The History, State, and Future of the Argentine Continuous Satellite Monitoring Network and Its Contributions to Geodesy in Latin America

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ABSTRACT

Since its creation in 1998, the Argentine Continuous Satellite Monitoring Network (Red Argentina de Monitoreo Satelital Continuo [RAMSAC]) has grown to include more than 100 continuously operating Global Navigation Satellite Systems (GNSS) stations in Argentina. RAMSAC Receiver Independent Exchange Format (RINEX) data and their derived positioning products (e.g., Networked Transport of RTCM via Internet Protocol [NTRIP] streams and time series) have been used in more than 20 peer-reviewed publications studying the inter-, co-, and postseismic geodynamic evolution of the subduction interface between the South America and Nazca plates. Most of this research has focused on the deformation associated with the near-field megathrust earthquake cycle. Nevertheless, many authors have begun to include in their analyses far-field GNSS observations, which in general do not follow the elastic/viscoelastic deformation predicted by current models. We review the contribution of RAMSAC to scientific knowledge of earthquake elastic deformation and associated phenomena. We also describe the future plans for RAMSAC and the societal impact beyond geodetic and geophysical science.

INTRODUCTION AND HISTORY OF RAMSAC

In 1993, the Argentine Military Geographic Institute (Instituto Geográfico Militar [IGM]), now the Argentine National Geographic Institute (Instituto Geográfico Nacional [IGN]), began a campaign to acquire Global Positioning System (GPS) measurements on ~120 benchmarks to produce Argentina's first GPS-based geodetic reference frame (RF), the Geodetic Argentine Positions (Posiciones Geodésicas Argentinas [POSGAR]) RF. This RF, later called POSGAR94, replaced the original national local system (Campo Inchauspe 69) and was based on GPS observations obtained during field campaigns (Lauría *et al.*, 2002) in collaboration with the National Science Foundation-funded Central Andes GPS Project (CAP).

In the mid 1990s, the Jet Propulsion Laboratory at National Aeronautics and Space Administration (NASA) and the Deutsches GeoForschungsZentrum (GFZ) deployed the first three continuous GPS (CGPS) stations at the Universidad Nacional de La Plata (Buenos Aires), Universidad Nacional de Salta (Salta), and Estación Astronómica Río Grande (Tierra del Fuego) as part of the early global International GNSS Service (IGS) network. At the same time, CAP deployed stations at the seismic station Coronel Fontana (San Juan), Universidad Nacional de Tucumán (Tucumán), Parque Nacional Lihué Calel (La Pampa), and Aeropuerto de Ushuaia (Tierra del Fuego). Both the NASA/GFZ and CAP groups collaborated with Argentine universities and national laboratories, and CAP also collaborated with the IGN and the National Parks Administration.

The IGN proposed creation of an open collaborative GPS network using data provided by these seven sites in Argentina to support governmental, commercial, and scientific geodesy and surveying. This network was named the Argentine Continuous Satellite Monitoring Network (Red Argentina de Monitoreo Satelital Continuo [RAMSAC]), and its main goal was to be the foundation for the development and maintenance of the national geodetic RF. Figure 1 shows a summary of the RAMSAC stations grouped by installation date.

Until 2009, RAMSAC depended mainly on other agencies and institutions (both national and international) to provide GPS/Global Navigation Satellite Systems (GNSS) stations to expand the network. During this period, thanks to the effort of multiple national and international collaborators, the network incorporated stations such as Universidad Nacional de Rosario (Santa Fe), and Centro Regional de Investigaciones Científicas y Tecnológicas (Mendoza; MZAC), among others. In late 2009, IGN obtained Argentine government funding to begin to build and operate its own GPS/GNSS stations. This triggered the rapid RAMSAC expansion shown in Figure 1.

One of the strengths of RAMSAC is that all installations are performed using monumentation that guarantees the stability of the GPS/GNSS antennas. Also, in an effort to maintain the best possible continuity of the time series (with the least possible time-series jumps), IGN has always tried to keep the antenna changes to a minimum unless a degradation in the solutions quality is noticed.

