Isr. J. Earth Sci.; 50: 39–47

The GIL network of continuous GPS monitoring in Israel for geodetic and geophysical applications

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(Received 10 January 2001; accepted in revised form 19 July 2001)

ABSTRACT

Wdowinski, S., Bock, Y., Forrai, Y., Melzer, Y., and Baer, G. 2001. The GIL network of continuous GPS monitoring in Israel for geodetic and geophysical applications. Isr. J. Earth Sci. 50: 39–47.

GIL (**G**PS in **I**srae**l**) is a network of 12 continuous GPS stations, of which 11 stations are fully operational and one station is to be installed in 2002. The network provides a reference frame for precise GPS measurements in Israel and serves basic and applied geophysical research, including (1) monitoring plate motion and crustal deformation across the Dead Sea Fault, (2) mapping atmospheric water vapor content, and (3) monitoring ionospheric total electron content. Results from 36 months of continuous GPS measurements reveal that the current displacement rate within the State of Israel is 1–4 mm/yr, reflecting interseismic deformation across the Dead Sea Fault due to 2–4 mm/yr of relative motion between Sinai and Arabia and possibly post-seismic deformation induced by the 1995 Nuweiba earthquake.

INTRODUCTION

Over the last decade, the space-based Global Positioning System (GPS) has become the leading tool for precise geodetic measurements. A wide variety of GPS receivers are now used at all levels of surveying. In many countries, including Israel, GPS has become the standard for surveying measurements and is required for cadastral measurements. Precise GPS geodetic measurements are also used in geophysical research for studies of tectonic plate motion (e.g., Larson et al., 1997), earthquake-induced deformation (e.g., Wdowinski et al., 1997), monitoring of atmospheric water vapor content (e.g., Bevis et al., 1992), and ionospheric total electron content (e.g., Calais and Minster, 1995). Although some of these studies can be conducted in campaign or survey mode (occupation of a site every one or two years), continuous GPS (CGPS) monitoring provides significantly more accurate results and is the only way to observe time-varying phenomena with GPS (Bock et al., 1997). As the cost of geodetic GPS receivers has decreased, more and more receivers are being devoted to CGPS monitoring.

Regional and global CGPS networks have operated

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 0021-2164/01 $4.00

worldwide for about a decade. The first CGPS network was established in Japan in 1988 and consisted of 15 permanent stations (Shimada and Bock, 1992). In 1989 the network recorded a precursory signal to an underwater volcanic eruption (Shimada et al., 1990). Today the Japanese CGPS network consists of over 1000 permanent stations. The second CGPS network was the Southern California Permanent Geodetic GPS Array (PGGA), which was established in 1990 with 5 permanent stations (Bock et al., 1997). This network first detected both coseismic and post-seismic displacements induced by the 1992 Landers earthquakes (Blewitt et al., 1993; Bock et al., 1993; Wdowinski et al., 1997). The PGGA network was later unified with a dense GPS array in the Los Angeles basin to form the Southern California Integrated GPS Network (SCIGN), which now consists of 250 permanent stations. Other regional CGPS networks have been established in Western Canada (Dragert and Hyndman, 1995), Northern California (King et al., 1995), Scandinavia (Jaldehag et al., 1994), the Alps (Calais, 1999), and other regions. The primary global CGPS network is the International GPS Service (IGS), which consists today of about 160 permanent tracking stations. The IGS provides the geodetic and geophysical communities with precise GPS orbits, tracking data, and other high-quality GPS data and data products in near-real-time to meet the objectives of a wide range of scientific and engineering applications (IGS, 1995).

