Energy Efficient System for Environment Observation

Giorgio Giordanengo, Luca Pilosu, Lorenzo Mossucca, Flavio Renga, Simone Ciccia, Olivier Terzo, Giuseppe Vecchi, Vincenzo Romano, Ingrid Hunstad

Abstract Environment observations provide a unique source of consistent information about the natural environment and they provide resource managers the information to assess the current state of the environment, weight the requirements of different uses by multiple stakeholders, and manage the natural resources and ecosystems in a sustainable manner. Most of the observations are based on satellites, but remote-sensing technologies alone cannot guarantee observations at the spatio-temporal resolution and with the accuracy requested for monitoring and modeling applications targeting, like weather and climate extremes and the complex feedback processes between the natural environment and human activities. Dense networks of standard and in-situ weather related sensors are present in EU and US, but it may happen that their data are not always available in real-time or updated with the required scale for various weather and climate applications. Then, high-resolution, (near) real-time on field monitoring systems are needed to satisfy the demand to sample environmental data, both in dense populated regions and in less developed and getting more populated regions, where essential in-situ observational capabilities can be lacking or deteriorating. The paper would demonstrate the possibility to have energy efficient computing and communication systems that can be employed for environment observation and that can enrich traditional in-situ and remote sensing environmental data, to enable a significant step forward in the environment monitoring of a wide range of weather and climate data. The paper will present an approach going in this direction (computing/communication everywhere with low-power constrains), tested in a harsh environment, by exploiting low-power boards to perform data pre-processing and reconfigurable antennas to send data in a more energetically convenient way applied to a real case as it may be the monitoring of ionospheric scintillation in Antarctica.

1 Introduction

Since 2003 a specially modified GPS receiver has been used by INGV, Upper Atmosphere Research Unit, for recording the phase and amplitude of the L1 sig-

Giorgio Giordanengo, Luca Pilosu, Lorenzo Mossucca, Flavio Renga and Olivier Terzo
Istituto Superiore Mario Boella (ISMB), Torino, Italy, e-mail: {giordanengo,pilosu, mossucca,renga,terzo}@ismb.it

Simone Ciccia and Giuseppe Vecchi
Department of Electronics and Telecommunication (DET), Politecnico di Torino, Torino, Italy, e-mail: {simone.ciccia,giuseppe.vecchi}@polito.it

Vincenzo Romano and Ingrid Hunstad
Istituto Nazionale di Geofisica e Vulcanologia (INGV), Rome, Italy, e-mail: {vincenzo. romano,ingrid.hunstad}@ingv.it

nals during events of ionospheric scintillation at high latitude [1]. In Antarctica the first Global Navigation Satellite Systems (GNSS) receiver, for ionospheric purposes, was installed in 2006 at the Italian station "Mario Zucchelli", Terra Nova Bay (74.7°S, 164.1°E), in the frame of the Italian National Program for Antarctic Research (PNRA). This site became part of the wider Ionospheric Scintillations Arctic Campaign Coordinated Observation (ISACCO), the Italian project for monitoring ionospheric scintillations and total electron content (TEC) in polar regions with modified GNSS receivers. Since then, three more installations have been done in Antarctica in the Italian-French station of Concordia (75.1°S, 123.4°E) on the Antarctic plateau, at 1200 km from Mario Zucchelli base.

GNSS receivers constitute a very useful tool to investigate the Earth's ionosphere. A radio wave, such as GNSS radio signals, that travels through the ionosphere is affected by a rapid amplitude and phase fluctuations called ionospheric scintillations [2]. Amplitude scintillation can create deep signal fades while phase scintillation are characterized by rapid carrier-phase changes that can produce cycle slips. Both effects can prevent a GNSS receiver from locking on to the signal and make it impossible to estimate a position [3]. Following the success of the first ionospheric scintillation event on Galileo, recorded in Antarctica in the frame of the DemoGRAPE Project [4], a multi-constellation GNSS receiver has been installed in the Mario Zucchelli station during the last summer campaign, in December 2016. The Italian Antarctic Ionospheric Observatory is nowadays covering almost one solar cycle of continuous GNSS data. The new facility to record also Galileo and GLONASS data make the observing facility unique and relevant to investigate the solar-earth physics and the ionosphere dynamics. Maintaining a continuous and unmanned observatory, needs an appropriate infrastructure in terms of computing, power, and connectivity. To fulfill this need the receiver has been integrated by an ad-hoc energy-efficient and self-sufficient GreenLab system realised by Istituto Superiore Mario Boella (ISMB) in the frame of "Upper Atmosphere Observations and Space Weather" PNRA Project [5]. Data management system is also crucial to make data available and useful to scientific and application community. For this reason in the last years a lot of efforts have been devoted to develop data management platforms [6] and ICT infrastructures [7].

