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FIRST EPOCH GEODETIC GPS MEASUREMENTS ACROSS THE AFAR PLATE BOUNDARY ZONE

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Abstract. In November 1991, a geodetic network was installed across the actively rifting plate boundary zone between Africa and Arabia. Using the microwave signals transmitted by the satellites of the Global Positioning System (GPS), the relative positions of 37 stations are estimated with an average WRMS scatter of 12 or 14 mm for lines shorter or longer than 100 km, respectively. Assuming that the measurements can be repeated with the same precision in 1999, we expect to obtain horizontal uncertainties of 2.1 or 2.4 mm/yr in the rate of change in the short and long lines, respectively. This level of precision will tightly constrain geological models for the spatial distribution of deformation around the rift in Djibouti, and for the far-field plate motions surrounding the Afar depression.

Introduction

The Afar triangle, at the southern end of the Red Sea, is a complex and actively deforming plate boundary between three continental blocks: Nubia, Somalia, and Arabia (Figure 1). It is the only place on Earth, besides Iceland, where the mid-ocean ridge is visible on land. Following a major rifting event in 1978 [Anis Abdallah et al., 1979], the Quaternary tectonics of the area have been extensively studied, as recently reviewed by Acton et al. [1991] and Stein et al. [1991]. In this paper, we report on GPS observations designed to measure the active deformation in Afar. These data constitute the first point in a time series that will provide the rate of change in relative horizontal station coordinates. The resulting map of the deformation field is intended to test geological models for the spatial distribution of deformation around the rift in Djibouti, and for the far-field plate motions surrounding the triple junction.

Djibouti

The GPS network focuses on the deformation in Djibouti (Figure 2). This area is actively deforming, as highlighted by the 2 meters of extension that occurred during a seismo-volcanic rifting event in 1978 [Ruegg et al., 1979]. The GPS network installed in 1991 extends a substantial history of

measurements designed to characterize the deformation field in both time and space [Ruegg, manuscript in preparation]. The horizontal deformation within the 10 km-wide rift valley has been measured by trilateration [Ruegg et al., 1984; Ruegg and Kasser, 1987]. The 1991 measurements extend the time series enough to detect a temporal decay in the post-seismic deformation rate [Briole et al., manuscript in preparation]. For example, the length of the line between stations C and F, which crosses the rift at a right angle, increased by 16 cm during the period from 1984.3 to 1991.8. This result implies an extension rate of 21 mm/yr, noticeably slower than the 34 mm/yr observed in the post-seismic period between 1979.9 and 1984.3 [Ruegg et al., 1987]. The measurements also extend the ability to detect deformation up to 100 km off the rift axis because many of the stations were tied to the 1950 national triangulation network [Institut Géographique National, hereafter IGN, 1952]. Although the early measurements are considerably less precise than the GPS estimates, a comparison of the two data sets should resolve the far-field deformation associated with the 1978 event [Feigl et al., manuscript in preparation].

Future GPS occupations will provide a profile of deformation rate as a function of distance from the rift. The shape of this function will constrain models for the rheology of rifting between spreading events. We also seek to estimate the rates of rotation between the tectonic blocks, which are of the order of 8°/Ma, based on paleomagnetic declinations [Courtilot et al., 1978]. If these long-term average rates apply to the present-day deformation, the GPS network would undergo rotations of 140 nanoradian/yr, changing a typical 30-km baseline by 4.2 mm/yr. Detecting such a signal with a signal-to-noise ratio of 2 will require an uncertainty of 2.1 mm/yr in both horizontal components. The objective is to test three models invoking block rotation: the bookshelf-

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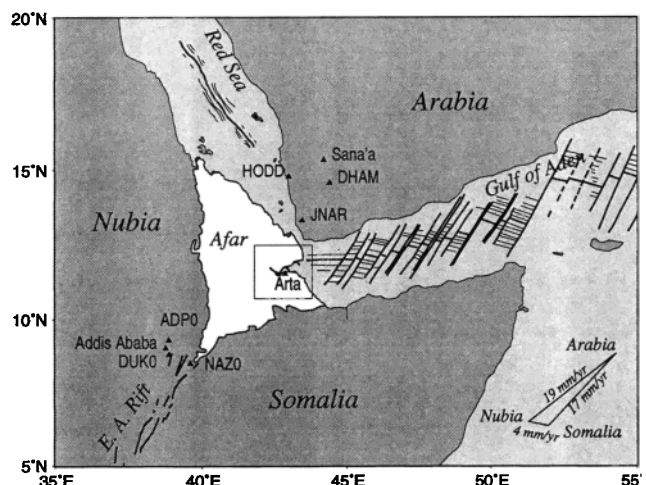


Fig. 1. Tectonic setting. GPS stations observed in 1991 (triangles) and area of Fig. 2 (box). Relative velocity triangle and magnetic anomalies from Acton et al. [1991].

