Contemporary global horizontal crustal motion


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SUMMARY
An analysis of Satellite Laser Ranging (SLR) data to the LAGEOS satellite has yielded improved estimates of the horizontal motion for a subset of 34 tracking sites within the global tracking network. The analysis, called SL8.3, utilized data acquired between 1980 January and 1993 June by the global network composed of 71 sites. The solution design provides for the simultaneous estimation of site positions and their velocities within a pre-defined kinematic frame. The solution is statistically rigorous and retains the full correlation information content. Least-squares estimates of relative poles of rotation, which are used to model the motion of one plate relative to another, were made based on the SLR estimated velocities for sites known to be well away from deformation zones. The resulting SLR-based relative rotation poles differ slightly from those of NUVEL-1, but in general, indicate that the magnitude of the SLR implied velocities is slower than those implied by NUVEL-1, consistent with the 4-5 per cent slowing in relative spherical rates noted in earlier comparisons. Spherical rates between sites in western North America support models of extension in the Basin and Range Province and the rotation of the Sierra Nevada microplate. An analysis of the spherical rates crossing the North Atlantic shows that SL8.3 estimated extension between North America–Eurasia sites is generally smaller than those implied by NUVEL-1; meanwhile SL8.3 rates between North America–Africa sites are in better agreement with NUVEL-1, although they are not so well determined. The maintenance and ongoing monitoring of global SLR site kinematics provides a well-defined global reference which will aid in combination global kinematic solutions where information from other technologies are merged (e.g. Very Long Baseline Interferometry and Global Positioning System) and in providing the context for densification studies of regional kinematics derived from terrestrial and Global Positioning System observations.

Key words: plate tectonics, satellite laser ranging, space geodesy.

INTRODUCTION
One fundamental geophysical process detectable by space-based geodic technologies is the large-scale motion of the Earth’s major plates. Over time, Satellite Laser Ranging (SLR) systems, located at key positions around the globe, provide a sequence of measurements from which the tracking site motions can be deduced. SLR site motion results reported thus far have largely been based on range measurements to the Laser Geodynamics Satellite (LAGEOS). These results showed recovery of time-averaged horizontal positioning at the 4–5 mm level and horizontal linear motion at the 2–3 mm yr⁻¹ level (Reigber et al. 1990; Smith et al. 1990; Biancale, Cazenave & Dominh 1991). Since the publication of Smith et al. (1990), several improvements have been made in our analysis strategy which contribute towards realizing a more rigorous solution for horizontal tracking site motion. These improvements, along with four more years of tracking data, strengthen the results.

The present solution, denoted SL8.3, uses SLR observations to LAGEOS acquired from 1980 January through 1993 June. Range observations acquired before 1980 January were omitted since the precision of the data worsens for the period before 1980 January (Smith et al. 1991). Improved performance after 1980 is mainly due to laser-tracking
hardware and software upgrades to the NASA tracking systems which were deployed in late 1979 and hardware changes made within the network originally operated by the Smithsonian Astrophysical Observatory. The resulting SLR data set used in this analysis comprises 700 701 two-minute average range observations acquired by a network of 71 tracking sites. A measure of the quality of the data and hence the solution through time is provided by the monthly root mean square (rms) fit of the data to the orbit which, since 1985, has remained steady at the 30 mm level.

ANALYSIS AND RESULTS

The SL8.3 analysis differs from the process followed in the SL7.1 global SLR analysis reported in Smith et al. (1990, 1991). Instead of following a series of analysis steps to derive horizontal velocity estimates from a sequence of tracking site positions, advantage is taken of new software capabilities that allow for the direct estimation of 3-D site velocity parameters simultaneously with the site epoch positions and other geodetic parameters. Although velocities are estimated in all three dimensions, this paper will limit itself to an assessment of the horizontal components which are directly interpretable as tectonic motion. A discussion of the vertical component can be found in Dunn et al. (1993).

The data are reduced in a least-squares estimation scheme using the GEODYN II and SOLVE analysis packages (Putney et al. 1990). The model parameters adopted in the solution generally follow the 1992 standards of the International Earth Rotation Service (McCarthy 1992) with principal upgrades in the geopotential (JGM2 model; Lerch et al. 1993) and in the modelling of more complete non-resonant ocean tidal terms.

