Section 1
Science Report

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SCIENCE REPORT

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INTRODUCTION

SLR and the Future of Geodesy

"A middle-aged rocky planet, Earth offers a wondrous combination of interconnected systems. From its molten core below to the ionosphere above, planetary layers interact dynamically, moving constantly, affecting climate and environment, and impacting life of all forms on the planet. Quantifying these changes is essential to understanding the underlying processes well enough to identify their root causes and to anticipate and respond to future changes. Precise global geodesy is an essential tool to capture these changes".

Precise Geodetic Infrastructure: National Requirements for a Shared Resource
Committee on the National Requirements for Precision Geodetic Infrastructure; Committee on Seismology and Geodynamics; National Research Council, ISBN: 0-309-15812-5, (2010)

To improve our four-dimensional understanding of the Earth system and the insights derived from recovery of like geophysical parameters in planetary settings, it is essential to recognize the limitations we currently face and the steps needed to improve them. Fundamentally these challenges center on acquiring the measurements needed to directly measure the state and sustainability of the Earth and its environmental systems, establish reference frames that retain mm-levels of accuracy over decadal time frames, and leverage insights gained from the study of terrestrial-like bodies in comparison with Earth.

The broad challenges for space geodesy and geodynamics will likely intensify despite the great progress geodesy has made in delivering key climate related trends. Geodesy has isolated many important phenomena related to the health, state, and sustainability of the Earth's environment like global sea level rise and precise measurements of ice sheet mass loss. These demands are driven by the need for greater modeling understanding, complexity, and detail. For example, while global sea level rise and active zone tectonic motions are now being captured at the sub-cm level over societal relevant time scales, their utility especially within the context of predictive climate and/or tectonic models demand continued improvement in solution error assessment, and much greater understanding and insight into the constituent parts of the signal being captured. We are currently focused on capturing remarkable and unprecedented sources of mass flux, defining stable reference frames, and developing an integrated and interdependent understanding of the Earth's system in four dimensions at increasingly detailed but ever longer timescales scales. With many new sensors, we are improving our understanding of the geosphere and its interaction with the hydrosphere and atmosphere. Observations from space and suborbital platforms are also essential for defining the framework and providing observational resources for making measurements of some of the key manifestations of these natural and anthropogenic impacts. Geodetic investigations will continue to make significant contributions to a wide span of geoscience disciplines. This is a result of the wide recognition that geodesy and geodetic methods are powerful for isolating critical signals across a broad range of observational investigations.

SLR TECHNIQUE

The SLR technique offers one of the best ways to unambiguously position a satellite in near Earth orbit.

The SLR network is sparse and only capable of directly tracking a satellite 10% or so of the time. Thereby, the passive, spherical, and dense satellites designed exclusively as range targets, have this level of data available for precision OD. The easy to model shape and high density of these objects mitigates to a large extent un-modelable non-conservative forces needed for accurate OD and orbits at the 1 to 2m level have been achieved on these SLR-only satellites like LAGEOS and Starlette.

There are a significant number of active satellites with varied shapes and attitude control laws, which are tracked by SLR along with DORIS and/or GPS. For these satellites there are near global networks proving tracking in combination with SLR. With SLR contributing to these combination solutions, the combination of these data have yielded the first sub-cm orbits in the radial direction.

Whether used alone or with a mix of other tracking systems, the overall unique characteristics of the SLR systems include:

- Simple range measurement
- A space segment is passive
- Simple refraction model with far reduced sensitivity to propagation delay arising from water vapor
- Night/Day Operation
- Near real-time global data availability
- Satellite altitudes from 300 km to synchronous satellites, and the Moon
- Short laser pulse widths (30 - 50 ps) to improved return pulse definition

The most important of these characteristics requires re-visitation given current and future accuracy requirements. A level of improvement is needed for all tracking technologies, but here we will only explore SLR. These shortcomings must be overcome to achieve the goals of a stable and highly accurate Terrestrial Reference Frame and the precise navigation of SLR sites within it.

