The Chilean GNSS Network: Current Status and Progress toward Early Warning Applications


ABSTRACT

Chile is one of the world’s most seismically active regions and is therefore extensively studied by the earthquake sciences. The great length of the country hosts a variety of measurement systems allowing for the characterization of earthquake processes over a wide range of timescales and in different phases of the seismic cycle. Starting in the early 1990s, several research groups began to deploy continuously operating geodetic networks in Chile, forming the core of the modern network of Global Navigation Satellite Systems (GNSS) receivers used to monitor geodynamics from the southern tip of the Americas to the central Andes. Today, the Centro Sismológico Nacional (CSN) of the Universidad de Chile maintains and improves this network, increasing its coverage and spatial density while greatly reducing solution latency. We present the status of the GNSS network, its data streams, and the real-time analysis system used to support real-time modeling of earthquakes. The system takes 2 s, on average, to collect raw data, estimate positions, and stream results. Such low latency is essential to enabling early warning of earthquakes and tsunamis in Chile.

Electronic Supplement: Figures showing schema of communication from the stations to the servers used at Centro Sismológico Nacional (CSN), comparison between velocities derived from real-time Global Navigation Satellite Systems (RT-GNSS) data, kinematic finite-fault inversion results and waveform comparison, and results of the estimation of $M_w$ as a function of time, and tables of station locations and estimated total coseismic displacement.

INTRODUCTION

Deformation rates of the Earth’s surface, derived from modern space geodesy, constitute the observational basis for physical models of the earthquake deformation cycle, providing key information to describe the processes leading up to and following great events (e.g., Vigny et al., 2011; Ruiz et al., 2014; Schurr et al., 2014; Duputel et al., 2015; Melnick et al., 2017). Along the Chilean subduction zone, the Chilean network of Global Navigation Satellite Systems (GNSS) has been steadily growing from the early 1990s to the present day, with the earliest stations coming from different international research projects and institutions such as the central Andes Global Positioning System (GPS) project (CAP) (Bevis et al., 1999; Kendrick et al., 1999), the German Research Centre for Geosciences (GFZ), the currently active Integrated Plate Boundary Observatory Chile (Angermann et al., 1999; Klotz et al., 2017; Moreno et al., 2017), the French National Research SUBChile project by Institut de Physique du Globe de Paris et École Normale Supérieure in Paris, France (Ruegg et al., 2009; Vigny et al., 2009), and the Central Andean Tectonic Observatory Geodetic Array of the California Institute of Technology (Caltech) (Simons et al., 2010; Bejar-Pizarro et al., 2013).

At the end of the twentieth century, GNSS data from continuous and campaign observations were primarily used in Chile and neighboring countries to estimate plate motion and interseismic deformation (Norabuena et al., 1998; Angermann et al., 1999; Bevis et al., 1999, 2001; Kendrick et al., 1999, 2003, 2006; Brooks et al., 2003; Ruegg et al., 2009; Moreno et al., 2011; Bejar-Pizarro et al., 2013; Metois et al., 2013; Melnick et al., 2017). The GNSS network now provides good spatial coverage throughout Chile’s seismogenic zone, enabling the observation of the complete seismic cycle, including the coseismic deformation caused by the $M_w 8.8$ giant Maule event in 2010 (Vigny et al., 2011; Moreno et al., 2012; Lin et al., 2013), and by events in Iquique ($M_w 8.1$) in 2014 (Ruiz et al., 2014), Illapel ($M_w 8.3$) in 2015 (Duputel et al., 2015; Melgar, Crowell, et al., 2015; Ruiz et al., 2016), and Chiloé ($M_w 7.4$) in 2016 (Melgar et al., 2017; Ruiz, Aden-Antoniow, et al., 2017; Ruiz, Moreno, et al., 2017). The GNSS network also records the postseismic transients caused by these events (Bedford et al., 2013, 2016; Klein et al., 2016). Several researchers proposed the use of real-time GNSS (RT-GNSS) data to estimate not only the magnitude of an event but also its rupture geometry.
(e.g., GPSlip, Böse et al., 2013; G-larmS, Grapenthin et al., 2014; Bayesian Evidence-based Fault Orientation and Real-time Earthquake Slip, Minson et al., 2014; Geodetic first Approximation of Size and Timing [G-FAST], Crowell et al., 2016). These methods take advantage of the fact that GNSS data do not saturate with magnitude, and directly deliver displacement waveforms, thereby avoiding the serious problems associated with the double integration of accelerograms (Melgar et al., 2013). GNSS data have also been successfully utilized in prototype tsunami early warning systems (Melgar, Allen, et al., 2015; Chen et al., 2016; Riquelme et al., 2016), rapidly inverting for the slip distribution of the earthquake on a predefined plate geometry using both GNSS displacement and seismic observations.

