eSWua: a tool to manage and access GNSS ionospheric data from mid-to-high latitudes

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ABSTRACT

The electronic space weather upper atmosphere (eSWua) is a hardware–software system that is based on measurements collected by instruments installed by the Upper Atmosphere Physics Group of the Istituto Nazionale di Geofisica e Vulcanologia (INGV, Italy). More recently, it has also included the Global Navigation Satellite System (GNSS) ionospheric scintillation and total electron content (TEC) monitor (GISTM) stations that are managed and operated by the University of Nottingham (UK). By visiting the eSWua website, it is possible to access the database that has been implemented to organize and manage the large amount of information acquired. The section of the database designed for the TEC and scintillation data has been designed to address the needs of the space weather community as well as of scientific users. Through the web tools, it is possible to visualize, plot, extract and download the data from each station. This interactive website is supported by a structured database, and it provides a powerful tool for the scientific and technological community in the field of telecommunications and space weather. At present, the data transmission procedure, the database population algorithm, the linear plot and polar plot visualization tools, the statistics page, and the user management system are fully operational. Web access to the data and tools has been realized to handle the data from the sites at low, mid and high latitudes. In this report, we present the results of the system for the GNSS data in the Arctic, the Antarctica, and the three GISTM stations operated by the University of Nottingham: Nottingham, Trondheim and Dourbes. Case studies of the efficacy of this system for scientific and application purposes are also presented and discussed.

1. Introduction

The Istituto Nazionale di Geofisica e Vulcanologia (INGV) manages different kinds of observations of the upper atmosphere, and for several decades it has been collecting data from a number of instruments. Among these there are ionosondes, which are used to study the electronic density profile, and Global Navigation Satellite System (GNSS) ionospheric scintillation and total electron content (TEC) monitor (GISTM) receivers, which are designed to study ionospheric irregularities [Van Dierendonck et al. 1993]. These instruments produce a huge amount of data. Such a huge amount of information needs to be organized in the correct way, to allow significant contributions to scientific and technological improvements. This involves an interactive website that is supported by the *ad-hoc* organized database, and this represents a powerful tool in the field of science, telecommunications, and space weather at the national and international levels.

The electronic space weather upper atmosphere (eSWua) system can support the acquisition, elaboration, evaluation, sharing, and archiving of multi-instrument observations of the ionized atmosphere at high, middle, and more recently, equatorial latitudes. A dynamic website is also the key to success for real-time access to these data.

The eSWua system is the outcome of a large effort that includes manpower, time, and funds, and it is motivated by the awareness that geosciences have to rely on structured digital data and on the appropriate scientific procedures. These need to be developed *ad hoc* by experts, and to be open and shared with the international community [Romano et al. 2008]. Through the web tools, it is possible to visualize, plot, extract and download the data of all of the available instruments. The database has also been designed with the expansion of the observational network in mind. In the future, the system will include tools and models for contributing to nowcast and forecast the ionospheric conditions throughout the above-mentioned latitudes.

What makes eSWua unique and useful is the possibility to collect data that also comes from instruments installed, managed and operated by other scientific in-
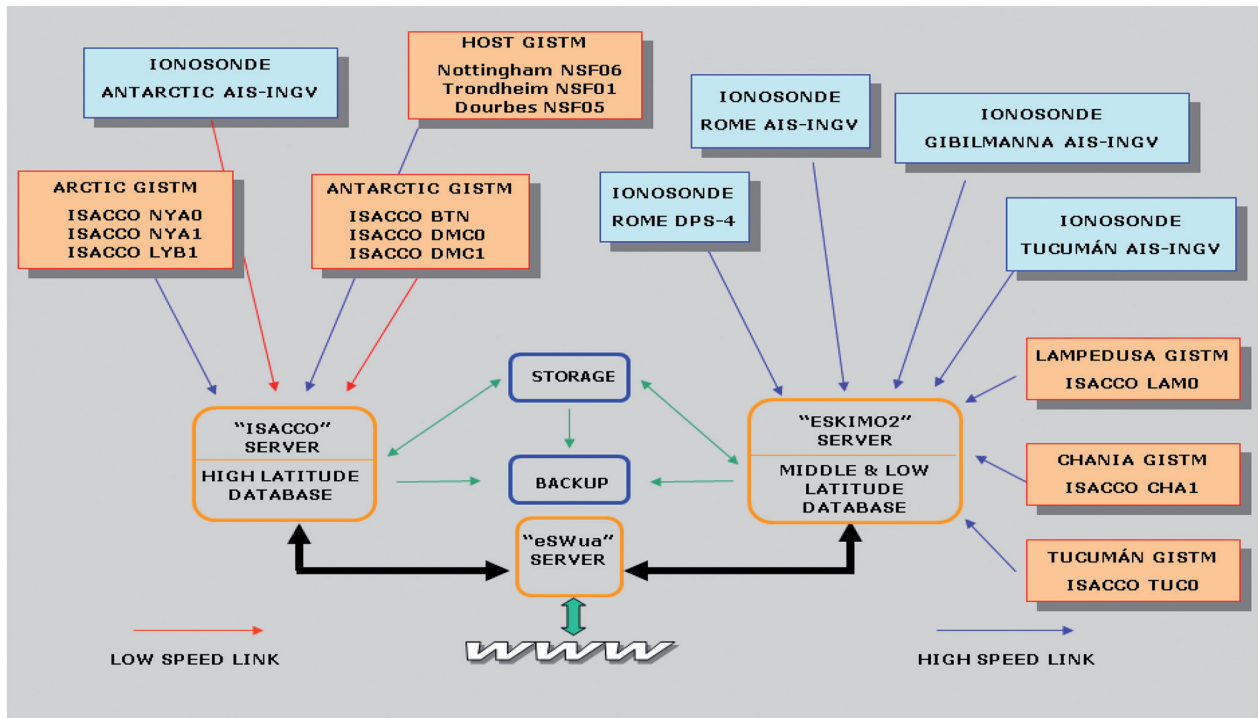
Figure 1. The eSWua system architecture.

