakhstan Satellite System for Scientific Purposes (Moldabekov et al., 2011). Later, this software was adapted for DEMETER data analysis.

Thus, the developed DIA (Detection of Ionosphere Anomalies) software package and data from scientific instruments onboard DEMETER satellite allow to provide a complex research of the various in the ionosphere and correlate them with natural and human-induced phenomena.

It is known that, geomagnetic storms, as a powerful change in the Earth's magnetic field due to the ejection of a huge number of high-speed streams (solar wind, shock wave, charged particles from space) during an increase in solar activity, somehow affect many parameters of the ionosphere. In this paper the state of the medium-latitude ionosphere according to its various parameters from DEMETER Satellite and processed using the DIA Software during a geomagnetic storm on January 20, 2010, are considered.

In Section 2 we review the DEMETER satellite and its scientific payload. In Section 3 we develop a new software for complex analysis of ionosphere anomalies based on input data from DEMETER scientific instruments. The example of DIA Software implementation for scientific research of ionosphere parameters during geomagnetic storm at January, 20, 2010 are given in Section 4 and main results are outlined in Section 5.

2 DEMETER Satellite

DEMETER (Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions) was to the investigation of the Earth ionosphere variations due to seismic and volcanic activities and was developed by French National Centre of Space Studies (CNES) in collaboration with scientific institutes of Poland, Japan, USA et al.

Of particular interest to DEMETER is that it was the first satellite to provide a complex research on ionosphere variations associated with natural and artificial hazards on Earth.

The satellite weight was 130 kg and it was launched on June 29, 2004 from the Baikonur launch site into a solar-synchronous orbit of the Earth with a height of 710 km and an inclination of $98.3°$. According to the mission program the scientific on-board experiments was stopped on December 9, 2010.

The science payload is composed of five instruments:

1. Instrument Champ Electrique (ICE), three electric sensors from DC up to 3.5 MHz (Berthelier et al., 2006);

2. Instrument Magnetometre Search Coil (IMSC), three magnetic sensors from a few Hz up to 18 kHz (Parrot et al., 2006);

3. Instrument Detecteur de Plasma (IAP), an ion analyzer (Berthelier et al., 2006);

4. Instrument Detecteur de Plasma (IDP), an energetic particle detector (Sauvaud et al., 2006);

5. Instrument Sonde de Langmuir (ISL), a Langmuir probe (Merikallio, 2006).

ICE instrument is designed to measure variations of electric field in the ionosphere in Ultra Low Frequencies (ULF) band (0-20 Hz), Extremely Low Frequencies (ELF) band (0-1250 Hz), Very Low Frequencies (VLF) band (0,02-20 kHz) and High Frequencies (HF) band (0-3.3 MHz). IMSC magnetometer is designed to measure magnetic field variations in the ionosphere. The instrument consists of 3 orthogonal magnetic antennas connected to the preamplifier with a shielded cable 80 cm long. At the output of the IMSC device, the researcher is provided with magnetic data in ELF band (0-1250 Hz) and VLF band (0-40 kHz). The IAP ion analyzer is designed to measure the composition of H^+, He^+ and O^+ ions, their density, temperature and velocity. The charged particle detector IDP is designed to detect weak flows of electrons in the range from 70 to 1000 keV. The output of the IDP for seismic regions of the Earth is the energy spectrum of electrons (cm^2/s/ster/keV). For the rest of the Earth surface, the electron fluxes for 3 energy ranges (90.7 - 526.8 keV; 526.8 - 971.8 keV and 971.8 - 2342.4 keV) are provided. The ISL Langmuir probe is designed to measure the density of electrons and their temperature.

3 DIA software

The DEMETER project team developed a different modules and software to extract and analyze data from output files, but all were not very convenient for the researcher. Therefore, it became necessary to create a universal tool that is simple and accessible to any user. The main task of the DIA software is to provide the researcher with a convenient tool for satellite data processing and analyses for detection and identifying the sources of various disturbances in the ionosphere.

The main functions of the system are:

– visualization of all types of scientific data from DEMETER satellite;

– data mapping on different types of maps;

– data multiupload (simultaneous upload a large amount of data);

– constructing of a spectrogram from a time series data row;

– signal-to-noise ratio calculation for studying how the radiation from the transmitters affect on the ionosphere.

