The Antarctic Seismographic Argentinean Italian Network (ASAIN): Recording Earthquakes in the Scotia Sea Region

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Abstract

The Antarctic Seismographic Argentinean Italian Network (ASAIN) is a permanent broadband seismic network that has operated since 1995 in the Scotia Sea region, the Antarctic peninsula, and the polar area. It was deployed and is managed in the framework of cooperation between the National Institute of Oceanography and Applied Geophysics and Dirección Nacional del Antártico–Instituto Antártico Argentino and is financially supported by the Programma Nazionale di Ricerca in Antartide. The network consists of seven seismological stations with broadband sensors. ASAIN provides data to Incorporated Research Institutions for Seismology, Observatories and Research Facilities for European Seismology, and GEOFOrschungsNetz. It improves the worldwide seismic networks' detection capabilities and contributes to refining regional earthquake locations released by the U.S. Geological Survey. The proximity of the seismic stations to the Antarctic continent and their continuous operation in the long term also allows for having a privileged observatory on the ice-related seismicity along the Antarctica peninsula.

In this article, we discuss the historical development of ASAIN, its current configuration, and the main characteristics of the seismic stations. Finally, we also provide information on the ASAIN data exchange and the contribution to the scientific research in Antarctica.

Introduction

The Scotia Sea region (Fig. 1) is formed by the southernmost part of South America (Patagonia and Tierra del Fuego), the Antarctic peninsula, and the oceanic region surrounded by the islands and ridges of the Scotia arc. It is a complex tectonic area, characterized by numerous active processes and changes in the movement and configuration of the plates. In the Scotia Sea region, two small plates, the Scotia and Sandwich plates, are located between the South American and Antarctic plates. Bird (2003) identified a possible small third plate, the Shetland plate. Their boundaries, highlighted by the distribution of the epicenters (Vuan *et al.*, 2014), lie mostly along the Scotia arc. The plate motions (Smalley *et al.*, 2007) are mainly along the east–west direction. The seismicity is mainly due to the subduction of the South Atlantic oceanic crust below the South Sandwich plate (Vuan *et al.*, 2014). Different studies (e.g., Dalziel *et al.*, 2013) have investigated the main tectonics characteristics of the Scotia Sea and its evolution, but some details of the interactions and the geometry of the plates and of their relative movement remain uncertain (Vuan *et al.*, 2014). In this sense, the assessment of the main lithospheric features and the study of the earthquakes' focal mechanisms play an important role in understanding the tectonic history of the area. These studies can only be carried out if the analysis of waveforms recorded by a regional seismic network is possible.

Unfortunately, no permanent broadband land stations were operating in the Scotia Sea region before 1992, and only a few temporary installations of sea-bottom seismographs have been carried out (e.g., Robertson Maurice *et al.*, 2003). However, since then, national Italian and Argentinian Antarctic programs focused on installing a broadband regional network capable of monitoring the seismicity in real time and providing the seismological database necessary for improving the geodynamic and seismological knowledge of the area. Furthermore, the recordings of the seismological broadband

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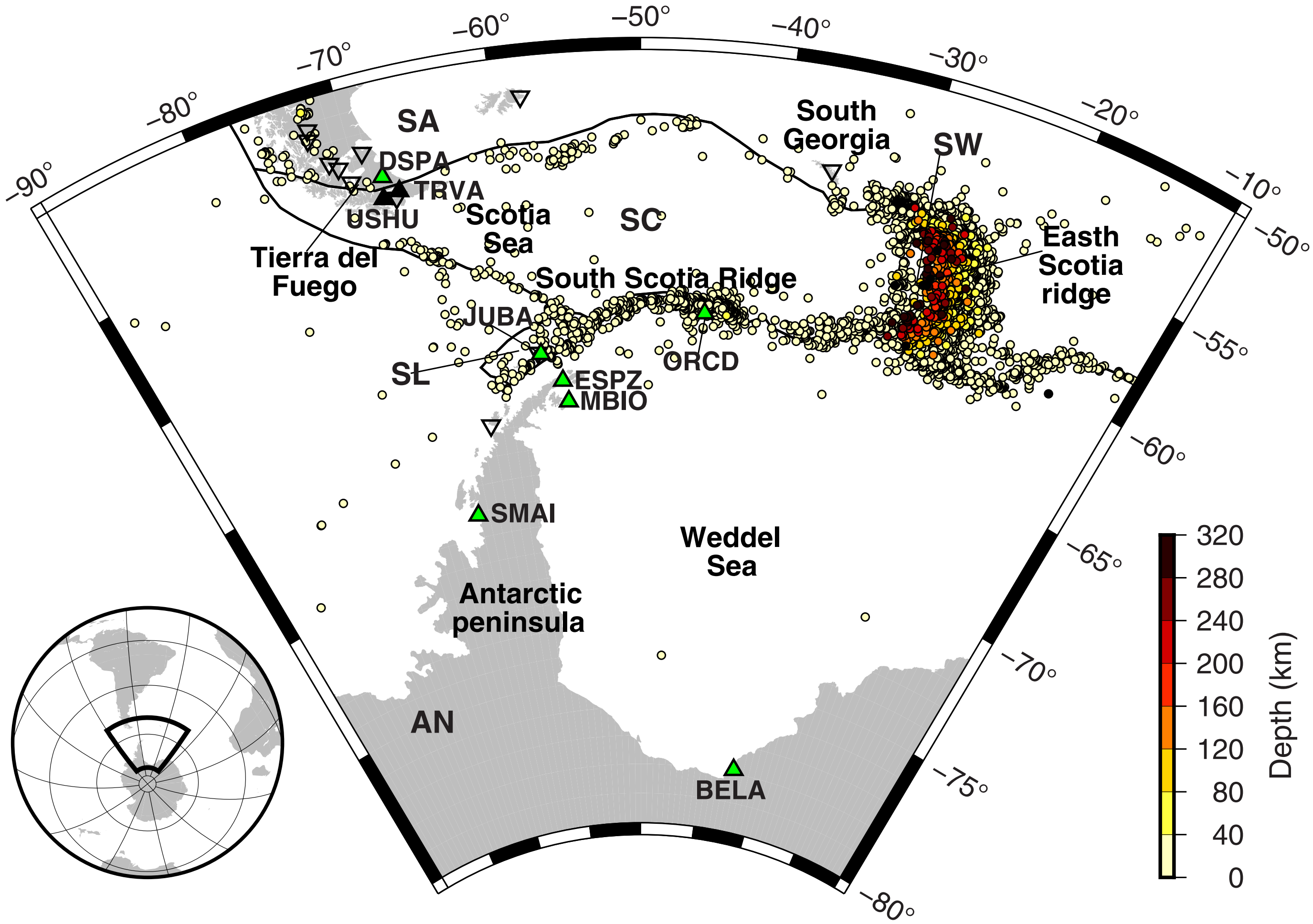

