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Methods for Monitoring Strong Space Weather Disturbances to Support International Air Navigation

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Abstract—The object of research is the methods for monitoring and forecasting strong space weather disturbances affecting the radiation environment and radio communication during air travels. The monitoring techniques used by the existing space weather centers are analyzed: the U.S. Center, the PECASUS consortium (Great Britain, Finland, Germany, Poland, Austria, Italy, the Netherlands, Belgium, Cyprus, and South Africa), the AJCF consortium (Australia, Japan, Canada, France), and the Russian-Chinese space weather consortium.

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INTRODUCTION

In accordance to the decision of the Council of the International Civil Aviation Organization (ICAO), Amendment 78 was introduced to Annex 3 to the Convention on International Civil Aviation “Meteorological Service for International Air Navigation,” that came into effect on November 8, 2019. It implies the introduction of the space weather information advisory service and the creation of Space Weather Centers (SWXC) to provide information on space weather events. The Russian Federation takes part in the creation of such service as one of the centers. The SWXC must provide the monitoring (including short-range forecasting) of strong space weather disturbances that may have a negative effect on the high-frequency and satellite radio communication, navigation and observation systems based on the GNSS and/or may pose a risk of radiation exposure to people onboard the aircraft.

POTENTIALLY HAZARDOUS SPACE WEATHER DISTURBANCES

The ICAO documents define the threshold values for space weather disturbances that are hazardous for aeronautics (Table 1). The disturbances of lower levels are not practically interesting for aviation, only very strong disturbances are hazardous, which can be caused only by two events in the solar atmosphere (it should be noted that all geoeffective disturbances are sun-induced): coronal mass ejections (CME) and solar flares.

The solar flare is a rapid process of the release of energy of magnetic origin, as a result of which X-ray fluxes and high-energy particles (protons, electrons, and heavy ions) are injected to the surrounding space. The X-ray fluxes reaching the Earth’s ionosphere induce additional ionization on the illuminated side and, hence, the radio wave absorption. This leads to the deterioration of radio communication and the disruption of global positioning systems. The solar proton fluxes during the flare, besides the direct effect on the iono-

Table 1. The threshold values of space weather parameters for the production of advisory messages

Object	Measured characteristic (designation, unit)	Disturbance	
		Moderate	Strong
Navigation (GNSS)	Amplitude scintillations (S4, dimensionless)	0.5	0.8
	Phase scintillations (, rad)	0.4	0.7
	Vertical total electron (TEC, TEC units)	125	175
Radiation exposure	Dose rate (mSv/hour)	30	80
Communication (HF)	Auroral absorption (Kp)	8	9
	Absorption in the polar cap (dB for 30 MHz riometer data)	2	5
	X-rays 0.1–0.8 nm (W/m^2)	10^{-4} (X1)	10^{-3} (X10)
	MUF reduction after the ionospheric disturbance	30%	50%

Note: Kp is three-hour quasi-logarithmic local index of geomagnetic activity.

sphere state and the impact on the radio signal propagation, cause failures in the avionics, lead to the radiation exposure of passengers and aircraft crew.

The space weather monitoring implies the continuous observation and real-time (or with a time lag, that is much smaller than the time of space weather disturbance development) reception of data on the environment state and processes determining the space weather and a disturbance development scenario. The result of such monitoring is the preparation and production of advisory messages about the observed moderate and/or strong disturbances and the scenario of changes in their characteristics in the nearest future. Let us briefly consider the main tasks of the SWXCs providing aviation with space weather information.

RADIATION

The radiation environment on the flight routes is variable, which causes a need to control and to predict it. It is caused by the galactic and solar cosmic rays, that are accelerated during solar flares. Primary protons with energy above 100 MeV are particularly dangerous [1]. Lower-energy protons are shielded by the Earth's atmosphere and do not reach the altitude of aviation flights (8–18 km). The variability of the flux of galactic cosmic rays and its spectrum in the energy region <10 GeV was primarily caused by such phenomenon as the modulation of galactic cosmic rays in the solar cycle: their interaction with solar wind streams, that are highly dependent on the solar activity cycle. As a result of the dependence on the activity cycle phase, the galactic cosmic rays dose varies by 1.5–2 times for the aviation flight altitude in polar regions.

