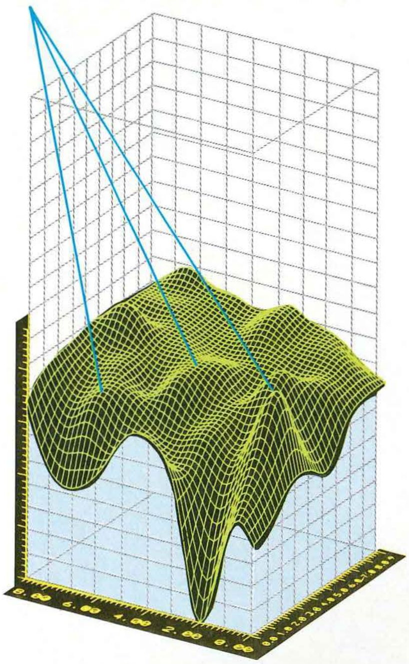

Laser Ranging to GPS Satellites with Centimeter Accuracy

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In 1960, Theodore H. Maiman, of the Hughes Aircraft Company, successfully operated the first device to generate an intense beam of highly coherent monochromatic radiation. He called his device a laser — for light amplification by the stimulated emission of radiation. The laser has become ubiquitous, with literally hundreds of uses ranging from optical surgery to precision machining. Lecturers use laser pointers; surveyors use laser distance-measuring devices; police officers use laser radar units to catch speeders. Most of us unwittingly use a laser each time we listen to our CD players — the light reflected from the the microscopic pits on the CD is generated by a precisely positioned laser.

One application of the laser that is not so well known is satellite laser ranging. In this month's column, John Degnan and Erricos Pavlis, from the Laboratory for Terrestrial Physics (LTP) at NASA's Goddard Space Flight Center (GSFC), in Greenbelt, Maryland, introduce us to satellite laser ranging and describe the efforts to track two of the Navstar GPS satellites using this technique. Dr. Degnan is the head of LTP's Space Geodesy and Altimetry Projects Office. He has been employed at GSFC since 1964 when, as a coop student from Drexel University, he participated in the first laser-ranging experiments to the Beacon Explorer B satellite. Dr. Pavlis is a senior geodesist in the LTP and is affiliated with the Department of Astronomy at the University of Maryland. His research interests include satellite orbital dynamics and the analysis of space geodetic data.

"Innovation" is a regular column in GPS World, *featuring discussions on recent advances in GPS technology and its applications as well as the fundamentals of GPS positioning. The column is coordinated by Richard Langley and Alfred Kleusberg of the Department of Geodesy and Geomatics Engineering at the University of New Brunswick. We appreciate receiving your comments as well as suggested topics for future columns.*

On August 30, 1993, the Department of Defense (DoD) launched the GPS-35 (SVN35, PRN05) satellite into orbit, placing it in the GPS satellite constellation's B-4 orbital plane position. This particular Block IIA satellite differs slightly from its predecessors in that it carries a small panel of optical retroreflectors, enabling it to be tracked by an international network of centimeter-accuracy satellite laser ranging (SLR) stations. Laser tracking of GPS-35 began on October 17, 1993. On March 10, 1994, GPS-36 (SVN36, PRN06), carrying an identical retroreflector package, was launched into the C-1 orbital slot. Laser tracking of GPS-36 was initiated on April 21, 1994.

The GPS Laser Retroreflector Experiment (GPS/LRE), which focuses on these two satellites, is a joint effort by several groups working in cooperation with the Navstar GPS Joint Program Office. These include the Naval Research Laboratory (NRL) in Washington, D.C.; the National Aeronautics and Space Administration (NASA) through its Goddard Space Flight Center (GSFC) in Greenbelt, Maryland; the University of Maryland at College Park, Maryland; and the Russian Institute for Space Device Engineering in Moscow.

