Insights on the Fort Davis - Mc Donald Site Stability : a GPS Footprint

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ABSTRACT

In june 1990, NASA's Crustal Dynamics Project (CDP) has established a geodetic footprint for the Satellite Laser Ranging (SLR) and Very Long Baseline Interferometry (VLBI) systems located near Fort Davis, Texas using GPS measurements. The purpose of such a footprint is to assess both the tectonic and physical stability of the main observing monuments. Included in the survey were four new monuments forming a 20 to 30 km quadrilateral, as well as four existing monuments near the McDonald Laser Ranging System (MLRS), the Harvard Radio Astronomy (HRA) 85' antenna, and the new 85' antenna of the Very Long Baseline Array (VLBA). This network was partly reoccupied by the University of Texas Austin in may 1992. Three additional sites not observed in 1990 were occupied, two of them being old monuments in the observatory area (Harvard-RM4 and VLBA-SLR), and a new monument 80 km away across the closest active fault near Valentine, Texas. Thanks to existing ties between nearby monuments in the observatory area, the comparison between the two epochs was made possible. Significant motion of more than 1 cm of any of the implied sites over a two year period can be ruled out. Despite this quite reassuring results, smaller displacements cannot be detected mainly because of the poor quality of the 1990 data. Therefore it is strongly advised that a third occupation of the footprint sites takes place in the close future. Such a survey, occuring five years after the first one and three years after the second one, should definitely answer the questions on the Fort Davis area stability at the millimeter per year level.

INTRODUCTION

The Fort Davis - McDonald observatory is located approximately 180 miles southwest of El Paso, Texas on the southern edge of the Fort Davis mountains and 8 miles northwest of the town of Fort Davis. With the 2.7-meter telescope, This site includes many different instruments and positioning systems. Among those are the McDonald Laser Ranging System (MLRS), the 26-meter polaris antenna of the Harvard Radio Astronomy system (HRAS 085) operational until 1991, and the new Very Long Baseline Array (VLBA) antenna. A new pad for the MLRS and a guest mobile laser pad (TLRS) have been constructed since then. A permanent GPS receiver was installed in 1993. The observatory is then quite important for measurements supporting the determination of plate motions, polar motion and Earth rotation, regional deformation, and intercomparison of measurement techniques. As a consequence, it was decided to ascertain the stability of the observatory different monuments using GPS measurements. A first survey was conducted in 1990, and some of the sites observed during this survey were reoccupied two years later. Here I report on the comparison between those two epochs, and on the site motions inferred from this comparison.

Figure 1 shows the networks observed in 1990 and 1992, along with the fiducial network of three north american CIGNET stations (Mojave, California; Richmond, Florida; and Westford, Massachusetts) used in the data analysis to compute precise orbits. The particular design of the footprint network in two distinct sets of monuments is aimed at two different goals. One goal is to be able to detect physical motions of the observatory sites. Such motions would be due to unstable benchmarks, either deformation of concrete pillars or pavements. For this particular purpose one needs to monitor distances between all the implied monuments. The second goal is to detect local tectonic motions which would affect all of the Fort Davis monuments, and decorelate the local measurements from the regional tectonic. For this goal, one needs to install a set of monuments around the observatory area, distant from 10 to 100 km from one to each other.

Surveys

The 1990 survey took place between June 7th and June 20th spanning 14 days of 7 hours measurements. Four dual frequency Trimble SST were used simultaneously, leading to the measurement of 20 out of the possible 28 baselines. Baselines between the four new furthermost monuments were measured 8 times. Other baselines linking the inside monuments to each other or to the set of remote sites were measured only two or three times.

The 1992 survey took place between May 17th and May 21st spanning only 4 days. Again, four dual frequency Trimble SST were used. The increased number of satellites in the GPS constellation (17 in May 92 compared to 8 in June 90), allowed shorter observing sessions which enabled the field team to carry out two sessions per day. For this experiment, the TLRS/VLBI guest pad at McDonald(NASA's monument 7850, named TX10 VLBA-SLR here) was chosen as a reference station and occupied most of the time. Because of the lack of time, 3 out of the 4 inner sites of the first experiment were not reoccupied.

Table 1 summerizes the actual number of usable baseline measurements, both in 1990 and 1992. The upper right triangle is for the 1990 survey, and the lower left triangle is for the 1992 survey. A zero indicates the particular baseline was not measured during the survey, and an empty line or column indicates the corresponding site was not occupied during the survey. The large number of empty boxes could generate some anxiety on our ability to compare the two surveys, but thanks to a couple of existing ties between nearby observatory monuments, the task does not turn out to be an impossible one.

DATA ANALYSIS

As a first try, the 1990 Fort Davis data have been examined closely in an intercomparison of several analysis techniques (Bell et al., 1991). The data were processed using both the NGS software OMNI and MIT's GAMIT (King and Bock, 1991), using independent editing and different orbital models. The basic outcome of these processings was that the quality of the data was poor. Because of that, resolving phase ambiguities was not attempted at the time, and the comparison was carried out only on "bias-free" solutions. The repeatabilities of the individual solutions were barely sub-centimetric, and this was only obtained by eliminating 3 or 4 outlier days of data from the global combinations. Such a necessity would of course weaken the solutions and lead to higher discrepancies between the OMNI and the GAMIT solutions. Those discrepancies would be as high as 2 to 3 cm for the horizontal baseline components, and 10 cm for the vertical components. Some background information on the 1990 Fort Davis survey itself may explain part of the poor quality of the data. This survey was the first GPS survey conducted by GSFC's Crustal Dynamics Project. The post-fit residual plot shown on figure 2, illustrate a random multipath signature from day to day across the network. This signature does not repeat itself in the same way from day to day, nor does it appear at the same station day after day. This phenomenon may be due to early survey techniques.

Since 1991, a lot of additional work was done on the Fort Davis data set, and it became clear that, as shown by figure 2, mostly low elevation data were affected by multipath. The data analysis was then continued with the GAMIT software, and different solutions were computed with different elevation angle cutoffs. In those solutions, both station positions and satellite orbital parameters are estimated. In order to estimate precise orbits, data from the three CIGNET stations described earlier are merged with the footprint data. No field meteorological data were available to compute troposphere induced propagation delays, but instead the data themselves are used to estimate one "atmospheric parameter" per session. Figure 3 shows the mean repeatability of each of those solutions, plotted agains the elevation angle cutoff. This mean repeatability is simply the mean of the individual baselines repeatabilities, and is computed for the three baseline components (north, east, and vertical) and for the two kinds of computed solutions (bias-free and bias-fixed, i.e. unresolved and resolved phase ambiguities). For "bias-free" solutions (open symbols), the general tendency is that the higher the elevation angle cutoff, the worse the repeatabilities. The latter is particularly true for the vertical components, and is of course due to the fact that for increased elevation angle cutoff, less and less data are taken into account in the solutions. The pattern is quite different for "bias-fixed" solutions (full symbols), where the unweighting of doubtful data leads to a better bias fixing. This is particularly obvious for the east baseline components for an elevation angle cutoff of 25 degrees. For that particular value, the mean repeatability is divided by a factor of two compared to the value obtained with an elevation angle cutoff of 5 degrees less. It is also remarquable that the improvement of the horizontal component repeatabilities when phase ambiguities are resolved, is obtained against the degradation of the vertical component repeatabilities. the latter leads us to conclude that a certain number of unmodeled parameters are still acting in the solutions. Their effects mostly affect the vertical components when strengthening the horizontal components to their real values. In the following, I will then focus on the horizontal components, assuming that the vertical components have little or no significance in this analysing scheme.