network improved the spatial coverage of seismic stations, therefore supporting also global seismology studies. In particular, in the framework of cooperation between the National Institute of Oceanography and Applied Geophysics (OGS) and Dirección Nacional del Antártico (DNA)–Instituto Antártico Argentino (IAA), with financial support by the Programma Nazionale di Ricerca in Antartide (PNRA), seven land stations have been installed, forming the Antarctic Seismographic Argentinean Italian Network (ASAIN) that operates in the Scotia Sea region, the Antarctic peninsula, and the polar area (see Table 1 and Fig. 1).

In the following, we will briefly summarize the development of ASAIN, its current configuration, and the main characteristics of the existing stations. Finally, we will provide information on the data exchange and the contribution to the scientific research of the ASAIN data.

Figure 1. Antarctic Seismographic Argentinean Italian Network (ASAIN) stations locations: Black triangles represent former ASAIN stations, light-color triangles represent ASAIN stations, inverted empty triangles represent stations of other permanent networks (see Data and Resources). Colored circles indicate the seismicity and depth in the area from 1970 to September 2018 from the International Seismological Centre (ISC) revised bulletin (International Seismological Centre [ISC], 2020). Black lines are the boundaries between plates according to Bird (2003). The inset map shows the position of the involved area on the globe. AN, Antarctica plate; SA, South America plate; , SC, Scotia plate; SL, Shetland plate; SW, Sandwich plate. The color version of this figure is available only in the electronic edition.

Network Development

The development of ASAIN started in 1992 with the installation of the Esperanza seismic station (ESPZ) located in the Argentinean Esperanza Base, which became a permanent seismological observatory at the beginning of 1995. Table 1 summarizes the positions of the stations and changes in the instrumentation over time.

Because a detailed description of the network development from 1992 to 2009 is reported in Russi *et al.* (2010), in this article, we only briefly describe the main modifications that occurred to the network in that period. In particular, it is worth mentioning that, between 1995 and 2001, four new seismic stations were installed, namely Ushuaia (USHU, located at Lapataia bay, Tierra del Fuego, Argentina), Orcadas Base (ORCD, located at the Orcadas Permanent Argentinean Antarctic Base, on the Laurie Island on the Laurie Island—South Orkney Islands), Jubany (JUBA, located at the Carlini Argentinean Antarctic

TABLE 1
Antarctic Seismographic Argentinean Italian Network (ASAIN). Network Station Coordinates and Instrumental Characteristics Chronology

