Southern Hemisphere **S**eismic **A**rray
SOSA

- Host Institution : Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy
- Proposal full title: Southern Hemisphere Seismic Array
- Proposal short name: SOSA
- Proposal duration in months: TBD
- Corresponding PI: TBD (INGV, Italy)

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Introduction
The objective of the SOSA project is to build a stable (or long term) dense seismic array in the southern hemisphere of the Earth, focusing on research based on advanced seismic array processing techniques. The SOSA project is founded on the synergy between geophysics and particle physics communities, shearing   facilities of the Pierre Auger Observatory (PAO) , the international cosmic ray observatory located in Malargue (Argentina), on the vast plain of Pampa Amarilla in the western Mendoza Province.
   The SOSA, taking advantage of the existing infrastructures at the PAO and sharing   part of the site of the 1600 water Cherenkov Detectors, can be deployed on an extension of about 50 x 60 km by choosing the most appropriate configuration for an optimal detection of seismic signals in the 1 – 100 km wavelength range. Such a broad range will allow for an optimal study of any earthquake of magnitude greater than about 3-4, from near regional distances to global seismicity, providing data able to improve the image of the interior of the Earth structure at several scales (local, crustal, mantle, core). In addition, improving the signal-to-noise ratios of the recorded seismic signals and allowing an higher-resolution via "beamforming", the SOSA will be used to investigate   the episodic tremor and slip (ETS),   a discovered phenomenon associated with the subduction zone of some convergent plate boundaries, such as the Cascadia subduction zone under the Puget Sound (USA) or in Japan.

The SOSA Localization

The SOSA will be located on plain above the subducting slab, at a distance of about 250 km from the trench where the plate dynamics is dominated by the subduction of the Nazca Plate beneath the South America Plate at an high rate. The South America arc extends over 7,000 km from the Chilean margin to its intersection with the Panama fracture zone offshore the south coast of Panama in Central America (fig. 1). It marks the region where the oceanic crust and lithosphere of the Nazca plate begin their descent into the mantle beneath South America .
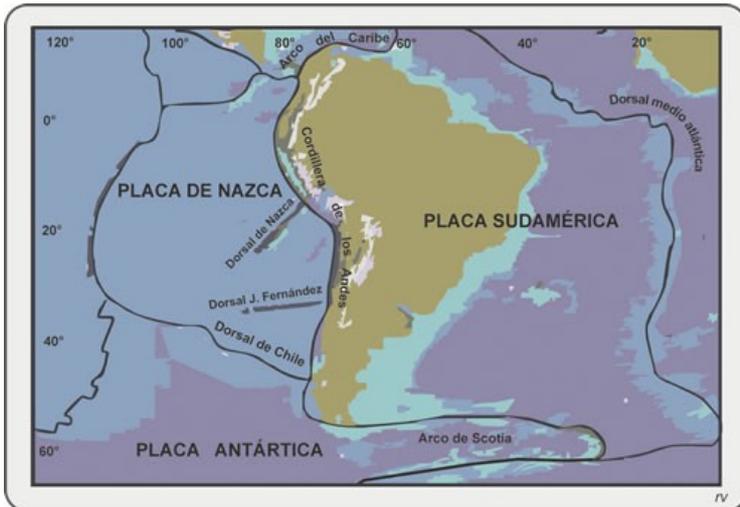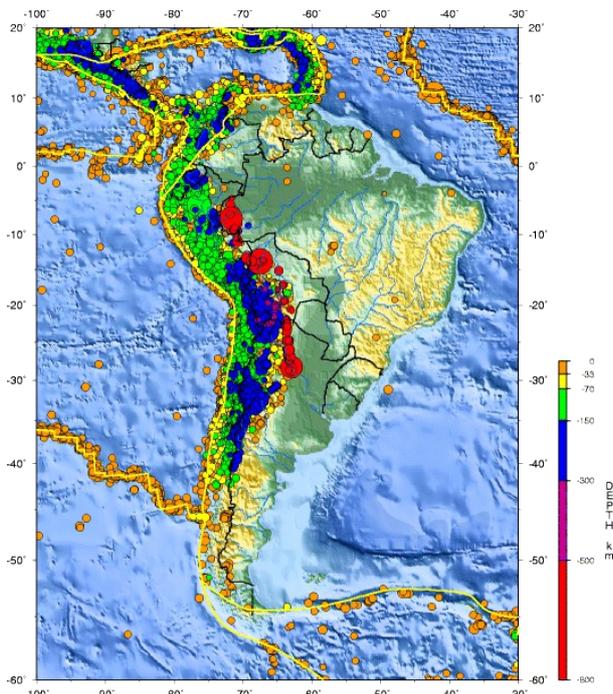