The GIL (**G**PS in **I**srae**l**) network was established in 1996 by the Survey of Israel and Tel Aviv University, in collaboration with Scripps Institution of Oceanography. Its establishment was a natural continuation of several campaign-style GPS studies in Israel focusing on the current crustal movement across the Dead Sea Fault (DSF) (Adler et al., 1994) and relative plate motion of the Sinai subplate (Bechor et al., 1999). Since its establishment, the network has provided continuous GPS data for local geodetic applications (Ostrovsky, 2001, this issue), global geodetic applications (e.g., IGS), regional geodynamic studies (e.g., McClusky et al., 2000; Pe'eri et al., submitted), and atmospheric and ionospheric geophysical research (Na'aman et al., 2000). In this study, we describe the GIL network including its geometry, infrastructure, and operational procedures, as well as its major applications in geodetic and geophysical research.

THE GIL NETWORK

The GIL network consists of 12 CGPS stations distributed throughout the State of Israel (Fig. 1, Table 1). It was designed to provide infrastructure for both geodetic applications and geophysical research. The geodetic considerations in designing the network were:

1. strong network geometry,
2. complete coverage of the country, and
3. site locations near population centers, where most surveying work is conducted.

The geophysical considerations were primarily measuring the current interseismic displacement rate across the DSF, and secondarily monitoring atmospheric water vapor content in northern and central Israel. The long and narrow shape of Israel imposed the predominantly N–S geometry of the network (Fig. 1). E–W expansion of the network occurs in the north, where Israel has access to both sides of the DSF, and in the central part, where the country is wide enough to measure the interseismic displacement rate, but only west of the fault. Further E–W expansion of the network is planned across the Northern Negev.

The network was built in two stages. During the first stage (1996–1998), five CGPS stations were constructed from internal funds of the Survey of Israel (SOI) and Tel Aviv University (TAU). SOI constructed the TELA, KATZ, ELAT and BSHM stations on roofs of stable buildings mainly for geodetic purposes. In 1996 TAU constructed the DRAG station near the Dead Sea, using a geodynamic monument, for monitoring crustal deformation along the DSF. However, due to extreme heat conditions that damaged the receiver and limited resources, the station operated for only 8 months during this first stage. Operations of the DRAG station were renewed only in 2000 with additional external funding. The second stage of operation began in 1998, when external funding from the Israeli Space Agency (ISA) and SOI enabled further expansion of the network, with an emphasis on geophysical research. During this stage, 6 CGPS stations (RAMO, KABR, GILB, ELRO, LAHV, and JSLM) were constructed with geodynamic monuments. A seventh station will be constructed in 2002 in the Arava region. The site locations were determined according to:

1. bedrock exposure,
2. undisturbed view of the sky for clear signal reception, and
3. logistics, including power and telephone connection and protection from vandalism.

Due to the above constraints, four of the six geodynamic sites were built in kibbutzim, one at the TAU