3.1 Input data

DIA package uses data files with different APIDs (Application Process IDentifier - is DEMETER project files identifiers):

- – waveform of three components of the electric field in the ULF band (APID 1129);

- – waveform of three components of the electric field in the ELF band (APID 1130);

- – waveform of one component of the electric field in the VLF band (APID 1131);

- – spectrum of electric field in the VLF band (APID 1132);

- – waveform of one component of electric field in HF band (APID 1133);

- – spectrum of the electric field in the HF band (APID 1134);

- – waveform of three magnetic field components in the ELF band (APID 1135);

- – waveform of one component of the magnetic field in the VLF band (APID 1136);

- – magnetic field spectrum in the VLF band (APID 1137);

- – ions parameters (density, temperature and velocity) in "Burst" mode (APID 1139);

- – ions parameters (density, temperature and velocity) in "Survey" mode (APID 1140);

- – spectrum of energetic electrons in "Burst" mode (APID 1141);

- – spectrum of energetic electrons in "Survey" mode (APID 1142);

- – parameters of electrons (density, temperature and potential) in "Burst" mode (APID 1143);

- – ion parameters (density, temperature and potential) in "Survey" mode (APID 1144).

These files can obtained from the DEMETER project webpage: http://demeter.cnrs-orleans.fr/.

3.2 Data Series Operation Mode

In data series operation mode the graph is plotted as shown in Figure 1. For multi-component measurements, all graphs are displayed in the same field in different colors with the ability to select the row of interest.

The main window consists of 3 parts:

- – top main menu;

- – right control panel;

- – the graphics display area.
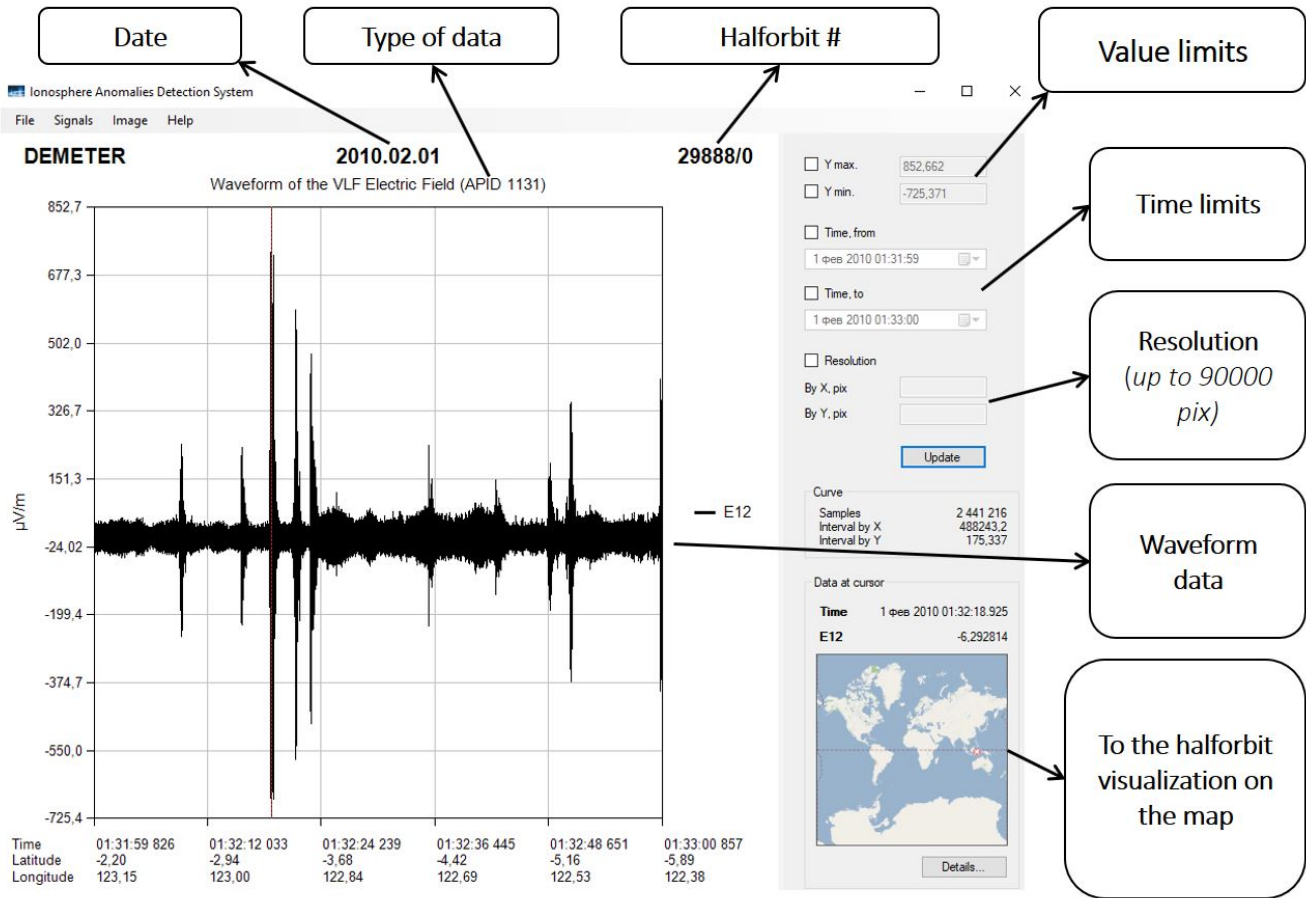
Figure 1. The screenshot of main window of the DIA package with an example of graph of electric field in VLF band.