Fig. 1 The Nazca plate

The convergence associated with this subduction process is responsible for the uplift of the Andes Mountains, close to the SOSA location, and for the active volcanic chain present along much of this deformation front. Relative to a fixed South America plate, the Nazca plate moves slightly north of eastwards at a rate varying from approximately 80 mm/yr in the south to approximately 70 mm/yr in the north. This high rate of crustal deformation and slip along the dipping interface between the two plates generates frequent and often large earthquakes at depths of approximately 10 -200 km (fig.2), reaching magnitude 8 or greater (the Chile 1960 M9.5 is at present the largest instrumentally recorded earthquake). At regional scale, earthquakes are also be generated to depths of 800 km from internal deformation of the subducting Nazca plate.

Seismicity of South America, 1990 - 2006

Fig. 2 The earthquake distribution along the convergence margin of the Nazca plate

The SOSA, located on the same area of the PAO, close to this extended seismogenetic structure, will ensure for a wide range of seismic signals paths produced by frequent medium (M>4) to high energy (M>7) earthquakes, which includes also deep sources, and will fill a gap of the distribution of the stable seismic arrays into the southern hemisphere of the Earth.
The SOSA will be very important for the following studies:

Study of the Earth interior, including inner-core anisotropy and imaging iscontinuities in the mantle.

Observation of body waves produced by large earthquakes occurred at very far distance from the observation point is the most efficient way to study the deep interior of the Earth. P waves are the most useful because for large earthquakes they are characterized by shorter wavelength compared with S waves, which ensures a higher spatial resolution power of the crossed medium. For distances up to about 78 degrees the direct P wave is the first arrival, therefore it is usually characterized by high signal to noise ratio. P, PP and PcP phases are the most useful to study the mantle structure, which is known to have transition zones and anisotropy among its features (Earle et al., 2011; Schmerr and Thomas, 2001). The 75 degrees distance range from Malargue includes plate boundaries that produce a lot of medium to large size earthquakes appropriate for this kind of study. The entire boundary between Nazca and South America plates, between Cocos and Caribbean plates to the north, Scotia plate boundary to the south, and large parts of the Atlantic and Pacific ridges are included in the 75 degrees distance range.

PcP and Pdiff phases are very important to study the core-mantle boundary, the most striking interface inside the planet, located at a depth of about 2900 km, separating the solid mantle from the liquid outer core of the Earth. An increasing number of papers published in recent years suggest that the core-mantle transition is more complex than expected, with perhaps a very low velocity thin layer (Hutko et al, 2009), and an irregular topography (Rost and Thomas, 2010). In the distance range appropriate for this kind of studies we find California, Mid Atlantic ridge, the boundary between Pacific and Antarctica plates.

For epicentral distances greater than about 90 degrees other seismic phases are detected after have crossed the outer liquid core (PKP, PKiKP), and even the inner core (PKIKP). Since the amplitude of such phases is very low in the seismograms, their detection by a large array is very important to improve the signal to noise ratio by signal stacking and by applying array methods of analysis. Some of the most seismic active plate boundaries are located at such high distance from Malargue, including Japan, Kuriles, Aletians, Philippines, Sumatra. A sufficient number of medium to large size earthquakes is expected to be recorded in these areas in a few years of array operation.

Recent studies (Poli et al., 2012, Boué et al., 2013) evidenced that the long range correlation of seismic noise is able to determine teleseismic Green's function accurately. The joint analysis of the SOSA array data together with those of other large aperture seismic arrays (e.g. NORSAR) could be very useful to study the internal structure of the Earth at different scales and for different purposes. In particular Boué et al., (2013) listed a number of possible studies which could greatly benefit from this analysis, including the imaging of the lithospheric structure, the study of the core-mantle boundary and the anisotropy of the inner core. The analysis ambient noise recorded at sensors located various distances in a dense seismic configuration as the SOSA can contribute effectively to these investigations.

