

IESID: Automatic system for monitoring ground deformation on the Deception Island volcano (Antarctica)

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Abstract

When establishing the relative distance between two GNSS-GPS stations with sub-centimeter accuracy, it is necessary to have auxiliary data, some of which can only be collected some time after the moment of measurement.

However, for monitoring highly-active geodynamic areas, such as volcanoes and landslides, data precision is not as essential as rapid availability, processing of data in real-time, and fast interpretation of the results.

This paper describes the development of an integrated automatic system for monitoring volcanic deformation in quasi real-time, applied to the Deception volcano (Antarctica). This experimental system integrates two independent modules that enable researchers to monitor and control the status of the GNSS-GPS stations, and to determine a surface deformation parameter. It comprises three permanent stations, one of which serves as the reference for assessing the relative distance in relation to the other two. The availability of GNSS-GPS data in quasi real-time is achieved by means of a WiFi infrastructure and automated data processing. This system provides, in quasi

real-time, a time series of varying distances that tells us the extent to which any ground deformation is taking place.

Keywords: Volcano Monitoring, GNSS-GPS Satellite Geodesy, Antarctica.

1. Introduction

The multidisciplinary scientific field of Volcanology uses mainly geological, geophysical and geochemical surveying techniques and methods. To determine the risk and degree of danger of an impending volcanic eruption, it is essential to evaluate the state of the currently-existing volcanic activity. The geodetic and geophysical parameters commonly used for volcanic monitoring and surveillance include seismic activity, gravity anomalies, analysis of volcanic gases, geomagnetic anomalies, thermal anomalies, and ground deformation parameters. Volcano monitoring requires real-time or quasi real-time evaluation. To determine the risk of eruption, the faster the parameters are evaluated, the greater the opportunities to reduce those risks for the population.

Previous experiences in volcano monitoring using GPS include the following. The Taal volcano in Philippines was monitored by a GPS network comprising three GPS stations, with sampling intervals of 30-s and elevation mask of 10° ; data was processed 18-24 hours after the end of UTC day (Lowry *et al.*, 2001). In Stromboli Island three continuous GPS stations were deployed sampling at 1 Hz. These stations were computed relative to a fourth, with the object of studying the shallow plumbing system. This monitoring system is used as part of a tsunami warning system for the coasts of Sicily and Calabria (Mattia *et al.*, 2004). Since 2003, in the same volcano (Puglisi *et al.*, 2005), an integrated geodetic monitoring system has been deployed,

based on both GPS and geodetic techniques, and focused on real-time detection of the ground deformation related to potential slope failures. This system is remotely-controlled and provides continuous measurement of ground deformations. Likewise, in the Kilauea volcano, data analysis strategies were developed using data from a GPS network on this volcano. The precision was enhanced by methods for filtering position estimates (Larson *et al.*, 2010).

This paper describes the design and development of an automated system capable of determining a ground deformation parameter in quasi real-time observations from GNSS (Global Navigation Satellite System) satellites, at monitoring stations established on the Deception volcano in Antarctica.

Deception Island is located in the region defined by the archipelago of the South Shetland Islands, the Antarctic Peninsula and the Bransfield Sea. This is a geodynamically-active region, manifested by the presence of three emerged volcanoes: Deception, Penguin and Bridgeman, and six submarine volcanic structures aligned in the direction NE-SW between the parallels 60° and 63° S, which define an extensional axis of approximately 500 km. in length. The existence of active volcanism, together with the seismic activity recorded along this axis, indicate the continuity in the extensional process of the Bransfield Rift. Of these three volcanoes, Deception (63° S, 60° W) is the one that currently presents active volcanism (Canals *et al.*, 1997; González-Ferrán, 1991; Smellie, 2001). Its most recent eruptive processes have been dated to 1842, 1967, 1969 and 1970, and there were others, not confirmed, in 1912 and 1917 (Martí *et al.*, 1996) (see Figure 1).

During the 1967–1970 eruptive period, the volcanic activity caused the destruction of the Chilean and British Scientific Bases, located at Pendulum Cove and Whaler's Bay respectively. These eruptions changed the morphology of the island: an islet formed

that was subsequently connected to the island near to Telefon Bay. In this period a large volume of ash was emitted and deposited on the neighboring islands, as can be observed in the Johnson glacier at Livingston Island. Due to these eruptive events and their destructive consequences, the scientific activities of Argentinean, Chilean and British researchers were interrupted.

