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C. A STRAWMAN SLR PROGRAM PLAN FOR THE 1990s

J.J. Degnan

In developing this strawman SLR Program Plan for the 1990s, certain assumptions were made. They are:

- 0 GPS will completely take over regional deformation work from SLR and VLBI mobile systems;
- 0 One roving NASA transportable is needed in North America for station backup, system collocations, and special science studies such as post-glacial rebound in Canada, TOPEX/Poseidon calibration, etc;
- 0 A global network of well-distributed SLR stations will be needed to support terrestrial reference frame, gravity field and geoid studies, precise orbit determination, technique intercomparisons, and special science missions; and
- 0 The operational cost must be substantially reduced through increased system standardization and automation.

In keeping with these objectives, NASA should dedicate itself, in the 1990s, to achieving a series of programmatic and technical goals as outlined below.

1. Standardize The Performance Of The Global SLR Network.

There is presently a wide disparity in performance among the approximately 43 stations in the international SLR network. The single shot precision varies from about one centimeter at NASA sites (and a few foreign sites) to about 20 centimeters at second generation foreign sites. The poorest quality stations are typically located in the republics of the former Soviet Union. NASA has successfully negotiated wide-latitude space geodetic agreements with the countries which were part of or allied with the former Soviet Union. These agreements permit the exchange of data, technical and scientific information, equipment and personnel. Three Russian government entities (Russian Academy of Science, Russian Space Agency, and Russian Time and Frequency Institute) have deployed, or are deploying, as many as 15 SLR stations across the former Soviet Union. NASA should utilize the new international agreements to ensure that at least some of the Russian SLR sites, especially those within central Asia where there is little or no SLR coverage, achieve subcentimeter performance. Where warranted, NASA should also send in survey teams to ensure that local survey ties between collocated SLR, VLBI, and/or GPS monuments are performed with adequate precision. A precedent exists since, through a University of Texas grant, NASA is presently providing SLR components to Chinese stations in return for TOPEX/POSEIDON tracking support. NASA should also distribute standardized normal point software (and host PCs if necessary) to stations with chronic data format and normal point problems.

2. Improve The Geographic Distribution Of Stations.

The current SLR network consists of approximately 43 stations worldwide, but only four of these are located in the Southern Hemisphere - two in Australia, one in Peru, and one in Chile/Easter Island. There is also a shortage of good stations in Central Asia. Because of the cost of building and operating traditional SLR systems, the burden of improving SLR coverage in the Southern Hemisphere and the Asian continent in the near term will fall on NASA and its European and possibly Australian partners. NASA should:

- Continue to upgrade the decommissioned MOBLAS-6 and provide it on long term loan to South Africa for permanent deployment to either the Sutherland Astronomical Observatory (north of Capetown) or the VLBI facility in Hartebeesthoek (west of Pretoria). Both sites were already visited by the German MTLRS-1 system during the summer of 1993 and found to be good sites.

- Upgrade the TLRS-2 station performance and establish rotating occupations at Santiago and Easter Island to avoid weather outages at Easter Island. (The Huahine site has recently been terminated due to budget cuts and high per diem costs.)

- Consider the relocation of one California Moblas site (preferably Quincy because of its poorer weather) if it is no longer required to support the San Andreas Fault Experiment or TOPEX calibration at the Harvest Platform near Point Concepcion. Important alternate sites would be Ascension Island (British), India, or New Zealand.

- Encourage France to establish a permanent site with SLR, DORIS, and GPS site at Pamate in French Polynesia through deployment of the new transportable SLUM system.

- Encourage Poland to follow through on their plans to establish a new SLR station in Tunisia.

- Encourage and support Latvia in their attempts to establish a new SLR station in the Southern Hemisphere.

- Encourage the temporary or permanent deployment of the European transportables (MTLRS-1, MTLRS-2, or TLRS-1) to Southern Hemisphere sites. Toward the end of the decade, the new German TIGO (Totally Integrated Geophysical Observatories) systems could provide additional coverage.

- Encourage AUSLIG in Australia to take over the operations of Moblas-5 in Yarragadee and to work with New Zealand to establish a site there.

- Provide enthusiastic and comprehensive laser tracking and infrastructure support to foreign entities developing new satellites which will improve our knowledge of the solid Earth, gravity field and oceans or which will test new applications of SLR such as in the fields of time transfer and relativity.

