Mobile VLBI and GPS Measurement of Vertical Crustal Motion

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Mobile VLBI and GPS geodetic measurements have many error sources in common. Calibration of the effects of water vapor on signal transmission through the atmosphere, however, remains the primary limitation to the accuracy of vertical crustal motion measurements made by either technique. The two primary methods of water vapor calibration currently in use for mobile VLBI baseline measurements have been evaluated: radiometric measurements of the sky brightness near the 22 GHz emission line of free water molecules and surface meteorological measurements used as input to an atmospheric model. Based upon a limited set of 9 baselines, it is shown that calibrating VLBI data with water vapor radiometer measurements provides a significantly better fit to the theoretical delay model than calibrating the same data with surface meteorological measurements. The effect of estimating a systematic error in the surface meteorological calibration is shown to improve the consistency of the vertical baseline components obtained by the two calibration methods. A detailed error model for the vertical baseline component indicates current mobile VLBI technology should allow accuracies of order 5 cm with WVR calibration and 10 cm when surface meteorological calibration is used. A statistical analysis of the results of repeated measurements of the 336-km baseline from Big Pine, CA, to Pasadena, CA, shows the scatter in the vertical baseline component to be consistent with this model. A similar model for a hypothetical GPS baseline measurement is presented. A covariance analysis based upon this model shows current GPS technology to be capable of accuracies in the vertical baseline component comparable to present mobile VLBI measurements. Expected improvements in system components for both technologies should allow reduction of the uncertainty in the vertical component to less than 3 cm by 1989.

I. Introduction

The measurement of vertical crustal motion with microwave techniques such as Very Long Baseline Interferometry (VLBI) or ranging to Global Positioning System (GPS) satellites presents difficulties not encountered in the measurement of horizontal motion. Inherent in the measurement of the vertical baseline component is a geometric dilution of precision (GDOP) arising from the fact that signals from the sources (quasars or satellites) can only be viewed along positive values of this coordinate whereas both positive and negative views of the sources are possible in measurements of horizontal baseline components. In addition to this inherent geometrical weakness, the vertical baseline component is much more sensitive to errors in the calibration of tropospheric effects, particularly that portion due to atmospheric water vapor. This is especially true for the regional baselines measured by the mobile VLBI units. The relatively short length of these baselines causes essentially all of the tropospheric errors to map into the baseline vertical component. In the case of longer intercontinental baselines, a greater fraction of the tropospheric error would map into the horizontal components. To a large degree then, the precision which can be achieved in the measurement of vertical crustal motion rests upon how accurately we can calibrate the effects of the troposphere on the microwave signals.

Two techniques are currently in use for the calibration of the wet troposphere: a direct measurement of the 22-GHz emission of free water molecules along the antenna line of sight with a microwave radiometer and the use of an atmospheric model whose parameters are determined from surface meteorological measurements to infer the amount of water vapor along the line of sight. These two calibration methods have been compared using data from several recent mobile VLBI baseline measurements. In all cases it was found that calibrating data with WVR measurements provided a better fit to the theoretical delay model than did calibrating the same data with surface meteorological based estimates of atmospheric water vapor. As expected, the major differences in the values of the estimated baseline parameters for the two different calibrations were in the vertical baseline component where differences as large as 20 cm were seen.

The major sources of error in GPS-based vertical measurements are identical to those encountered in VLBI measurements. An important error source not found in VLBI measurements, however, is the uncertainty of the GPS satellite orbits. Described here is how data from a fiducial network of GPS receivers located at *a priori* well-known sites can be used to allow accurate determination of these orbits. Finally, the results of a covariance analysis of a simulated GPS baseline measurement in the Caribbean region are presented. These results show that the uncertainty in the wet troposphere calibration is the dominant source of error in the baseline vertical component just as in the case of mobile VLBI measurements.

