Chapter 23

Tectonic Motion in Western USA From Satellite Laser Ranging

D. C. Christodoulidis[1]
D. E. Smith
Goddard Space Flight Center
Geodynamics Branch
Greenbelt, Maryland, U.S.A.

S. M. Klosko[2]
J. W. Robbins[2]
P. J. Dunn[2]
M. H. Torrence[2]
EG&G/Washington Analytical Services Center Inc.
Lanham, Maryland, U.S.A.

[1]Now at Jet Propulsion Lab, Pasadena, California, U.S.A.
[2]Now at ST Systems Corp, Lanham, Maryland, U.S.A.

ABSTRACT

A model of the vector motions of eight laser sites located in the western United States, Peru and Mexico has been developed from an analysis of 7 years of LAGEOS tracking data. This data represents the most comprehensive set of laser observations ever acquired on a near-earth satellite. Annual solutions of the global laser network from 1979 through 1985 have been used to determine the motion of the sites of interest with respect to the Minster and Jordan (1978) AM1-2 plate motion system. A new methodology has been implemented which has permitted a free least-squares adjustment for the vector motions of the sites with respect to an external reference frame developed from the observed motion of three of the strongest "base" tracking stations.

Of the laser sites for which vector motions are being determined, four are located in California; two stations are on the Pacific plate in southern California, and two northern California sites are on the North American plate. These California measurements are an augmentation to the NASA San Andreas Fault Experiment (SAFE), which has monitored baseline rates since 1972. East/west control to this network is provided by sites located in Colorado and Texas. The seventh station is located on the North American plate in Mexico. Finally, the South American laser station in Peru is included in the solution to enhance north/south control, thus completing the network.

A second technology based on radio astronomical techniques has provided observations of the motion of Very Long Baseline Interferometry (VLBI) antennas on the West Coast over this same time span. The VLBI model agrees quite well when compared with the motions observed from Satellite Laser Ranging (SLR), especially for the stronger SLR sites. Both models go far in explaining why the observed compression between Monument Peak and Quincy (the well-known "SAFE" baseline) is less (-2 to -3 cm/yr) than that expected from geological models (-5.3 cm/yr). Both VLBI and SLR models indicate that Quincy is not moving in its predicted AM1-2 southwest direction and that Monument Peak is moving at less than the full Pacific plate rate.

INTRODUCTION

Understanding and modeling the tectonic activity within the western part of the United States has been one of the major objectives of NASA's Geodynamics Program. This region is of great interest to the scientific community, not only because of the complexity of the tectonic motions and crustal deformation associated with the Pacific-North American plate boundary, but also because of the enormous social and economic impact that major earthquakes have when they occur in this locale. The Pacific-North American plate boundary is not well defined; it is diffuse, with different modes and patterns of motion occurring across its numerous geologic features. Whereas the San Andreas fault is the boundary's predominant geologic feature, other faults are also actively accommodating tectonic motions between the numerous platelets which exist in this area. As a consequence, the temporal deformation of a dense network of sites needs to be monitored frequently if local, regional, and platewide motions are to be resolved and understood. This understanding permits the development of comprehensive plate tectonic kinematic models and furthers the understanding of earthquake mechanisms and processes.

Over the last three decades, a large number of classically surveyed baselines have provided data to monitor crustal motions and deformations within the western United States (Savage et al., 1981; Savage, 1983). For the most part, however, individual baselines obtained in this way are limited to distances of 50 to 60 km. These measurements are almost always densest in the vicinity of the faults and their application is largely aimed at the detection of local deformation and resulting strain accumulation. Assessing large-scale distortions within the plates or determining interplate motions by means of terrestrial surveys (primarily traverses) suffers from the accumulation of errors with distance. Space techniques on the other hand are well suited for such large-distance determinations. Very Long Baseline Interferometry (VLBI) and Satellite Laser Ranging (SLR) provide accurate geodetic positioning on vastly larger spatial scales than those obtained with ground-based measurements. Both technologies have been used for more than a decade to monitor West Coast crustal motions. For example, during the last decade, SLR has provided numerous measures of the baseline connecting a tracking site located on the Pacific plate near San Diego with a site in north-central California, Mt. Quincy, located on the North American plate. Early results from this San Andreas Fault Experiment (SAFE) produced baseline rates and served as a proof-of-concept establishing SLR as a viable approach for observing present-day tectonic motions and deformations. Under the auspices of NASA's Crustal Dynamics Program numerous VLBI and laser tracking sites were established globally with the western United States receiving a dense distribution of stations. Currently, laser tracking sites in 23 countries provide SLR with a well-distributed global reference network for observations of tectonic processes. A special satellite devoted to laser ranging was launched in 1976. This satellite, LAGEOS, is in a high-altitude, high-inclination, stable orbit and provides and excellent target for state-of-the-art satellite geodesy.

The laser network reached its full potential in mid-1979 with the deployment of NASA mobile tracking systems. Seven years of these data have been analyzed and the results are described herein. From the observed motions of the dominant base stations, the contemporary relative motion between five major plates—North American, Pacific, Australian, Eurasian, and South American—has now been broadly defined (Christodoulidis et al., 1985). Results obtained from annual solutions of the laser tracking coordinates indicate that, on a global scale, there is good agreement between the present-day SLR-observed baseline changes and the changes predicted by geologic models (Christodoulidis et al., 1985), especially for sites located within the stable interior of the major plates.

This paper concentrates on crustal motion within the western US/Mexico being observed by SLR. The heavier concentration of tracking stations in this region has permitted an extension of our previous approach—that of assessing distance changes on an individual baseline basis—to the computation of a consistent model of station velocity vectors for the dominant participating sites in this region. A reference frame defining the motion observed between three stations from the global SLR network is used for these solutions, and the motion of the remaining sites is computed with respect to this frame.

SL7 LAGEOS LASER RANGE SOLUTION

The analysis of the LAGEOS range data follows a two-stage process. First, the data are segmented into monthly arcs. Each arc is reduced to a single orbit trajectory used to interrelate the laser observations in time. We use a complex,

Table 1. GSFC SL7 LAGEOS geodetic solution.

- Reference Frame
  - SL7 tracking positions
  - LAGEOS Earth rotation and orientation (every 5 days)
  - Wahr's nutation series
  - JPL DE-200 planetary ephemerides: J2000 reference system
- Force model
  - GEM-T1 gravity field (complete to degree and order 20)
  - Luni-solar and planetary gravitational perturbations (Venus through Saturn)
  - LAGEOS derived GM = 398600.4359 km^3/s^2
  - Wahr's solid Earth tides
  - Ocean tides from GEM-T1
  - Direct solar radiation pressure
  - Along-track acceleration parameters
  - General and special relativistic effects are not applied
- Measurement model
  - Marini-Murray tropospheric refraction model with exclusively site meteorological measurements
  - Velocity of light (299792458 m/s)
  - Vertical and horizontal tide displacements ($h_2 = 0.609$, $l_2 = 0.085$)
  - Normal points (2-minute bins) following Herstmonceaux recommendations
- Data Span
  - May 1976 to December 1985

ever evolving force and earth orientation model in these orbital calculations. The observations are evaluated, validated, and edited to eliminate those that are aberrant. Then, after a satisfactory data set is realized, normal equations are calculated for a set of orbital, station, earth orientation, and force model parameters from each arc's data.