Study of the subduction zone, including seismic imaging of subducting slabsb and 3-D modeling of slab deformation.

Among the plate boundaries, subduction zones are the most interesting for the role they play in generating the most catastrophic earthquakes, tsunamis,

volcanoes, and for the complex interaction of the subducting slab with the surrounding mantle. Malargue is located right upon a subduction zone. The subduction trench is located about 250 km to the west, while the depth of the subducting slab beneath Malargue is of about 150 km, estimated from the hypocenters of local earthquakes.

Beside well known seismicity observed in the world wide subduction zones, some new interesting phenomena have been discovered during the last decade: slow earthquakes and deep nonvolcanic tremor. Slow earthquakes (or slow slip) are fault dislocations occurring over areas of hundreds km length at a very low speed, some cm/day rather than some km/s, as it occurs in the ordinary earthquakes. Slow earthquakes last from days to weeks, and to date they have been observed in the subduction zones of Cascadia (Dragert et al., 2001), Japan (Obara and Hirose, 2006), Alaska, Mexico and New Zealand (Wallace et al., 2013).

In several subduction zones it has been also observed a nonvolcanic seismic tremor. This is a very low amplitude seismic signal with frequency generally in the band 1-10 Hz, that may last from hours to months (Obara, 2002; Rogers and Dragert, 2003; Schwartz and Rokosky, 2007; Beroza and Ide, 2011). In some cases the nonvolcanic tremor occur with a surprising regularity and it is spatially and temporally coincident with slow slip (Rogers and Dragert, 2003). In such cases both phenomena are located on the subduction interface (Shelly et al., 2007; La Rocca et al., 2009). In many cases the nonvolcanic tremor is triggered by the passage of surface waves produced by large earthquakes (Rubinstein et al., 2007, 2010). Recently the nonvolcanic tremor has been detected in the triple junction region where Nazca, South America and Antarctica plates interact to each other, in central Chile (Gallego et al., 2013). It is very probable that non volcanic tremor and slow slip occur, perhaps occasionally, in the subduction zone beneath or near Malargue. In that case the Auger array would allow for a prompt detection and location of such seismic signals.

Study of the local lithospheric structure.
Regional seismicity is very high in the region around Malargue, therefore in a few years of data acquisition a large number of medium size earthquakes are expected to be recorded. The analysis of those earthquakes would give important insight about the local and regional lithospheric structure, including the downdip extension of the subducting slab. Local and regional earthquakes are appropriate for many different studies regarding the wave propagation through the crust and upper mantle, thus allowing for study of attenuation, scattering, and anisotropy.

Hundreds of volcanoes related with the subduction dynamics rise along the Andes chain. Many of them are active, and some are located near Malargue. A small dense subset of seismic stations of the Auger Array may be very useful to detect seismic signals possibly related with the volcanic activity. Long Period and Very Long Period seismic signals produced by volcanic activity would be properly detected by the Auger array.

A number of techniques are available for the analysis of data recorded by seismic arrays. Depending on the signal characteristics, the array extension and configuration, and the aim of the analysis, we can choose the most appropriate method. For a review of array methods see for example Rost and Thomas (2002).

The SOSA Project

The SOSA will be realized has a cluster of variable inter-distance broadband seismic stations grouped in sub-arrays.
Considering the large coverage of the PAO sites and facilities, the SOSA geometry will be related to the distribution (fig. 3) of the   of PAO Surface
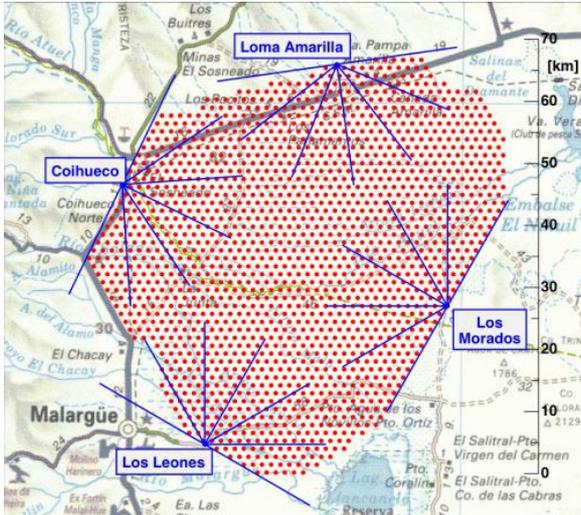
Detectors (SD, fig. 4), where it will be possible to

