5 Years of GPS Observations of the Afar Triple Junction Area

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Abstract. In November 1991, a network of about 30 GPS sites was measured in Djibouti (Somalian plate). Additional points were also measured in Yemen (Arabia) and in Ethiopia (Nubia). Since then, a few points of this network were re-occupied several times (from January 1993 to March 1995) for short durations. The present day data set include measurements from 1991 to 1995 on the large-scale baselines (Arta, Djibouti - Sana'a, Yemen - Addis Abeba, Ethiopia) and repeat measurements on more local baselines in Djibouti. The station of Arta in Djibouti shows very large displacements: locally representative (as attested by a local tie), but different from other stations located on the stable zone outside the overlap area of the Asal-Tadjoura rifts. This motion does not seem to be linear with time, but rather suggests postseismic deformation (related to the Arta earthquake of March 5, 1992, magnitude 5.4). Except for the episodic Arta displacement, coherent motions of three stations in Southern Djibouti with respect to Yemen are observed, determining a more stable zone south of the overlap area. The observed opening of the Afar triple junction yields at least the NUVEL1-A estimate of 16 mm/a between Yemen and Djibouti.

Introduction

In November 1991 first observations of a GPS network were made in the junction zone of the Somalian, Arabian and Nubian plates around the Afar region [*Ruegg et al.*, 1993]. This is the second place on Earth, besides Iceland, where the mid-ocean ridge is visible on land, and the only well developed triple rift junction emerging on land. While the Red Sea and Gulf of Aden rift zones separate the Arabian from the African plate, the East African Rift splits the African plate into the Nubian and the Somalian plate (Figure 1). The baselines between Arta (Djibouti) on the Somalian plate, Sana'a (Yemen) on the Arabian plate, and Addis Abeba (Ethiopia) on the Nubian plate, span the actively rifting plate boundary zones. The NUVEL1-A model [*DeMets et al.*, 1994] predicts a diverging rate of 16 mm/a along azimuth 29° for Sana'a (Arabia) with respect to Arta (situated on the African plate of this global model), indicated by the arrow in Figure 1. Another recent kinematic model, taking into account the Somalian plate, predicts a similar rate of 17 mm/a along azimuth 030° [*Jestin et al.*, 1994]. *Izzeldin* [1987] observes by seismic, gravimetric and magnetic surveys 17 ± 2 mm/a between the Nubian and the Arabian plates. For the East African Rift zone separating the Nubian and

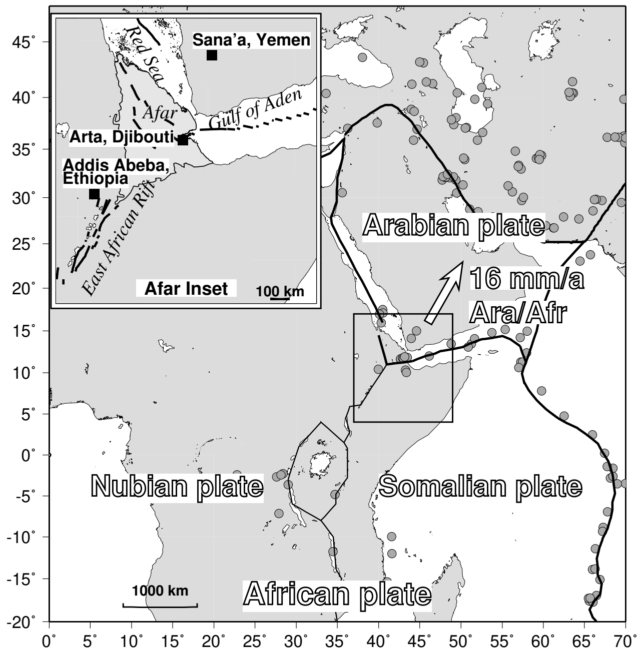

Figure 1. The global tectonic context of the Afar triple junction: the Arabian, Nubian and Somalian plates with their actively spreading plate boundaries, the Red Sea, East African and Gulf of Aden rifts (heavy lines in Afar Inset). Grey dots represent Harvard CMT earthquakes since 1976. Moreover, the predicted spreading rate of the southern Arabian plate with respect to Africa fixed according to NUVEL1-A [*DeMets et al.*, 1994] is indicated by the arrow. Squares in the inset show the major GPS sites of the Afar network presented in this study.

the Somalian plates observed (geodetically) and predicted diverging velocities differ considerably: 1 mm/a [*Asfaw et al.*, 1992] and 5 mm/a [*Jestin et al.*, 1994], respectively.