II. Mobile VLBI Measurement of Vertical Motion

The essential components of a mobile or any other VLBI system are a pair of radio telescopes, high-precision frequency standards (hydrogen masers) at each antenna, and a special purpose computer known as a correlator. During a baseline measurement, the broadband emission from an extragallactic radio source is recorded on some magnetic medium at each of the stations. The tapes from each station are then brought to the correlator which computes a cross correlation of the quasar signals recorded at the two stations. The resulting interferometric fringe pattern allows the difference in arrival times of the quasar signals at the two stations (delay) and its rate of change (delay rate) to be calculated. These delays and delay rates obtained from many separate quasar observations over a 24–36 hour period are used as input to a multiparameter least-squares estimation program that fits a detailed earth model to the observables from which the baseline coordinates and other parameters are extracted. More complete discussions of the interferometry technique can be found in Refs. 1–4 and of mobile VLBI measurements in Ref. 5.

III. Sources of Error in Mobile VLBI Vertical Measurements

Any deficiencies in either the earth model or the methods of calibration will ultimately degrade the accuracy of the estimated baseline components. Because baseline results are expressed in an earth-fixed system, the earth model must include effects due to the orientation and motion of the earth with respect to the coordinate frame of the quasars. These include the rate of earth rotation (UT1), precession, nutation, and polar motion. As has already been mentioned, the vertical component is particularly sensitive to the effects of propagation media on the delay observable. While the introduction of dual-frequency recording systems has essentially removed the effect of the ionosphere from mobile VLBI measurements, the calibration of the tropospheric delays, particularly that due to atmospheric water vapor, remains the single most important source of error in the measurement of the vertical baseline component. This is especially true for the relatively short regional baselines where tropospheric delays map almost entirely into this component. In addition to earth orientation and water vapor calibration, the measurement of the vertical baseline component is also subject to errors from several other sources including: instrumental phase calibration, receiver noise, and errors in the survey tie from the ground monument to the mobile antenna. Table 1 summarizes the error budget for the vertical baseline coordinate as it presently stands and how it may be expected to improve within the next few years. The error budget for the length coordinate is included for comparison.

A. Earth Orientation

Because we have detailed theoretical models which describe the orientation of the earth in space, it is, in principle, possible to use the delay and delay rate observables to estimate these parameters along with the baseline parameters as part of the overall least-squares estimation process. Because the mobile VLBI baselines are relatively short, however, they would not provide as accurate a determination of earth orientation parameters as is presently available from external sources using results obtained with much longer baselines (Ref. 6). Presently earth orientation data from Ref. 7 are used, which are derived from a combination of Project POLARIS VLBI results (Ref. 8), VLBI measurements made by the antennas at the Deep Space Network stations (Ref. 9), and the TEMPO project at JPL (Ref. 10), and data from lunar laser ranging experiments (Ref. 11). Data from these sources are combined with a Kalman filter based upon studies of atmospheric effects on the earth's angular momentum budget. The values of UT1 determined from this analysis are input explicitly to the parameter estimation program. Present accuracies of these UT1 values lie in the range of 0.1 to 0.6 milliseconds. In the case of polar motion data, presently obtained from BIH Circular D (Ref. 24), accuracies of 0.007 arc seconds were assumed for both the x and y components. The resulting uncertainties in the estimated vertical coordinate from these two sources are shown in Table 1 for a typical regional baseline of 300 to 500 km in length.

Expected improvements in both polar motion and earth rotation data should reduce the contributions of these sources to the levels shown in the second column of Table 1 by 1989. These improvements will result from the upgrades to the VLBI systems of the POLARIS project, addition of new lunar laser ranging stations, and incorporation of earth orientation data obtained from laser ranging to the Lageos satellite.

B. Troposphere Calibration

It is evident from Table 1 that the tropospheric portion of the delay model represents the most serious concern for estimation of vertical baseline components with mobile VLBI measurements. Although it is possible in principle to estimate the tropospheric delay (using the mobile VLBI data) as part of the overall parameter estimation process, it is undesirable for several reasons. First, there may be large spatial and temporal inhomogeneities in the troposphere which are virtually impossible to model realistically. Second, for the relatively short regional baselines monitored in the Mobile VLBI Program, the troposphere and baseline vertical parameters are strongly correlated, resulting in greatly reduced precision in the estimation of the latter. Third, correlations notwithstanding, the requirement that the data be used to estimate the tropospheric delay will seriously weaken its strength for baseline estimation. For these reasons, the effect of the troposphere on the quasar signals must be removed prior to parameter estimation by an external means of calibration.

