

## SLR and the Next Generation Global Geodetic Networks

E. C. Pavlis, M. Kuźmicz-Cieślak

JCET/UMBC and NASA Goddard, Maryland, USA

[epavlis@umbc.edu](mailto:epavlis@umbc.edu)/Fax: +1-410-455-5832

### Abstract

*The Global Geodetic Observing System—GGOS, places the utmost importance on the development, maintenance and wide distribution of an International Terrestrial Reference Frame (ITRF) with very stringent accuracy attributes. We present here results from simulation studies aimed at designing optimal global geodetic networks to support GGOS. At present, our goal is an origin definition at 1 mm or better at epoch and a temporal stability on the order of 0.1 mm/y, with similar numbers for the scale and orientation components. These goals are based on extensive deliberations within the Earth science community. In particular, oceanographers, a prime user group that these products are intended for, require this level of accuracy and temporal stability in order to address sea level rise issues with confidence. The stability, integrity and applicability of the ITRF are directly related to how accurately we can account for mass redistribution during the analysis and reduction process of the data used for its development. Long wavelength variations of the gravity field driven by these mass redistributions produce geometric effects that are manifested as changes in the origin and orientation between the instantaneous and the mean reference frame. This insidious coupling between the product and the reference with respect to which the product is generated makes the problem extremely complex and sensitive to systematic errors. An uneven distribution of the stations realizing the ITRF results in biases and distortions in the combined product due to the dissimilarity of the combined networks and their de facto lopsided overlap. Poor geometry results in increased correlations between the similarity transformation parameters, leading again to biased and unstable results. In this presentation, we are examining SLR's contribution in establishing the optimal network along with VLBI, since these two techniques alone are sufficient for this task. Using simulations of geodetic data that we expect to collect with the future geodetic networks, we look at various designs of several co-located networks and the resulting accuracy in the origin, scale and orientation definition of the realized ITRF.*

### Introduction

Space techniques are indispensable for the development of the terrestrial reference frame and for geodetic metrology. It is well-known and generally accepted that the current state-of-the-art does not meet the science requirements primarily due to the poor area coverage and aging equipment for all of the deployed space geodetic techniques. To meet the stringent future requirements as set forth for the Global Geodetic Observing System—GGOS, 1 mm accuracy in the origin of the reference frame and 0.1 mm/y stability over time [Pavlis et al., 2008], we need to design a new network and deploy modern hardware systems. These observations form the motivation behind the work that is reported here, focusing on the contribution of Satellite Laser Ranging (SLR). We need to clarify that this task is very complicated and involves not only scientific research, but also political and policy-dependent decisions, which evolve over the years and the prevailing socioeconomic conditions. What is thus presented here should be understood as work in progress and not as the final answer to the posed questions.

