Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 58 (2016) 1940–1959

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

Review on space weather in Latin America.
2. The research networks ready for space weather

Clezio Marcos Denardini[a,*], Sergio Dasso[b,c], J. Americo Gonzalez-Esparza[d]

[a] *Embrace, National Institute for Space Research, 12227-010 S. J. dos Campos, SP, Brazil*
[b] *Instituto de Astronomía y Física del Espacio, CONICET-UBA – Departamento de Ciencias de la Atmósfera y los Océanos, Ciudad Universitaria, 1428, C1428ZAA Buenos Aires, Argentina*
[c] *Departamento de Física, FCEN-UBA, Ciudad Universitaria, 1428, C1428ZAA Buenos Aires, Argentina*
[d] *SCiESMEX, Instituto de Geofísica, Unidad Michoacán, Universidad Nacional Autónoma de México, Antigua carretera a Pátzcuaro # 8701, Ex-Hda. San Jose de la Huerta Morelia, Michoacán C.P.58089, Mexico*

Received 16 December 2015; received in revised form 4 March 2016; accepted 8 March 2016
Available online 25 March 2016

Abstract

The present work is the second of a three-part review of space weather in Latin America, specifically observing its evolution in three countries (Argentina, Brazil and Mexico). This work comprises a summary of scientific challenges in space weather research that are considered to be open scientific questions and how they are being addressed in terms of instrumentation by the international community, including the Latin American groups. We also provide an inventory of the networks and collaborations being constructed in Latin America, including details on the data processing, capabilities and a basic description of the resulting variables. These instrumental networks currently used for space science research are gradually being incorporated into the space weather monitoring data pipelines as their data provides key variables for monitoring and forecasting space weather, which allow these centers to monitor space weather and issue watches, warnings and alerts.

Keywords: Space science; Space weather; Space physics; Latin America

1. Introduction

Since the late 1950's, there have been many international scientific efforts to conduct coordinated space science research like the International Geophysical Year (IGY) held in 1957–1958 and International Heliophysical Year (IHY) held in 2007. Other more recent efforts have included initiatives to establish long lasting programs or projects with the potential to improve space sciences facilities, e.g. the International Living With a Star (ILWS) program and International Space Weather Initiative (ISWI), both sponsored by the United Nations.

In May 2010, the World Meteorological Organization (WMO), a body devoted to the global coordination aspects of the operational weather forecasting centers, established a team of space weather specialists known as the Interprogramme Coordination Team on Space Weather (ICTSW). The purpose of the ICTSW was to discuss the standardization and enhancement of space weather data, the harmonization of end products and services, the integration of space weather observations into operational systems, and to encourage the dialogue between the research and operational space weather communities. In conjunction with international initiatives, the Latin American Space Geophysics Association (ALAGE), created in 1993 to

---

[*] Corresponding author at: Embrace/INPE, Av. dos Astronautas, 1758, Jd. da Granja, 12227-010 São José dos Campos, SP, Brazil. Tel.: +55 12 3208 7180; fax: +55 12 3208 6990.
E-mail address: clezio.denardin@inpe.br (C.M. Denardini).

http://dx.doi.org/10.1016/j.asr.2016.03.013
0273-1177/

promote the scientific advance in space geophysics, endeavored to extend its aims to collaborate on space weather research and services.

In the present work we summarize the scientific challenges in space weather research which are considered to be open scientific questions. We discuss how they are being addressed in terms of instrumentation by the international community, including the Latin American groups. In addition, we also provide a (limited) list of the networks and collaborations being constructed in Latin America, including details on the data processing, capabilities and a basic description of the resulting variables. These instrumental networks currently used for space science research are gradually being incorporated into the space weather monitoring data pipelines as their data provides key variables for monitoring and forecasting space weather, which will allow these centers to monitor space weather and issue watch, warnings and alerts, after the standardization and enhancement into the ICTSW framework.

2. Scientific challenges in space weather research

From the scientific perspective, there are several challenges that still need to be addressed. Schrijver et al. (2015) listed several scientific needs for an integrated approach to space weather science that focused on research projects and instrumentation investments they deem feasible in terms of technological requirements and budgetary constraints. According to these authors, one high-priority research subject in space weather is related to characterizing the solar-wind magnetic field, and, in particular, the field connected with Coronal Mass Ejections (CMEs). To address this scientific question, they state that in-situ measurements upstream of Earth at the Sun–Earth L1 sentinel point are insufficient. The current technological means and budgetary resources are also inadequate to position, in situ, sentinels on the Sun–Earth line sufficiently close to the Sun, or to launch a fleet of moving sentinels maintaining one near that position. Another option would be to obtain the solar-wind magnetic field variables associated with active-region eruptions from the forward modeling of observed solar eruptions through the embedding corona and inner heliosphere, based on the inferred magnetic field of erupting structures. Therefore, a key goal of space science is to determine the origins of the Sun's impulsive eruptive activity, which will eventually drive the magnetospheric and ionospheric variability.

Under this framework, uncovering information on low-lying twisted field configurations in the deep interiors of unstable solar Active Regions (AR) before and after eruptions is essential for determining what propagates towards Earth and affects space weather. According to Schrijver et al. (2015), a three-dimensional (3D) model would be able to provide this information. A probable input to this model could come from chromospheric vector-magnetic measurements, in addition to photospheric ones, which can aid in the mapping of the 3D Active Region field. These measurements provide observational access to electrical currents threading the solar surface and allow us to observe the details of the low-lying flux ropes before, during, and after eruptions to quantify the 3D field ejected into the heliosphere.

Once the solar eruptions and their propagation towards Earth are addressed, the coupling questions relating solar wind to the magnetosphere and ionosphere still remain. Key processes in the chain of magnetospheric energy release leading to large field-aligned currents and hence Ground Induced Currents (GICs) are still relatively unknown, such as the dynamics nearer to Earth at the inner edge of the plasma sheet where the bulk flows (i.e. CMEs) brake and presumably give rise to a number of more or less effective plasma instabilities or the coupling of these processes with the ionosphere along magnetic field lines (Schrijver et al., 2015). Although it would be fairly difficult to accomplish, a possible solution to this issue could be the proper positioning of a sufficient number of spacecraft at the two key locations in the magnetotail. These spacecraft should fly near the inner edge of the plasma sheet, in the transition region from dipolar to tail-like magnetic fields, investigating plasma instabilities and flow braking. Others should provide multi-point plasma and electrodynamic field measurements in the auroral acceleration region to determine the dynamical magnetosphere–ionosphere coupling.

Besides the above examples whose sources of space weather disturbance come from outside of Earth, there still are scientific issues that are not solved in the Earth's upper atmosphere alone. It is a fact that ground-based observations have been expanded extensively in the last decade, especially utilizing new coherent and incoherent radars, new ionosondes, new all-sky photometers, and new digital imagers from several different generations, mainly set close and around the magnetic equator and at high latitudes to observe and study plasma bubbles and auroral instabilities and their driving mechanisms. However, the day-to-day forecasting of plasma bubbles, as well as the forecasting of the day-to-day neutral wind that drives their development has still not been successfully achieved with consistency (Schrijver et al., 2015).

These three examples illustrate a few of the scientific challenges in space weather that could substantially improve space weather forecast. However, most of these challenges require space access and, to the best of our knowledge, no Latin American country has successfully completed the full cycle (designing a mission, conceiving and developing instruments, conceiving and developing a space platform, conceiving and developing launchers, launching and placing it in the right orbit) for launching a Latin American scientific (space weather or not) satellite, nor have any researcher led a Latin American space satellite mission (developed, built and successfully launched).

We certainly acknowledge that Argentina has successfully launched satellites, especially the Scientific Applications Satellite (SAC) series, which had a significant contribution from the Jet Propulsion Laboratory from the National Aeronautics and Space Administration (NASA) since the very begin of SAC-B in 1989 (INVAP, 2015). The SAC series involved 4 satellites (SAC-B, SAC-A, SAC-C, SAC-D). The most recent satellite from this series, the SAC-D satellite relied on support provided by the Canadian Space Agency (CAS), the Italian Space Agency (ASI), and the National Center for Space Studies (CNES)'s support on the development of instruments. The launch itself was delegated to NASA and was carried out on June 10th, 2011 from the Space Launch Complex 2W at Vandenberg Air Force Base using the Boeing Delta II 7320-10 as the launch vehicle.

In addition to the projects of the INVAP SE, an enterprise of technology stablished at Provincia de Río Negro – Argentina, the Argentine National Commission on Space Research (CONAE) has projected the following new satellites for the coming years: Argentine Microwaves Observation Satellite (SAOCOM) that is a system of two satellites for terrestrial observation from space in the microwave range, the High Revisit Rate Satellites (SARE) which are a set of passive and active satellites in the optic band, and the Argentine-Brazilian Marine Environmental Information Satellite (SABIA-MAR) that derives from a cooperation with the National Institute for Space Research (INPE) to perform sea observations. CONAE also has a project to produce its own launcher named Tronador. Moreover, Argentina has also built two geostationary communications satellites (ARSAT-1 and ARSAT-2), which are already in orbit and were named after and are operated by the Argentine state company AR-SAT.

However, even with these great accomplishments and detailed planned development, Brazil seems to be the country that has gotten the closest to completing the full cycle of successfully launching a Latin American scientific (space weather or not) satellite. Brazilian researchers have launched two scientific satellites from the Scientific Applications Satellite (SACI) series, microsatellites designed, developed, built and tested by Brazilian technicians, engineers and scientists, working at INPE. But none of those satellites have succeeded in collecting any data. However, the SACI-1 was not launched by a Brazilian launcher and not even from a Brazilian base. It was launched on October 14th, 1999 from the Taiyuan Launch Center using the Long March 4B rocket as a secondary payload in the launch of the China–Brazil Earth Resource Satellite (CBERS)-1, but failed to open the solar cell panels and orbited Earth only once. SACI-2 was launched on December 11th, 1999 from the Brazilian base in Alcântara (MA), using the Brazilian launcher VLS-1 V02 rocket. Unfortunately, due to failure in its second stage, the rocket veered off the planned track and had to be destroyed 3 min and 20 s after launch (Gamboa, 1999; Sousa, 2007; Rocha, 2004). The only satellite in orbit is the U-class satellite Brazilian CubeSat Project-1 (NanoSatC-Br1), which was developed at the Southern Regional Space Research Center in collaboration with the Space Science Laboratory of the Federal University of Santa Maria (RS), Brazil. The objective of the mission is to provide monitoring of Earth's magnetosphere by measuring the magnetic field over Brazil and to study the magnetic phenomena of the South American Magnetic Anomaly (SAMA).

The spacecraft itself is a 1U CubeSat with a size of $10 \times 10 \times 11.3$ cm and a mass of about 1 kg, and was purchased from the Innovative Solutions in Space BV, at Delft, Netherlands. The Brazilian contributions to this U-class satellite were mainly focused on the development of the payload and student participation in activities such as mission analysis and design, integration, testing and operation, in addition to specific studies on the platform itself. The NanoSatC-Br1 was launched as a secondary payload on June 19th, 2014 (19:11:11 UTC) on a Dnepr-1 vehicle of ISC Kosmotras (cluster launch), from the launch site at the Yasny Cosmodrome in the Dombarovsky region of Russia and placed in its polar orbit at about 600 km (Schuch et al., 2012), and it is still flying and producing data.

On the other hand, when compared to Brazil and Argentina, Mexico seems to be far behind in its capabilities of building and launching satellites. The Mexican government has traditionally relied on third parties to build and launch their satellites, but none have been scientific. In this context, it is important to mention that all the commercial satellites used to carry Space Environment Monitors, which are sensors used to provide information to the satellite operators like the noise level of the electric circuits, are normally associated with solar energetic particle precipitation (useful to space weather studies). However, to the best of our knowledge, we did not find this kind of information being provided to the Regional Warning Center (RWC)-Mexico, nor to the Mexican scientific community. The most recent event involving Mexican satellites deals with the Mexican communication Satellite named Centenario (MEXSAT-1) and Morelos III (MEXSAT-2). The Russian Proton-M rocket that was carrying the Centenario satellite failed to enter orbit minutes after its launch from Kazakhstan on May 16th 2015, causing the loss of the satellite. On the other hand, Morelos III was successfully launched by United Launch Alliance using a V 421 AV-059 rocket on October 2nd 2015. This situation seems to be in the course of change as the creation of the Mexican Space Agency (AEM) in 2010 led to the commencement of microsatellites being developed by scientific groups (Juan Americo González-Esparza, Private Communication).