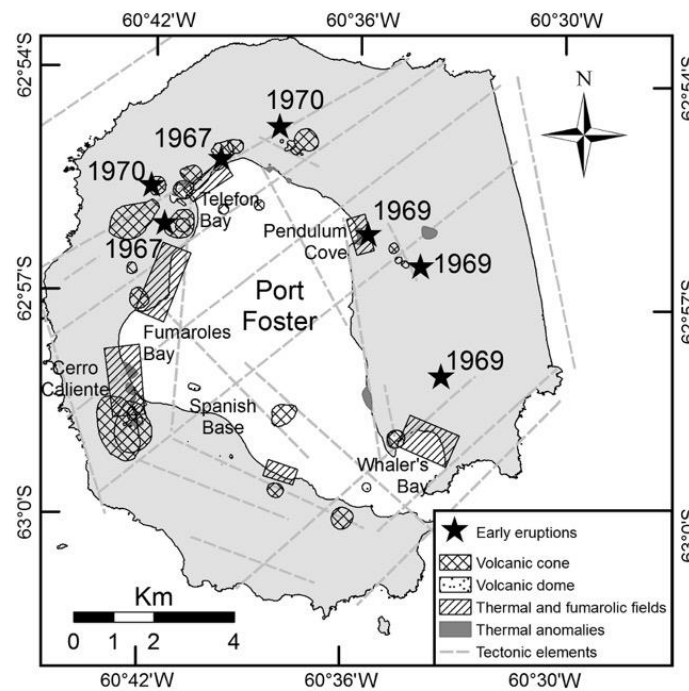


Fig. 1. Location of historical eruptions, thermal anomalies, tectonic elements, and volcanic cones on Deception Island.

Activities to monitor and measure the volcanic activity by means of geodetic and geophysical techniques were resumed in 1986, when the first Spanish Antarctic research campaign took place. Presently, the superficial evidence of volcanic activity is mainly the presence of fumarole areas with emissions of gases at 70°C and 100°C, in Fumaroles and Whaler's Bay respectively, hot soils at 100°C in Cerro Caliente, and thermal springs at 45°C and 65°C in Pendulum Cove and Whaler's Bay (see Figure 1). In addition, there are numerous areas where significant seismic activity is detected (Carmona *et al.*, 2012). Also in the 1991-1992 and 1998-1999 campaigns, two

seismic/volcanic crises were detected in Fumaroles Bay (Ibáñez *et al.*, 2003). This activity has two different sources: one is tectonic activity due to the expansion of the Bransfield Rift; the other has a purely volcanic origin (Berrocoso *et al.*, 2006).

2. Geodetic infrastructure and system hardware architecture

Three stations of the geodetic network define a plane whose spatial position varies with time due to geodynamic factors - for instance, those of volcanic origin. These spatial and temporal variations can be determined by analyzing the variations of slope distances between a reference benchmark and the other two. By obtaining accurate geodetic positions in certain real-time or quasi real-time from three GNSS stations, it is possible to take these variations like a parameter enabling of evaluating, rapidly and easily, of the changes taking place in ground deformation. This deformation does not represent the absolute deformation; it does, however, provide clues as to its behavior in relation to expansion or contraction effects. The absolute deformation model and the geodynamic behavior have been previously established from a denser station network, which includes the three stations mentioned above, and another outside the study area. These stations have been selected from those comprising this network, on the basis of the geodynamic behavior, ease of access to the physical site, and simplification of the communication infrastructure.

To evaluate the ground deformation on Deception volcano, a system designated 'IESID', consisting of the above mentioned GNSS stations, has been established; this provides geodynamic observations in continuous mode by GNSS-GPS satellites; it includes a GNSS-GPS data transmission / reception system using WiFi technology (Kameswari *et al.*, 2006), designated 'IESID-H', and a set of software tools, designated

'IESID-S', developed for the remote control of the stations and for automatic processing of the GNSS-GPS data received.

2.1. Geodetic infrastructure

There is a pre-existing geodetic network (designated REGID) on Deception Island that constitutes the frame of reference not only for the geodetic studies but also for other research. It consists of twelve benchmarks distributed along the inner coast of the Island (Port Foster). In every Antarctic campaign this network is observed with GNSS-GPS sensors. The accuracy of the GNSS System, especially for horizontal positioning, makes the REGID network very useful for understanding geodynamic activity on the island. For the IESID system the three stations BEGC (Base Antártica Española 'Gabriel de Castilla'), FUMA (Fumaroles Bay) and PEND (Pendulum Cove) have been selected. BEGC is located in the surroundings of the Spanish Antarctic Base and it has direct current power supply. Changes observed in the positioning of FUMA and PEND represent the geodynamic behavior of the island, as shown in Figure 2. They are located in easily accessible places and can be directly seen from BEGC. All three stations have been observed during all the Antarctic campaigns since 1995.