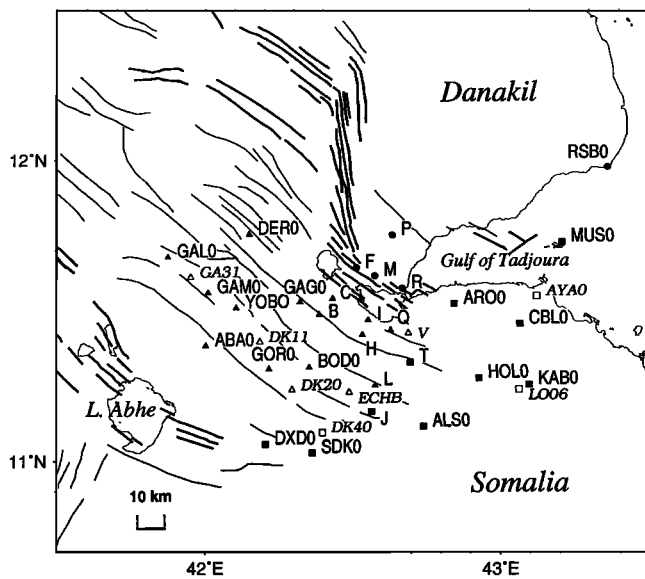


Fig. 2. Stations in the 1991 GPS network (solid symbols) and stations from the 1950 IGN network remeasured with GPS in 1991 (open symbols and italic labels). Stations have been assigned to the Danakil block (circles), the Somali plate (squares), and the overlap zone (triangles). Traces of active Quaternary faults (heavy lines) and other mapped faults (thin lines) after Stein et al. [1991].

faulting model [Tapponnier et al., 1990], the microplate model [Acton et al., 1991], and the spreading bookshelf model [Sigmundsson, 1992].

An additional motivation for the network is to measure the co- and post-seismic deformation following a large earthquake in the future. Like the 1973 network installed in Djibouti before the 1978 rifting event [IGN, 1973; Chabbert, 1975], the 1991 GPS measurements constitute an investment for the future. To protect this investment, we have documented and deposited the data in the archives of the University Navstar Consortium (UNAVCO) and IGN.

Plate Boundary Zone

The area shown in Figure 1 covers the boundaries of at least two plates, Africa and Arabia, which are diverging at 17 ± 4 mm/yr [DeMets et al., 1990]. The uncertainty for this rate is larger than at most other plate boundaries due to poor knowledge of the spreading rate and the number of plates. Careful review of the data in the Gulf of Aden and the Red Sea leads to a model in which Africa is split into two different plates, Somalia and Nubia, by the East African rift [Jestin et al., 1993]. Yet a fourth block, including the rigid Danakil Horst, has been proposed [Sichler, 1980; Acton et al., 1991]. Finally, the actively deforming region in Djibouti is obviously not rigid and must be considered separately. It has been treated as a "microplate" [Acton et al., 1991] and as an "overlap zone" [Tapponnier et al., 1990]. Clearly, there is no shortage of models for the motions of the plates bounding the Afar region. Since these models form the far-field boundary conditions for the tectonics of the Afar, testing them on the decade time scale is one of our primary objectives.

In Ethiopia, our network contains four points in a line passing through Addis Ababa and ending in the middle of the East African rift. The line could not be extended across the rift onto the Somalia plate due to political troubles in 1991. The Ethiopian part of the network acts as an anchor point on the Nubia plate and shares two stations with the network installed in Ethiopia by Jackson et al. [1992].

On the Arabia plate, the network includes four stations in Yemen. These include a reference station at Sana'a, and three others. They will provide the motion of the Arabia plate, as well as any internal deformation toward its southwestern boundary.

Data

The GPS observations were performed between November 2 and 30, 1991. Because of our limited access to the northern part of Djibouti, the 1991 network contains only five stations in Djibouti on the north (Danakil) side of the rift, but 10 stations on the south (Somalia) side, and 15 in the overlap zone between them. Of the 29 GPS stations in Djibouti, 12 were part of the trilateration network established in 1973. In addition, we tied nine stations from the 1950 triangulation to the 1991 network using short (3 hour) GPS occupations.