In regard to its capabilities and the topics being researched, we are compelled to think that Mexico requires further space weather research in order to understand how the geomagnetic field in Mexican territory responds to space weather events. A new network of geomagnetic field stations covering the territory, could quantify, for example, how the GICs might affect federally commissioned electric power stations during strong or extreme geomagnetic storms. This information is necessary to evaluate the vulnerability of the country's electric power grid.

Furthermore, since the early 1970's, the main income of the Mexican government comes from the national oil company (Rippy, 1972; Hanson, 1973). The offshore oil drilling in deep water like those in the Gulf of Mexico require high precision platform positioning and therefore, oil exploration and distribution could also be affected by space weather phenomena. Monitoring the status of the ionosphere over the territory is then a critical aspect in terms of national security. Strong perturbations in the ionosphere could affect telecommunications, aviation, military operations and the precision of Global Positioning System (GPS) measurements. Fortunately, Mexico has recently established the RWC-Mexico and therefore has already taken significant steps towards establishing space weather awareness. However, further support is necessary to improve the ground network of space weather instruments in order to acquire the critical data mentioned before.

In addition to the space access discussed above, from the point of view of three Latin American countries (Argentina, Brazil and Mexico) some of the scientific challenges in space weather research and operations involve expanding the ground network of sensors or setting missing instrumentation in place (for details, see the next session) as well as the establishing proper infrastructure to collect the data. Fortunately, some of these challenges are being addressed by Latin American scientific and operational teams, for example, the development of regional magnetic indices like the Ksa (Denardini et al., 2015) and the South American Total Electron Content (TEC) Maps (Takahashi et al., 2014). Other challenges remain open issues to be addressed, such as neutral wind measurements at low latitudes[1] in the American continent, which are needed to properly develop an self-consistent ionospheric model and to predict plasma bubble development. Other issues include the precise information and theoretical studies about magnetic reconnections of CMEs leading to geomagnetic storms and their effects, and the continuous development of solar telescopes for space weather studies, expanding the capability to measure spectral bands that have not yet been studied.

All of these challenges involving both ground- and space-based instrumentation require specific instruments and effort that must be put into action to provide such development (Elias et al., 2010), which can be translated into human and material resources (including the proper legislation). However, there is another class of challenges that can be easily confronted with little effort from the Latin American research community and operational groups, which is the exchange of expertise. Take, for instance, the limited ionospheric and geomagnetic research in Mexico. During our research, we detected that Mexico does not have data networks to quantify ionospheric perturbations in real time, even though they have several oil offshore platforms in the Gulf of Mexico. This is partially and historically attributed to the centralization of space research to the space sciences group at the National Autonomous University of Mexico (UNAM), which has been concentrated in Mexico City for the last few decades. The solution is tough in terms of the diversification and decentralization of the research and operational centers, like the creation of the Mexican Space Weather Service (SCiESMEX) in Morelia. Among their objectives SCiESMEX claims to implement two space weather programs in the near future: (1) to produce TEC maps in real-time by using the data available from regional networks of the Global Navigation Satellite Systems (GNSS) receivers (e.g. TLALOCNet and National Seismological Service); and (2) to implement a magnetometer network to produce a regional magnetic K index, answering to regional needs. Also, this Mexican initiative configures itself in an opportunity to use the capabilities installed in other countries to fulfill the Mexican needs. In the present case, Mexican students can complete PhD programs in other countries with more background in ionospheric research and then return to Mexico to operate the instruments installed there. Ideally, these ionospheric instruments should be installed prior to their PhD programs to be completed and the data shall be used to develop the PhD work.

In summary, it seems that the research community in Latin America is aware of most of the scientific challenges regarding space weather. Some actions are being taken by isolated Latin American research groups like the purchase and/or the development of the scientific instruments needed to expand or advance the knowledge regarding space weather. More importantly, a few coordinated actions are being taken by several institutions in Latin America in order to develop real Latin American networks, such the South American Very Low Frequency (VLF) Network (SAVNET) and the Embrace Magnetometer Network (Embrace MagNet) developed by the Brazilian Study and Monitoring of Space Weather (Embrace) Program, which will described in detail ahead. However, there is a clear need for a space platform like a space weather satellite mission to address the open issues especially associated with (but not limited to) solar physics. The ideal solution would involve: conceiving the mission; developing, building, and integrating both the payload and the platform; and successfully launching a satellite from the Latin America. Hence, the great challenge is to coordinate the efforts of the Latin American countries to pursue this solution.

3. Scientific and operational networks in Latin America

One method that Latin American Research Center/Universities (institutions) have employed to compensate the limited amount of resources (humans and material) as a pathway to face the above mentioned challenges, is the establishment of a large network of instruments and

---

[1] There is no exact definition where the low latitudes upper boundary lies. In this manuscript it means the two latitudinal bands surrounding Earth from 3-5° to about 50° of magnetic latitude, in both Northern and Southern hemispheres.

collaborations between Latin American research groups and "external" groups. However, we were not able to verify if the majority of the links are with external or Latin American partners. In addition, we interpreted the development of this assortment of networks as an important tool to investigate the Solar–Terrestrial relationship with scientific phenomena, relevant to space weather investigations, monitoring and forecasting.

In Table 1, we summarize basic information on the selected networks, facilities and stations. They are listed in this table according to the main properties the network was established to measure, independent of other properties that can be derived from these measurements.

The first group of instruments in Table 1 is formed by networks designated to measure properties of the neutral and ionized atmospheres of Earth. The second group is formed by networks capable of measuring magnetic properties of the Earth's magnetic fields, involving the main field and/or the variations of the field coming from magnetosphere and ionospheric currents, and from energetic particle populations. The third group is formed by the networks with the ability to measure properties of the interplanetary medium between the Sun and the Earth, including cosmic ray properties. And finally, the fourth group is dedicated to networks that provide measurements of the Sun's properties related to the Sol–Earth relationship. Detailed descriptions of each network and/or instrument are provided in the following subsections and the distribution of the most of the network and/or instrument is presented in Fig. 1.

In Fig. 1a, we locate the instruments related to the neutral and ionized atmospheres of Earth. In this map, the blue diamonds show the locations of the All-sky imagers belonging to the Embrace Airglow All-sky Imagers Network (Embrace GlowNet), the green square gives the location of the Argentine Airglow Spectrometer, the yellow circles provide the positions of the riometers of the South America Riometer Network (SARINET), the red diamonds offer the locations of the VLF receivers of the SAVNET, the orange stars provide the positions of the ionospheric sounder belonging to the Embrace Digisonde Network (Embrace DigiNet), the blue circles gives the locations of the riometers and ionospheric sounder belonging to the Argentine Antarctic Institute, and the red star shows the location of the site at the National University of Tucumán where we find the Doppler HF radar and the Advanced Ionospheric Sounder. Please note that we omitted the locations of the GNSS receiver sensor network because they are more than 180 receivers from 4 different networks and these networks are really dynamic (with receivers going on and off very frequently). In replacement, we recommend the readers to visit the Embrace/INPE internet web portal[2] where one can find a dynamic map showing the position of the four GNSS receiver sensor networks placed in Latin America.

Fig. 1b provides the distribution of the instruments capable of measuring magnetic properties of the Earth's magnetic fields. In this map, red diamonds provide the locations of the magnetic stations belonging to the Embrace MagNet, the green squares gives the position of the Intermagnet Observatories in Mexico and Argentina, and the blue circles show the location of the magnetic stations belonging to the Argentine Antarctic Institute. Also, the white line superimposed to the map shows the position of the dip equator at 100 km of altitude obtained from the International Geomagnetic Reference Field (IGRF) model for 2005.

Finally, the distribution of those instruments with ability to measure properties of the interplanetary medium between the Sun and the Earth, including cosmic ray properties and solar observatories is provided in the Fig. 1c. In this map, the green square corresponds to the Global Muon Detector telescope, the red diamond shows the location of the Pierre Auger Observatory, the blue circles provide the locations of the Latin American Giant Observatory (LAGO, previously called Large Aperture GRB Observatory) stations, the orange star gives the position of the Solar Submillimeter Telescope (SST), the yellow square locates the SCiESMEX Neutron Monitor, the yellow circle shows the position of the Mexican Array Radiotelescope (MEXART) array, and the green diamonds offer the locations of the 3 Brazilian radio telescopes: the Itapetinga Radio Observatory, the Northeast Radio Space Observatory, and the Brazilian Decimetric Array.

3.1. Embrace Airglow All-sky Imagers Network

Airglow observations started at INPE in 1972 with a 2-channel tilting filter photometer. A multichannel airglow photometer operated from 1978 to 2000 and measured OI 630 nm, OI 557.7 nm, OH(NIR) 715–930 nm, and O2 atmospheric bands. The airglow emission rate and atmospheric temperature in the mesosphere and thermosphere have been monitored by these photometers at Cachoeira Paulista (SP) and Cariri (PB). In 1998, the INPE's group began to build a new airglow all-sky imaging system. This new generation airglow all-sky imager currently use a 180-degree wide-angle fisheye lens, with a telecentric lens system, narrow band optical filters and a high sensitive Charge-Coupled Device (CCD) camera. For ionospheric weather monitoring, two optical filters are used to measure the airglow OI 630 nm for ionospheric plasma bubbles and OH(NIR) 715–930 nm for mesospheric Gravity Waves (GW). The 630 nm image covers a horizontal extension of 1600 km (at the zenith angle of 75°) at an altitude of 250 km, covering the latitudinal and longitudinal extension of the plasma depletions. The OH image, on the other hand, covers a horizontal extension of 800 km at an altitude of 90 km. In addition to the 630 nm and OH(NIR)

---

[2] Available online at http://www2.inpe.br/climaespacial/portal/tec-map-stations/.

Table 1
Summary of the scientific networks/facilities, operating in Latin America.

Group	Name (acronym)	Origin (year)	Objective of investigation (primary objective)	Current status (FO, PO, NO[a])
Atm.	Embrace GlowNet	1998	Gravity Waves (85 km) and Plasma Bubbles (260 km) footprints signature and propagations	PO
Atm.	UNT-Doppler-HF	2012	Gravity Waves and Plasma Bubbles	FO
Atm.	AAS	1998	Airglow in mesopause region	FO
Atm.	SARINET	1999	D-Region density variations and solar flares related effects	FO
Atm.	SAVNET	2006	D-Region (daytime) and E-Region (nighttime) density variations and solar flares related effects	FO
Atm.	NDMC	1998	Mesopause region and changing climate	FO
Atm.	RIOM-SMN	2012	Absorption in ionosphere	PO
Atm.	IAA-Riometer	1986	Absorption in ionosphere	PO
Atm.	Schumann station	2014	Schumann resonance frequencies	FO
Atm.	Embrace DigiNet	1990	Bottom-side ionospheric profile measurements and upper-side ionospheric profile theoretical extrapolations, Maximum Usable Frequency from oblique HF ionospheric reflections	PO
Atm.	IAA-Iono-sounder	1986	Bottom-side ionospheric profile measurements	PO
Atm.	UNT-AIS	2007	Bottom-side ionospheric profile measurements	FO
Atm.	RBMC	1996	TEC content and positioning for several purposes like geodynamics studies of the South American plate	FO
Atm.	Calibra	2012	TEC content and positioning for several purposes like topographical and geodetic surveys, land management and offshore operations	PO
Atm.	RAMSAC	1998	TEC content and positioning for several purposes like geodynamics studies of the South American plate	FO
Atm.	UNT-GPS	1997	TEC content	FO
Mag.	Embrace MagNet	2011	Geomagnetic field variations and geomagnetic storm detections	PO
Mag.	Intermagnet in Mexico	2002–2012	Geomagnetic field (absolute, variations), geomagnetic storm detections, long term secular changes and contribute to IGRF	PO
Mag.	Intermagnet in Argentina	1991	Geomagnetic field (absolute, variations), geomagnetic storm detections, long term secular changes and contribute to IGRF	FO
Mag.	SMN-LAS	1961	Geomagnetic Storms. South American Magnetic Anomaly	FO
Mag.	IAA-MAG	1986	Geomagnetic Storms near south pole	PO
I. M.	GMDN in Brazil	2006	CRs, ICMEs through Forbush decrease	FO
I. M.	SciCRT-GMDN in Mexico	2014	CRs, ICMEs through Forbush decrease	FO
I. M.	LAGO	2011	CRs, ICMEs through Forbush decrease	PO
I. M.	Pierre Auger Observatory (Low Energy Modes)	2005	CRs, ICMEs through Forbush decrease	FO
I. M.	Cosmic Ray Observatory	1999	CRs, ICMEs through Forbush decrease	FO
I. M.	MEXART	2005	Tracking of solar wind disturbances using the IPS technique	FO
Sun	Solar Submillimeter Telescope	1999	Active Region	FO
Sun	Callisto-MEXART	2015	Solar radio bursts	FO
Sun	Solar Neutron Telescope Network	2004	Solar energetic particles	FO
Sun	Itapetinga Radio Observatory	1974	Galactic and extra-galactic studies, solar physics, specially the solar continuous emission and transition region monitoring	FO
Sun	Brazilian Decimetric Array	2004	Galactic and extra-galactic studies, high resolution solar physics	PO
Sun	Northeast Radio Space Observatory	1993	Geodetic studies as well as galactic and extra-galactic studies	FO

[a] FO = Fully operational, PO = Partially Operational, NO = Not Operational.

