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Monitoring global climate change using SLR data from LARES and other geodetic satellites

Antonio Paolozzi[a,b]*, Claudio Paris[b,a], Erricos C. Pavlis[c], Giampiero Sindoni[a], Ignazio Ciufolini[d,b]

[a]Scuola di Ingegneria Aerospaziale, Sapienza University of Rome, Via Salaria 851, 00138 Rome, Italy; [b]Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi, Via Panisperna 89, 00184 Rome, Italy; [c]Joint Center for Earth Systems Technology, University of Maryland, Baltimore County and NASA Goddard, Baltimore, Maryland USA; [d]Dipartimento di Ingegneria dell'Innovazione, University of Salento, Via per Monteroni snc, 73100 Lecce, Italy

ABSTRACT

The Earth Orientation Parameters (EOP), i.e. the spin axis of the Earth, is influenced by the mass redistribution inside and on the surface of the Earth. On the Earth surface, global ice melting, sea level change and atmospheric circulation are the prime contributors. Recent studies have unraveled the majority of the mysteries behind the Chandler wobble, the annual motion and the secular motion of the pole. The differences from the motion of a pole for a rigid Earth is indeed due to the mass redistribution and transfer of angular momentum among the atmosphere, the oceans and solid Earth. The technique of laser ranging and the use of laser ranged satellites such as LARES along with other techniques such Very Long Baseline Interferometry (VLBI) allow to measure the EOP with accuracies at the level of ~200 μas which correspond to few millimeters at the Earth's surface, while the use of Global Navigation Satellite System (GNSS) data can reach an accuracy even below 100 μas. At these unprecedented high levels of accuracy, even tiny anomalous behavior in EOP can be observed and thus correlated to global environmental changes such as ice melting on Greenland and the polar caps, and extreme events that involve strong ocean-atmosphere coupling interactions such as the El Niño. The contribution of Satellite Laser Ranging (SLR) data such as from the LARES mission and similar satellites to this area is outlined in this paper.

Keywords: Smart Disaster Mitigation, Satellite Laser Ranging, Global Climate Changes, Earth orientation parameters, LARES satellite, Laser Relativity Satellite, Earth angular momentum, Greenland ice melting

1. INTRODUCTION

Mass movement on the surface (air, water, ice, biosphere) and in the interior of the Earth, will change its inertial properties that can be detected by accurate monitoring of the Earth rotation axis and center of mass. Particularly on this last one, very significant is the contribution of Satellite Laser Ranging (SLR). The technique of laser ranging is the most accurate in determining absolute distances. By targeting satellites equipped with laser retroreflectors it is possible to reconstruct their orbit with high accuracy and consequently the center of mass that theoretically is at the focus of the satellite orbit. About 40 laser ranging stations of the International Laser Ranging Service (ILRS) collect raw data (called full range data) and deliver a reduced set of data (called normal points) to data centers for further analysis. In combination with other techniques such as VLBI, GNSS and DORIS, the International Terrestrial Reference System Service (ITRS), develops up-to-date International Terrestrial Reference Frames (ITRF) that include daily resolution time series of the Earth spin axis and Length of Day (LOD). The Earth rotation axis is subjected to several motions such as the precession of the equinox that are due to gravitational pull of other bodies in the solar system. Limiting our attention to the internal causes, it is possible to extract information on climate change [1,2] due to the mass redistribution and/or angular momentum exchange with the solid

*antonio.paolozzi@uniroma1.it, phone +39 06 49919767; www.lares-mission.com

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Earth of the atmosphere, water and ice [3]. Particularly interesting is the correlation found in [4] between the ice melting in Greenland and polar caps and a deviation on the secular drift of Earth rotation axis.