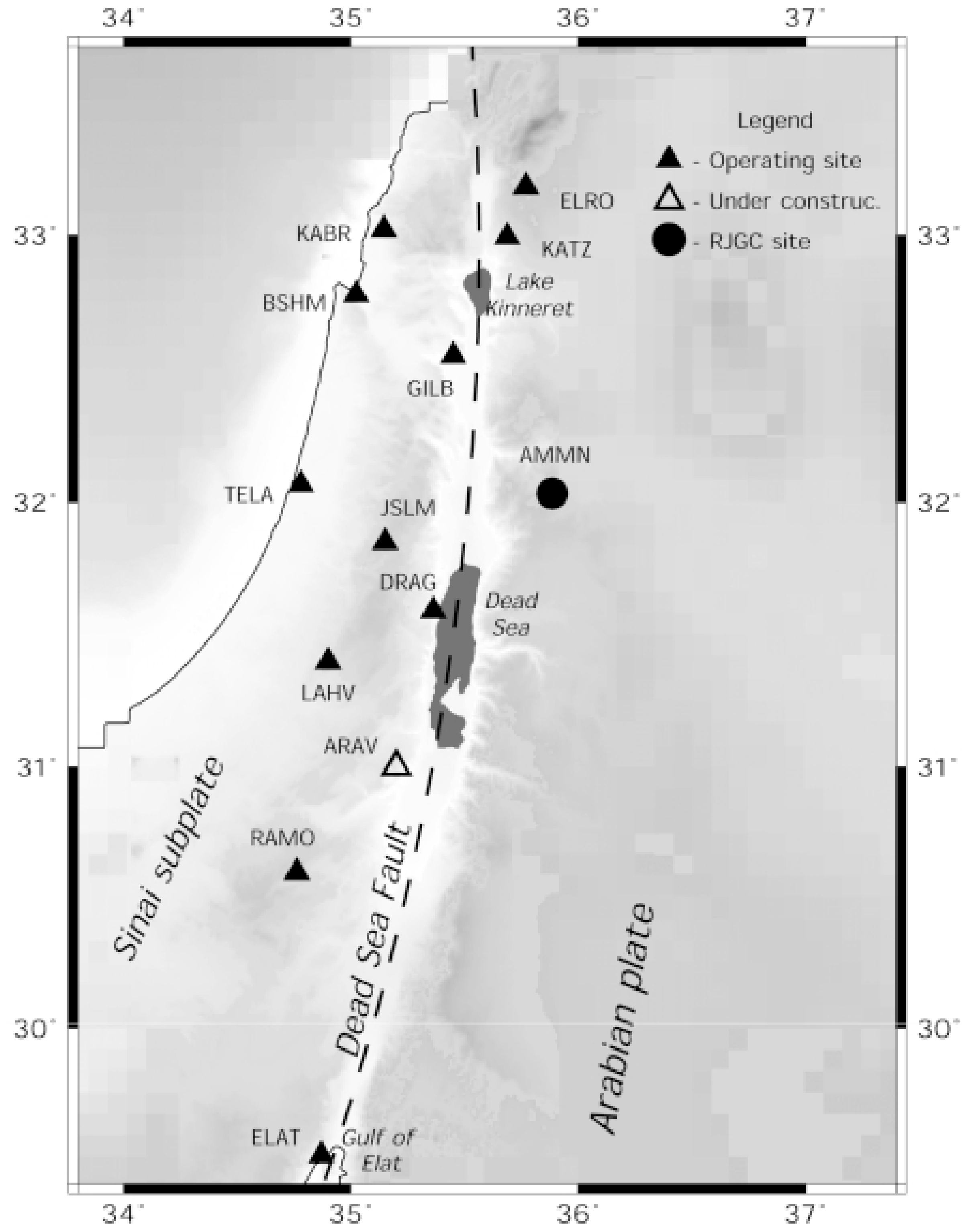

Fig. 1. Location map of the GIL network sites (triangles) in Israel and of the Royal Jordanian Geographic Center (RJGC) site (circle) in Amman, Jordan.

