Effects of Climate Change on Earth's Parameters
An Example of Exabyte-sized System

Giampiero Sindoni[1], Erricos. C. Pavlis[2], Claudio Paris[3,1], Antonio Paolozzi[1,3] and Ignazio Ciufolini[4,3]

[1]*Scuola di Ingegneria Aerospaziale, Sapienza University of Rome, Via Salaria 851, 00138 Rome, Italy*

[2]*Joint Center for Earth Systems Technology (JCET/UMBC), University of Maryland, Baltimore County and NASA Goddard, 1000 Hilltop Circle Baltimore, 21250 Maryland, U.S.A.*

[3]*Museo Storico della Fisica e Centro Studi e Ricerce Enrico Fermi, Via Panisperna, 89, 00184 Rome, Italy*

[4]*Dipartimento di Ingegneria dell' Innovazione, Università del Salento, Via per Monteroni, 73100 Lecce, Italy*

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Abstract: Climate change at global scale affects Earth characteristics that can be detected by measuring global parameters such as Earth rotation and centre of mass variations. Similarly, changes in the harmonics of Earth's gravitational field model are an indication of environmental changes and provide a measure of the mass redistributions causing these variations. There are four independent space geodetic techniques today that monitor Earth's geometric and dynamic parameters very accurately: Very Long Baseline Interferometry (VLBI), Satellite/Lunar Laser Ranging (SLR/LLR), Global Navigation Satellite Systems (GNSS) and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS). These techniques have been operational for decades, collecting a very large amount of data that after appropriate processing provide, among other things, the Earth geometric and dynamic parameters used in global climate change monitoring. The same techniques are also necessary for the establishment and maintenance of the International Terrestrial Reference Frame (ITRF). To make the large amount of data more easily usable, scientists and engineers employ reduction techniques to significantly reduce the amount of raw data with minimal loss of information. It will be shown that the total amount of data available today is of the order of exabyte. Due to the complexity of data management and processing several national and international bodies have been established.

1 INTRODUCTION

Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Global Navigation Satellite Systems (GNSS) and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) although each can provide independent Earth parameters, the combination of their data allows to negate the weaknesses and complement the strengths of the individual techniques. The first two techniques are the oldest and the available data span over periods of more than three decades. Processing is usually performed using the longest time series constructed going back to the oldest acquisitions. This improves confidence on the analysis that are substantially based on fitting the models of the Earth parameters evolution with the data.

The complexity involved in integrating the four techniques is very high. In fact the planning and operational management for the acquisition, storage, distribution, quality check, data formatting, and adherence to standards is the task of international bodies established as Services as will be described in detail in section 3. While GNSS have a mass market the other three techniques are more institutional oriented and in particular SLR that is devoted mainly to studies on geodesy but also to fundamental physics (Ciufolini et al., 2013b) and gravitational physics (Bosco et al., 2007). In particular the use of the orbital parameters of the two LAGEOS satellites allowed an accurate measurement of the Lense-Thirring effect, a manifestation of frame-dragging (Ciufolini et al., 2012b; Ciufolini and Ricci, 2002) of the General Relativity theory, with an accuracy of about 10% (Ciufolini et al., 1998; Ciufolini and Pavlis, 2004). LARES is the latest laser ranged satellite (Paolozzi et al., 2015), it has been funded by the Italian Space Agency (ASI) and launched on February 13, 2012 (Paolozzi et al., 2012;

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Paolozzi and Ciufolini, 2013) by the VEGA launcher provided by the European Space Agency (ESA). With the addition of this new satellite the accuracy in the measurement of the Lense-Thirring effect will be improved by one order of magnitude as shown by a Monte Carlo simulation (Ciufolini et al., 2013a), an error analysis (Ciufolini et al., 2012a) and the results of the preliminary orbital analysis (Ciufolini et al., 2015). The ever increasing accuracy of the geodedic techniques allow to detect very small variation of spin axis, angular velocity and center of mass of the Earth. Those small variations are related to several factors among which the angular momentum exchange between the solid Earth and atmosphere which is not perfectly co-rotating with the Earth because of winds, air jets, tornadoes etc...(Kouba and Vondrk, 2005). There have been also recent studies that found correlation between Earth Rotation Parameters (ERP) variations and global climate change. (Lehmann et al., 2009). Some more details on Earth global parameters and climate change are reported in section 4.