2. CONTRIBUTION FROM LARES-LIKE SLR

Passive geodetic satellites are characterized by spherical shape and by the use of Cube Corner Reflectors (CCRs), positioned on the surface of the satellite. By three reflections on the three back faces, CCRs guarantee the reflected signal return towards the ranging station of the ILRS [5] independent of the CCR orientation (within a certain acceptance angle which is about +/- 25 degrees from normal to the front CCR face). The accurate estimate of the time of flight allows the positioning of the CCRs and consequently of the satellite with accuracies that can reach the millimeter level. LARES satellite is the last among this class of satellites to be launched. It was put in orbit on February 13, 2012 with the VEGA launcher [6], with the main objective to improve the accuracy of the measurement of frame-dragging or the Lense-Thirring effect [7] from 10% [8] to about 1% [9] as shown by the error analysis [10] and by a Monte Carlo simulation [11].

To achieve this goal it was important to have the satellite approaching the behaviour of an ideal test particle. This objective was reached using a high-density material (tungsten alloy) [12] and a proper thermal design to reduce thermal trust perturbation [13,14]. The preliminary results confirm the good design of the satellite [15,16]. This design proves to be good also for geodesy: although LARES data are not yet officially introduced into the determination of the last ITRF, released in late 2015, it will certainly be part of the next determination of the ITRF with an expected accuracy improvement of about 20% [17]. The improved accuracy will allow smaller variation on global Earth parameters such as rotation axis vector variations and the motions of the geocenter. These in turn, if well correlated, can be used to monitor smaller and smaller global environmental changes. In the next sections we will show how the laser ranging data integrated with the other geodetic techniques VLBI, GNSS and DORIS show signature of the ENSO events.

3. EL NIÑO SOUTHERN OSCILLATION

The ENSO is a coupled sea/atmosphere circulation event in Earth's fluid envelope, that unravels in the equatorial part of the Pacific Ocean. It is quasi-periodic with no clear regularity: it appears every 2 to 7 years, its strength differing during each event, and to this date, there is no possibility to predict the most extreme ones. Those have happened for instance during 1982-1983, 1997-1998, 2002-2003 and more recently, during 2015-2016. There is no possibility to predict this event since what triggers this phenomenon is not known, although many relations among barometric pressure, wind speed and direction, sea level and temperature have been found. ENSO appears usually during Christmas time (that is where the name El Niño comes from). In normal conditions the east coast on the Pacific Ocean, off Ecuador and Peru there is a high pressure and dry whether while on the other side of the Pacific the conditions are reversed Figure 1. Trade winds flows from east to west causing an increase of the sea surface level of about 0.7 m. Water is warmer on the east and the weather is rather rainy. During an ENSO event, for not yet known reasons the trade winds that flow westwards (they are in fact also called easterly winds) reduce in strength. As a result the sea level difference between the east and west coasts of the Pacific Ocean reduces by about 0.5m, also the ocean temperature and pressure reverse, resulting in dry weather on the west coast and wet weather on the east (Figure 1). This condition produces weather anomalies all over the world. An index that characterizes El Niño is displayed in Figure 2 and based on observations of such events, they can be ranked for their severity (Figure 3), with the more recent one (2015-2016), preliminary set near the top and only second to the 1997 event.