Name	Type	Brand	Model	RAM	HD
Isacco, Eskimo2	Server	HP	Proliant DL 360 G4	8 GB	2x146 GB
eSWua	Server	HP	Proliant DL 360 G7	8 GB	2x300 GB
Back-up	NAS	Proware Technology	EP 2803E1 S3A3	n/a	7x2 TB
Mass storage	Fibre channel	Extreme Raidtec	n/a	n/a	14 TB

Table 1. Hardware specifications of the eSWua system.

stitutions. Data from the GISTM stations of Nottingham, Trondheim and Dourbes, which are all managed by the University of Nottingham (UK), have been stored and made available to the scientific community. Again, the possibility given to the user to visualize the corresponding scintillation data as polar and linear plots (with different user-chosen thresholds of visualization) is unique; this is very useful to have an immediate idea of the scintillation phenomena that characterize the areas from mid-to-high latitudes. Indeed, as well as developing and maintaining the database, one of the ideas for the future is to give the user the ever-new possibility of plotting patterns of interest that are not visible anywhere else. For instance, we are working towards the generation of climatological maps that can be used to identify the areas where the probability to have a TEC gradient or scintillation is high (see Alfonsi et al. [2011], Spogli et al. [2009]).

2. The eSWua architecture

The eSWua systems architecture is shown in Figure 1. It is based on three high-performing servers that are installed at the INGV in Rome (Italy). These servers

can store database tables, process user requests, and make different products available. The first server, the eSWua server, hosts the system website and is devoted to user interface management. This task is accomplished through the use of PHP and Java applications. The eSWua server applications have also been designed to guarantee protected access to the database tables and data files.

The other two servers, the Isacco and Eskimo2 servers, are dedicated to the collection and storage of all of the data that come from the instruments through the internet or through dedicated lines, and to arrange

Operative system	Windows server 2003
DB handling	MySQL 4.1.12
Scripts	PHP 4.4
Graphic library	JP Graph
Automatic data treatment	Visual basic, C
Web interface	PHP, java, html

Table 2. Software specifications of the eSWua system.

these into the different databases. The Isacco server is devoted to the gathering of the data from the high-latitude instruments, while the Eskimo2 server receives the data from all of the middle-latitude and low-latitude instruments. Upon reception of these data, both of the servers insert these into the databases and manage queries from the eSWua server, to process user requests and to make different outputs available.

As well as the servers, back-up and storage units complete the system hardware. The back-up process continuously updates a back-up copy of all of the databases through an incremental procedure, with no need to halt any of the database acquisition. Instead, storage processes are aimed at maintaining a copy of the original raw data that come from the different instruments, to have the possibility to recreate the databases at any time. The hardware and software specifications are summarized in Table 1 and Table 2, respectively.

The eSWua home page (http://www.eSWua.ingv.it) allows registered users to log in, and new users to register. Registered users are organized into three levels that allow access to different sections of the site. Without any registration, limited access to the different sections of the site is allowed, while through the free registration, the user can access all of the available data and plots.

In Figure 1, the different colors correspond to different instrument types. In particular, the orange rectangles represent the GISTMs, while the cyan rectangles indicate ionosondes. The blue arrows are real-time fast connections, while the red arrows represent once-a-day, 'on demand' connections. The green single and double-ended arrows are, instead, the internal connections used for back-up and mass storage purposes. The thick black arrows indicate the connections between the servers and the databases.
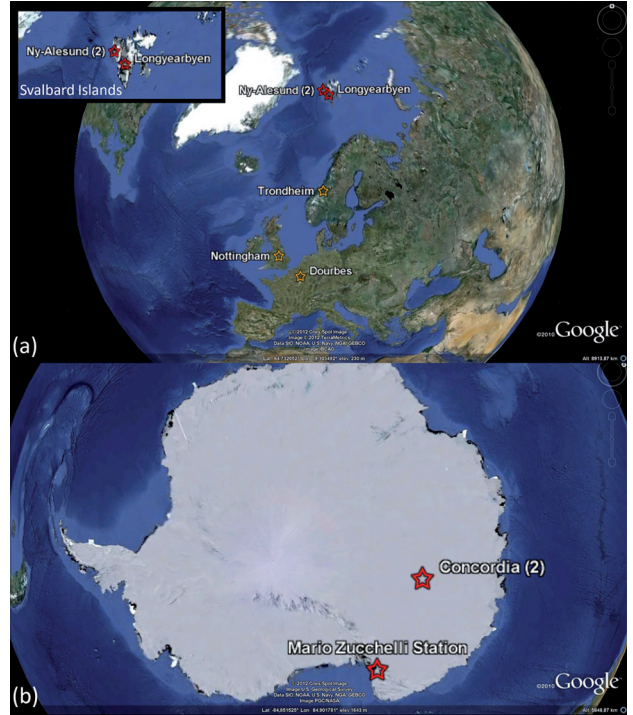

Figure 2. Location of the receivers in the eSWua and presented in the present study. Maps are from Google MAP TM.

3. GNSS data description

The GNSS database contains the scintillation values measured by the GISTM receivers. The INGV has installed three receivers in the Arctic and three in the Antarctica, which are all currently in operation. The Nottingham Geospatial Institute of the University of Nottingham has included three northern-hemisphere stations from mid-to-high latitudes. Other low-latitude and Mediterranean stations are included (e.g., ISACCO-LAM0, ISACCO-CHA1, ISACCO-TUC0), although these are not presented in this report, which is focused on the eSWua contribution within the framework of

ID	Station	Owner	Latitude (°N)	Longitude (°E)
BTN0	Mario Zucchelli Station	INGV	-74.70	164.11
DMC0	Concordia Station - Dome C	INGV	-75.10	123.33
DMC1	Concordia Station - Dome C	INGV	-75.11	123.31
NYA0	Ny-Ålesund			
(Dirgibile Italia Station)		INGV	78.92	11.93
NYA1	Ny-Ålesund			
(Kartverk)		INGV	78.93	11.86
LYB0	Longyearbyen	INGV	78.17	15.99
NSF01	Trondheim	University of Nottingham	63.44	10.40
NSF05	Dourbes	University of Nottingham	50.09	4.60
NSF06	Nottingham	University of Nottingham	52.94	1.19

Table 3. Main features of the receivers for the eSWua system.

the activities of the GNSS Research and Application for Polar Environment (GRAPE) Scientific Committe for Antarctic Research (SCAR) Expert Group (www.grape.scar.org). The locations of the stations considered are shown in Figure 2, and they are listed schematically in Table 3. Every 15 min, a binary file is produced by each instrument and sent to the Isacco server. The measurements are made with respect to every visible global positioning system (GPS) satellite with a 1-min sampling rate. The database tables include a total of 35 navigational and observational parameters that are real-time structured in the database for every station. Among the observational parameters, the most interesting are:

– the phase scintillation index (σ_{ϕ}), which is calculated over different time intervals (1, 3, 10, 30, 60 s);

– the amplitude scintillation index (S_4), which is calculated every 1 min;

– the slant (s)TEC and the vertical (v)TEC, which are calculated every 15 s;

– the relative TEC, which is calculated every 15 s;

– the code carrier and the standard deviation (calculated every 60 s) of the L1 frequency;

– the average carrier-to-noise ratio (calculated every 60 s) of L1 (L1 C/N) and L2 (L2 C/N).