The analysis begins by segmenting the data into monthly orbital arcs of 30 or 35 days in duration. All two-minute average range observations are given equal a priori weights since we assume that each laser system performs at the same level of accuracy. For each month, a single set of LAGEOS orbit parameters is estimated and a set of normal equations is created to be used in the final solution that includes all parameters of interest. The 13.5 yr sequence of these matrices is brought together into one single SOLVE solution in which site positions (for epoch 1988 January 1), site velocities, daily Earth orientation and Earth rotation rates (five day values before 1983 January), monthly orbit state vectors, bimonthly average along-track acceleration, and bimonthly values of a once-per-revolution acceleration parameter are estimated. All polar motion parameters were freely adjusted, whereas an initial A.1-UT1 value per month was fixed at values obtained from the IERS series (specifically, the 90 C 04 series). The remaining values of A.1-UT1 through the month were estimated yielding excess length of day measurements over that month. Estimation of the once-per-revolution acceleration essentially removes unmodelled effects acting upon the satellite and dramatically improves the overall orbital fits to LAGEOS.

Since the solution is formed simultaneously, all parameters which define the static and kinematic aspects of the geodetic reference frame are internally consistent. The maintenance of the reference frame over the time span of the observations in SL7.1 by a series of rigid-body transformations was discussed at length in Smith et al. (1990). These transformations to rectify reference system misalignments with respect to the computation surface (i.e. the ellipsoid) are not required in SL8.3 since the velocity estimation is no longer dependent on the computation of geodesic lengths and rates. The static part of the terrestrial reference frame is defined in SL8.3 by adopting an epoch latitude and longitude for the tracking site at Greenbelt, MD, and only the latitude of the site on Maui, in the Hawaiian Islands. The kinematic portion of the reference frame is established through the adoption of no net rotation NNR-NUVEL1 (Argus & Gordon 1991a) implied motion for the north and east components at Greenbelt and only the north component at Maui. The E–W component of Maui's position and motion is freely estimated, providing a parameter to absorb any deviation from NUVEL-1 that may exist for the rate between Greenbelt and Maui. Application of NNR-NUVEL1 motion components for these sites defines the evolution of the terrestrial reference frame in time. No constraints were applied in the directions of the local vertical.

The Earth orientation and length-of-day parameters, as well as the epoch geodetic positions and linear motion for each unconstrained site are all estimated within this reference frame. The statistics of the site velocities determined in the SL7.1 solution suffered from the fact that the full covariance information was not used in the calculation of the geodesic rates and their uncertainties. These compromises and approximations have been eliminated in the design of SL8.3, yielding a much stronger solution with improved error statistics.

The horizontal components of the estimated motion vectors are given in Table 1 and shown in Fig. 1. The remainder of the paper will discuss the implications of some of these results with regard to large-scale plate motions and will highlight the regional interpretation of results for sites located in areas of special kinematic interest and for tracking sites not previously treated in the literature. The discussion will involve the vector given in Table 1 and the implied relative spherical rates between particular sites.

PLATE-SCALE IMPLICATIONS

Global comparisons of space geodetic results (i.e. SLR alone or SLR combined with Very Long Baseline Interferometry, VLBI) to 'present-day' models of plate motion derived from geophysical evidence (e.g. AM0-2 of Minster & Jordan (1978) and NUVEL-1 of DeMets et al. (1990)) have been made by several authors (e.g. Smith et al. 1990; Cazenave et al. 1993; Robbins, Smith & Ma 1993). Relative rates of motion between sites located well away from plate boundaries were utilized in these studies to provide samples that were free from site motions in deformation zones. These studies showed that the relative rates implied by the 'geologic' models were generally faster in magnitude, on the order of 4-5 per cent, than those determined from space geodesy.

Recently, new evidence has come forward indicating that earlier K–Ar derived time-scales were ~5 per cent 'too young' spanning the Pliocene (Hilgen 1991; Wilson 1993; Baksi 1994), which includes the period of magnetic anomaly 2A, the normal polarity anomaly used to define the rate scale for NUVEL-1. The average difference seen between
the rates implied by NUVEL-1 and those determined from space geodetic observations could largely be reconciled by these adjustments in the geochronologic time-scale. This is true in general, i.e. the global case; as described below, not all plate pair rotational velocities may benefit from an across boundary zone deformation, the pole of rotation for the plate can be determined by inverting these equations through a weighted least-squares algorithm. To determine the three unknown quantities \((\phi, \lambda, \omega)\) a minimum of three velocity components from two tracking sites must be known.

From the SL8.3 velocities, relative poles of rotation between four plates (Eurasia, North America, Pacific and Australia) have been determined. This was done by first estimating, within the kinematic frame realized explicitly by the SLR analysis, poles of rotation for each individual plate via at least-squares approach described above. Parameters describing a pole of rotation for Eurasia were based on the three velocity components from two tracking sites well distributed across a particular plate and sufficiently far away from boundary zone deformation, the pole of rotation for the plate describing a pole of rotation for Eurasia were based on the three unknown quantities \((\phi, \lambda, \omega)\) a minimum of three velocity components from two tracking sites must be known.

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D. E. Smith et al.