2 EARTH'S MOVEMENT

In this section we will describe the Earth's movements since they are more complex than what usually taught in non-specialized courses. In fact besides the well-known revolution around the Sun, and the rotation about its axis of maximum inertia, there are other motions, some of which are induced by external forces and internal mass redistribution.

In the body reference frame (Terrestrial Reference Frame – TRF) there is the polar motion and the length-of-day variations, as well as variations of the center of mass due to mass redistribution in the Earth system (mostly seasonal), while in the Celestial Reference Frame (CRF), there are additional motions: precession, nutation and free-core nutation. Usually when referring to the body fixed reference frame, one considers the Earth Rotation Parameters (ERP), because the EOP include also precession and nutation.

2.1 ITRF and EOP

Earth orientation parameters, center of mass variations and scale are the essential elements that define the terrestrial reference frame that can have different realizations based on each individual space geodetic technique. The best realization of course is the one obtained after the combination of the data from all four techniques, since the combination benefits from the information provided by each one and eliminates the weaknesses of each technique. There is already a large amount of data from each of the techniques used in the development of these reference frames. The development of the ITRF involves the data from all four techniques, so a quadruple amount of data.

The current version of the ITRF, called ITRF2008, has been obtained using data collected from 934 stations in 580 sites (463 of which in the northern hemisphere) and distributed among the four techniques as follows: 29 years of VLBI data, 26 years of SLR data, 12.5 years of GPS data, and 16 years of DORIS data. 84 sites have the co-location of at least two of the four techniques.

3 GEODETIC TECHNIQUES

The huge amount of data and the complex relation among the data and the owners made necessary the establishment of international bodies established as Services under the International Association of Geodesy (IAG) and comprising several working groups for each individual technique. The coordination of activities of these Services is the task of their Governing Boards and Central Bureaus, while high-level guidance is provided by IAG. The operative part of IAG is the Global Geodetic Observing System (GGOS) that plans, designs, and advocates for the required infrastructure of all observing techniques. The data are available through the global data centers of each Service, one of which is the Crustal Dynamics Data Information System (CDDIS) located at the Goddard Space Flight Center, and the only data center that archives the data from all four Services. In particular the CDDIS provides online access to the GNSS data and products generated by the International GNSS Service (IGS). The organizations that specifically deal with the four techniques are listed in Table 1. The Services are also devoted to data analysis and each one has an analysis working group that coordinates these activities.

Table 1: Organizations specifically devoted to the single geodetic techniques.

Organization	Acronym	Technique
International VLBI Service for Geodesy and Astrometry	IVS	VLBI
International GNSS Service	IGS	GNSS
International Laser Ranging Service	ILRS	SLR/LRR
International DORIS Service	IDS	DORIS

IVS is a service of the International Association of Geodesy (IAG) and of the International Astronomical Union (IAU). VLBI has been exclusively ground based (the attempt to increase the baseline performed with the Japanese HALCA space borne radio-telescope provided limited results and the currently operating Russian Radioastron spacecraft has been used for astrometric observations only), while SLR/LLR, GNSS and DORIS need necessarily an operating space segment, besides the ground-based instruments. In the case of SLR/LLR the space segment can be purely passive. GNSS has an active space and ground segments. The GNSS constellations are continuously increasing due to the massive market of applications in navigators and to the will of Europe, China, India and Japan (the last two with two regional systems) to be independent of the GPS (USA) and/or GLONASS (Russia) systems.
In this section the four techniques, including an estimate of size of data, are described.

3.1 VLBI

VLBI is a measuring technique that uses radio-telescopes located on the Earth surface to observe radio signals from extragalactic sources (quasars) which are at practically infinite distance from Earth (Figure 1). The difference in arrival times of the same signal at two telescopes carries information about the length of the baseline between the two telescopes. By observing several quasars in different directions from a pair of telescopes, we can infer the length and absolute direction of the baseline between the two telescopes. Doing so from a global network of such telescopes allows to determine the shape and size of the network very accurately. Because the observations do not depend on the absolute location of the network in space (due to the infinite distance of the sources, VLBI does not sense the location of the geocenter, nor its variations. On the other hand, since the quasars form a quasi-inertial frame, VLBI can observe precession, nutation and free-core nutation, and determine the absolute orientation of Earth in space that are the primary contributions of VLBI in the development of the ITRF and the associated EOP series.