The effect of the dry component of the troposphere (i.e., all nitrogen and oxygen) on the VLBI data is calibrated using a combination of surface meteorological (SM) measurements used as input to an atmospheric model (Ref. 12). Errors in this calibration approach arise principally from the facts that the atmosphere is not in hydrostatic equilibrium, that there may be large horizontal gradients in barometric pressure, and that the line-of-sight delay must be inferred from the zenith delay using a model-dependent mapping function (Ref. 13). Under extreme conditions, these could combine to contribute a systematic error of up to 3 cm in the baseline vertical, although more typically the contribution is of order 1 cm (Ref. 5).

The calibration of the wet troposphere poses a more serious problem. Surface humidity measurements may bear little relation to the distribution of water vapor at altitude. Furthermore, since azimuthal symmetry in the distribution of the water vapor cannot be assumed, accurate mapping to the antenna line of sight cannot be guaranteed. For these reasons considerable effort and resources have gone into development of water vapor radiometers (WVRs) to directly measure the quantity of water vapor along the antenna line of sight (Refs. 14–16).

The WVRs currently in use for mobile VLBI measurements, fabricated by the NASA Crustal Dynamics Project (CDP) (Ref. 17), are the result of this ongoing effort. These devices measure the intensity of microwave emission near 22 GHz from free water molecules along the antenna line of sight. This data is then used to calculate an equivalent zenith path delay with an accuracy of 1 to 2 cm. Because the radiometer can be pointed with the telescope, the effects of spatial and temporal nonuniformity are removed. Future developments in WVR technology (Ref. 18) are expected to reduce the contribution of the wet troposphere to the vertical baseline uncertainty to less than 1 cm.

To illustrate the beneficial effect that use of water vapor radiometer calibration can have on VLBI measurements, nine baselines were compared where both surface meteorological and water vapor radiometer data were available. The mobile VLBI data were recorded during the CDP observing sessions of June 6, June 29, and August 28 of 1983. The Chao model (Ref. 12) was used to calibrate path delays using surface meteorological data, and the method of Resch (Ref. 25) was used to calibrate path delays from the WVR data. The VLBI data were then processed twice, using each of these calibrations to produce independent solutions. Table 2 contains a comparison of the rms scatters of the post-fit residuals resulting from the least squares fit to the delay model from these two sets of analyses. As this table shows, the use of the WVR data results in a better fit to the delay model (and hence a lower rms scatter) for all 9 baselines in the comparison. A simple analysis of the improvement indicates that for 6 of the 9 baselines, the use of WVR data represents a statistically significant improvement over surface meteorology data as a means of wet troposphere calibration. It should be noted that this analysis assumes no correlation between the rms scatters for the two calibration methods. Since, in fact, they are highly correlated (due to the fact that they have all but one error source in common), these levels of significance represent lower limits.

The effect of wet troposphere calibration on the actual values of the estimated baseline parameters is shown in Fig. 1. As can be seen, the largest effect is in the vertical baseline component where differences of up to 20 cm are seen between the SM and WVR approaches. As expected, the method of calibration is shown to have a significant effect on the estimated values of this component. In the horizontal components, the impact of changing the calibration method is much less severe.

