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Space Weather Center to Support International Air Navigation: Infrastructure and Software

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Abstract—The structure of the space weather center to support international air navigation established according to the ICAO resolution is considered. The brief review of space weather events, effects, and related risks is presented. The regulator requirements for space weather centers and their operation features are described.

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INTRODUCTION

The purpose of space weather centers [2] is to provide advisory information about the events in the Earth's ionosphere and magnetosphere, that can affect the flight safety, passenger and crew health. Some of these events, namely, an increase in the total electron content, an enhancement of the radio wave absorption in the layer D, and ionospheric scintillations lead to a decrease in the accuracy of satellite navigation, impede the operation of two-way satellite communications, reduce the range and quality of high-frequency (HF) communication. Other events affecting the whole magnetosphere lead to an increase in the radiation dose rate at high altitudes in the subpolar and polar regions, to the disruption of HF communication and the operation of instrumental piloting tools. They mainly occur during magnetic storms and solar events.

At first, future space weather centers were created to study the radio wave propagation or to be auxiliary military organizations, for example, the Interservice Radio Propagation Laboratory (currently Space Weather Prediction Center, Boulder, USA; swpc.noaa.gov). Since the moment of foundation, this organisation has provided information for aviation and is one of the first permanent space weather centers. The consumers of the center's products, besides civil organizations, are the U.S. Department of Defense and Federal Aviation Administration. The operation of such centers allowed assessing probable risks related to space weather disturbances and the impact of these risks on power industry and aviation. In 2018, the International Civil Aviation Organization (ICAO) developed the documents according to which special duty space weather centers were established to support air navigation. This became necessary, in particular, for the following reasons:

—the approach systems using global navigation satellite systems (GNSS) are becoming increasingly common and are a standard equipment on aircrafts like B748, B788 and some others [5];

—increase in air traffic density requires reliable and accurate operation of satellite positioning systems;

—the distribution of commercial operation of unmanned aircrafts also based on GNSS is growing;

—finally, the frequency of flights along polar and subpolar routes is increasing.

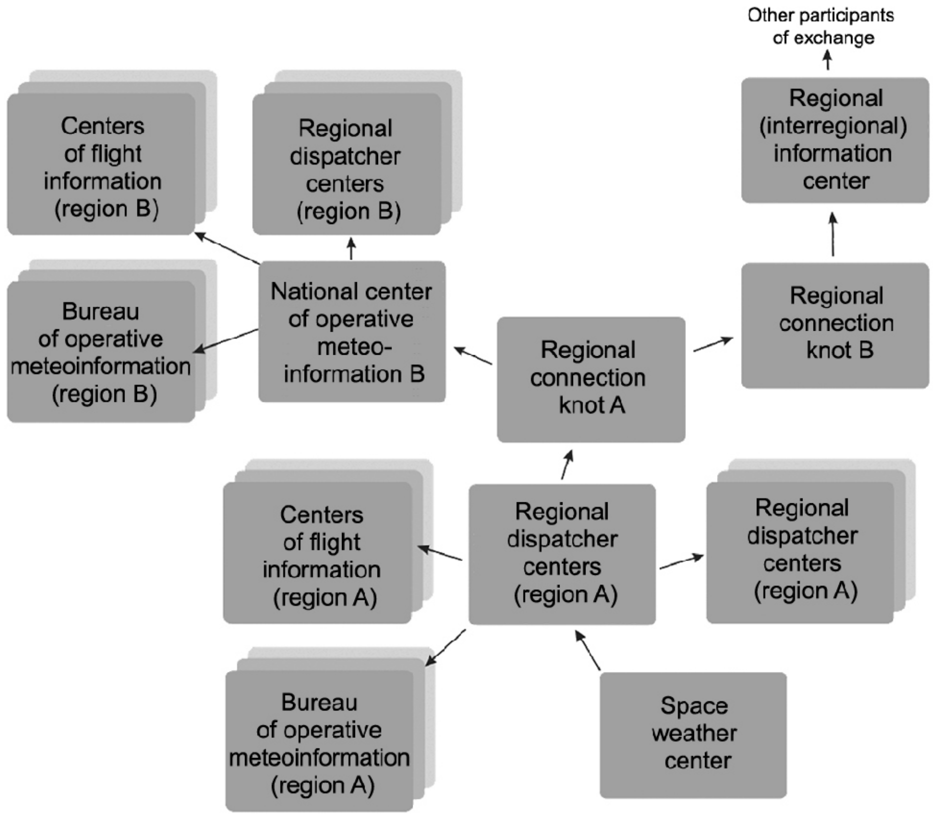

Fig. 1. The dissemination scheme of space weather advisory messages.