Among the navigational parameters, the most useful are:

– the locktime (calculated every 60 s) of L1 (L1locktime) and L2 (L2locktime);

– the azimuth and elevation of each satellite that is in view;

– the latitude and longitude of the ionospheric piercing point at 350 km along the ray path [Lat(350km), Long(350km), respectively];

– the pseudorange number (PRN), to identify the satellites.

The GISTM station performs 50 Hz sampling to produce the corresponding binary raw-data files. To allow fast access to the data, the raw-data files are stored in the eSWua storage device (Figure 1) and only addressed in the database. Considering the amount of data collected by the nine instruments, only the database organization allows extrapolation and comparison of the interesting events. In this way, the correlation between the data of different instruments is also possible. An extraction procedure automatically runs and converts the binary file into ASCII format. A PHP batch procedure reads this file and inserts the data into the database. The data for every GPS scintillation receiver are organized into monthly tables. In these tables, all of the measured values are stored along with some calculated parameters that are useful for the spatial localization of the measurements. Each record keeps all the parameters at a certain time with respect to a satellite. The different records can be referred to at the same time, because the records are related to the different satellites. The data are structured into tables that con-
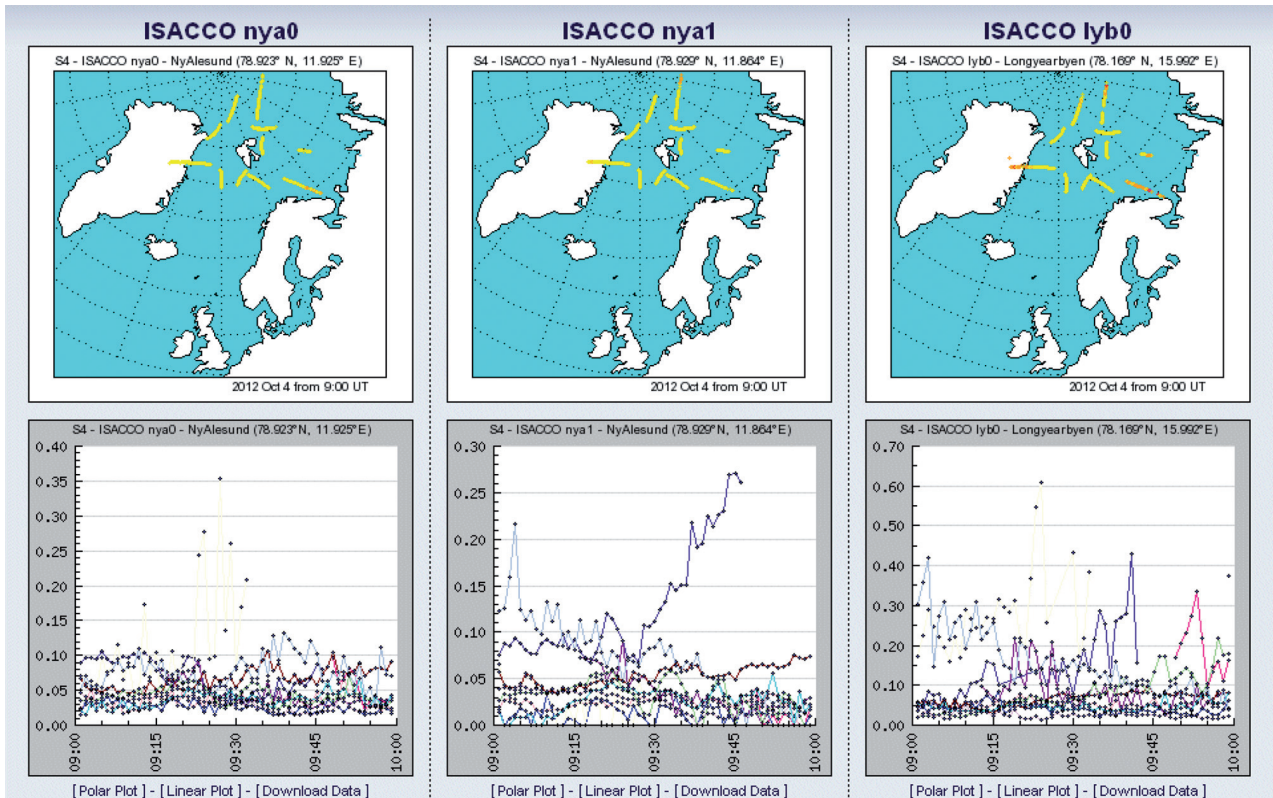

Figure 3. Snapshot of the Arctic region given by the eSWua web portal.

tain 29 measured parameters and six calculated values. All of the instrument-specific data and the station constants are stored in a further table. For the insertion of the data into the database, each instrument has its own automatic procedure.

4. GNSS tools description

The website is organized into four main sections, the labels of which are 'Ionospheric Monitoring', 'Scintillation Monitoring', 'Riometer Monitoring', and 'Miscellanea'.

Under the Scintillation Monitoring section, the user can access the 'Arctic', 'Antarctic', 'Mediterranean' or 'Equatorial' regions. There is also one additional icon button: 'Host', which allows the user to access the GPS receiver data that are managed by the University of Nottingham. Once the region of interest has been chosen, the user reaches a page that contains the latest available S4 hourly polar and linear plots pertaining to all of the receivers installed in that region (Figure 2). In this way, the user benefits from a quick look at the real-time ionospheric–plasmaspheric conditions. From this page, the user can click one of the following links: 'Polar Plot', 'Linear Plot', or 'Download Data'.

Through the Polar Plot link, the polar plots can be surveyed (Figure 3). In this subsection, the user can set the station, date, starting hour, time interval to which the plot has to refer (from 1, 2, 4, 6, 12 and 24 h), satellites to be plotted, and parameter(s) (among S_4, σ_Φ, vTEC, and Track) that need to be plotted. Moreover, a threshold on both the elevation angle and the L1 locktime frequency can be selected by the user. On the right of the webpage, the numbered squares listed represent the satellite IDs from where the data contribute to generate the plot.