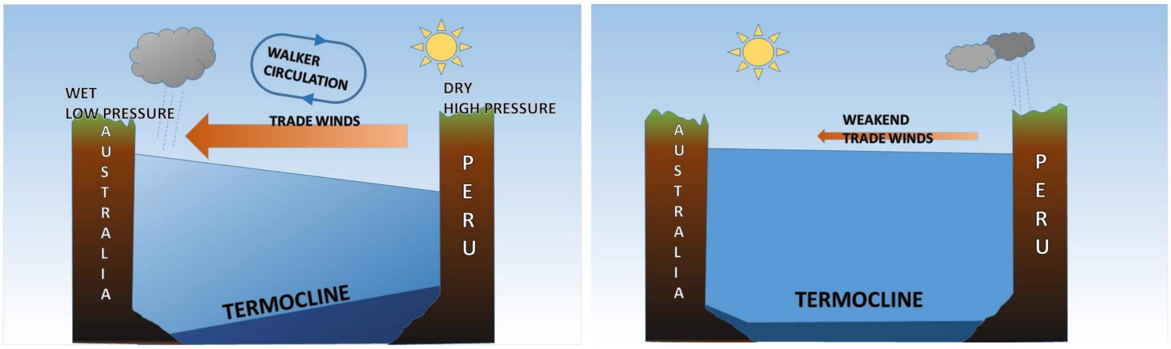

Figure 1. Schematic of the normal condition (left), schematic of the El Niño (right).

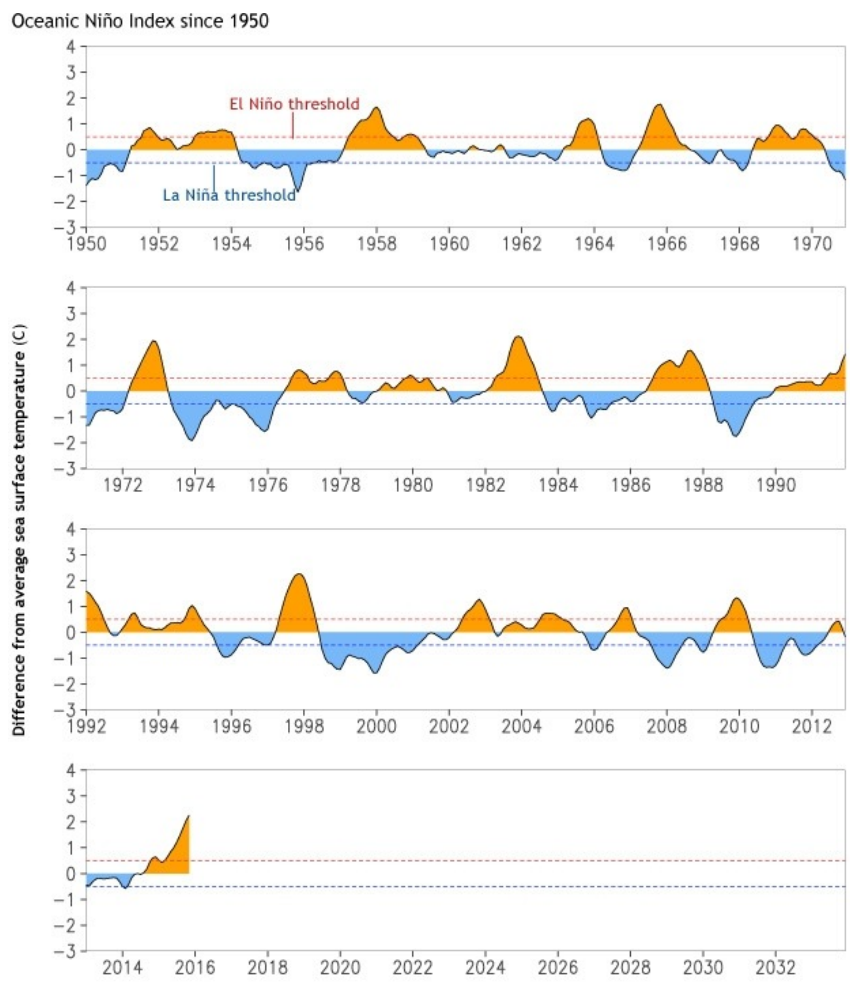

Figure 2: ENSO index 1950 to present. (source: NOAA Climate Change).