Table 1
Description of the GIL stations

Site code	Site name and location	Geodetic coordinates	Equipment type (receiver/ antenna)	Monument description	Start date YYYY.DDD
ARAV	Northern Arava	TBD	TBD	TBD	TBD
BSHM	*Haifa* The Binyamin Shmuter Memorial Station	32.78 N 35.02 E 225.1 m	Ashtech Z-XII3/ ASH700228D	Stainless steel pin attached to the roof of a stable building	1998.245
DRAG	*Metzokey Dragot,* Dead Sea	31.59 N 35.39 E 120.3 m	Ashtech Z-XII3/ ASH700936D_M Choke-ring	Stainless steel rod inserted into a concrete block	2000.038
ELAT	*Elat*	29.51 N 34.92 E 29.6 m	Trimble 4000SSE/ Trimble 4000ST L1/L2 GEOD	Stainless steel pin attached to the roof of a stable building	1997.040
ELRO	*Kibbutz Elrom,* Golan Heights	33.18 N 35.77 E 1080.4 m	Ashtech Z-XII3/ ASH700936D_M Choke-ring	Stainless steel rod inserted into a concrete block	2000.101
GILB	*Kibbutz Ma'ale Gilbo'a,* Mount Gilbo'a	32.48 N 35.42 E 525.4 m	Ashtech Z-XII3/ ASH700936D_M Choke-ring	Stainless steel rod in bedrock outcropping	1998.212
JSLM	*Jerusalem*	31.76 N 35.20 E 814.6 m	Ashtech Z-XII3/ ASH701945B_M Choke-ring	Stainless steel rod in bedrock outcropping	2001.171
KABR	*Kibbutz Kabri,* Western Galilee	33.02 N 35.14 E 119.4 m	Ashtech Z-XII3/ ASH700936D_M Choke-ring	Intermediate monument with 4 meter anchor	1998.205
KATZ	*Katzerin,* Golan Heights	33.00 N 35.69 E 347.0 m	Trimble 4000SSE/ Trimble 4000ST L1/L2 GEOD	Stainless steel pin attached to the roof of a stable building	1996.217
LAHV	*Kibbutz Lahav,* Northern Negev	31.38 N 34.87 E 488.9 m	Ashtech Z-XII3/ ASH701945B_M Choke-ring	Intermediate monument with 4 meter anchor	2001.012
RAMO	*Mitzpe Ramon,* The Tel Aviv University Wise Astronomical Observatory	30.60 N 34.76 E 893.1 m	Ashtech Z-XII3/ ASH700936D_M Choke-ring	Stainless steel rod in bedrock outcropping	1998.162
TELA	*Tel Aviv*	32.07 N 34.78 E 58.4 m	Trimble 4000SSE/ Trimble 4000ST L1/L2 GEOD	Stainless steel pin attached to the roof of a stable building	1996.217

TBD—to be determined.

Wise Astronomical Observatory (RAMO) and one within the grounds of the Israel Museum, Jerusalem (JSLM).

The expected slow crustal movements across the DSF (6 mm/yr according to Joffe and Garfunkel (1987)) require a sub-centimeter level of measurement accuracy, which must be obtained from highly stable monuments. We used three types of stable geodynamic monuments (Knafo and Wdowinski, 2000), two that were designed for the PGGA network in southern California (Bock et al., 1997) and a third type that was designed at GFZ (Germany) and was first used at DRAG. A fourth monument type was used by SOI, mainly for geodetic purposes. The four monument types are:

1. *Shallow monument.* This is the simplest and cheapest monument, and can be used only in areas where unfractured massive rock is exposed. The monument consists of a 1" diameter, 40 cm long stain-

