Short-term forecast of the auroral oval position on the basis of the "virtual globe" technology

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A nowcasting and even forecast of the auroral oval position and intensity is a highly needed resource for practical applications. The auroral oval is the region with a high level of ionospheric plasma turbulence, which provokes malfunctions of radio communication and navigation satellite systems, and the region with most intense irregular ionospheric electrojet exciting the geomagnetically induced currents (GICs) in electric power lines. We have elaborated a web service (http://aurora-forecast.ru) for continuous nowcasting, visualization and short-term forecast of auroras. The implementation tool of the developed geographic information system (GIS) is the Django framework. The web service is a software shell built on the basis of a virtual globe – a multi-scale digital 3D model of the Earth, rendering visualization of data provided by the NOAA service on the planetary distribution of the probability of the aurora occurrence. The NOAA service uses the output of the OVATION-prime model, which gives a forecast of auroras in advance of 30 minutes with a 5-minute update step, using real-time data from interplanetary monitors of the solar wind. The developed web-service can be used both to assess the probability of observing auroras anywhere in the world. This service may help to predict the deterioration of the satellite navigation signal quality or warn about possibility of intense GICs at high latitudes. *KEYWORDS:* Space weather; aurora; GIS technology; auroral oval.

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Introduction: The Importance of Monitoring the Position of the Auroral Oval

The most active manifestations of the space weather, such as overloading of power transmission lines caused by geomagnetically induced currents (GICs), intensification of electro-corrosion of oil/gas pipelines, and failures of short-wave radio communication, are observed within a region of the auroral oval. In this brief note we omit the description of the auroral phenomena physics, which is described comprehensively in many excellent books and reviews [cf., *Akasofu,* 1977]. The auroral oval is characterized by sharp gradients of the ionospheric plasma and a high level of turbulence, which provokes failures and significantly reduces the stability of global navigation satellite systems (GNSS), such as GPS/GLONASS [*Kozyreva et al.,* 2017; *Smith et al.,* 2008]. The need has ripened for the creation and practical testing of regional models for the Arctic Zone of the Russian Federation, allowing monitoring and an operative forecast of the auroral oval dynamics under various space weather conditions. To date, various

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approaches to nowcasting and predicting the auroral oval position have been developed. A weather-independent source of detailed information about the structure of the auroral oval is measurements of auroral electron fluxes (NOAA, DMSP) or field-aligned currents (CHAMP, Orsted, SWARM) on low-Earth-orbit (LEO) satellites. The parameters of the solar wind and interplanetary magnetic field (IMF), transmitted in real time from satellites at the Lagrange point L1 on the Earth–Sun line (at a distance of $\sim$ 200 Earth radii), are usually used as input data in such models.

This article discusses the possibilities of modernizing web services that provide monitoring and visualization of the auroral oval using the methods of geographical information systems (GISs). A new web service for visualizing the probability of the aurora occurrence is described, based on the statistical OVATION-prime model of auroral particle precipitation.

The OVATION Model Description

The OVATION auroral oval model (Oval Variation, Assessment, Tracking, Intensity, and Online Nowcasting) (https://www.swpc.noaa.gov/products/aurora-30-minute-forecast) is based on data acquired during more than 20 years of observations of electron and proton fluxes of different energies on satellites of the Defense Meteorological Satellite Program (DMSP). Compared to ground-based optical observations, the registration of particle fluxes on LEO satellites for both hemispheres is independent of the ionosphere illumination and atmospheric cloudiness, and is more sensitive ($\sim 10^{-2}$ ergs/cm^2 s) than ground-based or satellite-based optical observations. The boundaries of the auroral oval were automatically determined from the DMSP measured particle fluxes using specially developed algorithms. The equatorward boundary in the OVATION model is defined as the boundary for the soft electron precipitation [*Newell et al.,* 2014], and the poleward boundary corresponds to the open-closed field line boundary [*Sotirelis and Newell,* 2000]. The OVATION model predicted the total intensity of the fluxes of auroral electrons causing auroras, and the predicted boundaries coincided well with the position of the auroral oval.