One must notice that these present-day models are based, as far as rates are concerned, on magnetic anomalies and inversion of seismic data and therefore represent mainly the average motion for the last 2 or 3 Ma. However, tectonic studies of the Afar triple junction in Djibouti and in Yemen [e.g., *Huchon et al.*, 1991; *Manighetti et al.*, 1997] have shown complex interactions of the three rifts forming the Afar triple junction, as well as an episodic nature of rift propagation. The average motions predicted by "geological" instantaneous models provide therefore only boundary conditions

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Table 1. Afar Station Occupation: Antenna Types* and Station Days in Each Campaign

Epoch	Date	SANA	ARO0	LLL0	QQQ0	CBL0	MED0	ADD1
91	Nov.'91	AL 14	AL 24	AL 8	AL 3	AL 4	AL 4	AL 21
93.1	Jan.'93	AP 4	TT 4					
93.2	Apr.'93	AP 6	TT 6					
93.3	Dec.'93	AP 7	AP 7	AP 3				
95	Mar.'95	AL 9	AG 9	AP 2	AP 1	AP 1	AP 5	TT 9

*AL: Ashtech Geod L; AP: Ashtech Geod P; AG: Ashtech Geod III; TT: Trimble SST

Table 2. Mean Repeatabilities for Each Campaign Epoch

	North (mm)	East (mm)	Up (mm)	Length (mm)	ARO0–SANA equipment
91	6.8	16.8	35.0	10.9	both ASH, codeless
93.1	5.6	13.7	18.2	7.9	codeless TRM – P-code ASH
93.2	4.8	12.7	21.3	7.0	codeless TRM – P-code ASH
93.3	3.6	7.9	11.6	3.0	both ASH, P-code
95	3.4	17.1	18.8	10.3	P-code ASH – codeless ASH

for the observation of present-day motions over only some years in the rift zones, where we expect to find also evidence for short-term elastic strain.

Measurement of the Arta-Sana'a baseline has been repeated four times in the 4 years following its initial observation in 1991. The five independent measurements form a time series of the relative station coordinates. An evolution of the baseline components with a non-constant rate was observed. Three stations of the 1991 Djibouti network were re-measured in 1995. This allowed us to identify the motion of the Arta station as the source of the particular baseline development. Moreover, based on these local reference stations we could establish a first estimate of the horizontal rifting rate between the Arabian and the Somalian plates. Addis Abeba was also re-occupied in 1995, which gives a first constraint on the rate of motion across the Ethiopian rift.

Afar GPS observations 1991 - 1995

In our first epoch of Afar observations in 1991 we use data at 7 stations: the five Djiboutian sites ARO0 (Arta), MED0 (Medoc), LLL0 (Grand Bara), QQQ0 and CBL0 (Chabeley), the Yemenite site SANA (Sana'a), and the Ethiopian site ADD1 (Addis Abeba). They represent a subset of the AFAR91 campaign in the area [*Ruegg et al.*, 1993]. The station occupations during the five campaigns until 1995 presented in this paper are shown in Table 1. ARO0 and SANA have been measured in each campaign. In 1995, all stations were re-occupied, including the local tie between Arta and Medoc. The length of single sessions varies from 6 to 24 hours a day. The GPS antenna and receiver type used is Ashtech, except for one Trimble receiver at ARO0 (93.1 and 93.2) and ADD1 (95). For all epochs, the data collection interval was 30 s and the minimum elevation angle 15°.

To help constrain both the local station positions and the adjustment of the GPS satellite orbits we add in our analysis the data from GPS stations belonging to the IGS (International GPS Service for Geodynamics) global tracking network [*Beutler et al.*, 1994]. At epoch 91 we included the fiducial stations Wettzell and Hartebeesthoek. Since 1993 we used stations Wettzell, Hartebeesthoek, Matera, Maspalomas, and Usuda. None of these sites is closer than 3800 km to the local network, which means that intervals of simultaneous recording of the same satellites are short. Therefore, any possible distorsions of the IGS baselines imply only small distorsion of the local Afar network.