VLBI is the geodetic technique that collects the largest amount of raw data to deliver its products. The amount that it collects at present on a yearly basis for the entire network is about 0.3 EB, and one could estimate that over its 30 yrs of existence, it has collected well over 3 EB of data alone (the network was a lot smaller in the early years).

IVS coordinates VLBI observing programs, sets performance standards for VLBI stations, establishes conventions for VLBI data formats and data products, issues recommendations for VLBI data analysis software, sets standards for VLBI analysis documentation, and institutes appropriate VLBI product delivery methods to ensure suitable product quality and timeliness. IVS also coordinates its activities with the astronomical community because of the dual use of many VLBI facilities and technologies for both radio astronomy and geodesy/astrometry.

3.2 SLR

Satellite Laser Ranging (SLR) and Lunar Laser Ranging (LLR) use short-pulse lasers and state-of-the-art optical receivers and timing electronics to measure the two-way time of flight (and hence distance) from ground stations to retroreflector arrays on Earth orbiting satellites and the Moon. Scientific products derived using SLR and LLR data include precise geocentric positions and motions of ground stations, satellite orbits, components of Earths gravity field and their temporal variations, Earth Orientation Parameters (EOP), precise lunar ephemerides and information about the internal structure of the Moon. Laser ranging systems are already measuring the one-way distance to remote optical receivers in space and can perform very accurate time transfer between sites far apart.

The ILRS network (Figure 2) collects today roughly 110 TB per year, and with some averaging and considering the significantly smaller network and fewer number of target satellites, one can estimate that over its 30 year existence, SLR has collected about 1 PB or 10^{-3} EB raw data. SLR is thus a much more efficient system, producing its products on the basis of significantly less raw information than VLBI.

Laser ranging activities are organized under the International Laser Ranging Service (ILRS) which provides global satellite and lunar laser ranging data and their derived data products to support research in geodesy, geophysics, Lunar science, and fundamental constants (Pearlman et al., 2002). This includes data products that are fundamental to the International Terrestrial Reference Frame (ITRF), which is established and maintained by the International Earth Rotation and Reference Systems Service (IERS). SLR is the only technique that can determine accurately and in an absolute sense the origin of the ITRF, i.e. the geocenter, and along with VLBI, the scale of the ITRF network of stations. These are the primary contributions of SLR in the development of the ITRF, with minor contributions in the determination of the associated ERP series, especially as far as the long wavelength signals. The ILRS develops the neces-