Centro Sismológico Nacional’s (CSN) current priority is to implement tsunami and earthquake early warning systems in real time. We describe here the status of the GNSS network and the schedule of solutions generated during a rapid response to a moderate-to-large earthquake (magnitude 7.0 and above).

**NETWORK ARCHITECTURE**

Chile’s GNSS network grew most rapidly following the 2010 $M_w$ 8.8 Maule earthquake, when the CAP and Caltech groups joined to build 40 continuous GNSS stations in the immediate aftermath of the earthquake, using financial support from the U.S. National Science Foundation and equipment provided by UNAVCO. From 2013 to the present day, the CSN has deployed an additional 130 stations. These stations either supplement or replace those deployed in the projects listed in the Introduction. The map of all current GNSS stations can be seen in Figure 1 and their codes and locations are given in Table S1, available in the electronic supplement to this article. All the stations observe in continuous mode and 62% stream data to CSN servers. CSN’s goal is to increase the number of streams so as to include all available geophysical (GNSS, broadband seismic, or accelerometer) sensors. Data are sent to the CSN servers in one of the following three ways: (1) satellite communication with Intelsat 23 (VSAT), (2) cellular modem 3G/4G into the Internet Cloud (with optical fiber), and (3) wireless link (900 MHz or 5.8 GHz). In some cases, a combination of these communication methods is applied, depending on the specific site conditions (see Fig. S1).

For GNSS data at 1 Hz sampling, we stream the observations using the Radio Technical Commission for Maritime service protocol to an NTRIP Caster (Weber, 2002). At the CSN servers, these observations are processed using a precise point positioning (PPP) approach, including the International GNSS Service (IGS) real-time products (see Data and Resources). For coastal stations located between 18.4° S and 34.5° S we estimate the position on-site using the center point real-time positioning service, a method comparable to PPP (for details, see Glocker et al., 2012), before streaming these positions and respective errors to CSN servers. At the CSN servers, all observations are converted into a 15-s RINEX format (Gurtner and Estey, 2005) that are stored and published on an ftp server (see Data and Resources for details). CSN is currently using these data to produce daily solutions for several research efforts beyond the scope of early warning such as plate boundary and fault segmentation, locking rates, and interseismic straining (e.g., Bedford et al., 2013, 2016; Klein et al., 2016). In the following section, we will focus on the RT-GNSS products that are currently being used in the study of moderate-to-large earthquakes (magnitude 7.0 and above).

Currently, we are working on the implementation of a new system that is able to observe collocated displacement and acceleration (Minson et al., 2014). At each station, a smartphone generates smoothed position estimates derived from a single-frequency GNSS chip plus a three-component acceleration time series obtained from internal accelerometers. The idea of this system is to quickly detect an earthquake and then estimate its magnitude and location, similar to more conven-
ional early warning systems (Allen et al., 2009). Deployment was largely completed in 2017, and we expect to have an operational system in 2018.

RT-GNSS PRODUCTS AND THEIR APPLICATION TO SEISMOLOGY

Validation of RT-GNSS Products
The real-time positioning streams are monitored as continuous time series, so that the variation of position and respective errors can be clearly visualized. From these time series, we recover ground position, estimate peak ground displacement, derive ground velocity, and recover the static displacement due to moderate-to-large earthquakes (magnitude 7.0 and above). We tested the results obtained from RT-GNSS (the PPP solutions) by comparing them with strong-motion records (ACC) and PPP with ambiguity resolution (PPP-AR), using final orbits for recent events, as shown in Figure 2. PPP-AR solutions have a 15-day latency. Both GNSS time series (PPP and PPP-AR) are converted into velocity by differentiating, point by point, in the time domain. For the strong-motion records, for each trace, we first remove the trend, in the time domain, and then the instrumental response, in the frequency domain. We then integrate to obtain velocities in the time domain before applying a Butter-