The top main menu of the software allows the researcher work with data files, selected signals and images. The user can open, print or preview the data. It's possible to open one or several data files, print the resulting chart from the graphic display area, and the preview the image before printing or saving. When you click the "Signals" button, a row action window appears. Researcher can perform the following actions on data series:

- – choose to display or hide a series of data in the chart;

- – to save the necessary data row in the "Time (DDMMYYHHMMSSMLS) — Value" format (MLS here is milliseconds, and the quantity of letters corresponds to the number of signs of date);

- – to build an autospectogram for the selected data row using the fast Fourier transform algorithm;

- – to perform HF or low-frequency (LF) row smoothing;

– to save a data row as a *.wav audio file.

LF smoothing is performed as follows: for a given window there is an average value of the parameter, which is entered in the first point of the new row. The window is shifted by 1 point and the action is repeated. Then, its LF component is subtracted from the initial data row. The HF component is the difference between the original data row and its LF component.

In addition, for the selected time series, the software builds a spectrogram - the spectrum module in the sliding windows is calculated. The length of the spectrogram is equal to the length of the original data row. Each column of the histogram is a spectrum that has a length equal to half the length of the window. When the cursor moves along the spectrogram field, time (horizontally), frequency (vertically) and spectrum amplitude value are shown. The right control panel in time series data operation mode is intended for control and operations with values loaded into the software.

The top two fields "Y max." and "Y min." are used to scale along the Y axis.

The two following fields, "Time, from" and "Time, to", are used to scale along the X axis.

The "Resolution" feature allows to set arbitrary values for the chart size as desired by the user.

The "Curve" information field displays the service information about the chart: the number of points, grid spacing along the X and Y axes.

The small map in the "Data at cursor" field displays the position of the satellite for the loaded data on the world map, and it also acts as a link for map window opening.

"Details" section give a detailed information for each graph point. The composition of parameters varies depending on the type of data.

The data service information is contained in each data file and consists of 4 blocks:

– Block 1: General Header;

– Block 2: Orbital and Geomagnetic Parameters;

– Block 3: Attitude Parameters;

– Block 4: Measured values.

3.3 Spectral Data Operation Mode

Some of the data files (APID 1132, APID 1134, APID 1137 and APID 1141) contain spectral information which displayed as spectrgram in the central window of the Software.The examples of such spectral data visualisation will follows.

Same as in time series rows mode, the Software window in the spectral data mode is also divided into 3 parts: the upper main menu; right control panel and graphic display area.

In the graphic area, a spectrogram is displayed, where time and geographical coordinates of the satellite position are given for electromagnetic data on the X axis, for the Y axis - frequency in Hertz, and on the Z axis in the color scale the measured values are presented in the log scale $\log(\mu V^2/\text{m}^2/\text{Hz})$ for electrical measurements or $\log(\text{nT}^2/\text{Hz})$ - for magnetic. For the spectrum of

energetic electrons along the X axis, time and geographical coordinates of the satellite position are also given, for the Y axis, the electron energy in keV, and for the Z axis measured values are given in the color scale in units part/cm^2/ster/keV.

The following information can be obtained from spectrogram:

– amplitude of the spectrum at a certain frequency;

– spectral density;

– signal-to-noise ratio for disturbances at radio transmitter operating frequencies;

– search for "whistles" caused by lightning discharges.

It is possible to plot of values at a certain frequency (Curve on frequency, see Figure 2). Similarly, the "Spectral density" option allows to display the spectral density for a given frequency range as a graph. The "Signal-to-Noise Ratio" function provides a
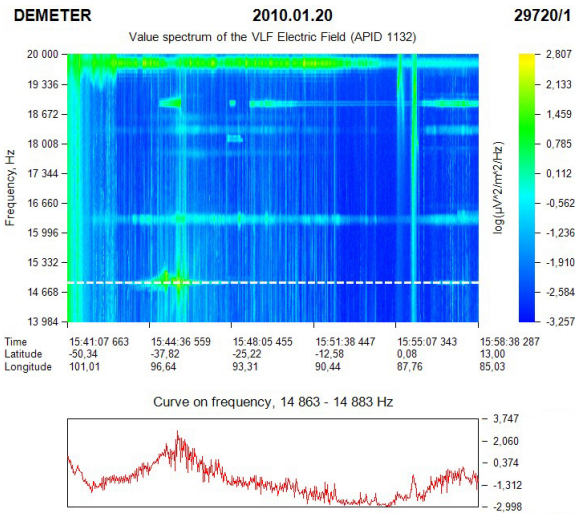
Figure 2. Spectrum of the electric component of the electro-magnetic field and amplitude (bottom graph) at the operational frequency 14,881 kHz (dash line) of the VLF transmitters of the Alfa (RSDN-20) radio system.