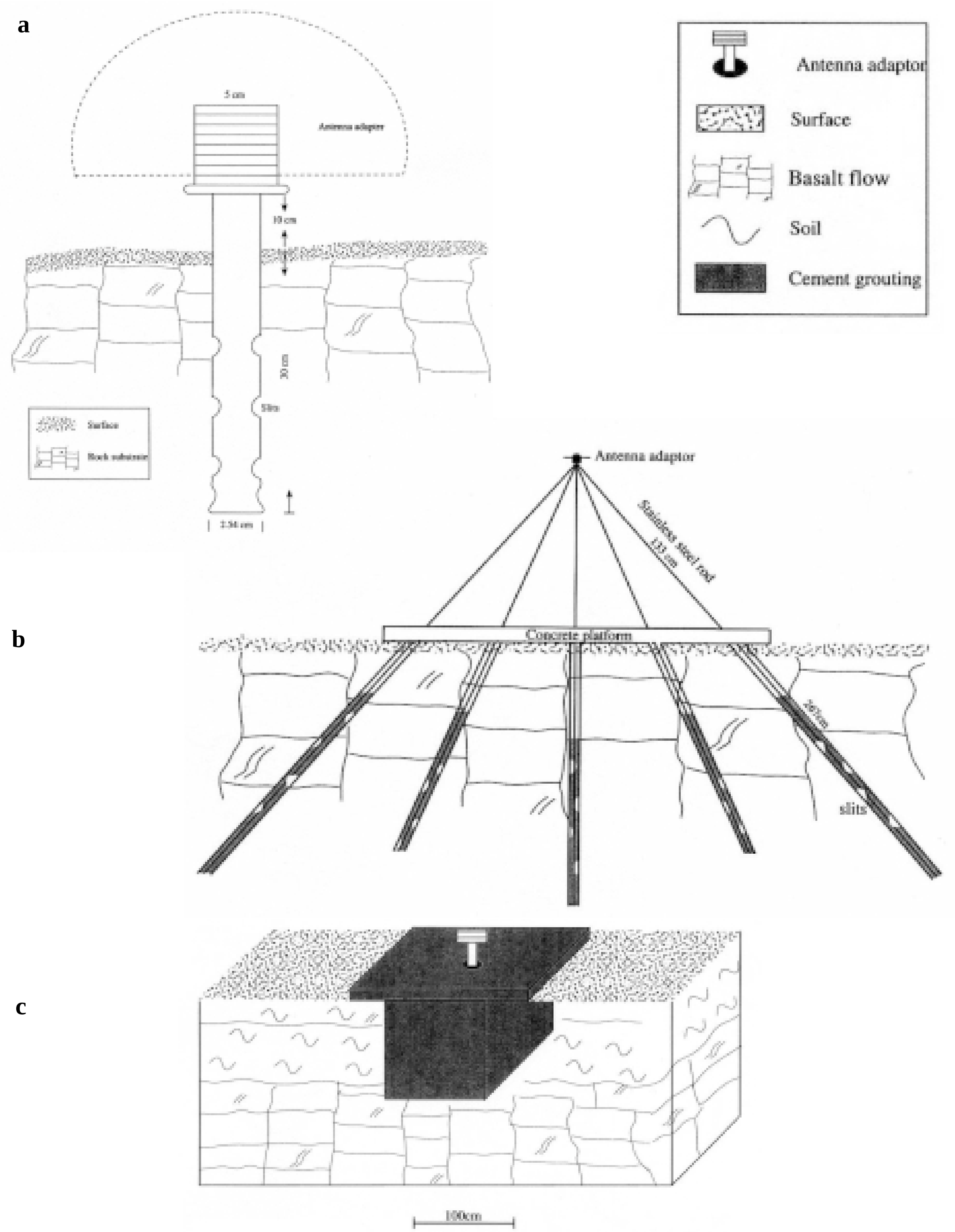

Fig. 2. Geodynamic monument types used in the construction of the GIL network stations: (a) shallow monument, (b) intermediate depth monument, and (c) concrete monument (after Knafo and Wdowinski, 2000).

less steel rod, on top of which a wide screw for holding the antenna adapter is welded (Fig. 2a). The lower 20 cm of the rod contains slits to provide a solid grip for the epoxy glue that is applied when the rod is inserted into the rock.
2. *Intermediate depth monument.* This monument is designed for areas of fractured massive rock. The monument is built from five stainless steel rods arranged in the shape of a pyramid and mounted on a concrete surface (Fig. 2b). The rods are 2" in diameter and 4 m in length, two-thirds of which is inserted below the surface, anchoring the monument to several blocks of rock. As with the shallow monument, the lower 2.5 m of the rods contain slits to provide a solid grip for the encasing glue.
3. *Concrete monument.* This monument is designed for areas where a thin layer (< 1 m) of soil or fractured rock overlies massive rock. The monument is built from a 1 m^3 cement block that is anchored into the massive rock by four thick stainless steel rods. As with the shallow monument, a 40 cm long stainless steel rod, which holds the antenna's adapter, is inserted and glued into the block's upper surface (Fig. 2c).
4. *Rooftop monument.* Stainless pin mounted onto the roof of massive stable buildings.