The advanced model of the auroral oval – OVATION-prime (OP), is parameterized to the solar wind and IMF parameters (https://ccmc.gsfc.nasa.gov/models/modelinfo.php?model=Ovation%20Prime). This model calculates the 2D spatial distribution of intensity of the main types of the auroral electron and ion precipitation [*Newell et al.,* 2010]. Diffuse auroras are caused by precipitation of soft electrons (0.1–1 keV) which are the main source of energy supply into the high-latitude upper atmosphere, although the auroras caused by these particles can be at a sub-visual level [*Newell et al.,* 2009]. Discrete auroras are caused by a precipitation of energetic electrons (0.1–30 keV). All types of auroras are combined to map the total aurora power [*Newell et al.,* 2009]. The input parameters of the model are real-time data on the solar wind and IMF from interplanetary satellites downloaded to the site of the U.S. Oceanic and Atmospheric Administration (NOAA) from the ACE satellite (https://services.swpc.noaa.gov/products/solar-wind/). The model uses the previously established statistical relationship between the parameters of the interplanetary medium and the dynamics of the auroral oval [*Newell et al.,* 2007]. The time shift ($\sim$ 1 hour) due to the propagation of the solar wind from space monitor to the magnetosphere boundary makes it possible in principle to provide a short-term forecast of the expected intensity and location of auroras. Based on the OP model, two types of web-services can be built:

- A 2D picture of charged particle fluxes of different energies and powers of auroral intensity for the northern and southern hemisphere. These fluxes are important for the geophysical community, because they provide information on the energy entering the upper atmosphere and its spatial distribution. Based on this information, models of the influence of space weather on technological systems are constructed [*Kozyreva et al.,* 2020]. As an example of such services, the OP Real-Time (OP-RT) web display (https://www.ngdc.noaa.gov/stp/ovation_prime/) can be mentioned;
- visual intensity of auroras calculated from data on particle fluxes [*Machol et al.,* 2012]. The empirical OP model makes it possible to calculate the relationship between the intensity of auroral emissions and the probability of their observation with a

naked eye, which is implemented on the NOAA web-service (https://www.swpc.noaa.gov/products/aurora-30-minute-forecast).
NOAA gives the probabilities of observing aurora ranked on a scale from 0 to 100 and tied to the latitude-longitude grid. This information is important for operators of technological systems, aurora observers, and the tourist industry.

There are also web services focused on regional nowcasting of the auroral oval, developed by the University of Alaska (https://www.gi.alaska.edu/monitors/aurora-forecast), the Meteorological Service of Iceland (https://en.vedur.is/weather/forecasts/aurora), University Center on Svalbard (http://kho.unis.no) [*Sigernes et al.,* 2011]. The aurora monitor is an essential part of the space weather services at Space Research Institute (http://spaceweather.ru) and Polar Geophysical Institute (http://pgia.ru). The site of Virtual Geophysical Laboratory (http://yamalgeo.rf) for Yamal also contains information about aurora activity.

Experience with the above services gave us a possibility to identify a number of typical and recurring shortcomings from these implementations which include: the inability to dynamically scale and add additional layers; a small number of displayed parameters; lack of data on the current state of space weather and basic tools for spatial analysis of visualized parameters. The development of web services that provide effective monitoring and visualization of the auroral oval by GIS methods is still an urgent task, the solution of which will help to build an effective forecast of space weather easily available to all interested customers.

Data Pre-Processing

An object of visualization in the presented GIC system is the probability of observing the aurora with a naked eye. The empirical OP model enables one to calculate the relationship between the intensity of auroral particles and the probability of the aurora occurrence. The NOAA web-service (https://www.swpc.noaa.gov/products/aurora-30-minute-forecast) provides the OP model output that can be used for short-term prediction of the aurora intensity. A prediction horizon of 30 minutes corresponds to an average solar wind speed of $\sim$ 800 km/s. The output file of the OP model is 1024×512 array, which corresponds to a longitude value from 0° to 360° in increments of 0.32846715° and a latitude value of −90° to 90° in increments of 0.3515625° on the NOAA website (https://services.swpc.noaa.gov/text/aurora-nowcast-map.txt). The array values are ranged from 0 to 100, where 0 corresponds to the minimum probability of observing auroras, and 100 to the maximum. Data are updated every 5 minutes.