The normal equations are combined and solved to produce annual and multiyear solutions. The results we are describing here are from a preliminary version of SL7, the latest in our series of solutions. Previous Goddard Space Flight Center (GSFC) satellite laser ranging results using this reduction approach can be found in Christodoulidis et al. (1985) and Smith et al. (1985). A summary of the force model and measurement models employed in SL7 is found in Table 1. LAGEOS orbits the earth in a stable high-altitude orbit. Consequently, it experiences reduced perturbations from the shorter wavelength portions of the earth's gravity field while strongly sensing the gravity field at longest wavelengths. The gravity model which has been utilized made use of data from 17 other satellites. This geopotential model is a preliminary version of GEM-T1 (Marsh et al., 1987), which is the most comprehensive satellite-only gravity model developed at GSFC to date. It has been developed to meet specific accuracy standards as required by the TOPEX/POSEIDON oceanographic altimeter mission. Because of the improved accuracies of the GEM-T1 model, orbital recovery for LAGEOS has improved substantially thereby enhancing the accuracy of solved-for geodetic parameters. As part of the SL7 solution, we used 5 years of LAGEOS data to solve for an improved dynamic model of the longest wavelength ocean tides and improved values for the Earth's elastic tidal deformation terms, h_2 and l_2. A polar motion series of high precision has also been solved directly from the LAGEOS observations. These models were then used for the annual estimation of station coordinates which form the basis for the investigation of interstation relative motions over the 1979 to 1985 time frame.

Although LAGEOS was launched in May 1976, the data used here begins in 1979. There are many reasons for this. First, the Smithsonian Astrophysical Observatory laser systems were upgraded during the summer of 1978 to the early spring of 1979. This upgrade, which involved the installation of a pulse chopper, improved the precision of these instruments by approximately a factor of 3. Second, which is perhaps even more important, mobile NASA systems were deployed globally in the fall of 1979 giving the laser network a greatly enhanced capability. This network grew considerably after 1979, with the present participation of about 23 countries and nearly 30 stations tracking worldwide. Therefore, the 1979 data was the first annual set suitable for inclusion in the investigation presented herein.

Third-generation laser systems typically have a data precision of 2 to 5 cm with data rates of a range every second or higher. Given the altitude of LAGEOS, a station ranges to the satellite for an interval of 30 to 45 minutes on each satellite passage. These range observations have been condensed to form "normal points" at 2-minute intervals which compress the noise and form observations that are nearly noiseless. Each station tracks a ranging target at a known distance prior to and after each satellite tracking interval (exception for one of the transportable systems, the TLRS-1 system, which has an internal calibration). Additionally, before any of the instruments are deployed in the field they undergo colocation trials against other systems to ensure ranging compatibility at the 2- to 3-cm level of overall agreement. This colocation requirement continues to become more stringent in time. Table 2 summarizes the yearly number of normal points contained within each of these annual solutions and the overall yearly RMS of fit to the total data set.

The West Coast of the United States, and more recently Mexico, have been heavily instrumented with laser stations. Numerous sites have been occupied over the lifetime of the NASA Crustal Dynamics Program. The station deployment scheme designates certain sites as "base" stations—stations with permanent or nearly permanent occupancy. Other sites are visited by mobile systems and provide data for intervals of several months to 2 years. A global set of base stations tracking LAGEOS over the time interval which is investigated here have been extensively utilized to calculate directly the motions of the sites found within the western United States/Mexico region. The sites used to infer motion of West Coast tectonics are summarized in Table 3, which also indi-

Table 2. Observation summary for annual solutions.

Year	Number of Normal Points	RMS of fit for Normal Solution (cm)
1979	17933	17.3
1980	34826	13.8
1981	30143	12.9
1982	31735	9.7
1983	38197	9.7
1984	62584	7.5
1985	63621	6.2

cates the years of their tracking participation. The SAFE line connecting northern and southern California has been observed at two sets of stations spanning this entire interval. However, the 1981 relocation of the southern site from Otay Mountain outside San Diego to Monument Peak some 50 km away has prohibited our combining the results for SAFE over this complete 6-year interval.

The geodetic positions for the station coordinates which will be discussed are given in Table 4. These values are those obtained from the annual SL7 solutions.

STATION MOTION REFERENCE FRAME

According to the plate tectonics theory, all points on the Earth's surface are located on a dynamic lithosphere. To better understand the tectonics of the western United States it is desirable to adopt a reference frame with respect to which we can compute the movements of individual stations. The global participation of a set of base laser stations on several of the world's major plates has provided us with a suitable geometrical configuration to achieve this objective.

The set of tracking stations we selected in this study to define the reference frame include Greenbelt, Hawaii, and Yaragadee, Australia. We will refer to these sites, in the remainder of this work, as those which define the "external" network. Two of these stations tracked LAGEOS during the entire 7-year interval which we studied, whereas the third, Hawaii, tracked during the last 6 years of this interval. This is a considerably more continuous level of participation than many of the sites of interest in the western United States.

The quantities from the annual solutions which are being analyzed involve observed changes in the geodesic distance connecting two stations. Although for short distances there is no significant difference between changes in the geodesics and the chord lengths, for long distances, changes in the geodesics give a more meaningful description of the relative horizontal motion between stations. The geodesic distances we have calculated involve changes in the horizontal positions of the stations along the Earth's surface and are therefore free of vertical movements and their errors.

Two approaches have been considered with regard to the definition of an external reference frame. The first was to use the AM1-2 model (Minster and Jordan, 1978, which will in this work be denoted as M/J)) to describe the motion of our chosen fiducial "external" sites. The AM1-2 model was deduced from geological evidence and is tied to a mantle plume (or hotspot) reference frame which is assumed to have "typical internal motions much slower than the motions of the plates" (Minster and Jordan, 1978). This approach was viable for, as seen in Table 5, AM1-2 predicts to a satisfactory level the relative motion of these sites with respect to one another (that is, the rate of change of their geodesic distances) when compared with the relative motion derived directly from SLR.

A second, more direct model of the motions of the external station frame was obtained from the SLR solution itself. The design of the SL7 solution imposed specific constraints on a limited number of individual station components in order to stabilize the reference frame within annual solutions. Three station geodetic components were modeled to move with AM1-2 model motion. These are the latitude (ϕ) and longitude (λ) of the Greenbelt laser site and the latitude of the Hawaiian laser site. Since the modeled latitudinal component of Hawaii's motion is largely perpendicular to the geodesic connecting it to Greenbelt, these modeled (unadjusted) coordinates did not constrain the estimated interstation distance between these two sites, but defined an understandable and geodynamically compatible reference frame within which all other sites could be adjusted. The coordinates of all remaining laser sites were freely solved on an annual basis with respect to this set of constraints. The external reference frame was then obtained directly by fitting linear rates to the time series of annually recovered latitudes and longitudes for each of these three "external" sites having robust tracking histories. This yielded a ϕ and λ motion component for each of these sites and provided a reference model for their motion. Note

Table 3. Years of tracking participation and estimated station position. Uncertainty (in cm) for external and internal sites.

Location	Station	1979	1980	1981	1982	1983	1984	1985
Reference Stations (External Network)								
Hawaii	7210	—	1.4	1.8	1.1	0.9	0.8	1.0
Yaragadee	7090	3.4	0.8	0.8	1.0	1.4	0.9	0.8
Greenbelt	7105	1.9	1.4	1.6	1.3	1.3	1.1	1.1
Western US/Mexico Stations (Internal Network)								
Otay Mtn.	7062	2.6	—	2.5	—	2.7	9.6	—
McDonald Obs.	7086	1.9	1.4	—	3.3	1.5	1.6	1.1
Quincy	7109	—	—	3.0	1.3	1.2	0.8	0.9
Monument Pk.	7110	—	—	1.5	1.3	1.3	0.8	0.8
Platteville	7112	—	—	1.4	1.4	1.7	1.6	—
Owens Valley	7114	1.9	1.2	3.1	2.8	—	—	—
Mazatlan	7122	—	—	—	—	1.5	0.9	0.9
Arequipa	7907	1.6	0.9	1.0	1.1	0.7	0.8	0.9

Table 4. Geodetic coordinates for SL7 stations. (Epoch is 1985 unless otherwise noted.)