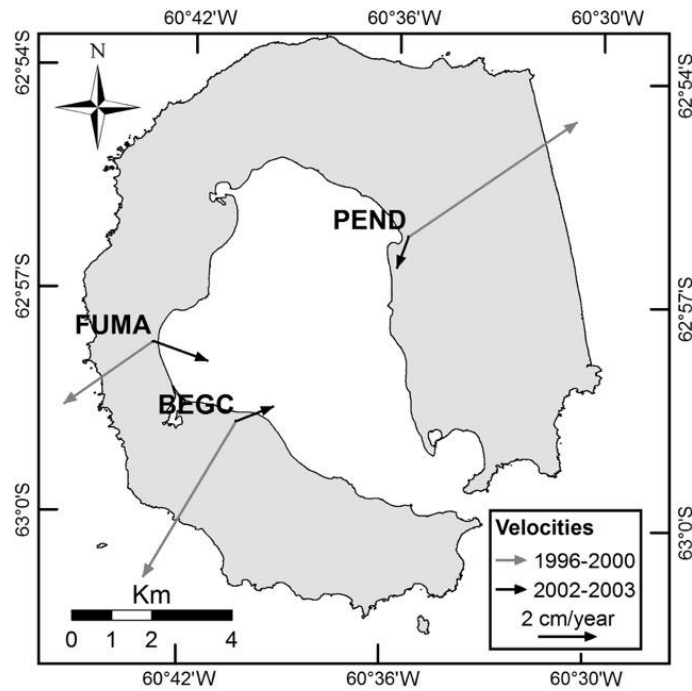


Fig. 2. Geodynamic behavior of the stations in the 1996–2000 and 2002–2003 campaigns. Modified figure from Fernández-Ros et al. (2007).

2.2. Hardware architecture of IESID-H

This architecture is responsible for the integration of the three GNSS stations in the WiFi network. This is a wireless network, in accordance with IEEE (Institute of Electrical and Electronics Engineers) 802.11b technology, set to infrastructure mode. It consists of three types of node: the central node, remote nodes and the repeater node (see Figure 3) (Flickenger *et al.*, 2007; Kropff *et al.*, 2006). No encryption or any other WiFi network security options have been used, given the relative isolation of the working area of Deception Island.

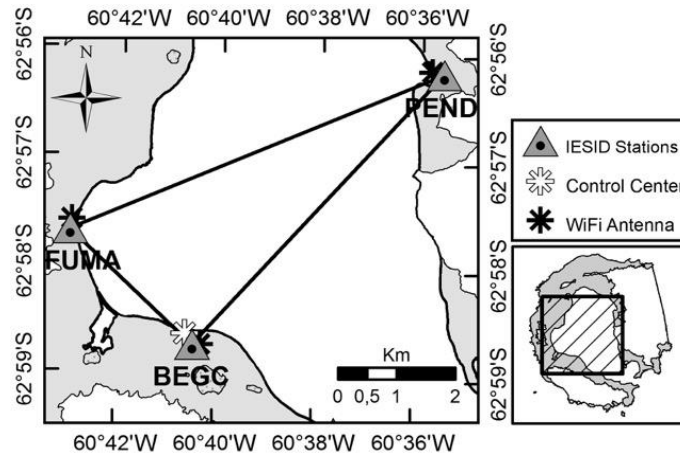


Fig. 3. Location of the geodetic infrastructure that integrates the automatic system for monitoring ground deformation on the Deception Island volcano.

2.2.1. Central node

This node is located in the science module of the BAE (Spanish Antarctic Base) ‘Gabriel de Castilla’. It consists of the Control Center and Processing Center (see Figure 4(d)). The Control Center is a laptop computer responsible for the management of GNSS-GPS stations. For this task it has a software module for downloading data and control of the stations. This module is responsible for the real-time control of the status of each GNSS-GPS station and for the automatic downloading of the tracking files from the stations (Bond *et al.*, 2007).

The Processing Center, like the Control Center, is another laptop computer. It is responsible for the processing of GNSS tracking files to obtain the time series of the ground deformation parameter to monitor the island's volcanic status in real-time. Both computers are integrated into the Ethernet network of the Base’s science module through a switch. Static addressing is used for all equipment in a class C private network. The switch is connected to a WiFi router that provides connection to other WiFi network nodes.

This router (NanoStation2 model, from Ubiquiti Networks™, Inc.), installed on the exterior of the science module, is configured as an access point. It is connected to a Stella Doradus™ 24 3360 Omnidirectional antenna of 13dBi.

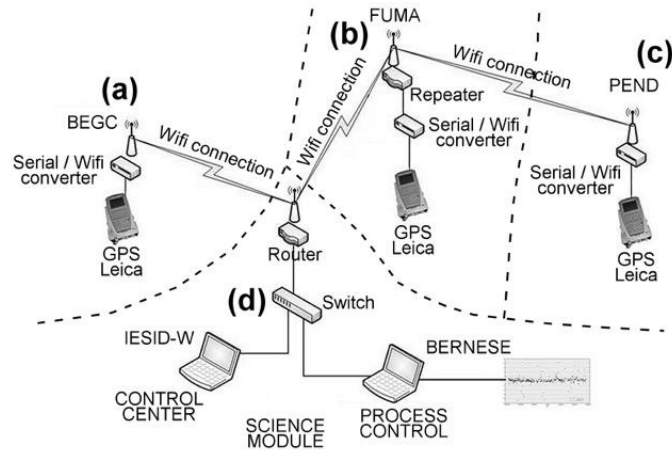


Fig. 4. Hardware infrastructure of the integrated automatic system for volcanic surveillance. (a) Remote node BEGC, (b) repeater node FUMA, (c) remote node PEND and (d) central node at the Spanish base ‘Gabriel de Castilla’.