Finally, we note that for longer baselines, the correlation of the troposphere and the baseline vertical is considerably reduced and estimation of an error in the zenith path delay may improve the results by accounting for any systematic error in the troposphere calibration. This may be especially true when surface meteorology calibration of the wet troposphere has been used. In this work, station zenith errors were estimated for several baselines from the set of 9 used in the above comparison (see Table 2), and it was found that the estimation of a constant zenith error for results calibrated with surface meteorology data does produce a significant improvement in the consistency of the estimated baseline parameters. This is especially true for the case of the baseline vertical component. Figure 2 shows the effect that the estimation of this additional parameter has on the length and vertical components for six baselines from our original comparison set. In all cases the estimated baseline parameters tend to move toward the results obtained with WVR calibrated data indicating that the average difference between the surface meteorology and WVR-based results is significantly reduced when this additional parameter is estimated. If the WVR-based solution is assumed to represent the "true" baseline, then this estimation procedure is seen to improve repeatability by a factor of over 2 in both the length and vertical components. An unfortunate (but expected) consequence of estimating a zenith troposphere error is that the formal uncertainty in the vertical baseline component is increased by a factor of between 2 and 3. This is a result of a still high correlation between the baseline vertical parameter and the estimated troposphere parameter and a result of the simple fact that the same amount of data is now required to estimate a larger number of parameters. Figure 3 shows how the formal uncertainties in the length and vertical parameters increase when this constant zenith offset parameter is estimated.

The calibration techniques described in this subsection are all suboptimal in various senses. The WVR-based calibration is clearly superior to the SM-based calibration. But the direct application of WVR calibration makes no allowance for the effect of WVR errors on the VLBI baseline results. The alternative approach of troposphere estimation improves the consistency of the VLBI results, but it also results in a serious loss of precision. A third alternative which combines the strengths of both the above is the hybrid approach in which WVR calibration is applied to the raw VLBI observables and a constrained calibration error is estimated, based on a realistic model of that error. The constraint is applied in the form of an *a priori* covariance, which limits the size of the error model parameters, in accordance with the demonstrated inherent accuracy of the WVR instrument. This hybrid approach is under development at JPL (Ref. 19) and testing with data is expected to begin soon.

C. Computation of Uncertainties

In lieu of an operational hybrid approach to computation of uncertainties, as described in the preceding subsection, it has not been a practice to attempt to estimate any sort of systematic errors in the troposphere calibration of the mobile VLBI data. However, since all calibration is subject to systematic error, we add additional uncertainty to the post-fit estimated baseline parameters in order to provide more realistic values for their uncertainties. In the cases where water vapor radiometer data is available, we add 2.0 cm in quadrature to the uncertainty in the local vertical coordinate for each station. To reflect the larger error expected when surface meteorological data is used for wet troposphere calibration, an uncertainty equal to one half the mean wet path delay is added to the local vertical for that station. Typically this results in an additional error of from 2.5 to 5.0 cm in the local vertical coordinate. The resulting uncertainties in the vertical baseline coordinate for a typical regional baseline are shown in Table 1. Expected improvements in water vapor technology should allow reduction of the contribution of the wet troposphere to less than 2.0 cm provided a sufficient number of these new instruments are made available for use at all observing stations.

Table 1 also contains the contributions from several other error sources which have some effect on the accuracy of the vertical baseline component including an estimate of the effects of unmodeled elements of the delay observable such as ocean loading and antenna flexure. The combined effects of these additional error sources, however, represent only a small fraction of the contributions from earth orientation and wet troposphere calibration to the uncertainty in the vertical component. A more extensive discussion of these and other sources of error in mobile VLBI measurements can be found in Ref. 5.

In order to test the validity of this error model for the vertical baseline component, the results of repeated measurements of a single baseline have been statistically analyzed. The 336-km baseline from the 40-meter telescope at the Owens Valley Radio Observatory located near Big Pine, CA to the mobile VLBI site at the Jet Propulsion Laboratory in Pasadena, CA has been measured 19 times since the first measurement in January 1980. From these 19 measurements we have taken a subset of 15 measurements consisting of 4 groups, each of which contains measurements made within a six month period. This was done to minimize the possible effects of tectonic motion on these tests of consistency for this baseline which crosses the San Andreas fault. The results of these measurements are shown in Fig. 4 in the form of error ellipses for baseline length and vertical components. All results are expressed as shifts from a nominal reference baseline. It is clear from the figure that the repeatability in the vertical coordinate is much worse than in the baseline length. This is not unexpected since the baseline length component is entirely unaffected by uncertainties in the earth orientation and only slightly affected by troposphere calibration errors. It should also be noted that some of these baselines used surface meteorological data to calibrate the wet troposphere and that in these cases no attempt was made to estimate a systematic error in the manner described earlier. This, as well as inadequacies in the current dry troposphere model, may be responsible for the poor repeatability in some cases.