Station	Latitude (°)	Longitude (°)	Height (m.a.s.l.)	Operation Dates	Instrumentation	Channels
BELA	−77.8750	−34.6269	262	2009–2011	CMG-3ESPCD, CMG-DM24, timing GPS	Vertical, north–south, and east–west continuous 2, 20, and 40 samples per second
				2012–present	CMG-3T polar type, CMG DM24, and timing GPS	Vertical, north–south, and east–west continuous 2, 20, and 100 samples per second
DSPA	−53.9536	−68.2668	150.7	2002–present	CMG-3T, CMG-DM24, and timing GPS	Vertical, north–south, and east–west continuous 2, 20, and 40 samples per second
ESPZ	−63.3981	−56.9964	31	1992–1994	BB13, PDAS-100, and timing radio	Vertical, north–south, and east–west continuous 0.2 and 2 samples per second
				1995–2000	CMG-3T, RefTek-72A-08, and timing GPS	Vertical, north–south, and east–west continuous 1 and 20 samples per second
				2001–2002	CMG-3T, CMG-DM24, and timing GPS	Vertical, north–south, and east–west continuous 1 and 20 samples per second
				2005–2011	CMG-3TD, CMG-DM24, and timing GPS	Vertical, north–south, and east–west continuous 2, 20, and 40 samples per second
				2012–present	CMG-3TD, CMG-DM24, and timing GPS	Vertical, north–south, and east–west continuous 2, 20, and 100 samples per second
JUBA	−62.2373	−58.6627	16	2002–2011	CMG-3T, CMG-DM24, and timing GPS	Vertical, north–south, and east–west continuous 2, 20, and 40 samples per second
				2011–present	CMG-3T, CMG-DM24, and timing GPS	Vertical, north–south, and east–west continuous 2, 20, and 100 samples per second
MBIO	−64.2405	−56.6227	215	2014–present	CMG-3ESPCD, CMG-DM24, and timing GPS	Vertical, north–south, and east–west continuous 2,20, and 100 samples per second
ORCD	−60.7381	−44.7361	20	1997–2004	CMG-3T, RefTek-72A-08, and timing GPS	Vertical, north–south, and east–west continuous 1 and 20 samples per second
				2004–2011	CMG-3T, CMG-DM24, and timing GPS	Vertical, north–south, and east–west continuous 2, 20, and 40 samples per second
				2012–present	CMG-3T, CMG-DM24, and timing GPS	Vertical, north–south, and east–west continuous 2, 20, and 100 samples per second
SMAI	−68.1302	−67.1059	9	2007–2012	CMG-3T, CMG-DM24, and timing GPS	Vertical, north–south, and east–west continuous 2, 20, and 40 samples per second
				2012–2020	CMG-3T, CMG-DM24, and timing GPS	Vertical, north–south, and east–west continuous 2, 20, and 100 samples per second
				2020–present	CMG-3T polar type, CMG-DM24, and timing GPS	Vertical, north–south, and east–west continuous 2, 20, and 100 samples per second

Information regarding instrumentation before 2010 was taken from Russi *et al.* (2010). GPS, Global Positioning System; m.s.a.l., meters above sea level.

Base, South Shetland Islands), and the DSPA station (Estancia Despedida, Tierra del Fuego; Fig. 1). Successively, between 2002 and 2005, the instrumentation was upgraded and homogenized. Importantly, satellite communication channels linking the Antarctic bases with Argentina were activated, allowing for the Internet connection among the ASAIN stations, the OGS, and the DNA-IAA. Before that, the operator visited the stations weekly to back up the data (Febrer *et al.*, 2000).

At the end of 2005, the USHU station was dismissed, and the sensor was moved to Termas del Río Valdéz, where a new ASAIN station (TRVA) was installed. Between 2007 and the beginning of 2009, the ASAIN Tierra del Fuego sites

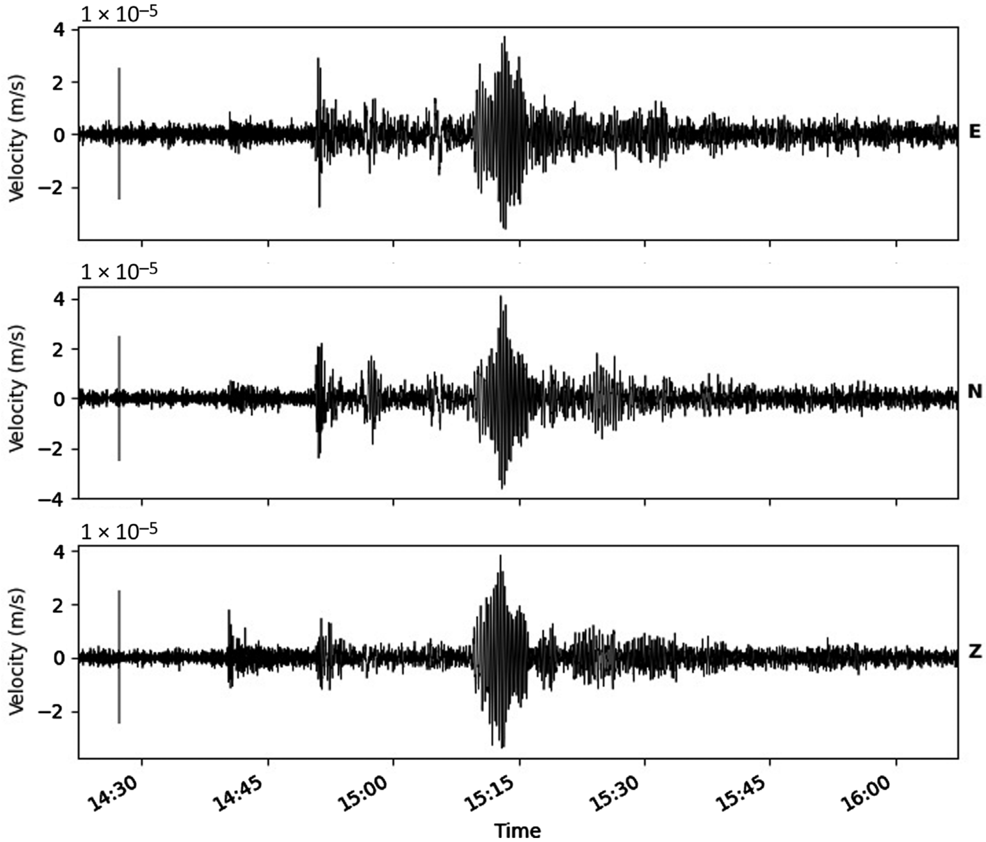

Figure 2. Seismograms of a teleseismic event recorded at MBIO: 18 April 2014 **M** 7.2 Guerrero, Mexico, 14:27:24 (UTC). Vertical gray line marks the origin time of the event. E, east–west component; N, north–south component; Z, vertical component.