2.2.2. Remote nodes

These nodes correspond to the geodynamic benchmarks located at BEGC and PEND. They are composed of: 1. a Leica™ GX1230 Geodetic GPS receiver of dual frequency with a Leica™ AX1202 antenna; and 2. a Moxa™ NPort W2150P RS-232 series / WiFi converter connected to the GPS receiver via a Leica™ GEV102 serial cable for data transfer. This cable connects the port 2 of the GPS receiver to the RS-232 port of the series / WiFi converter (see Figure 4(a) and 4(c)).

According to the station, this converter is connected to a Yagi directional antenna (ANT PheeNet™ 120YN model) of 20 dBi, in the case of BEGC, while it is connected to a Stella Doradus™ directional parabolic antenna (24 SD27 model) of 24 dBi, in the case of PEND.

To connect the GPS receiver to the media converter, the port 2 of the receiver and the RS-232 port of media converter have been configured with the same parameters of transmission rate and parity. Likewise, the RS-232 of the Moxa™ NPort media converter has been configured in its mode of operation as "Socket TCP Server", choosing a free port number for communications. Because the Control Center accesses each of the stations by means of the REGID-W, the Moxa™ NPort media converter devices are configured with static IP addresses. Each of the BEGC and PEND converters have two interfaces - Ethernet and WiFi; of these interfaces only the WiFi interface is configured. As has been specified, the Control Module of the stations accesses the communication port of each of the PEND and BEGC stations to request both the GPS data files and the control parameters of the stations from the OWI (Outside World Interface) command interface of Leica™.

2.2.3. Repeater node

This node is located at FUMA and provides coverage for the station located at PEND. Like the rest of the nodes, it consists of a Leica GPS geodetic receiver connected to a Moxa™ NPort serial / WiFi converter, and this converter is, in turn, connected to a Ubiquiti™ NanoStation 2 router via an Ethernet interface (see Figure 4(b)). This router has been configured in "WDS Station" (Portoles *et al.*, 2004) Wireless Mode and "Bridge" network mode, with the router of the science module as a gateway. The router is connected to a Stella Doradus™ 24 12015V sector antenna Base Station of 12dBi with a 120° beam pattern in the horizontal plane. Therefore, this router works as a network traffic repeater to and from the PEND station.

Figure 5 (a) and (b) shows the equipment deployment and installation diagram of the repeater node.

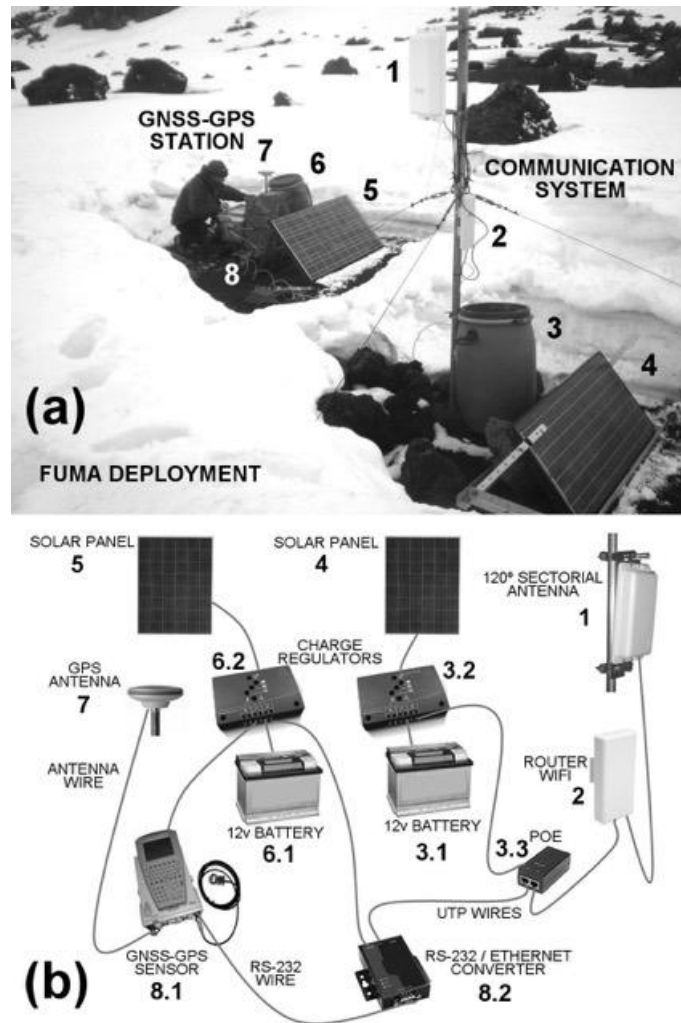


Fig. 5. (a) Equipment deployment and (b) installation diagram of the repeater node FUMA.

2.3. IESID-S software application

IESID-S is the software module responsible for both the remote control of the GNSS stations of the IESID system and the geodetic processing of the observations received at the control center (Amore *et al.*, 2002).

To implement the system, in this module, station BEGC is configured as the reference station, with the other two stations, FUMA and PEND, whose distances are calculated with respect to the reference; this provides quasi real-time variation of the distances separating the stations.