From a χ^2 analysis of these results, shown in Table 3, it is evident that the error model for the vertical baseline component is adequate for all but the second group of measurements where the scatter in the measurements is somewhat larger than would be expected on the basis of the formal errors. This is surprising, because all measurements in this group used water vapor radiometers to calibrate the wet troposphere delay. This may indicate that there exists a substantial systematic error in some of the WVR measurements which might be removed by estimating a zenith path delay error as was done for the surface meteorological data with some success. Beckman (Ref. 19) has proposed such a model, which is currently being evaluated at JPL.

The results contained in Table 3 also serve to illustrate the general improvement in consistency of repeated measurements since 1980. This is due to many factors including improvements in receiver technology, theoretical models, data processing software, as well as improved wet troposphere calibration. A more extensive discussion of these improvements is contained in Ref. 5.

IV. GPS Measurement of Vertical Crustal Motion

A. Measuring Baselines with GPS Receivers

By 1989 the full 18 satellite constellation of GPS/NAVSTAR satellites is expected to be in orbit (Ref. 20). These satellites will broadcast phase modulated signals at two L-band frequencies (1575.41 MHz and 1227.60 MHz) and are expected to have many civilian users for navigation, precise orbiter tracking and geodesy. Among the applications being investigated at the Jet Propulsion Laboratory is a GPS based system to measure geodetic baselines with accuracies comparable to those attainable using present mobile VLBI systems.

The basic observable obtained from all GPS measurements is the distance from the receiver to the satellite, called the "pseudorange." It is not exactly equal to the true satellite-receiver distance because of offsets between the satellite and receiver clocks and the effects of the troposphere and ionosphere on the broadcast signals. The covariance analysis described here, however, does not use the pseudorange directly but forms a new datum by taking the difference between the pseudoranges from two receivers to a single GPS satellite. Use of this differential pseudorange has the advantage of removing the clock offset term between the receiver and satellite. This still leaves an offset between the two receiver clocks, but it is also possible to form a second difference between two differential pseudoranges to two different GPS satellites. This second difference has the effect of canceling out the clock errors between the two ground receivers, thus removing all errors due to clock offsets from the GPS range data. When there are more than two receivers involved, a more elaborate linear combination of the pseudoranges is actually used to remove the clock offsets (Ref. 21). It is this more general double differencing technique which has been used in the covariance analysis presented here.

B. Fiducial Network Concept

Although the double differencing process removes all clock errors from the data, the uncertainty in the satellite ephemeris would limit accuracy to a decimeter or greater for baselines longer than 100 km. For this reason the concept of a fiducial network has been developed (J. L. Fanselow and J. B. Thomas, personal communication, 1983 and Ref. 22). The fiducial network consists of three or more GPS receivers whose locations have been accurately established by an independent technique such as VLBI or satellite laser ranging. During a GPS baseline measurement, receivers at *a priori* unknown locations observe the satellites simultaneously with the receivers located at the precisely known fiducial station locations. In the subsequent least squares analysis, the range data from the fiducial station receivers allows accurate values of the GPS orbits to be estimated along with values for the unknown station locations. Without this ability to estimate accurate GPS orbits, centimeter-level baseline accuracies for regional baselines longer than 100 km in length would not be possible. The schematic diagram in Fig. 5 shows a GPS measurement scenario using a 4-station fiducial network in conjunction with 2 mobile GPS receivers. Initially, fiducial sites will be located at Ft. Davis, TX, Westford, MA, and Richmond, FL. Other fiducial sites being considered are Quito, Ecuador; Sao Paulo, Brazil; Santiago, Chile and Cayenne, French Guiana (Ref. 23).