The DoD's goals for the GPS/LRE experiment are essentially the same as those of the Advanced Clock Ranging Experiment, which NRL originally proposed to DoD's Tri-Service Space Test Program in 1986. In his proposal, which later became the GPS/LRE, NRL principal investigator Ron Beard states that a primary objective of the experiment is to provide an independent, high-precision measurement of satellite position that, when compared with GPS pseudoranges, can unambiguously separate satellite-position errors from onboard atomic-clock errors. The accurate determination of satellite position and clock characteristics is essential to predicting GPS performance and reducing errors in both the short and long term. The laser measurements also support ongoing atomic-clock evaluations within DoD and their effect on overall GPS system performance.

NASA's interest in the experiment stems from the agency's current and future use of GPS in a variety of geophysics applications that previously had been carried out exclusively by two more mature space geodetic techniques: satellite laser ranging and very long baseline interferometry (VLBI). NASA's involvement in all three techniques is pervasive. The Jet Propulsion Laboratory (JPL) in Pasadena, California — with funding from NASA — serves as both the Central Bureau and an analysis center for the International GPS Service for Geodynamics (IGS) and has also been a leader in the engineering development of precise geodetic receivers for both ground and spacecraft use. The Goddard Space Flight Center (GSFC), which serves as an IGS Global Data Center, is also the primary Coordination and Data Analysis Center for both SLR and VLBI, operating 10 of approximately 43 stations in the global SLR network and three of approximately 30 VLBI field stations. GSFC hosts IGS GPS receivers at most of these sites.

As GPS demonstrated its ability to measure short- to medium-length baselines with comparable accuracy in the late 1980s, it gradually displaced the more-expensive mobile SLR and VLBI systems as the technique of choice in internationally sponsored campaigns to measure regional crustal deformation. These early mobile campaigns were principally conducted in the United States, Canada, Mexico, and Europe.

NASA investigators are now comparing global GPS network solutions with those obtained from SLR and VLBI. Following an appropriate, seven-parameter coordinate transformation (three translational parameters, three rotational, and one for scale), global station positions obtained by the three

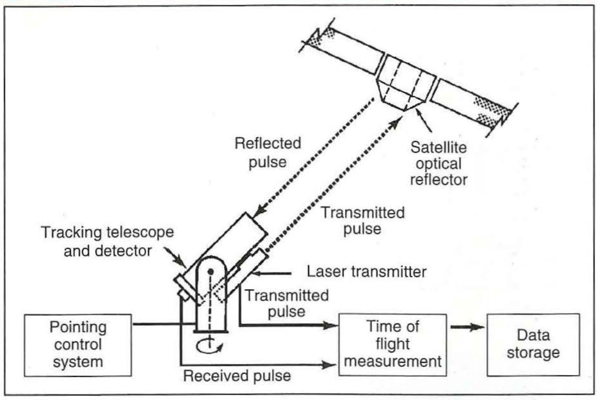

Figure 1. A simplified block diagram of a typical satellite laser ranging (SLR) station. By measuring the elapsed time between the transmission of a laser pulse and the reception of the pulse reflected by the satellite, the range to the satellite can be determined.

techniques agree at the one- to two-centimeter level at high-quality, collocated sites. This agreement is at a level consistent with the estimated modeling uncertainties for each technique. However, there are important geophysical phenomena where the expected rates of change of position are on the order of a few millimeters per year or less. Such phenomena include changes in mean sea level, postglacial rebound, and deformations due to atmospheric loading. A better understanding of the residual error sources and their magnitudes for each of the positioning techniques would be helpful, as would, if possible, the ability to make reliable measurements with millimeter accuracy, especially in the vertical direction. This rather ambitious goal can be accomplished convincingly only through routine and painstaking comparisons of the geodetic results obtained by different techniques at collocated sites.