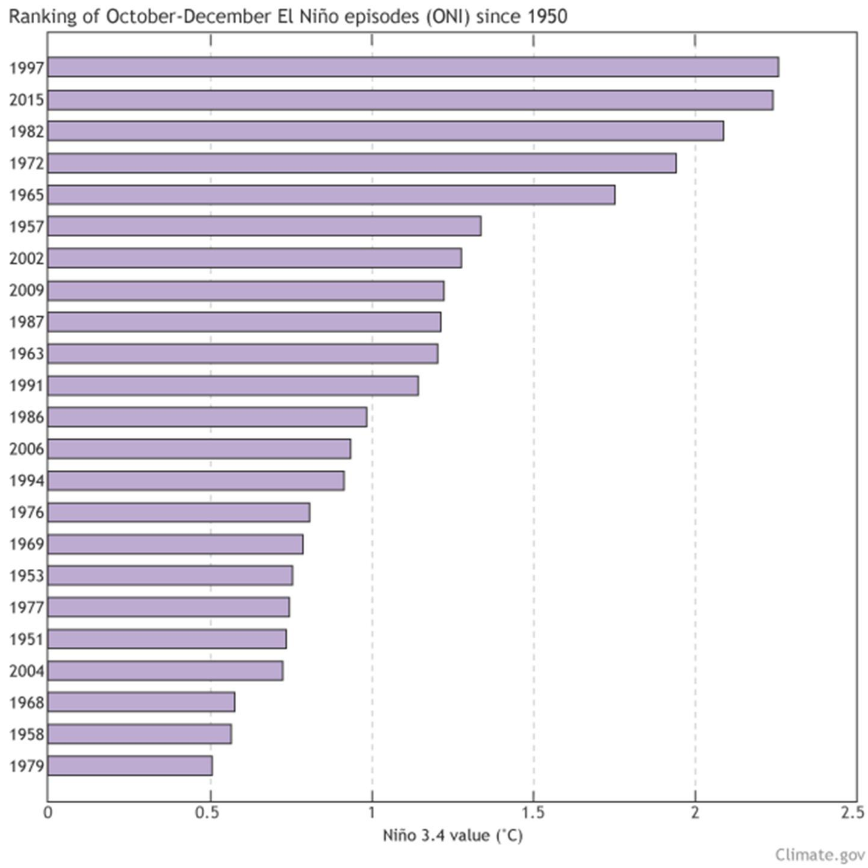

Figure 3: Ranking the various El Niño events from 1950 to present, (source: NOAA Climate Change).

4. SIGNATURE OF ENSO ON EARTH GLOBAL PARAMETERS

An El Niño event involves big changes in heat content over vast areas of the planet, the exchange of angular momentum between the ocean and the atmosphere and redistribution of masses in the Earth system. These processes impact Earth's rotation, especially in terms of its rate, and the location of the instantaneous center of mass with respect to the polyhedron of tracking sites located on the rigid surface of the planet. The satellites orbit about the instantaneous center of mass of the whole planet, in the case of Earth we refer to the "geocenter", and we thus have the unique opportunity to determine these variations from their precise tracking. Satellite Laser Ranging, uses very precise absolute ranging to stable targets such as the two LAGEOS and the LARES spacecraft, all of which are spherical with cube-corner retroreflectors, and after the appropriate reduction of these data, one can determine the Earth-fixed position of tracking stations as well as the orientation of the rotational axis of Earth (polar motion) and variations in its spin rate or the so-called excess length of day (LOD). The Earth Orientation Parameters can also be obtained from other geodetic techniques such as VLBI and GNSS, however, SLR is the only technique that can sense with sufficient accuracy the motion of the geocenter. The first significant El Niño event that was studied extensively using space geodetic data, was that of 1982-1983 (number #3 from top in Figure 3). In those early days of space geodesy the laser ranging network was very sparse to produce results from ranging to satellites, so data taken actually on reflectors on the Moon were used, and the only other contributing techniques were optical astrometry and VLBI. A decade later, studying the decomposition of the LOD series in its basic constituents revealed the huge effect that El Niño had on LOD, as it can be seen in Figure 4 from [18]. The same graph indicates that there may have been a previous event in 1972-1973 based on the interannual signal variations, which at the time it was not possible to assess, however, today, with the better understanding we have, this is identified as another major event and it ranks fourth in Figure 3.