As follows from the results of calculations presented in [1, 10], the galactic cosmic rays dose does not exceed 100–150 mSv even for many-hours flights. At the same time, the annual dose limit is 1 mSv for the public, 20 mSv for nuclear industry employees, and 500 mSv for cosmonauts. In Europe, the annual dose limit for the aircraft crew is 6 mSv per year.

Thus, the radiation hazard from galactic cosmic rays is small and can be significant only for aircraft crews performing regular transpolar flights. The global centers use similar techniques for the dose calculation: NAIRAS (USA), EPCARD (Germany) [5, 10, 11], input data for which are the measured particle fluxes and the atmosphere model. The comparison of calculations by these methods with the KRAT system developed by the authors [2] revealed that relative errors of calculating doses from galactic cosmic rays do not exceed 20%. In many countries, dosimetric control is carried out for crew members. For example, in France, all French airlines are required to carry out dosimetric control of flight personnel. The SIEVERTPN program provides airlines with the method for calculating cosmic radiation doses received during flights taking into account the selected route. Based on the data provided by the airlines regarding the flight and the presence of personnel on board, the SIEVERTPN program calculates an individual dose for each flight crew member every month. Then these dosimetry data are automatically transmitted to the French information system for the registration of SISERI professional dosimetry.

The greatest radiation danger for air travels is solar cosmic rays, that occur after such sporadic phenomena on the Sun as solar flares and CMEs. The dose from the solar cosmic rays can exceed that from the galactic rays by hundreds of times. Even during transatlantic flights, the dose from solar cosmic rays can be more than 2–10 mSv. Transpolar flights become especially dangerous. Currently, ICAO established the follo-

Table 2. The dose rate (mSv/hour) during solar proton events for = 2 and = 7

Flux, particle/(cm^2 s sr)		Altitude, km		
		15	12	9
100	2	6.3	5.0	4.3
	7	3	0.63	0.09
10	2	0.63	0.5	0.43
	7	0.3	0.063	0.09

wing standards for especially hazardous phenomena associated with solar cosmic rays: the radiation environment disturbance is considered moderate if the dose rate is 30 mSv/hour and strong if it is 80 mSv/hour (Table 1). In 2018, ICAO formulated requirements for space weather information providers to ensure radiation safety of flights. The main requirements are as follows:

—the state provider must provide close-to-real-time information on increased radiation exposure with a temporal resolution of 1 hour and information on the characteristics of increased radiation exposure with a time lag of not more than 10 minutes;

—the state provider must provide prognostic and current information about the area with an increased radiation exposure for flight crews and passengers with a time interval, that is smaller or equal to 1 hour, and with a vertical resolution of 1500 m for the next 6, 12, 18, 24, and 36 hours.

Let us consider in more detail particularly hazardous intrusions of solar protons to the Earth's atmosphere. It should be noted that the dose from solar cosmic rays is highly dependent on the spectral index of solar proton events (SPE). When varies from 2 to 7 under the same value of the flux, the dose can change by hundreds of times. Let us consider doses for the most unfavorable conditions of solar proton invasions for the altitudes of 15, 12, and 9 km, the cutoff rigidity of 0.05 (the polar zone), and terrestrial atmospheric conditions (for the summer, the altitude increases by ~1 km).

Let us assume that at the atmosphere boundary, there are SPE proton fluxes of 100 and 10 particle/(cm^2 s sr) (the proton energy is >100 MeV, the spectral index = 2 and = 7). The results of the dose rate calculations are presented in Tables 1 and 2 for = 2 and = 7, respectively.

For one of the most intense (for proton energy >100 MeV) events during solar cycle 23, that occurred on May 10, 2005, the maximum density of the flux of protons with energy >100 MeV was equal to 650 particle/(cm^2 s sr), the spectrum in this event was extremely hard: = 2, the dose rate for civil aviation (at the altitude of 12 km) for the polar regions was 32.5 mSv/hour. This is an extremely dangerous dose rate.

Thus, the task of monitoring solar proton fluxes and predicting their intensity and rigidity (it is carried out using geostationary satellites, such as GOES (USA) and Electro-L (Russia)) is urgent. The data can be recalculated to obtain the dose rate in the stratosphere. A much more difficult problem is predicting the appearance of proton fluxes, their intensity and spectrum. The problem of forecasting solar proton fluxes can be split into three separate tasks: the forecast of geoeffective solar flares, the prediction of proton fluxes by electromagnetic radiation of flares, and the forecast of SPE parameters by the first observations of proton fluxes.

