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Horizontal Crustal Motion in the Central and Eastern Mediterranean Inferred from Satellite Laser Ranging Measurements

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Abstract. Four campaigns to acquire Satellite Laser Ranging (SLR) measurements at sites in the Mediterranean region have been completed. These measurements to the LAGEOS satellite, made largely by mobile systems, cover a time span beginning in November 1985 and ending in June 1993. The range data from 18 sites in the central and eastern Mediterranean have been simultaneously analyzed with data acquired by the remainder of the global laser tracking network. Estimates of horizontal motion were placed into a regional, northern Europe-fixed, kinematic reference frame. Uncertainties are on the order of 5 mm/yr for sites having at least four occupations by mobile systems and approach 1 mm/yr for permanently located sites with long histories of tracking. The resulting relative motion between sites in the Aegean exhibit characteristics of broadly distributed pattern of radial extension, but at rates that are about 50% larger than those implied from studies of seismic strain rates based on seismicity of magnitude 6 or greater across the region. The motion estimated for sites in Turkey exhibit velocity components associated with the westward motion of the Anatolian Block relative to Eurasia. These results provide a present-day "snapshot" of ongoing deformational processes as experienced by the locations occupied by SLR systems.

Introduction

The fourth Mediterranean Laser (MEDLAS) ranging campaign of the Wegener Project [*Wilson*, 1987] was concluded in late April, 1993. Satellite Laser Ranging (SLR) measurements to the Laser Geodynamics Satellite (LAGEOS) have been obtained over a seven year period by many of the MEDLAS sites. Earlier analyses of MEDLAS data, after completion of only three occupations (spanning at most, 4 1/2 years), were made by several groups and presented at various colloquia associated with the Wegener Project and NASA's Crustal Dynamics Project. These earlier results varied somewhat between groups as differing solution strategies were explored and applied. The analysis by *Noomen et al.* [1993] provided one of the more comprehensive solutions, but the geophysical interpretation was limited due to the shorter time span of the observations then available. Inclusion of the data from the most recent campaign yields more reliable estimates of motion and provides a clearer description of real-time broad-scale Aegean and Anatolian kinematics. In addition to the SLR observational campaigns across the region, several Global Positioning System (GPS) observational networks have been established over the last five years stretching from the Calabrian arc in the west to across the Anatolia block in the east.

Analysis, Results and Discussion

In this study, SLR observations were used which span the period from January 1980 to the end of June 1993. The periods for which data were acquired at each of the MEDLAS sites are shown in Figure 1; the locations of which are illustrated in Figure 2. The horizontal motion vectors for the MEDLAS sites were estimated simultaneously with those from the rest of global network of SLR sites similar to the SL8.3 solution [*Smith et al.*, 1994]. The kinematic frame adopted for this solution constrains the north and east components of motion for the site at Greenbelt, Maryland and only the north component of motion for the site on the island of Maui in Hawaii to move with motions inferred from the NNR NUVEL-1 model [*Argus and Gordon*, 1991]. Full descriptions of the reference system, the models adopted, the ancillary adjusted parameters and details regarding the SL8.3 solution design can be found in *Smith et al.* [1994].

The main difference between the present solution and the SL8.3 solution lies in the treatment of a clearly identified error associated with one of the transportable tracking systems deployed in the 1992 MEDLAS campaign. The error arises from faulty determinations of the true azimuth for the TLRS-1 (Transportable Laser Ranging System) tracking system. This system visited four sites during the 1992 campaign: two in Greece–at Xrisokellaria and Roumeli, and two in Turkey–at Yigilca and Melengiclik. A +3° change in local horizontal azimuth has been applied to the survey eccentricities (which provide the coordinate relationship between the brass survey marker on each site's concrete pad to the optical axis of the laser system) to correct the azimuth error. The value for this correction was first ascertained by R. Noomen (private communication) and confirmed by us through estimates of station dependent range biases for the four sites in question. Unfortunately, there has been no way to directly recover a measure of this error from the ancillary engineering and operational data recorded during each occupation.