3. Reduce The Costs Of Field Operations And Data Processing.

Field and data operations within the SLR community are too manpower intensive. Factors contributing to the high cost include lack of automation, lack of standardization, system age, subsystem complexity and reliability, hardware obsolescence, and the presence of optical, electrical, and/or chemical hazards. In addition, communications costs at remote sites can be expensive if satellite links, such as INMARSAT, are used. To reduce these costs, NASA should:

- Make maximum use of NASA Science Internet for data transfer and routine communications. This activity is coordinated within NASA by the Ames Research Center in California.

- Install safety radars and modern controllers (with cable wrap hardware and software safeguards) to eliminate the need for a mount observer. This will reduce the required shift manpower from three to two people.

- Provide remote key modelocked laser monitors and controls (e.g. RF frequency control and Pockels Cell pulse switch-out adjustment) to the control console. This would permit eventual single person operation of the station. Alternatively, one can consider replacing the complex modelocked oscillator with a much simpler Q-switched microlaser-amplifier system, but the latter are not commercially available at present.

- Investigate the feasibility of highly standardized and totally automated eyesafe systems, such as SLR 2000. Build and test a prototype at GGAO.

- Provide additional automation of the communication and data processing activities.

- Phase out the generation and distribution of special or obsolete data products in favor of more timely distribution of standardized data products. For example, provide only tuned IRV elements (and not Keplerian elements) for satellite acquisition and online field generated normal points (instead of full rate data tapes which are redundant).

- o Distribute standardized normal point software through the CDDIS (and PCs if necessary) to stations with data format or normal point computation anomalies.

- o Encourage the phased takeover of Moblas-5 by AUSLIG.

- o Proceed with the transfer of the TLRS-1 system on long term loan to Italy.

4. Expand The 24 Hour Temporal Coverage To Better Serve The Growing Constellation Of Satellites.

At the October 1993 meeting in Potsdam, the CSTG SLR Subcommission established the following priority criteria for laser tracking. The two oceanography satellites, ERS-1 and TOPEX/Poseidon were given top priority. All remaining satellites were prioritized first with respect to altitude (lowest altitude gets highest priority), secondly with inclination angle (closest to 90^{o} inclination gets highest priority), and finally degree of international interest.

In FY94, the international SLR network is routinely tracking 13 satellites with the following prioritization:

ERS-1 (ESA)
TOPEX/Poseidon (U.S./France)
MSTI-2 (U.S.)
Starlette (France)
Stella (France)
Meteor 3/PRARE (Russia/ Germany)
Ajisai (Japan)
Lageos-1 (U.S.)
Lageos-2 (U.S./Italy)
GPS-35 & 36 (U.S.)
Etalon 1 and 2 (Russia)

In January 1995, we expect two satellites to be added to the list:

GFZ-1 (Germany)
ERS-2 (ESA)

Other near term potential missions include a Chilean satellite (FY95) and a South African satellite (SUNSAT in FY96).

Most of the international stations provide single or double shift operations. As a result, there is a period of 8 to 16 hours per day where satellites are not tracked from a particular site. In particular, weekend or holiday coverage is often poor. Single shift operations at many key tracking sites, combined with the vagaries of weather, can result in long intervals where a given satellite is not tracked over an important geographical area.

In the near term, savings on field manpower produced by increased automation can be used to create new shifts at little or no extra cost. For example, with the implementation of the new aircraft radar at Moblas sites, two three person shifts at a Moblas can become three two person shifts, providing 24 hour coverage. This approach, of course, implies that cost savings realized through automation are allowed to remain within the program.

In the long term (1998 and beyond), totally automated stations such as SLR 2000 can be deployed. A complete transition to automated systems would require a daylight ranging capability over the full constellation of retroreflector equipped satellites ranging in altitude from 300 Km (GFZ-1) to 20,000 Km (Etalon, GLONASS, and GPS). In the event that this technologically challenging goal could not be achieved for the highest altitude satellites (i.e beyond Lageos), approximately 10 to 15 well-distributed manned sites might be required worldwide to satisfy the requirements of the lunar and GPS/GLONASS communities.