The GPS/LRE experiment provides a totally new way to compare GPS and SLR, which we expect will highlight the inherent strengths of each technique in making important, new, scientific measurements. Analyses with a dense, global SLR tracking network — when it becomes available — can give us insight into the many sources of systematic errors in the radiometric (carrier phase and pseudorange) data. The nature of these measurements (one way, using two, L-band radio-frequency [RF] carriers), makes it impossible to separate completely clock errors from orbital errors. Residual ionospheric errors and errors from tropospheric-refraction mismodeling result in additional degradation. The reflection of RF signals near the antenna site (multipath) is an additional source of error that varies from site to site and is quite difficult to quantify or eliminate completely. A proper characterization of the error spectrum of the frequency standards on board the satellites is also of interest, especially to those using GPS signals for time transfer. Another source of error in computing orbits for the GPS satellites is the description of attitude changes, especially during eclipse seasons when a satellite spends a significant fraction of its orbit in the earth's shadow. Better handling of the nonconservative forces acting on the satellites (such as solar radiation pressure) can be achieved by using precise SLR tracking and the resulting orbits to "tune" models of these forces to each satellite individually.

Geodetic positioning can benefit from the increased orbit accuracy of retroreflector-carrying GPS satellites in two ways: the better orbits result directly in better positioning; and they can also help in the reliable resolution and "fixing" of the ambiguities of doubly differenced carrier-phase measurements. The latter strengthens the estimation procedure because it converts, in effect, the very precise but relative measure of change-in-range to absolute range (for more on GPS-carrier-phase measurements, see "The GPS Observables," *GPS World,* April 1993).

SLR PRINCIPLES

A satellite laser ranging system is, in simple terms, an optical radar. Figure 1 is a simplified block diagram of a typical SLR system. The modern laser transmitter uses a mode-locked Nd:YAG laser (a solid-state, pulsing laser using neodymium as a lasing impurity in a host lattice of yttrium aluminum garnet) with output frequency doubled to produce green light with a wavelength of 532 nanometers. The laser, which operates at a repetition rate of between 5 and 10 Hz, produces an ultrashort pulse with a pulse width between 30 and 200 picoseconds (full-width-at-half-maximum) and a single pulse energy between 10 and 100 millijoules. (To put this amount of energy in context, a joule is the amount of energy required to illuminate a single-watt flashlight bulb for one second or to heat a half-teaspoon of water by one-tenth of a Celsius degree. Laser pointers have a power output of a few millijoules per second.) The outgoing laser pulse, containing about 10^{17} photons, is sampled by the range receiver, which, in turn, starts a time-of-flight measurement. The laser pulse propagates through the atmosphere, is reflected by a retroreflector array on board the satellite, returns through the atmosphere to the source, and is collected on the ground by the receiver telescope.

Only a handful of the outgoing photons makes it back. The telescope focuses the returning radiation onto a high-gain, high-speed (subnanosecond) photodetector that stops the time-interval counter. A modern SLR counter has a time resolution on the order of 20 picoseconds or less, which corresponds to a single-shot range resolution of 3 millimeters or less. The epoch time of departure for the laser pulse is also recorded. Because the station master clock is typically a cesium standard, periodically updated by a GPS timing receiver, epoch time is accurate to a small fraction of a microsecond.

Typically, the photodetector is a photomultiplier tube. In a photomultiplier tube, incident photons strike a photosensitive surface, causing it to emit electrons through the photoelectric effect. These so-called photoelectrons are accelerated by a potential difference and strike an electrode, causing it to dislodge additional electrons. These electrons are attracted to another electrode, which in turn ejects more electrons. This process may be repeated 10 or more times, generating a current that can readily be measured.