Comparative Analysis of Visualization Tools

The processing and graphical interpretation of the structured set of spatial and attribute data of the auroral zone visualization is implemented via web-based GIS technologies. The experience of building a web-service for visualizing geomagnetic field variations has shown the consistency of the GIS software tools for solving such problems [*Vorobev and Vorobeva,* 2017a, 2017b]. In regard to geospatial data, existing GIS methods in general can be divided into classic flat maps and virtual globes [*Bobkov and Leonov,* 2017]. Given the specifics of the high-latitude location of the auroral oval, the obvious advantage of globes is the quality of their visual perception, preservation of the geometric similarity of contours, and the absence of cartographic distortions of projections inherent in flat maps, especially in the polar regions.

We have compared the characteristics and possibilities of using modern software libraries that make it possible to embed a virtual globe into a web application. The criterium for choosing a visualization tool is the image rendering speed, which determines the quality of small-scale details and realism of virtual globe itself and loaded layers. For the auroral zone rendering, we use small-scale (from $1 : 2,000,000$ to $1 : 10,000,000$) cartographic substrates. At this scale, spatial visualization can be realized by means of a ranked color display, which can be applied both to point-type objects and to polygonal associations. Comparative analysis of the Application Programming Interfaces (APIs) showed that the ArcGIS API fits well to solve the problem, given its advanced features of 2D/3D visualization of the Earth's surface, the use of various formats for rendering layers, and compatibility with Python programming language.

Architecture and Program Implementation

The proposed information system is based on a client-server architecture typical for web applications, implemented through the MVC (Model-View-Controller) design pattern and the component separation of application data, user interface, and control logic. The advantages of this approach include the open structure of the program code, possibility of its reuse, and reduced complexity of the web application. Implementation of the proposed solutions is based on the Django web development tool, which is a framework with many built-in high-level capabilities. This framework includes mechanisms to prevent common attacks such as XSS and CSRF, uses the object-relational mapping (ORM), and can withstand highly loaded applications through caching and load balancing. Django implements the RAD (Rapid Application Development) concept for organizing a software development process. Django uses Python as a programming language, which expands its functionality in favor of complex processing and visualization of big data [*Vorobev et al.,* 2020].

In the process of processing and visualization of spatially distributed geophysical parameters, CSV and JSON data from third-party sources are used. In order to avoid conflicts associated with the fact that most browsers follow the policy of a single source, access to remote sources is carried out only on the server side. The corresponding scripts are executed at the beginning of a user's session with a Django application and send requests to external data sources. The Python server-side script accesses digital data on the auroral oval (https://services.swpc.noaa.gov/text/aurora-nowcast-map.txt), IMF (https://services.swpc.noaa.gov/products/solar-wind/mag-6-hour.json) and solar wind (https://services.swpc.noaa.gov/products/solar-wind/plasma-6-hour.json). The results of the script are transferred to an appropriate template from the Django application and sent by the web server to the client side as a response for a subsequent rendering by the user browser. Processing of visualized data is carried out on the principle of federalization without data alienation, followed by local storage of sets of files on a web server.

Upon generation of resulting HTML code by the web application templates, the functionality of two external APIs was used. The Google Visualization API module serves as the basis for the formation and rendering of graphs on the client side. At initial stage, a separate plug-in module of the Google loader (loader.js) creates a gateway for graphical components to generate a client-side code. Then, directly in the template, the necessary external modules are connected to the application, which input is an array of data for visualization. Finally, after setting up the graphic components and specifying the HTML element, the plotting method draws the corresponding graphics on the application page using the callback function.

Another third-party ArcGIS API for JavaScript is responsible for visualizing spatial data in geographic coordinates. Work with spatial data begins with the initialization of the Map class, designed to render map layers. The Map accesses a remote ArcGIS server, receives the map substrate from it, and passes it to the previously created sample of the Map class. Custom map layers are formed as samples of the LayerViewClass class. As an input parameter, the constructor of the designated class accepts a CSV file containing the data that must be displayed on the map. At the output, a cartographic layer is formed, tied to a previously created copy of the cartographic substrate. At the final stage, the cartographic base with attached layers is converted into a sample of the virtual globe by initializing an element of the SceneViewClass class. The result of applying the above layers as part of the Django application template is a data stream sent to the client side as a response and containing HTML code, style sheets, and scripts for execution and rendering by a browser.