Figure 1. Horizontal vector motion estimated for SLR tracking sites. The kinematic frame is defined by adopting NNR-NUVEL1 motion in the north and east direction of motion at Greenbelt (hence, no error ellipse is shown at Greenbelt) and only the north direction at Maui. Error ellipses are $1 - \sigma$. The inset maps use the same vector scale as the main map.

Herstmonceux, England; Potsdam, Germany; Wettzell, Germany and Zimmerwald, Switzerland. Inclusion of the velocity of Shanghai, China, as an additional site nominally located on the Eurasian plate, was precluded since the spherical rates between Shanghai and sites in northern Europe exhibited statistically significant shortening. The pole of rotation for North America was based on velocities from six sites: Bear Lake, UT; McDonald Observatory, TX; Mazatlan, Mexico; Platteville, CO; Richmond, FL and Westford, MA. The velocity of Greenbelt was omitted since its motion is defined a priori by NNR-NUVEL1. The poles of rotation for the Australia and Pacific Plates were each based on velocities from only two sites and hence are more weakly determined than those for Eurasia and North America. The Pacific pole of rotation was determined without redundancy since only the east component of motion at Maui, Hawaii and both velocity components at Huahine Island were used in the calculation. The relative poles of rotation between plate pairs were formed by taking differences of the individual plate poles of rotation. This eliminates the effects of any possible kinematic frame misalignments between the SL8.3 frame and the NNR-NUVEL1 frame and yields poles which can be compared with the relative plate motion model NUVEL-1 of DeMets et al. (1990). The results are shown in Table 2.

In terms of their location, the SL8.3 and NUVEL-1 relative poles of rotation are generally positioned within 4° or less in spherical angle (equivalent to <450 km in distance) with the exceptions being for two of the relative poles of rotation that include Eurasia as one of the plate pairs. In all cases the respective pole locations agree well within the $3 - \sigma$ (99 per cent confidence) uncertainties. For the Australia–Eurasia pole of rotation, the SL8.3 poles lies 850 km to the south-east of the NUVEL-1 pole. The SL8.3 determined Eurasia–North America pole of rotation lies 1500 km to the north-northeast of the NUVEL-1 pole. This differs somewhat from a VBLI determined Eurasia–North America pole of rotation (Ward 1994) which was
Table 2. Relative poles of rotation implied from SL8.3 and from NUVEL-1 (DeMets et al. 1990). First plate rotates clockwise relative to second. One sigma error ellipses are specified by the angular lengths of the principle axis, their orientation (\( \zeta \)) from north and in the uncertainty of the rotational rate. The percentage difference shows the average increase of the magnitude of the NUVEL-1 inferred velocities with respect to those implied by the SL8.3 poles of rotation for those regions where the tracking sites are located on the rotating plate.

<table>
<thead>
<tr>
<th>plate pair</th>
<th>SL8.3 determined</th>
<th>NUVEL-1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \phi ) ( \lambda ) ( \omega ) ( \sigma_{max} ) ( \sigma_{min} ) ( \zeta ) ( \phi ) ( \lambda ) ( \omega ) ( \sigma_{max} ) ( \sigma_{min} ) ( \zeta ) ( \sigma_\omega ) % Diff. vect. mag.</td>
<td></td>
</tr>
<tr>
<td>au-eu</td>
<td>10.8 47.0 0.70 4.2 0.9 -57 0.05 15.1 40.5 0.72 2.1 1.1 -45 0.01 5%</td>
<td></td>
</tr>
<tr>
<td>au-na</td>
<td>27.4 52.2 0.75 4.3 3.2 -77 0.04 29.1 49.0 0.79 1.6 1.0 -53 0.01 5%</td>
<td></td>
</tr>
<tr>
<td>eu-na</td>
<td>73.3 157.6 0.22 11.3 7.8 -14 0.05 62.4 135.8 0.22 4.1 1.3 -11 0.01 6%</td>
<td></td>
</tr>
<tr>
<td>eu-pa</td>
<td>60.3 79.0 0.93 2.9 0.7 72 0.04 61.1 -85.8 0.90 1.3 1.1 90 0.02 1%</td>
<td></td>
</tr>
<tr>
<td>na-pa</td>
<td>49.9 -72.8 0.77 2.9 1.1 80 0.05 48.7 -78.2 0.78 1.3 1.2 -61 0.01 10%</td>
<td></td>
</tr>
<tr>
<td>pa-au</td>
<td>-59.3 -175.0 1.09 2.7 1.5 76 0.02 -60.1 -178.3 1.12 1.0 0.9 -58 0.02 4%</td>
<td></td>
</tr>
</tbody>
</table>

determined to lie 1000 km north-west of the corresponding NUVEL-1 pole of rotation. However, the results from both SLR and VLBI agree that the Eurasia–North America pole of rotation is located about 10° further north of the corresponding NUVEL-1 pole.