Figure 4 shows the repeatabilities (i.e. the weighted root mean square scatter of the independent daily solutions about their weighted mean) plotted against baseline length. Those repeatabilities are obtained with an elevation angle cutoff of 25 degrees, for which the "bias-fixing" scheme works best. The horizontal components don't show a significant trend of higher scatter for longer baselines, indicating that orbits are correctly re-estimated, thanks to the fiducial network. As expected, the improvement due to "bias-fixing" clearly appears on both horizontal components, and is particularly dramatic on the east component for almost all the baselines. Most of the baselines now show acceptable horizontal repeatability, below the centimeter level.

Happily enough, the 1992 data were of much better quality. The same processing scheme was applied and the repeatabilities depicted by figure 5 show more acceptable patterns. Again orbits are correctly re estimated and the horizontal components don't show any trend with the baseline lengths. The two longest baselines between 70 and 80 km correspond to the remote Valentine station and are not used in the footprint analysis but demonstrate the good quality of the solutions. When phase ambiguities are resolved, the horizontal repeatabilities fall below 5 mm for all baselines, and reach 2 or 3 millimiter for most of them. Although an independent analysis was again carried out at University of Texas, Austin with their MSODP software (Gutierrez, 1993), no intercomparison was done. Only a partial comparison of the lengths of some baselines measured both in 1990 and 1992 was possible. This was due to orientation problems due to different reference frames used in the 1992 MSODP and the 1990 OMNI and GAMIT solutions. The small number of common baselines in the 1990 and 1992 surveys increased this problem by the obligation of using external ties with the possibility of introducing orientation errors again.

RESULTS

Because they are now processed with the same software, the two epochs of the Fort Davis footprint can be easely compared. The output of the single-day GAMIT solutions are parameter adjustments and variance-covariance matrices. Those can be combined for the full duration of both experiments using a Kalman Filter Program GLOBK (Herring, 1991). The output of this global solution is then a set of site coordinates and velocities, consistent for the network over the full time span. Of course, because of their better quality, the "bias-fixed" daily solutions are used in the combination. In this global analysis, the reference system is defined by fixing TX10 VLBA-SLR (CDP 7850) coordinates to its ITRF91 value and constraining the coordinates of the CIGNET sites to their ITRF91 values within 5 cm in latitude and longitude, and 10 cm in height. Two ties are also imposed on the solution, in order to link between them nearby monuments observed during only one of the two surveys. TX01 MLRS-TLRS (CDP 7088) observed in 1990 is tied to TX10 VLBA-SLR observed in 1992, and therefore also fixed in the solution. TX02 VLBA-RM1 observed in 1990 is tied to TX11 HARV-RM4 observed in 1992, and therefore the two sites show the same velocity.

The heavy arrows depicted on Figure 6 map the velocity pattern obtained by this solution. Their associated ellipses show the 95% confidence level of their uncertainties. The first important result is that all the observed velocities are below 5 mm/yr. The second result is that, although no clear deformation of any tectonic style can be associated to the velocity pattern, a clockwise rotation of 3 out of the 4 remote sites is clearly visible. The solid rotation that best fits this velocity pattern is one of $1.7\ 10^{-7}$ rad/yr, centered at TX10 VLBA-SLR. The velocities generated at all sites by such a solid rotation are depicted by the thin solid lines. The residual velocities, computed from the observed velocities minus the solid rotation velocities, are depicted by the light arrows with their corresponding uncertainty ellipses. The residual velocity field has an amplitude reduced by a factor of two with respect to the observed velocity field. More important, most of the residual velocities are inside their 95% confidence ellipses, which indicates that very little significant motions remain. Whether this solid rotation is real or not is difficult to assess at that point. This rotation generates site motions of about 3 to 5 millimeters per year which is around the limit of the intrinsic significance of the data. Such a rotation could probably arise from fiducial coordinate inconsistencies, but the amplitude found here would yield metric velocities or coordinate adjustments at the distance of the fiducial stations. Such large numbers are not observed, and the fiducial coordinate adjustments required by the solution remain under the 5 cm a priori constrain.

CONCLUSIONS

Despite the large uncertainties mainly due to the poor quality of the 1990 data and the small number of common sites occupied during the two surveys, some firm conclusions can be drawned. No horizontal site motion significantly larger than one centimeter has been detected. Over a two year period, this leads to velocities not larger than 5 mm/yr at all sites. The latter is an important result, given the number of measurements taken at the Fort Davis observatory which rely on the stability of both the instrument monuments and the local area. However, a small solid rotation of 0.17 mrad/yr around the central sites TX01 and TX10 can be detected at the limit of the data noise. A third occupation of the footprint sites is therefore recommended in order to confirm the stability of the monuments and to investigate the question of the site rotation. It is also recommended that all the sites occupied in 1990 (especially those not occupied in 1992, TX07 and TX08) are measured during this survey. The improvement of the GPS surveys to the millimeter precision, already visible from 1990 to 1992, should make this third survey very advantageous, five years after the first one.

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Herring T., GLOBK: Global Kalman Filter VLBI and GPS Analysis Program, *Internal Publication*, 1991.

Bell L., G. Mader, M. Schenewerk, C. Vigny, R. King, B. Schutz, C. Wilson, M. Bryant, E. Pavlis, and V. Nelson, Precision of the 1990 Fort Davis site stability survey, *EOS, trans AGU*, 1991.

Gutierrez R., C. Wilson, and B. Schutz, West Texas FLINN Site: Comparison of OMNI, GAMIT, and MSODP Baseline Solutions for the 1990 and 1992 GPS Footprint Occupations, *EOS, trans AGU*, 1993.

Fig. 1. Fort Davis footprint. Figure 1a shows the 1990 survey, figure 1b shows the 1992 survey. Figure 1c shows the fiducial network used in both data analysis. In the footprint network, baselines run from 800 m to 50 km.

Fig. 2. Evidence for multipath at low elevation angles. The upper box shows the behaviour of the doubly differenced Lc phase as a function of time. Residuals between measured and modeled phases are plotted against time every 30 seconds (sampling rate of the receiver). The lower box shows the corresponding satellite elevations at the same time. Higher level of noise and quick drift from one epoch to another at low elevation angle are a clear evidence for multipath.

Fig. 3. 1990 repeatability vs. elevation angle cutoff. The mean repeatability over all the measured baselines is plotted against the elevation angle cutoff (from 15 to 45 degrees). The full symbols are for the resolved ambiguities solutions (bias-fixed) and the open symbols are for the non resolved ambiguities solutions (bias-free). Squares are for the north component, diamonds for the east component, and circles for the vertical components of the baselines. A clear drop of the bias-fixed East component repeatability (black diamond) is noticeable at 25 degrees.