GPS data analysis

We analyze our GPS observations session per session with the GAMIT 9.4 software [*King and Bock*, 1993]. The "observable" in the least square analysis is the doubly differenced ionosphere free linear combination (LC) of phase and pseudorange observations. For the campaigns prior to 1 January 1994, precise orbits provided by the IGS were not available. Therefore, for the 91 and 93 campaigns, orbits processed in ITRF91 reference frame [*Boucher and Altamimi*, 1991] by Scripps Institution of Oceanography (SIO) were used as a priori orbits and adjusted in the solution, keeping the fiducial sites heavily constrained to their ITRF91 coordinates.

For the 95 campaign, however, the orbits are fixed to the IGS solution in ITRF93 [*Boucher et al.*, 1993] and coordinates of the fiducial stations are adjusted. The data analysis in a different reference frame in 95 might have introduced a distorsion of the network. The largest difference of the ITRF91 and ITRF93 coordinates for the IGS stations used in our analysis is found for HART, evaluated at the 93.3 epoch to an order of 10 cm. Considering now that HART is one fiducial station out of five establishing the reference frame in 93, that the other IGS stations introduce a clearly smaller error, and taking into account the distance to the local Afar network, the maximum distorsion on the Arta-Sana'a baseline caused by the change of reference frame can be evaluated to a few millimetres. Therefore we do not expect the use of different reference frames to have any significant influence on our results.

The Afar station coordinates themselves are held loosely. Given the high level of ionospheric activity under the magnetic equator, and the mixing of antennas (between Dorne-Margolin antennas at fiducial sites and Ashtech and one Trimble antenna at local sites), the data noise is indeed higher than commonly expected for GPS surveys. Moreover, important P-code data were missing in several epochs at one of the main sites because of the use of a codeless receiver. Therefore, the phase ambiguities cannot be resolved in a satisfying manner to their integer values. So the results presented in this paper are based on the "biases free" solution (apart from a 40 m tie). The precision of the relative station coordinates at a particular epoch is estimated from the repeatabilities (root-mean-square scatter, or dispersion about their mean) of independent daily baseline solutions. The values are summarized in Table 2. Repeatabilities generally improve from 91 to 95, with the exception of the east and the vertical components of the 95 campaign. The latter is due to missing P-code data at Sana'a, one of the most frequently measured sites of the campaign, and mixing of different types of Ashtech antennas. This might cause differential antenna phase center variations, which, however, will be small at least for the horizontal components in the mostly homogeneous regional network, and negligible on the short baselines with identical antennas in Djibouti.

Results

The only baseline measured every campaign (5 times until now) is the 450 km long Arta-Sana'a line which crosses the rift zone of the Gulf of Tadjoura (the western extension of the Gulf of Aden, see Figure 5) in its western part. Figure 2 shows the evolution with time of this baseline. The first obvious structure in the evolution of the north component of this baseline is that the four measurements from 1993 to 1995 can be fitted by a linear trend, but that the first point clearly deviates from this trend. Whether a change of