Fig. 3 The PAO distribution of SD and FD   Fig. 4 One of the 1600 surface detectors (DS)

share the site for the seismic stations installation.
On each of the selected SD sites (fig.4), if compatible with the PAO activities some facilities can be shared for the seismic installations (es. tank supports for installation of extra solar cells and a radio link antenna, casing for the battery etc).

Other facilities are related to the seismic data transmission and centralization. As for the PAO activities, the same design can be followed by the SOSA, sharing the PAO communication towers to install the SOSA antennas for the concentration of the seismic data transmitted by the local seismic clustered array. For the seismic data centralization in these concentration sites it will be useful to   share (or to extend) the backbone network connected   to the campus in Malargue.

Considering these PAO facilities, it will be simplified to organize the SOSA   into four sub-arrays, each one transmitting the data to the closer communications tower realized by PAO near the   Flourescence Detector (FD, fig. 5) sites of
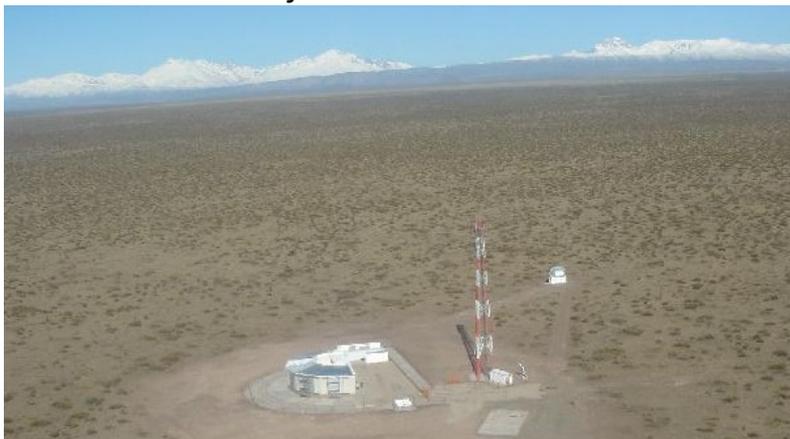
Los Morados, Coihueco, Los Leones and Norte (fig. 3) for the SD data transmission and a backbone network

Fig. 5 One of the four fluorescence detectors (FD)

On each tower it is planned to install the sector antennas of a WiFi/Hyperlan communication system with the closer seismic sub-array stations.

A typical configuration of a SOSA sub-array is shown on fig. 6, supposed closer to Los Morados concentration tower. This sub-array is composed by a total of 36 broadband stations, 32 using geophones with a flat response in the period range of 60 sec to 0,02 sec, located with an inter-distance ranging from 1,5 km to 5km. In addition 4 geophones with a response extended to a longer period (120 sec), are located at an inter-distance of about 20 km. One of the sub-array, more dense and with a circular shape could be located on the center of the PAO.