Fig. 4. 1990 repeatability. The weighted root mean square scatter of the daily solutions about the mean values of each baselines are plotted against the length of the corresponding baseline. Fig 4a depicts the bias-free solution (i.e. the phase ambiguities are not resolved). Fig 4b depicts the bias-fixed solution (i.e. phase ambiguities are fixed to integer values). In both figures, the upper box is for the north component, the middle box for the east component, and the lower box for the vertical component. Here the elevation angle cutoff is 25 degrees.

Fig. 5. 1992 repeatability. The weighted root mean square scatter of the daily solutions about the mean values of each baselines are plotted against the length of the corresponding baseline. Fig 5a depicts the bias-free solution (i.e. the phase ambiguities are not resolved). Fig 5b depicts the bias-fixed solution (i.e. phase ambiguities are fixed to integer values). In both figures, the upper box is for the north component, the middle box for the east component, and the lower box for the vertical component.

Fig. 6. 1992-1990 inferred site velocities. The arrows show the velocities computed with respect to site TX10 VLBA-SLR which is hold fixed in the analysis. TX01 MLRS-TLRS is tied to TX10 VLBA-SLR and has a null velocity. TX02 VLBA-RM1 is tied to TX11 HARV-RM4 and has the same velocity. TX07 MCDO-RM4 and TX08 FTDV-RM5 were not remeasured in 1992 and are not shown here. The heavy arrows show the observed velocities and the ellipses centered on the site coordinates show the 95% confidence level of their uncertainties. The solid bars show the velocities computed at the corresponding sites due to a solid rotation of 1.7 10^{-7} rad/yr which best fits the velocity pattern. The light arrows show the residual velocities.

Table 1. Site occupation table. Each box contains the number of independent measurements made on the corresponding baseline. the "above diagonal" numbers are for the 1990 experiment (14 days - 4 receivers), and the "below diagonal" numbers are for the 1992 experiment(4 days - 4 receivers). An empty line or column means the corresponding site was not occupied during the given survey.

Table 1. Observed Baselines (1990 - 1992)

92↘**90**	TX01	TX02	TX03	TX04	TX05	TX06	TX07	TX08	TX09	TX10	TX11
TX01		2	2	3	2	2	2	2		tie	
TX02			3	3	3	3	2	2			tie
TX03		1		8	7	7	0	0			
TX04		1	3		8	8	0	0			
TX05		2	1	1		7	0	0			
TX06		2	1	1	3		0	0			
TX07								2			
TX08											
TX09		0	0	0	0	0					
TX10	tie	2	3	3	3	3			3		
TX11		tie	0	0	0	0			2	2	

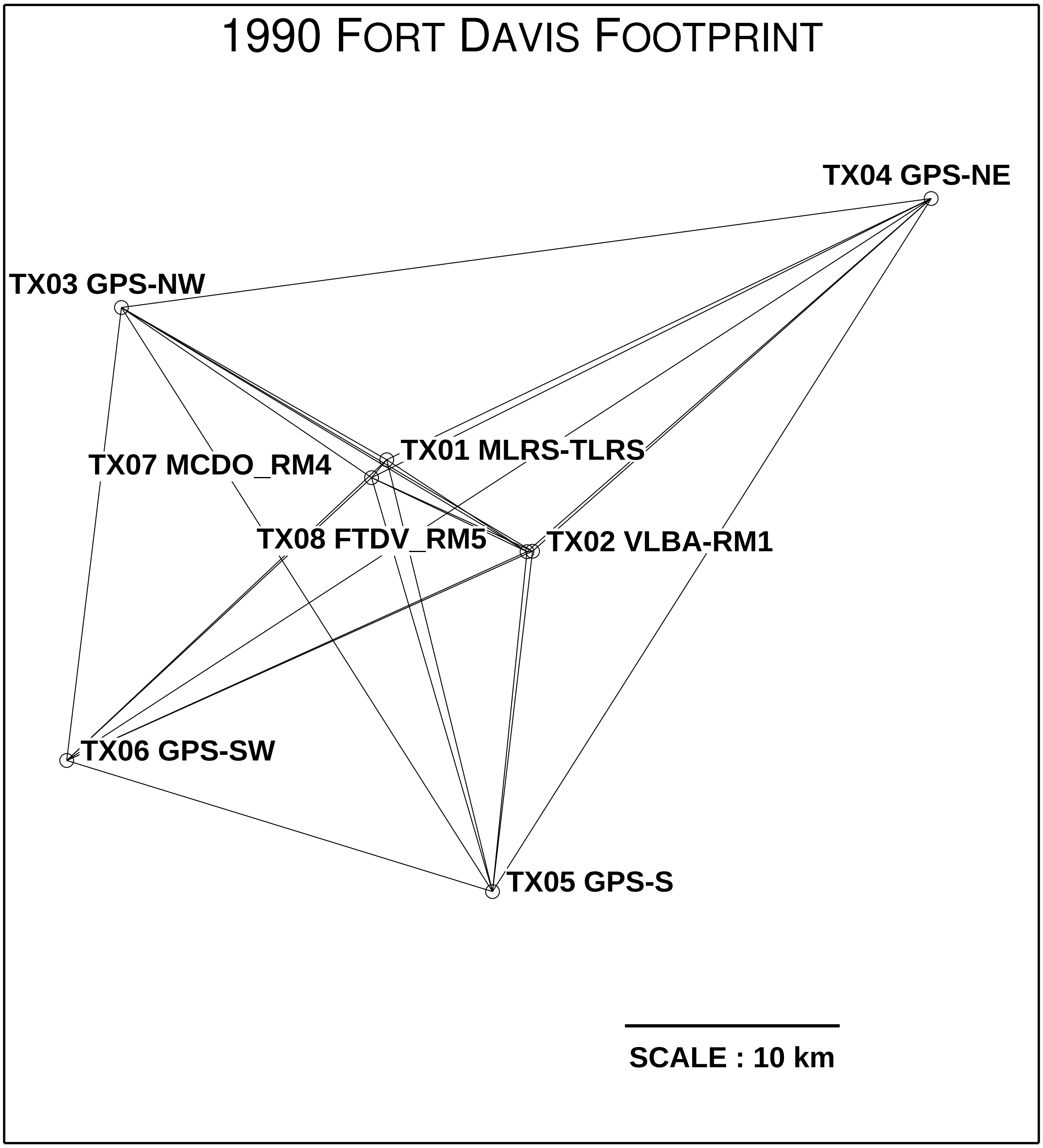
1990 FORT DAVIS FOOTPRINT
TX04 GPS-NE
TX03 GPS-NW
TX01 MLRS-TLRS
TX07 MCDO_RM4
TX08 FTDV_RM5
TX02 VLBA-RM1
TX06 GPS-SW
TX05 GPS-S
SCALE : 10 km