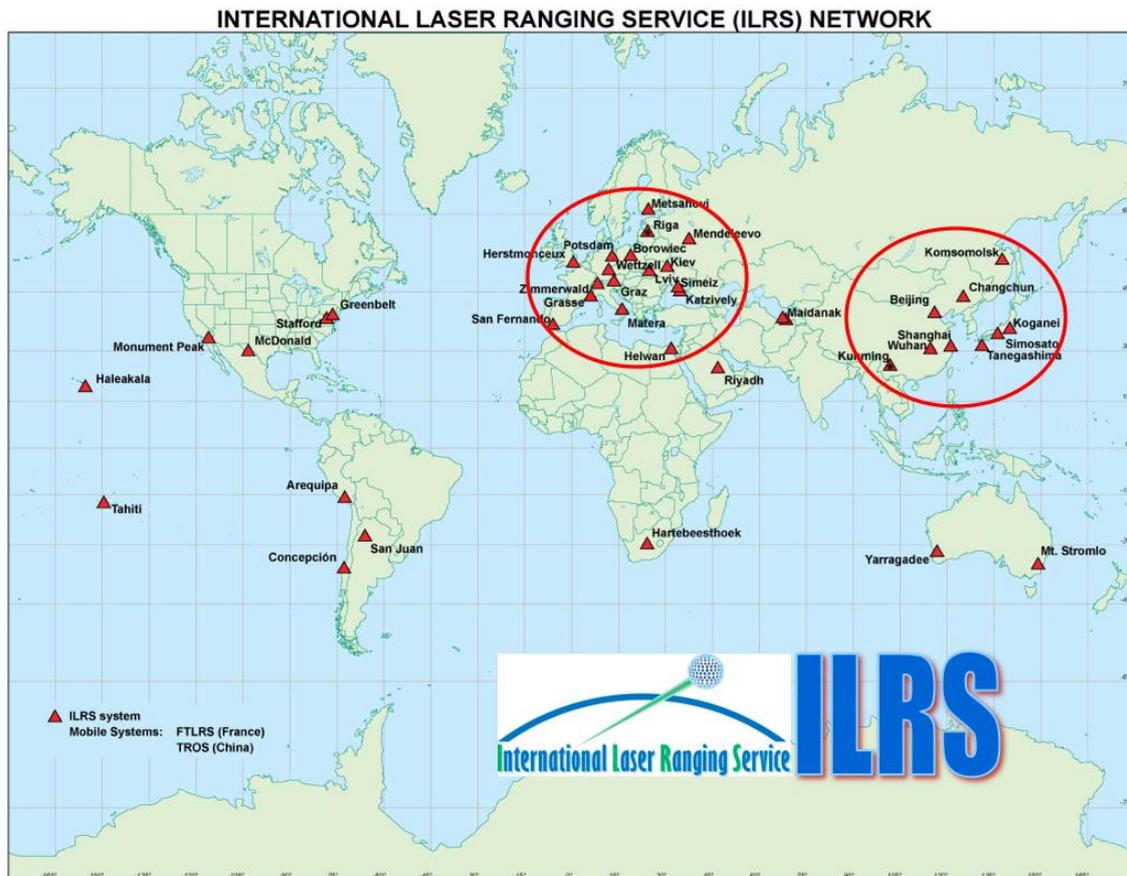
Technique Signal Source Obs. Type	<b>VLBI</b> Microwave Quasars Time difference	<b>SLR</b> Optical Satellite Two-way range	<b>GPS</b> Microwave Satellites Carrier phase
Celestial Frame UT1	<b>Yes</b>	No	No
Scale	<b>Yes</b>	<b>Yes</b>	<b>Yes</b>
Geocenter	No	<b>Yes</b>	<b>Yes</b>
Geographic Density	No	No	<b>Yes</b>
Real-time	No	No	<b>Yes</b>
Decadal Stability	<b>Yes</b>	<b>Yes</b>	<b>Yes</b>

**Figure 1.** Areas where the different space geodetic techniques can contribute to the process of the terrestrial reference frame development.

### The future GGOS network

A fundamental premise in the development of the terrestrial reference frame from space geodesy is that none of the available techniques is able to do the job alone. This is shown in some detail in Figure 1, where we consider GPS, SLR and VLBI and some of the most important processes and attributes that one encounters while developing the frame. Based on this observation, it has long been common practice to use a global network that comprises all techniques, in order to benefit from their complementarity. The benefit however can only be gotten if we have a highly accurate connection of the different techniques and in fact, in a reasonably global and uniform distribution. We generally call this connection, the “local ties”, i.e. the vectors that connect the reference points which are determined by each technique at each location where more than one technique coexist (are co-located). One very important caveat that we must enforce in the design of the future network then is that we not only try to co-locate the maximum possible number of techniques at each site of the fundamental network, but we also require that their local tie vectors are known and monitored with enough accuracy that they will not compromise the overall quality of the resulting frame. At present, the space geodetic techniques have a very poor overlap, with very few sites with all techniques present (2-3). Even in the case of the two of the most complementary techniques, SLR and VLBI, there were never more than 7-8 such sites. Furthermore, these overlaps are time-dependent, with stations appearing and disappearing over time, resulting in very biased frame realizations due to the lack of redundancy in this aspect of the network. Finally, the situation is further exacerbated by the fact that the SLR and to some extent the VLBI networks, are both biased towards the northern hemisphere, where most of the stations

are located. These are some of the deficiencies that the new design will address and ensure that they will no longer be present in the future network.