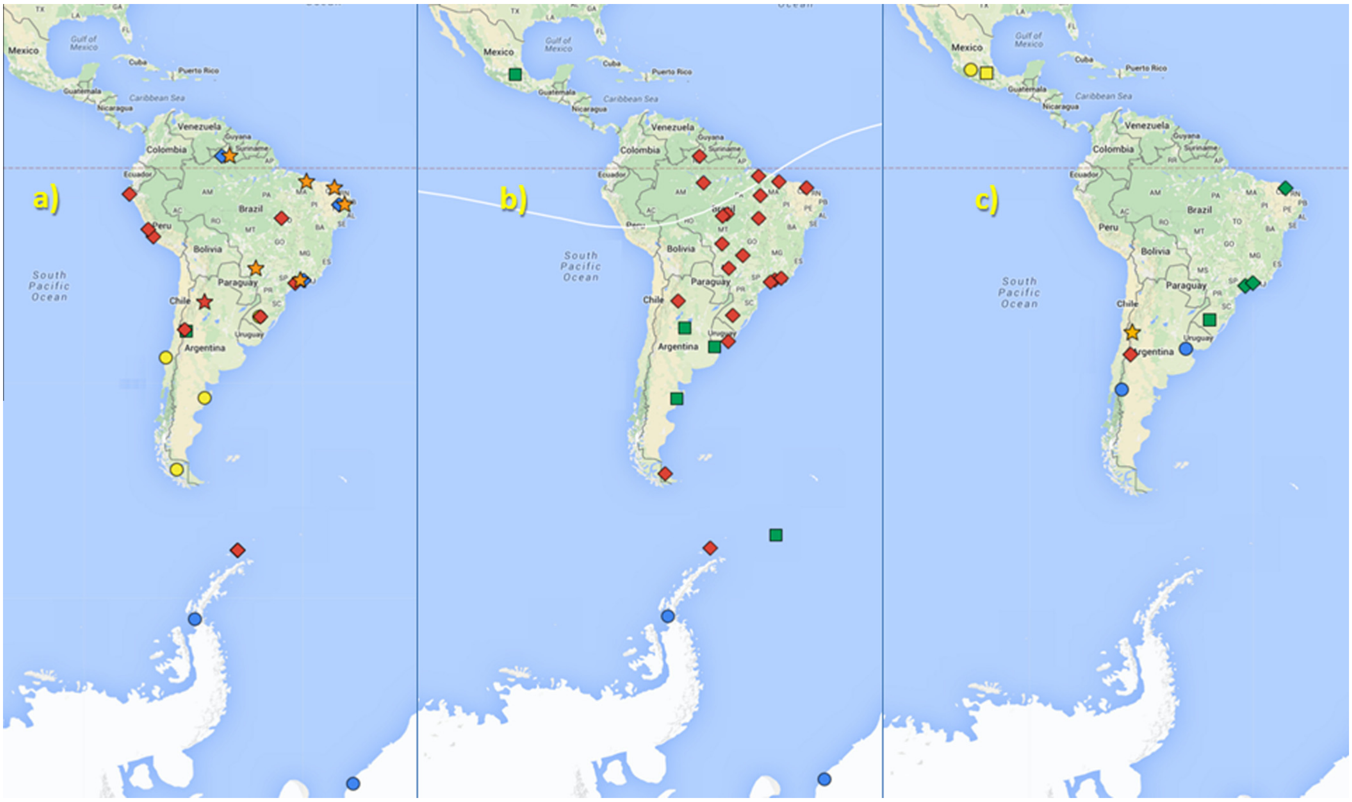

Fig. 1. Distribution of the most of the network and/or instruments related to the (a) neutral and ionized atmospheres of Earth, (b) instruments capable of measuring magnetic properties of the Earth's magnetic fields, and (c) instruments with ability to measure properties of the interplanetary medium between the Sun and the Earth, including cosmic ray properties and solar observatories. See Section 3 for a detailed description of this figure. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Airglow All-sky imager locations and data availability.

Location	Latitude	Longitude	Data available
Boa Vista	2.9°N	60.7° W	OI 630 nm, OH(NIR)
São João do Cariri	7.4°S	36.5° W	OI 630 nm, OH(NIR), OI 777.4 nm
Cachoeira Paulista	22.7°S	45.0° W	OI 630 nm, OH(NIR)
Antarctic (Ferraz station)	62.1°S	58.4° W	OI 630 nm, OH(NIR), OI 557.7 nm

emissions, imagers at the Cariri and Antarctic station make observations of the other emissions such as OI 777.4 nm and OI 557.7 nm. All the imagers are in automatic operational mode with internet data handling capabilities. In Table 2 the imager locations and characteristics are listed.

The mission of the Embrace GlowNet[3] is to monitor plasma bubble activity over the geomagnetic conjugate points, specifically at Boa Vista (RR) (02°48′02″N, 60°40′33″W) and Jatai (GO) (17°55′54″S, 51°43′06″W), respectively. The seeding and longitudinal-latitudinal development of plasma bubbles are important factors to monitor in ionospheric weather in the equatorial and low latitude regions. Spatial and temporal variations of TEC causes errors in the GNSS satellite based positioning system. Airglow OI 630 nm all-sky imagers monitor the plasma depletions and their temporal variations. Airglow OH(NIR) all sky imagers, on the other hand, monitor atmospheric GW activity in the 85–90 km altitude regions. These optical observations of plasma bubbles and GW activity contribute to ionospheric weather nowcasting and forecasting.

3.2. Observatories associated with the Argentine Network for the Study of the Upper Atmosphere

The Argentine Network for the Study of the Upper Atmosphere (RAPEAS) groups several observatories along the Argentine territory, In particular, the Faculty for Exact Science and Technology of the National University of Tucumán (UNT) holds instruments to measure different physical variable of interest for Space Weather such as: the Radar Doppler HF mainly dedicate to observe GW

---

[3] Available online at http://www2.inpe.br/climaespacial/SWMonitorUser/?lan=en.

and plasma bubbles; an Advanced Ionospheric Sounder (AIS) used for measuring ionospheric profile; and two GPSs receivers (single and double band) to estimate the TEC. Another institution associated with RAPEAS is the Argentine Antarctic Institute (IAA) that maintains ionosondes, magnetometers, and riometers at the two Argentine Antarctic bases: Belgrano II (77.9° S, 34.6° W) and San Martín (68.1° S, 67.1° W).

3.3. Argentine Airglow Spectrometer and Network for the Detection of Mesospheric Change

The Argentine Airglow Spectrometer (AAS) that measures rotational temperatures at two different altitudes in the mesopause region has been operational since the mid-eighties in El Leoncito (32° S, 69° W). Following the manual use mode of operation in its early years, automatic data acquisition started in 1998 (see Scheer and Reisin, 2001; and references therein, about instrumentation and retrieval technique) and continues today.

The database now covers more than 4200 nights of observation. It not only contains temperature data corresponding to nominal altitudes of 87 and 95 km, but the database also exhibits band intensities of the OH(6-2) and O2b(0-1) airglow emissions, which add independent but complementary information. Because of the good time resolution (the four parameters are sampled every 80 s) this data can be used to monitor the dynamics of the neutral atmosphere with reliable nocturnal coverage. These measurements now represent the Argentine contribution to the Network for the Detection of Mesospheric Change (NDMC, Reisin et al., 2014).

3.4. South America Riometer Network

An imaging Riometer for ionospheric study, which is capable of measuring shape, spatial scale and motion of ionospheric absorption, was first developed at the South Pole Station in the Antarctica to study the dynamics of auroral particle precipitation in the high-latitude region[4] (Detrick and Rosenberg, 1988; Detrick and Lutz, 1990). The first imaging Riometer was installed in 1999 at the São Martinho da Serra near Santa Maria (RS), Brazil. Since then, four additional stations have been subsequently established in Latin America.

The SARINET was designed to study the upper atmosphere phenomena in the SAMA in the low and middle latitudes. Seven Imaging Riometers and 17 single beam Riometers are currently operational in the American sector (Brazil, Argentina and Chile) and Japan in order to study the energetic particle precipitation, which can be a dominant cause of Cosmic Noise Absorption (CNA) in the ionosphere over the SAMA region.

The latitudinal dependence of CNA during a geomagnetic storm was studied by Moro et al. (2012a,b). The authors observed that the absorption was more pronounced in the region located nearest to the center of the SAMA, in Brazil, and the second highest value was found at the edge of SAMA, South of Chile, which has been explained in terms of the expansion of auroral oval to lower latitudes during the geomagnetic storm. Correlations between the CNA and the energetic electron flux in two energy channels (>30 KeV e > 300 keV) and the proton flux in three energy channels (80–240 keV, 500–2500 keV and >6900 keV) measured by the Medium Energy Proton and Electron Detector on-board the Polar Operational Environmental Satellite showed that different particles with different energy ranges precipitate in Brazil, Argentina and Chile, causing CNA with different intensity in each station (Moro et al., 2012a). In Table 3 the Riometer locations and characteristics are listed together.

3.5. South American VLF Network

The SAVNET began operations in 2006 (Raulin et al., 2009). Today, it is composed of 11 receiving stations located in Latin America (Argentina, Brazil, Mexico and Peru), being 8 of them fully operational. In the last decade, the SAVNET network has been involved in different international cooperation programs such as the IHY and the ISWI. As a result, many students from the previously mentioned countries began their scientific careers and getting their (master, doctorate) degrees using SAVNET data. The scientific output and production from SAVNET related studies has resulted in more than 20 papers in international journals.

SAVNET tracks propagation anomalies of VLF waves within the Earth-Ionosphere waveguide, revealing changes of the physical properties of the D region during the day and of the E region at night. Anomalies in the phase and amplitude of the received VLF waves traduce variations of the well-known Wait parameters, namely the reference height h′ (km) and the sharpness (km^{-1}), and can come from outer geospace or from the underlying atmosphere of the Earth. In Table 4 the VLF receiver locations in Latin America are listed.

During the last decade, SAVNET related studies have brought new insight on the lower ionosphere sensitivity in response to short-term solar activity like flares (Raulin et al., 2006; Pacini and Raulin, 2006; Raulin et al., 2010) and to longer timescale phenomena such as the solar cycle (Raulin et al., 2010). In particular, 100% of low-level Geostationary Operational Environmental Satellite (GOES) B-Class solar events are detected using the VLF technique. On timescales related to the solar cycle, SAVNET shows that the ionosphere may be used to indirectly estimate the amount of solar Lyman-radiation (Raulin et al.,

---

[4] There is no exact definition where that boundary of the high latitude lies for space weather purposes. Normally, the high latitude is situated around the 60° magnetic latitude and higher in both Northern and Southern hemispheres. However, when there are severe particle precipitations inside the auroral region due to space weather effect this boundary can expand down to 55° or even less.

Table 3
Riometer locations and data type.