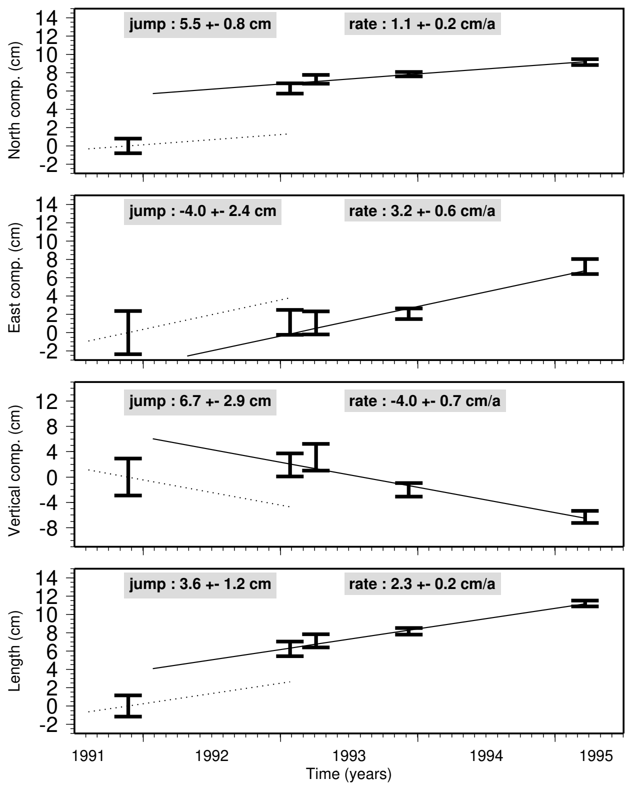

Figure 2. Evolution with time of the Arta-Sana'a baseline. Each box gives a component of the baseline : North, East, Vertical components and Length from top to bottom. Note the different scale for the vertical component. The bars show the weighted mean of all sessions in a given epoch and their uncertainty estimated from their repeatability. The linear trends since epoch 93.1 and their uncertainties as well as the simultaneous estimated offsets between epochs 91 and 93.1 are given in the upper part of each box.

displacement rate or an instantaneous motion occurred cannot be assessed given the uncertainties and the absence of more observations prior to 1993. In any case, we do not suggest a linear evolution over the whole observation time span from 1991 to 1995. We rather estimated simultaneously an offset between the first and the second epoch and a linear rate over the following 4 epochs (still more than a 2-year time span). This leads to a mean rate of 1.1 ± 0.2 cm/a and an offset of 5.5 ± 0.8 cm.

The magnitude of the offset clearly exceeds the measurement uncertainties, especially in the north component and on the total length of the Arta-Sana'a baseline. It is clear that a geophysical interpretation of the non-linear motion relies on the confidence one gives to the first determination of the baseline based on the 91 campaign. There are several error sources for a GPS survey. In this case all of them can be ruled out. The first possibility is a wrong set up of the tripod, or an out of calibration tribrach, leading to a poor centering of the antenna on top of the ground marker. Although 5 cm is a large number for such a "blunder", it could have happened. Fortunately, a local tie to the 40 m distant MED0 site was measured during the 91 campaign, using the untouched antenna set up in Arta. This tie was remeasured in 1995 and shows no significant differences at the millimeter level. Although there are no local ties in Sana'a, an error of the same type can be ruled out, since intermediate baselines from Sana'a to other points of the network (*e.g.* LLL0) show at most only 2 cm of displacement. The second possibility is an erratic motion of the GPS marker (which is set in concrete in Arta and on a stone building in Sana'a) in between the first and the second campaign. This again is excluded by ties or intermediate baselines that are apparently invariant. The third possibility is a systematic effect due to the incomplete GPS constellation and/or the relatively poor precisions of the GPS orbits in 1991. This is the most serious possibility, and some effect at the centimeter level might exist. In order to investigate the influence of random errors, we artificially degraded the orbits and reached a repeatability level of 6 cm. But even then, the mean value of 15 independent daily solutions did not differ more than 4 mm from the original campaign solution. The epochs 91 and 93.1 displaying the offset, and the two following 1993 epochs as well, are calculated in the same ITRF91 reference frame, so that different reference frames can also be ruled out as significant error source. That the abnormal displacement on the Arta-Sana'a baseline is also not due to systematically biased orbital information in this period, is shown by the coherent observations of this displacement (discussed in detail in the following paragraph) on the local baselines in Djibouti, which are with 25 to 40 km length too short to be affected by orbital errors.

Discussion

Once it is firmly established that the Arta-Sana'a line shows a true tectonic signal, the location of the deformation can be determined. Figure 3 shows on the same boxes the time evolution of three short baselines in southern Djibouti. From this figure, it is clear that there is little deformation between the three southernmost stations CBL0, LLL0 and QQQ0, as can be expected from their larger distance to the rift zone. The relative velocities between these stations are 3 mm/a at most on the horizontal components. In contrast, a very large motion of about 4 cm on the North component and 2 - 3 cm on the East component is seen very clearly between Arta on the one hand and CBL0, LLL0 and QQQ0 on the other hand.