When fit to a short orbital arc (less than one orbital revolution), the single-shot data from ranging to passive orbiting geodetic satellites, produced by state-of-the-art SLR field systems, typically exhibit a root-mean-square (rms) scatter of 6 to 10 millimeters. If one forms *normal points* by averaging individual range measurements over a two-minute time interval to reduce random errors, the rms scatter about the short arc is reduced to between 1 and 3 millimeters. Normal points are formed at the field sites after each satellite pass and transmitted electronically to three SLR analysis centers at the GSFC, at the University of Texas, and at the Technical University of Delft in The Netherlands. These "quick-look" analysis centers routinely monitor station performance by fitting the global SLR data set to multiday arcs of the Laser Geodynamics Satellite (LAGEOS), a passive geodetic satellite, orbiting at an altitude of 6,000 kilometers, which was launched by the United States in 1976. Although data quality varies widely among the approximately 43 international stations that make up the global SLR network, the weighted rms–fit to the multiday LAGEOS arc is typically on the order of 2 centimeters and of high enough quality to pinpoint systematic data problems rapidly, at the few-centimeter level, at individual stations.

Systematic errors in the hardware are controlled at the few-millimeter level by frequent calibration runs using carefully

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NASA MOBLAS-7 and a transportable SLR system were collocated at the Goddard Space Flight Center. A collocation is the most effective method of testing an SLR system for systematic errors.

Over the past three decades, the range-measurement precision has improved by about three orders of magnitude — from a few meters in 1964 to a few millimeters in 1994. Over the same period, the international SLR network has grown to more than 40 stations, including seven highly mobile systems (see Figure 2).

Laser-ranging observations have proved their scientific worth in a number of different areas. In addition to precise orbit determination, SLR (together with VLBI) pioneered measurements of global tectonic plate motion, regional crustal deformation near plate boundaries, and earth orientation. SLR uniquely defines the position of the earth's center of mass, which is the coordinate origin of the International Earth Rotation Service Terrestrial Reference Frame. SLR has contributed to studies of the earth's gravity field and has been used to calibrate microwave altimeters carried by oceanographic satellites such as ERS-1 and TOPEX/Poseidon, in addition to defining their operational orbits. Lunar laser ranging (LLR) to retroreflectors left on the moon's surface by three of the U.S. Apollo missions and to retroreflectors on two Soviet Lunokhod remotely controlled rovers supplied exciting new scientific information on earth–moon interactions and the dynamics and physical makeup of the moon and provided unique tests of competing theories of general relativity.

surveyed target monuments on the ground. Also, before deployment, new systems are usually collocated with a network standard, such as the NASA Mobile Laser (MOBLAS) -7 system in Greenbelt, Maryland. In a collocation, the SLR system under test is placed within 60 meters of the reference system, and the relative locations of the reference centers for the two systems are surveyed in, with an accuracy of two millimeters or less. Careful attention is also paid to the station clocks and meteorological sensors for each system. The two systems then simultaneously track a variety of satellites, and, in a successful collocation, the measured orbits will not differ by more than a few millimeters peak to peak. The photo above shows a collocation between the larger (75-centimeter telescope aperture) NASA MOBLAS-7 station in the background with a smaller (28-centimeter telescope aperture) transportable SLR system in the foreground.

The absolute accuracy of the laser-range measurement is currently limited by residual uncertainties in the atmospheric propagation delay. However, unlike space geodetic techniques that operate at microwave frequencies (such as VLBI and GPS), SLR measurements are relatively unaffected by the two most dynamic components of the atmosphere: the ionosphere and the "wet" troposphere. Although local, high-accuracy measurements of the relevant meteorological parameters (barometric pressure, temperature, and relative humidity) are routinely taken at laser sites and transmitted daily with the range data for atmospheric refraction models, there are still residual uncertainties that are believed to limit the absolute range accuracy to the 5–12-millimeter level, especially at low-elevation angles (for more on the problematic troposphere, see "Effect of the Troposphere on GPS Measurements," *GPS World,* January 1993).

NASA's GSFC performed the first successful laser ranging to an artificial satellite equipped with optical retroreflectors in 1964.