Figure 1a

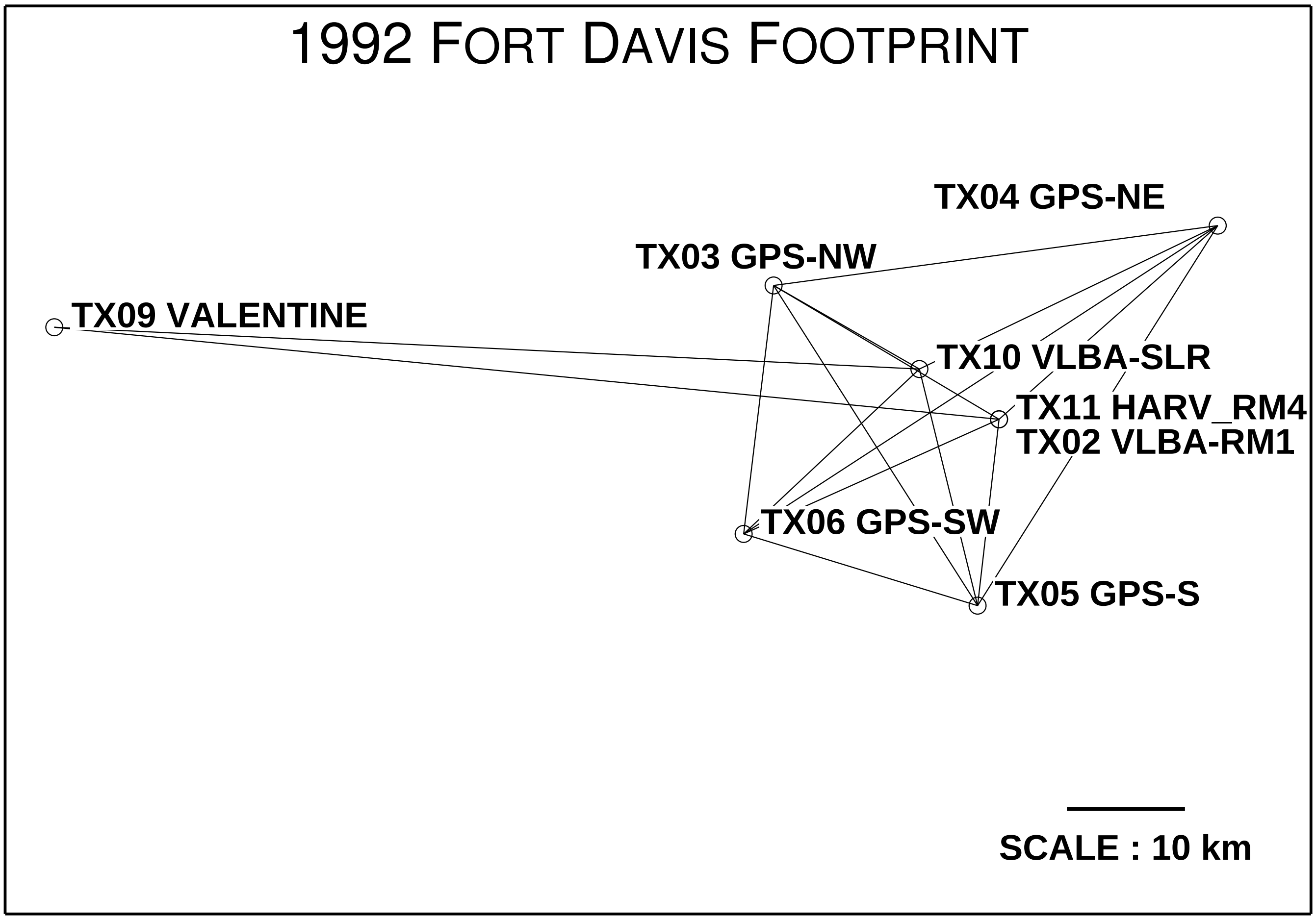
1992 FORT DAVIS FOOTPRINT
TX04 GPS-NE
TX03 GPS-NW
TX09 VALENTINE
TX10 VLBA-SLR
TX11 HARV_RM4
TX02 VLBA-RM1
TX06 GPS-SW
TX05 GPS-S
SCALE : 10 km