diagram for a given ratio for a particular transmitter. The "Base Frequency" field indicates the frequency of the transmitter, and the "Frequency df" window indicates the frequency range over which the radiation is propagated from the base frequency. The algorithm described in article (Molchanov et al., 2006) was used for this option. Here, the signal-to-noise ratio was determined by the formula: $SNR = 2A(F_0)/[A(F_+) + A(F_-)]$. Here, $A(F_0)$ is the spectral density amplitude at transmitter operating frequency F_0, $A(F_+)$ and $A(F_-)$ are amplitudes of spectral density of disturbance width higher and lower than base frequency of transmitter respectively.

The result of such analysis can be a spatial distribution of the electric field intensity in the southern and northern magneto-conjugate regions above the VLF transmitter NWC 19,8 kHz (see Figure 3). Naval Communication Station Harold E.Holt

(NWC) is located on the northwest coast of Australia and uses for submarines communication.The DIA Software has the possibility of displaying the amplitude of the analysed parameter in color along the trajectory of the satellite, which makes it possible the visual evaluation of the changes in ionosphere over the studied territory.
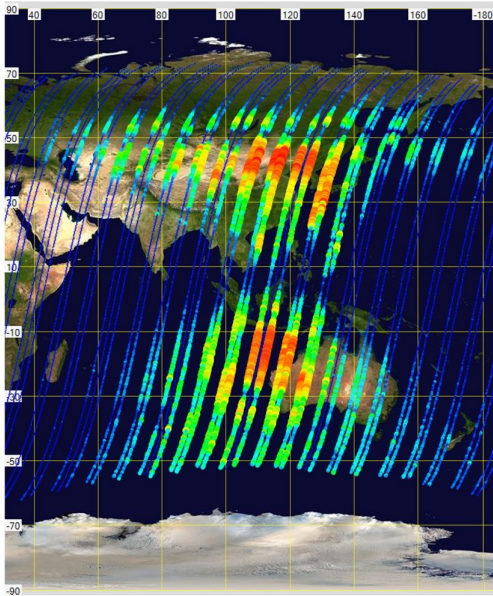
Figure 3. The electric field disturbance (signal-to-noise ratio) in the southern and northern magneto-conjugate regions above the NWC VLF transmitter with operational frequency 19,8 kHz.

The "Whistlers Searching" function allows user to research the disturbance of the ionosphere caused by lightning discharges using vertical structures on a spectrogram (thin vertical lines - "whistlers"). The DIA analyse the spectrogram of the electric and magnetic field in the frequency band from 2 to 10 kHz and find whistles corresponding to the coefficients settled by user. The coefficients control the spectral width of the whistle search, i.e. its sensitivity. The result of the analysis is given at the bottom of the spectrogram, as shown in Figure 4.

Also, it's possible to export the amplitude of the spectrogram for the selected time point to the *csv* format.