Station Number	Station Name	Latitude	Longitude	Ellipsoid Height (m)
7062*	Otay Mtn.	32° 36' 02.671"	243° 09' 32.922"	988.178
7086	McDonald Obs.	30° 40' 37.315"	255° 59' 02.624"	1961.380
7090	Yaragadee	−29° 02' 47.415"	115° 20' 48.265"	241.320
7105	Greenbelt	39° 01' 14.175"	283° 10' 20.301"	19.130
7109	Quincy	39° 58' 30.013"	239° 03' 19.087"	1106.279
7110	Monument Peak	32° 53' 30.257"	243° 34' 38.397"	1838.924
7112*	Platteville	40° 10' 58.013"	255° 16' 26.481"	1501.371
7122	Mazatlan	23° 20' 34.259"	253° 32' 27.300"	30.782
7210	Hawaii	20° 42' 25.980"	203° 44' 38.735"	3067.433
7907	Arequipa	−16° 27' 56.680"	288° 30' 24.748"	2492.265

Ellipsoid parameters: a_e = 6378137m, 1/f = 298.257.
*Epoch year is 1984.

Table 5. Geodesic distance changes between reference external stations.

Geodesic Line	SL7 Observed Geodesic Rate (cm/yr)	Predicted Rate from AM1-2 Model (cm/yr)	$(\dot{\phi},\dot{\lambda})$ Predicted Rate from SL7 Station Rates (cm/yr)
Hawaii–Yaragadee	−9.7 ± 0.9	−10.3	−8.5
Hawaii–Greenbelt	2.6 ± 1.0	1.7	1.7
Yaragadee–Greenbelt	−6.9 ± 0.7	−8.8	−6.8

Table 6. Vector motion models for reference external stations.

	AM1-2 Model		SL7 $(\dot{\phi},\dot{\lambda})$ Rates	
Station	Rate (cm/yr)	Azimuth (degrees)	Rate (cm/yr)	Azimuth (degrees)
Greenbelt	2.69	251.5	2.69	252.5
Hawaii	9.68	300.4	9.49	300.9
Yaragadee	7.97	21.7	5.84	19.4

that the horizontal motion for Greenbelt is common to both approaches. Table 6 compares the results obtained using this second approach $(\dot{\phi}, \dot{\lambda})$ with the observed geodesic distance rates observed between these three sites. This method agrees well with the observed SLR station distance changes.* Therefore, in the latter sections of this report, in addition to using the AM1-2 model to describe the station motions defining the external reference frame, we have also used the "fitted" motion vectors $(\dot{\phi}, \dot{\lambda})$ obtained directly from SL7.

The role of "external" and "internal" stations will be further clarified in the next section.

METHODOLOGY

In general, the basis for the determination of vector motions of laser tracking stations lies in a simple geometric model. The model consists of two networks of stations—an "external" network of the strong stations with a priori defined motions and an "internal" network of the stations whose motions are to be determined. The reference motions of the external stations are considered known and the quantities of interest—the motions of the internal stations—are determined with respect to this external network.

The external network of three stations is given in Table 7 along with the respective plates upon which they reside. Figure 1 shows a map of these stations and their motions as described by AM1-2. These three stations were chosen for several reasons. The quality and quantity of laser data collected at these three sites played a major factor in their selection. Also, each of these external stations is centrally located on a major tectonic plate.

The internal network consists of the laser stations also listed in Table 7. Many of these stations are situated on either side of the San Andreas fault and have a predominantly north/south orientation. The McDonald and Platteville stations provide east/west control, and Arequipa, Peru provides improved north/south geometry. A map identifying the "internal" network is given in Figure 2.

The computations for the motion vectors of the internal stations utilize the time variant laser station positions which have been determined in a uniform coordinate system (the

*The reason the SL7 $(\dot{\phi}, \dot{\lambda})$ model does not agree perfectly with the SLR intersite geodesic rates is attributed to instabilities in the reference frame from annual solution to annual solution. The relative positions of the laser stations within the network are better defined than the absolute orientation of this reference frame (that is, intersite distance recovery is insensitive to earth orientation, whereas the latitude and longitude determinations for the sites are not).

Table 7. Station network.

Station Number	Location	Plate
	External Network	
7210	Maui, Hawaii	Pacific
7090	Yaragadee, Australia	Indian
7105	Greenbelt, Maryland	North American
	Internal Network	
7109	Quincy, CA	North American
7086	McDonald Obs., TX	North American
7114	Owens Valley, CA	North American
7122	Mazatlan, Mexico	North American
7062	Otay Mtn., CA	Pacific
7110	Monument Pk., CA	Pacific
7112	Platteville, CO	North American
7907	Arequipa, Peru	South American

SL7 system). In particular, the stations have been estimated as annual mean three-dimensional positions.

A set of annual geodesic lengths are then computed from each annual solution using an algorithm of Vincenty (1974). One subset contains the annual geodesic lengths for the internal/external lines and the other subset is made up of the internal/internal lines. Estimates of the position uncertainties are propagated into the appropriate uncertainties in geodesic lengths. The computation of the geodesic lengths is independent of the height. Therefore, changes in geodesic lengths over a period of time reflect only horizontal motions. The annual geodesic lengths connecting two stations over the timespan are ordered temporally and a slope is computed by weighted least-squares yielding a geodesic rate. The weights assigned in this least-squares process for the observed geodesic lengths is determined from each length's formal uncertainty in the annual solution. The uncertainties are propagated and the slope thereby determined maintains its weighted formal uncertainty. The overall formal uncertainties are then scaled to yield a X^2 of 1 for the residuals obtained from the fitted series. These rates represent the relative tectonic motion between any two stations. This procedure is