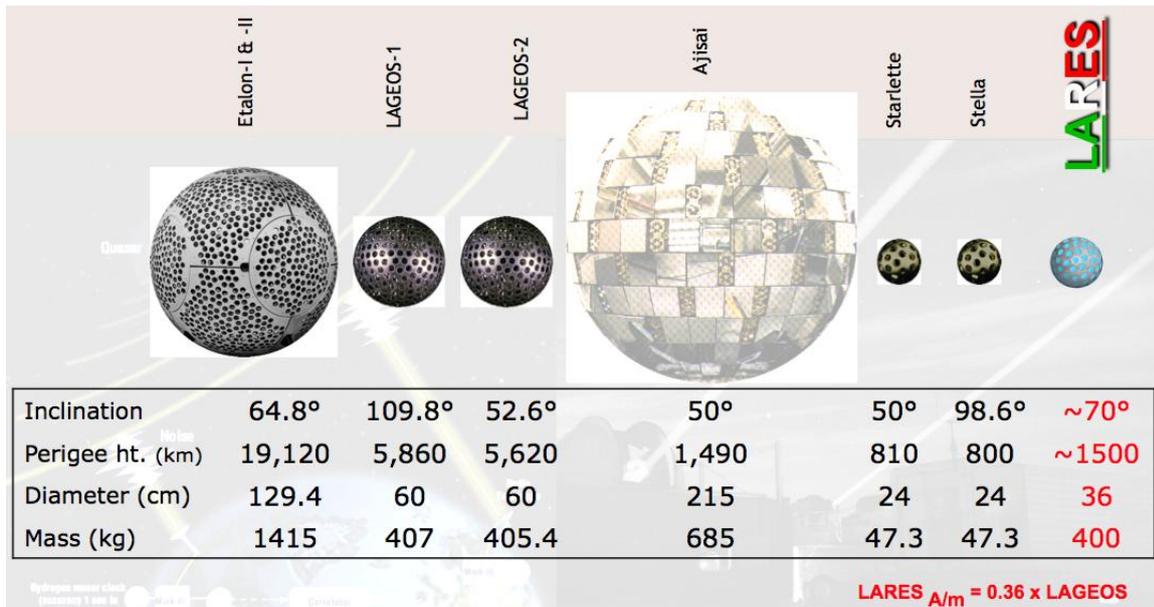
**Figure 2.** The ILRS SLR-station network of active stations (ca. 2008), with the high concentration of sites over Europe and Asia highlighted.

### The SLR network and future developments

It has been already stated that the new network should have a globally uniform site distribution and comprise all available space geodetic techniques. Figure 2 demonstrates the current situation for the SLR network, stressing its extremely lopsided nature. In addition to this observation, one should consider that the majority of the existing hardware was developed several decades ago, and it is kept operational thanks to painstaking efforts of the network engineers. The majority of the current sites require a crew on site while tracking, driving their operational costs to unsustainable levels. The future network will be based on newly designed hardware that addresses all of these issues and many more. The design parameters considered include among others:

- Single photon operational regime;
- Narrow laser divergence;
- Multi-kiloHertz operation (with multiple fires in flight);
- Autonomous, independent operations;
- Improved epoch timing;
- More stable/better defined pointing and ranging calibrations;
- Eye-safe operation, from LEO to GNSS altitude;

- Predictions and collected data submission via the internet (near real-time);
- New applications of these systems beyond Precision Orbit Determination (POD):
  - Satellite surface scanning for spin-axis orientation and rate of rotation;
  - Atmospheric seeing measurements along the laser beam path;
  - kHz Time Transfer (successful tests using AJISAI and the Graz system);
  - kHz LIDAR (under implementation now in Graz);
  - Detection of atmospheric layers, clouds, aircraft vapor trails;
  - ...