Each station is equipped with a geodetic GPS receiver (Trimble SSE or Ashtech Z-12), geodetic antenna (L1/L2 antenna for Trimble receivers and Dorne-Margolin antenna with choke rings for Ashtech receivers), AC power, emergency backup power (battery and UPS), dedicated telephone line, and modem. As described above, the antenna is mounted to a stable monument, whereas the rest of the equipment is stored in a specially designed metal box. Two of the stations (KABR and RAMO) also contain meteorological instruments for GPS meteorology studies. Data collection is obtained in 24-h segments (0–24^h UT) using a 30-s receiver sampling rate. However, in some stations we collect data at a higher sampling rate (5-s), as a service for local surveyors. Using automated procedures for GPS data download, the data collection and processing centers at TAU and SOI download the data once a day. The daily RINEX, raw, and MET data are kept at a dedicated archive that is available to all users via anonymous ftp (tecton.tau.ac.il) or the Internet (http://www.tau.ac.il/~shimonw/gps) and at the Scripps Orbit and Permanent Array Center (SOPAC, ftp://lox.ucsd.edu; http:/sopac.ucsd.edu).

Geodetic applications

The major geodetic application of the GIL network is to establish a national datum (reference frame) for precise geodetic measurements in Israel (Adler et al., 2001, this issue). An experimental survey of 160 sites of the G1 GPS geodetic-geodynamic reference network was conducted in 1996–1997 using 3 permanent stations (Ostrovsky, 2001, this issue). Results of this campaign showed that measurement accuracy was sub-centimeter in horizontal position and 1.5 cm in height (Adler et al., 2001, this issue). Such accuracies are almost an order of magnitude better than those achieved by terrestrial survey methods used until the mid-1990s. Today, with the GIL network, the accuracy of horizontal measurements can be reduced to a few millimeters. The continuous GPS data are also used by local surveyors for ordinary survey work.

Another important application of the GIL network is providing continuous GPS data to the International GPS Service (IGS) for calculating precise orbits and Earth orientation parameters. The official IGS station of Israel is RAMO, which is located in the central Negev, about 50 km from the Dead Sea Fault (DSF) and, hence, tectonically stable. The continuous data of RAMO and additional stations are also used routinely by the International Terrestrial Reference Frame (ITRF) and the European Reference Network (EUREF) for calculating very precise global and European, respectively, reference frames for precise measurements.

Geophysical research

The primary research goal of the GIL network is to monitor current tectonic movements across the DSF, which is a left lateral strike-slip fault, separating the Arabian plate from the Sinai sub-plate. The relative plate motion across the fault was estimated in the range of 0–10 mm/yr (e.g., Ben-Menahem and Aboodi, 1981; Joffe and Garfunkel, 1987; Ginat et al., 1998). The higher values reflect the average long-term (millions of years) motion across the fault, whereas the lower ones reflect the low to moderate level of seismic activity along the fault. The GIL network of continuous GPS stations allows us to measure the current rate of motion across the DSF.

We process the daily data using the GAMIT/GLOBK software packages (Herring, 2000; King and Bock, 1995). In order to achieve highest accuracy, we process the local station data simultaneously with

12–15 regional IGS data from Europe, Africa, and Arabia. Results from 36 months of continuous GPS measurements reveal that the current northward (fault parallel component) displacement rate between Tel Aviv and Katzerin (Golan Heights) is 1.4 ± 0.4 mm/yr and between Elat and Katzerin is 1.3 ± 0.6 mm/yr, and the eastward (fault normal component) rate between Tel Aviv and Katzerin is 1.6 ± 0.4 mm/yr and between Elat and Katzerin is 3.5 ± 0.5 mm/yr (Pe'eri et al., submitted). The observations reflect interseismic deformation across the DSF, due to 2–4 mm/yr of relative motion between the Sinai and Arabian plates and possibly post-seismic deformation induced by the 1995 Nuweiba earthquake (Pe'eri et al., submitted). Further collection, processing, and analysis of the GIL network data will verify the preliminary results at a higher confidence level and will provide a detailed description of the current deformation pattern along the DSF.