The solution to the first problem is still far from completion. The forecast of the flares cannot be considered satisfactory. Let us consider the second problem in more detail.

The forecast of SPE parameters based on electromagnetic radiation of flares has a horizon equal to the time interval between the registration of electromagnetic radiation of flares and the appearance of proton fluxes in the near-Earth space, which are dangerous for aircraft flights. Usually, this time interval is equal to several hours, but, in some cases, can be smaller than an hour. Here, it is very important to obtain the earliest possible and continuous information on electromagnetic radiation. Currently, this is possible only for soft X-ray radiation of solar flares. Data on X-ray solar flares are available at the website [6] round the clock and with a lag of 1 minute. They allow an automatic determination of the time of the X-ray flare maximum and the density of the X-ray flux at the flare maximum. Although soft X-ray radiation of flares is thermal, nevertheless, according to the Neuperts effect [12], the soft X-ray flux at the maximum is proportional to the integral flux of electrons accelerated in the flare with hard X-rays.

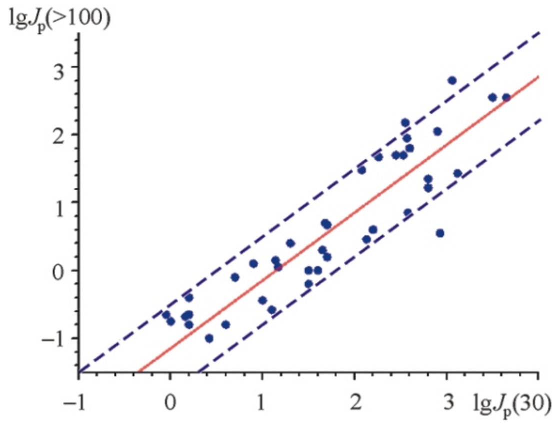

Fig. 1. The prediction of proton fluxes at the maximum of the solar proton event with energy >100 MeV based on proton fluxes with energy of 30 MeV. Data from the GOES satellite for solar cycle 23. The constraint equation: lgJ_p(>100) = lgJ_p(30) – 1.2. The dash line limit the area with the forecast error <250%.

Recently, in view of the above, the interest to the prediction of SPE parameters based on soft X-rays has risen [3, 4, 8, 9]. The authors of [3] described a method for the automated continuous short-term forecasting (nowcasting) of the occurrence of geoeffective proton fluxes with energy >10 MeV in the near-Earth space after the X-ray solar flares. The similar method was proposed in the USA [9]. In these methods, the X-ray flare parameters are used to calculate the probability of observing proton fluxes above the S1 threshold (>10 particle/(cm^2 s sr)), i.e., the forecast is probabilistic. The accuracy of the methods is about 60%.

The prediction of the intensity of protons with energy of 100 MeV is of greatest interest. It is shown in [4] that for such a forecast, it is hardly possible to expect an accuracy greater than an order of magnitude. Indeed, the elementary prediction, when based on the observations of protons with energy of 30 MeV near the Earth, the intensity of protons with energy of 100 MeV of the flux is predicted, can evidently be considered the best possible. Its results are presented in Fig. 1. At the fixed value of J_p(>30 MeV), there is a 20-fold change in J_p(>100 MeV), and the accuracy of the forecast lgJ_p(>100 MeV) is 0.65. The forecast error is 4.5 times; therefore, the real forecast based on electromagnetic radiation of flares is unlikely to allow getting the accuracy of the SPE intensity forecast higher than an order of magnitude.

The range of the SPE intensity at the fixed value of the flux density at the maximum of the X-ray flare according to [4] is very large: up to 7 orders of magnitude. Nevertheless, the use of time parameters characterizing an increase in the X-ray flare allows a significant reduction of the range.