<u>Simple range measurement with passive space segment</u>: While it is true that SLR produces an unambiguous range measurement, there are many models and translational links needed to produce a range between the satellite center of mass (CoM) and the optical axis of the ground laser system. The complexity of this task depends on the complexity of the satellite form, active fuel expenditures which move the CoM with respect to the retro-reflectors, the complexity of the return pulse (e.g. how many corner cubes are illuminated simultaneously as capture in a far field diffractive model, and for really complex satellites like TOPEX, thermal behavior, like warping of its large solar array, which causes cm level changes in CoM. mm-level accuracy will require much better understanding of the satellite's thermal behavior which is a real challenge given these objects are already on orbit and not accessible for direct thermal distortion measurements. In addition a significant improvement in range calibration is needed either for sites using external calibration targets measured pre and post a pass in multiple directions, or for systems with internal calibration capabilities. Currently these modeling error sources are at the 5mm to 1.5cm range. For SLR we form normal points, which very effectively reduce range noise to the 1-2 mm level for the high precision stations, but these systematic sources of error remain.
Lastly, a survey tie is needed to locate the laser optical axis with respect to the brass survey marker located on the site pad to tie multiple site occupations to a single reference point.

<u>Simple refraction model with far reduced sensitivity to propagation delay arising from water vapor</u>: Most of today's SLR systems use meteorological data acquired by the site. These measurements are inadequate to capture the full characteristics of the surrounding water vapor. In the case of the atmospheric delay, more sophisticated models (Pavlis et al, (2009), and VLBI-developed approaches which take into account horizontal gradients and azimuthal dependencies (especially at coastal sites) are being developed to improve SLR analyses. For SLR,

refraction biases are not solved for but use of atmospheric sounding data assimilated in global atmospheric circulation models has been shown to yield significant improvements in SLR solutions (Hulley and Pavlis, 2007). Approaches like these, perhaps tested using two color systems, are needed to improve SLR refraction modeling capabilities

TERRESTRIAL REFERENCE FRAME

The NRC report on **Precise Geodetic Infrastructure**: **National Requirements for a Shared Resource** recommended; "the United States …should invest in maintaining and improving the geodetic infrastructure, through upgrades in network design and construction, modernization of current observing systems, deployment of improved multi-technique observing capabilities, and funding opportunities for research, analysis, and education in global geodesy". The resulting integrated ITRF is envisioned to provide the services and products shown in Figure 1-1.