To monitor the ground deformation, the module requests the GNSS observation files from the stations every 30 minutes. These files are converted to RINEX¹ format (Gurtner *et al.*, 1990) and processed by Bernese GNSSTM software v5 .0 (Dach *et al.*, 2007), thus the time series of the variations in slope distances is obtained in quasi real-time.

2.3.1. Module for downloads and station control

This module is responsible for downloading observation files and for remote control of the GNSS stations.

The methodologies described by Pressman (2001) and Larman (2003) have been used for its analysis and design, and REM v2.3² software (Durán, 2000) has been used for the elicitation of requirements. Using this methodology means that prototyping (Naumann & Jenkins, 1982) has been selected as the life cycle model.

The module is composed of seven subsystems, each of which has the following functionality listed below:

- **Station Management:** this subsystem is responsible for adding, deleting or modifying the GNSS station data.
- **Table management:** this is responsible for adding, deleting or modifying data in the database tables.
- **Database Management:** this is responsible for adding, editing or deleting tables in databases.
- **Application Management:** this is responsible for modifying the configuration data of the module.

¹ <ftp://igscb.jpl.nasa.gov/igscb/data/format/>

² http://www.lsi.us.es/descargas/descarga_programas.php?id=3

- Stations Remote control: this is responsible for communication with the GNSS stations through the Outside World Interface (OWI) commands (Leica Geosystems™ AG, 2007).
- Graphics: this is responsible for the graphical representation of the parameters obtained by OWI commands; it also manages the graphical environment.
- Data downloading: this manages the downloading of GNSS observation data files.

This module has been developed in Java 6.0 (Candemhead *et al.*, 2008; Eckel, 2003; Flanagan, 2000; Gosling *et al.*, 2005; Schildt *et al.*, 2003) through the NetBeans 6.5³ Integrated Development Environment (IDE). The graphical interface has been designed in Java Swing.

The module is structured in layers. The bottom layer is responsible for implementing the OWI commands interface of Leica™; this layer provides the connection to the GNSS stations. The middle layer implements all the program logic and station management such as databases, tables, scheduled tasks, etc. Finally the top layer is responsible for providing the whole graphical interface to facilitate man-machine interaction (see Figure 6).

³ <http://www.netbeans.org/>

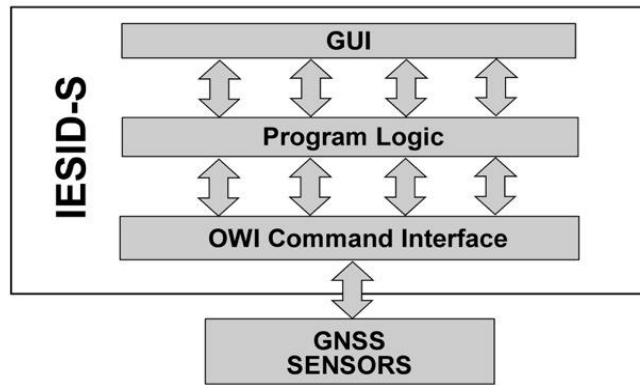


Fig. 6. Organizational structure of the IESID-S module.

To manage the information generated by the module, the Relational Database Management System (RDBMS) MySQL⁴ has been used. This database stores all the events generated in the communication between the control center and the MoxaTM NPort RS-232/WIFI converters, together with the module configuration (see Figure 7 (a) and 7 (b)). The Config and Stations tables of the IESID_W_Config_db database store all the parameters necessary for the operation of the module and the GNSS station data that make up the network (see Figure 7 (a)).

The IESID_W_Log_db database (see Figure 7 (b)) records all data obtained from the GNSS receivers through OWI commands, and the working information of the module. The module is a single-user client / server multithread application developed in Java. For each thread the application creates a TCP connection socket to communication port of the MoxaTM NPort RS-232/WiFi converter, connected in turn to the LeicaTM GX1230 GNSS sensor. The periodic requests, as OWI commands, are made through this converter; the GNSS observations and the parameters for the control of the stations are obtained in its answers. Among the OWI commands needed are: Battery status; Configuration; Directory of memory; Download file from sensor; GNSS

⁴ <http://www.mysql.com><http://www.mysql.com>

satellites in view; Global positioning system fix data; Memory status; Satellite position; Delete files; Message interruption; Point occupation begin; Set configuration; and Position and quality.