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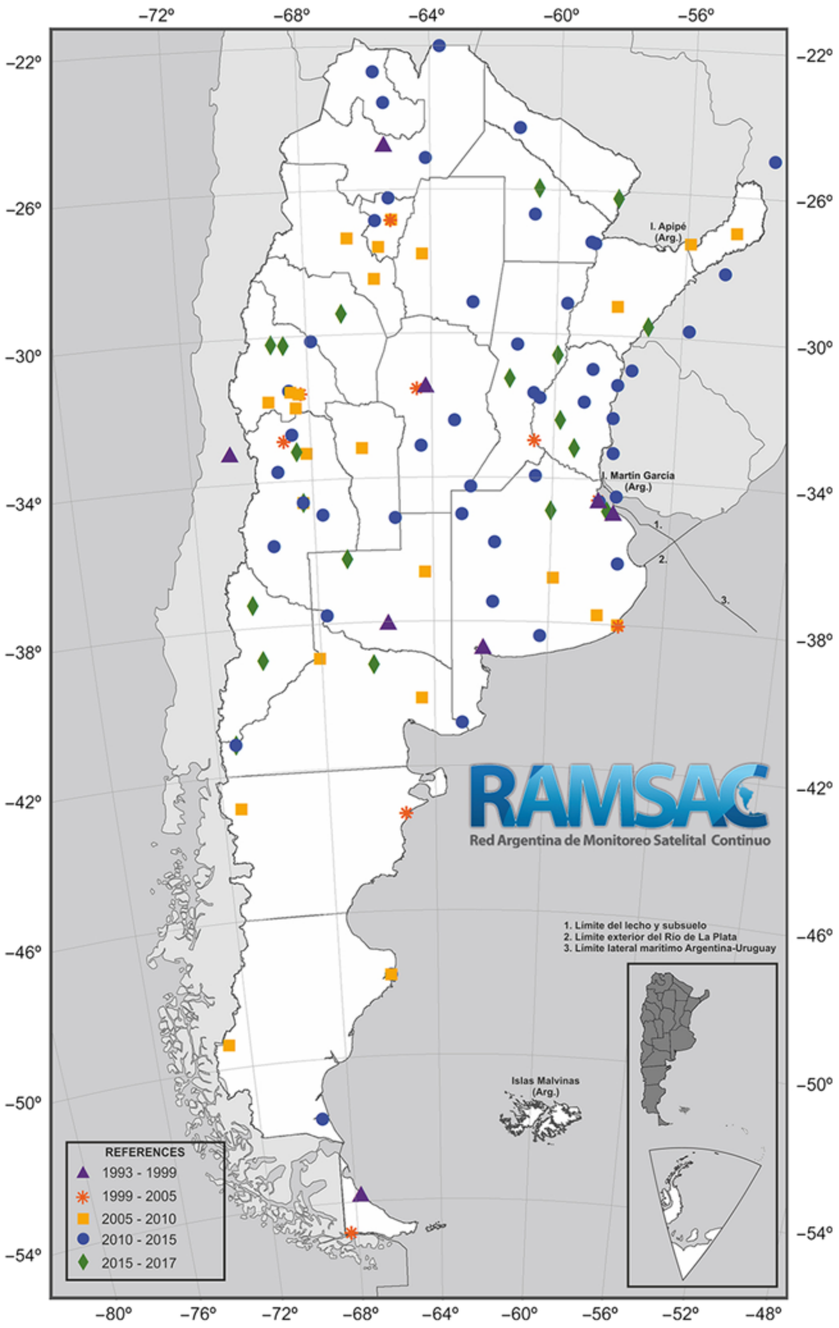


▲ **Figure 1.** Evolution of the Argentine Continuous Satellite Monitoring Network (Red Argentina de Monitoreo Satelital Continuo [RAMSAC]) continuous Global Positioning System (GPS) (CGPS) network (excluding scientific stations in Antarctica). Stations are grouped by installation date (shown as different symbols). The color version of this figure is available only in the electronic edition.