The GIL network also provides infrastructure for monitoring continuous variations of atmospheric water vapor content and ionospheric total electron content (TEC). Because the travel time of the satellite-transmitted GPS signal is delayed by several nanoseconds proportionally to the integrated amount of atmospheric precipitable water and is diffracted proportionally to the number of free electrons in the ionosphere, these quantities can be measured. Na'aman et al. (2000) used the GIL network data to monitor TEC variations induced by the August 11, 1999 solar eclipse, which reached 78–83% coverage over Israel. Their results show that during the eclipse the TEC above Israel decreased by 40% during 150 min. GPS meteorological studies are now in progress and their results will be integrated into a weather model of the Eastern Mediterranean region for generating more accurate weather forecasts. In order to increase the accuracy of these studies, we installed meteorological units that continu-

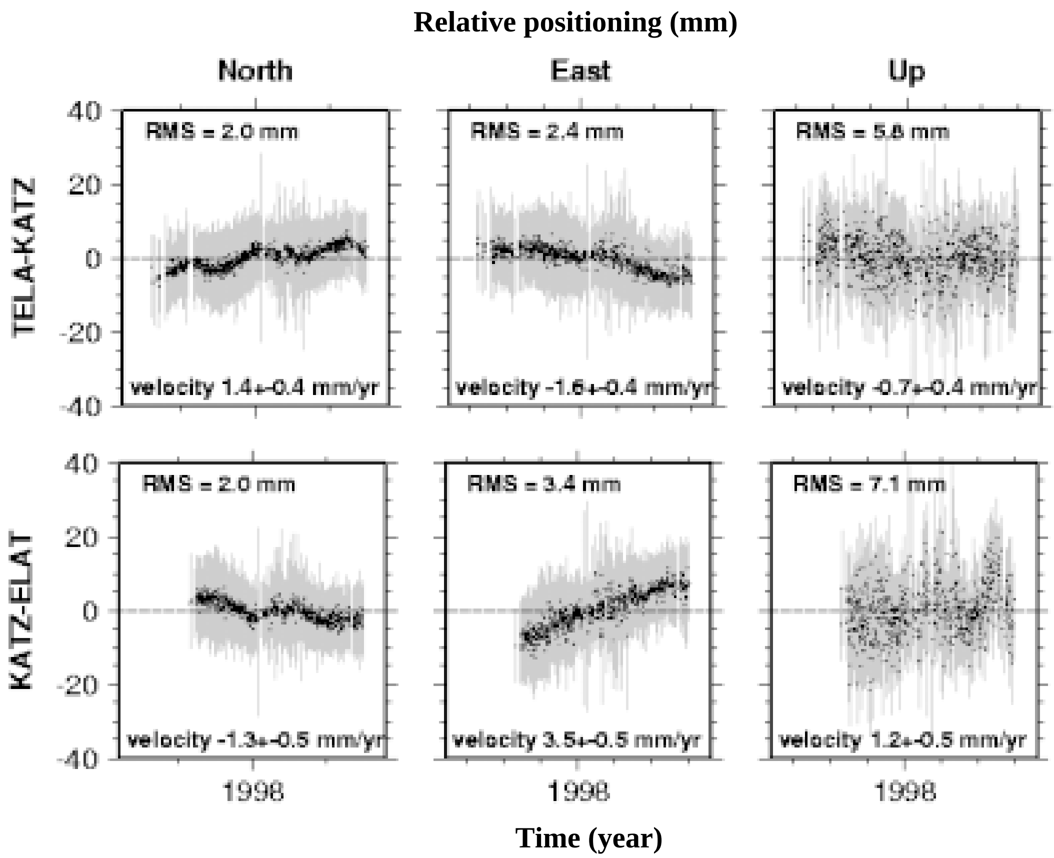

Fig. 3. Two-year time series of relative positions (mm) between TELA, KATZ, and ELAT stations (after Pe'eri et al., submitted).

ously measure pressure, temperature, and humidity at the KABR and RAMO sites. A third unit will be installed in the near future in the JSLM site.