V. Sources of Error in GPS Vertical Measurements

The primary sources of error in VLBI vertical measurements described earlier are also present in GPS-based measurements of vertical crustal motion. GPS measurements have the additional error source of uncertainties in the GPS orbits. Use of a fiducial network of observing stations in the manner described in Ref. 23 eliminates most of the error resulting from this source for baselines of less than 1000 km in length. This, of course, requires that we have adequate models of the satellite orbits which include effects of solar radiation pressure, higher order gravitational terms, uncertainty in the value of the gravitational constant and that we properly account for any relativistic effects. Table 4 contains the major elements of the error model assumed in our covariance analysis.

Table 5 shows the results of this analysis for the 370-km baseline between San Juan, Puerto Rico and Santo Domingo, Dominican Republic for both the current and the 1989 system components. As was the case for mobile VLBI vertical measurements, it is the troposphere calibration which dominates the uncertainty in the vertical baseline component. The approximately 8-cm uncertainty for the current GPS system is, in fact, comparable to the accuracy now achieved with mobile VLBI systems. It is clear from these results that improvements in the accuracy of the wet troposphere calibration are essential if vertical component accuracies of 2 to 3 cm are to be achieved with GPS technology. It is encouraging to note that errors associated with the determination of GPS orbits do not contribute significantly to baseline errors for baselines of this length.

VI. Conclusions

Four years of baseline measurements with mobile VLBI systems have shown that baseline vertical components can be measured with a precision on the order of 5 cm. The major sources of error in these measurements are uncertainty in the earth orientation, especially in the position of the pole, and errors in the calibration of the effects of water vapor in the troposphere. The wet troposphere calibration presently represents the most serious error source for mobile VLBI measurements of vertical crustal motion. Future improvements in WVRs promise to reduce the contribution of water vapor radiometer calibration errors to a level of 2 cm or less. Along with improvements in the knowledge of the earth's polar motion, this will allow baseline vertical components to be measured with a precision of 2 to 3 cm. The introduction of a WVR error model into the parameter estimation process may allow the effects of systematic errors in the wet troposphere calibration to be reduced even further, to the point that the calibration of the dry troposphere, including the effects of dynamic terms and horizontal gradients, may become the limitation on accuracy.

Baseline measurements using GPS satellites and receivers have the potential of achieving VLBI level accuracies in both the horizontal and vertical coordinates. The measurement of vertical motion with GPS technology will also require the use of water vapor radiometers to remove the effects of the wet troposphere from the satellite/receiver range measurements. Present accuracies in the vertical coordinate are predicted, on the basis of a covariance analysis, to be comparable to the present accuracies of mobile VLBI measurements. Improvements in receiver technology, WVR instrumentation, and GPS orbit determination could conceivably reduce the uncertainty in vertical measurements to the order of 2 to 3 cm by 1989.

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Table 1. Summary of mobile VLBI error sources in length and vertical coordinates[a]

Error Source	Contribution to Uncertainty in Baseline Length and Vertical Coordinate, cm			
	1984 System		1989 System	
	Length	Vertical	Length	Vertical
Earth Orientation				
UT1 – UTC	0	0.5	0	0.2
Polar Motion	0	1.5	0	1.0
Propagation Media				
Dry Troposphere	0.8	1.5	0.5	1.0
Wet Troposphere[b]	0.6	4.0	0.3	2.0
Wet Troposphere[c]	1.2	9.0	1.2	9.0
Miscellaneous				
Source Positions	0.3	0.3	0.3	0.3
System Noise	0.2	0.2	0.2	0.2
Mobile Antenna Survey Tie to Monument	0.3	0.5	0.3	0.5
Various Unmodeled Elements of Delay Model	0.5	1.0	0.2	0.5
Total (RSS)	1.2[b] 1.7[c]	4.7[b] 9.3[c]	0.8[b] 1.4[c]	2.6[b] 9.1[c]

[a]The contributions to uncertainties in the length and vertical baseline components shown in this table are meant to represent those expected for a typical regional baseline of 300 to 500 km in length measured with one mobile and one fixed antenna. Actual values will depend upon baseline length and orientation, and the performance of all system components.

[b]Water vapor radiometer data used to calculate wet path delays.

[c]Surface meteorological data and atmospheric model used to calculate wet path delays.