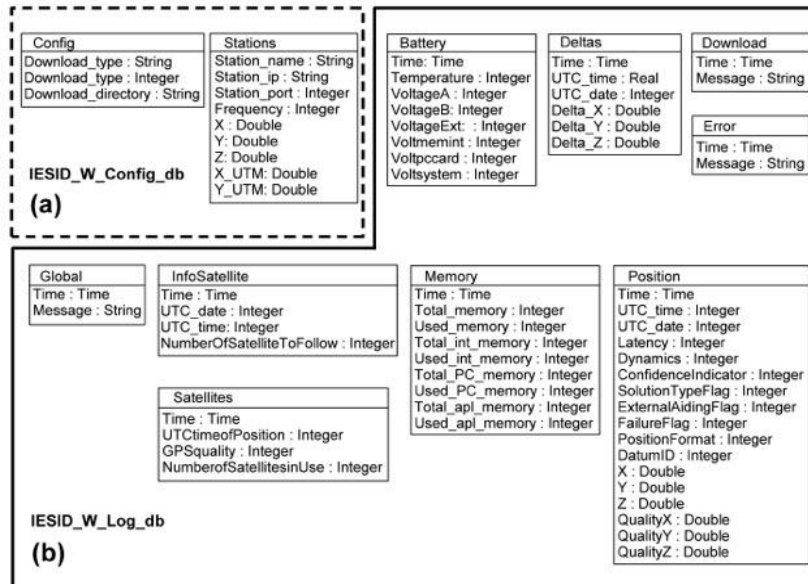


Fig. 7. (a) Table structure of the IESID_W_Config_db databases. (b) Table structure of the IESID_W_Log_db databases.

TCP sockets are used for communications between the control center and MOXA™ media converters, because of their reliability compared with UDP sockets.

An execution thread is created for each GNSS station; this thread has an execution schedule indicated by the frequency request parameter, with a maximum value of 1 Hz. To check the status of the connection to the MOXA™ server, the waiting time to generate an exception set in the socket is 1 minute. This exception is captured and used to check the status of connections to the GNSS stations.

One of the parameters requested from the GNSS sensor is the current position data, requested through the OWI command: "GNSS Fix Data".

The messages trace of this command is shown in Figure 8 (I). First the sensor is asked for the current position data in the format of latitude, longitude and altitude; and then the answer is obtained from the sensor, which supplies the data requested.

A TCP socket is also used to download GNSS observation files; the execution thread for this runs every 30 minutes. The sequence of OWI command messages for a GNSS data file download request is indicated in Figure 8 (II to IV). In Figure 8 (II) the sensor is asked to stop sending messages before the GNSS data file downloading, and the sensor sends back an acceptance response. Then, in Figure 8 (III) a request is sent to obtain the name and size of all files stored in the memory of the GNSS sensor. In each response message the sensor sends back the information on each of the files, until all the files are correctly identified and characterized.

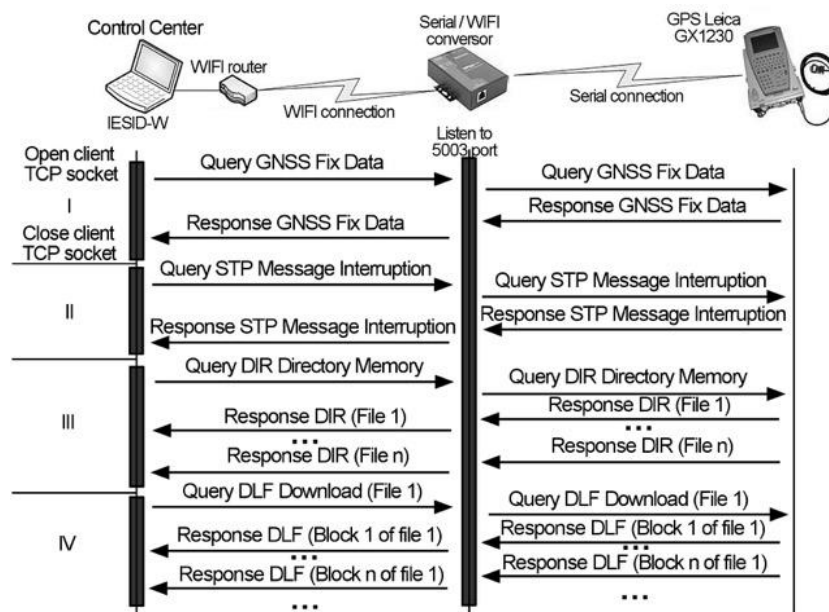


Fig. 8. Message sequence for obtaining the precise position and the downloading of GNSS observation files by means of OWI commands. (I) Request for position data in format of latitude, longitude and height; (II) request for interruption of routine message sending; (III) request for name and size of all files stored in memory of GNSS sensor; (IV) request for first file download.

In Figure 8 (IV) the download of file 1 is requested. The sensor sends back the file content divided into blocks. The module sends several consecutive messages requesting the remaining blocks to complete the content of the first GNSS data file. Then it is immediately requested to download the following file, and so on until the last file has been downloaded.

The download and control module has a graphical interface consisting of four screens with essential information for controlling the GNSS stations and monitoring the variation of the slope distance between BEGC-FUMA and BEGC-PEND stations.

The screen in Figure 9 (a) shows information related to the distanciometer stations of Deception: name, IP address, etc. On the right side it includes a keypad with the main features of the application. In the central part there are progress bars showing the download percentage of the GNSS observation files, and finally at the bottom, it shows status messages of the various events of the application such as error or success messages.