Through the Linear Plot link, the linear plots of the selected measured parameters can be surveyed (Figure 5). Again, the user can set the station, date, starting hour, time interval to which the plot has to refer (between 1 h and 6 h), contributing satellites data, and parameter(s), among which there are S_4, $\sigma_{\Phi 60s}$, $\sigma_{\Phi 1s}$, vTEC, sTEC, L1 C/N, L2 C/N, L1Locktime, L2Locktime, code carrier, standard dev, Lat(350km), Long(350km), relative TEC, PRN, azimuth, and elevation. As for the polar plots, a threshold for both the elevation angle and the L1locktime can be selected by the user. In contrast to the previous subsections, here the user has the possibility to plot data from all of the PRNs, both from the GPS and the satellite-based augmentation systems of the geostationary satellites. These latter data are not available for high latitude GISTMs. At the bottom of the plots, the numbered colored squares represent the satellite data used to generate the plots.

Through the Download Data link, the data can be downloaded in different file formats: binary (BIN), or converted from BIN to standard ASCII (EST) and RAW (Figure 6). The user can set the station, date, time, and corresponding parameters. Additionally the user has the possibility to select the elevation angle and L1locktime, as well as the PRN to which the data refer.

At the bottom-right corner of the eSWua home page, a tool is available to monitor the access statistics. Since its implementation, the eSWua system has been accessed ca. 16 times per day, on average. The eSWua administrators can also access a further statistical tool to monitor the more detailed data (single access, statistics on single pages, and so on).

For the eSWua access policies, the Polar Plot area is available without any kind of registration. On the
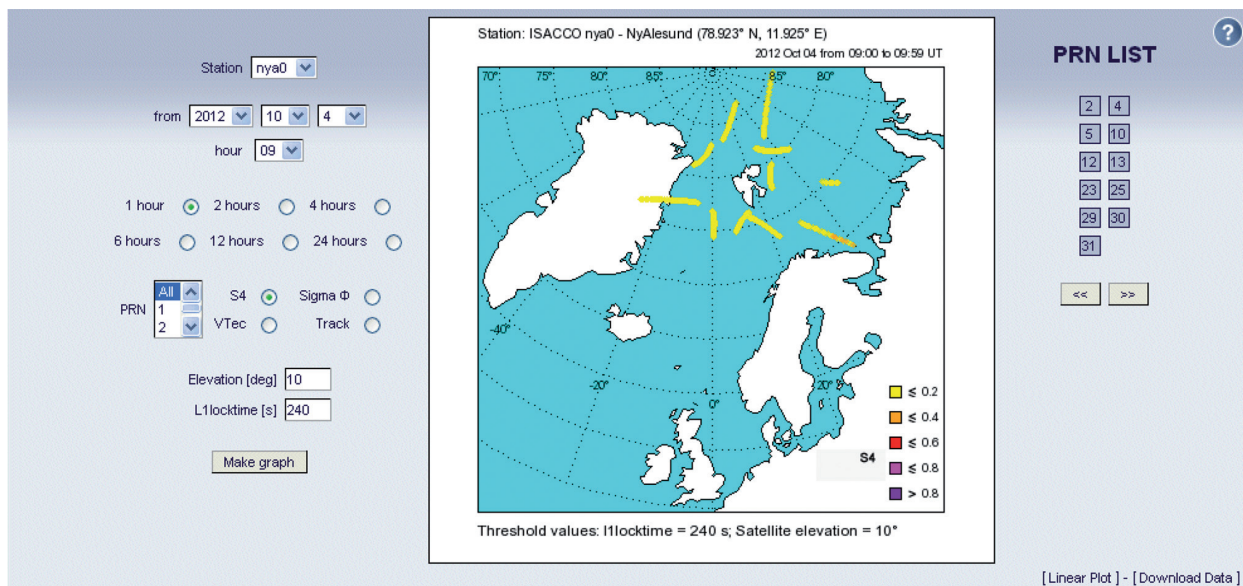

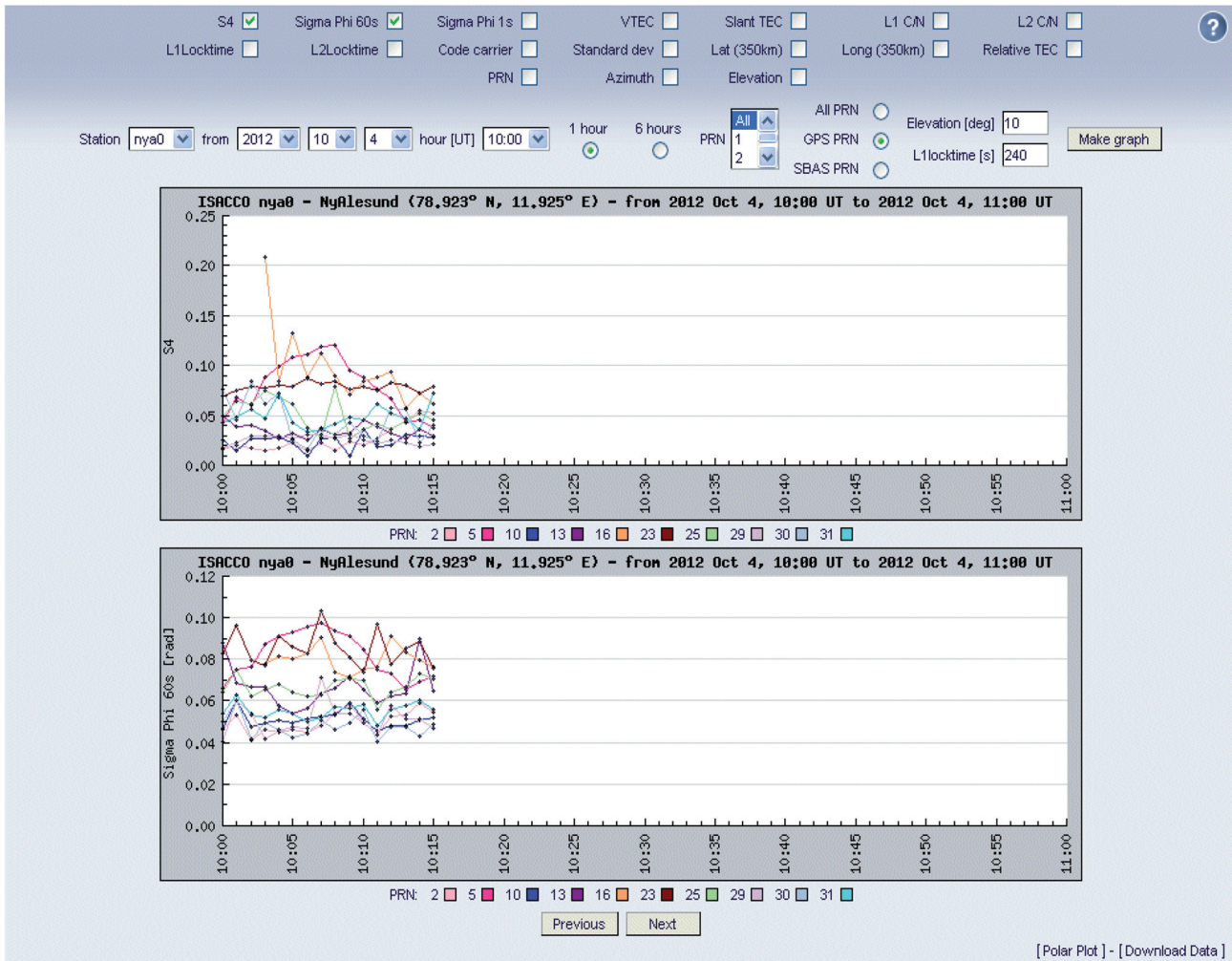**Figure 4.** Snapshot through the Polar Plot link, recorded at Ny-Ålesund on October 4, 2012.