Whether this motion happened rapidly during an episode of short duration or is linearly distributed in time is unclear. Two arguments play in favor of an episodic displacement. First, there are no known continuously active tectonic structures which could accommodate 1 – 4 cm/a in between Arta on one side and CBL0, LLL0 and QQQ0 on the other side. Second, the data in Figure 2 suggest by the indicated offsets that one large displacement might have occurred between November 1991 and January 1993, and more linear motions only since then.

The only phenomenon that could have affected Arta's position at that time is the March 5, 1992 earthquake of magnitude M_b = 5.4 (Figure 4). However, a simple model using a semi-infinite elastic half-space yields only mm-level ground displacements at 10 km distance, since Arta is located along the axis and outside of the active fault segment, which is shown by the aligned aftershocks of the March 1992 event in Figure 4. Nevertheless, the displacement of Arta parallel to the fault and aligned with the earthquake focal mechanism, determines the tectonic activity on the left-lateral strike-slip fault as most probable source of its episodic displacement. In the following, we propose some alternative tectonic phenomena which could be the possible cause, however, clear evidence for any of them has not yet been found. First, the earthquake may have triggered a tilting of the block on which Arta is located, inducing a southward displacement of 4 cm. Evidence of local tectonic blocks in the region is given by the geomorphology, *e.g.* by a

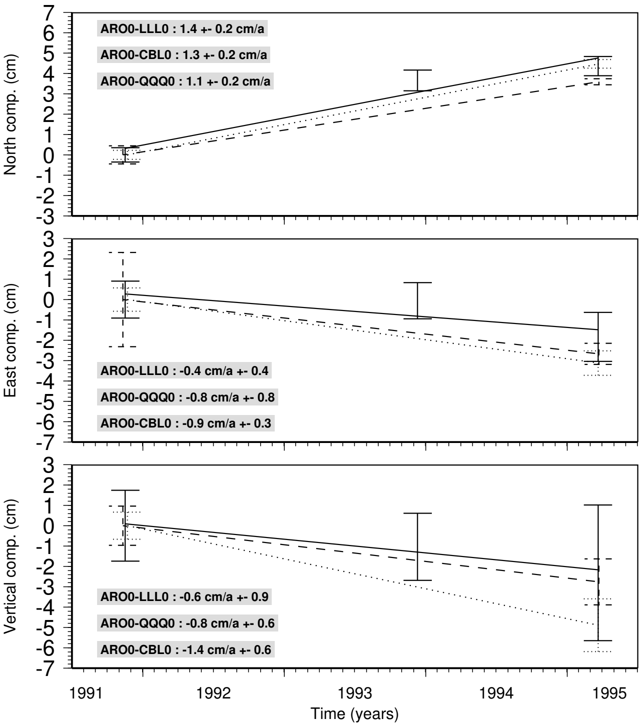

Figure 3. Evolution with time of the local South Djibouti baselines. Solid line Arta-LLL0 (length: 42 km), dashed line Arta-QQQ0 (26 km), dotted line Arta-CBL0 (25 km). Each box gives one of the baselines' North, East and Vertical components (from top to bottom). The error bars show the weighted mean of all the sessions and their uncertainties estimated from their repeatabilities.