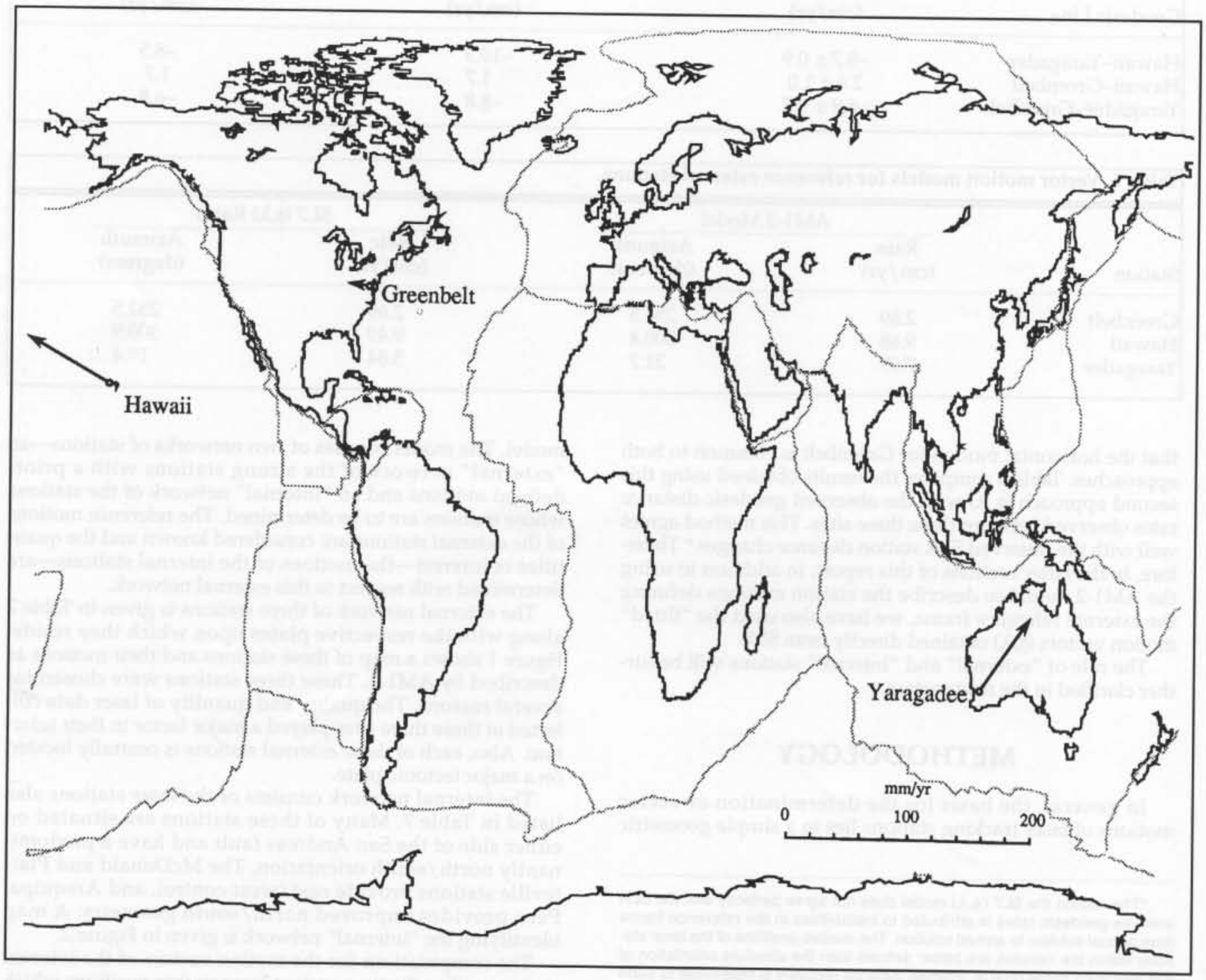

Figure 1—Laser Reference Network. Vector motions from Minster and Jordan (1978) AM1-2 model.

used on all stations (in both subsets of geodesic lengths) for those lines which have at least two annual geodesic lengths.

The contributions of the motions of the external stations, given by the adopted reference model (AM1-2 or the "fitted" motion model), are then removed from the external/internal geodesic rates. This is done simply by projecting the velocity vector for the external station onto the direction of the internal station and then subtracting this component from the respective geodesic rate. By removing the modeled motion for the external station from the geodesic rate, the resulting quantity is the motion for the internal station referenced to the external network's adopted motion. These computations are done in a vector mode and the reference motions of the external stations are considered errorless. Therefore, the errors in the geodesic rates for the external/internal lines propagate directly into the reference motion for the internal station. The internal/internal relative geodesic rates contain valuable network closure information and are used simultaneously in the estimation procedure. All rates are combined to yield a unique motion vector for each internal station. The combining process takes place in a least-squares algorithm.

Two kinds of observation equations can be written. For the external/internal lines the equation is written as

$$C_i = (X_n^2) + X_e^2)^{-1/2} \{\cos A_x + \cos A_i + \sin A_x \sin A_i\}$$

where

C_i is the "observed" motion in the direction of external station i. This value is determined by removing the reference motion of the external site from the determined geodesic rate between the external to internal stations,

X_n and X_e are the north and east components of the internal station's unique vector which we seek,

A_x is the azimuth of the internal station's unique vector which can be expressed in terms of X_n and X_e as $A_x = \tan^{-1}(X_e/X_n)$, and

A_i is the azimuth toward the external station, i.

These quantities are illustrated in Figure 3. The internal/internal lines have a somewhat similar observation equation of the form

$$r_{12} = X_1 \cos(A_{x1} - A_{12}) + X_2 \cos(A_{x2} - A_{21})$$

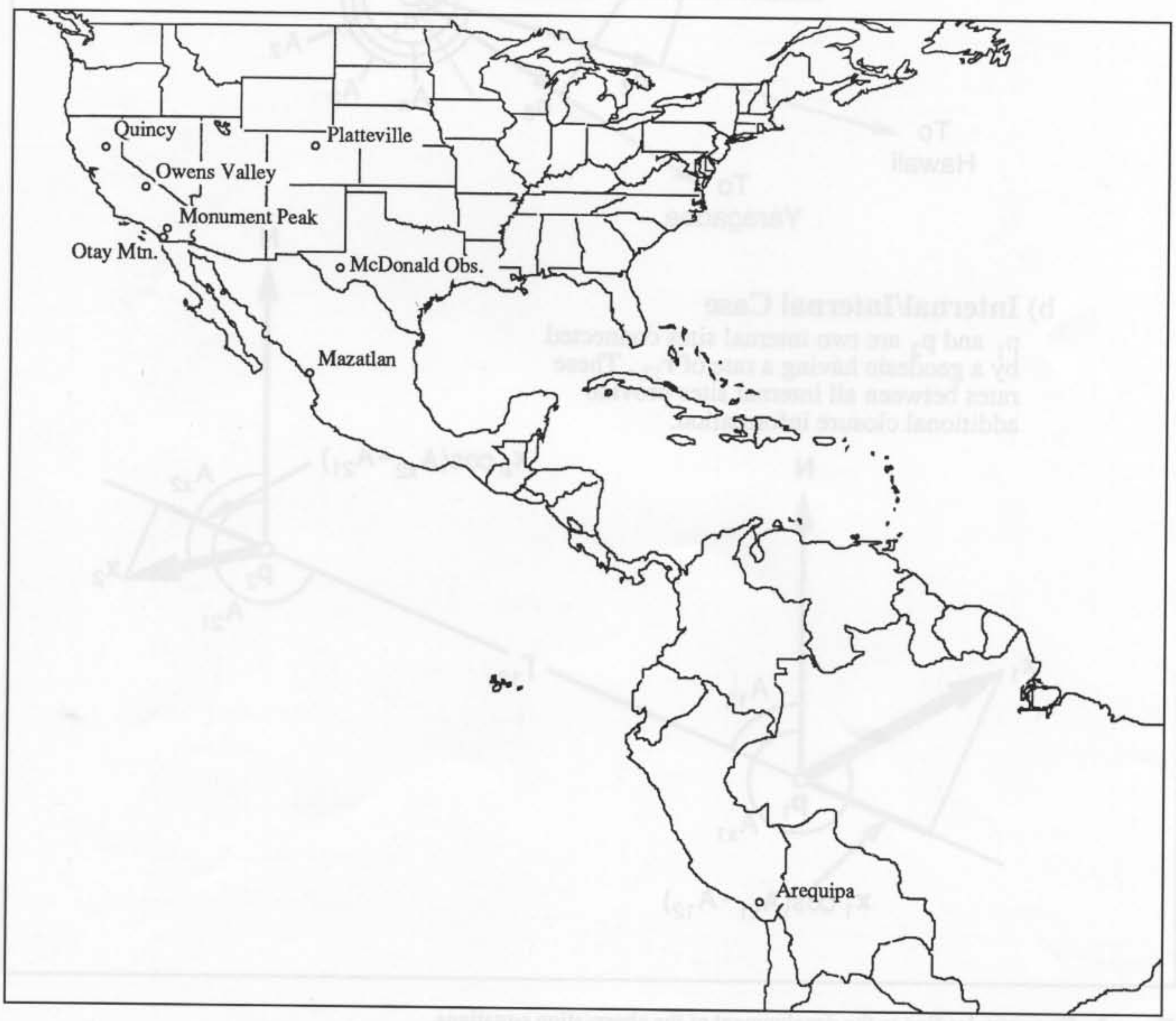

Figure 2—Locations of internal tracking sites.