A ROLE OF SPACE WEATHER CENTERS TO SUPPORT AIR NAVIGATION

Timely information on probable space weather events should be given to air traffic control, operators of controlled air space, meteorologists, and staff (crew members). To meet this aim, ICAO regulates standard procedures, types, and methods of notification of all air traffic participants. Four types of these notifications define the most likely situations arising due to space weather events:

—reduced quality, range, and performance of HF communication;

—reduced bandwidth (to zero) of satellite communication systems;

—decreased accuracy, in particular, to the complete inoperability of satellite positioning systems;

—increased ionizing radiation exposure by the crew and passengers during flights.

In addition, ICAO also regulates addressees responsible for their further interpretation and dissemination: these are area control centers, flight information centers, and bureaus of meteorological notifications. Such advisory messages are delivered using the same technologies and networks as for delivering information on tropical cyclones, volcanic ash, and weather phenomena. The dissemination scheme is presented in Fig. 1.

As there can be many options for the implementation of such centers, the space weather center coordination group (SWXCCG) formulated joint decisions on many aspects of the operation of space weather centers in support of international air navigation. While the method for the provision of advisory messages and general organizational issues of their dissemination were documented by ICAO, the concepts for organizing the operation of space weather centers have remained unregulated.

The key difference in the concepts of space weather centers is a degree of the human involvement. There are two opposite concepts. In accordance to the first concept, a human receives information about the space weather state and, based on it, forms an advisory message about expected phenomena. On the contrary, in the second concept, the automated system browses the incoming information about the space weather state and detects facts based on which advisory messages will be formed. Here, the human can intervene, but its participation is required only in the situations not implied by the system. The Space Weather Center

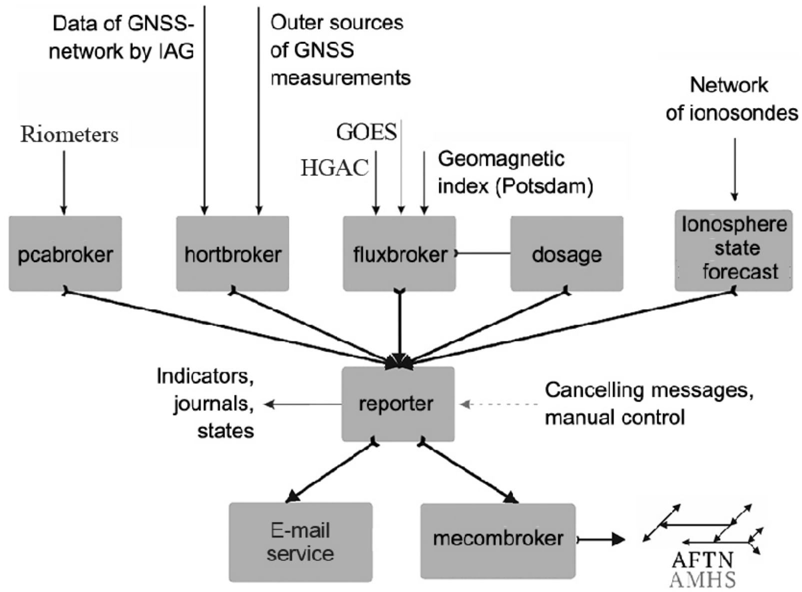

Fig. 2. The scheme of the components of the automated system for the preparation of advisory messages, data transmission paths, possible interactions with operator, and message delivery methods. Explanations are given in the text.

founded to support international air navigation in the framework of the ICAO initiative based on Fedorov Institute of Applied Geophysics (IAG) follows the concept of full automation.

AN AUTOMATED SYSTEM FOR PREPARATION OF ADVISORY MESSAGES

The concept of full automation implies the system operation without the human involvement. The data reception, the processing, production, and delivery of advisory messages are performed automatically. For control, the limited number of indicators and control elements is derived for a situation requiring human intervention. For example, before sending an advisory message in the network of aviation meteorological support, the system delays them for a minute to give the system operator time for making a decision about this message.

The architecture of the center was developed to implement such concept. It consists of three logically separated groups of components (data sources; decision-making system; advisory message delivery system) and has the following main objectives: the automatic operation without the human involvement; the fault tolerance at the level of data sources; the fault tolerance at the level of the decision-making system.