With respect to the rotational velocities, NUVEL-1 is faster than SL8.3 for four plate pairs (Australia–Eurasia, 3 per cent faster; Australia–North America, 5 per cent; North America–Pacific, 1 per cent; Pacific–Australia, 3 per cent), the same as SL8.3 for the Eurasia–North America plate pair and 3 per cent slower than SL8.3 for the Eurasia–Pacific plate pair. Based on the uncertainties in rotation rate, none of the SL8.3 Euler rotation rates differ significantly from those of NUVEL-1. On the other hand, the velocity of a site relative to another plate is a function of both the angular rate of the rotation pole and the perpendicular distance from the site to the axis of rotation (e.g. as \( v = \omega \times r \)). The difference between the magnitudes of motion vectors calculated for locations on the rotating plate between SL8.3 and NUVEL-1 poles of rotation provide a more meaningful

Figure 2. Selected spherical rates for lines in North America. NUVEL-1 model rates are shown in parentheses for lines crossing at least one plate boundary. Rates shown in brackets between Quincy and other sites take into account the Sierra Nevada/North American pole of rotation of Argus & Gordon (1991b). All rates in mm yr\(^{-1}\).
way to assess scale differences than by simply examining the rotational rates. The difference (in terms of percentage, shown in the last column of Table 2) of how much faster NUVEL-1 is relative to SL8.3 varies between 1 and 6 per cent with the exception being the North America/Pacific plate pair. The discussion here has involved a subset of the 10 plate pairs used in Robbins et al. (1993) and largely corresponds with the 4–5 per cent scale difference noted therein.

**REGIONAL INTERPRETATIONS**

**North America/north-eastern Pacific**

The relative spherical rates across this region discussed below are shown in Fig. 2. Several tracking sites in North America now have sufficient tracking histories to allow for the estimation of site motions. These include: Westford and Richmond, along the eastern seaboard of the United States; Bear Lake and Mojave, in the western US; Ensenada and Cabo San Lucas, Mexico, along the Baja of California.

The rate between Greenbelt and Westford is $2.0 \pm 2$ mm yr$^{-1}$ (all uncertainties quoted herein are $\sigma$ or 68 per cent confidence interval values, unless otherwise stated) suggesting the possibility of a small amount of extension. This result differs slightly with the no-motion result mentioned by Robbins et al. (1993) which was based on a preliminary SL8.3 solution. It should be noted that although the SLR tracking at Westford spans more than 10 yr, the site has only been occupied three times over the time span considered in this solution: 1980, 1988 and 1990. Rates from Westford and Greenbelt to Richmond indicate no significant motion with respect to the rather large uncertainty of $\pm 8$ mm yr$^{-1}$. This large uncertainty is due to Richmond having been occupied only twice, once in 1988 and again in 1990.

Across the central United States, the relative rates suggest only small amounts of motion between east coast tracking sites and Platteville, McDonald Observatory, and Mazatlan, Mexico. The rate between Greenbelt and Platteville is $-2.5 \pm 2$ mm yr$^{-1}$, consistent with earlier SL7.1 results. The rate between Greenbelt and McDonald Observatory indicates extension of $3.5 \pm 1$ mm yr$^{-1}$; considerably less than the $7 \pm 2$ mm yr$^{-1}$ determined in the SL7.1 solution. A small amount of shortening is detected between Greenbelt and Mazatlan of $-2.6 \pm 2$ mm yr$^{-1}$.

Extension is evident between Platteville and Quincy, at $9.5 \pm 2$ mm yr$^{-1}$ and between McDonald Observatory and Quincy at $11.6 \pm 1$ mm yr$^{-1}$. These results are more self-consistent than those determined in SL7.1 and more convincingly support theories regarding Basin and Range extension and the rotation of the Sierra Nevada Microplate near Quincy (e.g. Argus & Gordon 1991b). The velocity of Quincy relative to North America is $11.9 \pm 1$ mm yr$^{-1}$ in the direction $316^\circ$ (azimuths quoted herein are measured clockwise from north), in agreement with the motion predicted by the pole of rotation determined for the Sierra Nevada Microplate relative to North America (Argus & Gordon 1991b). Extension between Bear Lake and Quincy, spanning the entire breadth of the northern Basin and Range Province, is $3.2 \pm 2$ mm yr$^{-1}$. If Bear Lake is assumed to lie on stable North America, the rate to Quincy would be considerably less than the spreading anticipated across the region ($9-10$ mm yr$^{-1}$) based on geological and geophysical studies (Minster & Jordan 1987; Jones et al. 1992) or for that implied if Quincy is nominally located on the Sierra Nevada microplate ($6.5$ mm yr$^{-1}$). A clear explanation for the extension deficit between these two sites is elusive, and cannot be entirely attributed to variations in orientation between the direction of maximum stretching in the Basin and Range and the direction the spherical line takes between the two sites. Between Bear Lake and Platteville the rate is $2.2 \pm 3$ mm yr$^{-1}$, indicating no significant extension across the Rocky Mountains in southern Wyoming and northern Colorado. No motion is detected between Bear Lake and McDonald Observatory, but a small amount of shortening is suggested by the $-4.0 \pm 3$ mm yr$^{-1}$ rate along the line between Bear Lake and Mojave. The motion of Bear Lake is based on the laser tracking taken during four occupations in 1981, 1984, 1990 and 1991. Additional occupations of the Bear Lake site will help to further resolve its motion.