5. Improve The Absolute Range Accuracy to 2 mm at Key Stations.

Compared to radio or microwave techniques, SLR is 70 times less sensitive to the atmospheric water vapor content and is virtually unaffected by ionospheric variations. State-of-the-art SLR systems produce normal points with precisions at the 1 to 3 mm level. In terms of absolute accuracy, the limiting error source in modern SLR systems is the dry atmosphere. Estimates of the potential systematic error, due to transverse pressure gradients and/or deviation of the vertical profiles from hydrostatic equilibrium models, range from 5 to 12 mm and are largest at low elevation angles. To reduce this potential error source, NASA should:

- o Continue to develop two color systems for directly measuring the atmospheric delay and to validate or improve atmospheric models.
- o In the interim, consider utilizing locally available pressure data or estimation techniques to compute gradient corrections to the range data.
- o Cooperate with our international partners in the design, fabrication, and/or launch of the next generation satellite laser arrays which minimize target signature effects and can make two color millimeter absolute accuracy ranging a reality.

6. Improve Satellite Force, Radiative Propagation, And Station Motion Models And Investigate Alternative Geodetic Analysis Techniques.

Improved range accuracy alone will not translate into higher geodetic accuracies without continued improvement of dynamic satellite force (gravitational and nonconservative), radiative propagation, and/or station motion models. NASA should therefore:

- o Continue to search for satellite forces, propagation effects, and station motions not presently accounted for and incorporate them into GEODYN.
- o Investigate the relative merits of strictly *a priori* models versus models which include a limited number of solved for parameters.
- o Investigate geometric and reduced dynamic techniques using first Lageos, then Etalon, data.
- o Develop improved quality control procedures and global collocation methods to provide continuous near real-time monitoring of global SLR station systematics.

7. Support Technique Intercomparisons and the Terrestrial Reference Frame Through Global Collocations.

The 1989 Coolfont Meeting set as a goal the achievement of millimeter positioning accuracies by the end of the decade. In order to fully understand the performance and accuracy limits of the various space geodetic techniques, it will be necessary to perform routine and painstaking intercomparisons at a set of global sites. For various reasons, which are both scientific and economic in nature, GPS is gradually being collocated at existing VLBI and SLR sites. However, the number of collocated SLR/VLBI sites is extremely limited - especially in the Southern Hemisphere. To correct this shortcoming, NASA should:

- o Collocate TLRS-4 at selected VLBA/VLBI sites in North America
- o Collocate TLRS-2 with the Peldehue VLBI station near Santiago during bad weather periods at Easter Island. A side benefit of this action is that no per diem costs are incurred when the system is at its home base in Santiago.
- o Consider Moblas-6 installation at the Hartebeesthoek VLBI site in South Africa instead of Sutherland.
- o Encourage European transportables to periodically visit local VLBI sites in Europe
- o Monitor VLBI Mark IV development progress as a means of providing low cost VLBI capability at additional SLR sites in the Southern Hemisphere (e.g. Yarragadee, Easter Island, etc.).
- o Encourage the Japanese transportable, HTLRS, to visit VLBI sites in Japan.
- o Provide GPS and conventional survey support to quasi-collocated SLR/VLBI sites where anomalies exist (e.g. Shanghai, Simeiz, Orroral, etc.).

8. Investigate Potential Synergisms Between GPS And SLR.

The recent launch of two retroreflector equipped GPS satellites, GPS-35 in August 1993 and GPS-36 in March 1994, provides new opportunities for the synergistic use of SLR and GPS in a manner which takes advantage of the inherent strengths of each technique.

For its part, SLR offers an extremely stable and long term reference system which results from; 1) the subcentimeter precision and totally unambiguous nature of the laser range measurement; 2) compact, passive, and easily modelled "cannonball" target satellites; 3) insensitivity to dynamic atmospheric properties such as water vapor content; and (4) insensitivity to the ionosphere. For example, although SLR and GPS are both sensitive to the Earth center-of-mass, the SLR origin, as determined by Lageos observations, is stable at the one centimeter level over a period of years whereas independent GPS determinations show scatters of 10 to 15 centimeters. The one sigma single shot RMS laser range scatter about short GPS arcs (40 minutes or less) is about one centimeter while the corresponding five minute normal points exhibit a scatter of less than 2 millimeters. Furthermore, SLR has recently demonstrated a capability to position the GPS-35 satellite over long arcs (104 days) to better than three centimeters. Based on independent preliminary analyses carried out by NASA/GSFC and the University of Texas Center for Space Research, SLR agreement with IERS GPS-derived orbit solutions is at the decimeter level in the radial coordinate and at the 0.5 to 1.0 meter level overall.