Figure 1b

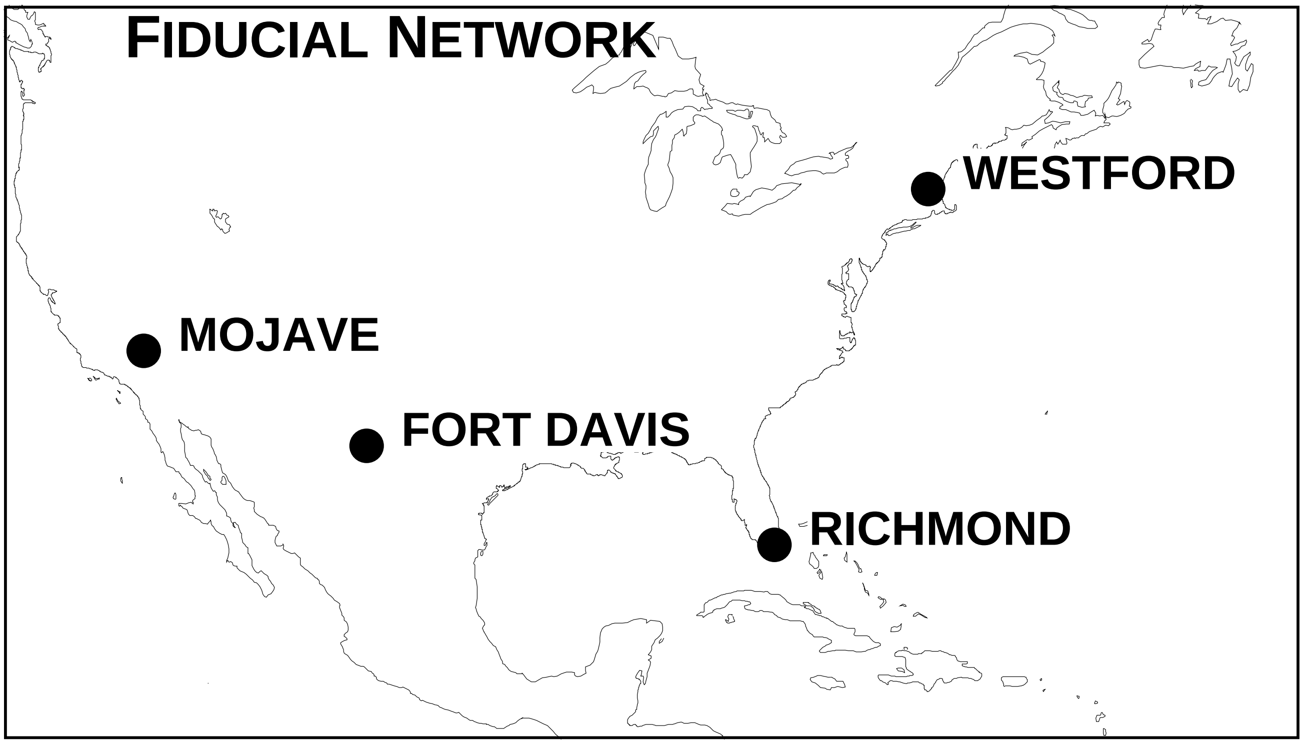

Figure 1c

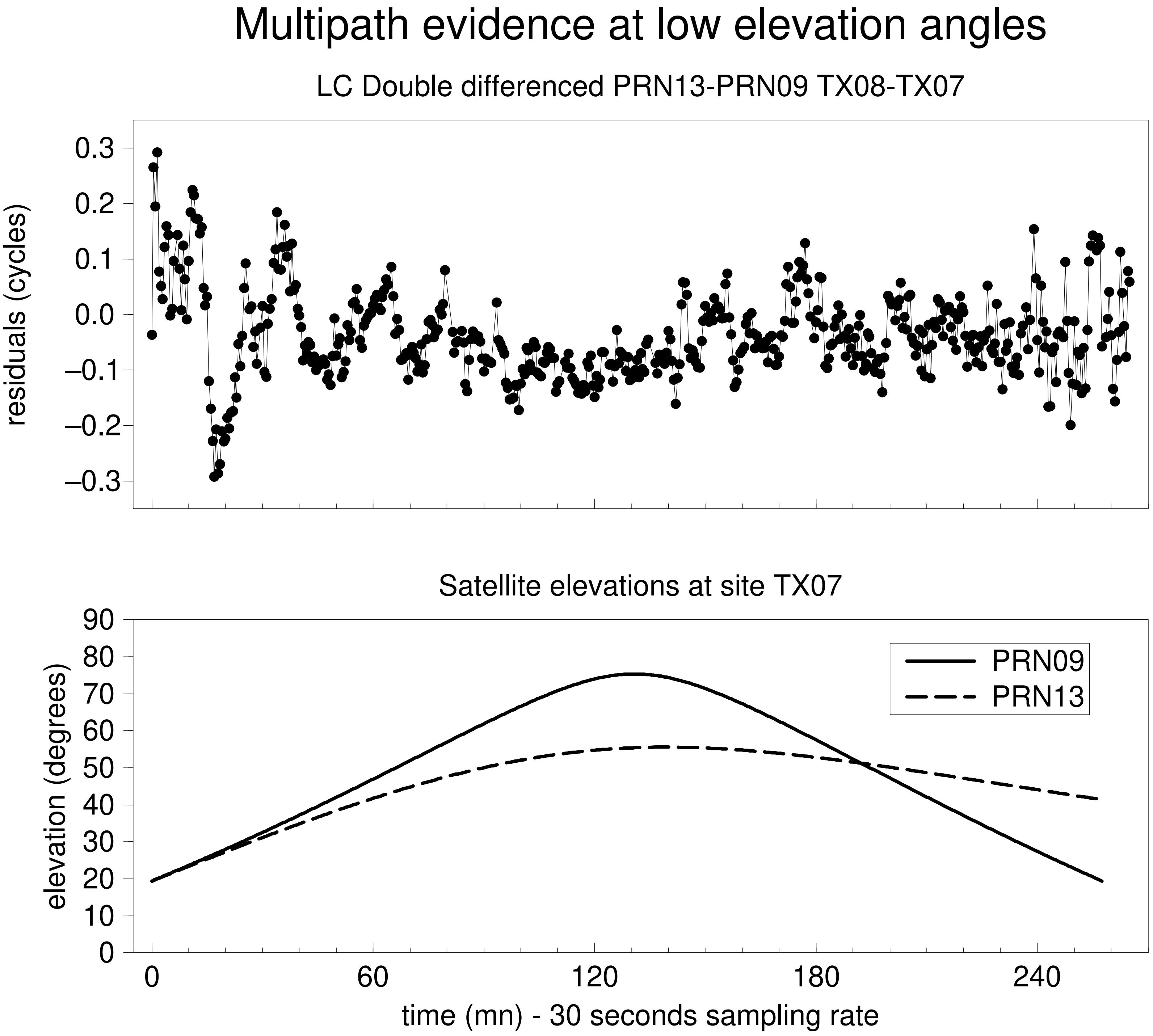
Multipath evidence at low elevation angles
LC Double differenced PRN13-PRN09 TX08-TX07
residuals (cycles)
0.3
0.2
0.1
0.0
–0.1
–0.2
–0.3
Satellite elevations at site TX07
elevation (degrees)
90
80
70
60
50
40
30
20
10
0
PRN09
PRN13
0
60
120
180
240
time (mn) - 30 seconds sampling rate

Figure 2

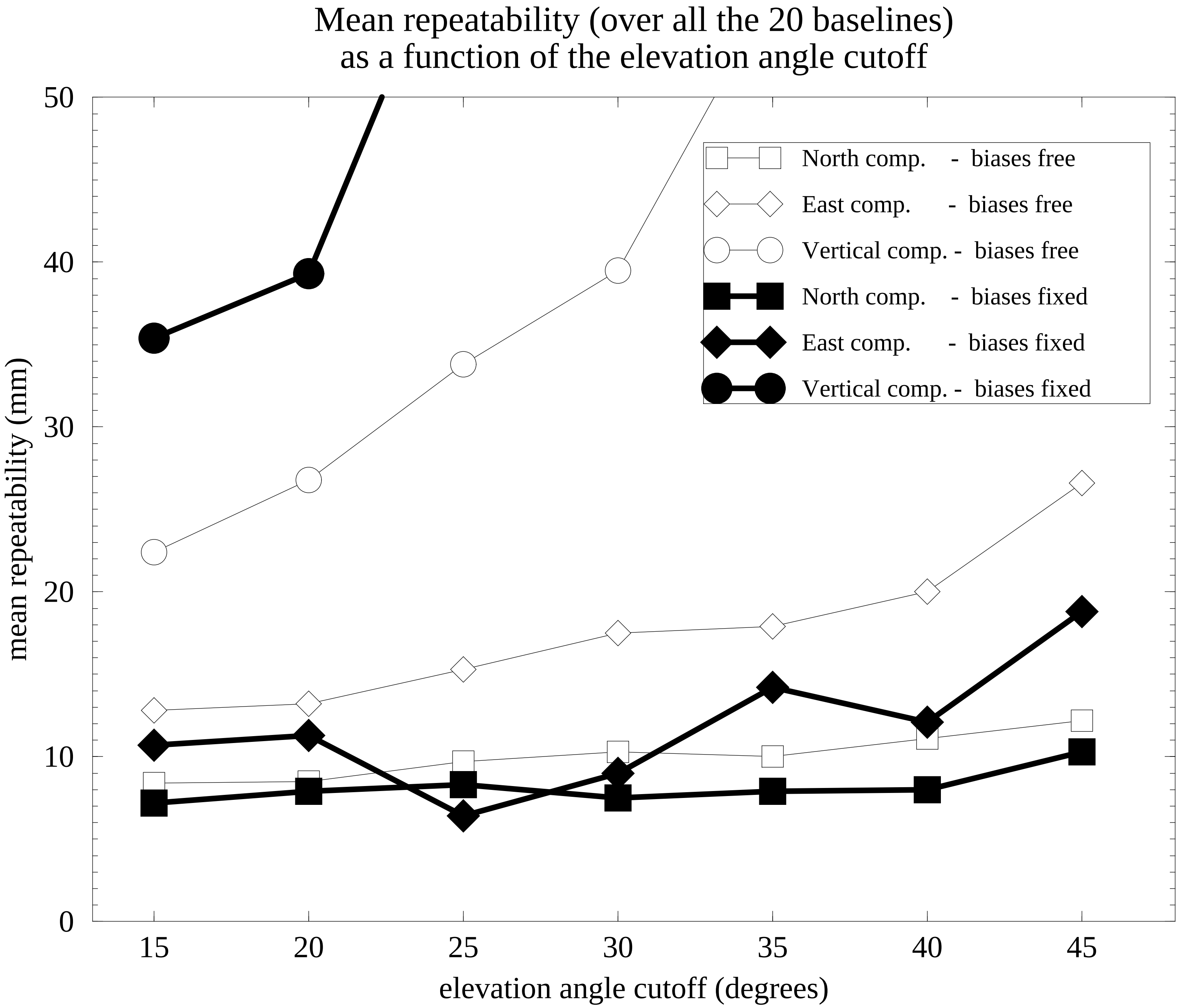
Mean repeatability (over all the 20 baselines)
as a function of the elevation angle cutoff
mean repeatability (mm)
0
10
20
30
40
50
15
20
25
30
35
40
45
elevation angle cutoff (degrees)
North comp. - biases free
East comp. - biases free
Vertical comp. - biases free
North comp. - biases fixed
East comp. - biases fixed
Vertical comp. - biases fixed