The rate between Quincy and Monument Peak, (the San Andreas Fault Experiment or ‘SAFE’ line) is $-26.8 \pm 1$ mm yr$^{-1}$, a result consistent with SL7.1 ($-27.2 \pm 2$ mm yr$^{-1}$). If Quincy’s velocity is modelled by the Sierra Nevada microplate, the rate to Monument Peak (on the Pacific plate) is $-34.0$ mm yr$^{-1}$, leaving only $-7$ mm yr$^{-1}$ of ‘San Andreas discrepancy’ left to explain. The relative rate between Quincy and Mojave (on North America) is consistent with the Sierra Nevada microplate hypothesis. To complete this triangle of California sites, the rate between Mojave and Monument Peak is $-31.0 \pm 3$ mm yr$^{-1}$, again indicating a discrepancy relative to the full plate rate of $-9$ mm yr$^{-1}$.

The fact that the rates for both of the lines, Quincy-Monument Peak and Mojave-Monument Peak, are roughly $7-9$ mm yr$^{-1}$ less than the shortening predicted by the NUVEL-1 may indicate that a component of the total North America/Pacific shear may be occurring south and west of Monument Peak. This may be indeed the case, as is evident in the rate between Monument Peak and Ensenada, Mexico, of $-9.7 \pm 9$ mm yr$^{-1}$. Even though this rate is at the fringes of significance, it implies that motion would need to be occurring along the Vallecitos–San Miguel and/or Agua Blanca fault systems, the former of which is seismically active (from catalogues of earthquake location data from the Southern California Earthquake Data Center).

Along the length of the Baja of California, between Ensenada and Cabo San Lucas, no significant motion is detectable within the large uncertainty associated with this rate. The estimated motion between McDonald Observatory and Cabo San Lucas and between Mazatlan and Cabo San Lucas is consistent with NUVEL-1 implied motion. The estimate of motion for Cabo San Lucas is based on tracking data acquired during occupations in 1984, 1988 and 1992.

**Trans North Atlantic results**

In general, as was noted in Smith et al. (1990), the SL8.3 rates of extension between sites in North America and Europe, crossing the North Atlantic, are less than those implied by the Eurasia/North America pole of rotation from...
the NUVEL-1 model (Table 3). Of the three Eurasian sites listed in Table 3, Wettzell has spherical rates to North American sites that are consistently ~2 mm yr$^{-1}$ slower than those from Herstmonceux and Graz. In the same way, one will note that McDonald Observatory exhibits spherical rates to Eurasian sites that are consistently faster than those from other North American sites. SL8.3 implied relative rates from Mazatlan and Platteville to sites across the Atlantic are consistent with one another to better than 1 mm yr$^{-1}$.

It is interesting that the rates between North American sites and those nominally located on the African plate mostly agree to within their uncertainties with NUVEL-1 (Table 4) while there is a general disagreement with NUVEL-1 for rates between sites on North America and Eurasia. The evidence from these results raises again the question regarding the alignment of the Eurasia/North America pole of rotation. Inclusion of data from tracking sites that have recently begun operations across central Eurasia will be extremely valuable to refine SLR and space geodetic estimates of relative poles of rotation taken with respect to Eurasia.

### Table 3. Relative spherical rates between North American and Eurasian sites. The SL7.1 results are from Table 5 of Smith et al. (1990).