Interface of the Model

The developed web service (http://aurora-forecast.ru) is a software built on the basis of a virtual globe. This multi-scale digital 3D model of the Earth provides visualization of data provided by the NOAA service on the intensity of aurora in a given region of the planet. The interface of the developed system is shown in Figure 1. The interface is logically divided into 8 functional areas:

- A is the local and UT time. The button "About aurora" provides an access to collec-

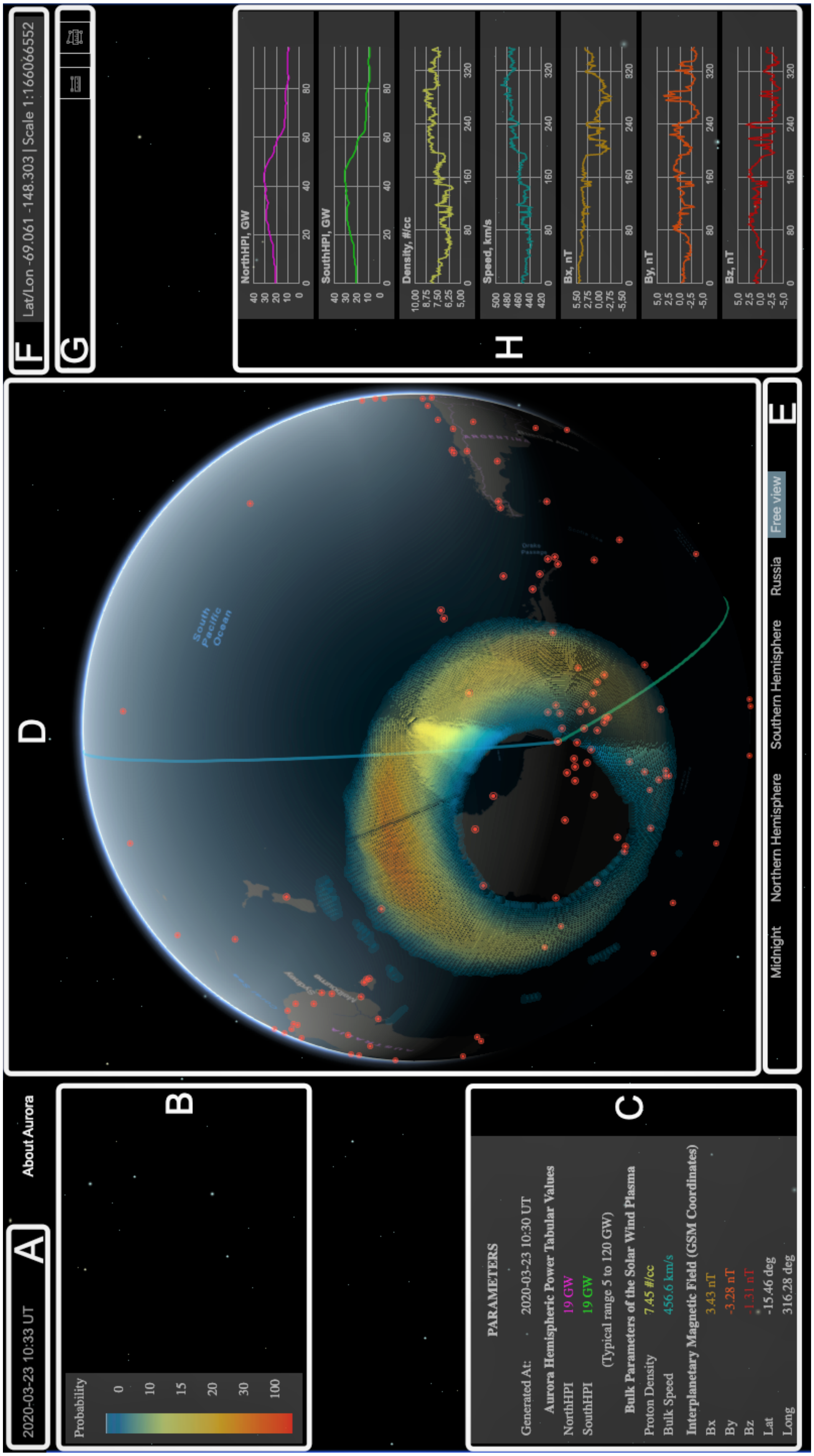

Figure 1. A screenshot of the service interface http://aurora-forecast.ru. Red dots on the globe indicate locations of magnetic observatories. The blue and green lines denote midnight and Greenwich meridians, respectively.