To study the low-energy electrons precipitation at the height of low-orbital satellites, in addition to spectrograms displaying, it is also possible to obtain a graph for the selected energy, energy range (spectral density) and for a time point. An example of such a spectrogram is shown in Figure 5. Here, below the spectrogram window, a graph is shown for electrons with an energy of 108.5 keV for the DEMETER half-orbit No.29720/1, 20.01.2010.
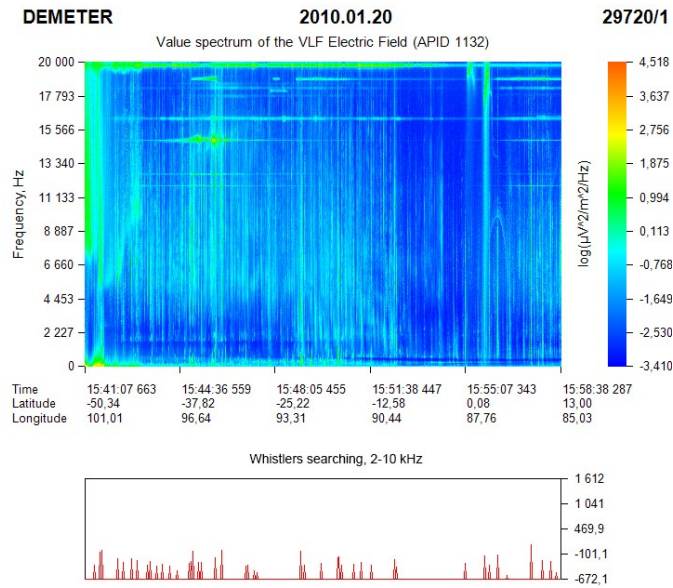
Figure 4. Spectrogram of the electric field in the VLF band with the result of whistlers searching (vertical red lines on bottom graph) with coefficient 3.
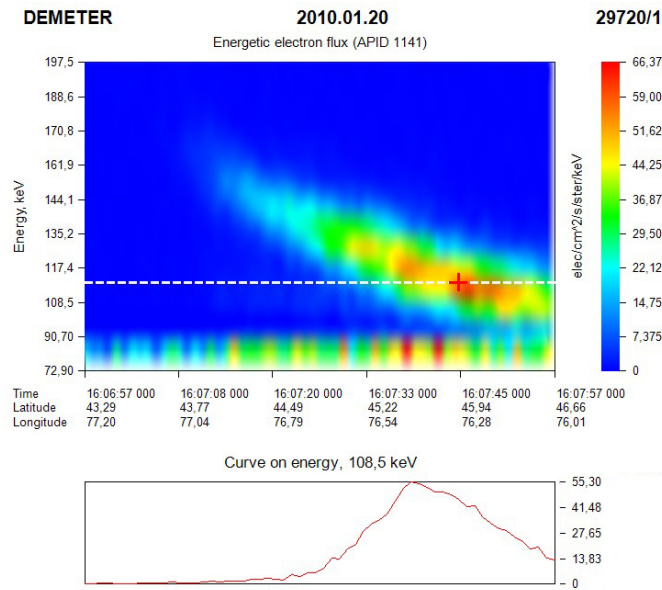
Figure 5. The energetic electrons spectrogram and graph for electrons with an energy of 108.5 keV for the ascending half-orbit of DEMETER satellite No.29720/1, 20.01.2010.

3.4 Data mapping

Another function of the DIA package it is data mapping - showing data place and value on different map types. The software supports 6 types of maps: 4 offline maps (geographic, topographic, tectonic and contour) and 2 online maps (Google Maps (satellite, political and terrain) and Bing Maps.

The software allow to operate of the different visual effects of the satellite track and user defined objects on the maps. User can see the satellite track and show or hide the visualisation of the south and north magnetically conjugate points at the altitude 110 km.

Also, the researcher can display on the map along the orbit track the values of the graph at frequency, spectral density and signal-to-noise ratio. The amplitude is displayed as circles with different diameter and color depending on its value - from a small point of blue color with minimum values to a circle of larger size of red color at maximum (Figure 3).

3.5 Data multiupload

Another advantage of DIA is the data multiupload, i.e. the simultaneous loading and processing of a large amount of similar type data. Some scientific tasks require the analysis of data over a geographical area of the Earth (the impact of LF transmitters on the ionosphere, the study of the earthquakes precursors, etc.), and since the satellite pass through the same territory about once per 3 days, scientists face the task of choosing the half-orbits passed under the region of interest and a complex analysis of data from these half-orbits.

The DIA allows you to simultaneously load data with the same APID. It is allowed to load data together with APID 1143 and 1144, as well as APID 1139 and 1140, since this is the same type data, but with different measurement frequency.

4 Analysis of the middle-latitude ionosphere parameters during the geomagnetic storm on January, 20, 2010

On January 20, 2010, various geomagnetic observatories of the world detected a geomagnetic storm (see Figure 6). The deviation of the Earth's magnetic field from normal during a three-hour interval is defined by the K-index. Kp index is calculated as the average value of K-indices determined at 13 geomagnetic observatories located between 44 and 60 degrees of north and south geomagnetic latitudes. Its range from 0 to 9. Kp reached its maximum value between 15 and 18 UT. According to the "Alma-Ata" geomagnetic observatory, at the same time, magnetic field disturbances were observed in all 3 magnetic field components (see Figure 7).

At the same time, according to the website www.spaceweatherlive.com there was an increase in the parameters of the solar wind and the intensity of the interplanetary magnetic field (Figure 8).