To better show the deformation across the Mediterranean region we place the MEDLAS motion estimates in a frame relative to sites in northern Europe which have exhibited no discernible intersite deformation [*Smith et al.*, 1990, 1994]. To do this, an Euler rotation pole was estimated, via least squares, from the SLR-determined motion of 5 tracking sites in northern Europe (Herstmonceux, England; Wettzell, Germany; Potsdam, Germany; Zimmerwald, Switzerland; and Graz, Austria). The motions of the MEDLAS sites inferred by this rotation pole were then removed from the SLR motion vector estimated for each MEDLAS site. This approach was taken since the SLR estimates of motion for northern European sites appear to be systematically rotated counterclockwise by 7-14° and are 1-5 mm/yr longer than those implied by NNR NUVEL-1 [*Smith et al.*, 1994]. The resulting northern Europe Euler pole has a rotation of 0.27 °/Ma and is located at 47.7°N and 98.7°W, placing the pole about 13° east and 3° south of the corresponding NNR NUVEL-1 Eurasian pole. The SLR estimates of the MEDLAS motion vectors within this northern European frame are given in Table 1 and shown in Figure 2. For sites not nominally located on the Eurasia plate, the corresponding NUVEL-1 vectors [*DeMets et al.*, 1990] relative to Eurasia are given in Table 1 and shown in Figure 2. The discussion which follows will progress from west to east and will limit itself to only the highlights in regard to the geophysical interpretation. A more detailed review of the structure and kinematics over the entire region can be found in *Mueller & Kahle* [1993].

Central Mediterranean

We begin with the tracking site at Grasse, France which lies in a complex tectonic setting as noted by *Rebaï et al.* [1991].

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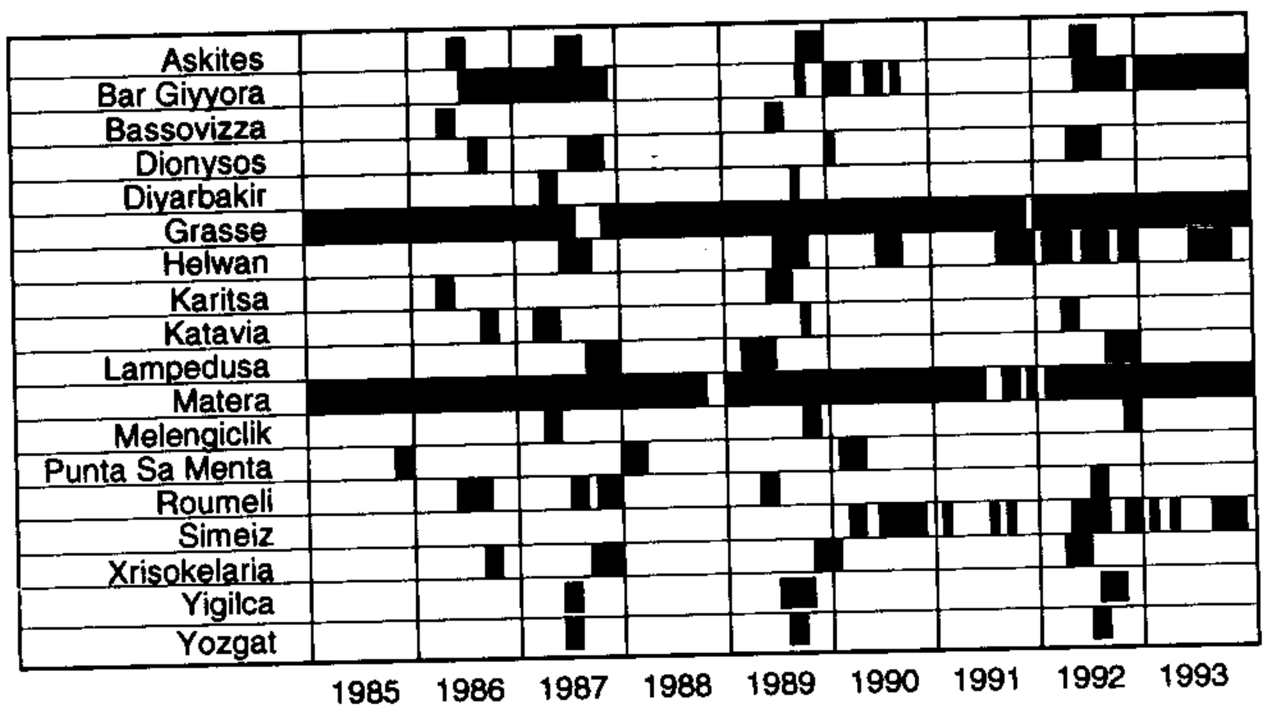

Figure 1. Periods when laser ranging observations were acquired for each MEDLAS site. The first MEDLAS Campaign took place in 1986, the second in 1987, the third in 1989, and the forth in 1992.