tion of books on physics of the aurora phenomena;

- B is an explanation of the color indication;
- C is real time parameters of the solar wind and IMF recorded by the DSCOVR satellite (https://services.swpc.noaa.gov/products/solar-wind/);
- D is the virtual globe tools;
- E is the visualization menu ("Midnight", "Northern Hemisphere", "Southern Hemisphere", "Russia", and "FreeView", providing maximum degrees of freedom during user interaction with a globe);
- F is the panel displaying the current cursor coordinates and scale;
- G holds basic tools for spatial analysis;
- H is for plots of the solar wind and IMF parameters for the last 6 hours;

The service also provides the values of the integrated power of the auroras in the Northern and Southern hemispheres. When loading, the globe is set in such a way that it turns into a local midnight meridian. There is a tool that displays the coordinates of the cursor, so one can determine position of a point relative to the auroral oval boundary. The coupling of additional layers provides the possibility to overlay on a virtual globe either all magnetic stations (option 1), or major cities (option 2).

An example of visualization of the aurora intensity for the Northern (a) and Southern (b) hemispheres is shown in Figure 2. Red dots represent location of magnetic stations. The screen information is updated automatically every 7 min.

The advantage of the suggested service in comparison with existing analogues is the possibility to use custom layers (e.g., a layer of magnetic observatories), its multi-scale and interactivity, which together enables one to study in detail the dynamics and structure of auroras relative to any region of the planet. As an example, Figure 3 shows the predicted position of the auroral oval for the Arctic zone of the Russian Federation.

Prospects of the Model Advancement

The development of web-oriented services that provide monitoring and visualization of the auroral oval, together with analysis using GIS methods, is rather complicated task that does not have the only solution. The developed prototype of the system is currently in beta testing, i.e. it is offered to developers and potential users for testing and validation in order to identify plausible errors and proposals for the system modernization. At the first stage, only the nowcast of visible auroras is provided, based on ready-made calculations using the OP model and interplanetary data supplied by the NOAA server. In the next step, an autonomous module will be introduced for calculating the particle precipitation pattern according to the OP model. This will make it possible, using the OMNI2 database (http://omniweb.gsfc.nasa.gov), to provide a 2D picture of the auroras for any past time. Later on, the proposed GIS system will include other methods for determining the auroral oval boundaries, e.g., according to the geomagnetic variations along a meridian [*Lunyushkin and Pensky,* 2019]; using field-aligned currents recorded by low-orbit satellites [*Lukianova and Christiansen,* 2006]; according to the latitudinal distribution of the intensity of geomagnetic Pc5 pulsations [*Kozyreva et al.,* 2016]; and applying the model of auroral precipitation [*Vorobjev and Yagodkina,* 2008].

Conclusion

Here we present a description of an interactive web-service (http://aurora-forecast.ru), which provides 30-min forecast of the auroral oval position and the aurora intensity. The construction of such information system with the integration of basic GIS methods has significant advantages over the currently known approaches. The domain name is officially registered and can be linked from any other website.