Location	Code	Latitude	Longitude	Data available
São Martinho da Serra, Brazil	SMS	29.4°S	53.8° W	Image riometer[a]
Concepción, Chile	CON	36.5°S	73.0°W	Image riometer[a]
Punta Arenas, Chile	PAC	53.1°S	70.8°W	Image riometer[a]
Trelew, Argentina	TRW	43.1°S	65.2°W	Single channel riometer

[a] 16 half-wavelength dipoles (4 × 4).

Table 4
VLF receiver locations.

Location	Code	Latitude	Longitude	Country
Atibaia	ATI	23.18°S	46.55°W	Brazil
Casleo	CAS	31.80°S	69.30°W	Argentina
Antarctic (Ferraz station)	EACF	62.08°S	58.40°W	Brazil
Ica	ICA	14.02°S	75.73°W	Peru
Palmas	PAL	10.17°S	49.33°W	Brazil
Punta Lobos	PLO	12.50°S	76.78°W	Peru
Piura	PIU	05.17°S	80.63°W	Peru
São Martinho da Serra	SMS	29.44°S	53.82°W	Brazil

2010). VLF anomaly observations provided by SAVNET are also important to complement space observations of energetic astrophysical phenomena like Magnetars and Gamma-Ray Bursts (GRB) (Tanaka et al., 2010; Raulin et al., 2014), especially during extremely intense events that saturate on-board X-ray and γ-ray sensors, or during events occulted by the Earth. More recently, SAVNET studies have shown that the VLF technique is also a very promising tool to detect disturbances originating from below the ionosphere, associated to subsequent seismic activity (Hayakawa et al., 2011; Samanes et al., 2015; Grant et al., 2015). If these initial results are confirmed, they could provide important precursory information about the 15-day timescale before large earthquake events.

3.6. Embrace Digisonde Network

Studies of the ionospheric profile started by means of periodic soundings of the ionosphere. These can be obtained from ionosondes which provide the vertical electron density profile of the bottom-side ionosphere. In Brazil, ionospheric soundings using ionosondes began in 1967 with the installation of an analogic C4 ionosonde in Natal (RN), under a collaborative project between INPE and the United States Air Force. In 1975, this equipment was transferred to Itaitinga in Fortaleza (CE). A second ionosonde (Magnetic AB) was then installed in Cachoeira Paulista (SP) in 1971. In 1990, INPE's Aeronomy Research Group started to replace the analogic ionosondes with new, more modern digital equipment, called digisondes. A Digisonde 256 (DGS256) was installed in Cachoeira Paulista in 1990 and, in 1994, INPE also installed a DGS256 in its new observatory in São Luis (MA). From 1990 to 2002, a Canadian Advanced Digital Ionosonde (CADI) was operated in Itaitinga, and then, in 2009, it was transferred to São João do Cariri (PB) where it remains operational today. In 2001, a new Digital Portable Sounder (DPS4) was installed in Itaitinga and later moved to Eusébio, Fortaleza (CE). Recently, this network has been incorporated into the Embrace DigiNet[5] through a profitable partnership between the Embrace/INPE Program and the Aeronomy Research Group. Consequently, Embrace/INPE expanded the network by installing the DPS4-D in Boa Vista (RR) and in Campo Grande (MS) in July 2013 and upgraded the DGS256 installed at Cachoeira Paulista to a DPS-4 model, in November 2014. Table 5 below lists the Ionosonde locations and system characteristics.

Essentially, the digital versions of the ionosondes are HF bi-static radars that are composed of a transmitter, a receiver and two sets of antennas. The transmitter is able to emit sequences of radio pulse-modulated waves with a peak power of tens of kW (usually an average power of 500 W). The frequencies of radio waves in subsequent pulses range from 0.5 to 15.0 MHz, in 0.5 MHz frequency steps. The ionospheric echoes collected by the digisondes allow us to construct graphs of frequency versus virtual height, which are called ionograms.

In the past decade, this class of equipment has been used to investigate several ionospheric phenomena. A recent study investigated the competition between neutral winds and electric fields in the equatorial regions of the ionosphere and the ionospheric parameters obtained by the digisonde make it possible to study this behavior (Mendonça, 1965; Takahashi et al., 1996; Medeiros et al., 2001; Resende, 2014). Results from this study revealed that some ionosphere irregularities have a dependence on the magnetic latitude, getting weaker as the magnetic equator

---

[5] Available online at http://www2.inpe.br/climaespacial/SWMonitorUser/?lan=en.

Table 5
Ionosonde locations in Brazil and system characteristics.

Station location	Code	Latitude	Longitude	System
Boa Vista (RR)	BVJ03	2.8°N	60.6°W	DPS-4
São Luís (MA)	SAA0 K	2.6°S	44.2°W	DGS-256
Fortaleza (CE)	FZA0 M	3.7°S	38.5°W	DPS-4
São João do Cariri (PB)	None	7.4°S	36.5°W	CADI
Campo Grande (MS)	CGK21	20.4°S	54.6°W	DPS-4
Cachoeira Paulista (SP)	CAJ2 M	22.6°S	45.0°W	DGS-256

departs from the sounding site (Resende, 2010; Resende et al., 2013), as well as solar activity dependence (Resende and Denardini, 2012).

3.7. Brazilian Network for Continuous Monitoring of the GNSS Systems

Since 1996, the Brazilian Network for Continuous Monitoring of the GNSS Systems (RBMC) has been providing data consisting of carrier phases and code ranges to derive precise geographic coordinates (latitude, longitude and altitude) with an accuracy of a few centimeters. This data supports three dimensional positioning (air and maritime navigation), combine operations (precision agriculture), meteorology (water content maps), space weather (TEC Maps), and geophysical applications (rural and urban mapping) throughout Brazil. The network is the result of a partnership among several public and private institutions in Brazil, of which the Brazilian Institute of Geography and Statistics (IBGE), the National Institute of Colonization and Agrarian Reform (INCRA) and INPE are especially noteworthy. The RBMC is a geodesic structure with 117 GNSS stations, each having a GNSS receiver connected to an internet link connected to the data centers. Of the 117 stations currently comprising the RBMC, 92 stations operate in real time, and the remaining stations transmit data for post-processing (Costa et al., 2012; Fortes et al., 2012).

The RBMC station consists of a receiver, a geodetic antenna, internet connection and constant power supply, which enables the continuous operation of the station. It is built on concrete pillars anchored to bedrock and masts attached to buildings. Most of the receivers can track GPS and Global Navigation Satellite System (GLONASS) satellites; however some of them can only trace GPS (Commins and Janssen, 2012). These receivers continuously collect and store the code and phase observations of the carrier waves transmitted by the satellites of GPS or GLONASS constellations.

An important aspect of the RBMC is the precise determination of the coordinates of each station. The geographic coordinates of every single station has managed to be ±5 mm-precise, making this network one of the most accurate networks in the world, allowing it to be integrated into the Geocentric Reference System for the Americas (SIRGAS) network. It also allows RBMC to contribute to the regional densification of the International GNSS Service (IGS) network for geodynamics.

With respect to space science, the Embrace/INPE is currently collecting all the available RBMC data for deriving the vertical TEC Map over Brazil, and assimilating it into space weather forecasting models. The basic processing is based on the pseudo-ranges (P1 and P2) derived from the GPS dual-frequency radio-wave signals (1575.42 MHz and 1227.60 MHz) transmitted by GPS satellites from an altitude of 20,200 km and provided by the ground-based GPS receivers. The difference between the pseudo-ranges ΔP (=P2 − P1) is directly related to TEC along the line of sight between the receiver and the GPS satellite (slant TEC). However, this difference provides only coarse data. The difference in the carrier phase delays between L1 and L2, i.e. ΔL (=L1 − L2), provides precise tracking, but the resulting TEC values are relative. Therefore, the level of TEC is adjusted to that which is obtained from the pseudo-ranges. To calculate the absolute TEC, instrumental bias must be eliminated. Furthermore, the satellite elevation angle must be considered when converting slant TEC to vertical TEC (vTEC) as described by Takahashi et al. (2014). The data handling method and the processing algorithm at Embrace/INPE is based on those used by Otsuka et al. (2002).

3.8. Countering GNSS High Accuracy Applications Limitations due to Ionospheric Disturbances in Brazil

Similar to the RBMC, the State University of São Paulo also holds a GNSS network named Countering GNSS High Accuracy Applications Limitations due to Ionospheric Disturbances in Brazil (Calibra). This network is the continuity of the Concept for Ionospheric-Scintillation Mitigation for Professional GNSS in Latin America (Cigala) Project, sponsored by the European partners: University of Nottingham (UNOTT) from Nottingham (UK), which led the project; the National Institute of Geophysics and Volcanology (INGV) from Rome (Italy); the University of New Gorica (UNG) from Slovenia; and the private company Septentrio Satellite Navigation from Belgium; and the Brazilian partners: Faculty of Science and Technology (FCT) at the Paulista State University (UNESP); and the private company ConsultGEL Geomatics Consulting (CSG), which ceased its operations in February 2012.

The Calibra Network was launched in November 2012 with the expectations to last for two years, having 12 GNSS receivers of the PolaRxS-PRO type, which are able to collect data at a rate up to 100 Hz, leading to the production of on-the-flight ionosphere scintillation indices at the rate of one sample per minute. For this new phase of the network, the State of São Paulo Research Foundation (Fapesp) and INPE joined the previous Cigala partners.

The Cigala project was set to exploit the precision of the GNSS signals, in particular the carrier phase like Real Time Kinematic (RTK), Wide Area Real Time Kinematic (WARTK) and Precise Point Positioning (PPP), and it has demonstrated that GNSS signal tracking under ionospheric scintillation can be effectively mitigated by new algorithms and loop configuration within the GNSS receiver signal tracking engine (Monico et al., 2012). However, it has also shown that the GNSS signal is especially sensitive to disturbances of the ionosphere, which are dependent on several variables: the solar cycle, season, local time, geographical location and geomagnetic activity. Therefore, the Calibra Network is justified in replacing Cigala and will be continued.

Monico et al. (2012) state that Brazil is located in one of the most affected regions of the Earth, with respect to the ionospheric interference in the GNSS signals, because it materializes one of the worst scenarios. Problems related to the solution of ambiguities, crucial to methods of high accuracy, had manifested itself even before reaching the apex of solar cycle 24 (2013–2014), inhibiting the accuracy levels expected by the industry. The impact of high solar activity yields risk, not only that of disabling the use of GNSS, but also leading users not to rely on the system for high accuracy applications. Those characteristics are relevant to the development of Galileo Constellations and are due to technological challenges that are imposed.

Consequently, the Embrace/INPE is currently handling data from the Cigala Network, which is partially integrating the RBMC. Furthermore, negotiations are being carried out in order to allow the complete Cigala Network data insertion in the Embrace/INPE system to increase the TEC Map accuracy.

3.9. Argentine Network for Continuous Satellite Monitoring

In 1998, the Argentine Network for Continuous Satellite Monitoring (RAMSAC) was created by the National Geographical Institute (IGN, former Military Geographical Institute – IGM) to materialize the Argentine geodesic reference frame. The motivation for RAMSAC was a new reference frame created in Argentina in 1994 (Argentine Geodetic Positions, POSGAR), which was adopted due to the need of adapting the Argentine reference frame system to the international World Geodetic System established in 1984 (WGS84). The change to this new POSGAR was made in 1997, when 127 nodes distributed all over the country were constituted, and formed part of the Argentine WGS84.

The main aims of RAMSAC are to contribute to the development and maintenance of the national geodetic reference frame; to contribute with permanent GNSS stations for the International Terrestrial Reference Frame; to satisfy technical requirements from modern techniques of satellite positioning; and to advise and collaborate in the installation of new permanent GNSS stations in all institutions that want to be incorporated into the RAMSAC net, so that the data can be posted openly online and free of charge. Today, RAMSAC offers the data of each of its permanent GNSS stations in Receiver Independent Exchange (RINEX)[6] format.

In the frame of RAMSAC, a center for GNSS data processing was created, which is in charge of processing the data from the permanent GNSS stations in Argentina. RAMSAC was crucial to the new POSGAR 2007, which began to be used compulsorily in May of 2009. The data processing center of RAMSAC was incorporated with SIRGAS in 2006 as an experimental center, and now processes data for all of Latin America.