Figure 3

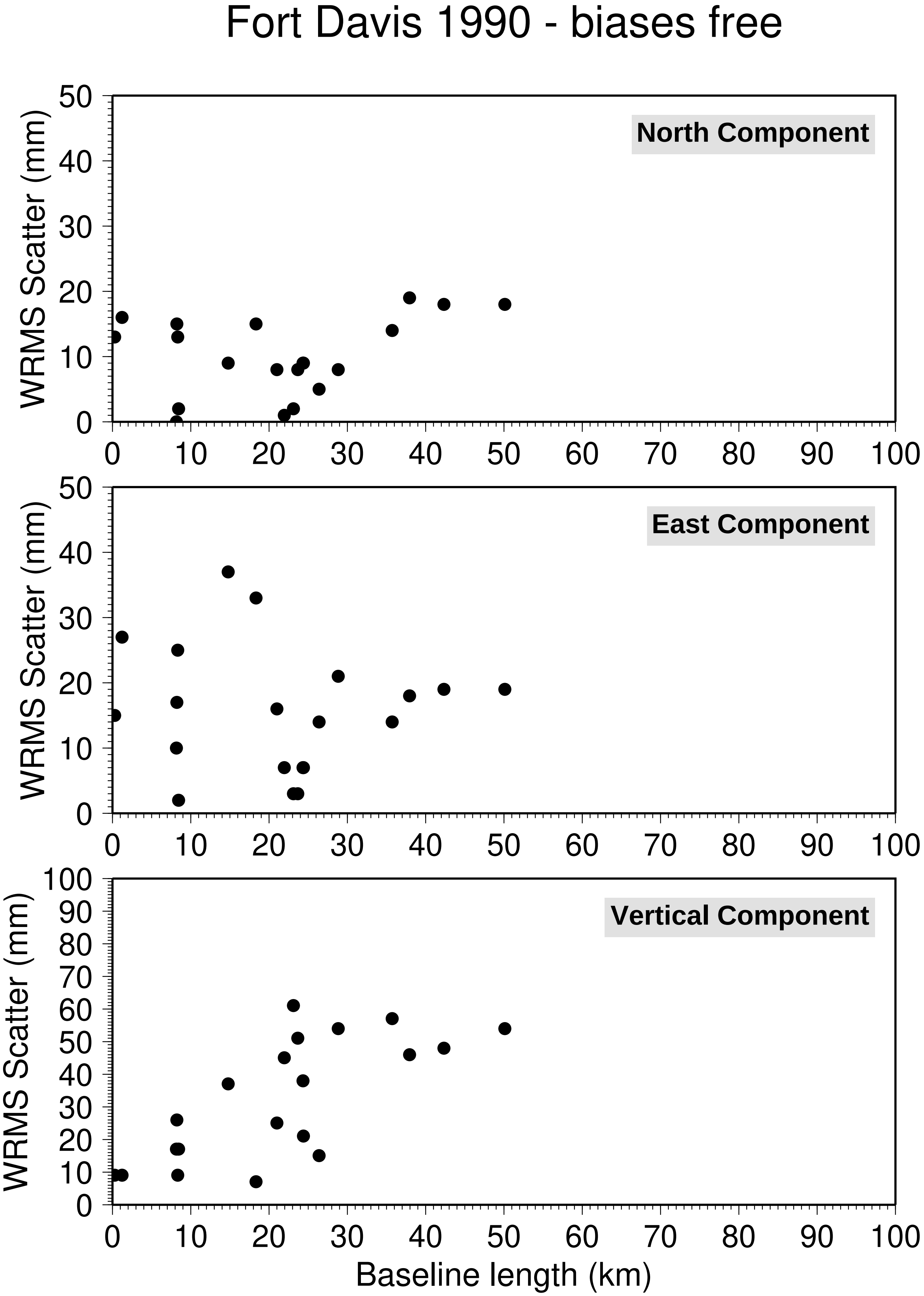
Fort Davis 1990 - biases free
North Component
East Component
Vertical Component
WRMS Scatter (mm)
Baseline length (km)
0
10
20
30
40
50
60
70
80
90
100

Figure 4a

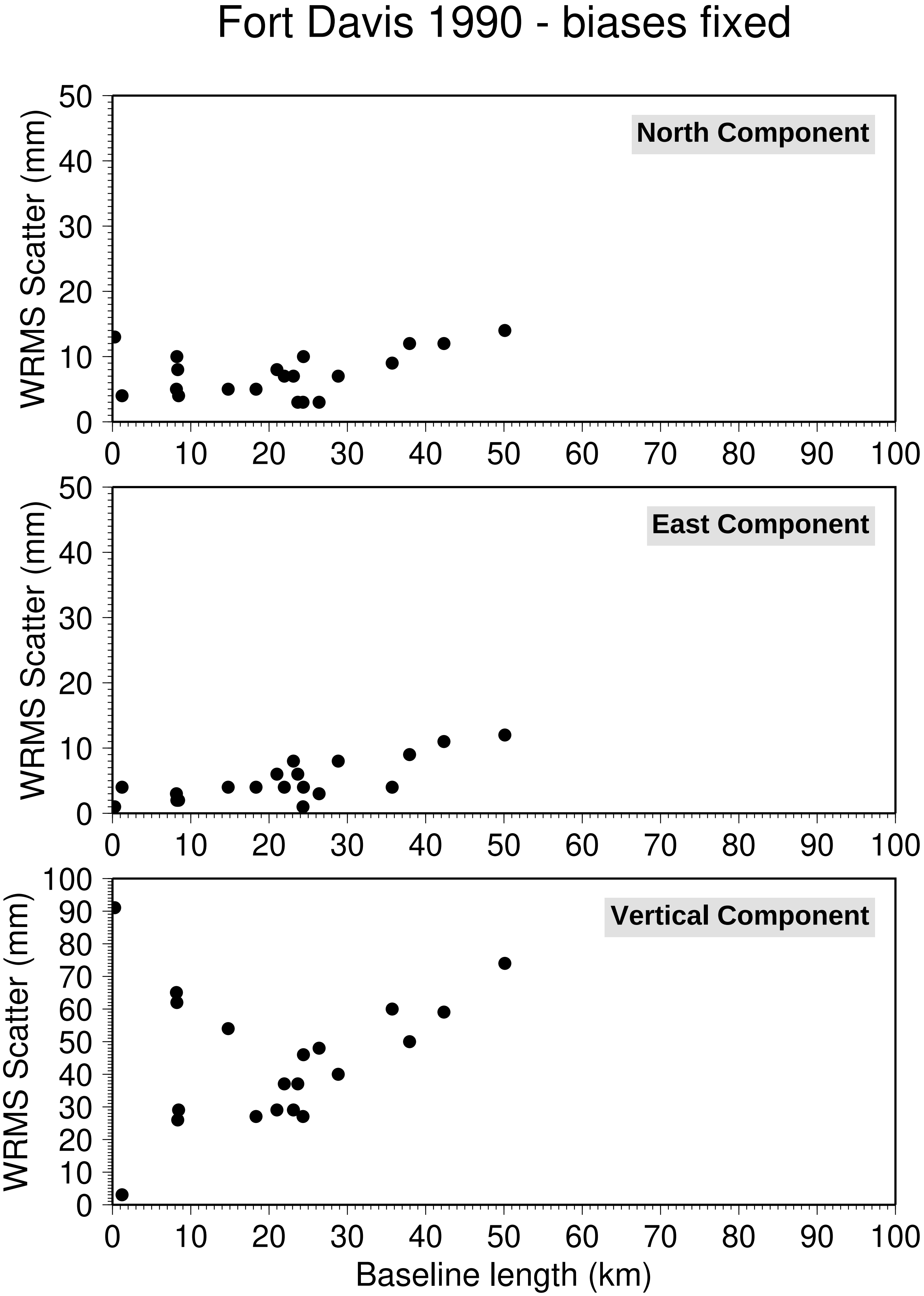Fort Davis 1990 - biases fixed
North Component
East Component
Vertical Component
WRMS Scatter (mm)
Baseline length (km)
0
10
20
30
40
50
60
70
80
90
100