(TRVA and DSPA) were connected in real time via radio transmission, and the network was further extended to latitudes beyond the Antarctic Polar Circle with two new stations: SMAI station at Base San Martín, on the Pacific side of the Antarctic peninsula, and BELA station, at the southeastern corner of the Weddell Sea. The main objectives of the installation of these new stations were to provide top-quality data to the global network from strategic locations still void of seismic stations, to improve the geographic coverage for the analysis of the moment tensor of earthquakes occurring along the South Scotia ridge and in the Drake Passage, and to increase the path coverage of regional tomography studies.

Since 2010, the TRVA station has been managed by Universidad Nacional de la Plata and is no longer a part of ASAIN. In 2012, the sensor at BELA was substituted with a CMG-3TD polar type. In 2014, the network was further extended thanks to the installation of the MBIO station in the Marambio permanent base in Seymour Island (Antarctic Peninsula).

As an example of the high quality of the recordings of ASAIN, Figure 2 shows a teleseismic event recorded by MBIO in its first period of activity. The station installation is still temporary, and it will be finalized as soon as a concrete plinth, where the sensor will be placed, is finished. The station will provide real-time data, and a new sensor will be installed to keep uniform the technical characteristics of the network.

It is worth mentioning that in 2014 extraordinary maintenance was carried out at the BELA station: a fiber-optic system was added to prevent static discharges. In the following years, other maintenance interventions were carried out: sensor substitution at ORCD (with a new sensor of the same type) in March 2017 and at SMAI at the beginning of 2020 and new plinth installation at JUBA (in 2018–2019) and ESPZ (2019–2020).

Network Configuration

At present, ASAIN consists of seven seismological stations with broadband sensors in Tierra del Fuego (DSPA), on the Scotia arc islands (JUBA and ORCD), in the Antarctic peninsula (SMAI, MBIO, and ESPZ), and at the southeastern corner of the Weddell Sea (BELA) (Fig. 1). The ones in the Scotia arc islands and in the northern part of the Antarctic peninsula (JUBA, ORCD, MBIO, and ESPZ) are the nearest to the most active areas in the region.

All of the stations (except DSPA) are hosted at Argentinean bases and, with the exception of BELA, are located in coastal regions (see Fig. 3). All of the stations are in insulated boxes and, except MBIO, are on bedrock (Table 2). The stations are equipped with Güralp sensors (CMG-3T in ORCD and JUBA, CMG-3ESPCD in MBIO, CMG-3TD in ESPZ and DSPA, and CMG-3TD polar-type BELA and SMAI) and digitizers (CMG-DM24). All stations (except DSPA and ESPZ) are now recording and transmitting three channels with 2, 20, and 100 samples per second. ESPZ records the same three channels, but it transmits in real time only the channels with 2 and 20 samples per second. DSPA still records three channels with 2, 20, and 40 samples per second because of limited bandwidth of the radio transmission. The geometry of the network, which is also constrained by logistic problems, nevertheless, allows for recording not only teleseismic data but also high-quality local

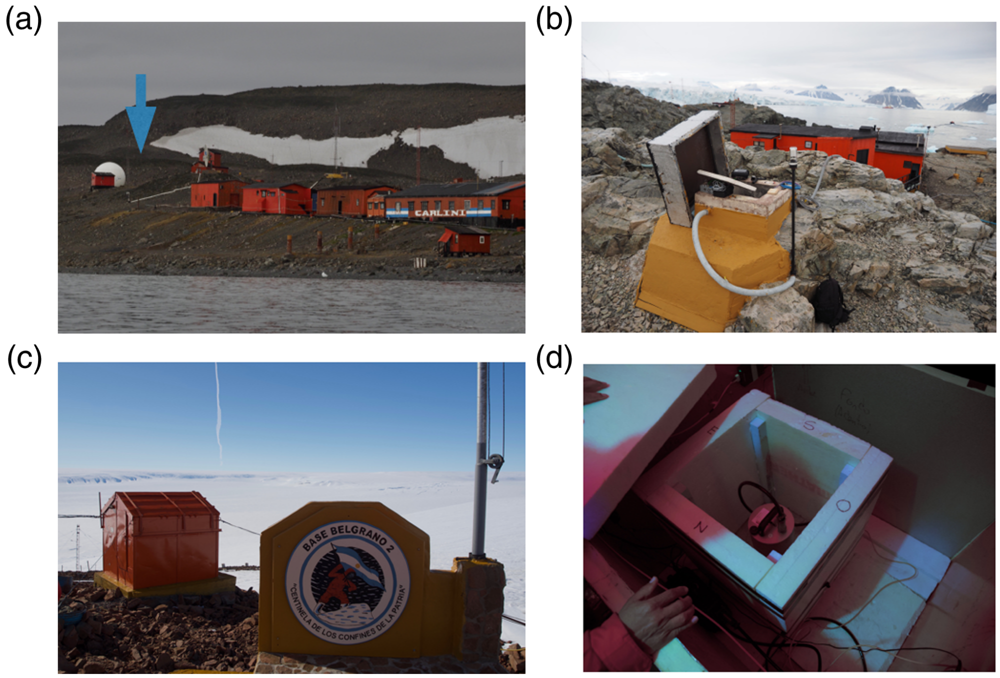

Figure 3. (a) Carlini base with position of the JUBA seismic station shown by the blue arrow; (b) SMAI seismic station; (c) BELA seismic station; (d) BELA seismic station, details of the sensor housing. The color version of this figure is available only in the electronic edition.