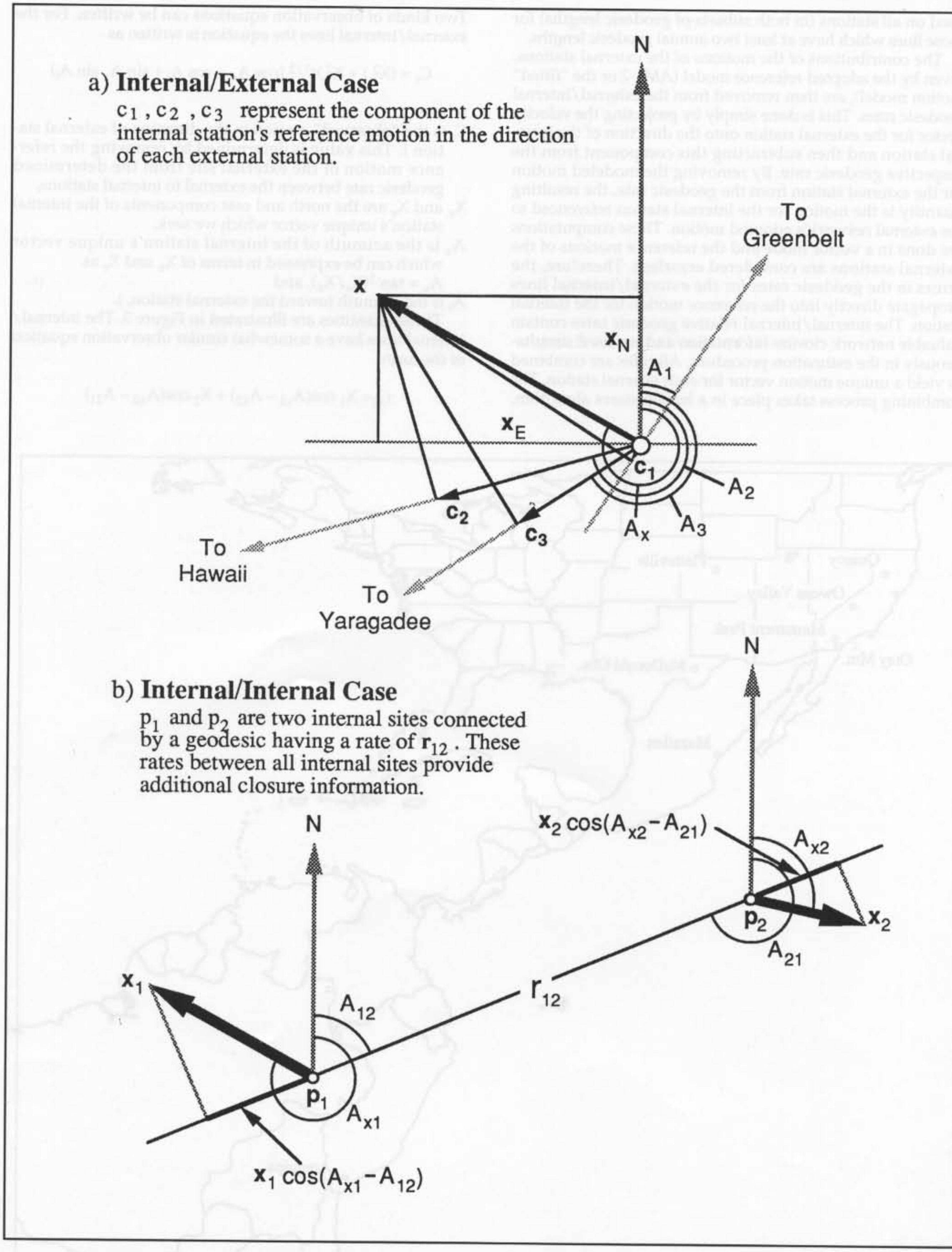

Figure 3—Geometry leading to the development of the observation equations.

where

r_{12} is the observed relative geodesic rate between station 1 and 2,

X_1 and X_2 are the unique vectors being solved for at each station,

A_{x1} and A_{x2} are the azimuths of X_1 and X_2, respectively, and finally

A_{12} and A_{21} are the azimuths of station 1 to 2 and 2 to 1, respectively.

For our experiment the geodesics connecting the internal network of stations to the external stations are predominantly east/west in orientation. Utilizing the internal/internal relative rates in the combining procedure strengthens the north/south-oriented motions, especially when Arequipa is included.

STATION POSITION ERROR MODEL

The 7 years of LAGEOS tracking which have been analyzed in SL-7 produced 51 relevant geodesic distance rate measurements. These rates involve those observed between the internal stations and the external stations, and rates between the internal stations themselves. These rates were obtained by fitting a slope to the observed changes in interstation geodesic distances with observation uncertainties obtained from the station uncertainties. For this investigation, we assumed that the normal point data have an accuracy of 20 cm. This is conservative and is meant to reflect the presence of unmodeled and unconsidered additional error sources beyond the noise in the data. The annual solution is solved and we obtain a formal estimate of station three-dimensional accuracy. Since Earth orientation parameters are also recovered in the estimation procedure, the formal uncertainties for the horizontal components at each station are affected by correlation with the determined polar motion parameters. However, the uncertainty in the height recovered for each site is virtually uncorrelated with any other determined parameter. For this reason, we have chosen to use the height uncertainty as the positional uncertainty in all directions, thereby assigning a unique error sphere for each station's determined annual position. These height uncertainties have been propagated throughout in estimating the motion vectors and their uncertainties. Table 3 presents these station positioning uncertainties determined in the individual annual solutions for the internal and external network.

DISCUSSION OF RESULTS AND COMPARISONS WITH VERY LONG BASELINE INTERFEROMETRY

There are 51 different SLR geodesic rates observed within the western United States for the station subset we have investigated over the 1979 to 1985 time interval. These lines connect the internal network sites to the three-station external network, and connect the internal sites to one another. The north and east vector motions for eight stations are determined through a weighted least-squares algorithm using two different models for the motion of the SLR external stations. As shown later in this section, these motion models obtained from satellite laser ranging are compared with similarly derived independent models developed from the radio astronomical technique of VLBI.

The quality of the laser observations and the intuition gained from the analysis of the data warrants mentioning. Some sites, like those chosen for the external network, are continuously occupied, yielding annual data sets which are uniformly sampled. They therefore provide a history of tracking which can be carefully monitored and compared, and define the SLR reference frame in which earth orientation can be assessed using near-earth satellite observations. The tracking histories of each considered external and internal site are shown in Table 8. Although only the chosen external sites are completely satisfactory in this regard, the sites at Monument Peak, Quincy, Mazatlan (Mexico), and Arequipa (Peru) have exhibited strong and robust data sets

Table 8. Summary of the number of LAGEOS passes per year.

Station	Year 1979	1980	1981	1982	1983	1984	1985	1986*
				External Network				
Greenbelt	159	141	182	212	156	179	270	171
Hawaii	0	112	255	170	329	289	220	130
Yaragadee	21	513	529	345	123	310	439	269
				Internal Network				
Strong								
Quincy	0	0	16	187	241	395	323	227
Monument Peak	0	0	103	210	140	369	373	257
Arequipa	285	338	290	325	525	319	280	178
Mazatlan	0	0	0	0	81	181	234	170
Moderate								
McDonald Obs.	76	120	0	43	127	114	204	176
Platteville	0	0	160	185	80	118	0	0
Weak								
Otay Mtn.	52	0	52	2	27	0	0	0
Owens Valley	131	188	29	37	28	0	0	0

*Only nine months of 1986 data analyzed.