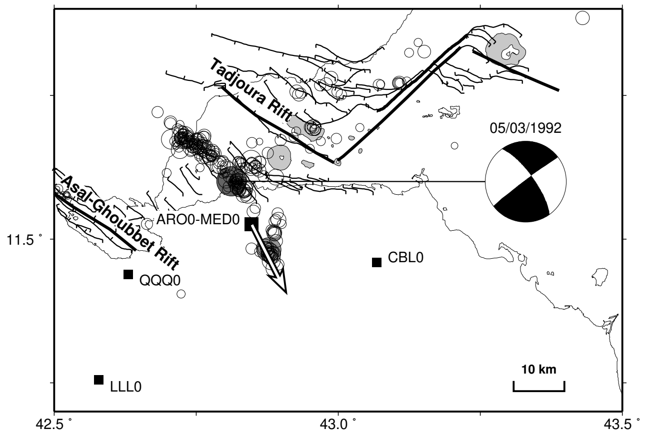

Figure 4. Seismic activity in Northern Djibouti during the 26 days following the master event on March 5th 1992. Locations are from the Geophysical Observatory of Arta [*Omar*, 1994], focal mechanism from Harvard (CMT solution), faults in the Gulf of Tajoura and in the Ghoubbet are from the '95 TADJOURADEN cruise [*Huchon et al.*, 1995; *Manighetti et al.*, 1995]. Thick lines show the principal directions of active rifting and the Maskali transform fault. Significant volcanism is indicated in grey. The arrow shows the direction of ARO0's episodic motion displayed on Figure 5.

cliff close to Arta. Nevertheless, we acknowledge that no geological observations of such a tilting were ever reported from the field examinations after the earthquake. Second, a southeastward displacement could be related with a slipping along the stratigraphic layers beneath the Arta station. These layers show an inclination to the southeast [*Robineau*, 1979]. Third, and most probably, the local tectonic activity is dominated by the overlap zone between the Tadjoura and Asal-Ghoubbet rifts, at the limits of which Arta is located (Figure 4). Therefore, Arta's motion with respect to South Djibouti could be accounted for by the "bookshelf faulting" mechanism which takes place along the normal faults oriented 150° in azimuth with their sinistral slip component [*Tapponnier et al.*, 1990].

Estimates of the station velocities obtained by the measurement campaigns from 1991 to 1995 are shown on Figure 5 with respect to the stable Djibouti block (assuming the average of the displacements of QQQ0, LLL0 and CBL0 to be zero). Displacement rates in this reference frame are summarized in Table 3. The uncertainties, indicated in Figure 5 by error ellipses, are simply set to the campaign repeatabilities (root-mean-square scatter of independent daily solutions in one campaign) of the baseline components divided by the time span. The motion of the principal baseline Djibouti - Sana'a is significantly larger than previous observations and predictions, which are also indicated in Table 3. Nevertheless, it must be noted that the North component corresponds well with the tectonic models. Cause for this overestimation is the East component, which is less constrained by GPS measurements than the North component. The uncertainties of the Addis - Djibouti baseline rates are still too high to resolve the predicted small relative motion between the Nubian and the Somalian plate. The extension of the observation span by a next measurement campaign will provide the first significant displacement rates between the two plates. The most precisely determined quantity representing velocities is the rate of change in baseline length over the longest interval (between epochs 91 and 95) with respect to the most frequently measured station, SANA. These values are also shown in Table 3. The total increase of the baselines relating SANA to Addis and stable Djibouti is clearly higher than expected according to tectonic models, but a differential motion of the Nubian and the Somalian plate is still not resolved. The episodic motion of the Arta block increasing the displacement rate is displayed consistently by ARO0 and MED0 even on this long baseline.

The planned reoccupation of the whole AFAR 91 network in 1998/99 will help to better constrain the motions, and especially improve the east component repeatability.

Conclusion

The high uncertainties (of the order of 1 cm/a) obtained for the velocities show the difficulty of the measurements of a very much reduced network following the extensive AFAR91 campaign. The use of different receivers and antennas, the fact that only a few points are measured for each of the later "campaigns", the short duration of some station occupations (a few hours only) and small numbers of independent sessions (sometimes just one) on individual points, represent the worst condition for precise GPS geodesy. Therefore, only rough numbers can be inferred from such measurements and many questions remain unanswered. Nevertheless, initial estimates are produced. It is clear that the opening of the Afar triple junction yields at least the theoretical estimate of 16 mm/a between Yemen and Djibouti. Observed changes in baseline length (the most sensitive quantity in the GPS data analysis) evaluate a spreading of 21 ± 1 mm/a between stable South Djibouti and Yemen, and of 24 ± 9 mm/a between Ethiopia and Yemen. The overestimation seems to be related in particular to problems de-