DISCUSSION AND CONCLUSIONS

CGPS networks provide valuable observations for both geodetic applications and geophysical research. The first networks mainly served geodynamic research in the seismically active regions of Japan and California (Bock et al., 1997; Shimada and Bock, 1997). Gradually, additional CGPS networks were introduced, mostly in developed countries (i.e., in North America, Western Europe, Australia, and Japan), as infrastructure for geodetic applications and geophysical research. The GIL network, established in 1996, is the first CGPS network to operate in the Middle East and, moreover, the first network to operate between Western Europe and Japan. Because only a few individual IGS tracking stations operate in this very wide region, the GIL network data provide a significant contribution for international and regional efforts, such as IGS and EUREF, to better utilize and implement space-based GPS technology.

The GIL network provides the infrastructure for several unique geophysical research objectives. Continuous monitoring of crustal movements along the DSF, which is one of the best-studied continental transforms, adds new important observations regarding fault system behavior at the various stages of the earthquake deformation cycle (i.e., inter-, pre-, co-, and post-seismic deformation). Furthermore, the tectonic environment of the DSF has unique characteristics, such as narrow rift morphology, pull-apart basins, and pressure domes, which can be studied now within the framework of the new geodetic observations. The GIL network also provides unique observations for meteorological studies because of the network's location within a climatic transition zone, from semi-arid to arid conditions, and the overall lack of humidity observations in arid regions.

Future development of the network includes: further densification of the network, additional installation of meteorological units at stations, near-real-time data collection and downloading, and collaboration with neighboring countries. These developments will:

1. improve the national datum,
2. provide local surveyors with near-real-time data,
3. allow higher accuracy monitoring of crustal deformation along the DSF, as well as along second-order tectonic features, such as the Carmel fault,
4. provide near-real-time estimates of atmospheric water vapor content for better weather forecasts, and
5. allow better integration between GPS and Interferometric Synthetic Aperture Radar (InSAR) monitoring of crustal movements (e.g., Baer et al., 1999, 2001).

ACKNOWLEDGMENTS

We want to thank all the people who helped us build and maintain the GIL network stations meeting the highest standards. The Geological Survey of Israel technical team responsible for setting up the GPS station monuments was managed by Robert Knafo and consisted of the GSI technicians Ya'akov Mizrahi, Shlomo Ashkenazi, Haim Hemo, and David Sidi. The Tel Aviv University staff and students who took an important role in the network building are Aharon Slonim, Aharon Dvir, Noa Bechor, Shachak Pe'eri, Shmuel Na'aman, Aya Mor, Sagi Dalyot, and Alon Shtibelman. We also thank the Tel Aviv University Dead Sea Research Center and Zvi Ben-Avraham for setting up the Dragot station. The Survey of Israel's technical team of Aharon Nahari and Elia Perlman helped at various stages of the project. At sites we received considerable support by Hagai Ron, David Romano, and Yan Van Horst (Kabri), Kobi Shacham (Ma'ale Gilboa), Sami Ben-Gigi and Ezra Mashal (Mitzpe Ramon), Oren Kliderman and Eli Raz (Dragot), Re'uven Siman-Or, Mike Ben-Har, and Yuval Ziv (El-Rom), Israel Birger (Jerusalem), and Zvi Shmueli, Moshe Tayar, and Avraham (Berri) Levi (Lahav). We also thank Hadley Johnson and Paul Jamason from the Scripps Institution of Oceanography for sharing with us the vast knowledge of setting up permanent stations they acquired in California. We are thankful to Tim Dixon and Rob Reilinger for their helpful comments. This study was funded by the Israel Space Agency and the Survey of Israel.

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