Figure 2. A comparison between velocities derived from real-time (RT)-GNSS data, obtained from precise point positioning (PPP) with corrected orbits and the ambiguities resolution (AP) with final orbits solutions (PPP-AR), shown in black dots and dashed lines, respectively. The corresponding errors are shown with vertical bars (PPP-AR) and gray shading (for PPP). Dark gray line show strong-motion data (ACC), when available. Data belong to the following stations and events: (a) PB01 for the 2014 $M_w$ 8.1 Iquique, (b) LSCH for the 2015 $M_w$ 8.3 Illapel, (c) QLLN for the 2016 $M_w$ 7.6 Chiloé, and (d) VALN for the 2017 $M_w$ 6.9 Valparaiso. Note the comparisons are made in velocity, for the three components. The color version of this figure is available only in the electronic edition.
worth low-pass filter at 0.5 Hz. Figure 2 also shows the errors estimated at each point, shown in gray area for PPP and vertical bars for PPP-AR. Error magnitudes are generally comparable for PPP and PPP-AR solutions but there are notable error reductions in PPP-AR solutions for QLLN east–west and vertical components (Fig. 2c, middle and lower panels) and LSCH vertical component (Fig. 2b, lower panel). These comparisons are made for velocities (transformed from errors in displacement). The time series of PPP (dashed lines) and PPP-AR (black dots) show clear similarities, with the PPP having greater scatter than the PPP-AR time series, due to the differences in the used orbits (corrected vs. final). Additionally, we can see the similarities between the GNSS and strong-motion data (ACC) for velocity time series despite the high-frequency noise observed in the GNSS PPP data. To quantify the possible differences of PPP with respect to PPP-AR and ACC, we computed the cross correlation for all available traces, as shown in Table 1 (see caption for details). From this table, we see high correlations (always above 0.6) for all cases. For the comparison between PPP and PPP-AR (Table 1), east–west components show better performance, whereas up component, in general, presents smaller correlation coefficients. This could be due to the fact that the vertical component of GNSS is intrinsically noisier than the horizontal components. For the comparison between PPP and ACC, the north–south component gives the strongest correlation, with the up component showing the weakest correlation coefficient. We believe that these results demonstrate the suitability of RT-GNSS data for studies that require displacement waveforms. Results for all available GNSS stations for each of the events are shown in Figure S2a–d.

We show the average results for each component (north–south, east–west, and up) and the number of stations considered in each case.

<table>
<thead>
<tr>
<th>Event</th>
<th>North–South</th>
<th>East–West</th>
<th>Up</th>
<th>N Stations</th>
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<tbody>
<tr>
<td><strong>PPP versus PPP-AR</strong></td>
<td></td>
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<td></td>
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<tr>
<td>2014 Iquique</td>
<td>0.84</td>
<td>0.85</td>
<td>0.80</td>
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<tr>
<td>2015 Illapel</td>
<td>0.82</td>
<td>0.89</td>
<td>0.77</td>
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<tr>
<td>2016 Chiloé</td>
<td>0.62</td>
<td>0.64</td>
<td>0.64</td>
<td>5</td>
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<tr>
<td>2017 Valparaíso</td>
<td>0.66</td>
<td>0.73</td>
<td>0.64</td>
<td>7</td>
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<tr>
<td><strong>PPP versus ACC</strong></td>
<td></td>
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<tr>
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<td>0.63</td>
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<tr>
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<td>2</td>
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</table>

Application to Seismology

Figure 3 shows the east–west component of displacement for all GNSS stations located near the epicentral area for the following events: (a) 2014 $M_w$ 8.1 Iquique, (b) 2015 $M_w$ 8.4 Illapel, (c) 2016 $M_w$ 7.5 Chiloé, and (d) 2017 $M_w$ 6.9 Valparaíso. In this figure, the upper left corner of each panel shows a scale indicating the relative size of the displacement (vertical axis) and the time scale (horizontal axis). A black star shows the location of the epicenter, see figure caption for more details. All displayed traces in Figure 3 were processed in the same way: displacements were computed with respect to the average position 10 min before the origin time of each event. Recently, Riquelme et al. (2016) used these data to determine magnitudes and focal mechanisms from large earthquakes in Chile ($M_w \geq 8.0$), using these data to retrieve the $W$ phase. We tested a simple kinematic inversion considering the elliptical patches method (Leyton et al., 2018) for the 2014 $M_w$ 8.1 Iquique earthquake, successfully estimating a finite-fault plane (considering a single ellipse), the moment magnitude, and focal mechanism, as shown in Figure S3. In this figure, we also show the radial components of the RT-GNSS (black) and predicted (blue) traces for the considered stations. From these results, we believe that the use of RT-GNSS time series will play a key role in the rapid characterization of future large earthquakes, potentially giving crucial information for early warning systems.

From displacement time series, Melgar, Crowell, et al. (2015) have shown that the peak ground displacement enables a fast and robust estimation of magnitude, given an approximate location of the hypocenter. Furthermore, Melgar, Allen, et al. (2015) and Crowell et al. (2016) implemented these estimations in early warning systems such as G-FAST, and successfully applied these systems to Chile (Crowell et al., 2018). We reproduced part of their results for the same set of events previously shown in this article and found that, within the first 60–90 s from the origin time, we obtain an estimation of the magnitude with error of less than 0.3 (see Figure S4). Considering these results, it is clear that the tested methodology has great potential for early warning applications (Melgar, Allen et al., 2015; Melgar, Crowell et al., 2015; Crowell et al., 2016, 2018).