During the maximum of these events ($\sim 16:00$ UT), the ascending orbit of the DEMETER satellite passed over the territory of Kazakhstan. The initial half-orbit time is 15:40 UT, and the final - 16:15 UT. No obvious disturbances were observed in the ULF electric field band (0-20 Hz). Analysis of the electric field in the ELF band at satellite altitude showed the presence of low-frequency electrostatic vibrations on the spectrum (horizontal structures in the left part of the spectrum in Figure 9). These
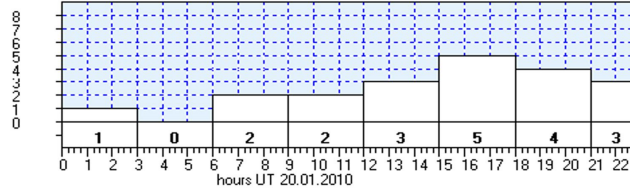
Figure 6. Values of Kp index on 20.01.2010.
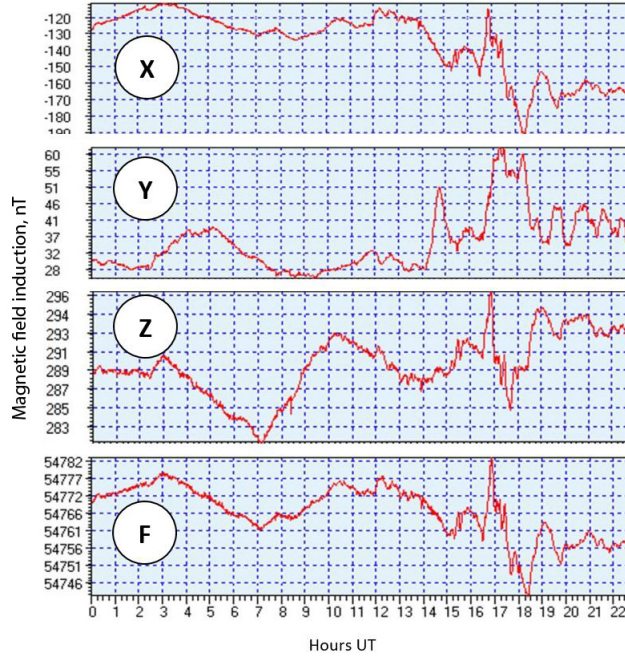
Figure 7. The intensity of the geomagnetic field at the "Alma-Ata" Observatory on 20.01.2010. X, Y, Z components and full field (F).

are bursts of electrical oscillations at 100-400 Hz frequencies, which are usually observed by the satellite in the zone of aurora polaris at various altitudes. Most often, these bursts are explained either by the crossing of small-scale spatial disturbances by satellite, or by the current generation of ion-sound or ion-cyclotron oscillations (Molchanov, 1985). However, in our case, these disturbances are observed at medium latitudes ($32° - 47°$ N), but it is quite difficult to associate them with a geomagnetic

5   storm, since for other similar half-orbits, under calm geomagnetic conditions, such fluctuations were also observed.

    In the right part of the spectrogram in Figure 9, plasmospheric hisses are apparently observed in the frequency band $\sim$ $450 - 550$ Hz. These radiations occur quite often and are dispersed throughout the plasmosphere with minor variations in intensity. In our case, probably, these noises were amplified just by electrons precipitation. The vertical structures on this spectrogram are electronic whistles caused by lightning discharges in the atmosphere.

10   Data from the IMSC magnetometer is quite "noisy" and it is not possible to analyze fine structures in this case.
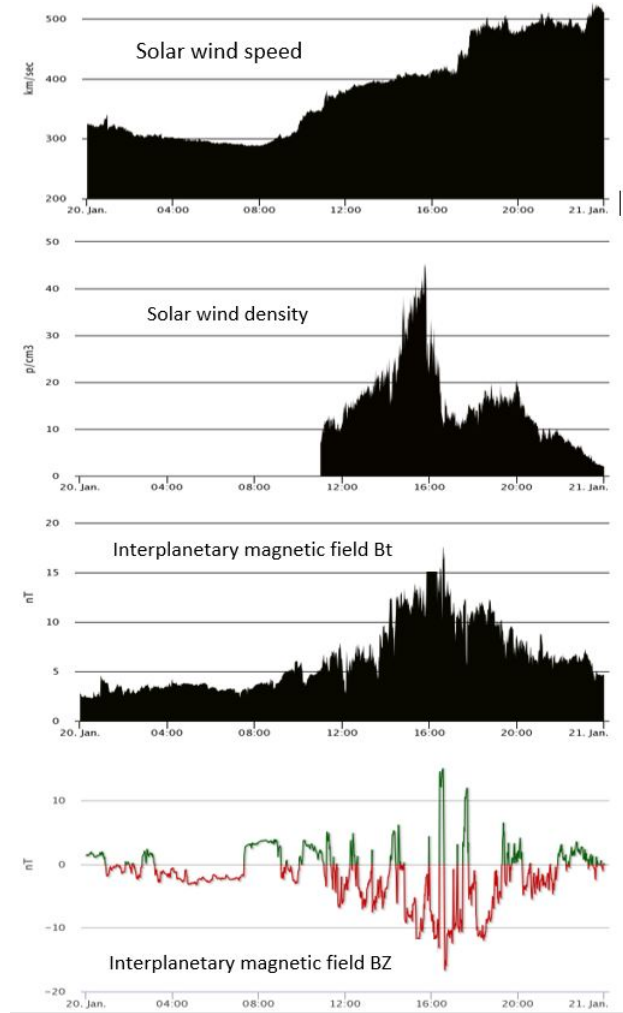
Figure 8. Parameters of solar wind (speed and density) and interplanetary magnetic field strength on 20.01.2010.