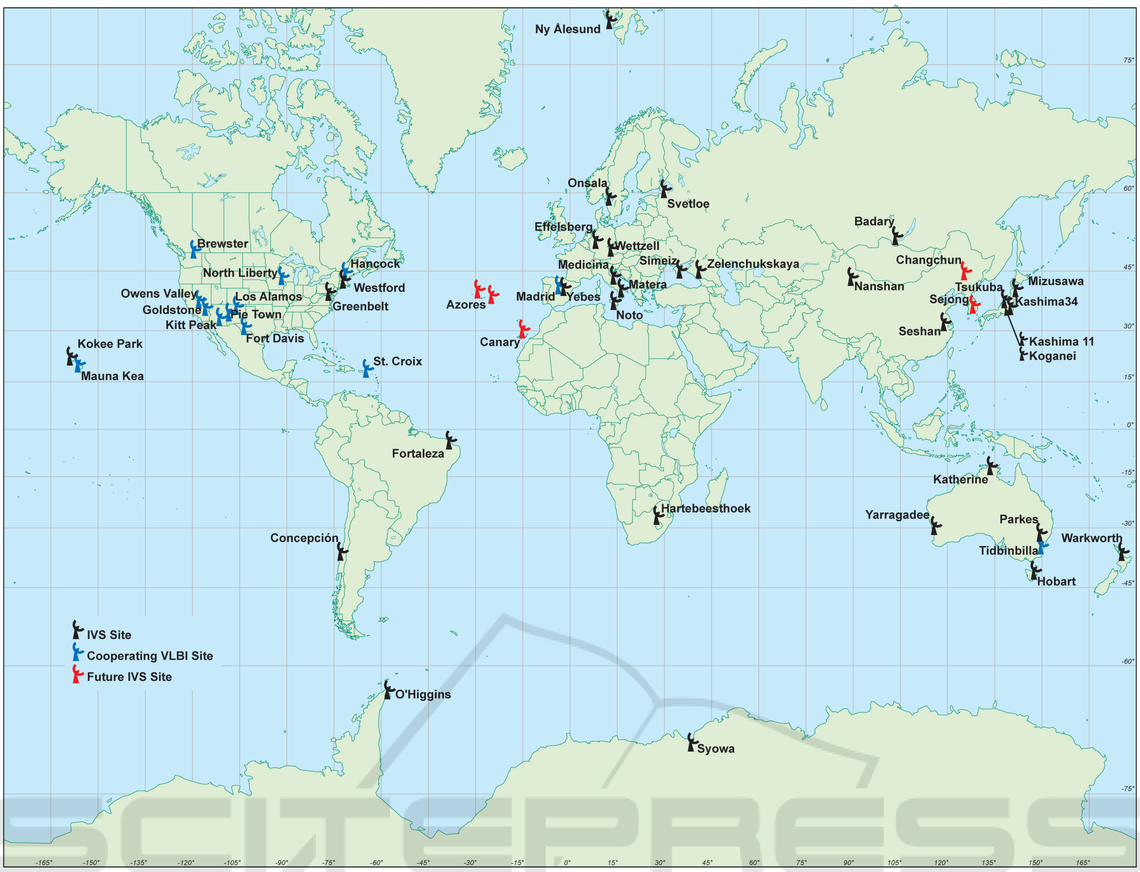

Figure 1: VLBI sites, the global IVS network.

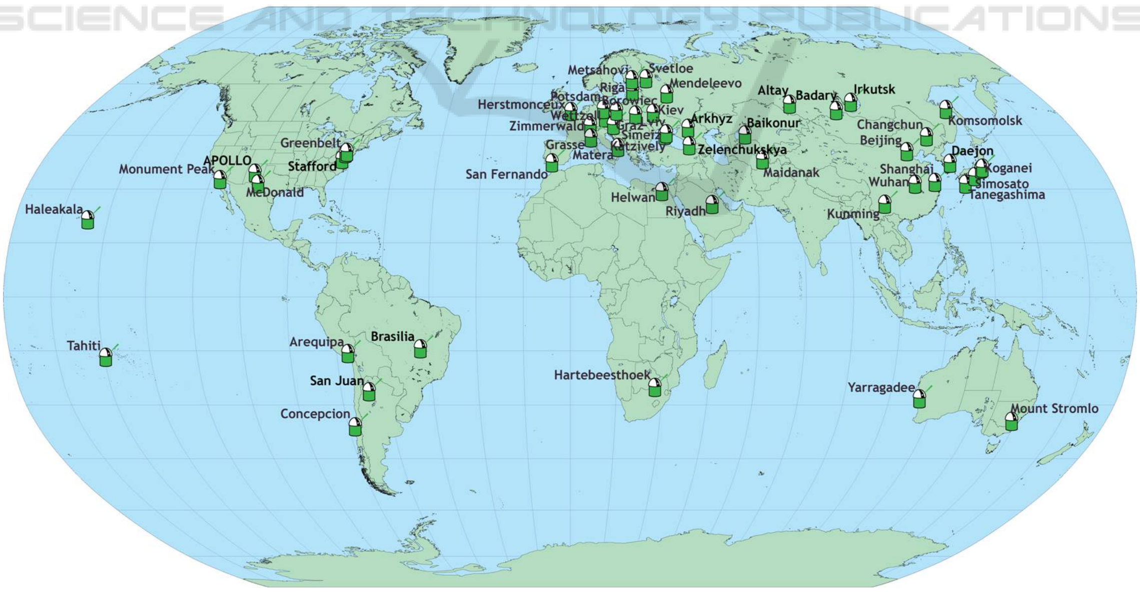

Figure 2: Stations of the International Laser Ranging Service (ILRS) global network.

sary global standards/specifications for laser ranging activities and encourages international adherence to its conventions.