Figure 5. Snapshots through the Linear Plot link, recorded at NYA0 on October 4, 2012.
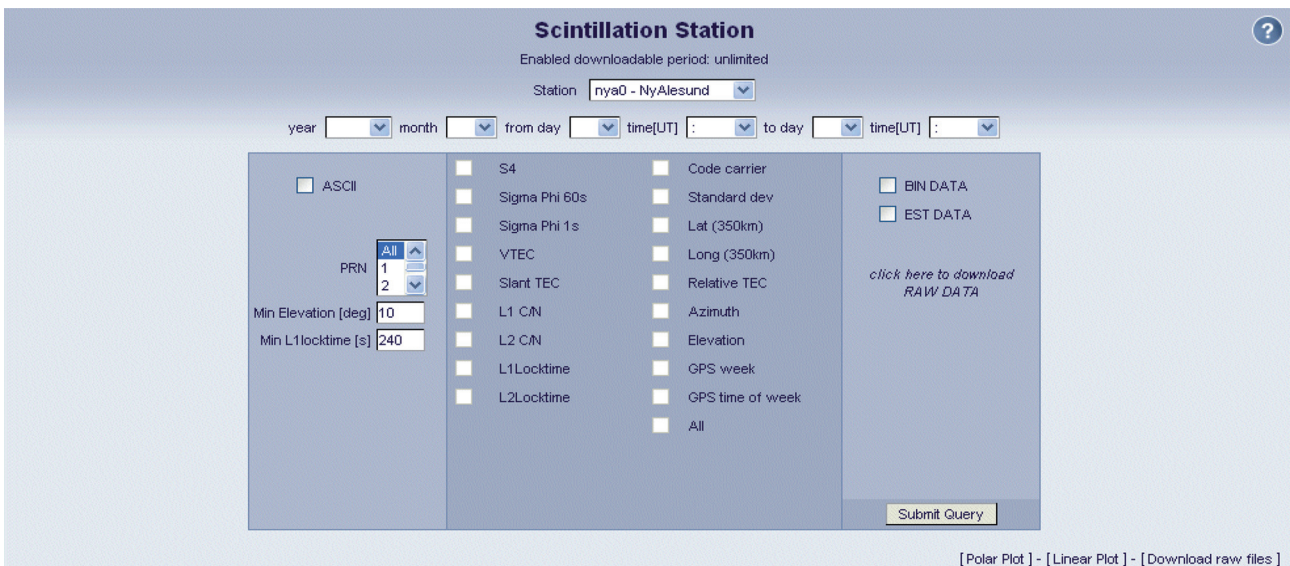

Figure 6. The download interface sub-page.

contrary, both the Linear Plot and Download Data areas are available only through the free registration process. This lets the eSWua administrators evaluate which kind of data or plots are mainly used by the different users, to provide indications on how to best de-

velop further targeted tools.

An anonymous user can register from the eSWua home page or from the dedicated page that appears after clicking either the Linear Plot or the Download Data links. The applicant has to provide some basic informa-

System	URL	Owner	Access policy
CHAIN	http://chain.physics.unb.ca/chain/	Consortium of Canadian institutions	Full access upon registration
eSWua	www.eswua.ingv.it	Istituto Nazionale di Geofisica e Vulcanologia (INGV)	Restricted anonymous access Registration required for full access Free full access for scientific purposes
IPS	http://www.ips.gov.au/	Australian Government – Bureau of Meteorology, Radio and Space Weather Services	Free full access
Madrigal	http://madrigal.haystack.edu/madrigal/	Massachusetts Institute of Technology (MIT – Haystack Observatory)	Registration required for full access
SWACI	http://swaciweb.dlr.de	German Aerospace Centre e. V. (DLR)	Restricted anonymous access

Table 4. GNSS ionospheric data system identification.

System	Scintillation indices	TEC data	GNSS parameter data	GNSS data plots	Data downloading tool	Scintillation raw data	Refreshing time data (min)	Data availability statistics	GNSS data geographic coverage	Other Ionospheric data
	Amplitude Phase	Yes No	Yes No	Yes No	Yes No	Yes (Hz) No		Yes No	Arctic Antarctic Low Latitude Mid Latitude	Yes No
CHAIN	A, P	Y	Y	Y	Y	Y (50)	5	Y	Ar	Y
eSWua	A, P	Y	Y	Y	Y	Y (50)	15	N	Ar, An, L, M	Y
IPS	A, P	Y	N		N	N	10	N	An, L, M	Y
Madrigal	planned to be included	Y	N		Y	N	N	Y		Y
SWACI	A, P	Y	N	N	N	N	1	N	Ar, L, M	N

Table 5. Feature comparison of five of the main GNSS data-management systems.

tion: name, surname, affiliation, country, a valid e-mail address, and a password. Once these data have been sent by clicking the 'confirm' button, the user will receive an e-mail at the address given during the registration process. This e-mail contains a link that once clicked, will activate the user account. Users are organized into three levels that allow access to different areas of the eSWua; the higher the level, the greater the ability to access the resources. In more detail, these levels are:

– level 1: the user is an unregistered user and can only access the Polar Plot area;

– level 2: the user can additionally access the Linear Plot area;

– level 3: upon an authorization by the eSWua administrators, the user can also download data.

