Displacement of the space geodetic observatory Arequipa due to recent earthquakes

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Summary

The space geodetic observatory at Arequipa (Peru) contributes to the maintenance of the International Terrestrial Reference Frame by providing continuous time series of GPS and SLR observations since many years. On June 23 and July 07, 2001 two earthquakes of magnitude 8.4 and 7.6, occurring at the boundary between the Nazca and South American tectonic plates, have severely damaged Arequipa. An analysis of six weeks of GPS data determines the coseismic displacements to 52.0 cm and 4.3 cm in SW-direction. The GPS observations allow also to assess significant postseismic velocities of 1.8 mm/day and 1.0 mm/day respectively. The occurrence of two minor earthquakes in early 2002 gave rise for processing again three weeks of GPS observations. There is no evidence of further coseismic displacements but the results confirm a slowing down of the last postseismic velocity. The observations acquired by the global SLR network were processed continuously up to April 2002. Due to the sparse data distribution compared to GPS as well as some lacks of observations at Arequipa itself, SLR is not capable of monitoring details of the displacements with the same resolution as GPS. Nevertheless, SLR confirms the main features such as the total displacement due to the two major earthquakes and the postseismic velocity after July 07, 2001.

Zusammenfassung

Die Satellitenbeobachtungsstation in Arequipa (Peru) trägt seit vielen Jahren mit kontinuierlichen Zeitreihen von GPS- und SLR-Beobachtungen zur Fortführung des Internationalen Terrestrischen Referenzsystems bei. Zwei Erdbeben der Stärke 8.4 bzw. 7.6, die sich am 23. Juni bzw. 7. Juli 2001 an der Grenze zwischen der Nazca- und der Südamerika-Platte ereigneten, haben in Arequipa erhebliche Schäden verursacht. Eine Analyse von sechs Wochen GPS-Messungen ergibt koseismische Verschiebungen von 52,0 cm und 4,3 cm in SW-Richtung. Aus den GPS-Daten lassen sich auch signifikante postseismische Geschwindigkeiten von 1,8 mm/Tag und 1,0 mm/Tag ableiten. Zwei weitere, allerdings wesentlich schwächere Erdbeben Anfang 2002 waren Anlass für die Auswertung einer weiteren Periode von GPS-Messungen. Die Ergebnisse zeigen keine erneute koseismische Verschiebung, sondern bestätigen das Abklingen der letzten postseismischen Bewegung. Die Beobachtungen des globalen SLR-Netzes sind kontinuierlich bis April 2002 prozessiert worden. Allerdings kann SLR wegen der vergleichsweise geringen Datenbelegung sowie des Fehlens einiger Messungen in Arequipa selbst die Details der Bewegungen nicht mit der hohen Auflösung wie GPS nachweisen. Die SLR-Ergebnisse bestätigen jedoch wesentliche Merkmale wie die Gesamtverschiebung aufgrund der beiden großen Erdbeben und die postseismische Bewegung nach dem 7. Juli 2001.

1 Introduction

The space geodetic observatory at Arequipa (Peru) contributes continuous time series of Satellite Laser Ranging (SLR) and Global Positioning System (GPS) observations since 1981 and 1994 respectively. As such, Arequipa is one of the most, if not the most important site in South America as regards the realization and maintenance of the International Terrestrial Reference Frame (ITRF). In particular, the SLR station is the only permanent one on the entire continent, and the system presently in operation belongs to the most well performing worldwide. The observations collected by both the SLR and the GPS are regularly processed at DGFI. The SLR data analysis is done in the frame of the International Laser Ranging Service (ILRS) global network, and the GPS observations are included in the permanent South American GPS network, processed by DGFI on behalf of the International GPS Service (IGS).