The GPS data were collected in two daily sessions from 05:00–08:00 UTC and again from 15:00–22:00 UTC, corresponding to 3 hours in the local morning, and 7 hours in the evening, including sunset. The pool of 12 dual-frequency receivers included three Ashtech MDXII, four Ashtech LDXII, one Ashtech PXII, two Trimble 4000 SST, and two Trimble 4000 SLD. With the exception of the last two, all receivers used the same design of microstrip antenna.

Three stations (Arta, Sana'a, and Addis Ababa) recorded data continuously for the entire duration of the campaign. Eighteen additional stations in the global tracking network were operational, providing the data for estimation of the satellite orbits [Bock et al., 1993].

Analysis

We analyze the GPS data using the GAMIT and GLOBK software using essentially the same strategy as described in Feigl et al. [1993]. The only important difference from their strategy is that we do not adjust the satellite orbital parameters. We use the orbits calculated by the California PPGA group, which have an internal consistency of better than 1 meter. For short baselines, such as the 30 km lines in Djibouti, the orbits are not the limiting source of error. The coordinates for Arta Observatory are constrained to be within 10 mm of their values in the ITRF 91 system [Boucher et al., 1992], estimated from DORIS.

To evaluate the precision of the estimated relative station positions, we measure the scatter between multiple (2–5) measurements of individual baselines. The weighted root mean square (WRMS) scatter is shown in Figure 3 as a function of baseline length. For baselines less than 100 km long, the average WRMS scatter is 7 mm in the north component, 12 mm in the east component, and 37 mm in the vertical component. These values are higher than those obtained for similar-length lines in California [Dixon, 1991]. The reason for the degradation in precision is probably due

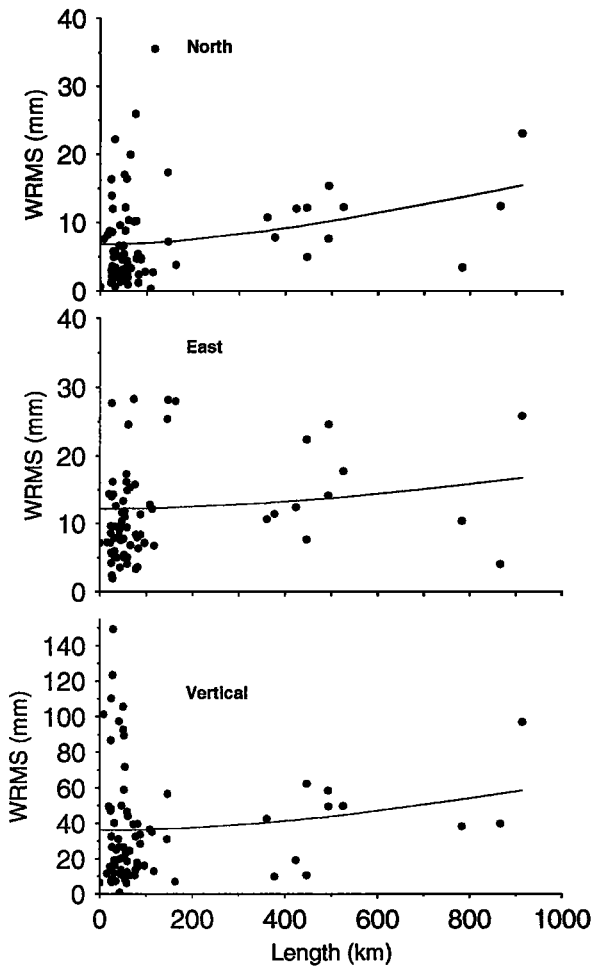


Fig. 3. Weighted root mean square (WRMS) scatter between multiple measurements of relative position vectors for north, east, and vertical components. The curves represent the length dependence.

to several factors: “noisy” data, misaligned antennas, and obsolete receiver software.

Our GPS data are “noisier” than we expected due to ionospheric perturbations and the resulting receiver misbehavior. Since Djibouti is within 10° of the magnetic equator, ionospheric fluctuations are greater than at mid-latitudes. The fluctuations were aggravated by the inclusion of sunset in the observation schedule, but were worse 5 hours after sunset than during the day. They appear as noise in the residuals at the level of 0.1 cycles RMS for a 50 km line, using the ionosphere-free L_C phase observable [Dixon, 1991].