For high-latitude regions of the Earth due to geometric distortions of projections, flat cartographic substrates are impractical to use, so it is worth to choose the virtual globe technique. From the existing libraries for visualization tools using virtual globe technology the choice has been made in favor

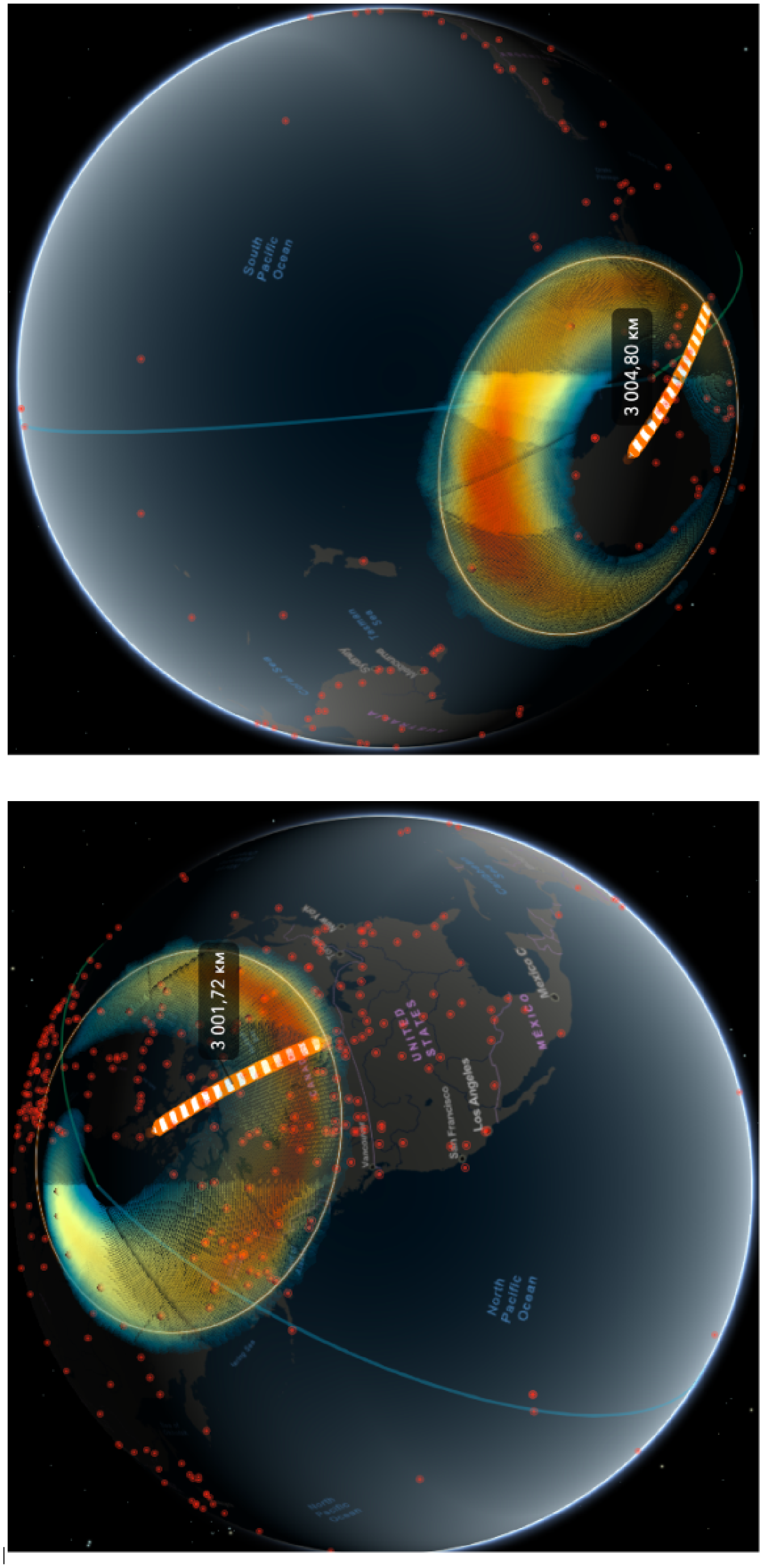

Figure 2. Visualization of auroras for the Northern (a) and Southern (b) hemispheres. An orange-white strip shows the option to measure the distance on the globe between any selected points.