On June 23 and July 07, 2001 two major earthquakes occurred close to the Pacific coast of Peru, mutually affecting the location of the Arequipa site. In order to assess the coseismic insitu displacements as well as to identify any postseismic signals, we have performed dedicated analyses of GPS and SLR time series. The data periods of several weeks and months respectively included both earthquake epochs. The occurrence of two minor earthquakes on January 30 and February 03, 2002 gave rise to process another three weeks period of GPS observations covering the epochs of these events, while the SLR analysis was continuously extended to mid April 2002. After summarizing briefly the main characteristics of the seismic events, we outline the data analyses performed, and finally the obtained results are discussed in detail.

2 The Earthquakes

The first of the two major earthquakes with a magnitude of 8.4 on the Richter scale occurred on June 23, 2001 at 20:33 UTC. The epicenter was localized at the boundary between the Nazca and South American tectonic plate (USGS 2001), about 200 km west of Arequipa at a depth of 33 km. According to geological-geophysical models these two plates are converging towards each other with a rate of more than 7 cm/yr (Argus and Gordon 1991, De Mets et al. 1994). The earthquake resulted from thrust faulting along the plate boundary as the oceanic Nazca plate is subsiding beneath the South American plate.

As a consequence of this earthquake, large structural damages occurred in Arequipa and other places in southern Peru. Fortunately, the anticipated large coastal tsunamis did not occur, but more than 100 people were killed. The earthquake was also strongly felt in northern Chile, and the tide gauge in Arica recorded tsunamis reaching peak to trough wave heights of up to 2.5 m. Also several aftershocks were recorded, the strongest one not exceeding a magnitude of 6.8 (USGS 2001).

Two weeks later another earthquake of magnitude 7.6 occurred, this time south west of Arequipa at a distance of about 100 km. Table 1 summarizes the main characteristics of these two earthquakes, presumably leading to significant displacements of the GPS and SLR systems at Arequipa with respect to their previous positions. The table includes also the same information regarding the two minor earthquakes of early 2002.

3 Data Analysis

3.1 GPS

In order to assess the impact of the Peru earthquakes on the position of the GPS station in Arequipa, we analyzed an array of permanent GPS stations surrounding the earthquake area. The selection criteria for the sites to be included in the network were the continuous operation with a minimum of data gaps during the first processed period between June 17, 2001 and July 28, 2001 as well as their distance to Arequipa. Table 2 lists the selected stations; the 4-characters identifications are those used by the IGS. The large distances between AREQ and the other sites of between 1649 and 4007 km indicate the rather sparse distribution of permanent GPS stations in this area. Fortunately, the only data outages occurred on one and a half days at CUIB. It should be noted that there is no evidence of any earthquake effects on sites others than AREQ itself. It should also be mentioned that the receiver at Arequipa ceased operating upon the first earthquake for about two hours. Thus, the position estimate

Date	Time [UTC]	Magn. Ms	Depth [km]	Latitude [°]	Longitude [°]	Distance [km]	Azimuth [°]
2001, June 23	20:33:15	8.4	33	−16.15	−73.40	208	279
2001, July 07	09:38:43	7.6	33	−17.38	−71.78	106	197
2002, Jan. 30	06:10:51	4.6	85	−13.92	−72.83	319	332
2002, Feb. 03	12:59:32	4.7	33	−15.65	−72.03	107	328

Table 1: Locations and magnitudes of the Peru earthquakes (USGS 2001, 2002), distances and directions from Arequipa to epicenters

ID	Location (Country)	Dist. [km]
CORD	Cordoba (Argentina)	1808
CUIB	Cuiaba (Brasil)	1649
EISL	Easter Island (Chile)	4007
GALA	Galapagos (Ecuador)	2679
RIOP	Riobamba (Ecuador)	1811
SANT	Santiago (Chile)	1844

Table 2: Stations included in the analyzed GPS network and distances to Arequipa

for AREQ on June 23, 2001 refers to the time period prior to the seismic event.

During the second earthquake on July 07, 2001 the receiver proceeded tracking without loss of lock, and the 24 hours data file was split accordingly. Considering the observation rate of 30 seconds it seemed not worthwhile to analyze the phase measurements around the earthquake epoch in detail. The second processed period of GPS observations between January 22 and February 14, 2002 was centered around the epochs of the two minor earthquakes. During this entire period RIOP did not provide any data at all, and no observations from CORD were available during the last week.