According to data from the IAP instrument (Figure 10), we can see that there was a increase in the temperature and velocity of ions from 16:03 to 16:08 UT with a maximum of 16:05:40, over the Central Tien Shan area $\sim 41 - 42°$ N. Also, there was a significant decrease in the concentration of oxygen ions and its alignment over the area of the Gobi desert at the level of 30-40 part/cm^3. In the helium and hydrogen ions density, minor variations and a general increasing tendency to north in latitude were observed.

The spectrogram of the IDP instrument (Figure 5) shows that from 16:07:15 to 16:08:33 electrons with an energy of 160 keV from the Earth's internal radiation belt are precipitated. The length of that precipitation at the satellite altitude is about 300 km with maximum at $\sim 46°$ N.
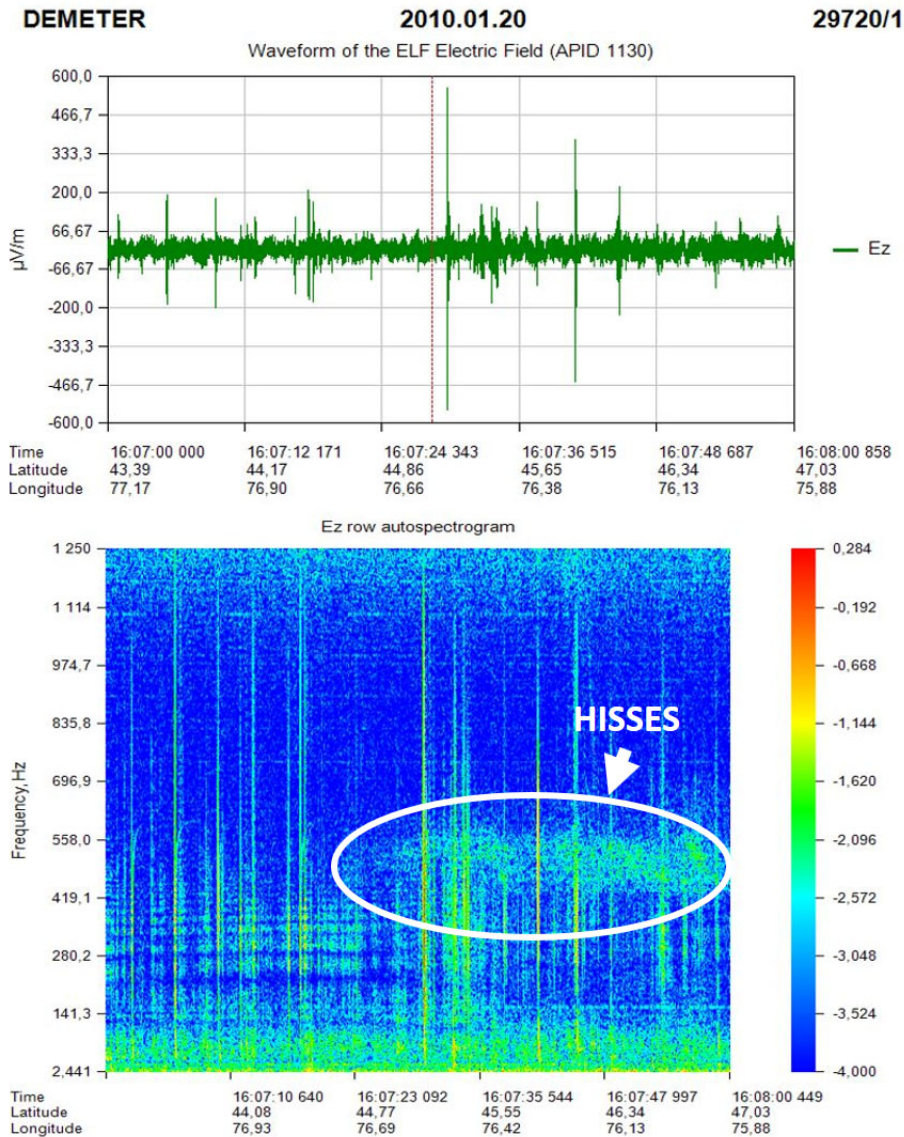
Figure 9. Graph and spectrum of electric field strength in the ELF band for the ascending half-orbit No.29720.