In this paper, the authors present a system able to satisfy the demand of more energetically efficient systems able to perform processing and (wireless) communications, with high quality link. To reach this result, the properties of reconfigurable antenna coupled to a software defined radio controller able to perform a real-time control of the antenna itself (e.g. to steer the main beam in the direction of the main station, or to vary the RF power needed to perform the communication), will be exploited with low power processing boards in order to ensure a global energy consumption sustainable with a system powered by (limited) renewable energies [8, 9].

The paper is organized as follows: Section 2 introduces the scientific and technological background and the chosen approach and architecture, Section 3 presents the experimental results of the tests performed in Antarctic Region, while Section 4 draws conclusions and perspectives.

2 System Design and Architecture

The system, formed by low power computing and communication technologies and powered by renewable sources, is sketched in Figure 2. This system has been installed in the Italian Antarctic station *Mario Zucchelli* [10]. As shown in Figure 2, the system is composed by four blocks:

Fig. 1 Panoramic view of the test site in which the Tx and Rx are highlighted.

1. energy supply unit, formed by solar panel and batteries to ensure energy in case of bad weather;
2. data acquisition, by the GNSS antenna and receiver for this specific application;
3. computing section, where collected data are pre-processed;
4. communication part, where pre-processed data are sent to the base-station.

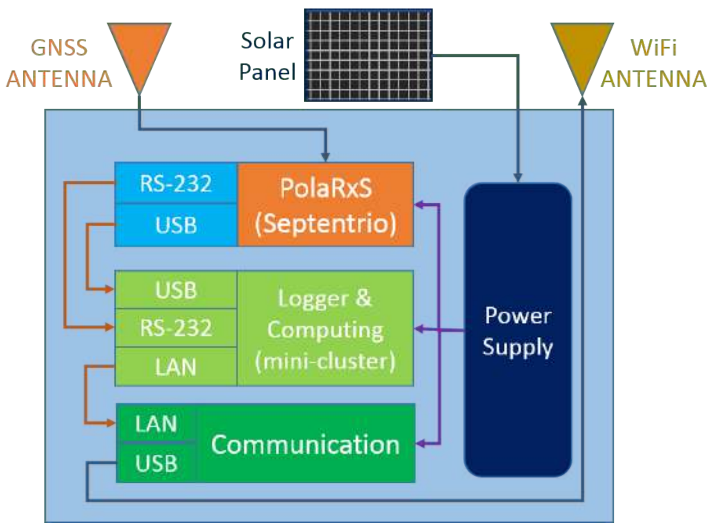


Fig. 2 Pictorial representation of the designed system.

Solar energy is commonly employed in this Region because the sun, during the Antarctic summer, is always present and this is the season selected for the on-field experiments. The power supply module exploits this type of energy source through an optimized power management, and orchestrating the duty cycles of all other modules by switching off modules as soon as they finish their tasks. During winter periods, when the sun never rises for several months, other renewable sources can be exploited (e.g. wind), but this is out of the scope of this demonstrator.

The core of the system is formed by the computing and communication parts which allow, together, to exchange data between the observation point and the base station, where all data are collected, keeping low the overall power consumption.

The computing mini-cluster performs raw-data pre-processing from the GNSS receiver (in the specific case a Septentrio PolaRxS [11]), to extract only a resume of all information collected to be sent in (near) real-time to the base-station. The communication module reads the reduced set of information coming from the computing part and, through a reconfigurable antenna coupled to Software Defined Radio (SDR) algorithms controlling the antenna itself, sends the data to the base-station. This solution allows to automatically discover the receiver's position without the need of an accurate pointing and, in the meantime, to reduce the transmitted power since the Signal to Noise Ratio (SNR) is reduced with this technology.