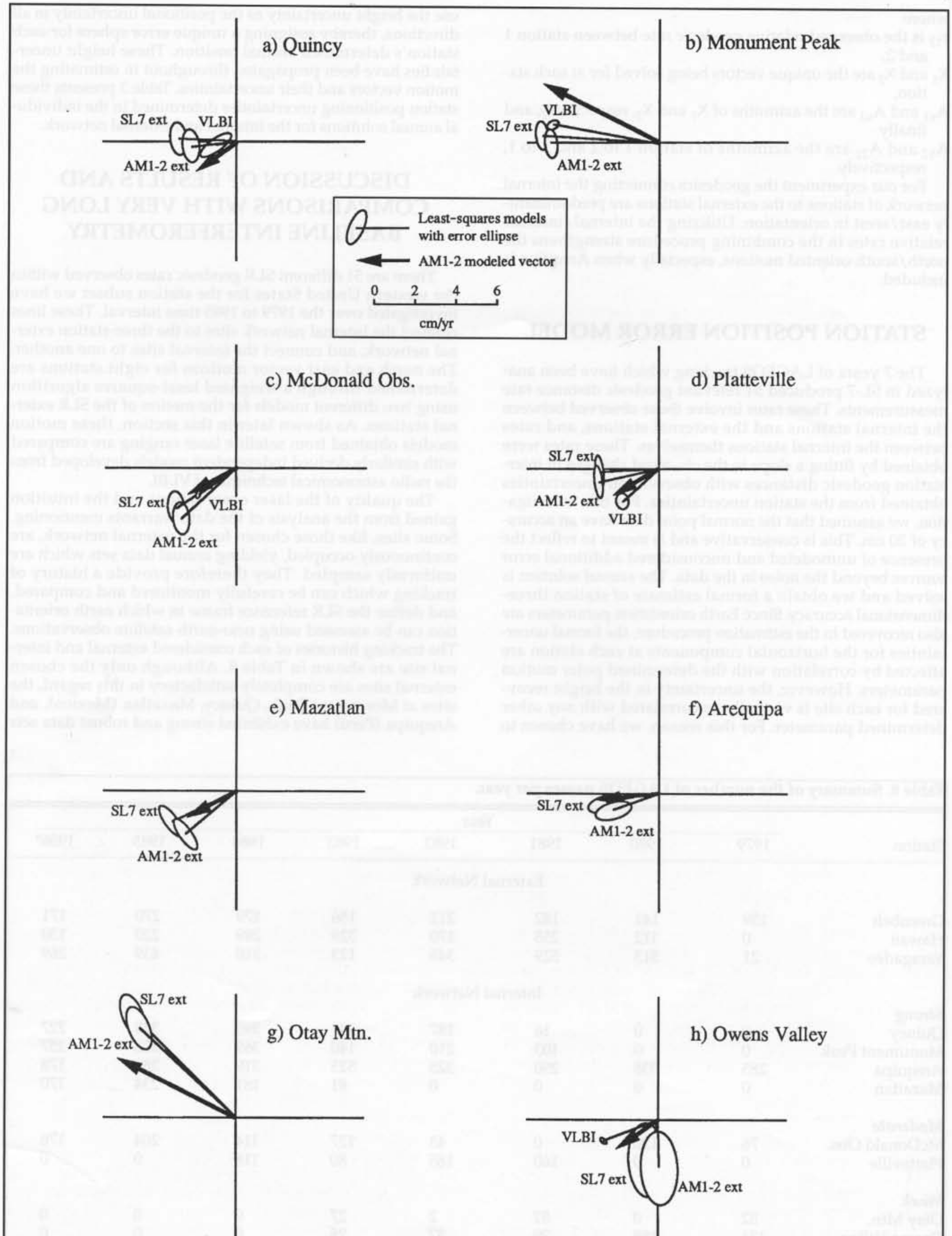

Figure 4—Vector motions of internal sites from SLR, VLBI solutions, and the AM1-2 model.

Table 9. Least-squares solutions for vector motion models.

Station	Station	SLR SL7 External Rate (cm/yr)	SLR SL7 External Azimuth (degrees)	SLR AM1-2 External Rate (cm/yr)	SLR AM1-2 External Azimuth (degrees)	VLBI* (Clark et al., 1987) Rate (cm/yr)	VLBI* (Clark et al., 1987) Azimuth (degrees)	AM1-2 Model Rate (cm/yr)	AM1-2 Model Azimuth (degrees)
Quincy	Strong	2.77	272	2.16	263	0.96	261	2.41	234
Owens Valley	Weak	2.01	195	2.25	179	2.84	249	2.49	235
McDonald Obs.	Moderate	3.57	235	3.64	227	2.18	234	2.67	241
Mazatlan	Strong	3.42	244	3.22	229	—	—	2.72	241
Platteville	Moderate	2.85	267	2.94	257	2.34	227	2.55	239
Monument Peak	Strong	5.65	274	5.37	270	5.24	280	6.31	297
Otay Mtn.	Weak	7.03	315	6.32	313	—	—	6.38	297
Arequipa	Strong	2.55	260	2.31	250	—	—	3.12	265

*Derived by assuming that Westford, MA has AM1-2 motion similar in geometry to SLR solutions which model Geenbelt, MD in this way.

Table 10. Error estimates of station motions.

Station Name	SLR s_a	SLR s_b	SLR AZ	VLBI s_a	VLBI s_b	VLBI AZ	SLR Characterization
Quincy	0.8	0.4	353°	0.9	0.3	54°	strong
Owens Valley	1.8	0.9	357°	0.2	0.1	131°	weak
McDonald Obs.	0.8	0.4	355°	0.2	0.1	21°	moderate
Mazatlan	0.9	0.3	325°				strong
Platteville	0.8	0.2	353°	0.4	0.3	171°	moderate
Monument Peak	0.7	0.3	354°	0.3	0.2	61°	strong
Otay Mtn.	1.1	0.5	338°				weak
Arequipa	0.9	0.4	253°	—	—		strong

s_a: major axis of error ellipse (units in cm/yr)
s_b: minor axis of error ellipse (units in cm/yr)
AZ: azimuth of major axis

since the time they were initially occupied. The other sites have been sporadically visited and (at times) have been occupied by highly transportable systems for short durations.

Of the sites for which vector motion is being estimated, both Quincy (7109) and Monument Peak (7110) are stations which acquired large and well-distributed data sets from 1982 to 1986. For both sites, the data in 1981 began late in the year and is somewhat weaker. These sites are part of the SAFE Experiment forming a baseline which has been monitored using laser techniques since the early 1970s (Christodoulidis and Smith, 1984). Otay Mountain (7062) and McDonald Observatory (7086) were weaker sites which suffered from problems when occupied for short durations by the TLRS-1 system. Owens Valley (7114) had only 2 years of strong data, and these were the consecutive years of 1979 to 1980. Its data were weaker in 1981 and quite sparse during other time periods. Platteville (7112) was occupied by one of the oldest NASA laser systems until it was abandoned in 1984. The Platteville system operated with an accuracy of only 15 to 20 cm per range and therefore, because of noise alone, is a suspect site.

The non-U.S. sites selected to improve the geometry of the internal network were quite good. The Mexican site, Mazatlan (7122) started tracking in May 1983 and has since provided an especially strong data set. And lastly, the Smithsonian Astrophysical Observatory site in Arequipa, Peru is equipped with one of the oldest lasers in continuous operation. It operated over the entire lifetime of the LAGEOS Mission but has data of a lesser precision than that routinely achieved by modern NASA laser systems (a precision of 10 cm).

On this basis, we have characterized our confidence in the SLR model for each of these stations. Although this characterization (strong, moderate, or weak station) is reflected in the statistics of the vector recoveries, the tracking histories themselves and the level of system performance form the basis for these additional model qualifications (see Table 8).

One of the advantages of adopting an external frame composed of strong base stations lies in the fact that mobile sites can be monitored whenever tracking exists, which is not the case when mobile sites are compared solely with one another. Also, the uncertainty in the rates of lines connecting internal to external sites is usually smaller than that for lines connecting internal stations. This approach thereby maximizes the information used in defining the motion of weaker sites occupied by highly transportable systems and gives a more robust definition of the reference frame for defining station motions.