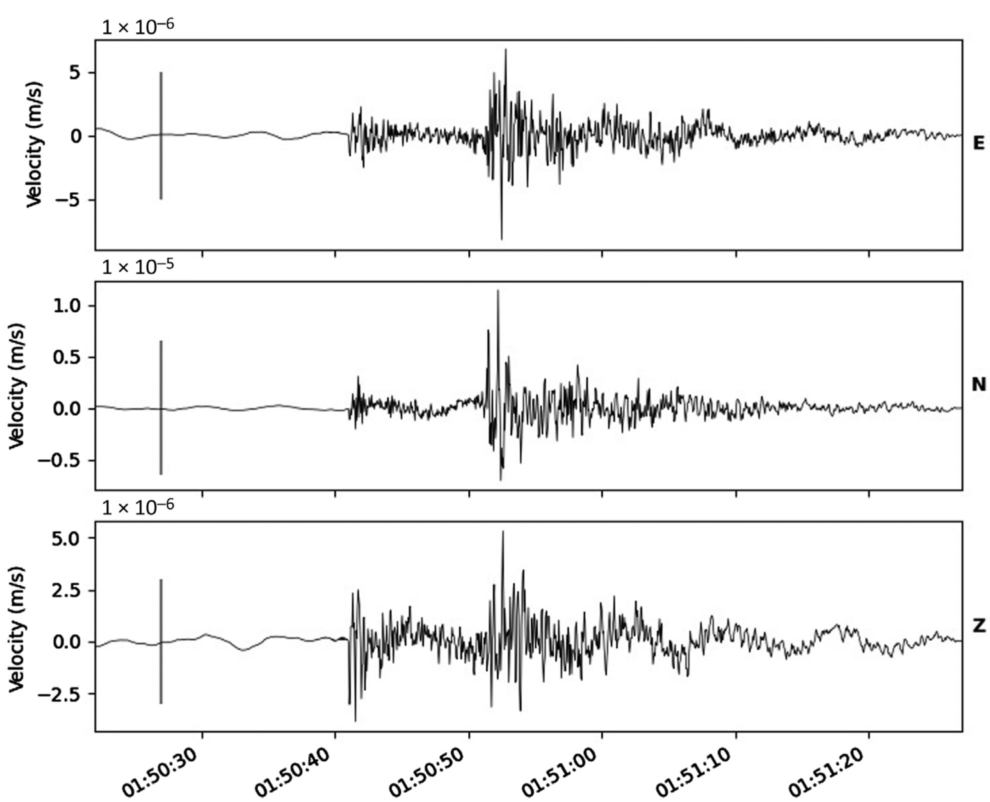

Figure 4. Seismograms of a local event recorded at the JUBA station: the 2 September 2014 in South Shetland Islands. The vertical gray line marks the origin time of the event.

earthquake data. Figure 4 shows an example of a local earthquake recorded by the JUBA station.

Data from the network are sent in real time by satellite transmission to local servers of OGS and DNA-IAA. The OGS local server is a Windows server that acquires the seismic data by Scream!, a Güralp software for first acquisition (see Data and Resources). Data on local servers are stored in original Güralp compressed format (GCF). The data are then streamed to a Güralp Network Appliance Module that converts it from GCF to miniSEED.

The network maintenance is made particularly difficult by environmental and accessibility conditions in the Scotia Sea and polar areas. During the winter, the seismic stations cannot be reached; therefore it is not possible to fix main malfunctioning of the instrumentation. The availability of Internet connections allows for controlling the efficiency of the stations and the parameter settings remotely by Scream!, the same software used for the acquisition of the seismic data. It is also possible to communicate with the Argentinean personnel taking care of the seismographs and to guide them to solve minor problems. Figure 5 shows the overall performance, during their operational period, of the seven ASAIN stations that are still active, in terms of data available on the OGS local server and from the Incorporated Research Institutions for Seismology (IRIS) service. The excellent continuity in data acquisition and transmission is remarkable.

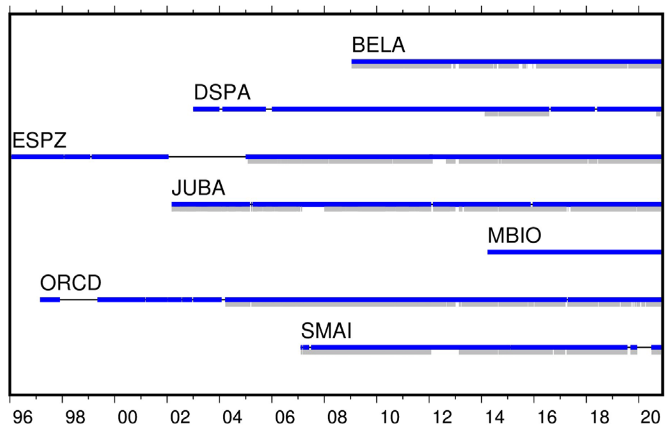

Figure 5. Overall performance of the ASAIN active stations since 1996. In blue, data available on National Institute of Oceanography and Applied Geophysics (OGS) server; in gray, data available from Incorporated Research Institutions for Seismology (IRIS) webservice (see Data and Resources). The color version of this figure is available only in the electronic edition.