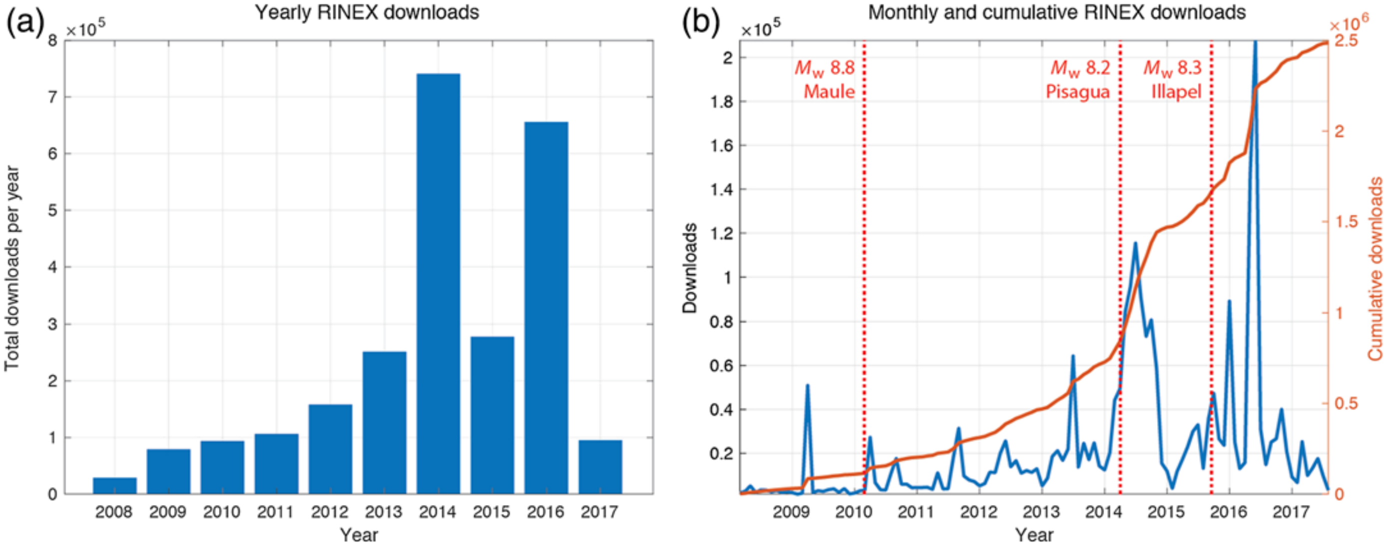
One important impact of RAMSAC is that it was the first Latin American GNSS network to provide Receiver Independent Exchange Format (RINEX) data and process results openly online. This policy, in place since RAMSAC began, has had significant impact in the public service, engineering, land surveying, and scientific communities. Figure 2a shows a steady increase in RINEX downloads using IGN's website interface between 2008 and 2017, revealing a growing interest and need for RAMSAC products. Also, Figure 2b shows spikes in RINEX downloads following three major South American seismic events. Downloads are currently anonymous, but such sporadic increases are unlikely to be due to engineering or land surveying users who generally require only a few days of data from a few stations at a time. During the last five years, more than 1000 RINEX files were downloaded per day on average, for a total of ~2.5 million files. The reader can refer to IGN's website for more statistics, such as yearly per-station downloads (see Data and Resources).

In 2010, RAMSAC introduced NTRIP streams in both RTCM v.2.3 and v.3.0 protocols. This service provides data for real-time kinematic positioning (used for engineering) and has potential to provide data to many nonscientific and scientific applications such as ionospheric and meteorological studies. Since creation, RAMSAC's NTRIP service has transmitted more than one billion GNSS observations, equivalent to more than 300,000 hrs and representing ~400 Gb of streamed data.

RAMSAC has also contributed significantly to development of South American GNSS science. RAMSAC's data, together with the campaign measurements it supports, have been used to quantify co- and postseismic deformation (e.g., Pollitz *et al.*, 2011; Vigny *et al.*, 2011; Klein *et al.*, 2016), study the ionosphere (e.g., Nogueira *et al.*, 2015; Kamogawa *et al.*, 2016; Takahashi *et al.*, 2016), provide co- and postseismic corrections to the POSGAR RF (Gómez, Piñón, *et al.*, 2015; Gómez, Smalley, *et al.*, 2015), constrain plate tectonic models (e.g., Drewes, 2009; Brooks *et al.*, 2003; Smalley *et al.*, 2003, 2007), and develop regional and global geodetic RFs (e.g., DeMets *et al.*, 2010; Sánchez *et al.*, 2012; Altamimi *et al.*, 2016).

As RAMSAC's twentieth anniversary approaches, it has grown to encompass more than 100 online GNSS sites distributed throughout Argentina, plus a small number of sites outside Argentina from the IGS network and collaborative agreements with the Instituto Brasileiro de Geografía e Estatística, the Servicio Geográfico Militar de la República Oriental del Uruguay, and the Institutio Geográfico Militar de Bolivia. RAMSAC has been, and continues to be, a collaborative effort led by the Argentine IGN. By providing GNSS equipment, hosting stations, or financially supporting the project, the collaborators, listed on IGN's website (see Data and Resources), have made possible the continuity and growth of RAMSAC.