Clark et al. (1987) have used 4 years of VLBI observations coincidental with the SLR campaign to determine the vector motions of 17 U.S. sites. By observing and correlating radio signals from distant quasars simultaneously at different antennas, the VLBI technique has become a highly valuable technology for precision geodesy. Using a least-squares algorithm similar to ours, the VLBI analysis group has

Table 11. Observed rate of change in baseline connecting Monument Peak to Quincy.

Source	Rate (cm/yr)	Uncertainty (cm/yr)
DIRECT OBSERVATIONS		
SLR annual solutions 1981-1985	−1.92	± .5
SLR annual solutions 1981-1986	−2.42	± .4
SLR short arcs 1981-1984	−2.56	±.3
VLB (Clark et al., 1987)	−3.39	± .6
MODELS		
SLR AM1-2 ext	−1.6	
SLR SL7 ext	−1.5	
VLBI	−2.9	
Minster & Jordan (1978) AM1-2 (Geologic)	−5.3	

determined the relative motion of the VLBI sites with respect to the fixed geometry of the Westford, MA to Mojave, CA line which was observed to have insignificant relative motion. Since the Greenbelt, MD to West Coast geometry is similar to that of Westford, we have, as an approximation, modeled Westford to have the motion defined by the AM1-2 model (as was done in the SLR solution for Greenbelt) and transformed this VLBI solution into a similar motion frame used for our SLR model.

In Table 9 we present the recovered vectors for the eight SLR internal network sites in western North America and Arequipa. These values have been obtained from two different least-squares adjustments each using a different model for the external stations; one model for the external network uses AM1-2, and the other uses the motion seen in SL7 directly (as mentioned previously). Both sets of results have been plotted along with AM1-2 predicted motion vectors in Figure 4. Returning to Table 9, it is apparent that when the SL7 fitted motion models are used to describe the external sites, the resulting internal motions are rotated clockwise by approximately 10° with respect to the internal motions determined when adopting the AM1-2 external model. The magnitude of the determined motions are similar (within 6 mm/yr). The uncertainties obtained for the models are identical between the two SLR solutions, since the only difference is the definition of the external motion model, which is assumed to be known perfectly in either solution. The error ellipses for the SLR recovered motion vectors are presented in Table 10.

In Figure 4, the internal motion results using both external station models are plotted along with the vectors for these sites predicted by Minster and Jordan's AM1-2 model directly. The error ellipses (Table 9) are based on one-standard-deviation uncertainties from the formal estimation process. However, the reader is reminded that a large noise level on the laser data was employed to represent unmodeled error sources; thus the formal errors obtained are believed to be quite realistic. Either model for the motion of the external stations fits the observed geodesic rates between the external stations with a weighted RMS of less

Figure 5—The SAFE line: Monument Peak to Quincy, 1981 through 1984, using the short-arc technique.

than 1 cm/yr. Certainly, in a relative sense, these estimates of errors can be effectively used to assess the strength of the individual station results.

For the SLR solution, the error ellipses for the North American sites are compressed in the east/west direction since the entire network (internal and external sites) favor east/west-oriented geodesics. Note also that the error ellipses for the two SLR solutions overlap. Therefore, the systematic misorientation of the SLR models due to the fixed motions ascribed to the external stations is within the uncertainties we are showing. Table 9 also contains the results from the VLBI model. In general, and especially for the strong SLR sites, there is good agreement between technologies for determination of the motion of the observing sites within the western U.S. The uncertainties for the VLBI determined motions are presented in Table 11 and can be compared with the SLR results. Figure 4 contains the VLBI station vectors where a common site was occupied by both SLR and VLBI systems.

The motion of the Pacific plate with respect to the North American plate is of central concern. We are fortunate that the results obtained for the SAFE/Monument Peak to Quincy baseline are well resolved by both SLR and VLBI techniques. The observed motion between these two sites since the early 1980s is summarized in Table 11. Included in this table are the results of an SLR "short arc" analysis (see Christodoulidis et al., 1985) which is summarized in Figure 5.

Early SLR results (Christodoulidis et al., 1985) found SLR rates for the SAFE line which were comparable with those predicted from the geological models. Clearly from Table 11, this is no longer the case. This raises the question of whether episodic motion may be a factor in the change which has been observed in this baseline rate. A reassessment of the earlier satellite results, although showing that they are repeatable, has led us to believe (that is, when newer gravity models are used, etc.) that they were less well resolved than previously stated. Therefore, we cannot establish with satisfactory certainty what changes have indeed occurred for the SAFE baseline rate, but we are confident about strong evidence for motion along this line since 1981 falling far short of the rate predicted if both sites had full-plate rates as predicted by the M/J AM1-2 model. Both the VLBI and SLR models have characterized the vector motion of the sites defining the SAFE line in a very consistent fashion. In Figures 4a and b, the motions for both Quincy and Monument Peak differ in orientation with respect to AM1-2, and in the

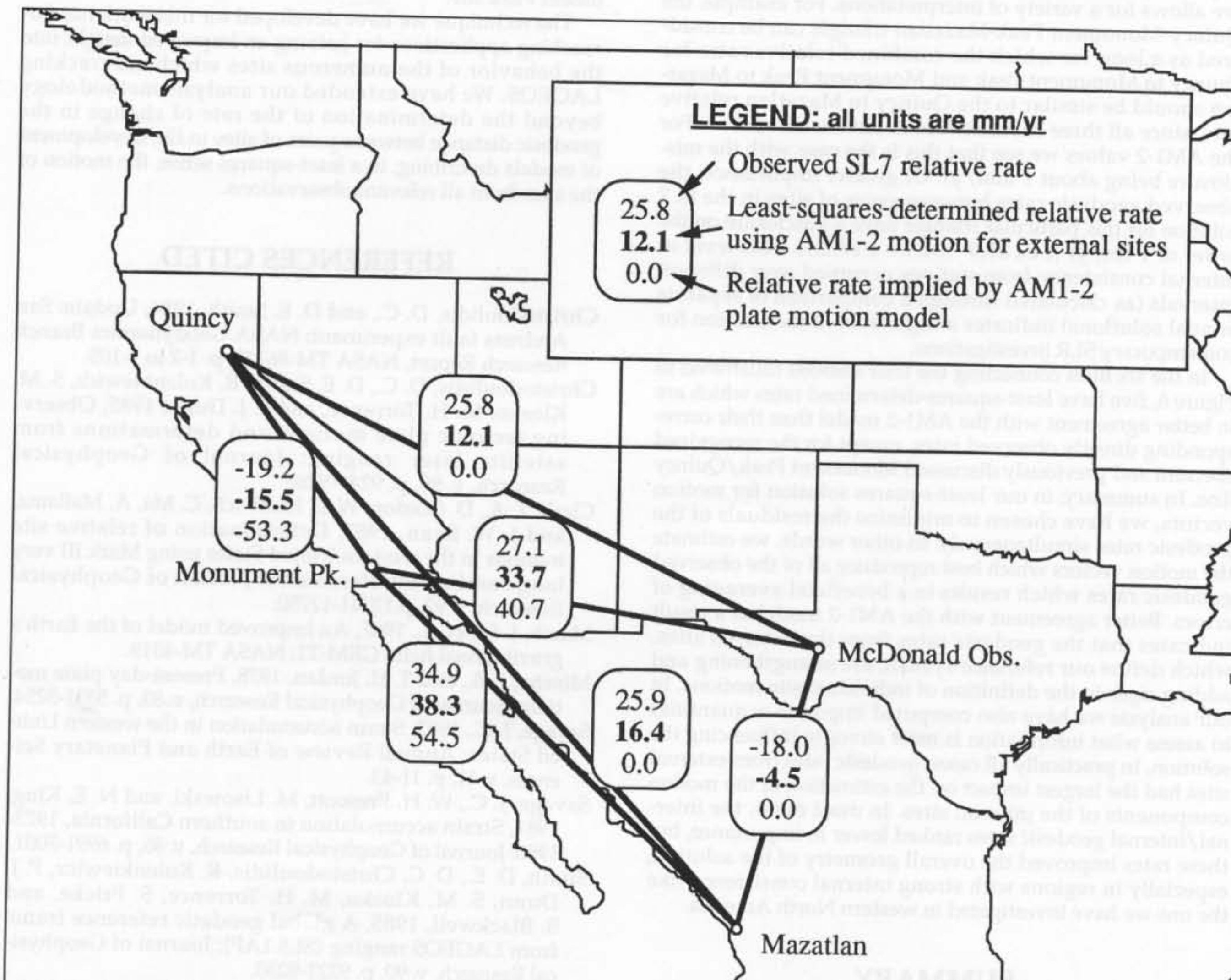

Figure 6—Relative motions for the western North America laser tracking stations.