The authors of [3] proposed to predict the occurrence of fluxes with energy above 10 MeV using the X-ray burst proton parameter P, that characterized both its intensity and growth with time:

$$P \quad 10 \quad (T_{r,1}/60 \quad 0.35\lg(J_{\mathrm{X,\,max}} \quad 10^3)) \quad 2 \qquad (1)$$

where $T_{r,1}$ is the time parameter, minute; $J_{\mathrm{X,\,max}}$ is the X-ray flux density at the maximum, W/m^2. The parameter $T_{r,1}$ is equal to the average width of the time profile of the X-ray flare in the range of flux density values from $J_{\mathrm{X,\,max}}/10$ to $J_{\mathrm{X,\,max}}$. Figure 2 shows the location of points corresponding to the solar proton event with proton energy >100 MeV in the $T_{r,1}$–P diagram.

The distribution of X-ray bursts by the parameter P significantly differs from their distribution by the X-ray flux density at the maximum and coincides with the distribution of flares by the maximum intensity of proton events J_p [6]. Hence, it can be concluded that lgJ_p = P + const. Figure 3 presents the real dependence of the intensity of SPE with proton energy >100 MeV. The straight lines correspond to the dependence lgJ_p = P + const. As clear from Fig. 3, the use of parameter P significantly improves the prediction of SPE with proton energy >100 MeV. The intensity for most events can be predicted with an error by 70 times. The use of additional parameters can, in principle, reduce the forecast error to 10 times.

Thus, the methods for the SPE prediction by X-ray radiation give quite large errors when predicting the occurrence of an event and its intensity. A significant improvement can be expected when using methods for predicting the SPE parameters based on the initial increase in the proton flux near the Earth. According to preliminary estimates, the accuracy of the SPE intensity forecast can be equal to 200–300%.

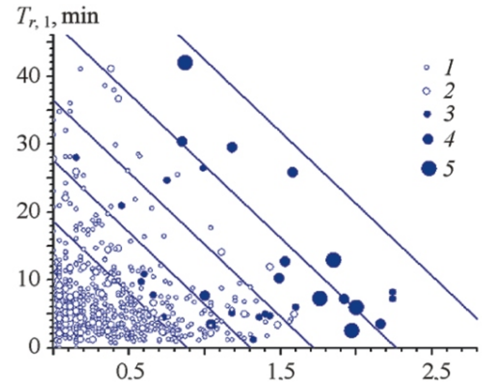

Fig. 2. The dependence of $T_{r,1}$ on $J_{X,max}$ (cycle 23, 0 –90 W) and the level of SPE with proton energy >100 MeV. (*1*) The absence of SPE; (*2*) the absence of SPE due to a high background from the previous events; (*3*) the events with $J_p > 1$ particle/(cm^2 s sr); (*4*) the events with $J_p > 10$ particle/(cm^2 s sr); (*5*) the events with $J_p > 100$ particle/(cm^2 s sr). The inclined straight lines correspond to the values of $P = -1.9, -0.4, 1, 3$.

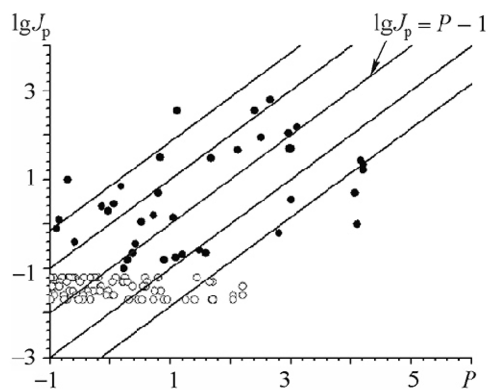

Fig. 3. The dependence of the intensity of proton events with proton energy >100 MeV on the X-ray burst proton parameter P (cycle 23, the western half of the disk).

RADIO COMMUNICATION DISRUPTION

The disruption of radio communication is caused by changes in radio wave propagation conditions due to changes in the ionosphere parameters (electron content, ion composition, temperature). These parameters vary with height in a complex way. Three main layers of the maximum electron content (D ~ 80 km, E ~110 km, and F-layer, that is divided into F1 ~ 170 km and F2 ~ 300 km) experience significant variations in their altitude, particle concentration, and temperature, both regular and sporadic ones. Irregular changes in the ionosphere parameters are associated with the impact of particles and radiation generated during solar explosive events.

The greatest impact on the stability of radio communication with aircrafts in polar regions is carried out by the absorption phenomena in the polar cap. They appear after solar flares in the years of increased solar activity, when proton fluxes invade the polar cap. In this case, the attenuation of radio signals can reach 100 dB and can last up to 10 days. The frequency of such phenomena during the periods of increased solar activity is 15–20 per year.