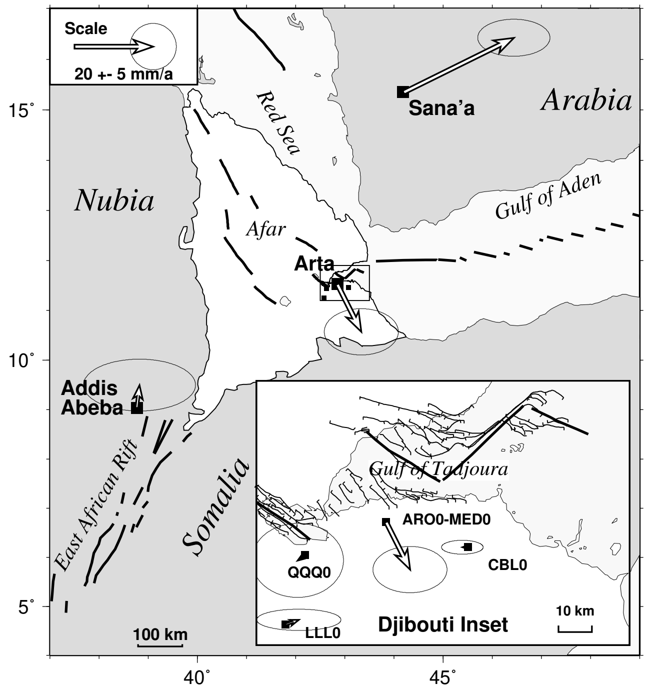

Figure 5. Velocities of the Afar stations observed between 1991 and 1995. Reference are the stable stations in south Djibouti, see details in Djibouti inset. The 1-σ error ellipses are based on the repeatabilities of the North and East components divided by the observation time span. The bold lines indicate roughly the rift axes.

Table 3. Displacement Rates Relative to Djibouti and Baseline Changes with Respect to SANA.

Site	North, mm/a	East, mm/a	Author	baseline length w.r.t. SANA, mm/a
SANA	14 ± 4	28 ± 8		–
pred.	14	8	*DeMets et al.* [1994]	
ADD1	6 ± 6	1 ± 12		24 ± 9
obs.	1 (total vel.)		*Asfaw et al.* [1992]	
pred.	5 (total vel.)		*Jestin et al.* [1994]	
ARO0*	-12 ± 5	6 ± 8		34 ± 4
MED0*	-16 ± 4	7 ± 13		36 ± 4
CBL0*	0 ± 2	-2 ± 5		22 ± 1
QQQ0*	-1 ± 8	-2 ± 10		
LLL0*	1 ± 2	3 ± 9		21 ± 1

Station velocities from the 91 to 95 Afar GPS campaigns, with uncertainties based on campaign repeatabilities. For comparison are given corresponding velocities predicted by different tectonic models. As most precise result are displayed baseline changes over the longest observation period with respect to SANA.

*Theoretically immobile on Djibouti block as chosen reference frame

termining the East component of the baselines, due to the use of codeless receivers and antenna mixing prohibiting the resolution of phase ambiguities. While the North component of the SANA velocity with respect to Djibouti shows with 14 ± 4 mm/a a very good agreement with the NUVEL1-A prediction at 14 mm/a, the East component is evaluated to 28 ± 8 mm/a, compared to predicted 8 mm/a.

The time series of five measurement campaigns clearly demonstrate that the station of Arta was affected, and may still be affected by short term tectonic phenomena. The large differential velocity of this station with respect to the rest of the "stable" Djiboutian block is clear. This is evidence of Arta being situated in the deformed rift zone, and not in the rigid part of the African plate (more precisely, of the Somalian plate). The origin of such anomalous motion remains largely unknown, but may be related to the overlap zone between the Tadjoura and Asal-Ghoubbet rifts, as shown by the seismicity and described by recent tectonic models [*Manighetti et al.*, 1997]. The quantification of the episodic Arta displacement by our GPS measurements is a new and highly relevant information to constrain geodynamic models of the Afar region.

Perspectives

It is expected that the next measurement of the full AFAR91 network, at least 7 years after the first epoch observations and with millimeter level precision, enables us to properly address the question of decade-scale kinematics of the plates surrounding the Afar triple junction. Combined with the observation results presented in this study, we will be able to clarify the kinematic interaction of the tectonics in the overlap zone with the Arta block and refine the knowledge of the complex tectonic mechanism *e.g.* by testing models of block rotation in Djibouti.

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