The organization of the ILRS as a scientific Service of the International Association of Geodesy (IAG) in the mid-90s resulted in a better-coordinated and stronger tracking network and the initiation of more products from the ILRS Analysis Centers. One of the first of such products was the frequent monitoring of the variations of the geocenter, initially at 15-day intervals [19] and eventually at weekly resolution [20]. A weekly time series of the geocenter position with respect to the origin of the reference ITRF (ITRF2000 at the time), is shown in Figure 5 [21].

Spectral analysis of these time series revealed a strong annual term with an amplitude of about 3 mm in the equatorial components ΔX and ΔY, and slightly larger one at about 5 mm for the axial component ΔZ. What is of interest here though are not the periodic constituents that can be easily rationalized by the seasonal redistribution of fluids on Earth's surface, but rather the transients that we observe after removal of the periodic constituents. Two large such terms are seen in the ΔX component, with a peak near 1997 and 2003, and similarly for ΔZ, although not as significant as in the case of ΔX.

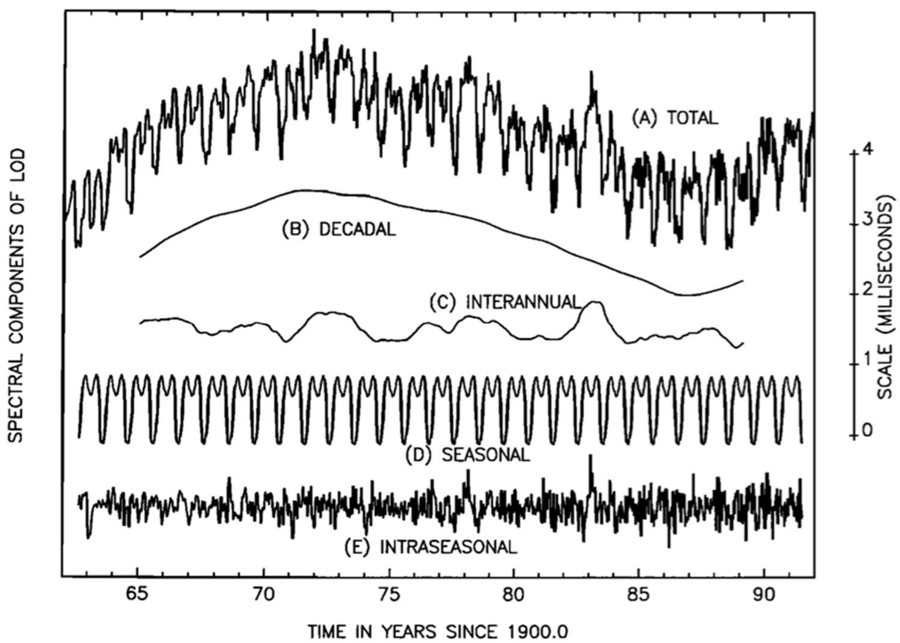

Figure 4: Decomposition of the LOD in its spectral components, revealing the significant contribution of the 1982-1983 El Niño to the interannual and intraseasonal components [18].