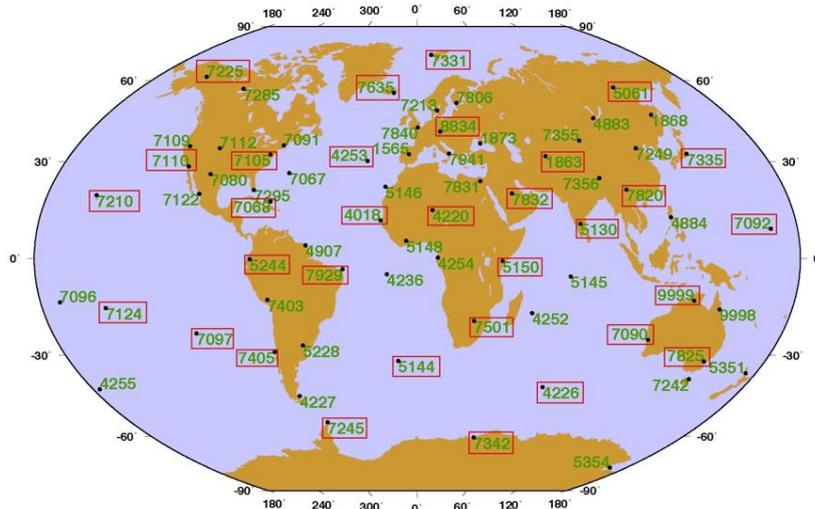


**Figure 3.** The currently available geodetic targets augmented with the soon-to-be-launched LARES spacecraft.

New studies and engineering tests of retroreflector cornercubes from the same lot that was originally used on some of the existing (in orbit) geodetic satellites, e.g. LAGEOS, ETALON, Starlette, etc., attempt to develop improved models for the center-of-gravity to effective reflection plane offset, for various operational regimes of the present network sites (e.g. signal strength, detection system, etc.). Narrowing down the value of this offset is critical in achieving an accurate, stable and unbiased scale of the SLR network.

Another effort that should have significant implications in the accurate and stable TRF of the future is the launch of additional geodetic targets that have been designed with the GGOS requirements in mind, i.e. for millimeter-level or better geodesy. One such target is LARES (Laser Relativity Satellite), a mission that is in the final stages with a launch date of sometime in late 2010, on ESA's Vega rocket inaugural launch. The LARES mission is an Italian Space Agency (ASI) mission, designed by a consortium of Italian and other universities from several European countries and the US [Ciufolini et al., 2008]. It is expected that the quick and significant improvement in modeling the static and temporal gravity field as a result of the unprecedented GRACE mission [Tapley et al., 2004], will soon allow geodesists to use even some of the much lower than LAGEOS-altitude and above targets for TRF work (i.e. Starlette, Stella, Larets, etc.). When this family of geodetic targets is tapped for TRF work, it will help generate a quasi-inertial frame of reference around Earth,

to be used for the determination of the TRF with high accuracy and using data collected over very short time periods on the order of a week or even less. This extended family of targets is displayed in Figure 3.



**Figure 4.** Globally distributed past and present space geodetic sites used in the network simulations. Sites in red rectangles are the maximal 32-site sub-network we examined.