Further efforts have been devoted to the develop-ment of a tool that provides the possibility for a simple overview of the data availability for each station, both yearly and monthly. If no data is available in the data-base, a gray cell will be visualized. The different amounts of data, as <20%, 20% to 50%, and >50%, will instead be represented by red, yellow, and green cells, respectively.

The eSWua has been designed to provide access to data and also to products, like the above-mentioned plots and maps, not only for the scintillation indices, but also for the main output parameters of the receivers and the TEC-related data. To support the technical solutions adopted to develop the eSWua, we report here also a comparative table with the four other main known data-bases that are devoted to GNSS ionospheric data. The selected GNSS ionospheric data systems are summa-
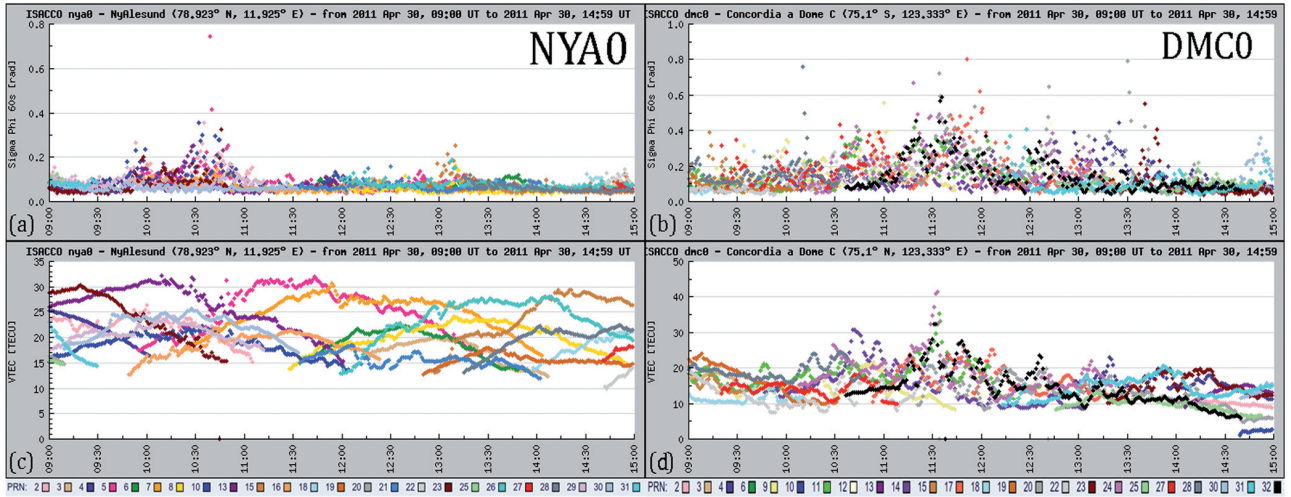
Figure 7. Linear plots (09:00 UT to 15:00 UT) of σ_Φ during the April 30, 2011, sun storm, as measured by the NYA0 (a) and DMC (b) stations, with the corresponding plots of vTEC as measured by the NYA0 (c) and DMC (d) stations.

rized in Table 4, in terms of the system names, access URLs, owners and policies to access the data. Table 5 gives the five different ionospheric GNSS data management systems, which are considered and compared through the selected features listed below:

– Scintillation indices: the presence of scintillation indices is reported both for amplitude (S_4) and phase (σ_Φ), with 'A' and 'P', respectively.

– TEC data: the availability of GNSS TEC data is reported.

– GNSS parameter data: the availability of other GNSS parameters, such as carrier-to-noise ratio, lock times, coordinates of the ionospheric piercing point, and others.

– GNSS data plots: the availability of visualization tools, such as linear plots, maps, and others.

– Data downloading tool: the accessibility to the data, by downloading them from the site.

– Scintillation raw data: the accessibility to high rate-sampling data. The sampling rate is indicated where available.

– Refreshing time data (min): the indication of the refreshing time, in minutes, between two consecutive data availability updates for the site.

– Data availability statistics: the indication of the presence of tools for data availability visualization and statistics.

– GNSS data geographic coverage: the indication of the geographic area that is spanned by the GNSS receiver data included in the site.

– Other Ionospheric data: the indication of the presence of complementary ionospheric data, such as those
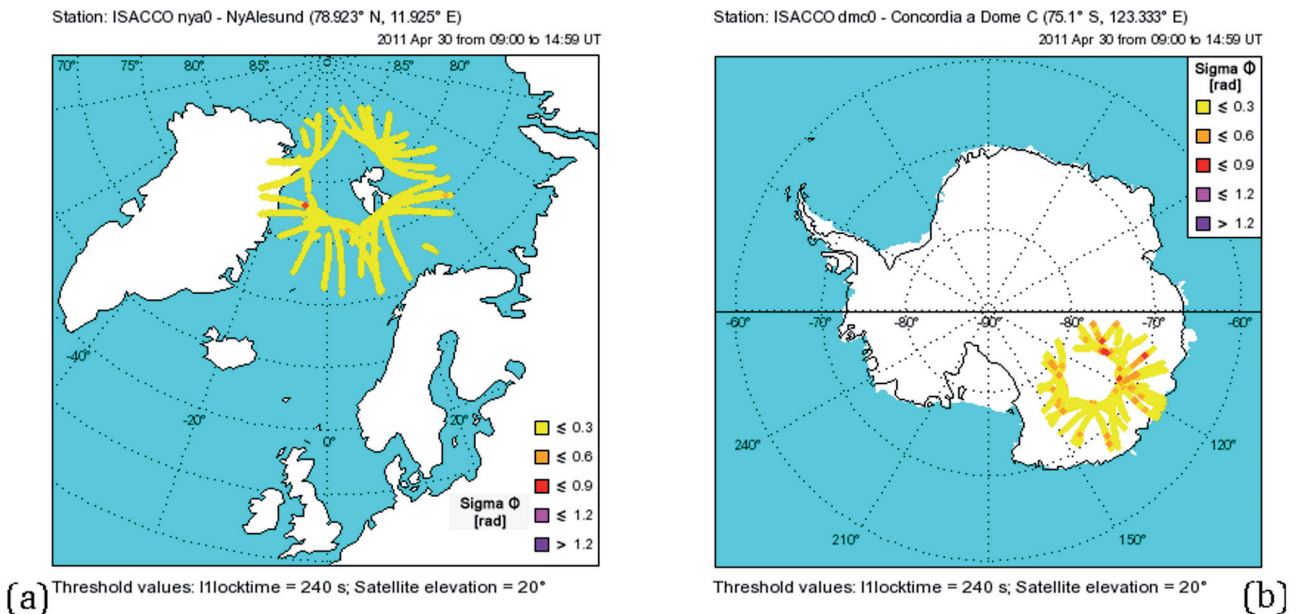