All components have been selected and developed taking into account the harsh environmental conditions of the deployment Region; in the installation area, the temperature ranges are between $-35°C$ to $8°C$. This means that all the materials employed need to be able to operate in these climate conditions and then components working in extended temperature range have to be used (since commercial equipment usually works in a range from $0°C$ to $40°C$). Finally, the whole system has also a receiver-side part located in the base station, which includes a receiver board and a network storage server. Even if important, this part is out of the scope of this work since it does not have constraints regarding power supply and temperature and then it will not be treated in the rest part of the paper.

2.1 Power management

In order to implement a completely autonomous device, the system described in this paper is powered by renewable sources (i.e. solar energy). Depending on where the system is installed, solar energy is not always available in site. This is determined by many factors: weather conditions, latitude of the installation, yearly seasons and time of the day. Therefore, care should be taken in order to optimize the overall power efficiency of the entire system. In this paragraph, the adopted power management architecture and behavior is described in detail. Figure 3 shows the

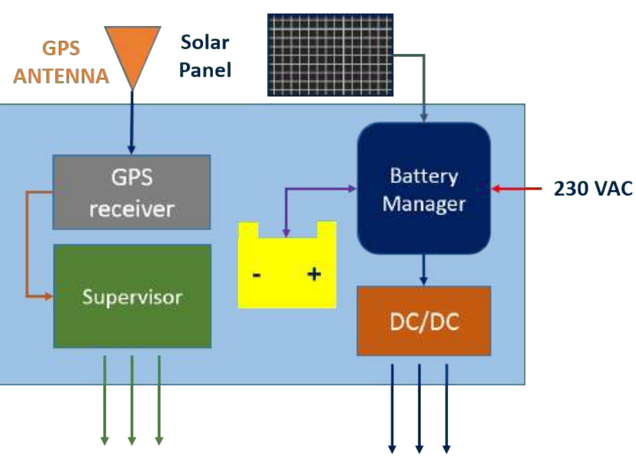


Fig. 3 Architecture of the power management unit.

power management architecture. The Battery Manager (BM) is in charge to extract all available electrical energy generated by photovoltaic panels (see Figure 4) and to store it into the battery module. The BM integrates also a Maximum Power Point Tracking (MPPT) algorithm, which is able to maximize the extracted power, as the external conditions change (e.g., panel temperature, solar radiation, presence of shades on a subset of photovoltaic cells), etc.). The DC/DC converter module, directly connected to the battery manager, is in charge to extract the available power from the battery, by generating all voltage needed to power the entire system. A GPS module is also included in the power management unit, with the main function to provide the absolute timing information to every component of the system architecture. An additional input power supply at 230 VAC is also included in the system architecture, to allow testing of the device without the need of photovoltaic modules.

In order to further optimize the power consumptions of the whole system, the power management unit integrates also a system supervisor. Such module feeds the electrical power to all other subcomponents of the system (i.e. computation, receiver, storage and antenna unit) using energy saving policies. Indeed, according to a series of preset operating profiles, the modules that are not used are safely switched off to save power. Various operating profiles (duty cycles) can be adopted on each power line, in order to implement specific energy saving behavior (e.g. the TX module can be temporarily powered on only once the acquisition and computation of new data is available). These profiles can be changed and stored on the fly using remote commands.

Fig. 4 Solar panels used as primary source of energy from the system.

2.2 Data Management

To acquire and process data from a multi-constellation GNSS Receiver (i.e. Septentrio PolaRxS), as well as to enhance data analysis by allowing pre-processing and providing it to users in near real time, data collection from Low Energy Boards has

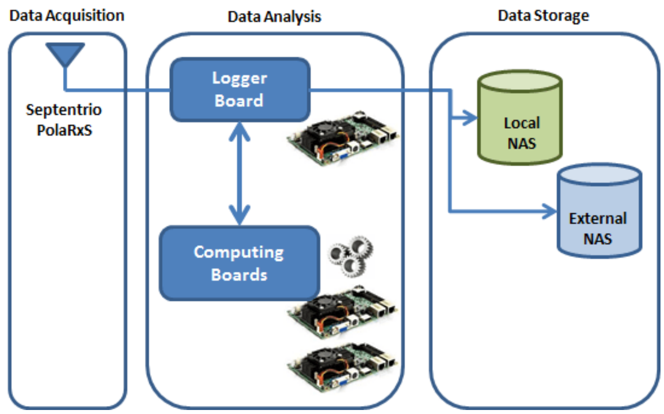


Fig. 5 Data Management System.

been exploited. The Data Management System, depicted in Figure 5, consists of three main modules:

1. Data Acquisition
2. Data Analysis
3. Data Storage

Data acquisition is based on the Septentrio PolaRxS receiver which runs over multiple frequencies and constellations for ionospheric monitoring and space weather observations. It is equipped with low noise control, and its features are high-quality, simultaneous Galileo, GLONASS and GPS signal tracking. This kind of receiver is particularly valuable for tracking rapid signal dynamics like those found in scintillation events. Thanks to its technology for analyzing interference and notch filtering for mitigation, it can be installed in crucial environments for radio broadcasting. GNSS receiver and logger board work together and are always active, 24 hours a day. They are fitted out of automatic procedures for auto-configuration in case of unexpected reboot.

The Data Analysis module is composed of two boards, i.e. logger and computing. It is devoted to data acquisition from the receiver and its pre-processing. The logger is a Single Board Computer (SBC) which integrates all the components of a traditional desktop computer (e.g., CPU, main memory, I/O interconnections, storage, etc.) in a compact board. The Computing stage is formed by several SBCs that have been devoted to process data coming from the logger board. Periodically, the computing boards are switched on as soon as a given amount of raw data are received and they allow to execute several analysis based on the type of data retrieved. One of these analysis is related to the ionosphere which is the single largest contributor to the GNSS error budget, and ionospheric scintillation in particular is one of its most harmful effects. The Ground Based Scintillation Climatology can ingest data from high sampling rate GNSS receivers for scintillation monitoring like the widely used GPS for Ionospheric Scintillation and PolaRxS (GISTM). As mention before, the logger board is always active, 24 hours a day, while, in a energy-saving perspective, the computing boards can be activated only when they are really necessary, based on actual workloads.

Finally, data storage allows to manage and store data and associated metadata. It consists of two NAS servers: the first one, namely Local NAS, is used for saving raw data; the second one, namely External NAS, stores elaborated data and makes them available for external users outside the base. In particular, the Septentrio PolaRxS receiver generates about 2 GB of raw data each day, that are reduced to about 100 MB a day after the pre-elaboration. The data storage module maintains data provenance and provides the necessary tools and interfaces to allow scientists to quickly identify outdated simulations using chronological traces. Data stored in Local NAS server allow to rerun simulations at any time, such as when a algorithm is updated.

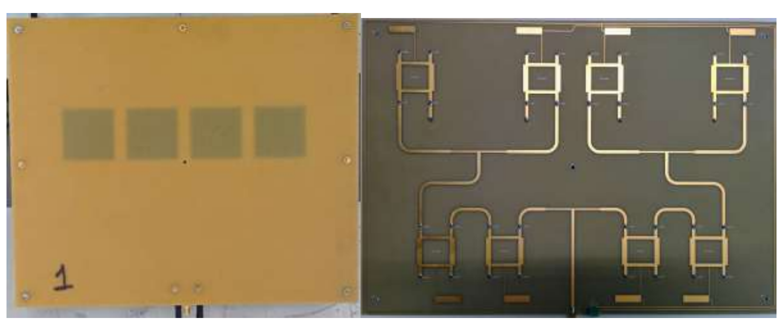
2.3 Communications

The communication system is composed mainly by three parts:

1. Antenna;
2. Front-End;
3. Low Power PC with communication protocol fully software-defined.

The system is configured, by default, in "bidirectional" mode, i.e. radio nodes are able to both transmit and receive data. Neverthless, the communication system can also be set up in unidirectional mode. For instance, the typical one-way data-flow situation from the observatory point (where the data are acquired) to the base-station (where the data are stored). For brevity, the description of the communication system building blocks is addressed from the receiving point of view. However, the transmission side is identical.

The antenna is constituted by a classical phased-array, as depicted in Figure 6, and it is formed by 4 patch antenna (Fig. 6a), coupled with a Beam-Forming Network based on phase-shifter (Fig. 6b) able to steer the beam of the antenna itself of about $\pm 50^\circ$ in the horizontal plane [12, 13]. This configuration allows a raw pointing since the receiver position is automatically discovered.



(a) (b)

Fig. 6 Antenna used: phase-array formed by 4 patches (a) coupled with a Beam-Forming Network based on phase-shifter (b).