The scatter is also due to the effects of misaligned antennas. Although all antennas were aligned with their arrows pointing north, there is a 45° difference in the orientation of the microstrip between the Trimble and Ashtech antennas. This misalignment implies that any horizontal offset between the phase and geometric centers of the antenna will not cancel between two unlike antennas. The horizontal offset may be as large as 8 mm for the L_C observable in each antenna [C. Rocken, pers. comm.]. The error increases the scatter in our results because most stations were observed with both types of antennas. In the future, proper orientation of the antennas should decrease the scatter

to the sub-centimeter levels obtained with matched receivers in Ethiopia [Jackson et al., 1992].

The ionospheric disturbances rendered tracking difficult, particularly in the L2 frequency for those Ashtech receivers equipped with the now obsolete 6A software. Although all receivers occasionally lost lock, creating cycle slips, the older Ashtechs sometimes provided noisy L2 phase observations with a characteristic sawtooth signature. We are able to detect all the full- or half-cycle slips, but the sawtooth signature is harder to eliminate completely. In many cases, the offset cannot be repaired with an integer or half-integer number of cycles, and is instead estimated with an additional, real-valued parameter. This effectively prevents resolution of the integer phase ambiguities, increasing the scatter in the estimated baseline components.

For the longer, inter-plate lines, the WRMS scatter in the GAMIT estimates is 10, 14, and 38 mm in the north, east, and vertical components, respectively. Again, these values are higher than those found in other studies [e.g., Feigl et al., 1993]. That they are also higher than the values obtained for the short lines is diagnostic of unresolved phase ambiguities.

Expected Precision of the Velocity Estimates

Given the real uncertainties in position for the 1991 survey, we predict the uncertainty in velocity we can expect to obtain after the next campaign. The standard deviation in velocity σ_v is inversely proportional to the time interval T between the measurements. For the case of two measurements, the formula (33) given by Dixon [1991] reduces to simply $\sigma_v = \sqrt{2}\sigma_p/T$. Here, σ_p is the standard deviation in position, which we assume to be 12 or 14 mm for the horizontal components of the short and long lines, respectively.

The most demanding application of the short baseline estimates is the measurement of block rotations, which will require a precision of $\sigma_v = 2.1$ mm/yr, based on the argument above. For the long, inter-plate lines, solving the problem of plate motions will require a precision at least as good as that of the 4 mm/yr uncertainty of the NUVEL-1 prediction for the Arabia-Africa rate [DeMets et al., 1990].

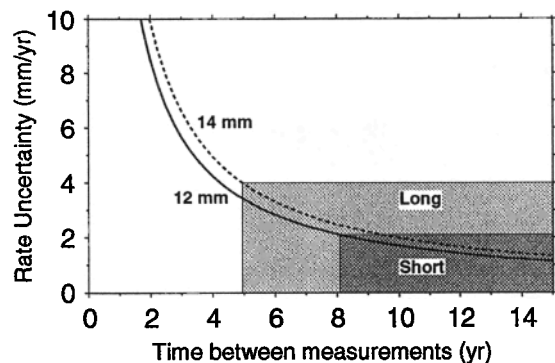


Fig. 4. Expected uncertainty in velocity as a function of time T between measurements. Each measurement is assumed to have a horizontal standard deviation of 12 mm for short lines (solid line), or 14 mm for long lines (dashed line). Shaded area indicates our plan for obtaining an uncertainty of $\sigma_v = 2.1$ mm/yr on the short lines by a second occupation of the 1991 GPS network after $T = 8.1$ years, in 1999.

Both these requirements are satisfied by a measurement period of $T = 8.1$ yr (Figure 4).

Conclusions

The 1991 Afar GPS campaign has yielded estimates of relative station positions which have an average horizontal WRMS scatter of 12 mm for lines shorter than 100 km, and 14 mm for longer lines. Although this GPS campaign is only the first in the area, the data have already measured deformation in the area around the Asal rift, through comparisons with existing triangulation and trilateration.

If we repeat this campaign with the same precision in 1999, we expect to obtain estimates of horizontal relative velocity with uncertainties of 2.1 and 2.4 mm/yr for the short and long lines, respectively. The former precision should be sufficient to test models of block rotation in Djibouti, and the latter to improve models for the decade-scale kinematics of the plates surrounding the Afar.

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