In the following sections, we will discuss the contribution of RAMSAC to the development of the official Argentine RF



▲ **Figure 2.** (a) Yearly Receiver Independent Exchange Format (RINEX) downloads. Data for 2017 end in August. Spikes not related to earthquakes, especially during 2014, which includes the 2014 M_w 8.2 Pisagua earthquake (also known as the Iquique earthquake), and 2016 after the 2015 M_w 8.3 Illapel earthquake are probably due to downloads of the full RAMSAC archive. (b) Cumulative and monthly statistics of RINEX downloads. Vertical dotted lines show the major seismic events in South America (visible from RAMSAC stations). The color version of this figure is available only in the electronic edition.

POSGAR07 and to the Geocentric Reference System for the Americas (Sistema de Referencia Geocéntrico para las Américas [SIRGAS]). We will then discuss how RAMSAC data have been used to study megathrust earthquakes in South America and the importance of RAMSAC in advancing the scientific knowledge of earthquake deformation. We will finally comment on the network's planned growth to increase coverage in areas that have few GNSS stations.

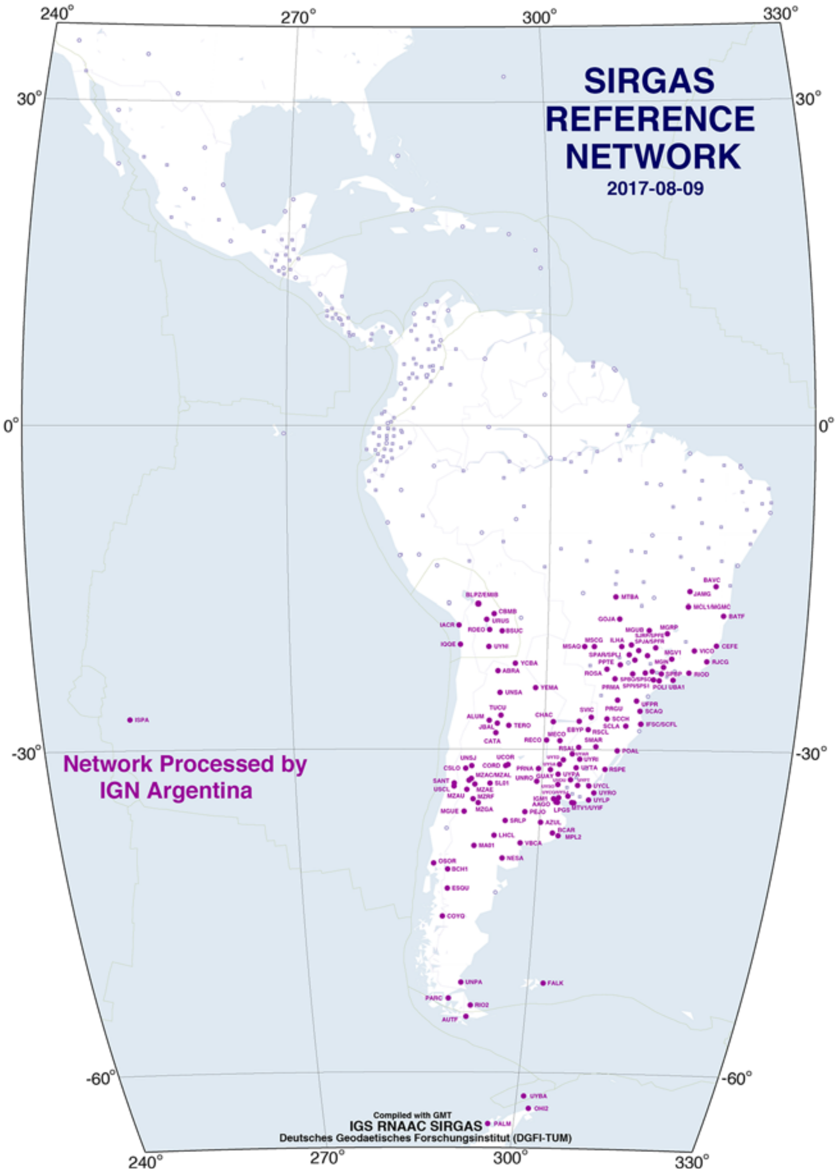
RAMSAC CONTRIBUTIONS TO THE POSGAR AND SIRGAS REFERENCE FRAMES

RAMSAC's principal goal is development, operation, and maintenance of the family of POSGAR GNSS-based geodetic RFs. RAMSAC's GNSS stations constitute the backbone of the latest realization of Argentina's geodetic frame POSGAR07 in contrast to its official predecessor POSGAR94, which was based on campaign measurements. The POSGAR07 RF was realized by measuring the original POSGAR94 benchmarks and incorporating ~60 new sites, mostly RAMSAC GNSS stations. Since the early POSGAR07 measurements, with collaboration of national/provincial agencies and CAP, IGN also added more than 3000 new benchmarks to the POSGAR07 RF through campaign observations between 2005 and 2017. This campaign measurement-based densification improved the network's geometry and allows frame access at more locations, especially in areas with low GNSS station coverage.