The Radio Frequency (RF) signal received by the antenna it is down-converted to base-band and digitized by exploiting a Universal Software Radio Peripheral (USRP) B200mini-i [14]. This is the front-end that, through an Analog to Digital (ADC) converter with 56 MHz of instantaneous bandwidth allows the interface between the RF and the digital world. It is a transceiver with the dimensions of a card (see Figure 7), which can be employed in a frequency range from 70 MHz to

6 GHz. Furthermore, it is provided by a user-programmable Xilinx Spartan-6 Field Programmable Gate Array (FPGA). Such devices, coupled with the reconfigurable

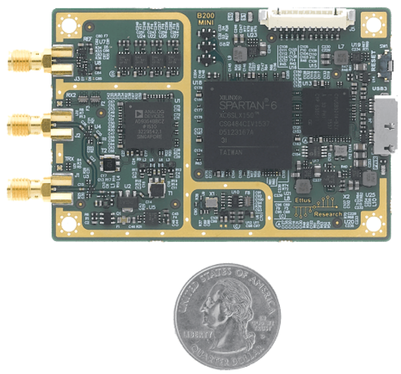
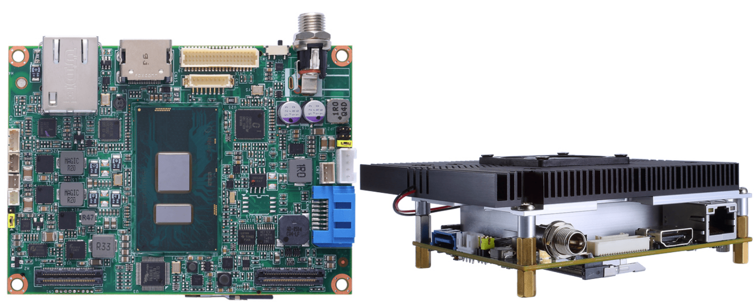


Fig. 7 USRP B200mini-i SDR/cognitive radio.

antenna, constitute the RF part and it is coupled to the board, through a high-speed USB 3.0 connection. Now, downstream of this device, the signal is digitized and it can be elaborate by the communication board, which is in charge to transmit/receive data coming from the computing part. For this purpose it has been exploited a Pico-ITX SBC board (see Figure 8); this embedded board mount the latest generation of Ultra-Low Power Intel Core (i.e. 6th generation 14nm) processors and it is equipped with one DDR4 SO-DIMM with 4 GB memory capacity [15]. Finally, the PICO500 is built to withstand wide temperature conditions, ranging from -20 to +70 Celsius.



(a) (b)

Fig. 8 Pico-ITX SBC embedded board: top view (a) and coupled with an with active thermal solution (b).

The board elaborates and treats the digital stream with a fully software implementation of a standard WiFi 802.11 receiver. The software algorithm exploits the signal information to control the antenna and to optimize the direction and the power of the signal to be transmitted/received. The IEEE802.11a/g/p wireless communication protocol has been implemented by exploiting GNURadio [16], a free and open-source software development toolkit that provides signal processing blocks to implement software radios. GnuRadio itself provides a baseline open-source version of the communication standard in question. Unfortunately, its computational complexity impedes operation in low power General Purpose Processors; thus, starting from this version, we developed a faster and lighter implementation of the transmitter and receiver, customized for Low-Power General Purpose Processor. The last link in the chain is the control of the antenna starting from the software; to do this an interface between the board and the antenna has been developed. This interface it is in charge to convert the digital signal coming from the software to a voltage that, applied to the beam-forming network of the designed antenna, it is able to steer the main beam, allowing to focus towards the base-station, where the receiver is waiting for the data.

The implemented test case is a point-to-point communication between the acquisition and the base-station; to perform the communication in a low-power perspective, the data collected and processed by the computing board are sent to the main station once an hour. This allows to reduce the power consumption, since the board and all stuffs connected to that board (i.e. antenna controller and USRP) are switched-on only to perform the data transmission, allowing to reduce the power consumption of the entire system.

3 Experimental Results

In this Section the results obtained on field will be depicted to demonstrate the validity of this type of system to perform low power processing and wireless communication, integrated together to be deployed in a critical environment like the Antarctic region.

3.1 Communication Performance

Prior showing the tabulated results of the wireless communication tests, it is essential to illustrate the working principle of the realized communication link. The link implemented for this application is a point-to-point topology composed by two radio nodes:

- The Observatory Point Radio (OPR), i.e. the radio in charge to transmit data, in this case the node presenting the highest consuming. Thus, the energy minimization process has been applied on this side;
- The Base Station Radio (BSR), i.e. the radio in charge to receive the data and to identify the radio process.