GPS RETROREFLECTOR ARRAY

The retroreflector arrays used on GPS-35 and 36 were built by the Russian Institute for Space Device Engineering in Moscow under contract to Professor Carroll Alley at the University of Maryland. The GPS array, constructed under the supervision of Dr. Victor Shargorodsky, is similar in design to those used successfully on all of the Russian GLONASS satellites. However, the total reflecting area of the GPS arrays is much smaller due to limited mounting space on the nadir-viewing face of the Block IIA satellites. A GPS array, illustrated on page 68, consists of 32 individual, fused-quartz retroreflectors. Each retroreflector is coated on the back reflective surfaces with aluminum, placed in a special holder, and arranged in a flat panel in alternating rows of either five or four. The array measures 239 millimeters in length by 194 millimeters in width by 37 millimeters in height and weighs 1.27 kilograms. At normal light incidence, the aperture of an individual retroreflector is a rectilinear hexagon equivalent in area to a circle 28.6 millimeters in diameter.

Figure 3 illustrates the relative locations of the GPS satellite center of gravity (CG), the effective laser array center of reflection, and the phase center of the L-band transmitting-antenna array. The positive-Z coordinate axis is in the direction of satellite nadir. The coordinates in millimeters of the nominal CG in the body-fixed reference frame are (0, 0, 1,011.4). This is really an average position because, over the life of the mission, the CG is expected to move by about 4.6 millimeters in the negative-Z direction, from Z = 1,013.7 millimeters to Z = 1,009.1 millimeters. In the same body-fixed reference frame, the coordinates in millimeters of the antenna array phase center are (279.4, 0, 1,967.9), and the coordinates in millimeters of the effective reflection center for the laser array are (862.6, −524.5, 1,669.8). The effective reflection center lies approximately 30 millimeters below the physical surface of the laser array.

SLR TRACKING OF GPS

Figure 4 shows a typical OMC (observed minus calculated) plot of the laser-range residuals for a calculated best-fit GPS short-arc orbit of approximately 40 minutes' duration. The data were taken on March 9, 1994, by the NASA MOBLAS-4 SLR station in Quincy, California. Single-shot, laser-range measurements are represented by open squares and show an rms scatter about the short-arc orbit of 1.16 centimeters. Normal points, representing laser-range data averaged over five-minute time intervals to remove random range errors, are indicated by black squares on the same figure and have an rms scatter of about two millimeters. This short-arc performance is only slightly degraded (by about 30 percent) from what is typically achieved on short arcs with geodetic satellites such as LAGEOS and Starlette (a smaller, retroreflector-covered satellite orbited by France in 1975).

Although the quality of the GPS laser-tracking data taken to date has been excellent, the data yield, as predicted from theoretical analyses prior to launch, has been relatively low. The low data yield results from two factors — one programmatic and the other technical. On the programmatic side, GPS-35 and 36 are currently ranked 10th and 11th in tracking priority in a group of 13 laser-tracked satellites. On the technical side, the principal limitation is a relatively weak optical link