The logical separation of the components comes to the creation of rather isolated operational system units, each solving one problem. When developing the software, the principle similar to the KISS ("keep it simple stupid," http://people.apache.org/~fhanik/kiss.html) is used. This facilitates the problem of searching and eliminating both operational problems and the problems with the components themselves. In addition, the separation eases the organization of fault tolerance: the components can be duplicated, both locally and territorially at another place (Fig. 2).

The implementation of the space weather center services is the set of components: data brokers that receive and prepare data, the decision-making system, and delivery agents. The space weather center utilizes data of the heliogeophysical complex on board the Elektro-L No. 2 satellite: the images with measurement data of the complex are available only via the terminals of the autonomous data reception system. The system receives data from meteorological satellites, SEIS (Space Environment In-Situ Suite) complexes, and X-ray solar sensors of GOES satellites (the series of geostationary operational environmental satellites), the current parameters and forecasts of the planetary geomagnetic index (Helmholtz Centre Potsdam), the network of ground-based GNSS stations (Fedorov Institute of Applied Geophysics (IAG) and IGS), riometers (Arctic and Antarctic Research Institute), as well as model data on the dose rate during aviation flights and data of the SIMP ionospheric model (IAG).

Data of high-energy particle counters, X-rays, as well as the values of the planetary geomagnetic index are collected by the first data broker that is technologically called "fluxbroker" (Fig. 2). This component

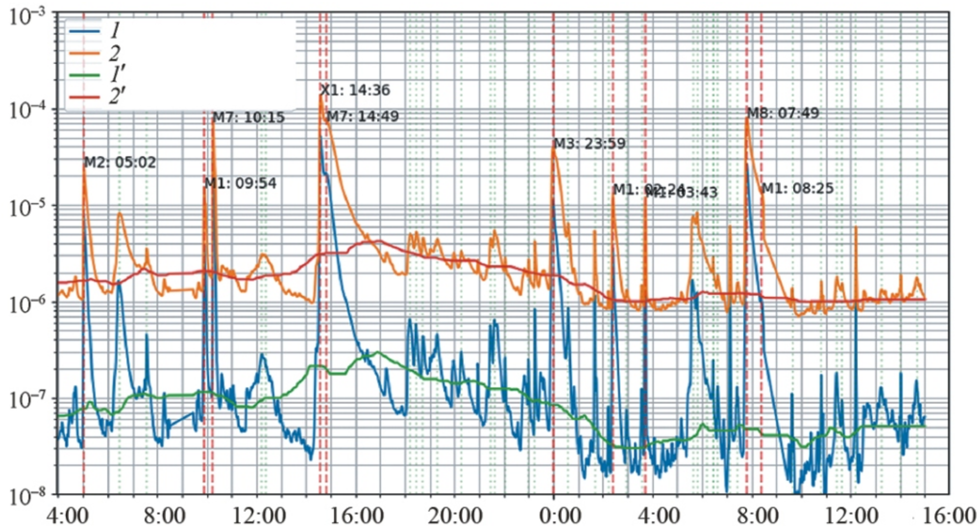

Fig. 3. The X-ray flare and subsequent proton events on September 7–8, 2017. (*1*)   = 0.5–4 nm; (*2*)   = 4–8 nm; (*1* , *2*) the median for the respective wavelength.

extracts data using several embedded methods and provides a software interface for the access to the copy of these data. The component stores retrospective data for two weeks. This is necessary for the operation of the other components that require retrospective data for the correct assessment of space weather conditions. Like any other system components, fluxbroker saves its state and, in case of a programming error or a stop by command, will recover the functioning without loss of data.

The second data broker, hortbroker, receives information from the network of ground-based GNSS stations of IAG and the international IGS network and determines the geographic coordinates of the zones with an exceeding of the parameters of total electron content and ionospheric scintillation. The regulator requires indicating such zones using rectangles with a minimum step of 5 . However, such zones are searched by the Marching Squares algorithm, which allows the subsequent reporting of anomalous zones with a complex geometry. The component uses the programming interface to provide information about the active and recently deactivated zones.

The third data broker, pcabroker, uses measurement data from the riometric stations and the model for the prediction of absorption in the layer D for providing information about the attenuation and maximal applicable frequency of HF communication. Using the software interface, the component reports geographic coordinates of the zones with the exceeding of permissible parameters of attenuation and reduction of the maximum applicable frequency.