The screen in Figure 9 (b) shows the status of the GNSS stations in a series of progress bars and labels. The data shown are: the state of connectivity; sensor temperature; percentage of battery charge; number of satellites; UTC date; UTC time; and space left on the compact flash memory.

In the third screen, in Figure 9 (c) the records of the status of events occurring in the system associated with the OWI command requests can be consulted. The tables in the IESID_W_Log_db database can also be managed.

Finally, Figure 9 (d) shows the variation of the slope distance parameter between the stations BEGC-FUMA and BEGC-PEND. To test whether the distance variation is the result of the ground deformation and not caused by errors due to lack of precision in the

resolution of the positioning problem, this value is contrasted with the number of satellites.

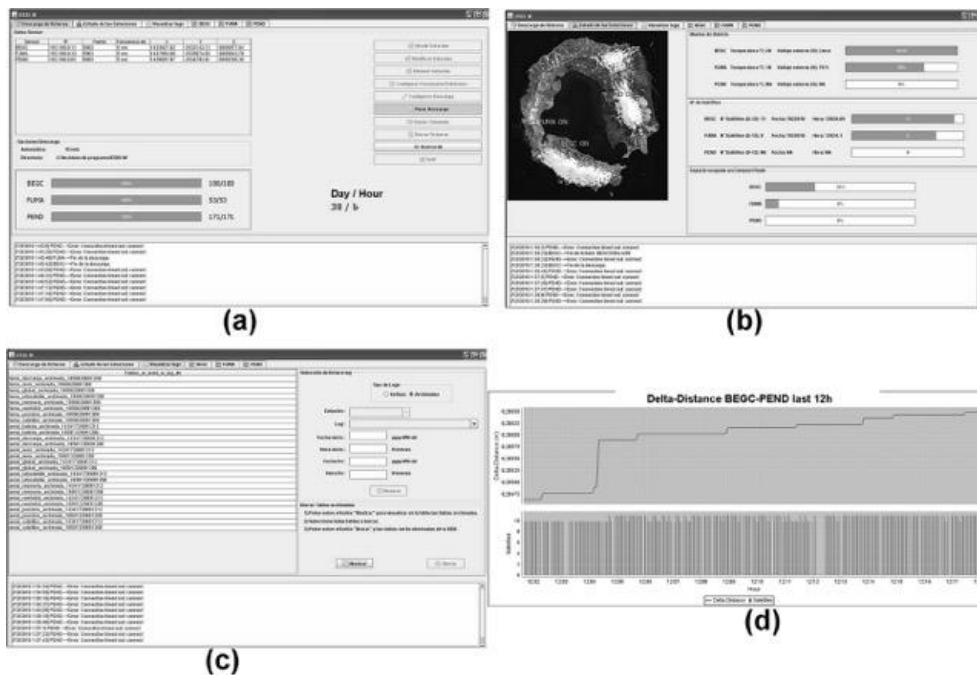


Fig. 9. Control module and data download screens.

2.3.2.. Module for management of the GNSS observation data

Once the download module has obtained the observation files requested from the GNSS stations, the management module is responsible for converting and processing the data to get the time series of the distance values between the stations BEGC-FUMA and BEGC-PEND. This part of the software has been developed primarily in the GNU Octave⁵ programming language (Eaton *et al.*, 1988), and has been sequenced in three parts (see Figure 10).

⁵ <http://www.gnu.org/software/octave/>

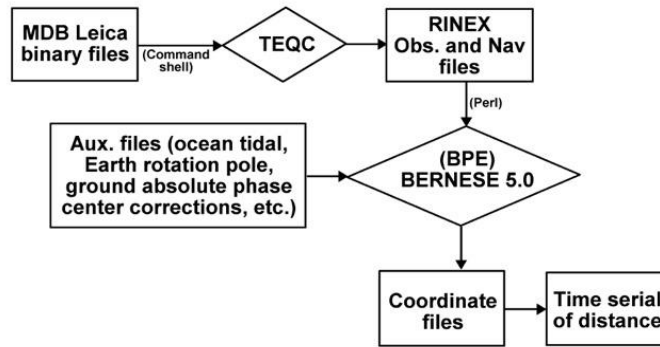


Fig. 10. Flow chart of the GNSS observation data management module.

The first part transforms GNSS observation data from the MDB binary format of Leica™ to the RINEX (Receiver INdependent EXchange) standard format. This transformation required the use of the tool known as TEQC (Translation, Editing and Quality Check) (Estey *et al.*, 1999) of UNAVCO (University Navstar Consortium). The TEQC tool is an application that runs on command lines and is capable of generating RINEX files of observations and events transmitted from Leica MDB files. It allows the header of each RINEX file to be edited to include specific information for each station, such as the reference coordinates, name of the station and observer data, among others. It also allows files to be chained and the duration of the registration data to be specified, as well as the filtering of the desired observable data.