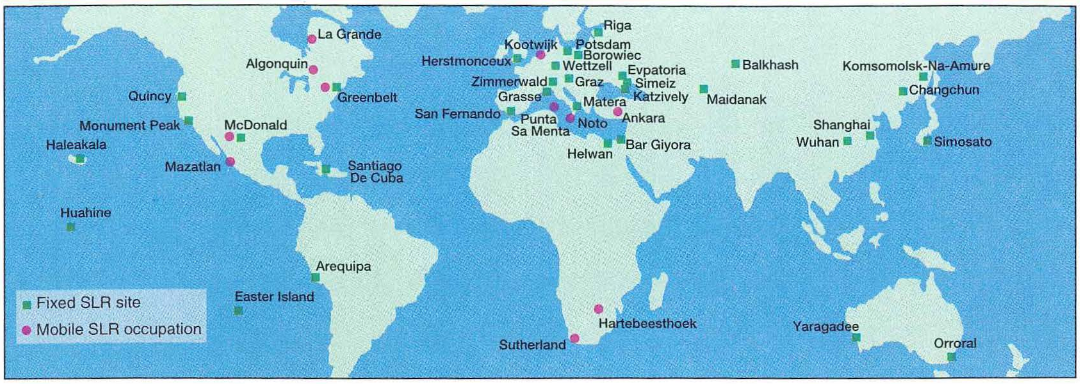

Figure 2. Locations of fixed (permanent) SLR stations and sites occupied by mobile SLR systems. Data were collected at more than 40 sites worldwide in 1993.

(one or two photoelectrons per range measurement) resulting from a combination of long slant ranges (greater than 20,000 kilometers) to a GPS satellite, the small size of the onboard retroreflector, and the engineering characteristics of most SLR stations, which were designed principally for precise day and night tracking of LAGEOS and lower-orbiting satellites.

SLR tracking priorities are periodically reviewed and set by the SLR Subcommission of CSTG (Coordination of Space Techniques for Geodesy and Geodynamics, an international commission created under the auspices of the International Association of Geodesy and the Committee on Space Research). At the CSTG SLR Subcommission meeting in Potsdam in October 1993, TOPEX/Poseidon and ERS-1, two oceanographic missions that use lasers as the primary source of tracking data, were assigned highest tracking priority. Among geodetic and other special satellites, low-orbiting satellites were assigned higher priority than high-orbiting satellites because of their shorter pass duration and potential capability to further our knowledge of the earth's gravity field and marine geoid. However, it is possible for interested GPS investigators to arrange special GPS laser-tracking campaigns of limited duration to meet specific experimental needs.

Lunar laser ranging stations, such as the MLRS station at the McDonald Observatory near Fort Davis, Texas, and the Centre d'Etudes et de Recherches Géodynamiques et Astronomiques site in southern France, are designed to detect weak laser signals from retroreflectors on the moon and therefore have several design features that make adaptation for ranging to GPS satellites relatively easy. First, because these stations operate only at night, LLR thresholds are set to detect single photoelectrons. Second, because the lunar ephemeris is well known and offset guiding based on lunar features or local star fields is possible, very narrow (about 2 arc second), atmosphere-limited laser beam divergence is used to transmit more light to the target and thereby increase the probability of detection. Finally, LLR stations use specially constructed multistop event timers to accommodate the relatively long 2.5-second roundtrip time to the moon. These devices allow the random multiplexing of start-and-stop pulses so that there can be several pulses in transit to and from the moon at any given time. The stop pulses associated with each start pulse are sorted out in software. These multistop epoch timers have a second important advantage: the occurrence of a random noise pulse does not terminate the time-of-flight measurement for a given laser pulse as in the more common single-stop time interval units used by most SLR systems.

In contrast to lunar ranging, SLR detection thresholds are typically maintained at the three- or four-photoelectron level so that satellite signals can be clearly distinguished against a strong daytime noise background. Unfortunately, the range returns from GPS satellites consist of one or two photoelectrons for most systems, so the probability of detection is relatively small. However, in recent experiments at the NASA MOBLAS-7 station, the simple inclusion of a postdetection, wideband (6 GHz) amplifier, with a gain of approximately 8, increased the nighttime laser data yield from GPS satellites by roughly an order of magnitude to about 100 ranges per minute. In contrast, Russian GLONASS satellites, which are at roughly the same altitude as the GPS satellites, are tracked relatively easily by many SLR stations, without need for amplification, because the reflecting array on GLONASS satellites is roughly 30 times larger in area than that on GPS satellites.

Additional experiments to enable daylight SLR tracking of GPS satellites are under way at the MOBLAS-7 site. These focus on reducing the spectral bandpass of the daytime range receiver by a factor of three and the spatial field of view by a factor of four, for an approximate factor-of-12 reduction in daylight-induced noise. This would allow the SLR systems to operate with the postdetection amplifier in daylight. If the ongoing experiments are successful, the receiver upgrade will be replicated at key SLR sites.