case of Monument Peak, the rate is considerably slower. VLBI and SLR motion models differ somewhat on the rate of motion for Quincy, but this rate is not well resolved by VLBI (as evidenced by the orientation of its error ellipse) and differs at a magnitude only slightly greater than one-standard deviation from the SLR models. Therefore, an understanding of contemporary SAFE motion is near, and results of complementing technologies show strongly similar explanations for the observed baseline rates. Preliminary results from an SLR solution containing 1986 data finds SLR absolute motion models predicting -2.23 cm/yr of compression along the SAFE line, so additional data may yet yield even better SLR/VLBI agreement.

For the other strong sites, Mazatlan and Arequipa both appear to have motions consistent with those predicted by the AM1-2 model. The weaker sites have less well resolved SLR motion, which is a situation that can only be remedied by reoccupation of these sites with improved mobile laser systems.

The relative motions between the western North American stations as implied from the least-squares solution for vector motions are summarized in Figure 6. The directly observed SL7 geodesic distance rates as well as the rates implied by the AM1-2 model are also summarized. This figure allows for a variety of interpretations. For example, the Quincy-Monument Peak-Mazatlan triangle can be considered as a loop for which the combined relative rates for Quincy to Monument Peak and Monument Peak to Mazatlan should be similar to the Quincy to Mazatlan relative rate, since all three baselines are in similar directions. For the AM1-2 values we see that this is the case with the misclosure being about 1 mm/yr. Of greater importance, the observed geodesic rates between pairs of sites in the SL7 solution for this particular triangle have a misclosure on the order of 1 cm/yr [i.e., 25.9 -(34.9 + (-19.2))]. This level of internal consistency from stations occupied over different intervals (as calculated through a comparison of separate annual solutions) indicates a high level of maturation for contemporary SLR investigations.

In the six lines connecting the four stations illustrated in Figure 6, five have least-squares-determined rates which are in better agreement with the AM1-2 model than their corresponding directly observed rates, except for the recognized aberrant and previously discussed Monument Peak/Quincy line. In summary, in our least-squares solution for motion vectors, we have chosen to minimize the residuals of the geodesic rates simultaneously. In other words, we estimate the motion vectors which best reproduce all of the observed geodesic rates which results in a beneficial averaging of errors. Better agreement with the AM1-2 model as a result indicates that the geodesic rates from the external sites, which define our reference system, are strengthening and adding rigor to the definition of individual site motions. In our analysis we have also computed importance quantities to assess what information is most strongly influencing the solution. In practically all cases, geodesic rates from external sites had the largest impact on the estimation of the motion components of the internal sites. In most cases, the internal/internal geodesic rates ranked lower in importance, but these rates improved the overall geometry of the solution, especially in regions with strong internal consistency like the one we have investigated in western North America.

SUMMARY

A model of the vector motion of the laser sites located within the western United States, Mexico, and Peru has been developed from annual SLR station solutions. The range data encompasses 7 years of tracking to LAGEOS and represents the strongest observational data analyzed by GSFC to date. The motion model has been determined with respect to an external set of three fiducial stations located on three of the earth's major plates. These so-called external stations have relative interstation motions which are consistent with the rates predicted by the geologic model of Minster and Jordan (1978) and direct observation of these motions in the laser solution. Upon adoption of these models for our external reference stations, recovered vectors for the sites in the western United States are in a systematically defined system. Eight station velocity vectors have been estimated. The quality of determination varies with stations having well resolved motions—Monument Peak, Quincy, Arequipa, and Mazatlan—to sites which are not as well resolved, such as the motion observed for Owens Valley.

The vector motion models from SLR have been compared with comparable models from VLBI. For strong stations, the agreement between technologies is quite good. This is especially true of the Monument Peak to Quincy SAFE line where the lost motion (that is, the SLR observed rate being slower than expected plate rates) is largely due to the direction of the vector and slower rate seen for the Monument Peak site.

The technique we have developed for this work has far-reaching applications for gaining an improved insight into the behavior of the numerous sites which are tracking LAGEOS. We have extended our analysis methodology beyond the determination of the rate of change in the geodesic distance between pairs of sites to the development of models describing, in a least-squares sense, the motion of the sites from all relevant observations.

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PART IV
Satellite Geodesy

Several chapters in this volume describe various aspects of the tectonic evolution of the Gulf of California, including detailed models of the current regime of active extension in the southern gulf and the northward transition to the strike-slip San Andreas system. Tectonic models can be tested for consistency. Geodesy makes direct measurements of relative motions between lithospheric plates and thus allows tests of the models. Unfortunately, for many geologic applications, extremely high geodetic accuracies may be required to obtain results even on decade time scales, and potential measurement sites (on separate plates or fault blocks) may be separated by large distances (> 100 km), too great to be spanned by conventional terrestrial geodetic techniques operating in a line-of-sight mode. Fortunately, space-based geodetic techniques are becoming available that promise high horizontal position accuracy (better than 1.0 cm) over distances of 1000 km or more. Such techniques are particularly desirable for measurement of total relative plate motion whenever the plate boundary is a broad zone of deformation, e.g., southern California and northern Baja California, or if large distances separate potential measurement sites, e.g., the southern Gulf of California.

Thus, the two chapters in this section review the status of space geodetic measurements in the Gulf of California. CHRISTODOULIDIS et al. describe Satellite Laser Ranging (SLR) results obtained by NASA's Crustal Dynamics Project. These data have already permitted an estimate of the rate of motion between Mazatlan on the North American plate and several sites in California on the Pacific plate, and they appear to be consistent with existing geologic models. Space geodetic measurements based on the U.S. Department of Defense Global Positioning System (GPS) offer denser and more frequent measurements. GPS consists of a constellation of high-altitude satellites and inexpensive, highly portable ground receivers. The first GPS experiment spanning the Gulf of California occurred in 1985, and DIXON et al. review these results and the current status of GPS measurements. The accuracy of both SLR and GPS has evolved rapidly in the last decade, and it is likely that these techniques will be capable of contributing to our understanding of tectonics of the globe.

In May 1989, a second GPS experiment was conducted that spanned the Gulf of California, and preliminary results have been determined. These results constitute the first rates of plate motion determined using GPS. Preliminary solutions show a rate of displacement for Cabo San Lucas relative to Mazatlan of 47 mm/yr ± 10 mm/yr (2σ) in the direction N57° W ± 11° (2σ) and a rate of displacement for Bahia Concepcion relative to Mazatlan of 45 mm/yr ± 10 mm/yr in the direction N56° W ± 28° (2σ). Although these solutions are preliminary, they agree very well with the most recent global plate motion model (NUVEL1) of Demets et al. These rates, however, are slower than the 65 mm/yr proposed by NESS et al. in this volume.