Once we have the RINEX files in the format we need for their processing, a script in Perl language is executed; this script runs the data processing with the BPE module of the Bernese GNSS™ Software v5.0. Standard procedures for data processing were applied. Broadcast Ephemeris and IERS (International Earth Rotation and Reference Systems Services) Bulletin A pole file were used to integrate the daily arcs for the satellites. All stations were corrected for site displacement using the ocean tide loading model from Onsala Space Observatory (Ray, R. D., 1999). Ambiguities were dealt with independently for each baseline, using the ionosphere-free observable. The data

processing is done from hourly observation files, thus 24 solutions per day are obtained. Finally, the slope distances between the reference station BEGC and the other two stations FUMA and PEND are calculated from the coordinate files obtained, once the data processing has concluded. Thus the time variation of the distances represented graphically is obtained (see Figure 11).

3. Conclusions

A fully automatic system has been designed and developed to determine the ground deformation parameter in a volcanic area. The IESID system uses GNSS-GPS receivers that provide relative distances between the established stations with sub-centimeter accuracy. The system operates continuously, and is capable of monitoring volcanic activity in real-time by means of ground deformation measurements.

The use of WiFi technology for transmission of real time GNSS-GPS data in active volcanic areas represents a considerable improvement with respect to previous technologies mainly focused on temporary deployments. WiFi technology not only facilitates rapid deployment but also improves performance both in consumption and in management of large datasets. A WiFi network is more robust against interference on an isolated volcano in Antarctica than any other previous technologies. It is not necessary physically to visit the GNSS-GPS station for its geodetic maintenance, since it is controlled remotely. The specific design of the system hardware has been subordinated to the Antarctic environment in terms of power requirements, protection of equipment and item selection of WiFi transmitters and receivers.

The integration in the IESID system of the Bernese™ software for GPS data processing makes it possible to obtain, in quasi real-time, relative distances with sufficient accuracy for geodynamic research studies.

The installation of the IESID system on the Deception volcano is providing continuous information on the volcanic activity and its evolution. Figure 11 shows the corresponding time series of the relative distances between the reference station BEGC and observation stations FUMA and PEND, together with the geodynamic significance.

In Figure 11 the results obtained in 2008-09, 2009-10 and 2010-11 campaigns are shown. Between the 2008-09 and 2009-10 campaigns it is noted that the decrease of the relative distances corresponds to the process of contraction calculated subsequently, indicated in the model (see Figure 11 (b)). This process is reversed between the 2009-10 and 2010-11 campaigns, as the increase in the relative distances corresponds to a process of expansion (see Figure 11 (c)). The very small absolute value of the distance variation between BEGC-FUMA, in comparison to that between BEGC-PEND, indicates that the benchmarks BEGC and FUMA present an analogue geodynamic behavior which is differentiated from that of the benchmark PEND.

Similarly, the IESID system offers the possibility of establishing the trends of the ground deformation within the observations obtained in each campaign. The processes of contraction and expansion observed during the 2008-09 and 2009-10 campaigns show these trends clearly. These results indicate the value of using the IESID system as an effective tool for volcanic surveillance in quasi real-time.

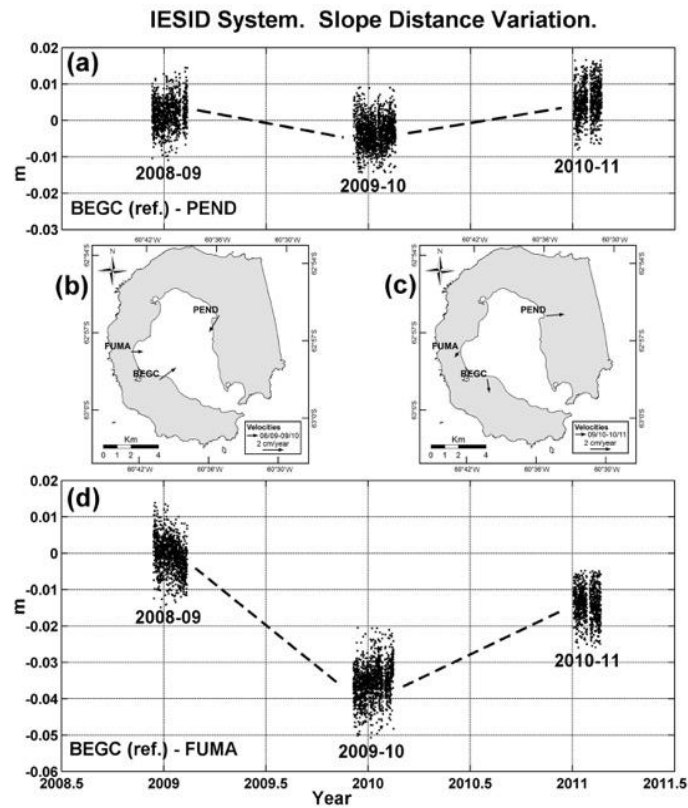


Fig. 11. Result of applying the IESID system to the Deception volcano; (a) and (d) show the relative processing between the reference station BEGC and stations FUMA and PEND; (b) and (c) show the geodynamic significance of the variations in slope distance. In the period 2008/09–2009/10, a contraction process existed on the island and in the period 2009/10–2010/11, an expansion process.

4. Acknowledgments

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