The behavior of energetic electrons trapped in the Earth's Van Allen radiation belts has been extensively studied, through both experimental and theoretical techniques. During quiet period, energetic radiation belt electrons are distributed into two belts divided by the electron slot at $L \sim 2.5$, near which there is relatively low energetic electron flux.

It is well known that large-scale injections of energetic particles into the outer radiation belts are associated with geomagnetic storms which can increase trapped electron population up to 105 times (Li and Temerin, 2001). In most cases, these injections
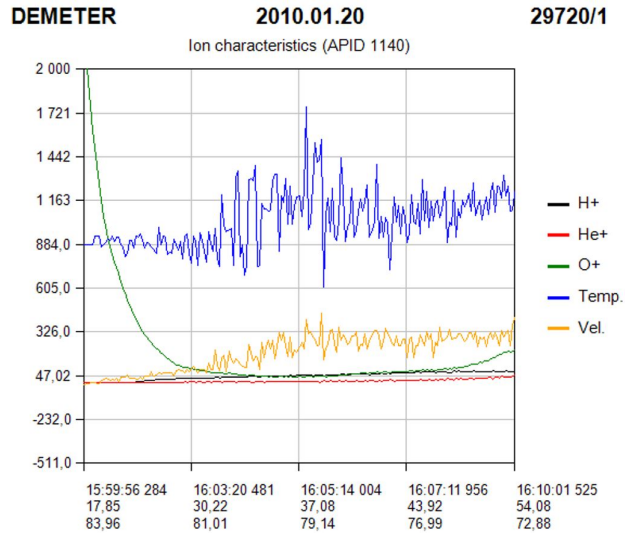
Figure 10. Temperature, velocity and density and of ions at satellite height for half-orbit No.29720.

do not penetrate into the inner radiation belt. Only in case of biggest storms, the inner belt gain a new population of energetic electrons (e.g. Baker et al., 2004).

Observations by the DEMETER near the powerful VLF transmitter NWC have shown that this transmitter causes heating of electrons and ions in the ionosphere at the satellite altitude (700 km), affecting around 500,000 km^2 area (Parrot et al., 2007).
5   There was shown increases in energetic electrons in the range 91–527 keV caused to NWC. Further experiments based on DEMETER wave and particle data show the significance of NWC upon electrons in the inner radiation belt and enhancements in the 100–600 keV drift-loss cone electron fluxes at low L values are linked to NWC operation and to ionospheric absorption (Sauvaud et al., 2008). Such enhancements, termed "wisps" and looking like on Figure 5, are only detected eastward of the transmitter location projection on the satellite high, as expected from the electron drift motion, and at energies that are consistent
10   with first-order equatorial cyclotron resonance between the NWC transmissions and electrons interacting in the vicinity of the magnetic equatorial plane (Gamble et al., 2008). These authors conclude that the NWC transmitter have a good position for potential influence upon inner radiation belt > 100 keV electrons.

In our case, the region in which an increasing of energetic electrons has been observed is the northern magneto-conjugate region of the NWC transmitter and it may well be, that the observed electron precipitation are related to the operation of the
15   NWC transmitter and the effects of a magnetic storm.

5 Conclusions

An original DIA package for detection, identification and analyzing of ionosphere anomalies from satellite spectrograms and time series rows data from instruments onboard DEMETER satellite was created. Using this software, the research of ionosphere parameters variations caused by various artificial and natural factors are provided in the ISTT.

The scientific data processing and visualization technologies used in the development of DIA can be used in the creation of software for other scientific space missions.

The application of the developed software on the example of complex analysis of the state of the medium-width latitude ionosphere according to its various parameters based on satellite data during a geomagnetic storm on January 20, 2010 is considered. According to these data, the presence of electrostatic vibrations in the frequency range of 100-400 Hz, which are quite difficult to connect directly with the geomagnetic storm, was revealed in the ELF spectrum of electric field strength. Also, there was variations in the temperature and velocity of ions, however, they fall at lower latitudes and it is also quite difficult to connect them with the effects of a geomagnetic storm, since similar variations were observed for quite half-orbits. During the maximum of the geomagnetic storm, electrons with an energy of 160 keV from the Earth's internal radiation belt are precipitated.

A Certificate of the Republic of Kazakhstan on the entry of information into the state register of rights to objects protected by copyright No.11767 of 26.08.2020 was received for the developed package.

Author contributions. AL proposed the idea and concept of the paper, made analytical calculations, wrote the initial version of the paper, and took part in the revision of the paper. VF and OK contributed to the data analysis and paper writing. All the authors took part in the results analysis, developing the concept of the paper and writing the initial version of the paper. AL and VF contributed to the preparation of the final version of the paper.

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