The final design of the SOSA will be based on the analysis of the data collected by a temporary array of broadband mobile station provided by INGV. The INGV mobile network can be configured both as stand-alone or radio-linked. As stand-alone, the power required is less than 200mA@12V and, if possible, during the experiment it could be powered by the PAO facilities at the SD.
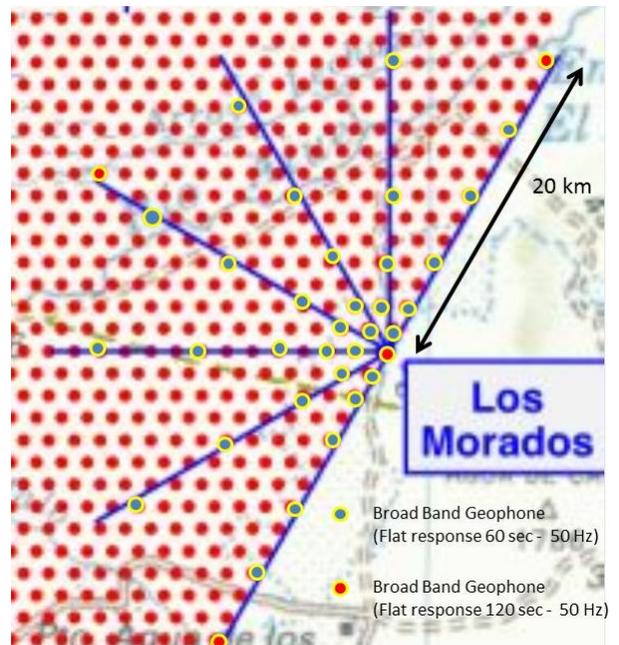

Fig. 6 – An example of a SOSA sub-array configuration

Finally, for the data collection, backup and analysis, a first small system for data buffering, control and temporary storage is planned in the communication intermediate concentration site near the FD, assuming available the AC power supply. The local main system will be setup at the PAO Campus in Malargue, assuming available a link to Internet for the SOSA remote control and data analysis.

SOSA Specifications

- The SOSA array is mainly composed by broadband geophones, with a flat response in the range of 60 sec - 50 Hz (type A stations). The geophones will be located in sites with ad inter-distance of a range of 1.5k – 6.0 km
  Each sub-array will be composed by about n. 32 type A geophones.
- Sites at a larger inter-distances of about 20 km will be equipped by broadband geophones with a flat response in the range of 120 sec - 50 Hz (type B stations).
  Each sub-array will be composed by about n. 4 geophones type B.
- The power required for each station, including the INGV data logger GILDA and the radio link equipment, is about 700 mA@12V.
- In case of stand-alone configuration (local data acquisition) for temporary tests, the power required for each station is about 160 mA@12V
- The data rate produced by each SOSA sub-array is of about 600 kb/s . Considering 4 sub-arrays the complete SOSA configuration, the overall data flux produced will be of about 2.4 Mb/s

SOSA Costs (personnel and mission costs not included)

Single Seismic Station Type A
(included costs for data transmission and power)
- Broadband Geophone (Flat response 60 sec - 50 Hz)   € 7.100
- Low Power acquisition GILDA (with casing)   €   2.000
- Hyperlan 5GHz radio transmission (with antenna)   €   1.500
- Power supply (solar cell + Battery)   €   500
- Extra for installation   €   500

<div align="right">Subtotal   € 11.600</div>

Single Seismic Station B
(included costs for data transmission and power)
- Broad Band Geophone (Flat response 120 sec - 50 Hz)   € 13.000
- Low Power acquisition GILDA (with casing)   €   2.000
- Hyperlan 5GHz radio transmission (with antenna)   €   1.500
- Power supply (solar cell + Battery)   €   500
- Extra for installation   €   500

<div align="right">Subtotal   € 17.500</div>

Local Concentration Site
(backbone link and power provided by PAO)
- Multi Hyperlan 5GHz radio for local links (with sector antennas)   € 15.000
- System for data control and buffering (AC power required)   € 5.000
- Extra for installations   €   5.000

<div align="right">Subtotal   € 25.000</div>

Control Center of SOSA   at the PAO Campus
(backbone link , internet and power provided by PAO)
- Systems for data processing, storage, archive   € 20.000

<div align="right">Subtotal   € 20. 000</div>

The SOSA with single sub-array, local concentration and   Center   € 486.200
Each additional sub-array and local concentration   € 466.200
The SOSA completed with 4 sub-arrays   € 1.884.800

Not jet calculated costs for:
- Missions and local transport facilities
- Local committed work (antennas installation, permissions, seismic site preparation etc.)

- In case, shared facilities costs (es. Power, Internet connection, local personnel cooperation etc)
- Maintenance
- Temporary test for the SOSA evaluation design. Il will be carried out using a INGV portable seismic network (Available n. 50 (30+20) broadband and n. 20 short period stations from the PON VULCAMED)

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