Relative to northern Europe, the SLR results indicate that Grasse moves SSE at 8 mm/yr. This would be consistent with shortening across the Balearic basin, to the south of Grasse, suggested by *Mantovani et al*. [1988]. Although stress and strain do not always share similar orientations, the alignment of the estimated motion is consistent with the N/S orientation of the regional stress field from *Rebaï et al.* [1991]. However, given the reverse and strike-slip faulting occurring nearby, the origins of the motion detected at Grasse could instead be due to local deformational processes rather than tectonic processes of a larger, more regional character. Regional surveys (by e.g. GPS) of the south coast of France and NW Italy would help to resolve this question.

Between Grasse and the Sardinian site at Punta Sa Menta, nearly 10 mm/yr of compression is implied from the SLR results. With respect to northern Europe, the SLR motion vector estimated for Punta Sa Menta implies essentially no motion at the 5 mm/yr level of uncertainty. This result is consistent with models that suggest that the Sardinia-Corsica block reached its present position some 13 Ma ago and no longer moves relative to Europe [*Mantovani et al.*, 1990], but contrasts with models that suggest that the block is still undergoing a rotation [*van Dijk and Okkes*, 1991].

The Lampedusa site, in the Pelagie Islands, has been visited by SLR tracking systems three times spanning a five year period. The SLR estimated motion vector is oriented NNE at 5 mm/yr relative to northern Europe, consistent within its uncertainty with NUVEL-1 Africa motion relative to Eurasia.

The SLR motion for the site at Matera, Italy was reported in *Smith et al.* [1994] where it was noted that its motion largely corresponded to NNR NUVEL-1 African motion. Matera lies east of the main axis of the southern Apennines, typically used to demarcate the SW boundary of the Adriatic block. Although the Matera region has a history of notable earthquakes, there has not been much recent seismicity greater than magnitude 3 in the immediate surrounding area [*Favali et al.*, 1993 and *Anderson and Jackson*, 1987]. Relative to northern Europe, the SLR estimated motion of Matera shares the alignment implied by NUVEL-1 Africa motion relative to Eurasia (NNW), but at a rate only half that of NUVEL-1. The fact that the Matera SLR motion shares the alignment with NUVEL-1 suggests an inconsistency with the proposed rotation of the Adriatic block relative to Europe about a point at 45.8°N and 10.2°E [*Anderson and Jackson*, 1987]. Given this Euler pole to describe Adriatic motion relative to Europe, the implied motion for Matera would be oriented 49.5°, differing nearly 70° clockwise from the motion estimated by SLR. SLR determined relative rates from Matera to other African sites (e.g. Lampedusa and Helwan, Egypt) are not yet sufficiently well known to address this issue.

The motion of Bassovizza, at the northern end of the Adriatic block, is not yet sufficiently known to address the issue of Adriatic rotation. Bassovizza has been visited by SLR systems only twice and resolution of its motion will improve with additional visits, which are planned.

Aegean Region

The tectonics and kinematics across the Aegean Sea and its surrounding region have been studied by many investigators (for a recent review, cf. *Jackson*, [1994]). The broad-scale kinematics across the region are largely characterized by strike-slip and extensional processes and are inextricably linked with the northward movements of the Africa and Arabia plates and the westward movement of Anatolia.

The motions estimated from the SLR data for the half-dozen sites in Greece provide a set of "point motions" which can act as constraints to regional kinematic models. In NW Greece, the velocity estimated from SLR for the Karitsa site shows rapid westward motion, on the order of 32 ± 8 mm/yr, consistent with the GPS velocity of Karitsa relative to Dionysos [*Kahle et al.*, 1993]. The velocity of Askites exhibits eastward motion of 8 ± 5 mm/yr relative to northern Europe. The SLR determined extension from Askites to sotes across the Aegean is consistent with simple kinematic scenarios described by *Taymaz et al.* [1991]. In these scenarios, the forcing comes from westward Anatolian motion which is transferred across northern Greece, ultimately colliding against the Apulia-Adriatic platform. The continental material of southern and central Greece, like pages of a book as described by *Taymaz et al.* [1991], are thrust southwestward, overriding the subducting Africa plate [*Stiros*, 1993].