The processing and analysis of POSGAR07 was initially mentored by the Geodesy and Geodynamics group of the School of Earth Sciences at the Ohio State University (OSU). In 2005, the OSU provided training to IGN's geodesy department personnel on GAMIT/GLOBK (Herring *et al.*, 2008). Upon completion, IGN opened a GPS processing center, known as the Argentine Scientific Processing Center (Centro de procesamiento científico Argentina [CPC-Ar]). After realization of the POSGAR07 RF in 2010, CPC-Ar became an official processing center of the SIRGAS-GT I group (Grupo de trabajo I). This was particularly important because IGN's use of GAMIT/GLOBK introduced independent results from an additional processing package into the final combined SIRGAS solutions. Since becoming a processing center, IGN has contributed to the realization of the SIRGAS RF by submitting loosely constrained weekly solutions of the SIRGAS continuous (SIRGAS-CON) network. SIRGAS-CON now includes more than 45 RAMSAC GNSS sites. Figure 3 shows the part of the SIRGAS-CON network currently processed by CPC-Ar at IGN. Most recently, IGN's NTRIP service is also contributing to the SIRGAS-RT (real-time) network.

Because of RF stability advances achieved in the past 20 years, previously nondetectable deformation signals are now visible and future RFs will have to take into account not only plate motions and inter-, co-, and postseismic deformations but also other observable deformations such as glacial isostatic adjustment. This represents a revolutionary change in geodesy in which the traditional goal of describing a static shape for the earth has changed. GNSS-based RFs therefore need the ability to state the position of a benchmark as a function of time using modeling advances such as extended trajectory models (ETMs; Bevis and Brown, 2014).

Figure 4a,b shows two GPS time series and their ETM fits. These data are the input needed to generate velocity fields and trajectory prediction models necessary to maintain and access POSGAR07. Figure 5a shows South America's interseismic velocity field, estimated using sites predating the February



▲ **Figure 3.** The Geocentric Reference System for the Americas (Sistema de Referencia Geocéntrico para las Américas [SIRGAS]) reference network currently processed by the Argentine National Geographic Institute (Instituto Geográfico Nacional [IGN]; stations with names). Image courtesy of SIRGAS (see Data and Resources). The color version of this figure is available only in the electronic edition.

2010 Maule earthquake. Figure 5b shows coseismic displacements from the Maule earthquake, the largest earthquake in the region since the advent of GPS technology. Finally, Figure 5c,d shows two instantaneous velocity fields following the Maule earthquake. These figures show RAMSAC's contribution, discussed further in the next section, to constrain the earthquake cycle's three stages: inter-, co-, and postseismic.