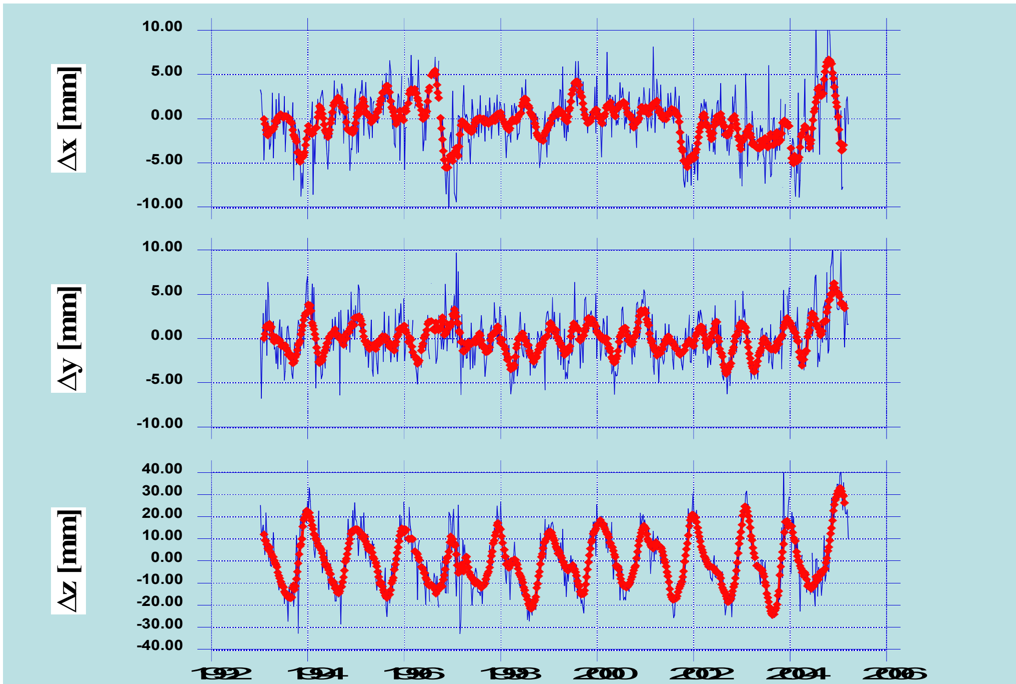

Figure 5: Weekly averaged offsets of the "geocenter" from the origin of the reference frame defined by the geodetic tracking stations collecting the SLR observations used to derive these results [21].

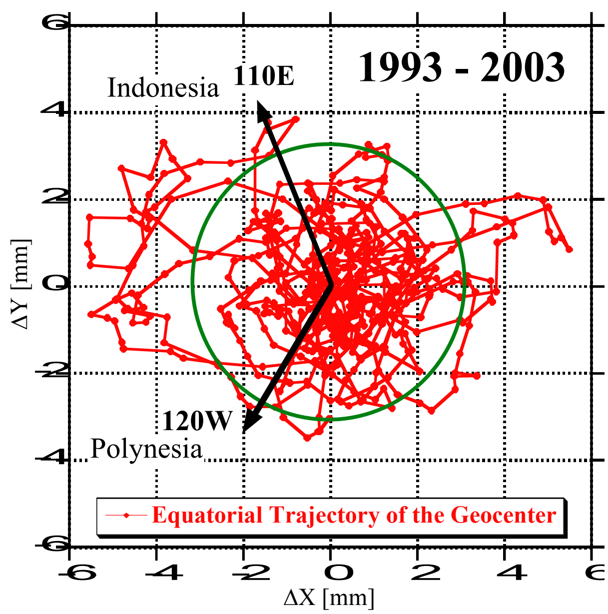

Figure 6: Equatorial projection of the trajectory of the weekly "geocenter" offsets from the origin of the reference frame defined by the geodetic tracking stations collecting the SLR observations used to derive these results [21]. The arrows mark the boundaries of the Pacific basin between Indonesia and Polynesia, the region where sea level rises during El Niño events.

If we plot the equatorial components ΔX and ΔY over the period covered by these series, nearly all of the weekly locations of the equatorial projection of the geocenter fall within a 3 mm radius circle around the origin of the ITRF in the form of a "cloud" of randomly distributed points (Figure 6). There are however some excursions outside this circle and if one examines these time periods, they happen to be those during the two El Niño events, the 1997-1998 (Figure 7a) and 2002-2003 (Figure 7b).