A horizontal velocity field has been derived by *Jackson et al.* [1992] from seismic strain rates based on seismicity of magnitude (M_S) 6.0 or greater. The SLR estimated velocity of Dionysos agrees in orientation with that from the velocity field, but further south, the orientation of the SLR velocity estimates for Xrisokellaria, Roumeli and Katavia are about 10°-15° counterclockwise of those from the velocity field. The magnitudes of the SLR velocities for these sites are approximately one and a half times larger than the magnitude of those implied in the velocity field. The implications of these results are that about 2/3 of the motion detected by SLR may be attributable to deformation associated with earthquakes of magnitude ≥6.0 and that small amounts of deformation associated with forearc boundary kinematics may not be fully represented in the velocity field.

The SLR estimated relative rates between the sites are, where available, consistent with those implied from analyses of historical terrestrial surveys [*Stiros*, 1993] and those derived from combin-

Table 1. Tracking Site Motions for the SLR MEDLAS Sites Relative to Northern Europe

Station Name	SLR Velocities Az. (deg)	SLR Velocities Rate (mm/yr)	Error Ellipse Parameters Semi-Maj. (mm/yr)	Error Ellipse Parameters Semi-Min. (mm/yr)	Error Ellipse Parameters Orientation (deg)	NUVEL-1 Model* Az. (deg)	NUVEL-1 Model* Rate (mm/yr)
Eurasian Plate							
Askites	116	8.1	4.7	4.0	53	0	0
Dionysos	216	35.5	4.8	4.3	75	0	0
Grasse	160	7.9	1.3	1.1	5	0	0
Karitsa	279	31.7	8.3	6.8	61	0	0
Katavia	200	28.0	3.6	3.5	-75	0	0
P S Menta	343	1.6	5.9	5.2	82	0	0
Roumeli	214	36.2	4.3	3.5	52	0	0
Simeiz	83	8.4	13.6	12.6	-21	0	0
Xrisokelaria	216	33.4	4.3	3.7	62	0	0
Yigilca	287	3.9	5.4	4.5	53	0	0
Adriatic Block							
Bassovizza	293	5.9	23.1	17.6	51	331†	8.6†
Matera	337	4.3	1.2	1.0	14	340†	8.5†
African Plate							
Bar Giyyora	336	9.0	2.9	2.5	60	3 346‡	10.9 19.9‡
Helwan	224	8.4	7.6	6.5	65	3	10.4
Lampedusa	17	5.2	4.8	4.6	48	343	7.6
Anatolian Block							
Melengiclik	312	17.6	6.0	5.5	-86	-	-
Yozgat	296	28.5	6.3	5.6	83	-	-
Arabian Plate							
Diyarbakir	355	24.1	13.2	12.2	85	338	25.4

* The NUVEL-1 motion is relative to Eurasia.

† African NUVEL-1 motion used to approximate Adriatic Block motion.

‡ Arabian NUVEL-1 motion.