3.10. Embrace Magnetometer Network

The Embrace MagNet[7] is planned to cover most of the Eastern Southern American longitudinal sector in order to fill the gap of magnetic measurements available on-line. The availability of fast internet, reliable energy supply and ease of access were the key points for deciding the location of the magnetometer stations of our network. We present the location of the Embrace MagNet stations in Table 6, which was initiated in May 2011.

Each magnetic station is composed of a three-axis fluxgate magnetometer, a controller system and a personal computer for local data storage and an Internet file transfer protocol server. The magnetometer sensors use single bars with a high level of magnetic saturation, covered by two copper coils, one for the excitation and the second for the sensing of the external field. It is built for compact and high performance precision measurements of the Earth's magnetic field vector with a total measuring range of ±70,000 nT and dynamic ranges of ±250 nT, ±1000 nT and ±2500 nT covering the amplitude diurnal variations of the magnetic components from low to high latitude (Veliz, 2010). The sensor is buried 1-m deep, under a cover made of metal-free material to provide protection against moderate rain, winds and solar exposure. It is installed in a location 20–50 m away from the main shelf where the controller system and the personal computer are located. The cable connecting the magnetic sensor to the controller system is sealed and buried 20-cm deep to avoid solar exposure and to provide at least the minimum temperature

---

[6] The Receiver Independent Exchange (RINEX) format is a file format developed by the Astronomical Institute at the University of Bern in order to provide the GPS data easy exchange.

[7] Available online at http://www2.inpe.br/climaespacial/SWMonitorUser/?lan=en.

Table 6
Geographical location of the Embrace magnetometer selected stations (and candidate stations) with the corresponding magnetic latitude, dip angle, estimated K9 lower limit and designed code.

Magnetic stations	IAGA code	UN[a]	Geographic		Geomag. Lat. (°)	Altitude (m)	DIP (°)	K9
			Lat.	Lon.				
Belém – PA	BLM	BR	01°26′28″S	48°26′40″W	−00.4	016	−00.80	600
São Luís – MA	SLZ	BR	02°35′39″S	44°12′35″W	−03.6	032	−07.26	500
Alta Floresta – MT	ALF	BR	09°52′13″S	56°06′15″W	−03.7	284	−07.50	500
Cachimbo – PA	CXB	BR	09°21′27″S	54°54′53″W	−04.0	464	−07.79	500
Manaus – AM	MAN	BR	02°53′18″S	59°58′11″W	+04.4	102	+08.09	500
Araguatins – TO	ARA	BR	05°36′01″S	48°06′02″W	−05.6	103	−11.30	450
Eusébio – CE	EUS	BR	03°52′48″S	38°25′28″W	−08.2	043	−16.51	400
Palmas – TO	PAL	BR	10°17′50″S	48°21′41″W	−08.3	231	−16.52	400
Cuiabá – MT	CBA	BR	15°33′17″S	56°04′10″W	−08.5	233	−17.10	400
Boa Vista – RR	BOA	BR	02°48′02″N	60°40′33″W	+09.4	076	+18.80	400
Jataí – GO	JAT	BR	17°55′54″S	51°43′06″W	−12.3	708	−24.60	350
Campo Grande – MS	CGR	BR	20°30′24″S	54°37′04″W	−13.7	540	−25.50	350
Tucumán – TU	TCM	AR	26°49′20″S	65°11′40″W	−15.8	431	−27.35	300
Cachoeira Paulista – SP	CXP	BR	22°42′07″S	45°00′52″W	−18.9	601	−36.43	300
São José dos Campos – SP	SJC	BR	23°12′31″S	45°57′49″W	−19.1	583	−36.64	300
Vassouras – RJ	VSS	BR	22°24′07″S	43°39′08″W	−19.7	443	−38.40	300
São Martinho da Serra – RS	SMS	BR	29°26′37″S	53°49′22″W	−21.6	462	−36.65	300
Rio Grande – TF	RGA	AR	53°47′09″S	67°45′42″W	−39.9	010	−50.03	400
Estação Cmdt. Ferraz – AC	ECF	BR	62°05′06″S	58°24′12″W	−58.4	010	−53.20	800

[a] UN = Country, BR = Brazil, AR = Argentine.

protection. It uses military certified connectors to ensure durability. The room temperature of the main shelf is maintained under control.

In order to assure the precision of the magnetic measurements performed with any network, it is usual to calibrate each individual sensor to either a reference fluxgate magnetometer or a high performance proton magnetometer, which can provide the absolute magnetic field. Since the goals of the Embrace MagNet are associated with measuring the variation of the magnetic field and its relative amplitude all over South America instead of only obtaining the absolute values of the magnetic field, we decided to adopt a reference fluxgate magnetometer to the network, which was set to be the one installed at Cachoeira Paulista (SP).

Thereafter, it is mandatory to submit all the magnetic equipment acquired to be part of the Embrace Magnetometer Network to a sensibility matching process within the reference magnetometer. This procedure consists of: (1) burying the sensor of the new magnetometer close (2–3 m apart) to the sensor of the reference magnetometer with no changes to the factory settings; (2) leaving it there to collect data for 3 months; (3) selecting the data collected during the 5 quietest days of each month from both magnetometers, the reference and the new one; (4) averaging all the data to obtain the mean Quiet Day Curve (QDC) for each magnetic component, which should be representative to the period of acquisition, avoid aliasing, outliers, and any other possible interference; (5) performing a correlation analysis based on the least squares linear fit of the QDC of reference versus the QDC under evaluation, for each magnetic component individually; (6) correcting the gain of the measurement of each individual magnetic component, based on the angular parameter derived from the estimated regression equation; (7) leaving it there to collect data for another month; and (8) repeating steps 3–6 from this procedure to ensure an angular parameter derived from the estimated regression equation between 0.99 and 1.01, i.e. a relative error lower than 1% (Denardini et al., 2015).

3.11. Intermagnet Observatories in Mexico and Argentina

Regarding magnetic observatories in Latin America (aside from Embrace MagNet), the International Real-time Magnetic Observatory Network (Intermagnet)[8] is the organization with the highest number of inter-calibrated observatories. Intermagnet is a global and international network of observatories that monitor the geomagnetic field, which can be used for monitoring and studying the absolute geomagnetic field and its variations. It also allows for geomagnetic storm detection, and can be used for monitoring long term secular changes and contribute to IGRF.

In Mexico, the Teoloyucan Geomagnetic Observatory (OMT, 19°44′40″N, 99°11′34″W) is a magnetic observatory operating since 1914, which is currently managed by the Institute of Geophysics at UNAM (IGF/UNAM). It was a part of the Intermagnet network from 2002 to 2012, and it is currently in the process of obtaining the required standards to become a full member again. In Argentina, the National Weather Service (SMN) is the institute that maintains a net of absolute magnetometers to record the

---

[8] Available online at http://www.intermagnet.org/institutes-eng.php.

geomagnetic field at Pilar-Córdoba (PIL), Orcadas-Antárctica (ORC), Trelew-Chubut (TRW), and Las Acacias-Buenos Aires (LAS). Among those magnetic stations/observatories, PIL and ORC are integrated with Intermagnet, similar to the Mexican stations. Observations from the magnetometer LAS are used to study the SAMA and Sun–Earth connection, and to contribute to the determination of the IGRF. SMN also manages the Argentine Riometers which are part of the SARINET (Trelew – Chubut and Bahía Blanca – Buenos Aires), mentioned above. More information about the net of magnetometers of SMN in Argentina can be found in Gianibelli et al. (2013).

3.12. Global Muon Detector Network

The Global Muon Detector Network (GMDN) was established in March 2006, when a hodoscope type cosmic ray detector (3 × 3 m, upgraded in 2015 to 5 × 4.3 m) in Kuwait was added to the previous network composed of the multi-directional detectors using plastic scintillators in Nagoya, Japan (started in 1969), Hobart, Australia (a 3 × 3 m installed in 1992 was changed from the University of Tasmania to the Australian Antarctic Division in 2006 and expanded to 4 × 4 m in 2010), and São Martinho da Serra (RS), Brazil (a prototype 2 × 2 m detector installed in 2001, with a first expansion to 4 × 7 m in 2005, a second expansion to 4 × 8 m in 2012, and a third expansion to 4 × 9 m is planned for 2016). In Mexico, as part of the GMDN, and to detect solar neutrons a SciCRT (3 × 3 × 1.6 m) was installed in the Sierra Negra volcano (18°46′50″N, 97°36′15″W) in 2013. Since then, the GMDN has been operated continuously and automatically. Data is published on the Internet with open access at its official web page.[9]

The main goal of the GMDN is provide information about solar structure like Interplanetary Coronal Mass Ejections (ICME) before this structure hit the Earth's magnetosphere. These cosmic ray precursors (loss of cones or enhanced variances) of the geomagnetic storms are caused by ICME arrivals at the Earth. Rockenbach et al. (2011) studied 181 geomagnetic storms, looking for cosmic ray precursors and they confirmed the important conclusion by Munakata et al. (2000) that solar structures that cause more intense geomagnetic storms presented precursors more frequently when compared with less intense storms. A complete description and the main results of the GMDN can be found in Savian et al. (2007) and Rockenbach et al. (2014).

3.13. The Pierre Auger Observatory (Low Energy Modes)

The Pierre Auger Observatory (The Pierre Auger Collaboration, 2015) was originally designed to study cosmic rays at the highest energies and is located in Malargüe, Argentina (69.3°W, 35.3°S, 1400 m a.s.l.). One of the techniques of the observatory is the direct measurement of particles reaching ground level. These ground level observations are based on measurements that come from its array of Surface Detectors covering a surface of 3000 km^2. This surface is covered by 1660 Water Cherenkov Detectors (WCD). In general, a WCD is basically composed by a volume of water and photomultipliers tubes and are used to detect Cherenkov radiation produced when a charged particle travels faster than the speed of the light in the water. Each WCD in Auger consists of a polyethylene tank (with an area of 10 m^2) and contains 12 m^3 of high-purity water in a highly-reflective bag. The Cherenkov radiation produced by the charged particles passing through the volume of water in each detector is measured by the three photomultiplier tubes that produce signals which are processed with a sampling rate of 40 MHz by six 10-bit flash Analog-to-Digital Converters (ADC), and are sent by a radio link to the central data acquisition system in Malargüe. A GPS system is used for timing and synchronization. Particles interact with the water producing pulses of different amplitudes (with the area of the pulse related to the energy deposited by the particle in the detector), which are recorded to set up histograms. The scaler mode consists of recording the total count of signals above a low threshold and below a high threshold. This low energy mode of the Pierre Auger Observatory has been used to observe details of Forbush events (Forbush et al., 1949; Forbush, 1957) with the lowest statistical error reached (The Pierre Auger Collaboration, 2011; Dasso and Asorey for The Pierre Auger Collaboration, 2012). Another low energy mode used in the Pierre Auger Observatory comes from the charge histogram (a histogram of the deposited energy by each of the detected particles, Asorey for the Pierre Auger Collaboration, 2011). This novel mode allows for the distinguishing of the energy of secondary particles, in opposition to Neutron Monitors that can only count all observed neutrons. With this capability, it is possible to make deeper analyses and to better understand the effects of the Interplanetary Magnetic Field (IMF) (e.g., turbulent diffusion) on energetic particles in the solar wind.

3.14. Latin American Giant Observatory

The LAGO Project has the design, installation, commissioning, and operation of an extended observatory of astroparticles on a global scale as its new aim. LAGO became a spin-off of The Pierre Auger Observatory and its main scientific aims are centered in three (basic and applied) research areas, linked with astroparticles: high energy phenomena (energies in the range of GeV–PeV), space weather (and space climate), and atmospheric radiation. Its main academic aims are: to boost the development of astroparticles and the particle branch of space weather in Latin America, and to establish and consolidate a Latin

---

[9] Available online at http://cosray.shinshu-u.ac.jp/crest/DB/Public/Archives/GMDN.php.

American network of researchers and students in physics of astroparticles.