### Network Design Studies

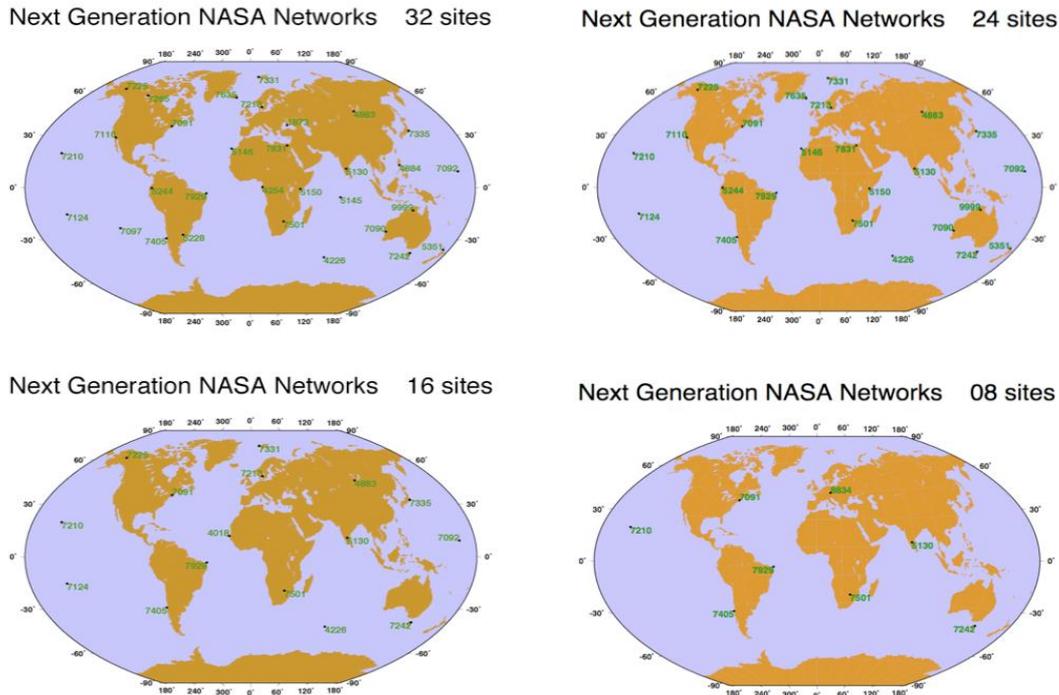
NASA has sponsored an activity that included an “Observing System Simulation Experiment (OSSE)”, using VLBI, SLR and GPS systems. Under this effort a network simulation capability was developed by the Joint Center for Earth Systems Technology (JCET) with participation from NASA Goddard and the University of Texas. This simulation system has been running since 2008 on NASA’s Columbia grid at Ames. Resources supporting this work have been provided by the NASA High-End Computing (HEC) Program through NASA Advanced Supercomputing (NAS) Division at Ames Research Center.

### Simulation and Trade-off Studies

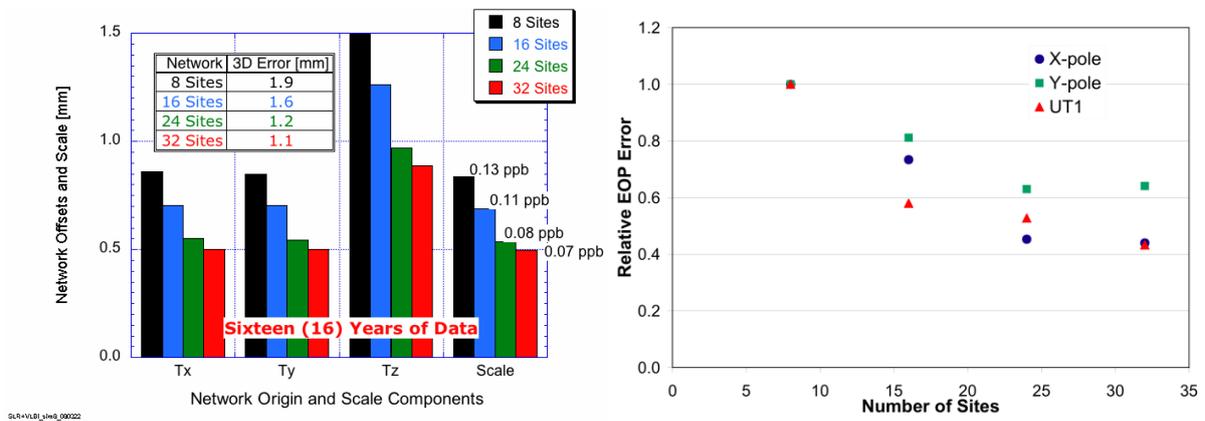
First we scoped the size and distribution of co-located VLBI and SLR stations, over a global network that would support the GGOS program goals. These two systems together can define completely the TRF, with no need for external information. We first identified seventy globally distributed sites occupied at present or at some point in time by at least one technique (not necessarily SLR or VLBI), Figure 4. We then selected from this group 32 sites that comprise the maximum size network we would examine, and we then generated three sub-networks of 24, 16 and 8 sites, each one a subset of the previous, (Figure 5), trying to keep as uniform a global distribution as possible for all sub-networks.