THE CONTRIBUTION OF RAMSAC TO STUDYING SOUTH AMERICAN MEGATHRUSTS

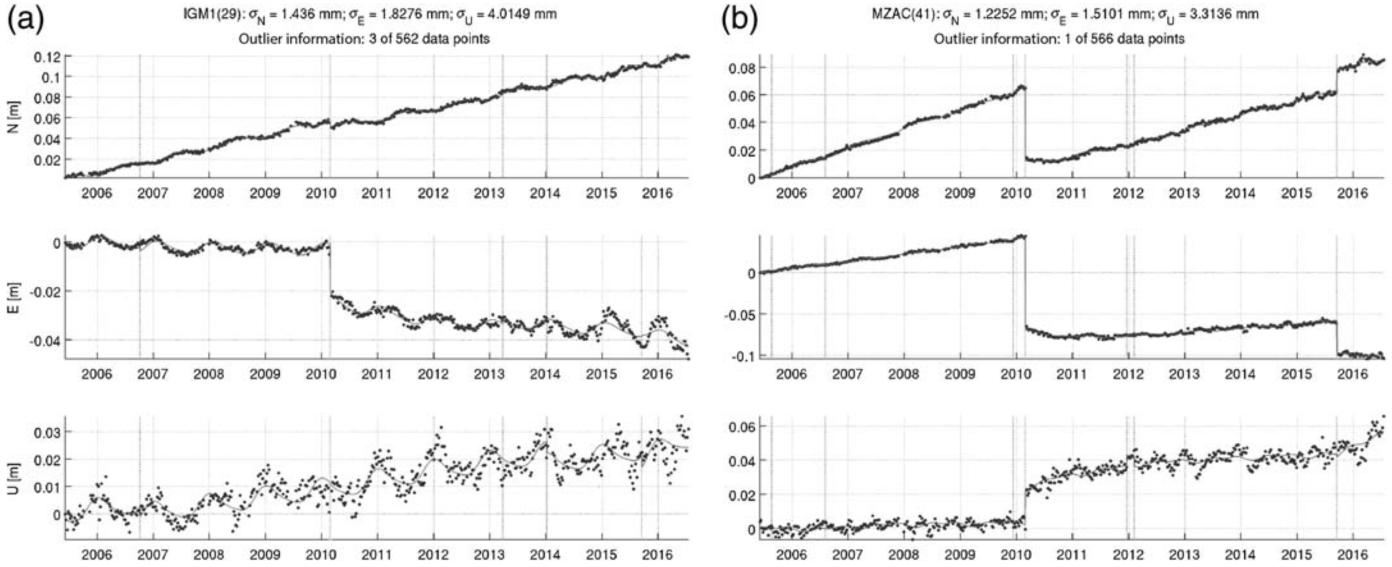
On 27 February 2010, the M_w 8.8 megathrust Maule earthquake occurred off the Chilean coast. This earthquake generated detectable displacements between latitude 28° and 40° S from the Pacific to the Atlantic oceans, with CGPS determined displacements ranging from 5 m on the Chilean coast to 2 cm on the Argentinean coast (see Fig. 5b).

This megathrust earthquake triggered a series of publications in various prestigious international journals (e.g., Lorito *et al.*, 2011; Pollitz *et al.*, 2011; Vigny *et al.*, 2011) that used RAMSAC to obtain the near- and medium-field coseismic displacements (using CSLO, MZAC, and CFAG) or used far-field stations as reference sites to provide well-defined geodetic RFs. Although most of these publications focused on elastic deformation produced by the earthquake, a number of publications discussed the Maule earthquake solely in the context of filling the Darwin seismic gap (e.g., Ruegg *et al.*, 2009; Lorito *et al.*, 2011; Métois *et al.*, 2013). We concentrate on reporting studies related to elastic deformation that in most cases make use of the western Argentina RAMSAC stations.

Surface deformation produced by the Maule earthquake has principally been modeled using formulations such as Okada (1985), or layered over half-space dislocation models (Wang *et al.*, 2003). Since the advent of GPS technology, these models have become very popular to explain earthquake deformation because they are easy to use. This ease of use, however, comes at a cost: these models do not incorporate sphericity or layering and, therefore, are unable to correctly explain the far-field deformation (beyond approximately two to five fault dimensions, in which RAMSAC provides data). The theory behind the discrepancy between model predictions and observations has been studied by Sun and Okubo (2002), Dong *et al.* (2014), and others and will not be discussed here.

Although previous megathrust events had already shown the importance of incorporating sphericity in co- and postseismic deformation models (Pollitz *et al.*, 2008), the first spherically layered model applied to the Maule earthquake was Pollitz *et al.* (2011), which included the full South America wide deformation field. Their modeled displacements, however, exhibited some discrepancies, especially in the far field, that were probably caused by crudeness of the fault model and also by ignoring the effect of gravity in coseismic deformation (Gómez *et al.*, 2017).

The observation of co- and postseismic deformation as far as 1300 km from the Maule earthquake rupture zone spawned efforts to model the mid- and far-field phenomenon triggered by this seismic event. Klein *et al.* (2016), for example, used a spherically layered finite-element model to predict both co- and postseismic effects from the Maule earthquake. This model



▲ **Figure 4.** Time series of (a) IGM1 in eastern Argentina and (b) Centro Regional de Investigaciones Científicas y Tecnológicas, Mendoza (MZAC) in western Argentina. Plots show the extended trajectory model (ETM) fits (solid lines), weekly GPS solution from the Argentine Scientific Processing Center (Centro de procesamiento científico Argentina [CPC-Ar]; dark gray dots), and outliers with respect to the ETM (light gray dots). Vertical lines represent geophysical (earthquakes; 2010.15 and 2015.71) or potential nongeophysical jumps (equipment changes). Periodic terms are more visible in IGM1 due to the small geophysical jump that occurred during the 2010.15 Maule, Chile, earthquake. Values shown as σ_N, σ_E, and σ_U represent the north, east, and up standard deviations of the solutions with respect to the ETM.

included deformation across Argentina to the Atlantic coast and discussed effects in the far field of neglecting or incorporating the craton in central Argentina. RAMSAC provided important data to this work to constrain effects on far-field subsurface structures. It is worth mentioning that such studies are feasible because the South America/Nazca subduction interface is located in one of the few tectonically active regions where subduction occurs beneath a continent and this allows continuous observation of the deformation field across more than 1000 km of uninterrupted continental lithosphere. Cascadia offers a similar situation, but with a much lower megathrust rate.