This observatory is an international project started in 2005 as a collaboration between groups from different countries in Latin America, and has been extended in recent years.[10] It is now operated by the LAGO collaboration, a non-centralized network, distributed and collaborative, integrated by researchers and students from nine countries of Latin America: Argentina, Bolivia, Brazil, Colombia, Ecuador, Guatemala, México, Peru and Venezuela. LAGO is formed by particle detectors, individual or formed by grouped small arrays, located at ground level and installed at different sites. The net covers a wide distribution of latitudes (from Mexico to Patagonia in Argentina, and soon in Antarctica) and altitudes (from sea level up to more than 5000 m of altitude), covering an extensive range of cut-off rigidities and different levels of reaction and absorption in the atmosphere. The LAGO detectors are WCDs that measure the time evolution of the radiation flux at ground level with extreme detail and are constructed by a commercial container for the storage the water, with a capacity of about 1 m^3 up to around 40 m^3, filled with purified water. A highly diffusive material covers the internal surfaces of the container to get a uniform flux of the radiation in times of the order of 15 ns, after the input of particles to the detector. These light signals are converted into electric signals using Photomultiplier (PMT). The signals from the PMT are digitalized using an electronic device designed by the LAGO collaboration. These electronic devices use fast (flash) ADC with a sample speed between 40 and 100 MHz, and with 10 bits resolution. For more details about LAGO and about these detectors see Asorey et al. for the LAGO Collaboration (2015).

Thus, LAGO will provide valuable measurements of secondaries at ground level, relevant for studies of Space Weather and Space Physics. In particular LAGO can measure different cosmic ray events, e.g. the electromagnetic part and muons from the shower of secondary Cosmic Rays (CR). They can also provide unique and detailed information on transient events of solar origin. These detectors can obtain relevant information about the energy and count the rate (per time unit and per surface unit) of these secondary CRs, i.e. for secondaries formed by primary CRs with energies of interest for solar-terrestrial physics. The different sites of the observatory are improving several aspects of the detectors and they are storing historical data, which show promise for a good opportunity to study different open questions linked with cosmic rays and their role in space weather. A new LAGO site will be created at an Antarctic base of Argentina.

3.15. Solar and cosmic rays single observatory

Unlike the previous networks mentioned here, which have been built based on the same sensor installed with almost the same configuration in several space-distributed sites, the solar observatories and cosmic ray single observatories (unlike the GMDN) are quite unique and may differ from each other when considering the kind of particles (protons or muons) observed by cosmic ray observatories or the frequency range of solar observatories (from Very High Frequency-VHF, Ultra High Frequency-UHF to the visible), including the size and kind of the sensor/antenna (gas or plastic for cosmic rays observatories, and lens, mirror, dish, Yagi for solar observatories). Quantity and configurations of sensors/antennas (single or double layers for cosmic rays observatories, and long array, single dish solar observatories), among several other specifications that can be customized, are also characteristics that define the capability of the observatory and contribute to making it difficult to build a homogenous spread array of observatories. Therefore, we will consider here those networks of observatories working together as well as the individual observatories working in coordination with other groups.

Regarding cosmic ray individual observatories, the IGF/UNAM group operates the neutron monitor station in Mexico City (19°19′51″N, 99°11′44″W) and the solar neutron monitor on Mt. Sierra Negra (18°46′50″N, 99°11′44″W), in the state of Puebla. These two cosmic ray instruments report data in real time to the SCiESMEX web server in order to monitor Forbush decreases.

When considering solar observatories, the SST is an important operational radio observatory in Latin America (Kaufmann et al., 2001). The SST is a radio telescope installed at the Astronomical Complex "el Leoncito" (CASLEO, 31.8° S, 69.3° W), which observes the Sun on a daily basis at 212 GHz (four radiometers) and 405 GHz (two radiometers) with 40 ms time resolution. This facility is part of the ground-based solar instruments for remote sensing in Argentina and has been operating since 1999 in Pampa del Leoncito (San Juan province), at an altitude of 2400 m, within the frame of the Argentina – Brazil agreement.

Another solar radiotelescope based in Latin America is the MEXART, an array of 4096 dipoles operating at 140 MHz installed at the Interplanetary Scintillation Observatory of Coeneo Michoacán (19°48′46″N, 101°41′48″W) to track large-scale disturbances of the solar wind using the Interplanetary Scintillation (IPS) technique. Using the Earth's rotation, the radiotelescope scans the whole sky daily to record the transit of extragalactic radio sources. The signal of these sources is affected by the turbulence in the solar wind producing a scattering effect on the wave fronts, and the signals arrive to Earth with intensity fluctuations (scintillation). The first light and identifications of ICMEs detected by MEXART was reported just recently (Mejia-Ambriz et al., 2010; Aguilar-Rodriguez

---

[10] More information available at www.lagoproject.org.

et al., 2014; Romero-Hernandez et al., 2015; Chang et al., 2016). There is a network of similar instruments based on the IPS technique like the Toyokawa radiotelescope at the Nagoya University in Japan, and the Ooty Radiotelescope in India. Combining the data from these instruments, it is possible to track large-scale solar wind disturbances between the Sun and the Earth, which can be used to forecast the arrival of ICMEs to the Earth. The application of these IPS observations for space weather forecasting is one of the products that SCiESMEX is working on at this moment. On the other hand, the infrastructure at the MEXART site created the conditions to incorporate new space weather related instruments including a magnetometer, a GPS station, a Compact Astronomical Low-cost Low-frequency Instrument for Spectroscopy and Transportable Observatory (CALLISTO) antenna, and a Schumann antenna. The data from these instruments are posted onto the SCiESMEX web site.

Brazilian radioastronomer research groups have also contributed to development of solar observatories. The first great step forward in this direction came with the Itapetinga Radio Observatory (ROI) in Atibaia (23.18° S, 46.55° W). This solar telescope was installed in 1974 and has a dish antenna 14-m wide. It was the home of virtually all the capabilities in radio astronomy installed in Brazil for a long time and it has a record of important discoveries in different fields such as galactic astronomy, extragalactic and solar physics. Currently, it is operated by INPE but it is open to the public. Sounding in the range from 18 to 90 GHz, it is still competitive in some research areas, compared to other instruments available in the Southern hemisphere.

Recently, two new facilities have been established in Brazil. As reported by Costa et al. (2010), radioastronomers have been operating the Northeast Radio Space Observatory (ROEN, 3.9° S, 38.5° W) since 1993, a cooperative project with National Oceanic and Atmospheric Administration (NOAA). This instrument has an antenna of 14.2-m diameter and it is able to make observations at 20 GHz. It is used primarily as an instrument for geodetic Very Long Baseline Interferometry (VLBI). The other is the Brazilian Decimetric Array (BDA), which is a 38-element radio telescope, employing modern radio interferometric techniques and working in the frequency range of 1.2–6.0 GHz. The final baseline of the interferometer will be 2.27 km in the East–West and 1.17 km in the Southern direction. This instrument will obtain radio images from the Sun with a spatial resolution of 4x6 arc seconds. Its prototype has been successfully put into operation for solar and non-solar observations at Cachoeira Paulista (SP) (22°41′19″S, 45°00′20″W) in November 2004, and one-dimensional brightness temperature maps of the Sun at 1.6 GHz have also been obtained. The estimated sensitivity of the prototype of the BDA consisting of 5 antennas of 4 m in diameter each is of about 3.5 Jy/beam for 1 minute of integration time for galactic and extragalactic observations at 1.4 GHz. In the case of the Sun, the estimated sensitivities/beam for time resolution of 100 ms is around 140 SFU/beam (1 SFU = 10000 Jy).

4. Summary and conclusions

We provided a list of existing ground based facilities within the available information, a substantial amount of space weather-related instrumental networks, as well as single instrumentation currently operational in Latin America, some only partially operational, while others are still being established or developed. Most of these instrumental networks are gradually being incorporated into the space weather monitoring data pipelines or are considering doing so. The order of priority is a prerogative of each RWC depending on its goals and needs, but there is no doubt that the data collected with the space science instruments contain key variables for monitoring and forecasting space weather, enabling these centers to monitor and issue warnings and alerts.

Acknowledgements

C.M. Denardini thanks CNPq/MCTI (Grant 303121/2014-9), FAPESP (Grant 2012/08445-9), and to the Brazilian Government (Program 2056, Budget Action N387, Budget Plan 08/2013-2017), which supported both the scientific and infra-structure projects that gave birth to the Embrace Magnetometer Network and to the Embrace/INPE Program. S. Dasso acknowledges partial support from the Argentine grants UBACyT 20020120100220 (UBA), PICT-2013-1462 (FONCyT-ANPCyT), PIP-11220130100439CO (CONICET) and PIDDEF 2014-2017 nro. S.D. is member of the Carrera del Investigador Científico, CONICET. J. A. Gonzalez-Esparza recognized that the SCiESMEX operation is funded partially by the Catedras CONACYT program, DGAPA-PAPIIT grant IN109413, CONACyT grant 152471, and the Fondo Sectorial CONACyT-AEM grant 247722. The authors would also express their deep gratitude to the valuable contributions by (in alphabetical order by the first name): Dr. Adriana Gulisano, Dr. Ana Osella, Dr. Andrea Costa, Dr. Carolina Vera, Dr. Cristina Mandrini, Dr. Daniel Gómez, Lic. Graciela Molina, Dr. Hebe Cremades, Dr. Hisao Takahashi, Dr. Inez Staciarini Batista, Dr. Jean-Pierre Raulin, Dr. João Francisco Galera Monico, Dr. Joaquim Eduardo Rezende Costa, Dr. Jonas Rodrigues de Souza, Dr. José Humberto Andrade Sobral, Dr. Juliano Moro, Dr. Julio Gianivelli, Dr. Jurgen Scheer, Dr. Laysa Cristina Araújo Resende, Dr. Mangalathayil Ali Abdu, Dr. Marcos Machado, Dr. Maria Virginia Alves, Dr. Marlos Rockenbach da Silva, Dr. Marta Mossert, Dr. Marta Zossi, Dr. Miguel Cabrera, Dr. Nalin Babulal Trivedi, Dr. Paulo Ricardo Jauer, Dr. Paulo Roberto

Fagundes, Dr. Sonia Maria Alves Costa, and Dr. Walter Demétrio González Alarcon. In addition, the authors would also express their gratitude to referees of this article who significantly contributed to improve it, and to Dr. Peggy Ann Shea, the Past Editor in Chief of Advances in Space Research who made great efforts to assist the publishing process.

Appendix A

Abbreviations for organizations (institutions, associations, committees, groups, observatories, services and related terminology)

AEM	Mexican Space Agency, from the Spanish Agencia Espacial Mexicana
ALAGE	Latin American Space Geophysics Association, from the Spanish Asociación Latino Americana de Geofísica Espacial
ASI	Italian Space Agency, from the Italian Agenzia Spaziale Italiana
CAS	Canadian Space Agency
CASLEO	Astronomical Complex “el Leoncito”, from the Spanish Complejo AStronómico el LEOncito
CNES	National Center for Space Studies, from the French Centre National d’Etudes Spatiales
CONAE	National Commission on Space Research, from the Spanish Comisión Nacional de Actividades Espaciales
CSG	ConsultGEL Geomatics Consulting, from the Portuguese ConsultGEL Consultoria em Geomática Ltda.
Embrace	Brazilian Study and Monitoring of Space Weather program, from the Portuguese Estudo e Monitoramento Brasileiro de Clima Espacial
Fapesp	State of São Paulo Research Foundation, from the Portuguese Fundação de Amparo à Pesquisa do Estado de São Paulo
FCT	Faculty of Science and Technology, from the Portuguese Faculdade de Ciências e Tecnologia
IAA	Argentine Antarctic Institute, from Spanish the Instituto Antártico Argentino
IBGE	Brazilian Institute of Geography and Statistics, from Portuguese Instituto Brasileiro de Geografia e Estatística
ICTSW	Interprogramme Coordination Team on Space Weather
IGF/UNAM	Institute of Geophysics at UNAM, from the Spanish Instituto de Geofísica de la Universidad Nacional Autónoma de México
IGM	Military Geographical Institute, from the Spanish Instituto Geográfico Militar
IGN	National Geographical Institute, from the Spanish Instituto Geográfico Nacional
IGS	International GNSS Service
IGY	International Geophysical Year
IHY	International Heliophysical Year
ILWS	International Living With a Star program
INCRA	National Institute of Colonization and Agrarian Reform, from Portuguese Instituto Nacional de Colonização e Reforma Agrária
INGV	National Institute of Geophysics and Volcanology, from the Italian Istituto Nazionale di Geofisica e Vulcanologia
INPE	National Institute for Space Research, from the Portuguese Instituto Nacional de Pesquisas Espaciais
ISWI	International Space Weather Initiative
LAGO	Latin American Giant Observatory, the former Large Aperture GRB Observatory
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
OMT	Teoloyucan Geomagnetic Observatory, from the Spanish Observatorio Geomagnético de Teoloyucan
ROEN	Northeast Radio Space Observatory, from the Portuguese Radio Observatório Espacial do Nordeste
ROI	Itapetinga Radio Observatory, from the Portuguese Rádio Observatório de Itapetinga
RWC(s)	Regional Warning Center(s)
SCiESMEX	Mexican Space Weather Service, from the Spanish Servicio de Clima Espacial, México
SMN	National Weather Service, from the Spanish Servicio Meteorológico Nacional
UNAM	National Autonomous University of Mexico, from the Spanish Universidad Nacional Autónoma de México
UNESP	Paulista State University, from the Portuguese Universidade Estadual Paulista “Júlio de Mesquita Filho”
UNG	University of New Gorica
UNOTT	University of Nottingham
UNT	National University of Tucumán, from the Spanish Universidad Nacional de Tucumán
WMO	World Meteorological Organization