In order to allow to relate the seismic effects to the kinematic of Arequipa prior to the events, figure 1 displays the horizontal velocities of the seven sites included in the analysis as predicted by the geophysical model NNR NUVEL-1A (Argus and Gordon 1991, De Mets et al. 1994) and as resulting from geodetic space technique observations. The two geodetic solutions represented in the figure are:

- The latest realization of the International Terrestrial Reference Frame, ITRF2000 (http://lareg.ensg.ign.fr/ITRF/ITRF2000). ITRF2000 is a combination of global network solutions based on different space techniques, as well as regional GPS densifications. Besides GPS, in particular Satellite Laser Ranging (SLR) and Very Long Baseline Interferometry (VLBI) contribute. The ITRF realization implies also no net rotation conditions and includes data up to early 2000.
- The most recent solution of the permanent South American GPS network computed by DGFI as IGS Regional Network Associate Analysis Center (RNAAC): this adjustment labeled DGFI01P02 includes observations from July 1996 on to end of July 2001. It is based on ITRF2000 by referring the network to a few highly accurate fiducial sites. A brief discussion of the applied analysis strategy is given in (Seemüller et al. 2002). The advantage of this regional solution over ITRF2000 should be the higher reliability of position and velocity estimates due to the considerably increased data time spans of some rather lately or not continuously operational sites. Regarding the present analysis, this applies in particular to the stations CORD, CUIB and RIOP.

The tremendous discrepancies between the geophysical model and the geodetic results showing up at AREQ and SANT are due to the fact that NUVEL-1A is not modeling deformations in plate boundary zones. Another, but yet well known phenomenon is the slower convergence of the Nazca plate towards South America compared to the geophysical prediction (Angermann et al. 1999, Norabuena et al. 1998, Norabuena et al. 1999).

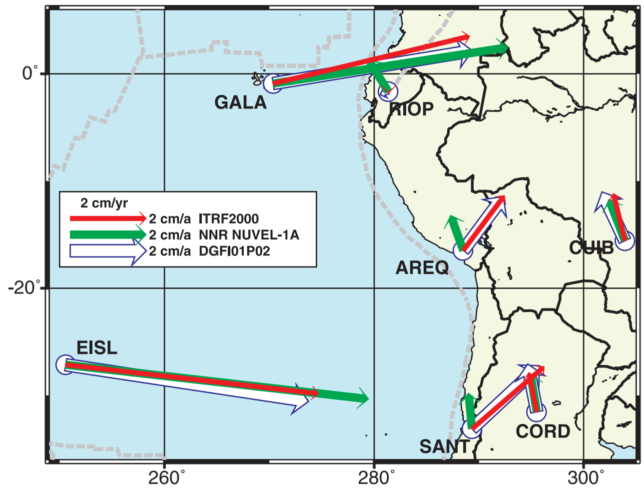

Fig: 1: Locations of the GPS stations included in the analysis and their horizontal velocities according to NNR NUVEL-1A, ITRF2000 and the latest DGFI solution

Both data sets covering 42 and 24 days respectively were processed with the Bernese Software version 4.2 (Hugentobler et al. 2001), the main characteristic of which is the analysis of between stations and between satellites double difference phase observables. The satellite orbits, satellite clock offsets and Earth orientation parameters were fixed to the final IGS products, being a combination of the results provided by several analysis centers and referring to the ITRF adopted at the observation epoch. The selection of models and settings for the least squares adjustment was based on experiences gained in previous analyses (Kaniuth et al. 1998, Kaniuth et al. 2002):

- The model by Saastamoinen (1973) and the mapping function by Niell (1996) were applied for predicting the tropospheric path delays; residual zenith delays were estimated for two hours intervals.
- The minimum elevation angle was set to 10°, and no elevation dependent weighting was applied in order to fully exploit the low elevation data.
- The Quasi Ionosphere Free (QIF) strategy was applied for fixing the initial L1 and L2 phase ambiguities.
- The periodic site displacements due to ocean tide loading were modeled according to the FES95.2 ocean tide model (Le Provost et al. 1994).