Power Spectral Density (PSD) Characterization

To evaluate the quality of the recordings of the ASAIN stations, we calculated the noise PSD (e.g., Peterson, 1993) and its probability density function for each station of the network. We used the PPSD class of the ObsPy package (Beyreuther *et al.*, 2010; Megies *et al.*, 2011), which is based on the procedure described in McNamara and Buland (2004). Following this approach, transient signals (e.g., earthquakes) have not been removed because, due to their low probability of occurrences over the total time span considered, they do not affect significantly the results obtained by analyzing the stationary background ambient noise. We analyzed recordings from 2013 (installation date for MBIO) to 2019, subdivided in 1 hr time segments overlapping by 50%. We remark that the ORCD station shows a significant change in noise level after the substitution of the sensor in 2017; therefore, for sake of homogeneity, we considered only data starting from April 2017.

The PSD of each station versus the standard new low-noise model and new high-noise model (NHNM; Peterson, 1993) is depicted in Figure 6. The figure shows the median PSD for each component of each station. Furthermore, we also evaluate the seasonality in the noise level by computing the median of the PSD for summer (from November to January) and winter (from May to July) separately to highlight possible seasonal variation of noise amplitude.

The BELA station shows the lowest values of PSD at all considered periods; this is probably due to the presence of the Filchner–Ronne Ice Shelf that protects the area from noise all year. DSPA has the highest mean values of PSD, greater than NHNM for horizontal components at long periods (from 10 to 100 s). The remaining stations (all located in the Scotia arc islands and Antarctic peninsula) show medium to high noise levels, in particular at periods from 1 to 10 s (microseismic band). This is related to the stations being located in proximity to the ocean. As observed by Anthony *et al.* (2015), the high-broadband noise levels of the Antarctic peninsula with respect to the rest of Antarctica are primarily due to the high winds and the turbulent seas in the area, accentuated by the narrowness of the peninsula and station proximities to the coast. The same argument can be applied to the Scotia Sea Islands. The noise at short periods also has an anthropogenic source because of the location of the seismic stations inside the bases.

The noise of horizontal components of all stations is greater than the vertical one for periods longer than 10 s, probably because of tilt-coupled horizontal noise (e.g., Anthony *et al.*, 2015). The stations show the highest level of noise in summer. As observed by Anthony *et al.* (2015), the noise level in Antarctica is strongly affected by the annual growth and decay of sea ice around the continent, with a maximum during the

TABLE 2
Antarctic Seismographic Argentinean Italian Network (ASAIN) Network Station Installation Features

Station	Building	Plinth	Bedrock	Notes
BELA	In wooden hut polystyrene insulation	Concrete	Yes	
DSPA	Brick container and polystyrene	Concrete	Yes	
ESPZ	In wooden shelter, wood box, and polystyrene insulation	Concrete	Yes	It will soon be moved away from anthropogenic noise
JUBA	Concrete container and polystyrene insulation	Concrete	Yes	
MBIO	In fiberglass box, wood, and polystyrene box	Steel and crystal	No	Sensor on steel pole planted in the permafrost layer; it will soon be moved to a new pit just nearby
ORCD	Concrete hut and polystyrene insulation	Concrete	Yes	
SMAI	Concrete container and polystyrene insulation	Concrete	Yes	