Appendix B

Abbreviations for assets (networks, systems, instruments, devices, models and related terminology)

AAS	Argentine Airglow Spectrometer
ADC(s)	Analog-to-Digital Converter(s)
AIS	Advanced Ionospheric Sounder, an ionospheric digital sounder
BDA	Brazilian Decimetric Array
CADI	Canadian Advanced Digital Ionosonde, an ionospheric digital sounder
Calibra	Countering GNSS high accuracy Applications Limitations due to Ionospheric disturbances in BRAzil network
CALISTO	Compact Astronomical Low-cost Low-frequency Instrument for Spectroscopy and Transportable Observatory
Cigala	Concept for Ionospheric-Scintillation Mitigation for Professional GNSS in Latin America network
CBERS	China-Brazil Earth Resource Satellite
CCD	Charge-Coupled Device
DGS256	Digisonde 256, an ionospheric digital sounder
DPS-4	Digital Portable Sounder, an ionospheric digital sounder
Embrace DigiNet	Ionospheric digital sounding Network developed by the Embrace Program
Embrace GlowNet	Airglow All-sky Imagers Network developed by the Embrace Program
Embrace MagNet	Magnetometer Network developed by the Embrace Program
GLONASS	Global Navigation Satellite System, from Russian Globalnaya Navigatsionnaya Sputnikovaya Sistema
GMDN	Global Muon Detector Network
GNSS	Global Navigation Satellite Systems
GOES	Geostationary Operational Environmental Satellite
GPS	Global Positioning System
IGRF	International Geomagnetic Reference Field model
Intermagnet	International Real-time Magnetic Observatory Network
MEXART	MEXican Array RadioTelescope
MEXSAT	MEXican communication SATellite
NanoSatC-Br1	Brazilian CubeSat Project-1
NDMC	Network for the Detection of Mesospheric Change
POSGAR	Argentine Geodetic Positions network, from the Spanish POSiciones Geodésicas ARgentinas
RAMSAC	Argentine Network for Continuous Satellite Monitoring, from the Spanish Red Argentina de Monitoreo Satelital Continuo
RAPEAS	Argentine Network for the Study of the Upper Atmosphere, from the Spanish Red Argentina para el Estudio de la Alta Atmósfera
RBMC	Brazilian Network for Continuous Monitoring of the GNSS Systems, from Portuguese Rede Brasileira de Monitoramento Contínuo
SAMIA-MAR	Argentine–Brazilian Marine Environmental Information Satellite from the Portuguese Satélite Argentino–Brasileiro de Informações Ambientais Marinhas
SAC	Scientific Applications Satellite, from the Spanish Satélite de Aplicaciones Científicas
SACI	Scientific Applications Satellite, from the Portuguese Satélite de Aplicações Científicas
SAOCOM	Argentine Microwaves Observation Satellite, from the Spanish SAtélite Argentino de Observación COn Microondas
SARE	High Revisit Rate Satellite, from the Spanish Satélite de Alta REvisita
SARINET	South America Riometer Network
SAVNET	South American Very Low Frequency Network
SIRGAS	System Geocentric Reference for the Americas network, from the Portuguese SIstema de Referência Geocêntrico para as AméricaS
SST	Solar Submillimeter Telescope
VLBI	Very Long Baseline Interferometry
WCD	Water Cherenkov Detectors

Appendix C

Abbreviations for physical and technological definitions (phenomena, techniques, procedures and related terminology)

3D	Three-dimensional
AR(s)	Active Region(s)
CME(s)	Coronal Mass Ejection(s)
CNA	Cosmic Noise Absorption
CR(s)	Cosmic Ray(s)
GIC(s)	Ground Induced Current(s)
GRB(s)	Gamma-Ray Burst(s)
GW(s)	Gravity Wave(s)

ICME(s)	Interplanetary Coronal Mass Ejection(s)
IMF	Interplanetary Magnetic Field
IPS	Interplanetary Scintillation technique
PPP	Precise Point Positioning technique
PMT(s)	Photomultiplier tube(s), of photomultipliers for short
QDC	Quiet Day Curve
RINEX	Receiver Independent Exchange format for GPS data files
RTK	Real Time Kinematic
SAMA	South American Magnetic Anomaly
TEC	Total Electron Content
UHF	Ultra High Frequency
VHF	Very High Frequency
VLF	Very Low Frequency
WARTK	Wide Area Real Time Kinematic
WGS84	World Geodetic System established in 1984

References

Aguilar-Rodriguez, E., Rodriguez-Martinez, M., Romero-Hernandez, E., Mejia-Ambriz, J.C., González-Esparza, J.A., Tokumaru, M., 2014. The wavelet transform function to analyze interplanetary scintillation observations. Geophys. Res. Lett. 41 (10), 3331–3335.

Asorey, H.for the Pierre Auger Collaboration, 2011. Measurement of low energy cosmic radiation with the Water Cherenkov Detector Array of the Pierre Auger Observatory. In: Proceedings of the 32th ICRC Conference, Beijing, 0920.

Asorey, H., Dasso, S., Núñez, L.A., Peréz, Y., Sarmiento-Cano, C., Suárez-Durán, M.for The LAGO Collaboration, 2015. The LAGO space weather program: directional geomagnetic effects, background fluence calculations and multi-spectral data analysis. In: Proceeding of Science, PoS(ICRC2015), 142. Available online <http://pos.sissa.it/archive/conferences/236/142/ICRC2015_142.pdf>.

Chang, O., González-Esparza, J.A., Mejia-Ambriz, J., 2016. IPS observations at 140 MHz to study solar wind speeds and density fluctuations by MEXART. Adv. Space Res. 57, 1307–1313. http://dx.doi.org/10.1016/j.asr.2015.12.023.

Commins, R., Janssen, V., 2012. Improving GNSS CORS design: the CORSnet-NSW adjustable antenna mount (CAAM). J. Global Positioning Syst. 11 (2), 109–115. http://dx.doi.org/10.5081/jgps.11.2.109.

Costa, J.E.R., Válio, A., de Castro, C.G.G., Simões, P.J.A., Bertoni, F., Raulin, J.P., Andrei, A., Penna, J., Sawant, H.S., Rosa, R.R., Cecatto, J.R., Fernandez, F.C.R., Selhorst, C.L., 2010. Sobre o futuro da física solar no Brasil (in English: On the future of solar physics in Brazil). Available online <http://www.sab-astro.org.br/CEA>.

Costa, S.M.A., de Almeida Lima, M.A., de Moura Jr, N.J., Abreu, M.A., da Silva, A.L., Souto Fortes, L.P., Ramos, A.M., 2012. RBMC in real time via NTRIP and its benefits in RTK and DGPS surveys. Geodesy for Planet Earth, International Association of Geodesy Symposia, vol. 136. Springer-Verlag, Berlin Heidelberg, pp. 917–922. http://dx.doi.org/10.1007/978-3-642-20338-1-115.

Dasso, S., Asorey, H., for the Pierre Auger Collaboration, 2012. The scaler mode in the Pierre Auger Observatory to study heliospheric modulation of cosmic rays. Adv. Space Res. 49, 1563–1569. http://dx.doi.org/10.1016/j.asr.2011.12.028.

Denardini, C.M., Rockenbach, M., Gende, M.A., Chen, S.S., Fagundes, P.R., Schuch, N.J., Petry, A., Resende, L.C.A., Moro, J., Padilha, A.L., Sant'Anna, N., Ribeiro, L.A., 2015. The initial steps for developing the South American K index from the embrace magnetometer network. Braz. Geophys. J. 33 (1), 79–88.

Detrick, D.L., Lutz, L.F., 1990. The 16-beam phased-array radio wave imager for studies of cosmic noise absorption at U.S. AGO sites. Antarct. J. – Rev. 1994, 354–355.

Detrick, D.L., Rosenberg, T.J., 1988. IRIS: an imaging riometer for ionospheric studies. Antarct. J. U.S. 23 (5), 196–198.

Elias, L.A.R., Berbert, C.O., Janot, E., Bica, E.L.D., Oliveira Fl, K.S., Barbuy, B.L.S., Novello, M., Miranda, O.D., Bruch, A.J.R., Silva, D.F., de La Reza, J.R., 2010. Plano Nacional de Astronomia (in English: National Plan for Astronomy). Available online <http://www.sab-astro.org.br/CEA>.

Forbush, S.E., 1957. Solar influences on cosmic rays. Proc. Nat. Acad. Sci. U.S.A. 43 (1), 28–41. http://dx.doi.org/10.1073/pnas.43.1.28.

Forbush, S.E., Gill, P.S., Vallarta, M.S., 1949. On the mechanism of sudden increase of cosmic radiation associated to solar flare. Rev. Mod. Phys. 21, 44–48.

Fortes, L.P.S., Costa, S.M.A., Abreu, M.A., Silva, A.L., Júnior, N.J.M, Barbosa, K., Gomes, E., Monico, J.G., Santos, M.C., Tétreault, P., 2012. Modernization and new services of the Brazilian active control network. Geodesy for Planet Earth, International Association of Geodesy Symposia, vol. 136. Springer-Verlag, Berlin Heidelberg, pp. 967–972. http://dx.doi.org/10.1007/978-3-642-20338-1-121.

Gamboa, A., 1999. Brazilian Rocket Destroyed in Flight. Agence France-Presse: newscast of December 15th, Rio de Janeiro, December 11th.

Gianibelli, J.C., Quaglino, N., Gil, M.I., Nollas, F., Ruiz, F., Gimenez, M., Ochoa, H., 2013. La Red de Observatorios Magnéticos Permenentes (OMP) de la República Argentina (in English: The Network of Permanent Magnetic Observatory (OMP) of Argentina). Latinmag Lett. 3 (OA01), 1–5.

Grant, R.A., Raulin, J.-P., Freund, F.T., 2015. Changes in animal activity prior to a major (M = 7) earthquake in the Peruvian andes. Phys. Chem. Earth, Parts A/B/C 85-86, 69–77. http://dx.doi.org/10.1016/j.pce.2015.02.012.

Hanson, E.J., 1973. Review on the oil and the mexican revolution. J. Econ. Hist. 33 (4), 902–903.

Hayakawa, M., Raulin, J.P., Kasahara, Y., Bertoni, F.C.P., Hobara, Y., Guevara-Day, W., 2011. Ionospheric perturbations in possible association with the 2010 Haiti earthquake, as based on medium-distance subionospheric VLF propagation data. Natural Hazards Earth Syst. Sci. 11 (2), 513–518. http://dx.doi.org/10.5194/nhess-11-513-2011.

INVAP Investigaciones Aplicadas (in English: Applied Research), 2015. Available online <http://www.invap.com.ar/es/la-empresa/multimedia/linea-de-tiempo.html>.

Kaufmann, P., Costa, J.E.R., Gimnez de Castro, C.G., Hadano, R., Kingsley, J.S., Kingsley, R.K., Levato, H., Marun, A., Raulin, J.P., Rovira, M., Correia, E., Silva, A.V.R., 2001. The new submillimeter-wave solar telescope. In: Proc. of the SBMO/IEEE MTT-S International Microwave and Optoelectronics Conference, pp. 439–441. http://dx.doi.org/10.1109/SBMOMO.2001.1008800.