Each day was preprocessed separately, saving the unconstrained normal equations for further combination. The following two alternative strategies were applied for deriving the effects of the earthquakes on AREQ:

- Performing daily network adjustments solving for the position of AREQ and tightly constraining the fiducial sites, thus generating a time series of daily position estimates;
- performing common adjustments of all 42 or 24 days respectively solving for the instantaneous displacements of AREQ and for the inter- and postseismic velocities as linear functions in time, again constraining the fiducials.

Thus the reference frame was in both approaches realized by the positions and velocities of the six fiducial stations, either adopted from ITRF2000 or from the regional DGFI solution. The constraining is achieved by either simply fixing the fiducials, solving for similarity transformation parameters between the free and the fiducial sets of positions and velocities, or applying individual weights to the fiducial points. Among these alternatives, the latter one seemed to be the most appropriate choice accounting best for the accuracy differences between the fiducials. Considering its mentioned advantages over the ITRF 2000, the regional South American GPS network solution by DGFI was adopted as reference frame for the final results.

Figure 2 displays the time evolution of the daily position components of AREQ during the first analyzed period. The figure is not only showing the instantaneous displacements caused by the two major earthquakes but demonstrates also the high consistency of the daily estimates, in particular of the horizontal position components. As expected both earthquakes of magnitude less than 5 in early 2002 did not lead to any significant coseismic effects on AREQ. However, the new position estimates provide further information regarding the evolution of the postseismic velocity after July 07, 2001.

The results of the second approach, the common adjustment of all days of data, are summarized in table 3, again for the solution based on applying individual weights to the fiducials. The table gives the coseismic displacements due to both major earthquakes and the postseismic velocities in the horizontal as well as the vertical components. The one sigma standard deviations resulting from the adjustment are less than one mm for the horizontal and vertical coseismic displacement components. In case of the postseismic velocities the standard deviations of the estimates are less than 0.1 mm/day for all three components.

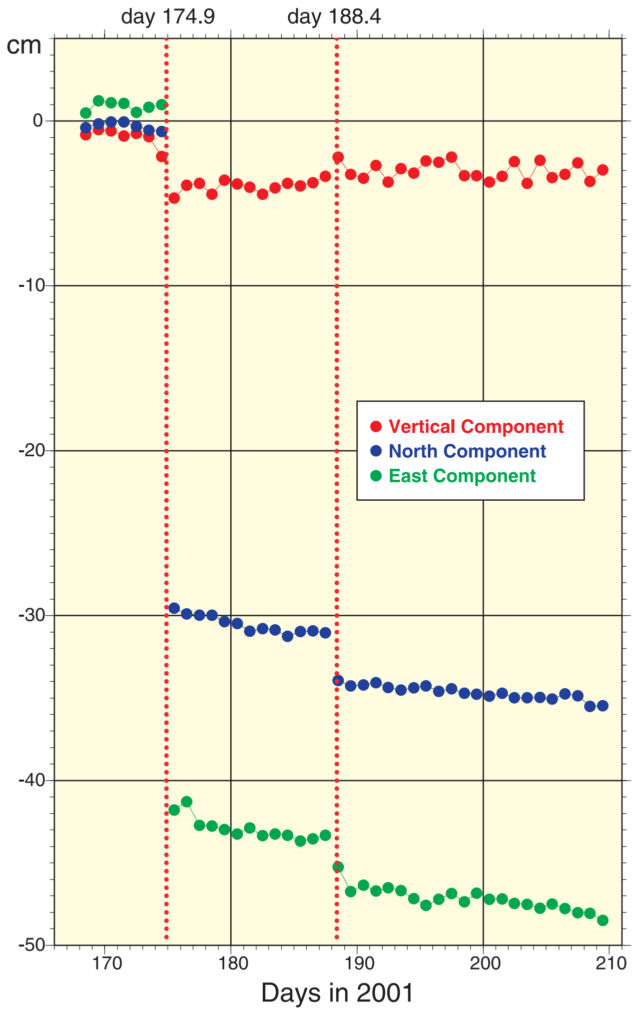

Fig. 2: Daily estimates of the AREQ position components in the reference frame realized by the fiducial stations