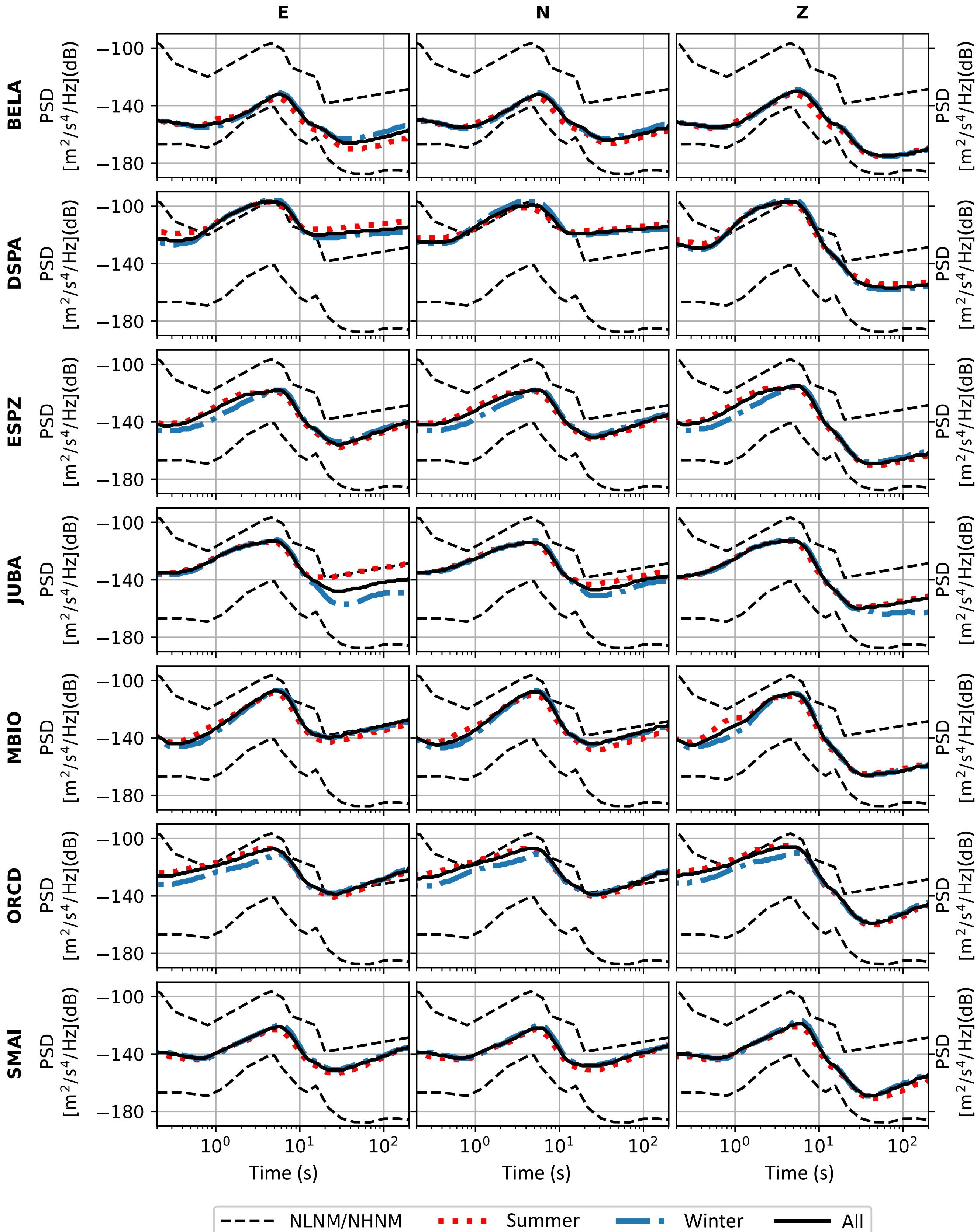

Figure 6. Median power spectral density (PSD) of the three components of each station compared with the standard new low-noise model (NLNM) and new high-noise model (NHNM), computed for the whole dataset and separately for summer (from November to January) and winter (from May to August). The color version of this figure is available only in the electronic edition.

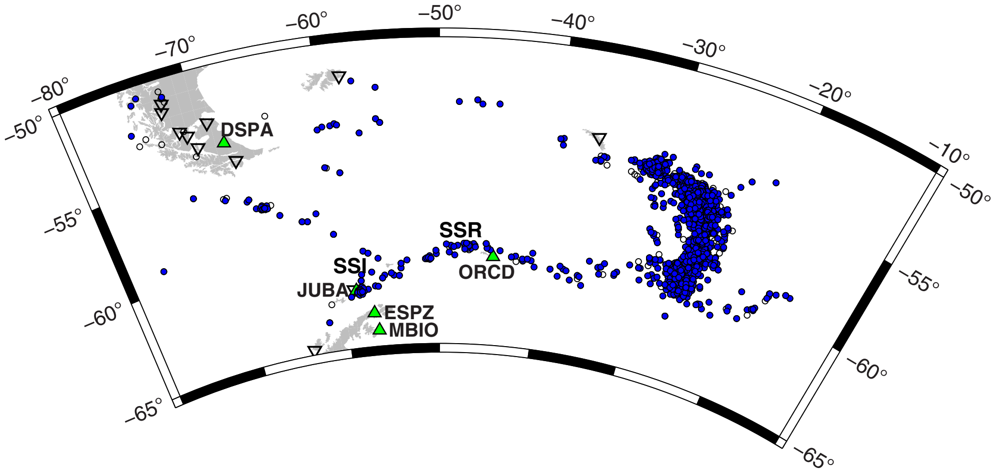

Figure 7. Events localized by the U.S. Geological Survey (USGS) from 2015 to 2020 in the Scotia Sea region. Filled dots represent events localized using phases from ASAIN stations, empty dots represent events localized without phases from ASAIN stations, filled triangles represent active ASAIN stations, and empty inverted triangles represent stations of other permanent networks (see Data and Resources). SSI, South Shetland Islands; SSR, South Scotia ridge. The color version of this figure is available only in the electronic edition.

sea ice minimum (in summer). The ESPZ, MBIO, and ORCD stations are mainly affected by seasonal variations in the period band lower than 0.5 s, whereas DSPA and especially JUBA are mainly affected at periods greater than 10 s.

Data Distribution and Contribution to Scientific Research of the ASAIN Data

The network code assigned by the International Federation of Digital Seismograph Networks to identify ASAIN is AI (see Data and Resources). The waveforms, available in miniSEED format, are sent from the OGS local server to IRIS and Observatories and Research Facilities for European Seismology (ORFEUS), and from there, they are provided to GEOFOr schungsNetz (GEOFON). The real-time waveforms of the ASAIN stations are therefore immediately freely accessible from the IRIS and the ORFEUS services. If required, the data can be provided in different formats (e.g., Seismic Analysis Code format) and samplings on request to the first author.

The amount of ASAIN data downloaded from IRIS shows the importance of the data collected by ASAIN in such a remote area. In 2019, the largest amount of data was downloaded from the United States and China (more than 100 GB), followed by India, Italy, Chile, Germany, Spain, Panama, and Nicaragua (1–100 GB). This data improves the detection capabilities of the worldwide seismic networks and contributes to refining regional earthquake locations released by the U.S. Geological Survey (USGS). The seismic phases recorded by the ASAIN stations are systematically used by the USGS starting from the second half of 2014, and they are the nearest stations used to localize earthquakes in South Shetland and the South Scotia ridge (Fig. 7) (see Data and Resources).