<table>
<thead>
<tr>
<th>N. Amer. Site</th>
<th>Eur. Site</th>
<th>SL8.3 (mm yr$^{-1}$)</th>
<th>SL7.1 (mm yr$^{-1}$)</th>
<th>NUVEL-1 (mm yr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greenb.</td>
<td>Herstm.</td>
<td>19.2±1</td>
<td>17±2</td>
<td>21.8</td>
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<tr>
<td></td>
<td>Wettzell</td>
<td>17.0±2</td>
<td>17±2</td>
<td>21.4</td>
</tr>
<tr>
<td></td>
<td>Graz</td>
<td>19.1±1</td>
<td>17±2</td>
<td>21.6</td>
</tr>
<tr>
<td>Plattev.</td>
<td>Herstm.</td>
<td>15.0±2</td>
<td>15±4</td>
<td>21.2</td>
</tr>
<tr>
<td></td>
<td>Wettzell</td>
<td>12.9±2</td>
<td>15±4</td>
<td>20.5</td>
</tr>
<tr>
<td></td>
<td>Graz</td>
<td>14.4±2</td>
<td>15±4</td>
<td>20.6</td>
</tr>
<tr>
<td>Mazatlan</td>
<td>Herstm.</td>
<td>15.7±2</td>
<td>14±2</td>
<td>21.8</td>
</tr>
<tr>
<td></td>
<td>Wettzell</td>
<td>13.3±2</td>
<td>14±2</td>
<td>21.2</td>
</tr>
<tr>
<td></td>
<td>Graz</td>
<td>15.1±2</td>
<td>14±3</td>
<td>21.3</td>
</tr>
<tr>
<td>McDonald</td>
<td>Herstm.</td>
<td>22.4±1</td>
<td>24±2</td>
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<tr>
<td></td>
<td>Wettzell</td>
<td>20.9±2</td>
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<tr>
<td></td>
<td>Graz</td>
<td>21.9±2</td>
<td>24±2</td>
<td>21.2</td>
</tr>
</tbody>
</table>

### Table 4. Relative spherical rates between sites in North America and sites nominally located on the African plate. Rates to Lampedusa and Helwan were unavailable in the SL7.1 analysis. The SL7.1 results are from Table 5 of Smith et al. (1990).

<table>
<thead>
<tr>
<th>N. Amer. Site</th>
<th>African. Site</th>
<th>SL8.3 (mm yr$^{-1}$)</th>
<th>SL7.1 (mm yr$^{-1}$)</th>
<th>NUVEL-1 (mm yr$^{-1}$)</th>
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<tr>
<td>Greenb.</td>
<td>Matera</td>
<td>16.1±1</td>
<td>15±2</td>
<td>15.8</td>
</tr>
<tr>
<td></td>
<td>Lampedusa</td>
<td>19.5±2</td>
<td>-</td>
<td>17.6</td>
</tr>
<tr>
<td></td>
<td>Helwan</td>
<td>13.5±9</td>
<td>-</td>
<td>16.1</td>
</tr>
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<td>Plattev.</td>
<td>Matera</td>
<td>10.5±2</td>
<td>14±4</td>
<td>13.3</td>
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<td></td>
<td>Lampedusa</td>
<td>13.3±5</td>
<td>-</td>
<td>15.2</td>
</tr>
<tr>
<td></td>
<td>Helwan</td>
<td>9.3±9</td>
<td>-</td>
<td>12.1</td>
</tr>
<tr>
<td>Mazatlan</td>
<td>Matera</td>
<td>12.1±2</td>
<td>13±2</td>
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<td></td>
<td>Lampedusa</td>
<td>16.1±5</td>
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<td></td>
<td>Helwan</td>
<td>10.0±9</td>
<td>-</td>
<td>14.8</td>
</tr>
<tr>
<td>McDonald</td>
<td>Matera</td>
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<td>21±2</td>
<td>14.5</td>
</tr>
<tr>
<td></td>
<td>Lampedusa</td>
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<td>-</td>
<td>16.6</td>
</tr>
<tr>
<td></td>
<td>Helwan</td>
<td>16.7±9</td>
<td>-</td>
<td>14.0</td>
</tr>
</tbody>
</table>

### European results

In general, little relative motion is detectable between the sites in northern Europe, that is, between Herstmonceux, Wettzell, Potsdam, Zimmerwald and Graz (Fig. 3). The velocities estimated for these sites exhibit a $7^\circ$--$14^\circ$ systematic anti-clockwise rotation with respect to the NNR-NUVEL1 Eurasian motion vectors (Table 1), again related to a possible alignment difference in the Eurasia pole of rotation. This systematic rotation, of the motion vectors was noted in SL7.1 as well. Rates along lines from these sites to those in the Mediterranean region seem to indicate the occurrence of significant deformation. For example, rates from Herstmonceux and Zimmerwald to Grasse, France, indicate extension of about 8--9 mm yr$^{-1}$. If one supposes that northern Europe is moving largely as a block, then this would imply that Grasse is moving southward relative to northern Europe. This would be consistent with deformation and stress variations in the region of southern France and in the Balearic Basin as suggested by Mantovani et al. (1988) and Rebai, Philip & Taboada (1992).