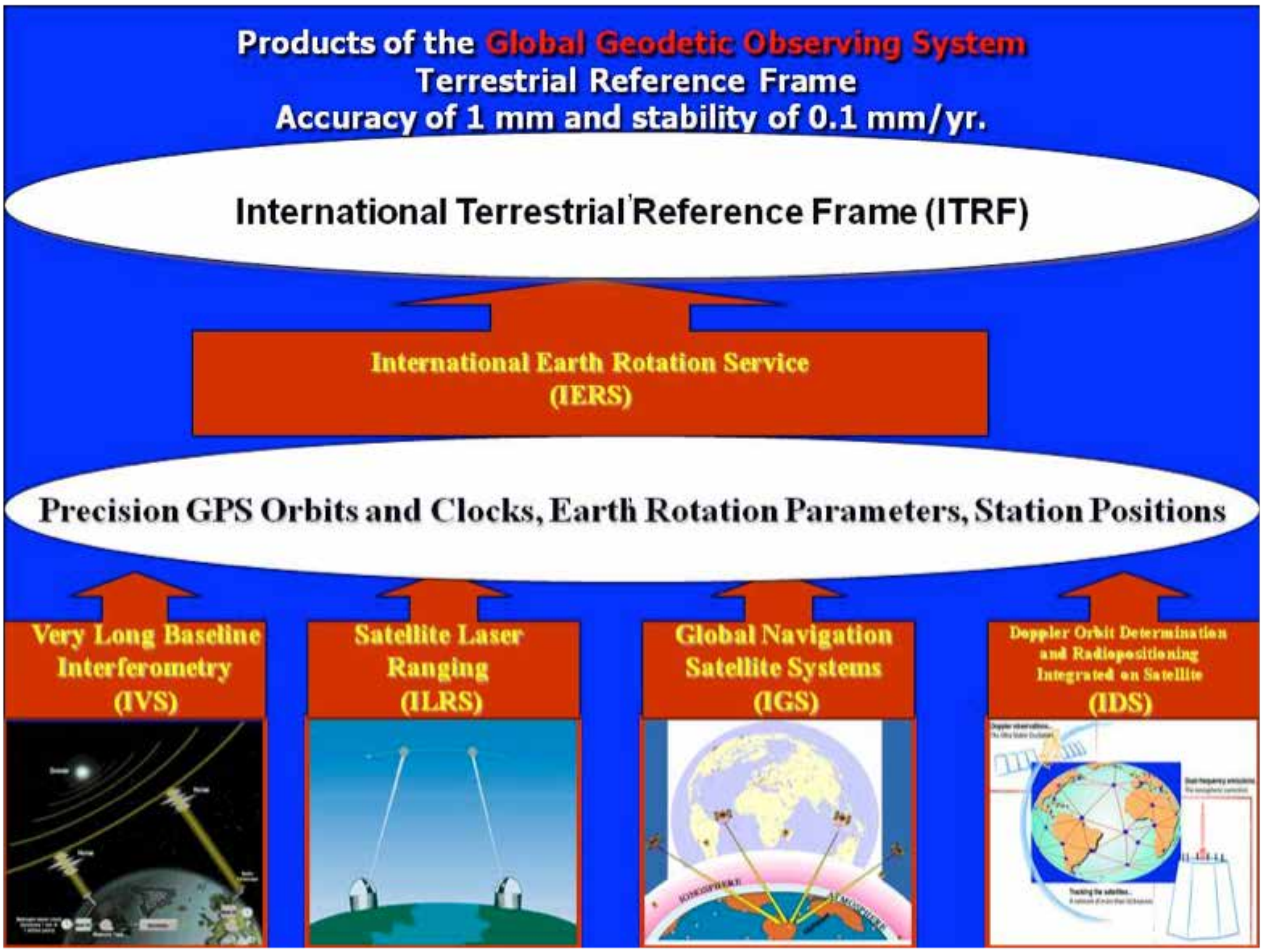

Figure 1-1. Products and services offered by contemplated future ITRF implementations.

This recommendation is made with the knowledge that the underlying VLBI and SLR networks have infrastructures that are old, hard to maintain, and are at risk of significant downtime due to their fragility. The sites used to anchor the ITRF must significantly upgrade through the deployment of the latest geodetic technologies, much better survey ties between instruments, and much improve monitoring of local surface motions through the use of absolute gravity meters.

The ITRF that we are seeking has characteristics that exceed all current capabilities of the current networks. A list of the objectives follows;

- An accurate, stable set of station positions and velocities needed for tracking and interpreting data acquired by flight missions and multiple sensors;
- ITRF should be accurate to 1 mm and stable to a 0.1 mm/yr,
- Static geoid should be accurate to 1 mm and stable to a 0.1 mm/yr.

These are goals given in GGOS plan developed by Plag and Pearlman (2009). Should these goals be met, the ITRF would:

- Be the stable foundation for all space-based and ground-based metric observations;
- Meet the need to establish and maintain the global space geodetic networks;
- Provide network measurements that are:
  - precise, continuous, robust, reliable, geographically well distributed
  - balanced over the continents and oceans
  - interconnected using highly accurate surveys between the different observing techniques

And the ITRF will support the following products:

- Hyper stable Terrestrial Reference Frame (Center of Mass and Scale)
- Sub- 0.1 mm/y monitoring of Plate Tectonics and Crustal Deformation
- Static and Time-varying Gravity Field
- Earth Orientation and Rotation (Polar Motion, length of day)
- Orbits and Calibration of Altimetry Missions (Oceans, Ice)

LASER RANGING DEVELOPMENTS

SLR technology is under a continual state of improvement driven by the Global Geodetic Observing System and the high accuracy and data yield requirements for the evolution of the reference frame. SLR development efforts are divided between those aimed at making the stations easier to maintain, and others looking to improve tracking performance. Major upgrades, implementations, and new concepts include:

- High repetition rate lasers (0.1 – 2 kHz) to improve data yield and more rapid pass interleaving;
- Event timers with near-ps resolution for higher range resolution;
- Automation and autonomous operations to reduce manpower and permit operations during non-manned shifts;
- Two wavelength experiments to test refraction models;
- Testing of eye-safe concepts;
- Improvements in the design of retroreflector arrays for GNSS and synchronous satellites to increase data yield;
- Experiment aimed at demonstrating optical transponders for interplanetary ranging;
- LRO-LR one-way ranging to the Lunar Reconnaissance Orbiter;

Many groups are participating in upgrades and developments. NASA has focused on developing a new generation of systems, which may lead to a prototype for some replication. Many of these items will be discussed on the Section on Emerging Technologies.

Several new stations are being built and will help improve the global distribution of the SLR network. In particular we note the new stations underway in Russia and Korea.

Strong interest continues in Lunar ranging with new design in retroreflectors and the transponders for the lunar surface.