Figure 4b

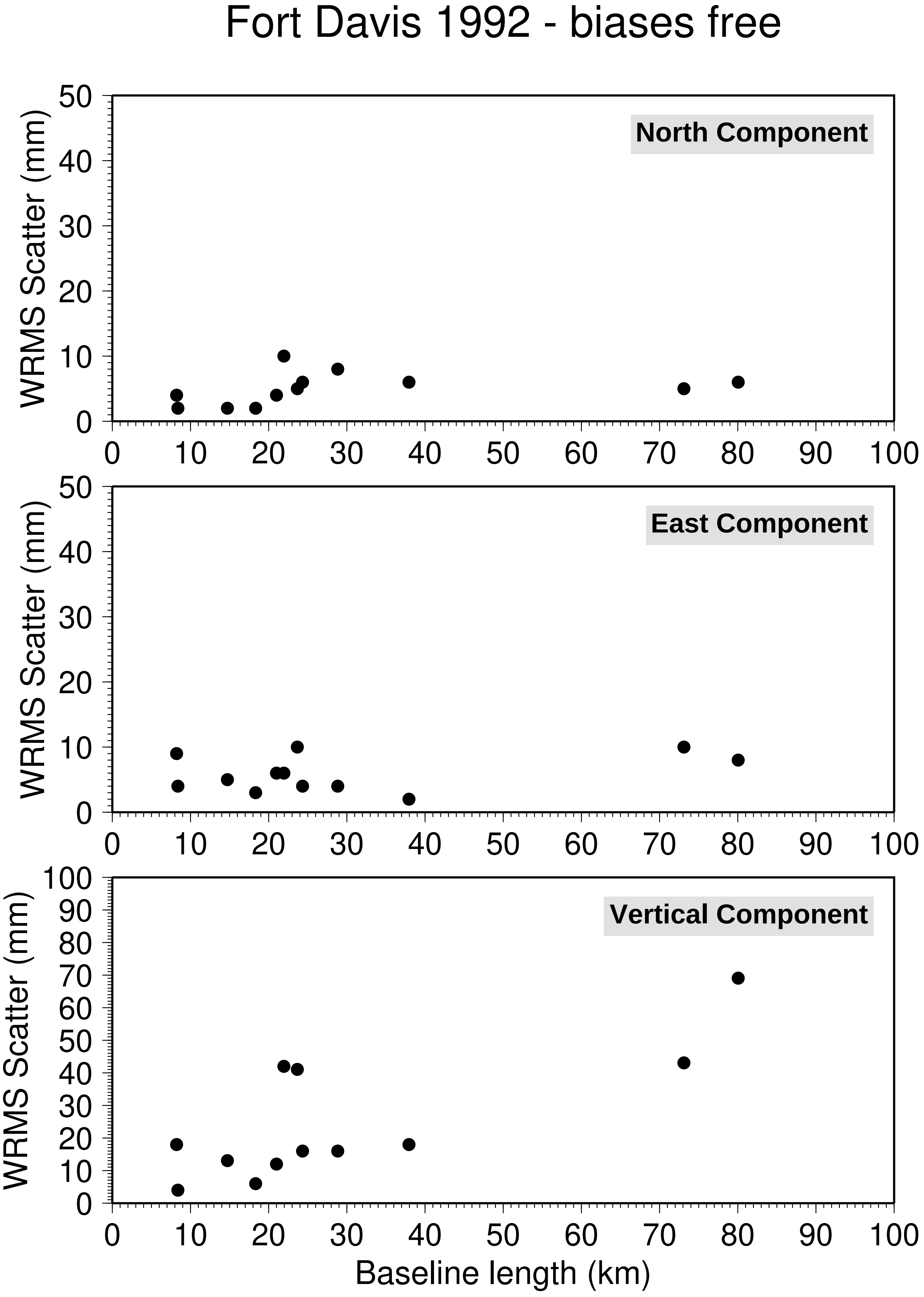
Fort Davis 1992 - biases free
North Component
East Component
Vertical Component
WRMS Scatter (mm)
Baseline length (km)
0
10
20
30
40
50
60
70
80
90
100