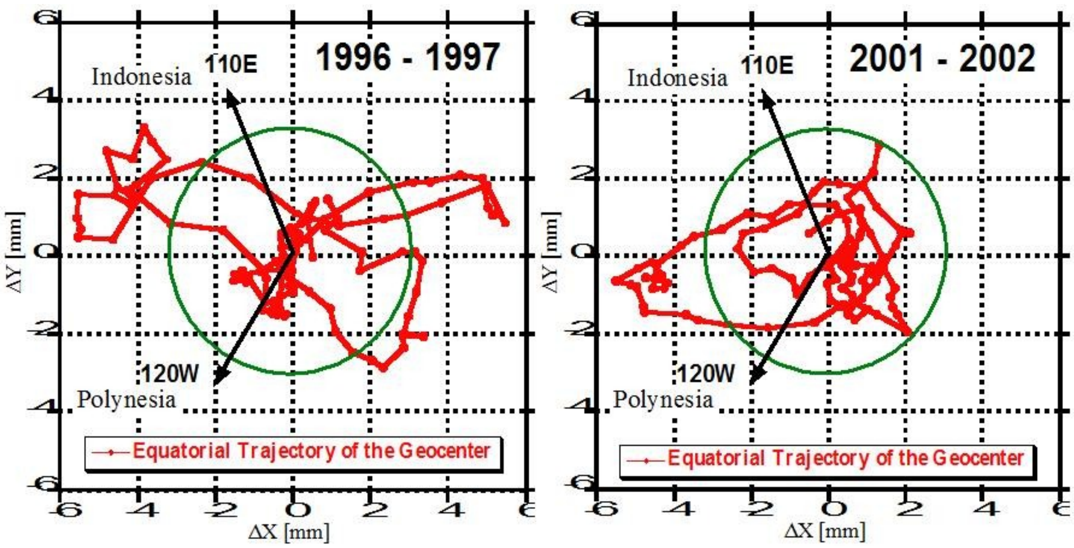

Figure 7: Equatorial projection of the trajectory of the weekly "geocenter" offsets as in Fig. 6, except that in these cases the time period covered by the plotted data are the years indicated on each plot. On the left (a) shows the geocenter trajectory just before and during the 1997-1998 event [21]; on the right figure (b) similar to (a) but this time for the 2001-2002 event.

In the case of the 1997-1998 event, the geocenter shifted (primarily equatorially) by about an additional 2 mm in the direction of Southwest Pacific, that was preceded by a smaller excursion towards Indonesia (both along the X-axis). The shift in the second case, for the 2002-2003 event, can be explained by a water mass of about 2000 km^3, that spread over a ~50° cap centered over the area, which implies a ~2 cm increase in SSH. During the 2002-2003 event, the geocenter shifted again (primarily equatorially) by about an additional 2 mm in the direction of Southwest Pacific, this time though, this shift was preceded by a smaller shift towards the middle of the Pacific basin. Furthermore, this time the shift is a combination of anomalous X and Y change, while in the 1997-1998 event it was almost entirely due to the change in the X component.

The current event is being monitored now and by the time it reaches culmination, over the next few months or so, the SLR-derived geocenter time series covering the period 2015-2016 will be examined for similar excursions as in the case of the above two mentioned prior events.

5. CONCLUSIONS

The products of the SLR technique from tracking with highly accurate ranging systems dedicated targets such as the two LAGEOS and LARES satellites, are used to monitor significant changes in the location of the instantaneous geocenter with respect to the origin of the conventional reference frame and in Earth rotation. Recent past ENSO events with major signals have introduced clear signatures in the geocenter and in Earth rotation as seen from the examination of the SLR-derived series at the time. The SLR data collected during the 2015-2016 period are used to develop similar products that will help determine if the new event will impact the geocenter and Earth rotation in same way as in the case of past El

Niño events. The addition of more LARES-like satellites in orbit will allow SLR to generate accurate geocenter determinations at even higher resolution (e.g. daily instead of weekly), and several efforts are focused in that direction today.

6. ACKNOWLEDGMENTS

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