3.2 SLR

The SLR data analysis comprised the processing of the range measurements to Lageos-1 and Lageos-2 acquired by the global laser tracking network during the period

Displacement	North	East	Height	Length	Azimuth
Coseismic displacement [mm]					
– June 23, 2001	–294	–428	–38	520	234°
– July 07, 2001	–30	–31	+7	43	225°
Postseismic velocity [mm/day]					
– June 23, 2001 → July 07, 2001	–1.3	–1.3	0.4	1.8	223°
– July 07, 2001 → July 28, 2001	–0.6	–0.8	0.0	1.0	214°
– July 07, 2001 → Feb. 14, 2002	–0.2	–0.2	0.0	0.3	216°

Table 3: Displacements of the GPS station AREQ resulting from the common adjustment of the two data sets in the reference frame realized by the fiducial stations

January 01, 2001 to April 12, 2002. Each measurement represents a normal point generated at the tracking site from all observations performed during a two minutes interval. We used DGFI's Orbit and Geodetic parameter estimation Software DOGS; a documentation can be found under projects at http://www.dgfi.badw.de .

In a first step 67 weekly orbital arcs were processed separately for both satellites. Compared to GPS the data distribution is rather inhomogeneous. Therefore, the number of involved stations varied between 18 and 28, and each arc comprised between 89 and 197 satellite passes with about 900 to 2200 normal points. Table 4 summarizes the data resources available during the periods prior to the first major earthquake, between the two events and after the second major shock. The reference frame definition, the force field and measurement modeling followed the IERS conventions (Mc Carthy 1996). The a priori station coordinates were based on our multi-years SLR solution (Angermann et al. 2001).

Period	Lageos-1		Lageos-2	
2001/2002	SP	NP	SP	NP
Jan. 01 – June 23	52	550	69	747
June 24 – July 06	2	8	2	30
July 07 – Sept. 30	49	515	36	348
Oct. 01 – April 12	35	285	35	295

Table 4: Number of available satellite passes (SP) and normal points (NP) at Arequipa

The set of adjustment parameters included six orbital elements, weekly corrections to the empirical along track acceleration and the solar radiation pressure as well as daily Earth orientation parameters. In addition, depending on statistical tests, we solved for pass specific range and time biases. Table 5 gives some information regarding the quality of the adjusted orbits. As can be seen the root mean square (rms) fit between the Arequipa data and the orbits is slightly worse than for the entire network. This is due to the fact that we did not exclude any measurements at Arequipa. From these single satellite arcs normal equations including station positions and velocities as solve for parameters were generated. These weekly normal equations were accumulated and solved after adding datum information.

The datum of the SLR solution is realized by applying six condition equations (Gerstl 1999) minimizing the common rotation and rotation rate with respect to our multi-years solution for eight globally distributed stations of high performance.

Satellite	All Stations	Arequipa
Lageos-1	9.8	11.0
Lageos-2	9.7	12.9

Table 5: Root mean square orbital fit [mm]

It is obvious from table 4 that the few observations at Arequipa during the two strong earthquakes do not allow to separate the coseismic displacements and the motion between the shocks from each other. Therefore, our displacement estimate includes all three contributions. In order to assess whether the postseismic motion after the second major quake on July 07 is constant or is easing off with time we solved for the velocities during two time spans, the first one from the event to September 30, and the second one from October 01 to April 12, 2002. Table 6 summarizes the obtained results.

The standard deviations of the displacement components given in table 6 are 4.5 mm on the average. In case of the velocity estimates these are less than 0.1 mm/day.