The ASAIN data improved the knowledge of the complex lithospheric structure in the Scotia Sea region. Initially, Russi *et al.* (1996, 1997) and Vuan *et al.* (1997, 1999) applied the inversion of surface-wave dispersion properties to the area. Later, taking advantage of the increased number of stations available, Vuan *et al.* (2000, 2014) and Vuan, Maurice, *et al.* (2005) investigated the crustal- and upper-mantle structure of the area by Rayleigh and Love earthquake surface-wave tomography. Park *et al.* (2012) investigated the upper-mantle structure below the northern Antarctic peninsula by modeling *P*-wave travel-time residuals from teleseismic events recorded by broadband stations of ASAIN and other networks in the area. The analysis of receiver functions for the area was carried out by Vuan (2001) and Biryol *et al.* (2018) and for the Tierra del Fuego by Buffoni *et al.* (2019). Shen *et al.* (2018) constructed a seismic model for the crust and the uppermost mantle for central and west Antarctica by jointly inverting Rayleigh-wave phase and group velocities with *P*-wave receiver functions using data from a set of permanent and temporary stations, including ASAIN stations. The integration of the seismological data from ASAIN and the seismic data (e.g., Vuan, Lodolo, *et al.*, 2005; Civile *et al.*, 2012) allowed for investigating the crustal structure beneath the Scotia Sea and the tectonics of the Scotia–Antarctica plate boundary. The improved knowledge of the lithospheric structure of the area allows for more precise determination of seismic moment tensor of regional events (Vuan *et al.*, 2001; Guidarelli *et al.*, 2003; Guidarelli and Panza, 2006; Plasencia Linares, 2008; Plasencia Linares *et al.*, 2018).

The proximity of the seismic stations to the Antarctic continent and their continuous operation in the long term also allows for having a privileged observatory on the ice-related seismicity. Cannata *et al.* (2019) investigated the link between microseism and sea ice in Antarctica using data also from ASAIN.

The scientific impact of the network is not limited to local studies but includes research at a broader scale. Data from ASAIN were used for seismic source imaging based on waveform inversion (e.g., Okuwaki *et al.*, 2016) and on waveform backprojection (e.g., Okuwaki *et al.*, 2019) and for global tomography studies (e.g., Lei *et al.*, 2020).

Conclusions and Outlook

ASAIN has operated with permanent broadband stations since 1995 in Tierra del Fuego (DSPA), on Scotia arc islands (JUBA and ORCD), in the Antarctic peninsula (SMAI, MBIO and ESPZ), and at the southeastern corner of the Weddell Sea (BELA). The level of noise at the ASAIN stations is generally not low, apart from station BELA, due to the proximity of the ocean (for long periods) and the human-generated noise at polar bases (for short periods). The real-time waveforms from ASAIN are freely accessible from IRIS and ORFEUS services. It improves the worldwide seismic networks' detection capabilities and contributes to refining regional earthquake locations released by the USGS. We are testing the use of a SeisComp server for the automatic detection, location, and magnitude estimation of the recorded earthquakes, especially of the small local events only recorded by the ASAIN stations. The proximity of the seismic stations to the Antarctic continent and their continuous operation in the long term also allows for having a privileged observatory on the ice-related seismicity along the Antarctica peninsula. At the moment, there is no planned extension of the network, but efforts are focused on ensuring a good performance of seismological instruments, improving, where necessary, the quality of installations, and reducing data gaps to a minimum , which will guarantee the regular flow of the data for the scientific community. In this regard, the station equipment will be updated in the next 5 yr by replacing the Güralp instrumentation in all stations with polar Streckeisen STS-2.5 sensors and Quanterra Q330HRS 26-bit acquisitions. The MBIO station will be moved in the next Antarctic campaign to a new structure, near the actual one. In addition, station ESPZ will be moved to a new site to reduce the anthropogenic noise and the problems due to seasonal thaw.

Data and Resources

The seismic data used in this study were collected by Antarctic Seismographic Argentinean Italian Network (ASAIN) (AI, DOI: 10.7914/SN/AI). The figures were produced using the Generic Mapping Tools (GMT) software package (Wessel *et al.*, 2019) and Matplotlib package (Hunter, 2007). Coordinates of operating permanent stations from other networks were taken from Incorporated Research Institutions for Seismology (IRIS) Google Map generator (http://ds.iris.edu/gmap/) that is based on federated International Federation of Digital Seismograph Networks (FDSN) data center metadata holdings. Availability of ASAIN waveforms on IRIS service was checked using IRIS Data Management Center (DMC) FDSN availability web service (https://service.iris.edu/fdsnws/availability/1/). The use of seismic phases of ASAIN stations for the U.S. Geological Survey (USGS) locations was verified using the USGS Advanced National Seismic System (ANSS) Comprehensive Catalog (ComCat) Python interface (DOI: 10.5066/P91WN1UQ). Data regarding Güralp software are available at www.guralp.com. All websites were last accessed in January 2021.

Declaration of Competing Interests

The authors acknowledge that there are no conflicts of interest recorded.

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