Figure 8. Polar plots (09:00 UT to 15:00 UT) of σ_Φ during the April 30, 2011, sun storm, as measured by the NYA0 (a) and DMC (b) stations.
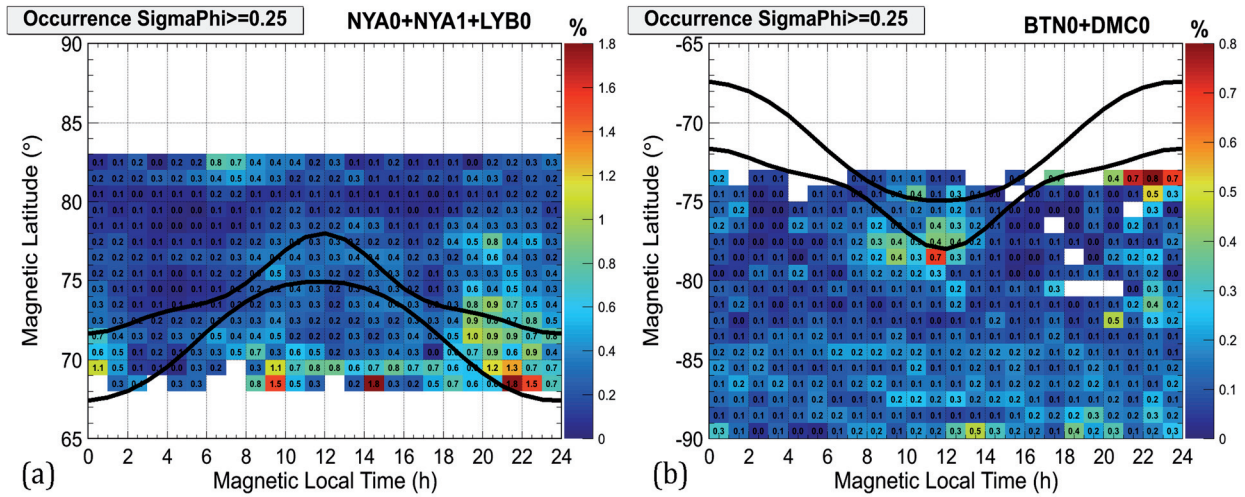
Figure 9. Maps of the percentage occurrence of phase scintillation index σ_Φ above 0.25 radians for the northern (a) and southern (b) hemispheres through the GBSC applied to the 2008 scintillation data. The black curve is the modeled Feldstein oval for IQ = 1.

acquired by ionospheric radars, riometers, and others.

As an outcome of the comparison, the eSWua can be considered a state-of-the-art system for GNSS ionospheric data.

5. Case studies

In this section, three examples of the application of the eSWua database are described:

– A recent geomagnetic storm event as simultaneously measured by a receiver in the Arctic (ISACCO-NYA0) and the Antarctica (ISACCO-DMC0).

– The climatological representation of scintillation data at both high latitude hemispheres by means of the Ground Based Scintillation Climatology (GBSC) technique.

– The application for the site characterization of one of the GISTM stations (ISACCO-DMC0).

5.1. Storm event (scintillation and TEC gradients)

A solar wind stream hit the Earth magnetic field during the early hours of April 30, 2011. The solar wind speeds exceeded 700 km/s, which sparked a G1-class (minor) geomagnetic storm. During the day, the Kp index ranged from 3 to 5 (Kp sum = 31). Between 09:00 UT and 15:00 UT, several events of concurrent scintillation were recorded for both of the hemispheres in the morning sector. The snapshots in Figure 7 show the linear plots from the eSWua website for 09:00 UT to 15:00 UT of the σ_Φ scintillation index during the geomagnetic storm, as measured by NYA0 (a) and DMC (b), and the corresponding plots of the vTEC, as measured by the NYA0 (c) and DMC (d) stations. The color code correlates the curves in the plots and the satellite PRNs. This visualization allows the user to easily cross-correlate the TEC gradients and the phase scintillation index enhancements. Figure 8 shows the polar plots of the

sole σ_Φ for the NYA0 (a) and DMC0 (b) stations, which corresponds to the same time interval as in Figure 7. The curves represent the projection of the satellite passes at the ionospheric piercing point, which is assumed to be at 350 km, while the color code here indicates the level of scintillation, as summarized in Figure 8 itself. Visualization through these polar plots allows easy identification of the region of the ionosphere in which the scintillation events occurred.