The simulations characterize the degradation in the accuracy of the resultant TRF as the size of the network progressively decreases. The currently co-located VLBI and SLR sites are not more than eight. The results indicate that we need 24 – 32 sites to implement and maintain the reference frame to the required level of accuracy (Figure 6). A larger uniform network is required to maintain the stable origin and scale, while orientation can be maintained even with a smaller network, of about 24 sites (Figure 6). Additional future studies will establish reliable limits on the sensitivity of the chosen network to outages of individual sites and

groups. Although such catastrophic outages do not happen often, we need to know how poorly the network will behave when portions become inoperable over extended periods of time.



**Figure 5.** Initial 32-site network and the three variants of 24, 16 and 8 sites used in the simulations.



**Figure 6.** Origin and scale accuracy (left) and orientation accuracy (right) as a function of the size of the defining network.

### Conclusions

In order to achieve the accuracy requirements of the GGOS project, it is necessary to redesign our space geodetic networks and to deploy new, automated tracking systems. Simulations that consider an ideal network of co-located SLR and VLBI systems provide guidance in the required size and global distribution of this future network. Examining four alternative networks of 32, 24, 16 and 8 sites, we have reached some initial conclusions.

Firstly, the simulation validates the real world experience with the 8 co-located SLR and VLBI sites. The biggest improvement is seen when going from 8 to 16 sites. The largest impact of an 8-site addition in the origin is seen when going from 16 to 24 sites (~22%), and the least, from 24 to 32 (~8%). Results for a 13-year time span (corresponds to the data record used in the development of ITRF2005) show a 4- or 5-fold improvement compared to what we estimate for ITRF2005. A projection for a 16-year time span (similar to what will contribute to the *ITRF2008* realization) shows that a 32-site network approaches the GGOS goal of accuracy in the origin and scale.

While the above provide some boundary conditions for the design of the future network, we should note that the current study has some significant limitations and these will require additional studies to be done to address them. We currently work with only two geodetic techniques (SLR & VLBI), assuming that GNSS and DORIS will become de facto available for any size of such a fundamental network of core sites. We are currently optimizing the network size on the basis of a constrained system performance and assuming a background model quality that is similar to what is available today. Additionally, we have assumed that we have perfect ties between the two systems (SLR and VLBI), far from what is happening today and certainly an item that deserves careful consideration, given its large contribution to the successful realization of the TRF from multiple techniques. The criterion we use for a successful design is TRF quality: origin, scale and orientation. We eventually need to also consider temporal variations of the TRF parameters, to investigate the ability of the network to determine accurate velocities and maintain a stability of all other attributes over long periods of time. Solutions will be soon repeated with the addition of local tie errors with varied weighting schemes. In the future we plan to use the 16-site network to investigate the effect of choosing alternate sites on the results (varying the uniformity of the network), since the actual realization of any design will meet some very practical problems that will in several cases force us to deviate from the theoretical optimal design.

## References

- Ciufolini, I., A. Paolozzi and E. C. Pavlis, (2008), "Toward a One Percent Measurement of Frame Dragging by Spin with Satellite Laser Ranging with the LAGEOS, LARES and GRACE satellites", *Space Sci Rev.*, Springer-Verlag, Heidelberg.
- Pavlis, E. C. et al., (2008), "Observing Systems Needed to Address Sea-level Rise and Variability", in *Understanding Sea-level Rise and Variability*, Aarup, T., J. Church, S. Wilson, and P. Woodworth (eds.), Blackwell, Oxford (*in press*).
- Tapley, B. D., S. Bettadpur, M. Watkins and Ch. Reigber, (2004), "[The gravity recovery and climate experiment: Mission overview and early results](#)", *Geophysical Research Letters* 31 (9).