As the near field becomes increasingly well understood, previously poorly studied areas, both in terms of data collection and theoretical modeling, become more important for scientific studies. Many authors have turned attention to studying the far-field deformation, where current model predictions do not fit the full deformation field observed by the expansion of GNSS networks (e.g., Lin *et al.*, 2013).

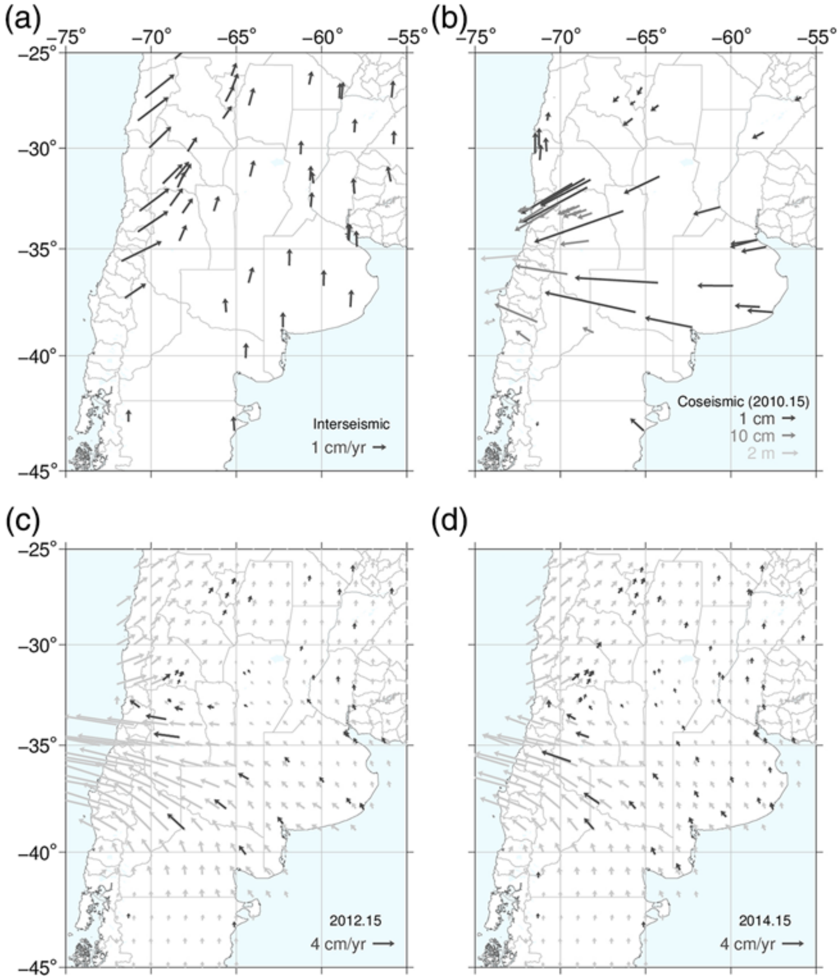
The misfit between predictions and observations highlights the importance of obtaining additional GNSS data from the misfitted region. RAMSAC will not only contribute to the study of the earthquake cycle, but will also help understand how stress and strain are distributed under the plate tectonic model throughout the continental lithosphere by providing far-field observations of the South America–Nazca plate boundary. We suggest that a future collaboration of RAMSAC with the National Seismological Center of Chile (that will include ~150 GNSS stations) would create a GNSS network, similar to the Plate Boundary Observatory, in the southern cone of South America. Such collaboration would facilitate the data access to scientists studying megathrust signals from the rupture zone to the far field.

DISCUSSION: THE FUTURE OF RAMSAC

As of 2017, RAMSAC covers most of north and central Argentina, although some gaps exist in regions with limited access (e.g., the Puna, the Principal Andes Cordillera from northern Mendoza to the Puna, and the Monte Chaco-Salteño, among others). However, the most significant hole is in Patagonia, where communications is the limiting factor for installing new online/real-time RAMSAC stations. As cellular and satellite communications improve and become more economical, installing new stations in Patagonia becomes more feasible. IGN's plan is to install more than 25 new sites in the next five years in regions lacking stations, with a final goal of having a 100-km station spacing within Argentina.