Finally, we estimate the coseismic static offset at each station produced by the earthquake (as shown in Fig. 4). These data have been extensively used to retrieve source parameters such as the slip distribution and moment magnitude (Moreno et al., 2012; Ruiz et al., 2014, 2016; Ruiz, Aden-Antoniow et al., 2017; Ruiz, Moreno et al., 2017). Figure 4 shows results of the slip distribution for the selected events (see figure caption for details). Note the changes in scale in each panel, ranging from centimeter deformations (panel (a) and (b) for magnitudes 7.7 and 6.9, for 2007 Tocopilla and 2017 Valparaíso earthquakes, respectively), up to several meters (central
panel for the 2010 $M_w$ 8.8 Maule earthquake). Slip distributions from coseismic static offsets can be determined within the first few minutes after the origin time, and are therefore another tool for early warning applications for moderate-to-large events (magnitudes 7.0 and above). We also tested the static offset results by comparing RT-GNSS data (PPP) with the better derivations that use final orbits (PPP-AR) (as shown in Table S2). Table S2 shows the coseismic static offset of both methods ($\text{PPP}$ and $\text{PPP-AR}$), estimated using the methodology described below; the root mean square (rms) of the difference between PPP and PPP-AR, along with the percentage difference with respect to the absolute value ($\text{PPP-AR}$) in Table S2. Finally, we compute the average coseismic offset and estimate the moment magnitude ($M_w$), as done in previous studies (Ruiz $et al.$, 2014, 2016; Ruiz, Aden-Antoniow, $et al.$, 2017; Ruiz, Moreno, $et al.$, 2017) for both estimations (PPP and PPP-AR). As seen for the RT-GNSS velocity time-series results (see the RT-GNSS Products and Their Application to Seismology section), even though we find differences between these two estimations, we believe that the results obtained from RT-GNSS data (PPP) can be successfully applied to the study of moderate-to-large earthquakes.

To recover the coseismic static offset, we identified the epoch $\tau_1$ of the onset of deformation at each station (following Psimoulis $et al.$, 2013), using a sliding window of 60 s for the average ($\mu$) and standard deviation ($\sigma$); $\tau_1$ will be defined as the epoch when the ratio between the corrected displacement (removing $\mu$) over $\sigma$ exceeds a threshold parameter $k = 3$ (see Psimoulis $et al.$, 2013, for details). The end of the main transient was defined as the epoch $\tau_2$, at which $\sigma$
diminished to three times its value at the detection onset. To retrieve the static offsets, we performed least-squares linear regressions in windows of 15 min, one just before $\tau_1$ and another immediately after $\tau_2$ and evaluated the difference between the linear trends at $\tau_1$.

An example is shown in Figure 5, where a 5 cm displacement to the west was successfully retrieved for the 2017 $M_w$ 6.9 Valparaíso event at station VALN; this figure shows the location of the epoch $\tau_1$ and $\tau_2$ described above.

**FINAL COMMENTS**

Many of the most exciting discoveries in subduction zone phenomenology during the last two decades have precipitated from the increased spatial density of continuously operating GNSS networks. We believe that such density increase will also benefit earthquake and tsunami early warning systems. In this study, we presented the state-of-the-art methods and products of the Chilean GNSS network, managed by CSN, with focus on the applications to real-time detection of coseismic deformation and rapid response capabilities for moderate-to-large earthquakes. GNSS data and modeling present two main advantages over traditional seismic products: (1) GNSS solutions do not saturate with magnitude; and (2) GNSS provides waveforms directly in displacement, avoiding the known problems of double integration of accelerograms. Currently, considerable resources are being devoted to testing and developing methodologies that rapidly provide useful and robust information for moderate-to-large earthquakes (magnitude 7.0 and above) using the RT-GNSS data.

In general, all CSN GNSS stations are analyzed using PPP software to produce continuous streams of positioning. Some of them work at each receiver, using correction products obtained from satellites, taking less than 1 s, on average, to arrive at the acquisition system. At other stations, the observations are streamed to CSN servers, where the PPP, including IGS corrections of orbit and clock, is performed. This data procedure takes 2 s, on average, to estimate and stream the results from the acquisition system. We do not believe that these time lags represent a significant delay to the rapid-response methodologies presented in this study. Therefore, real-time high-rate GNSS of the CSN network currently provides useful information to rapidly extract the static offset of earthquakes and to assess their seismic hazard.
DATA AND RESOURCES

All data used here were provided by Centro Sismológico Nacional (CSN) of the Universidad de Chile and can be retrieved from the Global Navigation Satellite Systems (GNSS) database (http://gps.csn.uchile.cl, last accessed June 2017). The other information can be found at International GNSS Service (IGS) can be retrieved from the Global Navigation Satellite Systems (GNSS) database (last accessed April 2018).

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