CHALLENGES IN REAL-TIME GENERATION OF SCINTILLATION INDEX MAPS

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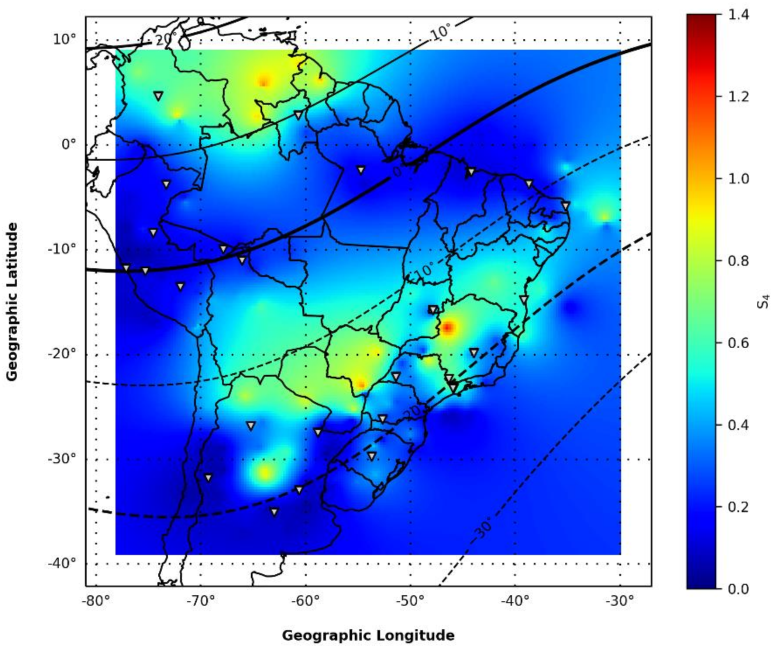
The purpose of this work is to show the feasibility of real-time maps of amplitude scintillation index covering the Brazilian territory, using data from two ionospheric monitoring networks of GNSS stations: LISN (Low Latitude Ionospheric Sensor Network) [1] and INCT GNSS-NavAer [2]. Besides the proposed approach, the challenges related to the implementation of the infrastructure and software are discussed. Amplitude scintillation is given by the S4 index, estimated from radio signals acquired at 50 Hz by receivers of GNSS monitoring stations. Typically, the signal intensity of 3,000 samples of a 1-minute period is used to calculate the S4 index value given by the intensity standard deviation normalized by the mean intensity [3]. The S4 index is calculated for each GNSS satellite-station link from the several constellations currently available (GPS, GLONASS, GALILEO, BEIDOU, SBAS). In addition, for the constellation, calculations of the index S4 are compatible between stations using different receivers [4]. As a consequence, the number of GNSS satellites visible by a station can be close to 40 at the same minute. The LISN and INCT GNSS-NavAer networks can provide data from up to 38 stations simultaneously, or 1520 values (38 times 40) of the S4 index per minute. There are 14 LISN and 24 INCT monitoring stations currently active. These two monitoring networks employ different equipment. Each LISN station has a Novatel 4004B receiver connected to a computer via USB cable, performing data acquisition by the SCINDA [5] software. Each INCT station employs a stand-alone Septentrio PolaRx5S receiver that compresses and stores the acquired data in the internal persistent flash memory, being such data transferred via FTP to a central server every 15-minute or every hour. Generating and publishing scintillation maps on a web application server requires four data processing steps: acquisition, pre-processing, interpolation and image rendering. However, real-time generation of scintillation maps requires performing all these steps in about every minute. Just the data acquisition is quite challenging, since it requires analysis and testing of different ways to acquire the S4 index data with 1-minute resolution from each Septentrio PolaRx5S receiver. Its default mode involves acquiring 15-minute of raw data that is then compressed, sent via FTP, decompressed and post-processed to generate the S4 index, thus precluding real-time requirements. This issue was solved here by exploring an alternative approach. These receivers also provide real-time calculation of the S4 index, which is locally stored in the receiver memory, these data blocks also include the position of each employed GNSS satellite. Therefore, it was possible to configure the receivers of all INCT stations to transmit these blocks via TCP/IP to a specific real-time server implementing a TCP/IP multithreaded client software. In the case of the LISN network stations, a different solution was adopted, since there is a local computer at each station to perform the raw data acquisition using SCINDA. Nevertheless, this software does not allow configuring a TCP/IP server for data transmission. This restriction required implementing a new software to monitor and process the text data files stored by the original software in order to send the S4 index and satellites positions at a 1-minute rate via the HTTP protocol to a web application server running in the real-time server, also developed in this work. The real-time server processes the data received from the GNSS stations of both networks in order to conform it to the format defined in the database. A second challenge involved choosing a suitable database manager. The retrieval of new data every 1-minute using a SQL-like Database Management System (DBMS) requires performing a query for each connected client in the web server application in order to produce the scintillation map, which is not applicable in the case of many