3.3 GNSS

The Global Navigation Satellite Systems are constellations of satellites (identical or very similar), that

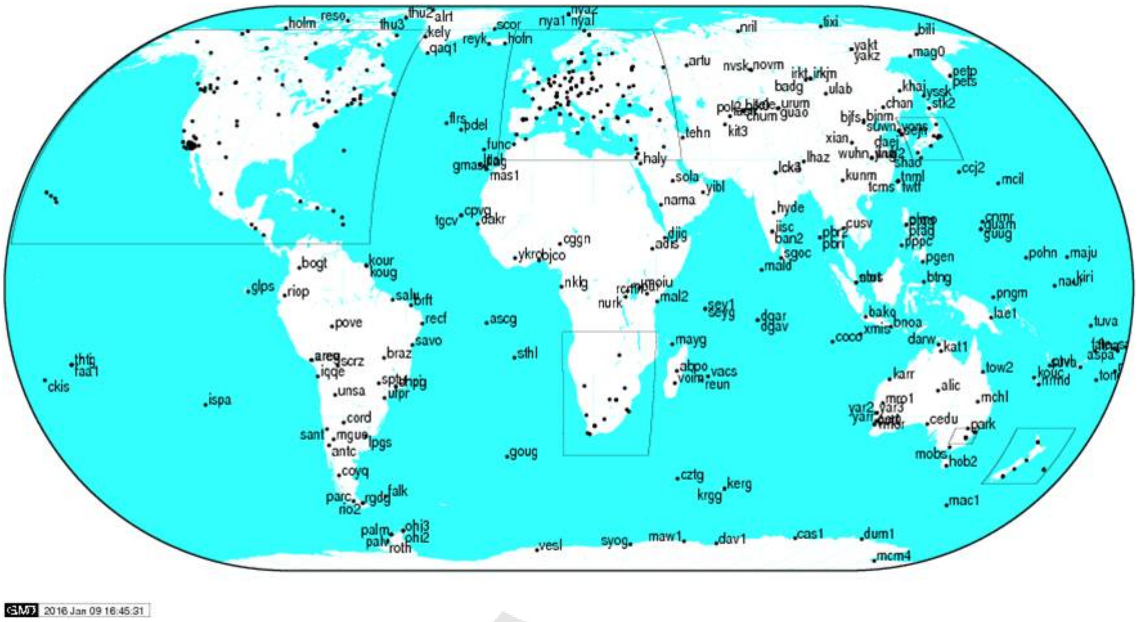

Figure 3: Stations of the IGS global network.

emit radio signals with encoded information, that can be tracked by receivers located practically anywhere (ground, sea, air, on static or moving platforms), in order to determine their position, velocity and time. In simple terms, the technique used is based on solving a point-positioning problem from the measurement of at least four simultaneous pseudorange (biased range) measurements to four different satellites from the same receiver. These allow for the determination of the observer's position and the time-difference between the receiver's clock and the time kept by the satellites atomic clocks. For higher accuracy, scientific receivers collect also phase measurements for each signal and at two different frequencies, so that ionospheric delay effects can be calibrated out. Further modeling or estimation of the tropospheric delay in the observed signals allows to reach ultra precise levels, delivering geodetic products with an accuracy of a few millimetres.

Since 1994 the International GNSS service (IGS) provides GNSS products that are used for many applications including the realization of the ITRF. The number of stations has continuously increased reaching today 500 units (Figure 3). The IGS supports research for the continuous development of new applications and products through Working Groups and Pilot Projects supporting geodetic research and scholarly publications. Using average data collection estimates, we can infer that the GNSS network collects some 25 TB of raw data per year in the current state. The network and the available satellites were significantly smaller in size/number in the early years, so taking that into account, the entire lot of data collected since the early 90s is roughly 0.5 PB or 0.5×10^{-3} EB raw data, again, similar in order of magnitude to the SLR raw data set.

3.4 DORIS

The Doppler Orbitography and Radiopositioning Integrated by SatelliteDORIS system is a French civil precise orbit determination and positioning system (Figure 4). It is based on the principle of the Doppler effect with a network of transmitting terrestrial beacons and on-board instruments on the satellite's payload (antenna, radio receiver and ultra-stable oscillatorUSO).