Before each installation there is an important question that has to be answered: who will use the data from the station? In the past, RAMSAC was designed primarily to provide real-time (or near-real-time) data for engineering and land surveying and to be useful for RF access and maintenance. That criterion, however, has been slowly changing as it becomes more evident that RAMSAC's audience is broadening.

In this article, we have shown that RAMSAC data have been leveraged to produce important scientific work. For many of these applications, GNSS data are not needed in real time



▲ **Figure 5.** (a) Interseismic velocities (in POSGAR07, IGS05 reference frame) calculated using the ETM as shown in Figure 4. Additional non-RAMSAC sites are shown in Chile; (b) ETM estimates of coseismic displacements produced by the 2012 M_w 8.8 Maule earthquake. The gray scale arrows show, from dark to light, horizontal displacements $< 8, 8$–40, and > 40 cm, respectively; (c) instantaneous postseismic velocity field (epoch 2012.15) after the Maule earthquake at the RAMSAC sites (dark arrows) and interpolated field (light arrows); and (d) same as (c) but for epoch 2014.15. A decrease in the instantaneous velocities of western Argentina is clearly visible, as well as the increase in GPS station coverage. Interpolated velocity fields in (c) and (d) were estimated using the trajectory prediction model of Gómez, Piñón, *et al.* (2015) calculated using CPC-Ar time series. The color version of this figure is available only in the electronic edition.

and can be downloaded after a major natural phenomenon (e.g., an earthquake, geomagnetic storm, etc.) or during regular field campaigns. Although the primary goal of RAMSAC is (and will probably always be) to support the national geodetic RF, new GNSS installations in remote locations can have an indirect impact in IGN's activities while providing important scientific and commercial applications. For example, data from an active geophysical region, such as the Andean Cordillera, will very likely impact, say, the development of RF trajectory or coseismic deformation models, which are scientific advancements that also have societal and economic impacts. These new models will later enhance the way RFs (e.g., POSGAR) are realized and maintained.

In other cases, seemingly unusable stations that are in remote locations with low population (but with Internet access) can potentially be used to provide not only a stronger RF but also other important data. These GNSS stations could enhance precipitable water vapor or snow pack estimations, or measure the amount of water in a reservoir using the deformation of the earth's surface that results from supporting the weight of the water. GNSS data from stations that have a view of the ocean can measure both the position of the GNSS antenna with respect to the center of the earth and the height of the ocean surface with respect to the GNSS antenna, making a tide gauge (Larson *et al.*, 2013). These coastal GNSS stations are especially important because processes such as postglacial rebound (glacial isostatic adjustment) and loading from sea level change are affecting the coastline. These data can later be used by government agencies for hazard mitigation, weather and water resources forecasting, and coastal flooding.

RINEX RAMSAC data are also regularly being used by international institutions and agencies such as the National Seismological Center of Chile (Centro Sismológico Chileno [CSN]) and IGM Chile. CSN plans to incorporate RAMSAC NTRIP streams into their future tsunami warning system, with the goal of preventing loss of life during megathrust seismic events and associated tsunamis (J. C. Báez, personal comm., 2017).

IGN is always searching for opportunities to collaborate with other agencies, scientific or commercial, private or public, national or international, that are interested in supporting the development and growth of the GNSS network in Argentina. In the past, such collaboration has been significant, contributing to the current state and success of RAMSAC. In the future, IGN will continue to leverage the expansion of the network. Hazard mitigation, weather and water resources forecasting, coastal flooding, and tsunami warning systems are just a few of the many applications that will benefit from the expansion of RAMSAC, and, beyond just RF realization, will also show RAMSAC's broader utility to society.

DATA AND RESOURCES

All the Argentine Continuous Satellite Monitoring Network (Red Argentina de Monitoreo Satelital Continuo [RAMSAC]) Receiver Independent Exchange Format (RINEX) data (including metadata) can be found at the Instituto Geográfico Nacional's (IGN) website http://www.ign.gob.ar/NuestrasActividades/Geodesia/Ramsac/DescargaRinex (last accessed January 2018). File transfer protocol (FTP) access to the database is available upon request. Downloads and other statistical information can be found at http://www.ign.gob.ar/NuestrasActividades/Geodesia/ramsac/estadisticas (last accessed January 2018). A list of past and current RAMSAC collaborators can be found at http://www.ign.gob.ar/NuestrasActividades/Geodesia/Ramsac (last accessed January 2018).

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