clients. The data push feature is a lighter way to export data, i.e., to send updated data from the database to other applications in the real-time server and even to eventual further remote clients. Therefore, another DBMS that has such a feature was chosen and implemented in the real-time server, the NoSQL RethinkDB [6] DBMS. Another challenge was to perform a specific analysis about the interpolation of the S4 index values of the GNSS stations that render the scintillation maps. Four interpolation methods were tested taking into account the minimization of the interpolation error, smoothness of the map, processing time, and automatic parameterization. This evaluation included two standard interpolation methods for scintillation maps [7][8] and two newly-proposed ones, the Radial Basis Function (RBF) [9] and the Gaussian Process Regression (GPR) [10]. In addition, some preprocessing choices were also explored. The GPR with a specific kernel function and a set of pre-processing options was deemed the best choice and thus was adopted in this work. An example of the resulting scintillation map covering most of South America can be seen in Figure 1. The quality of the maps can be assessed by its smoothness, absence of artifacts, and the error and correlation metrics. It is important to stress that S4 data (from a total of 2,544 IPPs) was split into interpolation (2,289 IPPs each) and validation sets (255 IPPs each) using a 20-fold cross-validation scheme that employs 20 training-test subsets of IPPs obtained by random shuffle. In each IPPs subset, 90% are for training and 10% for test. Considering the average cross-validation results (Figure 1 depicts one of the 20 maps that were produced), the S4 error metrics are 0.0925 (mean average error), 0.1397 (root mean square error), 0.6823 (maximum error), and 0.1047 (standard deviation of the error), while the corresponding S4 Pearson correlation is 0.8695. These values are very good, with quite an expected RMS, considering the high variability of the S4 index along minutes, besides the poor coverage of GNSS stations in some regions of the map. Our approach to produce real-time S4 scintillation maps is to collect scintillation data every minute using the DBMS push feature that imports new data from the GNSS stations. Such data are stored in a main-memory buffer of the real-time server, which contains the previous 15-minute S4 data for all monitoring stations. Then, we use a sliding window that allows generating a sequence of maps with 1-minute resolution, each one corresponding to the integration of the previous 15-minute of data. It is important to note that each acquired S4 value is projected in the corresponding Ionospheric Pierce Point (IPP), and then each set of S4 values of neighboring IPPs is grouped and reduced to a single point and value (given by the mean, maximum, etc.). Finally, the resulting scintillation maps are then made available by a web server application in the real-time server. The proposed real-time approach was feasible, allowing to process arriving S4 data and produce S4 maps for the Brazilian territory in less than 1-minute, thus in real-time. It is expected that this real-time monitoring of ionospheric scintillation maps (S4 maps) will provide warnings for several GNSS-based applications, including aerial navigation, takeoff and landing procedures, precision agriculture and positioning of offshore oil prospecting platforms. In addition, these real-time maps can be assimilated by ionospheric models and/or used in scintillation research. Another possibility would be to include the implemented approach for real-time scintillation maps as part of the services provided by the Brazilian Airspace Control System (SISCEAB).

Figure 1 – Example of a scintillation map for 2014-12-02 00:54 UT, generated by the proposed approach (color scale refer to S4 values and triangles depict the GNSS monitoring stations).



Source: Author’s production.

Keywords: ionospheric scintillation; S4 index; scintillation map interpolation; real-time acquisition and processing.

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