ORBITAL ANALYSIS AND RESULTS

At the time this article was written, GPS-36 had been tracked for less than a month; therefore we will restrict our discussion of data collection and analysis to GPS-35. There are 12 sites that, with varied frequency, have successfully tracked GPS-35 over the past six months: Monument Peak, California; Greenbelt, Maryland; Quincy, California; Fort Davis, Texas; Haleakala (Maui), Hawaii; Yarragadee, Australia; Hestmonceux, England; Graz, Austria; Wettzell, Germany; Potsdam, Germany; Maidanak, Uzbekistan; and Evpatoria, Ukraine.

If we examine the distribution of the tracked segments in time and by station, we find that some of the sites have tracked only over certain periods of time in a nonuniform way. This is because not all sites have the capability to track targets at such long distances, in broad daylight. Most of the systems are undergoing modifications that will allow them to track day or night in the future. In the meantime, there are only short periods of a day or so when several sites were simultaneously successful in tracking GPS-35.

With minor exceptions, we have adopted the models and algorithms in a set of standards for processing SLR data promulgated by the International Earth Rotation Service to ensure as much compatibility as possible with the results from other analysis centers. A long arc (at this point its length is about 104 days), used to check the fidelity of the force models, is continuously extended as new data become available. The laser data fit the arc with an rms of 3 centimeters. Figure 5 shows the residuals to this trajectory. As we mentioned before, there are several days without any data, and in most cases, even on the days when data are available, their geographical distribution is limited. In particular, Yarragadee started ranging to GPS-35 only recently, and there is an obvious lack of Southern Hemisphere tracking that can induce significant biases in our orbits.

Without uniform data control, the quality of the fitted orbit is hard to assess. On one occasion, however (November 18, 1993), the SLR network managed to acquire a fairly large number of passes (10) from the majority of the tracking sites. This being the best day for data collection during the period we were studying, we decided to use it as a test day to verify the quality of our orbits and gain some insight into the level of agreement with the radiometric data-determined orbits that IGS is routinely distributing.

We fit a 15-day arc to the data that were collected over the period November 5–18 inclusive. We fit another arc to the data over the 14-day period beginning on November 18. These two 14-day arcs have only one day's worth of data in common: November 18. In fact, the data span on that day covers the time from 11:00 UT to 23:00 UT, so the common data in the overlapping segment of the two arcs span only 12 hours. The data fit either arc with an rms residual of about 1.9 centimeters.

Despite the fact that the SLR data distribution is not as optimal as we would prefer for a precise orbit determination, it is still worthwhile to compare our orbits to the radiomet-

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The laser retroreflector array used on GPS-35 and GPS-36 is made up of 32 individual retroreflectors that reflect light back in exactly the same direction from which it comes.

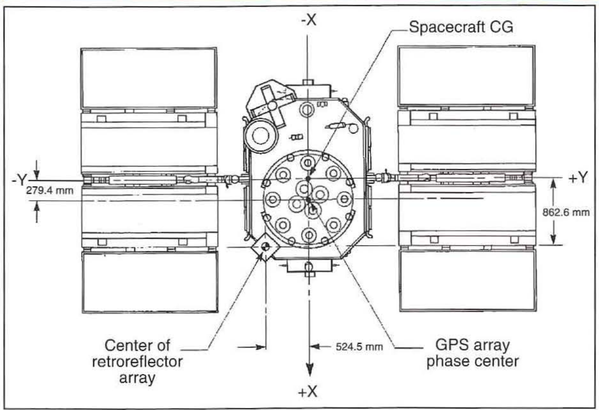

Figure 3. A sketch of a GPS satellite shows the locations of the retroreflector array, antenna array phase center, and the satellite center of gravity (CG). The positive Z-direction points out of the page.