The fourth component, dosage, based on the data on high-energy particles, calculates the dose rate during the flights at different altitudes in the regions limited by the specified latitudes, taking into account a season and the parameter K of the solar cycle phase. This broker stores in memory and regularly updates the dose rate map with a spatial resolution of 1 and 1 km in altitude.

The decision-making system, that has the technological name “reporter,” is the central part of the automated system. The component implements a discrete-event model (like in [1]). This makes it easier to test the system by simulating the speed, time, and input data. The logic of the discrete-event model, in addition to the tracking of the excess of regulated parameters, also registers complex events such as solar flares and magnetic storms by the correct processing of all their phases. In particular, the flare detection (Fig. 3) is based on the certain scheme of software detector readings, that detects a dramatic increase in high-energy X-rays. As soon as their dramatic increase is detected, the respective peak is searched in the low-energy X-ray pattern, and the maximum flux and growth time are determined. Based on these parameters, the strength of the probable proton of the flare and the class of the flare are estimated.

The only data source connected directly to the decision-making system is the ionospheric state prediction system [4]. The independence of all these components allows having their copies without a need in their synchronization.

A separate component, mecombroker, is used to send advisory messages. This component receives information from the decision-making system and prepares advisory messages in a regulated format, in accordance with Appendix [2] and the rules for exchanging TAC (Traditional Alphanumeric Code) messages. The prepared messages are transmitted to the regional data collection and transmission center for further dissemination. This component implements a synchronization mechanism based on the “master-slave” principle: only one such component can operate at a time, the rest should not send advisory information in order to avoid its duplication in the aviation meteorological support networks. In addition to the sending to the Aeronautical Fixed Telecommunications Network (AFTN), the dissemination in the form of simple emails is also used for diagnostic purposes.

In the future, it is planned to work with the IWxXM (ICAO Meteorological Information Exchange Model) machine-oriented format [3], that provides greater flexibility in the formulation of information about the phenomena, allows saving more information, while the decision to display additional information lies in the consumer’s systems. In the IWxXM format, the transformation procedure is required to display a human-readable form: using the certain rules, information from IWxXM can be converted to TAC or to any other form, including graphical one.

The automated system implies placing each component in isolation from the others by using the virtualization. Thus, each component runs on a separate virtual machine, sharing resources with a different computing load of the virtual infrastructure. The use of virtualization and architecture features allows the non-stop operation of the system in case of any hardware failures, provided that the virtual infrastructure has free resources to replace the left ones. The system also implies duplication out of the single data center and the single virtual infrastructure. A copy of the system is deployed at the facilities of Roshydromet Aviamettelekom, the communication between the systems is organized via the MEKOM departmental network. All critical infrastructure components are backed up following the $N + 1$ scheme.

CONCLUSIONS

The space weather is a new page for ICAO and WMO. The requirements for space weather centers to support civil air navigation often change due to the development of this area. Methodological trends in the space weather science and the development of collaboration among the ICAO space weather initiative participants are the key drivers of changes. Currently, the Space Weather Center of IAG and the National Center for Space Weather of China Meteorological Administration formed a consortium. This consortium acts as the fourth global space weather center under the auspices of ICAO along with the PECASUS (Finland, Belgium, Great Britain, Poland, Germany, Holland, Italy, Austria, Cyprus), ACFJ (Australia, Canada, France, Japan), and SWPC (USA) centers.

REFERENCES

1. S. D. Ivanov and I. M. Aleshin, “Continuous Monitoring System Architecting with Elements of Discrete-event Modeling,” Voprosy Inzhenernoi Seismologii, No. 2, **45** (2018) [in Russian].
2. *Annex 3 to the Convention on International Civil Aviation: Meteorological Service for International Air Navigation, 20th ed. (Appendix 78)* (International Civil Aviation Organization, Montreal, Quebec, 2018) [Transl. from English].
3. *Annex 3 to the Convention on International Civil Aviation: Meteorological Service for International Air Navigation, 21st ed. (Appendix 79)* (International Civil Aviation Organization, Montreal, Quebec, 2019) [Transl. from English].
4. G. K. Tsybulya, *Patent of the Russian Federation No. 2697433 “The Method for Automatic Determination of Ionospheric Layer Parameters from Ionograms*,” Bulletin No. 23 (2019).
5. *GBAS Quick Facts*, Document No. TC-16004 (Department of Transportation, Federal Aviation Administration, USA), https://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/library/factsheets/media/GBAS_QFactSheet.pdf.