GPS, on the other hand, offers: 1) low cost operation of stations; 2) a truly global distribution of sites; 3) site densification; and (4) continuous visibility to low Earth orbiting satellites and aircraft. Combining the two techniques should permit:

- The rapid and precise positioning of retroreflector-equipped GPS satellites in the highly stable SLR reference frame and, by inference via the GPS ground network, non-equipped GPS satellites as well.

- The unambiguous separation of onboard clock errors from satellite ephemeris errors.

- Direct, real-time, comparisons of GPS pseudorange with laser range at collocated sites. AS potential benefits include:

    a. Monitoring and possible correction of SA and AS-induced errors;

    b. Rapid resolution of cycle ambiguities in scientific analysis; and

c. Identification of multipath or antenna phase errors.

- Verification and monitoring of the accuracy of stochastic atmospheric models used in GPS data analysis.

- Improved absolute accuracy of GPS-determined baselines and LEO orbit trajectories.

In order to achieve these goals, NASA should strive to:

- Encourage the international community to install GPS receivers at all SLR sites and use them for the establishment of epoch time.

- Deploy its own network in a manner which makes continuous tracking of Lageos and GPS feasible and encourage its international partners to do the same.

- Upgrade its stations for the purpose of demonstrating reliable daylight tracking of GPS and share the technology with its international partners.

- Perform "simultaneous" laser tracking of GPS and satellites which carry onboard GPS receivers and retroreflectors to produce datasets which can shed light on systematic errors. Such a dataset was first collected on the TOPEX/Poseidon calibration overflight of California in December 1993.

BELMONT SLR WORKSHOP PARTICIPANTS

Bills, Bruce G., Goddard Space Flight Center, Code 921

Bosworth, John M., Goddard Space Flight Center, Code 920.1

Crooks, Henry A., AlliedSignal Technical Services Corporation

Degnan, John J., Goddard Space Flight Center, Code 920.1

Dunn, Peter J., Hughes STX Corporation

Eanes, Richard, Center for Space Research, UTX at Austin

Jessie, Lawrence, Goddard Space Flight Center, Code 920.1

King, Robert W., Massachusetts Institute of Technology

Klosko, Steven, Hughes STX Corporation

Ma, Chopo, Goddard Space Flight Center, Code 926.9

McGarry, Jan F., Goddard Space Flight Center, Code 920.1

Nerem, Robert S., Goddard Space Flight Center, Code 926

Pavlis, Erricos C., University of Maryland

Pearlman, Michael R., Smithsonian Astrophysical Observatory

Ries, John C., Center for Space Research, UTX at Austin

Schutz, Bob E., Center for Space Research, UTX at Austin

Shum, C.K., Center for Space Research, UTX at Austin

Smith, David E., Goddard Space Flight Center, Code 920

Tapley, Bryon D., Center for Space Research, UTX at Austin

Varghese, Thomas K., AlliedSignal Technical Services Corporation

Watkins, Michael M., Center for Space Research, UTX at Austin

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John J. Degnan, Editor

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13. ABSTRACT *(Maximum 200 words)*
Satellite laser ranging (SLR) was first demonstrated by NASA three decades ago. Today, an international network of 43 stations in 30 countries routinely collects data from 13 satellites in Earth orbit, which has been used to study the solid Earth and its interactions with the oceans, atmosphere, and Moon. Data products include centimeter accuracy site positions on a global scale, tectonic plate motions, regional crustal deformation, long wavelength gravity field and geoid, polar motion, and variations in the Earth's spin rate. By calibrating and providing precise orbits for spaceborne microwave altimeters, SLR also enables global measurements of sea and ice surface topography, mean sea level, global ocean circulation, and short wavelength gravity fields and marine geoids. It provides tests of general relativity and a means for subnanosecond time transfer. In the 1990s, SLR faces competition in a number of applications from relatively inexpensive radio techniques, notably the Global Positioning System (GPS). In February 1994, NASA convened a two-day workshop at the Belmont Conference Center in Elkridge, Maryland, to define future roles and directions for SLR. Key technologists and analysts from the domestic space geodetic community presented short summaries reproduced in Sections III and IV of this report.

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