The spherical rates between these northern European sites and Shanghai, China exhibit statistically significant shortening. For example, between Wettzell and Shanghai the rate is $-9.9 \pm 5$ mm yr$^{-1}$, between Graz and Shanghai the rate is $-10.8 \pm 5$ mm yr$^{-1}$ and between Herstmonceux and Shanghai the rate is $-13.7 \pm 5$ mm yr$^{-1}$. The Shanghai tracking station began operation in 1983 but the SL8.3 results for the motion of Shanghai are heavily weighted towards three years of tracking data acquired between 1990 and early 1993. Although the tracking data acquired before 1990 were taken rather sporadically, it none the less is consistent with data taken after 1990. Continued laser tracking at this observatory will help to further improve the estimate of the site's motion.

The motion of the Matera tracking site (based on over 10 years of tracking) is much more similar to NNR-NUVEL1 African motion (Table 1) than with Eurasian motion. As discussed in Smith et al. (1990), the Matera tracking site is generally thought to be located on the Adriatic Block. Several hypotheses have been proposed regarding the kinematics of the Adriatic Block (cf. Mantovani et al. 1990, for a list). Anderson & Jackson (1987) suggest that the Adriatic Block (or Adria) behaves as a relatively rigid block and that its motion can be described through a pole of rotation relative to Eurasia. They positioned this pole at $\phi = 45.8^\circ$ and $\lambda = 10.2^\circ$ based on slip vectors from fault-plane solutions. The SL8.3 determined direction of motion for the Matera site, placed within a kinematic reference frame relative to Eurasia is $33^\circ$. This differs by only $3^\circ$ from the direction of NUVEL-1 African motion with respect to Eurasia ($34^\circ$) and is in poor agreement with the $51^\circ$ direction of motion implied by the pole of rotation suggested by Anderson & Jackson (1987) and with the $29^\circ$ direction of motion determined from three years of VLBI observations at Matera (Ward 1994). It should be remembered that boundaries of blocks of microplates are not always clearly distinguishable and that it is entirely possible that the tracking site at Matera may lie in a deforming region through which the northward velocity of the African plate is transferred to the Adriatic Block.

To the south-west of Matera, the motion of Lampedusa...
Island exhibits motion similar to that predicted by African NNR-NUVEL1 with no significant motion notable between these sites. The motion of Dionysos, Greece is influenced by well-known Aegean Basin extension (Taymaz, Jackson & McKenzie 1991) as evident from the extension between Graz and Dionysos. Dionysos lies at the centre of the WEGENER Mediterranean laser network, the results and details of which are discussed in Smith et al. (1994).

To the east, the direction of the SLR estimated motion of Bar Giyyora, Israel (40°, from Table 1) is aligned better with NNR-NUVEL1 Arabian motion (35°) than African motion (52°). However, the rate of motion (27.2 mm yr⁻¹) is less than both the Arabian (34.8 mm yr⁻¹) and African (32.5 mm yr⁻¹) motions predicted by NNR-NUVEL1. The implication of this result causes relative rates to other sites that are nominally located on the African plate (e.g. Lampedusa and Matera) to exhibit departures from zero motion that are statistically significant. For example, between Bar Giyyora and Lampedusa the rate is −11.4 ± 6 mm yr⁻¹ and between Bar Giyyora and Matera the rate is −7.6 ± 4 mm yr⁻¹.

The motion estimated for Helwan is aligned with African NNR-NUVEL1 motion but, like Bar Giyyora, has a rate (23.3 mm yr⁻¹) which is less than that predicted by the model (32.4 mm yr⁻¹). The rate between Helwan and Bar Giyyora shows no significant departure from zero motion. However, the relative rates between Helwan and other sites nominally located on the Africa plate also show no significant motion, but this is at a relatively large (8–13 mm yr⁻¹) uncertainty. Further range measurements by the Helwan tracking site will improve the resolution of its motion.

The results for the tracking site at Simeiz, Ukraine, along the north shore of the Black Sea, indicate largely Eurasian motion (Table 1). No significant relative motion is evident between Simeiz and other sites in northern Europe (e.g. to Graz and Potsdam; Fig. 3). The uncertainty of the velocity estimate is quite large because this site has only been tracking since early 1990.

### Across the Pacific Basin

The site at Simosato, Japan, is in a region of deformation associated with the offshore collision of the Philippine and Eurasian plates (Fig. 4). The results for Simosato continue to support a broad strain regime across southern and eastern Japan as discussed in Smith et al. (1990) and Robaudo & Harrison (1993). The SLR estimated vector motion of Simosato with respect to Eurasia is 29.5 mm yr⁻¹ in a direction of 301°. NUVEL-1 motion of the Phillipine plate with respect to Eurasia is 40.6 mm yr⁻¹ in a direction of 310°. It seems quite clear then that the motion experienced by the Simosato site is influenced by the transfer of strain associated with the offshore collision.