DORIS is one of three systems used for precise determination of the Jason-1 satellite's orbit. Several of these techniques are sometimes onboard the same satellite: Jason-1 satellite includes three tracking systems, DORIS, GPS and SLR array. The DORIS system perfectly corresponds to the specifications required for the ocean's topography observations and the amplitude of the observed phenomena: it now enables to measure the satellite position on its orbit close to 1 cm. It is interesting to compare this precision with the precision obtained at the beginning of the space age, where the satellite position was estimated close to 20 km, then close to 20 meters in the 80's. Since 1998, the Diode navigator has added real-time measurement processing capability for satellite navigation.

The DORIS system was designed by CNES, the

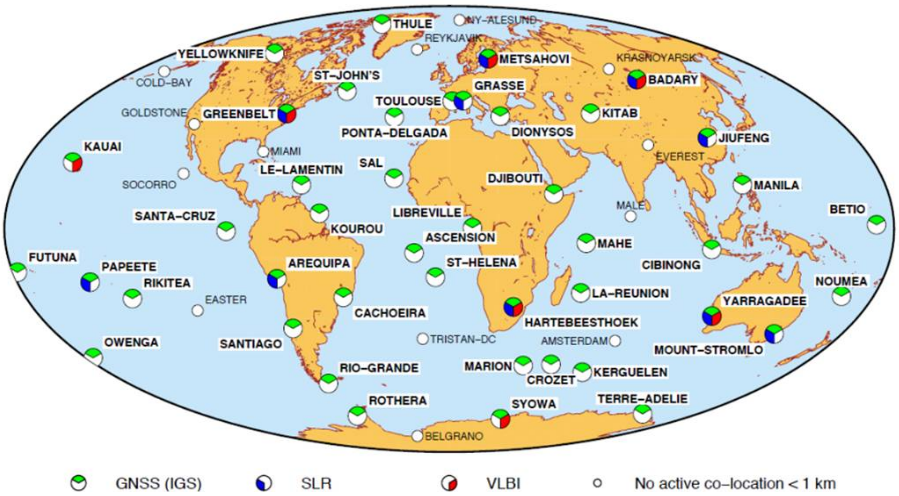

Figure 4: DORIS stations co-located with other IERS techniques (VLBI, SLR or GNSS).

French space agency, in partnership with France's mapping and survey agency IGN and the space geodesy research institute GRGS. The successive missions since Spot 2 and Topex/Poseidon have truly demonstrated its performance. It is currently onboard the Cryosat-2, Jason-2, HY-2A and SARAL altimetric satellites and the remote sensing satellite SPOT-5. It also flew with SPOT-2, SPOT-3, SPOT-4, TOPEX/POSEIDON, ENVISAT and Jason-1.

Since 2003, IDS is an international service that supports science through DORIS data and products for geodetic, geophysical, and other research and operational activities. IDS contributes its products for the development of the ITRF and with the newest systems in orbit it can determine near-real time orbits onboard the platform carrying the system, thence allowing the geolocation of the collected data (e.g. sea-surface heights) in near-real time. The DORIS system collects the raw data on-board the satellites that carry DORIS receivers and subsequently downloads that data to the appropriate master stations of the network for further processing and archiving. The amount of collected data over the period of its existence is at the same order of magnitude as the GNSS, perhaps a little lower, but in any event, by far less than the dominating VLBI data set that defines the order of magnitude and complexity of this observing system.