Other significant phenomena disrupting radio communication are auroral absorptions. The probability of their occurrence is about 40%, but the duration is small and does not exceed 2 hours. Due to the high probability of their occurrence, they can overlap one another. Auroral absorptions are associated with the precipitation of energetic electrons with an energy of >40 keV from the magnetosphere, are observed in the area of the auroral oval, are recorded by riometers located near it, and affect radio communication only if the source or receiver of the radio signal is located in the area of the auroral oval (the latitude is 64 – 67).

Modern aviation crosses this zone during 10–15 minutes. However, during the flights along the oval, radio communication can be disrupted for a long time.

To provide stable radio communication, the monitoring of the ionosphere state variability is needed. One of the most accessible methods for such monitoring is the measurement of the space radio noise absorption using riometers. To monitor the absorption of radio waves in the ionosphere, the chains of riometric stations were created around the world, mainly at the high latitudes.

The riometer operates in the range of 15–50 MHz (the standard frequency is 32 MHz). The operation principle is based on the comparison of radiation received by the antenna of the Yagi type with the radiation of the noise diode. The ionosphere monitoring with riometers is quite advantageous, as it is relatively cheap equipment, reliable and proven in operation. In [7], the relationship between the electron density at the altitude of 100 to 70 km and the total absorption of radio waves is analyzed. It is concluded that riometer data can be effectively used to determine the electron density at the selected altitude. The relationship between the electron density $N_e(h)$ and absorption A (dB) of the radio wave with an angular frequency $\omega = 2\pi f$ has the following form:

$$A = 4.6 \times 10^{-5} \int \frac{N_e(h)\nu(h)}{\omega^2 + \nu(h)^2} dh \qquad (2)$$

where $\nu(h)$ is the frequency of electron collisions with neutral atmospheric particles. While $\nu(h)$ is the parameter characterizing the current state of the atmosphere, $N_e(h)$ depends on the density of the flux of precipitating electrons, as well as on the particle energy. It follows from formula (2) that there is a high correlation between the riometer readings (an increase in the radio wave absorption (dB)) and the absorption in polar caps associated with an increasing electron content, which is confirmed by the corresponding research. It is important to keep in mind the following:

—riometers determine the value of absorption A (the comparison with the reference curve, that is unique for each riometer) at the frequency of 30–38 MHz and, using the original techniques, analyze the frequency of electron collisions with neutral particles $\nu(h)$, with the subsequent determination of concentration $N_e(h)$ at the selected altitude;

—the analysis of methods for the radio wave absorption calculation based on riometer data revealed that the value of radio wave absorption in the ionosphere is determined using the ionosphere models (for estimating the collision frequency) and the model of solar flares and coronal mass ejections (according to GOES and SOHO observations);

—riometer observations regularly conducted across the world are needed as a supplement to satellite observations for analyzing radio wave propagation conditions in the ionosphere. According to the statistical studies and radiometer observation data, threshold values of potentially hazardous disturbances were obtained (2 dB, 5 dB (see Table 1)). It is noted that solar flares are often registered during such events, which are accompanied by proton fluxes, X-rays bursts of the classes higher than X1. Since the spectrum of ionizing electrons is not constant, an accurate relationship between the radio absorption and electron density cannot be expected. However, there are no completely random spectra.

CONCLUSIONS

The space weather monitoring to support air navigation must provide the diagnosis and prediction only of extremely strong space weather disturbances, whose source is solar flares and coronal mass ejections.

The dose limits for the public, aviation personnel, and nuclear industry employees are presented. It is shown that during air travels, the radiation dose received by passengers and aircraft crew can significantly exceed the standards for civil population. The methods are given for diagnosing and forecasting the characteristics of proton fluxes in the near-Earth space, which are hazardous for passengers and crews during the flights. It is demonstrated that the minimum possible errors of calculating maximum proton fluxes can reach an order of magnitude of the flux.

The analysis of riometer data provides additional opportunities for assessing potentially hazardous events during air travels. The monitoring of the ionosphere using ground-based real-time riometer observations should preferably be supplemented with observations from the GOES and SOHO/LASCO satellites.

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