Figure 5a

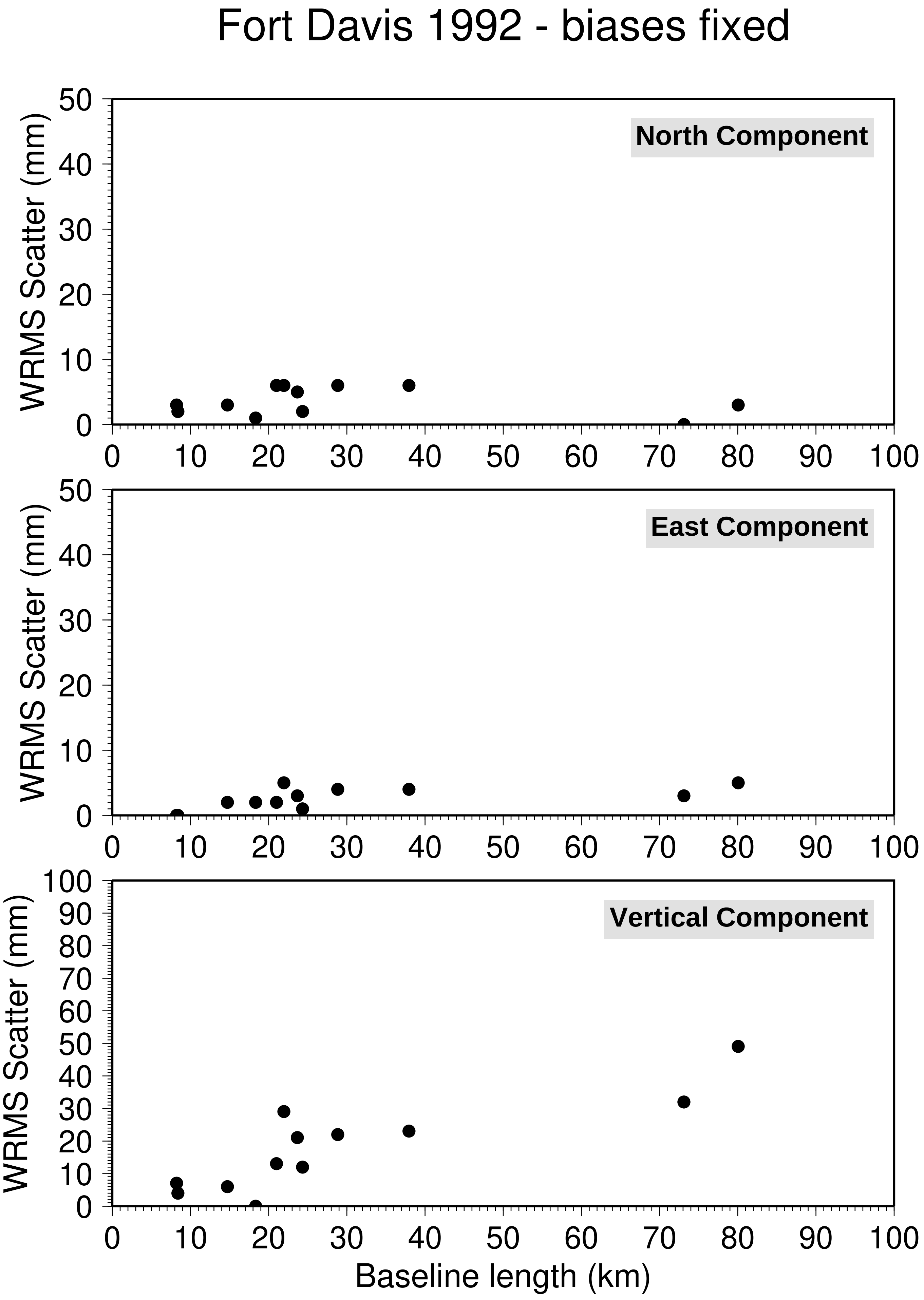
Fort Davis 1992 - biases fixed
North Component
East Component
Vertical Component
WRMS Scatter (mm)
0
10
20
30
40
50
60
70
80
90
100
Baseline length (km)

Figure 5b

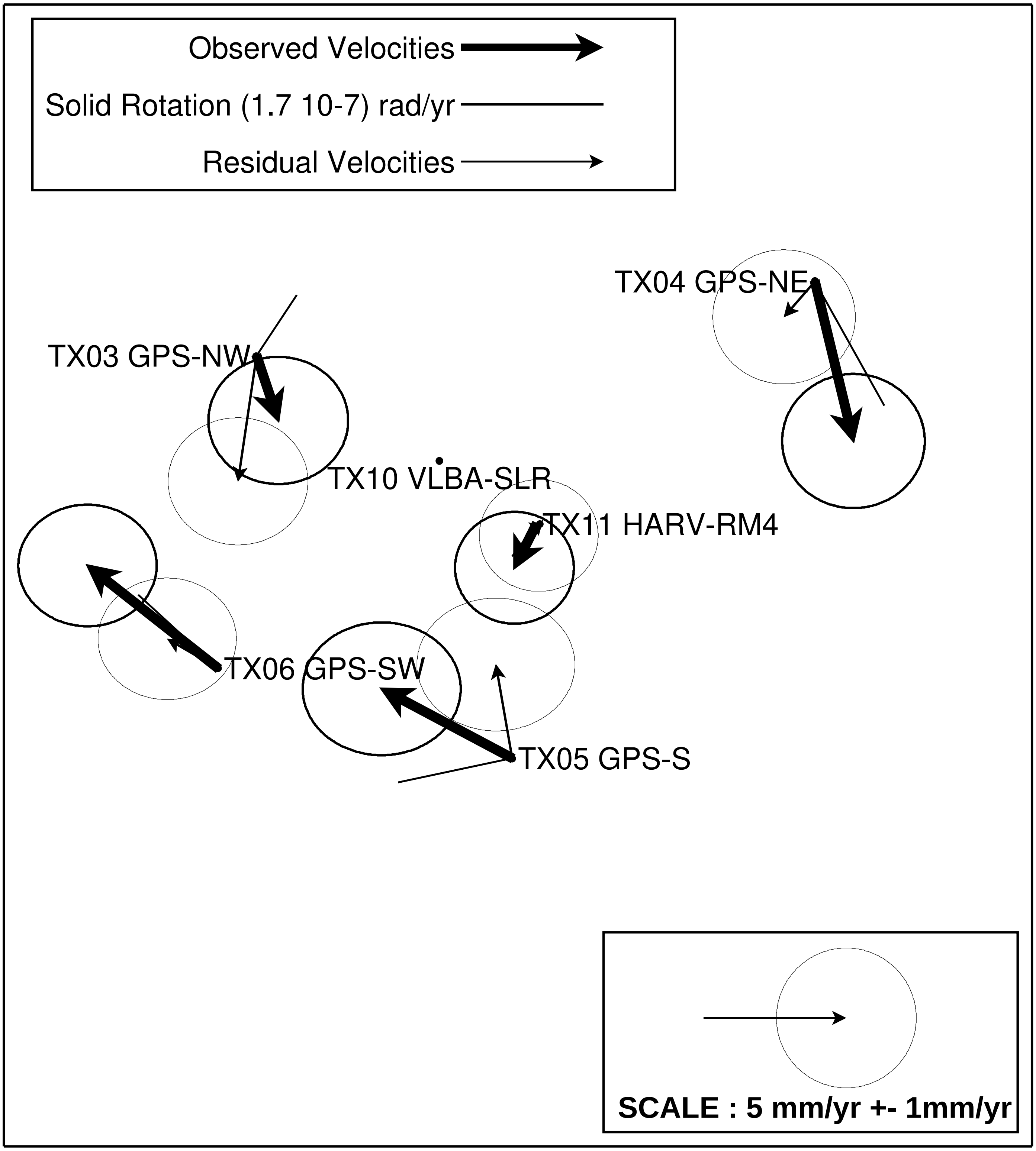
Observed Velocities
Solid Rotation (1.7 10-7) rad/yr
Residual Velocities
TX04 GPS-NE
TX03 GPS-NW
TX10 VLBA-SLR
TX11 HARV-RM4
TX06 GPS-SW
TX05 GPS-S
SCALE : 5 mm/yr +- 1mm/yr

Figure 6