Medeiros, A.F., Taylor, M.J., Takahashi, H., Batista, P.P., Gobbi, D., 2001. An unusual airglow wave event observed at Cachoeira Paulista 23 degree S. Adv. Space Res. 27 (10), 1749–1754.

Mejia-Ambriz, J.C., Villanueva-Hernandez, P., González-Esparza, J.A., Aguilar-Rodriguez, E., Jeyakumar, S., 2010. Observations of interplanetary scintillation (IPS) using the mexican array radio telescope (MEXART). Sol. Phys. 265 (1–2), 309–320.

Mendonça, F. de, 1965. Ionospheric electron content measurements in regions of low magnetic dip and through the Brazilian Magnetic Anomaly. Space Research V, Proceedings of the Fifth Int. Space Science Symposium, Florence, May 12-16. North Holland, Amsterdam, 687-701.

Monico, J.F.G., De Franceschi, G., Bougard, B., Aquino, M., Soley, M., 2012. Cigala: a FP7 innovative activity to tackle the threat of ionospheric scintillation to gnss operations in Latin América. Revista Brasileira de Cartografia, 1808-0936 64 (6), 767–779, Sociedade Brasileira de Cartografia, Geodésia, Fotogrametria e Sensoriamento Remoto.

Moro, J., Denardini, C.M., Abdu, M.A., Correia, E., Schuch, N.J., Makita, K., 2012a. Latitudinal dependence of cosmic noise absorption in the ionosphere over the SAMA region during the September 2008 magnetic storm. J. Geophys. Res. 117, A06311. http://dx.doi.org/10.1029/2011ja017405.

Moro, J., Denardini, C.M., Abdu, M.A., Correia, E., Schuch, N.J., Makita, K., 2012b. A comparison of two different techniques for deriving the quiet day curve from SARINET riometer data. Annales Geophysicae (Berlin) 30, 1159–1168.

Munakata, K., Bieber, J.W., Yasue, S., Kato, C., Koyama, M., Akahane, S., Fujimoto, K., Fujii, Z., Humble, J.E., Duldig, M.L., 2000. Precursors of geomagnetic storms observed by the muon detector network. J. Geophys. Res. 105 (A12), 27457–27468. http://dx.doi.org/10.1029/2000ja000064.

Otsuka, Y., Ogawa, T., Saito, A., Tsugawa, T., Fukao, S., Miyazaki, S., 2002. A new technique for mapping of total electron content using GPS network. Earth Planets Space 54 (1), 63–70.

Pacini, A.A., Raulin, J.-P., 2006. Solar X-ray flares and ionospheric sudden phase anomalies relationship: a solar cycle phase dependence. J. Geophys. Res.- Space Phys. 111 (A9). http://dx.doi.org/10.1029/2006ja011613.

Raulin, J.-P., Bertoni, F.C.P., Gavilán, H.R., Guevara-Day, W., Rodriguez, R., Fernandez, G., Correia, E., Kaufmann, P., Pacini, A. A., Stekel, Tardelli R.C., Lima, W.L.C., Schuch, N.J., Fagundes, P.R., Hadano, R., 2010. Solar flare detection sensitivity using the South America VLF network (SAVNET). J. Geophys. Res.-Space Phys. 115 (A7). http://dx.doi.org/10.1029/2009ja015154.

Raulin, J.-P., David, P., Hadano, R., Saraiva, A.C., Correia, E., Kaufmann, P., 2009. The South America VLF Network (SAVNET). Earth Moon Planet 104 (1–4), 247–261. http://dx.doi.org/10.1007/s11038-008-9269-4.

Raulin, J.-P., Pacini, A.A., Kaufmann, P., Correia, E., Aparecida, G., Martinez, M., 2006. On the detectability of solar S-ray flares using very low frequency sudden phase anomalies. J. Atmos. Solar Terr. Phys. 68 (9), 1029–1035. http://dx.doi.org/10.1016/j.jastp.2005.11.004.

Raulin, J.-P., Trottet, G., Giménez De Castro, C.G., Correia, E., Macotela, E.L., 2014. Nighttime sensitivity of ionospheric VLF measurements to X-ray bursts from a remote cosmic source. J. Geophys. Res.-Space Phys. 119 (6), 4758–4766. http://dx.doi.org/10.1002/2013ja019670.

Reisin, E.R., Scheer, J., Dyrland, M.E., Sigernes, F., Deehr, C.S., Schmidt, C., Höppner, K., Bittner, M., Ammosov, P.P., Gavrilyeva, G.A., Stegman, J., Perminov, V.I., Semenov, A.I., Knieling, P., Koppmann, R., Shiokawa, K., Lowe, R.P., López-González, M.J., Rodríguez, E., Zhao, Y., Taylor, M.J., Buriti, R.A., Espy, P.J., French, W.J.R., Eichmann, K.-U., Burrows, J.P., von Savigny, C., 2014. Traveling planetary wave activity from mesopause region airglow temperatures determined by the Network for the Detection of Mesospheric Change (NDMC). J. Atmos. Solar Terr. Phys. 119, 71–82. http://dx.doi.org/10.1016/j.jastp.2014.07.002.

Resende, L.C.A., Denardini, C.M., Batista, I.S., 2013. Abnormal fbEs enhancements in equatorial Es layers during magnetic storms of solar cycle 23. J. Atmos. Solar Terr. Phys. 102, 228–234. http://dx.doi.org/10.1016/j.jastp.2013.05.020.

Resende, L.C.A., 2010. Estudo do comportamento dos parâmetros de frequência das camadas Es na região equatorial durante períodos perturbados (in English: Study of the behavior of the frequency parameters of Es layers in the equatorial region during storm time), p. 172. MSc Dissertation (Space Geophysics), São José dos Campos, Brasil. Available online <http://urlib.net/sid.inpe.br>.

Resende, L.C.A., 2014. Estudo sobre a formação e dominância das camadas E-esporádicas considerando a competição entre ventos e campos elétricos (in English: Study of the formation and dominance of the layers E-sporadic considering the competition between winds and electric fields)., p. 217. PhD Thesis (Space Geophysics), São José dos Campos, Brasil. Available online <http://urlib.net/sid.inpe.br>.

Resende, L.C.A., Denardini, C.M., 2012. Equatorial sporadic E-layer abnormal density enhancement during the recovery phase of the December 2006 magnetic storm: A case study. Earth Planets Space 64, 345–351.

Rippy, M., 1972. Oil and the Mexican Revolution. Ed. Leiden: E.J. Brill (Ed.), 345p

Rocha, F.C.W., 2004. Acidente com o Veículo Lançador de Satélites (VLS-1 V03) no Centro de Lançamentos de Alcântara (in English: Accident with the Satellite Launch Vehicle (VLS-1 V03) at the Alcantara Launch Center). Report prepared for the Brazilian Chamber of Representatives. Retrieved October 7th. Available online <http://bit.ly/226XCHE>.

Rockenbach, M., Dal Lago, A., Schuch, N.J., Munakata, K., Kuwabara, T., Oliveira, A.G., Echer, E., Braga, C.R., Mendonça, R.R.S., Kato, C., Kozai, M., Tokumaru, M., Bieber, J.W., Evenson, P., Duldig, M. L., Humble, J.E., Al Jassar, H.K., Sharma, M.M., Sabbah, I., 2014. Global muon detector network used for space weather applications. Space Sci. Rev. http://dx.doi.org/10.1007/s11214-014-0048-4.

Rockenbach, M., Dal Lago, A., Gonzalez, W.D., Munakata, K., Kato, C., Kuwabara, T., Bieber, J., Schuch, N.J., Duldig, M.L., Humble, J. E., Al Jassar, H.K., Sharma, M.M., Sabbah, I., 2011. Geomagnetic storm's precursors observed from 2001 to 2007 with the global muon detector network (GMDN). Geophys. Res. Lett. 38, l16108. http://dx.doi.org/10.1029/2011gl048556.

Romero-Hernandez, E., González- Esparza, J.A., Aguilar-Rodriguez, E., Ontiveros-Hernandez, V., Villanueva-Hernandez, P., 2015. Detection of solar wind disturbances: Mexican array radio telescope IPS observations at 140 MHz. Sol. Phys. 2553–2566. http://dx.doi.org/10.1007/s11207-015-0690-3.

Samanes, J.E., Raulin, J.-P., Macotela, E.L., Guevara Day, W.R., 2015. Estimating the VLF modal interference distance using the South America VLF Network (Savnet). Radio Sci. 50 (2), 122–129. http://dx.doi.org/10.1002/2014rs005582.

Savian, J.F., Da Silva, M.R., Dal Lago, A., Echer, E., Vieira, L.E.A., Munakata, K., Gonzalez, W.D., Schuch, N.J., 2007. Forbush decreases on November 6–12, 2004 observed by the muon detector network. Braz. Geophys. J. 25 (2). http://dx.doi.org/10.1590/S0102-261X2007000600020, São Paulo.

Scheer, J., Reisin, E.R., 2001. Refinements of a classical technique of airglow spectroscopy. Adv. Space Res. 27 (6–7), 1153–1158.

Schrijver, C.J., Kauristie, K., Aylward, A.D., Denardini, C.M., Gibson, S. E., Glover, A., Gopalswamy, N., Grande, M., Hapgood, M., Heynderickx, D., Jakowski, N., Kalegaev, V.V., Lapenta, G., Linker, J.A., Liu, S., Mandrini, C.H., Mann, I.R., Nagatsuma, T., Nandy, D., Obara, T., O'Brien, T.P., Onsager, T., Opgenoorth, H.J., Terkildsen, M., Valladares, C.E., Vilmer, N., 2015. Understanding space weather to shield society: a global road map for 2015–2025 commissioned by COSPAR and ILWS. Adv. Space Res. 55 (12), 2745–2807. http://dx.doi.org/10.1016/j.asr.2015.03.023.

Schuch, N.J., Durao, O.S.C., Loureiro, G., Pimenta, A.A., Mendes, O., Jr, Trivedi, N.B., Gomes, N.G., Martins, J.B.S., Stekel, T.R.C, Costa, L.L., Burger, E.E., Bohrer, R.Z.G., 2012. Progress in the Brazilian INPE-UFSM NANOSATC-BR Cubesat Program. In: Proceedings of the 63rd IAC (International Astronautical Congress), Naples, Italy, Oct. 1-5, paper: IAC-12.B4.1.5, Available online <http://toc.proceedings.com/17524webtoc.pdf>.

Sousa, F., 2007. Desenvolvimento de satélites e plataformas espaciais no INPE no período 1961-2007 (in English: Development of satellites and space platforms at INPE in the period 1961-2007). PhD Thesis (Space Geophysics), São José dos Campos, Brasil. Available online <http://urlib.net/sid.inpe.br>.

Takahashi, H., Clemesha, B.R., Simonich, D.M., Melo, S.M.L., Teixeira, N.R., Eras, A., 1996. Rocket measurements of the equatorial airglow: Multifot 92 database. J. Atmos. Solar Terr. Phys. 58 (16), 1943–1961.

Takahashi, H., Costa, S., Otsuka, Y., Shiokawa, K., Monico, J.F.G., Paula, E., Nogueira, P., Denardini, C.M., Becker-Guedes, F., Wrasse, C.M., Ivo, A.S., Gomes, V.C.F., Gargarela Jr., W., Sant'Anna, N., Gatto., R., 2010. Diagnostics of equatorial and low latitude ionosphere by TEC mapping over Brazil. Adv. Space Res. 54, 385–394.

Tanaka, Y.T., Raulin, J.P., Bertoni, F.C.P., Fagundes, P.R., Chau, J., Schuch, N.J., Hayakawa, M., Hobara, Y., Terasawa, T., Takahashi, T., 2010. First very low frequency detection of short repeated bursts from magnetar sgr j1550–5418. Astrophys. J. Lett. 721 (1), L24–l27. http://dx.doi.org/10.1088/2041-8205/721/1/l24.

The Pierre Auger Collaboration, 2015. The pierre auger cosmic ray observatory. Nucl. Instrum. Methods Phys. Res. A 798 (21), 172–213. http://dx.doi.org/10.1016/j.nima.2015.06.058.

Veliz, O., 2010. Manual Operación: JRO-ML-103 Triaxial Magnetometer (in English: Operation Manual: JRO-ML-103 Triaxial Magnetometer). Jicamarca Radio Observatory.