4 EXAMPLE OF EARTH PARAMETER INFLUENCED BY THE GLOBAL WARMING

Global warming is believed to occur faster than in the recent past. This will cause an anomalous ice melting on polar ice caps and on Greenland. As a consequence the rotation axis of the Earth will show an anomalous drift. In Figure 5 are reported real data of polar motion, i.e. the intersection of the Earth rotation axis with the Earth surface as seen from an observer fixed with the Earth. The graph has been obtained also using about two years of LARES data. The circular path is the Chandler wobble that can be qualitatively explained by solving the rigid body Euler equations in the torque free case. The variation in diameter of the polar motion is due to a beating phenomenon with an annual forcing component. The slow drift of the center is mainly attributed to the post glacial rebound (the slow recovery of the ground after the release of the weight after the glacial era). The change in direction of this drift that occurred in 2005 is attributed to accelerated ice melting in polar ice caps and Greenland (Chen et al., 2013). Besides polar motion also gravitational harmonics of the Earth gravity field and position of the center of mass are affected by global changes (Pavlis et al., 2015a; Pavlis et al., 2015b; Sindoni et al.,). We report for the sake of clarity the displacement of the center of mass of the Earth (Figure 6). The analysis was performed using SLR data of the last 25 years. The results, taken from (Pavlis et al., 2015a), show clearly the accuracy that is below 1 mm. We observe predominantly annual oscillations with an amplitude of $\sim$3 mm in X and Y, and $\sim$5 mm in Z. These are caused by the redistribution of mass during the year between the northern and southern hemispheres, thence the larger Z-component amplitude.

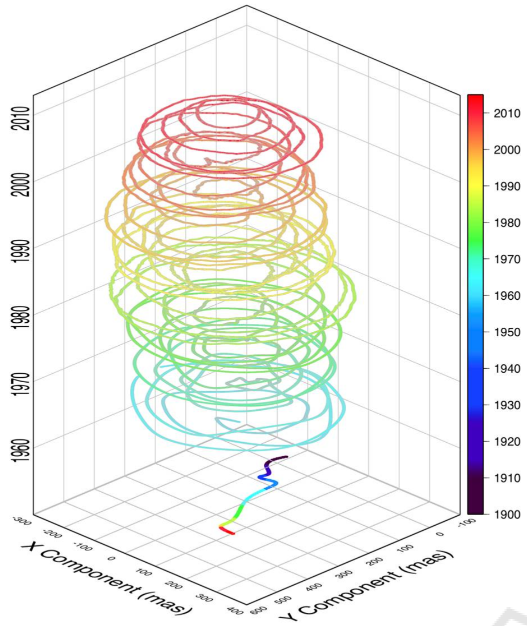

Figure 5: Polar motion from 1962 (Pavlis et al., 2015b).

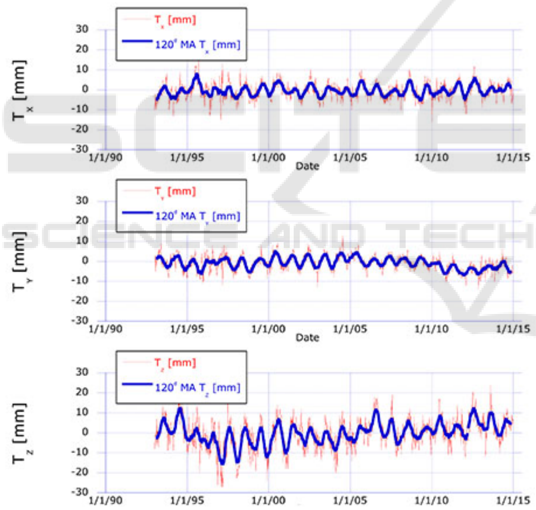

Figure 6: Components of the center of mass obtained analyzing SLR data from 1990 to 2015 including the last two years of LARES data (Pavlis et al., 2015a).

5 CONCLUSIONS

The four geodetic techniques described constitute an exabyte size system. The data analysis provides, among other things, Earth global parameters such as spin axis and center of mass of the Earth. The accuracy of the combined techniques allow to reach millimiter accuracy that are capable to signal events such as accelerating ice melting in Greenland or sea level rise in part of the globe due to global climate change. When we add up all the data collected by all four space geodetic techniques, VLBI, SLR, GNSS and DORIS, the amount of data products that they deliver to IERS/ITRS for the development of the ITRF and its associated EOP series, reaches the level of about 3.5 EB, dominated by the VLBI data. As the networks of all techniques expand to meet the goals of the next generation networks as outlined by GGOS and considering the exponentially increasing number of satellite targets due to the proliferation of navigation constellations (Galileo, BeiDou and IRNSS are all launching new satellites with a fully operational state by 2020 or so), we can easily predict that this global geodetic observing system will surpass the current 3.5 EB of data and perhaps reach the 5 EB level by 2020.

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