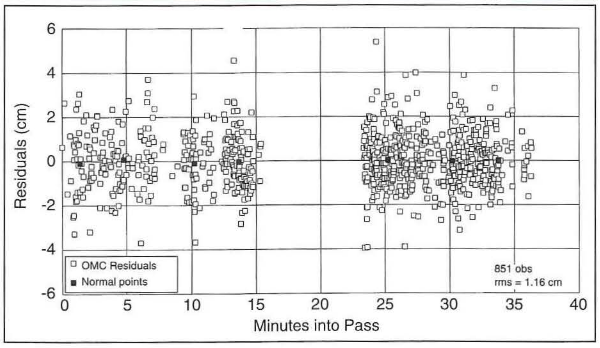

Figure 4. Range residuals from the analysis of data from a pass of GPS-35 collected by the MOBLAS-4 system at Quincy, California, on March 9, 1994, starting at 03:47 UT.

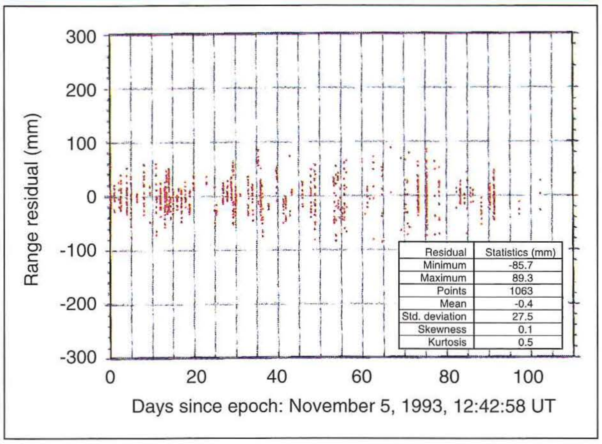

Figure 5. Range residuals from a fit of SLR data to a 104-day orbital arc for GPS-35

ric data-derived orbits distributed by IGS. Since the commencement of the operational phase of IGS on January 1, 1994, the official product, in terms of GPS orbits, consists of a weighted mean of the individual results from the contributing analysis centers. In anticipation of the operational phase, the analysis centers had already begun testing the procedure for merging their results into a single, reliable, and uniform orbit. The orbit for GPS week 723 was one of the first to become available. Our test day, November 18, 1993, falls in that week. The IGS orbit was rotated into the inertial frame and used as pseudo-observations with our data-analysis software package, GEODYN, to reconstitute a dynamic orbit fitting that data. When this process converged, a trajectory file was produced consistent with those from the SLR analyses for subsequent comparisons.

With only one day to compare, it is hard to come to firm conclusions. We believe, however, that the comparisons show at least a compatibility of the SLR and IGS orbits at about the decimeter level in the radial direction and 0.5 to 1.0 meter in the cross-track and along-track directions. This is a very limited test, where neither technology has put forward its best accomplishments and capabilities. A much more uniform and extended SLR data set will be required before we can reliably determine the orbit at the few-centimeter level of accuracy. On the other hand, reduction of GPS data directly within GEODYN will remove any inconsistencies in the standards and the reference frames used by the IGS analysis centers and the SLR group.

CONCLUSION

About a dozen stations in the international laser-tracking network are currently tracking the two GPS satellites equipped with retroreflectors. Modifications to the ground receivers will allow for a further increase in the tracking capabilities of several additional sites and add some desperately needed Southern Hemisphere tracking within the coming months. When the data distribution increases, further tests can explore the strengths of the SLR and GPS technologies, to assess the quality of the models used in the data reduction process, to link the reference frames of each technique in a direct way, and to investigate possible benefits in the geodetic products from a combined data analysis. The reduced orbits will also be used by our partners at NRL to study the short-term and long-term behavior of the frequency standards on board GPS satellites. ■

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