These nodes employ the following high level ad-hoc protocol in order to communicate efficiently:

1. Observatory Point side, the energy supply unit turn on, with a programmable timer, the OPR board to load and transmit the stored information;
2. OPR board disseminates a request of transmission and poses to listening mode later;
3. BSR, at the reception of the request, sends a training sequence with the aim of revealing its spatial position;
4. OPR elaborates the training sequence by means of a spatial scan, i.e. electronically moves the antenna main beam. For each discovered position, the optimization algorithm keeps track about the training sequence power. At the end

of the spatial scan, the processor directs the antenna main beam toward the direction of maximum received power. This configuration is maintained for all the permanence of the data transmission;
5. After data transfer success, OPR advices the energy supply unit that shutdown. The energy supply unit cut off power supply to the radio.

The reconfigurable antenna approach in a wireless communication link establishes two important advancement: first, by focusing all radiated energy toward the base station, it reduce in considerable manner the amount of power emitted by the transmitter. The latter is directly proportional to the radio instantaneous power consumption. In other words, the reduction in the transmitted power results in a decreased consumption of the radio. Second, since the antenna main beam is strongly focused toward the intended direction, noise and interferer are attenuated accordingly. This allows the transmitter to employ the highest communication rates to transfer the information. The greater is the communication rate the faster is the data transfer. Consequently, less time the radio is in active mode. These two factors critically affect the daily energy consumption of the proposed link Figure 9 reports the out-

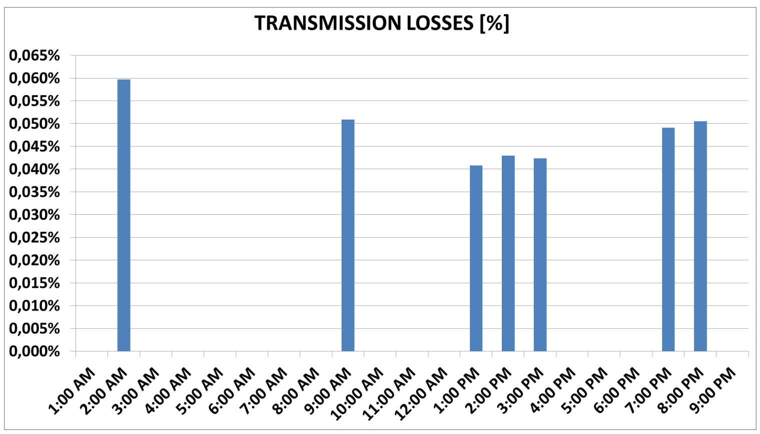


Fig. 9 Automatic Transmission Outcomes.

comes of one-day transmissions. Each data transfer consists in a merge of 4 files of variable size, collected from the observatory system in one hour of monitoring. An example is reported in Table 1. The information about the total size of the data to be transmitted is included in the merged file. This way, the BSR system knows in advance how much data expects from the OPR system. At the end of the data transfer, BSR counts the amounts of received data. Then, the comparison of this number with the one retrieved from the header of the merged file it gives an estimation on the amounts of loosen bytes.

4 Conclusions and Perspectives

An advanced prototype of a low power computing and communication system, self-sustained by means of renewable energy and advancements in communication, has been designed, realized and tested in Antarctica, allowing to test an autonomous system able to manage, pre-process and send data for a real test-case. All components,

Table 1 Example of one hour data collection

Merged Files	Transmitted[Bytes]	Received[Bytes]	Losses[%]
BTN0P_352o00.16_.ismr	152.765	152.465	0,20
BTN0P_352o15.16_.ismr	148.123	148.123	0,00
BTN0P_352o30.16_.ismr	145.168	145.168	0,00
BTN0P_352o45.16_.ismr	143.902	143.902	0,00

designed to allow the collection and transmission of scientific data in field, have been selected to be able to work in really harsh conditions; this allows to overcome unscathed the Antarctic summer campaign. Communication between measurement station and base station has been successfully tested and compared with data collected and sent in more standard way (i.e. wired transmission).

Future development of this systems include a fine tuning of its single building blocks, as well as possible improvements in terms of energy consumption and transmission extension by exploiting other low-power small-form-factor boards.

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