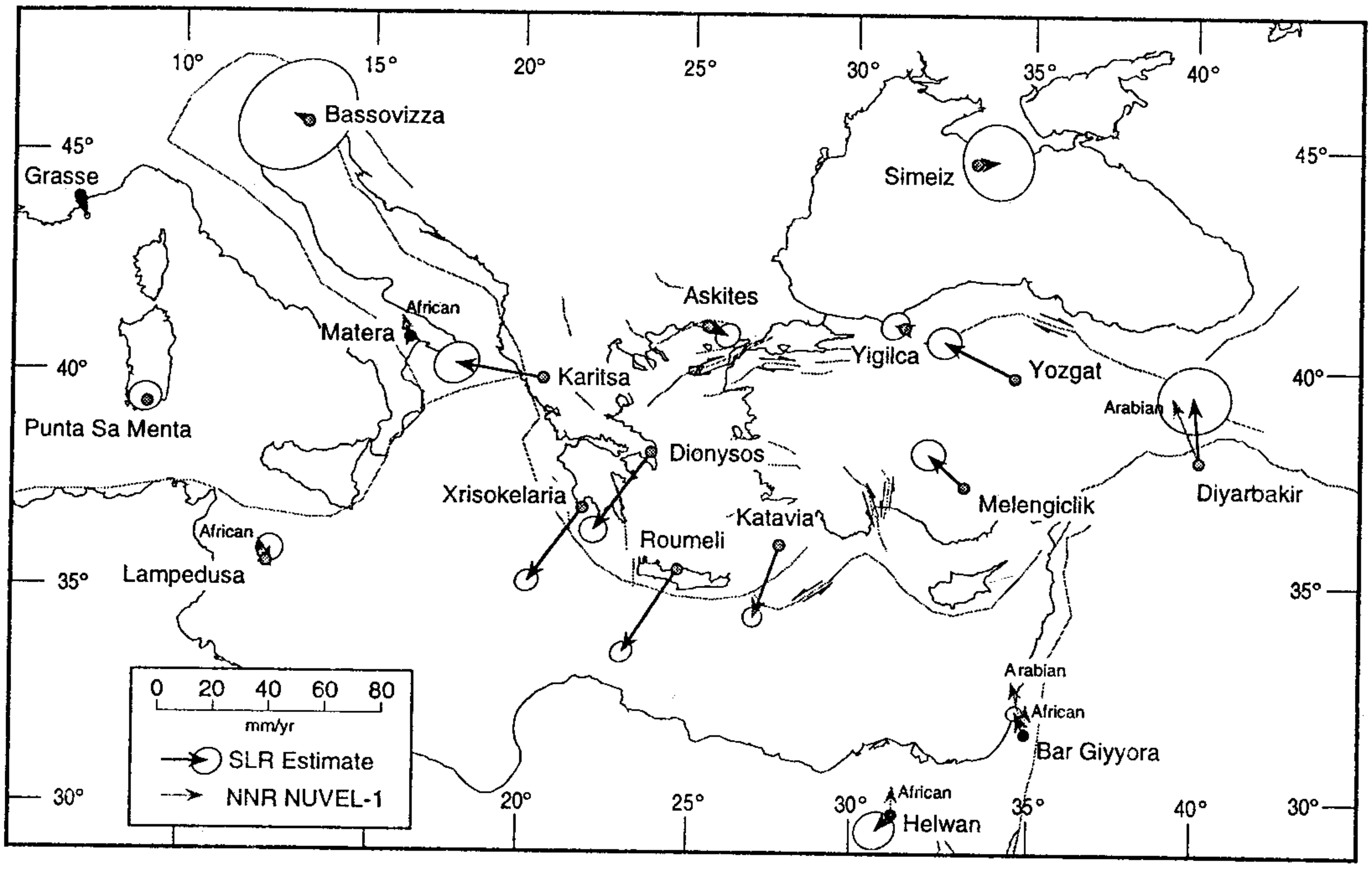

Figure 2. Estimates of horizontal motion relative to northern Europe for SLR tracking sites across the central and eastern Mediterranean. Permanently located tracking sites are indicated with black symbols. Sites visited periodically by transportable systems are shown with gray symbols. NNR-NUVEL1 vectors are relative to NNR-NUVEL1 Eurasia motion. Error ellipses represent 1-σ estimates of error.

ing these surveys with recent GPS measurements [*Billiris, et al.*, 1991]. Both of these studies traverse the Pelopennisos in south-central Greece, a portion of which is spanned by the line between SLR sites at Dionysos and Xrisokellaria, where the SLR results imply shortening of -2 ± 6 mm/yr. Across the whole region spanned by the terrestrial survey/GPS study, extension on the order of 9 to 11 mm/yr is reported, however, between sites of the terrestrial survey/GPS network situated near Dionysos and Xrisokellaria, *Billiris, et al.*, [1991] report a relative rate of 2 mm/yr with an uncertainty on the order of 5 mm/yr, consistent with the SLR-determined rate.

Turkey and the Anatolian Block

The Anatolian block moves generally westward relative to Eurasia with the western portion of the block undergoing additional E-W oriented stretching [*McKenzie*, 1978]. The SLR estimated motions for the sites Melengiclik and Yozgat largely reflect this westward motion of the order of 20 to 30 mm/yr. Both of these sites are located well away from any major faults and relative motion between the two is not statistically significant, emphasizing that little, if any, N-S convergence or divergence is detectable across the breadth of the Anatolian block.