Significant shortening of −36.5 ± 5 mm yr⁻¹ is estimated between Simosato and Shanghai, a fair amount of which is attributable to the aforementioned strain associated with Simosato's motion. The SLR motion estimated for Shanghai differs from that expected from NNR-NUVEL1 Eurasia motion in that the SLR result is oriented 40° counter-
Figure 4. Selected spherical rates for lines crossing the Pacific Basin. NUVEL-1 model rates are shown in parentheses for lines crossing at least one plate boundary. All rates in mm yr$^{-1}$.

clockwise and is $\sim 5$ mm yr$^{-1}$ longer relative to the modelled motion. Although tracking at the Shanghai site began in late 1983, much of this early data is of experimental quality. Substantial operational tracking at the Shanghai site began in late 1989, hence the motion of this site is based largely on three and a half years of data.

The vectors estimated for the two sites in Australia, at Yaragadee and Orroral, are in good alignment with NNR-NUVEL1 Australian motion (Table 1). The relative motion across Australia implied by these vectors is $-2.8 \pm 2$ mm yr$^{-1}$. This result now indicates the possibility of a small amount of shortening which contrasts with the SL7.1 result of a slight amount of extension of $3 \pm 2$ mm yr$^{-1}$.

The E-W component of motion for the site on Maui is freely estimated in SL8.3 and is $-3$ mm yr$^{-1}$ faster in a westerly direction than predicted by NNR-NUVEL1. The rate from Maui to Huahine continues to indicate the possibility of extension of $2.2 \pm 2$ mm yr$^{-1}$ (SL7.1 had $3 \pm 5$ mm yr$^{-1}$). The magnitude of the vector estimated for Huahine is $-13$ mm yr$^{-1}$ slower in SL8.3 than was determined in SL7.1. The magnitude of the vector estimated for Easter Island is also slower in SL8.3 than SL7.1 by $\sim 13$ mm yr$^{-1}$. The resulting SL8.3 relative rate between Huahine and Easter Island is $140.4 \pm 3$ mm yr$^{-1}$ compared with $157.2$ mm yr$^{-1}$ from NUVEL-1 and $166 \pm 6$ mm yr$^{-1}$ from SL7.1. It should be noted that these two sites share the same laser tracking system creating a situation where no simultaneous data exist between these two sites. The capability to estimate the relative rates between sites under the circumstances is considerably improved by the SL8.3 solution strategy over that followed in SL7.1.

The motions of the two sites nominally located on the South American plate, Arequipa, Peru and Cerro Tololo, Chile are influenced by distributed deformation across the western Andes due to the offshore collision of the Nazca and South America plates (Fig. 1). The results for Cerro Tololo should be viewed as preliminary but will improve with further occupations. In the case of Arequipa, its motion relative to NNR-NUVEL1 South American motion is $15.5$ mm yr$^{-1}$ in the direction of 80$^\circ$. By comparison, NUVEL-1 indicates that Nazca motion relative to South America is $81.6$ mm yr$^{-1}$ oriented at 77$^\circ$. The SLR results for Arequipa, like those for Simosato, indicate that a component of the collision of the Nazca plate with South America influences the motion of the site. The velocity at Arequipa is essentially unchanged from that reported in the SL7.1 solution.

CONCLUSIONS

An improved analysis of more than 13 years of laser range observations to LAGEOS has yielded horizontal site velocities approaching a precision of $1$ mm yr$^{-1}$ for those sites with the longest histories of continuous operation. Estimating parameters within a simultaneous least-squares solution removed the need for approximations and reference system alignment adjustments made in SL7.1 and provided
robust statistics for the results. The tectonic motion results for the sites having longer tracking programs have not deviated significantly from those in Smith et al. (1990) and the geophysical interpretations offered there remain valid. The vectors estimated for sites that are intermittently occupied benefit tremendously from the new solution design. These improvements enable the recovery of motion for 12 such sites that until now have received little attention in the literature.

Further solutions with additional laser tracking observations of LAGEOS and LAGEOS II, as well as other geodetic satellites, will further strengthen the results of the overall solution. The maintenance and ongoing monitoring of the global SLR site kinematics is important for it provides a well-defined global reference to aid densification studies of regional kinematics derived from terrestrial and Global Positioning System observations.

ACKNOWLEDGMENTS

The SL8.3 solution presented here can be accessed through the Crustal Dynamics Data Information System. Contact Carey Noll via internet for further information at noll@cddis.gsfc.nasa.gov.

REFERENCES