4 Conclusion

The horizontal motions of the Arequipa site as resulting from the GPS and SLR data analyses are displayed in figure 3. As concerns GPS, the coseismic displacements due to both major earthquakes as well as the released postseismic velocities are shown. In case of SLR the figure gives the total difference between the positions prior to the June 23 shock and after the July 07 event. In addition, the creeping motion after July 07 is shown.

Comparing the results, one should consider that the GPS estimates are based on continuous series of observations during the processed periods, resulting in a total of 4.8 million double difference phase measurements, whereas the SLR solution suffers from some lacks of observations at Arequipa itself. Thus, although the agreement between both techniques is not perfect, SLR confirms the main features and the appearing differences are within the confidence margins. One should also consider that the monumentation of both systems at Arequipa is quite different. Whereas the GPS antenna is mounted on

Displacement	North	East	Height	Length	Azimuth
Total displacement [mm]					
– June 23, 2001 → July 07, 2001	−334	−487	−13	590	236°
Velocity [mm/day]					
- July 07, 2001 → Sept. 30, 2001	−0.1	−0.3	0	0.3	252°
- Oct. 01, 2001 → April 12, 2002	−0.1	−0.1	0.1	0.1	218°

Table 6: Total displacement of the SLR station Arequipa due to both major earthquakes and postseismic velocities

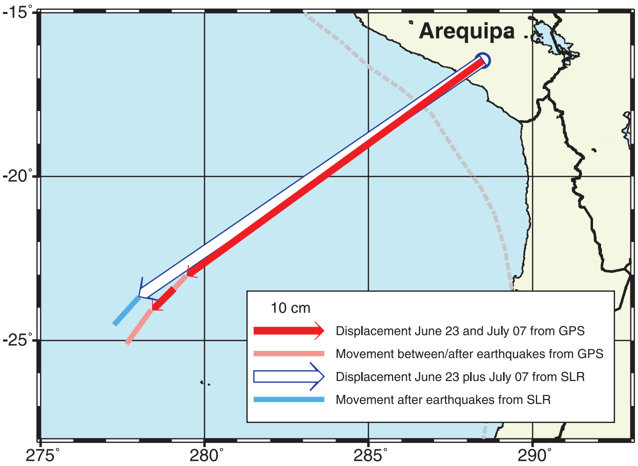

Fig. 3: Coseismic displacements and postseismic motions of Arequipa resulting from GPS and SLR analyses

the roof of an office building of the Smithsonian Astronomical Observatory, the Transportable Laser Ranging System (TLRS) is housed in a container placed on a concrete pad. Thus, both set-ups might have experienced slightly different shock effects.

An attempt to solve in the GPS adjustment for nonlinear postseismic motions indicated indeed that the velocities given in table 3 are averages during the specified periods but might not completely match the real site motion in detail. In particular, the motion after the June 23 earthquake of 1.8 mm/day may be superimposed by small additional episodic displacements because about 30 aftershocks of magnitudes stronger than 5.0 occurred during the first days after the main shock.

As concerns the postseismic motion after the July 07 earthquake, both GPS and SLR confirm that the initial velocity of 1.0 mm/day during the first weeks was slowing down and eased off completely after a few months. As regards the vertical component, the coseismic subsidence of about 38 mm on June 23 was partly compensated by subsequent uplift.

Trying to assess the implications of the earthquakes at the Arequipa site on the International Terrestrial Reference Frame (ITRF) we refer mainly to the GPS results. The following corrections to the ITRF should enable users to meet the earthquake effects to a large extent:

- Application of leaps to the previous ITRF cartesian coordinates [mm]:

June 24, 2001		
ΔX = −445	ΔY = −23	ΔZ = −270
July 07, 2001		
ΔX = −474	ΔY = −30	ΔZ = −300

- Application of average velocities [mm/day]:

After June 23, 2001		
VX = −1.3	VY = −0.4	VZ = −1.3 until July 06
After July 07, 2001		
VX = −0.5	VY = −0.1	VZ = −0.4 for about two months.

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