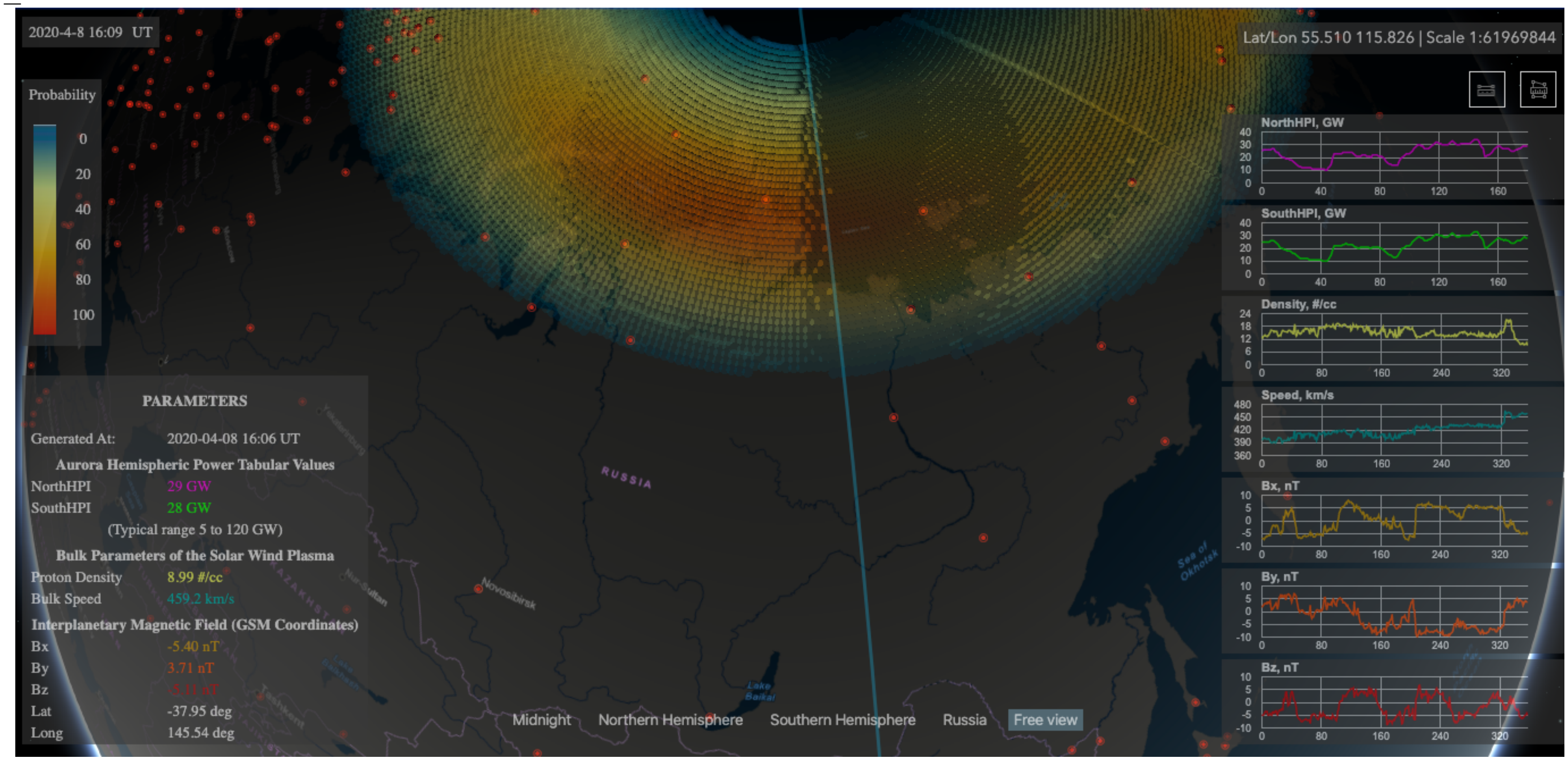

Figure 3. An example of visualization of a short-term forecast of the aurora visibility for the Arctic zone of the Russian Federation.

of the ArcGIS API, although some other libraries (e.g., NASA World Wind and Cesium) also have a significant potential for construction of such systems.

The proposed service can be used by operators of both ground-based technological systems and satellite systems to monitor the status of space weather in real time. Besides meteorological services and research organizations, this visualization tool can be used by aurora-watchers. Further elaboration of the system in order to improve its functionality and visualization efficiency is ongoing, so the authors will greatly acknowledge any suggestions to improve the proposed service.

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