Across the North Anatolian fault, the SLR estimated motion vector of Yigilca is statistically consistent with northern European motion. The SLR relative rate between Yigilca and Yozgat is -25 ± 7 mm/yr which shows that the -39 ± 9 mm/yr rate reported by *Noomen et al.* [1993] indicated a bit too much shortening. Since this line intersects the North Anatolian fault at an angle of about 40°, the implied right-lateral slip along the axis of the fault would be 32 mm/yr. Geologic and seismically determined rates along the North Anatolian fault have remained uncertain [e.g., *Oral et al.*, 1993], but the SLR result given here is remarkably similar to the 31 mm/yr rate proposed by *Jackson and McKenzie* [1984] as well as the 25 ± 9 mm/yr rate reported from GPS studies [*Oral et al.*, 1993].

Further north, across the Black Sea, the motion vector for Simeiz, based on three (consecutive) years of data, indicates no significant departure from northern Eurasian motion. Additional tracking data acquired at Simeiz and Yigilca will help to better resolve the motion between these sites and address questions regarding the possibility of subduction in the Black Sea as suggested by *Jackson and McKenzie* [1984].

In eastern Turkey, the SLR estimate of motion for Diyarbakir is, within its uncertainties, consistent with that expected from NUVEL-1 Arabian motion relative to Eurasia. Unfortunately, the laser monumentation and concrete pad have been destroyed and no future SLR occupations are planned. Nonetheless, the data from two occupations separated by just more than two years provides a consistent tectonic result. If one considers this result as representative of Arabia motion, then the implied convergence of Arabia with Eurasia, as sampled between Simeiz and Diyarbakir, is 24 ± 13 mm/yr, agreeing well with the NUVEL-1 predicted convergence of 28 mm/yr.

Southeast Mediterranean

Bar Giyyora, Israel and Helwan, Egypt are permanently located stations and have had their share of system difficulties, but recent upgrades to these systems have helped to improve system performance and will insure consistent data quality and quantity in the future. A comprehensive analysis of the data available from these two sites was made, involving judicious data editing and the application of timing and range biases as required.

The site at Bar Giyyora is located in a region of highlands about 35 km west of the Dead Sea, nominally on the Sinai side of the Jordan-Dead Sea transform zone. The amount of left lateral slip along this zone is not very well known but is thought to be on the order of 5 to 11 mm/yr based on studies of the historical (and pre-historical) seismicity [*El-Isa*, 1990]. Relative to the Arabia plate (defined via NNR NUVEL-1), the SLR vector estimate for Bar Giyyora implies a motion of 6.1 mm/yr with an azimuth of 153°, consistent with the generally accepted slip rate and lying between the vectors implied by the Arabia-Sinai rotation pole given by *Joffe and Garfunkel* [1987] (5.8 mm/yr with an azimuth of 190°) and the NUVEL-1 prediction of Africa motion relative to Arabia (10.0 mm/yr with an azimuth of 147°). A direct measure of the amount of slip on the Jordan-Dead Sea transform fault will help to better resolve the situation. For example, a terrestrial/GPS network has been recently established [*Karcz et al.*, 1992] which crosses the transform zone 100 km north of the Dead Sea. Anticipated results from the monitoring of this network, along with improved SLR rate estimates, will be invaluable for the development of kinematic models of the region.

The SLR estimate of horizontal motion for Helwan is based on tracking obtained sporadically since 1987. The vector estimated for Helwan differs drastically compared to that predicted by NUVEL-1 Africa motion relative to Eurasia (Figure 2). However, due to the rather limited amount of data available at this time from the site, the result is considered somewhat preliminary and will improve as additional ranging data is acquired.

Summary

Satellite laser ranging data acquired during the fourth MEDLAS tracking campaign plays a crucial role in making possible the reliable estimation of tectonic motions of the individual tracking sites across the central and eastern Mediterranean. Tectonic processes, such as radial deformation across the Aegean and the westward escape of Anatolia are clearly evident in the SLR motion estimates. Future tracking campaigns will help to reduce the uncertainties quoted here and will include recently established sites across the region, including; Noto, Sicily; Ankara, Turkey and Medicina, Italy (near Bologna). The estimated motion vectors of the SLR sites provide a kinematic framework within which more detailed models can be established based on seismology and other geodetic information from terrestrial surveys and GPS measurements.

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