5.2. Bipolar climatology

The large amount of data stored in the eSWua and the data download tool facilitate the accessibility and the interaction of the database with statistical techniques and tools, which is useful for scientific and technological purposes. In this section, an example climatological representation is given, making use of the GBSC technique [Spogli et al. 2009, 2010, Alfonsi et al. 2011]. Figure 9 shows the maps of the percentage occurrence of the phase scintillation index σ_Φ above 0.25 radians for the northern (a) and southern (b) hemispheres, using the GBSC applied to the 2008 scintillation data. The position of the Feldstein auroral oval [Feldstein 1963, Holzworth and Meng 1975] has been superimposed on the scintillation occurrence maps for low levels of magnetic activity (IQ = 1), as 2008 was a year of quiet conditions of the near-Earth environment. Figure 9a was generated by merging the data from the NYA0, NYA1 and LYB0 Arctic stations, while Figure 9b shows the merged data from the BTN0 and DMC0 Antarctic stations. It is beyond the scope of this study to go into the details of these maps, but they show how the GBSC technique can identify areas of the ionosphere in which scintillation is more likely to occur. In the example, the scintillation occurrence is mainly enhanced in correspondence with the boundaries of
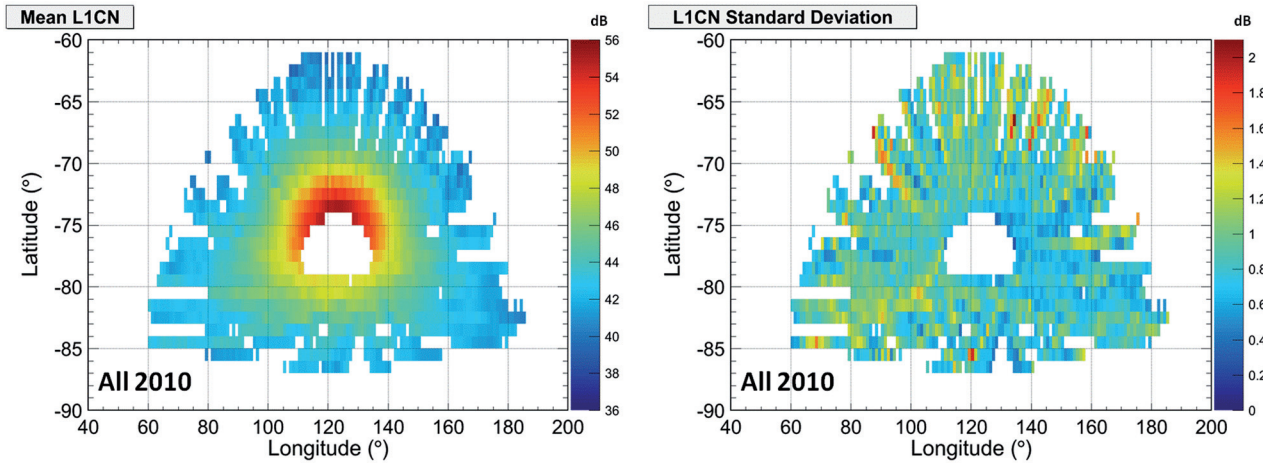
Figure 10. Maps of the mean (left) and standard deviation (right) of the carrier-to-noise ratio of the L1 frequency evaluated on the whole of the 2010 data collection of the DMC0 station.
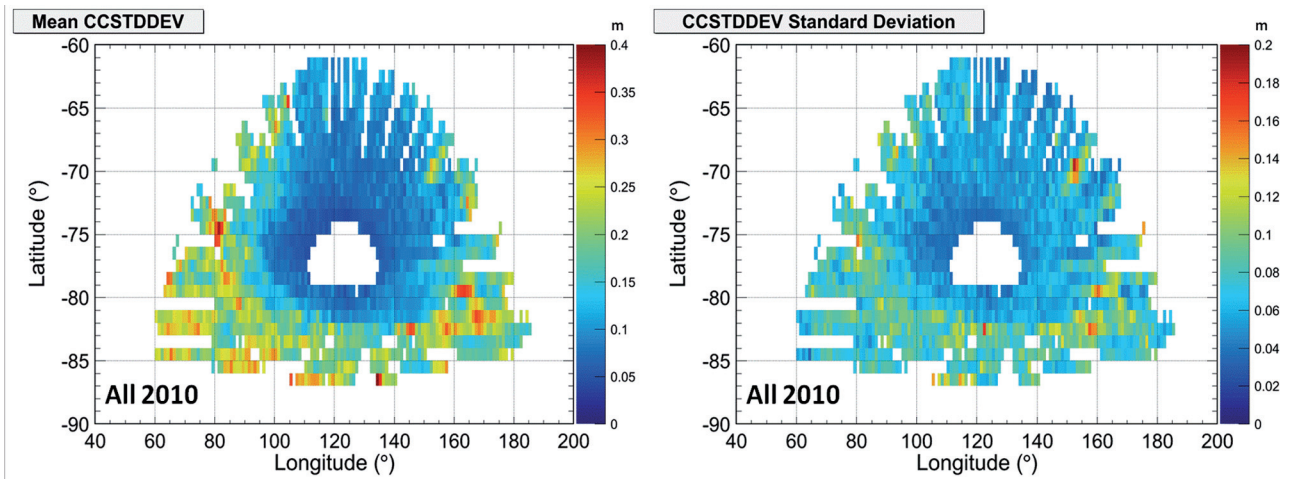

Figure 11. Maps of the mean (left) and standard deviation (right) of the code carrier standard deviation evaluated on the whole of the 2010 data collection of the DMC0 station.

the auroral oval. For a deeper discussion about the GBSC capabilities and the main results, the reader is referred to Spogli et al. [2009] and Alfonsi et al. [2011].

5.3. Station characterization

An application of the eSWua database relates to assessment of the receiver site features through the characterization of the GNSS station. The characterization consists of the analysis of the signal quality over the field of view spanned by the antenna receiver, through signal-quality parameters, such as the carrier-to-noise ratio of both L1 (L1C/N) and L2 (L2C/N), and the standard deviation of the code carrier (CCSTDEV). L1C/N indicates the quality of the reception, while CCSTDEV gives an indication of the multipath activity on the L1 frequency. This allows the determination of the possible sources of signal distortions that affect the scintillation and TEC measurements for each single station included in the database. As an example, Figure 10 shows the maps of the mean value (left) and the standard deviation (right) of the carrier-to-noise ratio of the L1 frequency,

evaluated over the whole data from the year 2010 of the DMC0 receiver (Antarctica). These maps are produced through the GBSC technique [Spogli et al. 2009, Alfonsi et al. 2011] in the azimuth *versus* elevation frame. In this case, both the L1C/N mean and standard deviation maps show that the signal quality was stable over the whole of the year. The mean values range from 36 dB to 56 dB, and reach a peak standard deviation of 2.1 dB in a few of the bins of the maps. Figure 11 shows the maps of the mean value (left) and standard deviation (right) of the code carrier standard deviation, evaluated from the same dataset as for Figure 10. The bins at the borders of the maps correspond to measurements carried out at low elevation angles (below ca. 20°), which are expected to be affected by reflections and multipath, as indicated by the larger CCSTDEV. Even if it is already clear from the map of the mean values, the sigma map shows an increase in the CCSTDEV standard deviation in the region (latitude 90° to 120°), which indicates a greater variability of the CCSTDEV there, a behavior which will be investigated in the future.

6. Summary

The INGV and the University of Nottingham manage a network of GISTM receivers that covers from low-to-polar latitudes of both hemispheres. In the framework of the GRAPE SCAR Expert Group, the eSWua system hosts GNSS data from the two institutions. The eSWua allows this large amount of data to be organized in a correct database, which can contribute to scientific and technological improvements at international levels. The eSWua is now a mature system that can support the acquisition, elaboration, evaluation, archiving, visualization, and downloading of multi-institute observations of the ionized upper atmosphere through GNSS.

In this study, different uses of the eSWua capabilities as a scientific and applicative service are shown, from the simple visualization of a historical geomagnetic storm event, to a refined analysis of an entire year of data that were acquired by five receivers through a climatological tool, by passing through station site characterization, as a technological application.

The eSWua philosophy is supported by the awareness that modern geosciences have to rely on structured digital data that can interact with services and tools for the scientific and social communities.

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