Table 2. Values of post-fit residual delay scatter

Experiment Date (UT)	Stations[a]	Baseline Length, km	RMS Scatter, ps		Probability That RMS Are the Same, %[b]
			WVR Calibration	Surface Met.	
06/09/83	HAT CREEK GRAS	1933.5	87.3	139.2	0.04
	GRAS WESTFORD	3134.9	115.6	167.0	0.10
	HAT CREEK WESTFORD	4032.8	124.3	167.8	1.20
06/29/83	OVRO 130 HAT CREEK	484.3	48.8	104.6	4.0×10^{-6}
	OVRO 130 MOJAVE	245.3	61.0	163.5	1.0×10^{-5}
	HAT CREEK MOJAVE	729.1	42.2	106.7	4.0×10^{-7}
08/28/83	OVRO 130 MOJAVE	245.3	104.0	120.5	36.0
	MOJAVE DSS 13	12.6	197.9	204.2	84.0
	OVRO 130 DSS 13	257.6	151.4	159.1	68.0

[a]DSS 13 – Venus Antenna, NASA Deep Space Network Complex, Goldstone, CA
GRAS – George R. Agassiz Radio Astronomy Station, Ft. Davis, TX
HAT CREEK – Hat Creek Radio Astronomy Observatory, Cassel, CA
MOJAVE – Mojave Base Station, NASA Deep Space Network Complex, Goldstone, CA
OVRO 130 – Owens Valley Radio Observatory, Bishop, CA
WESTFORD – Haystack Observatory, Westford, MA

[b]Calculated assuming that residual scatter is Gaussian and that the values from the two different calibration methods are independent. Because this is not true, these numbers represent an upper limit.

Table 3. Owens Valley → JPL baseline precision[a]

Dates	Degrees of Freedom	RMS Scatter, cm		x^2	
		Length	Vertical	Length	Vertical
5/80 – 11/80	3	2.2	10.2	0.33	0.55
8/81 – 11/81	3	0.8	12.6	0.28	2.29
10/82 – 2/83	3	1.1	5.9	0.83	0.17
6/83 – 11/83	2	0.8	5.6	0.40	0.17

[a]The data from which these results are calculated are displayed in Fig. 4.

Table 4. Inputs to GPS baseline covariance analysis

Input	1984 System	1989 System
Data Type	Double differenced integrated Doppler	Double differenced range or integrated Doppler
Data Noise	3.0 cm	1.0 cm
Fiducial Network	Ft. Davis, TX Westford, MA Richmond, FL	Ft. Davis, TX Westford, MA Quito, Ecuador
Considered Parameters	Uncertainty	
Relative Position of Fiducial Station	3 cm horizontal 9 cm vertical	1 cm all components
Troposphere Calibration Error	2.0 cm (zenith)	0.75 cm (zenith)
Solar Radiation Pressure	5% @C_R = 0.5	
Geopotential	10% of GEM 6 – APL50	
GM	10^{-8} of the total value	
Estimated Parameters	A Priori Uncertainty	
Range Bias Parameters	1000 m (integrated Doppler only)	
NAVSTAR Position	10 m in each component (X, Y, Z)	
NAVSTAR Velocity	0.1 cm/s in each component (V_x, V_y, V_z)	
Mobile Station Location	20.0 m in each component (X, Y, Z)	

Table 5. Covariance analysis results for San Juan to Santo Domingo baseline[a]

Error Source	Contribution to Uncertainty Baseline Vertical Coordinate, cm	
	1984 System	1989 System[b]
Range Measurement Accuracy	3.4	1.4
Solar Radiation Pressure	<< 1	<< 1
Geopotential	<< 1	<< 1
GM	<< 1	<< 1
Relative Position of Fiducial Stations	0.8	0.1
Location of Geocenter	<< 1	<< 1
Troposphere Calibration	6.9	2.6
Total (RSS)	7.7	2.9

[a]The values in this table are based upon the results for a single baseline of 370 km between San Juan, Puerto Rico and Santo Domingo, Dominican Rep. The values for other baselines will depend to a degree upon baseline length and orientation.

[b]These results correspond to the integrated Doppler data type. Results for the carrier range data type are virtually identical for this short baseline.

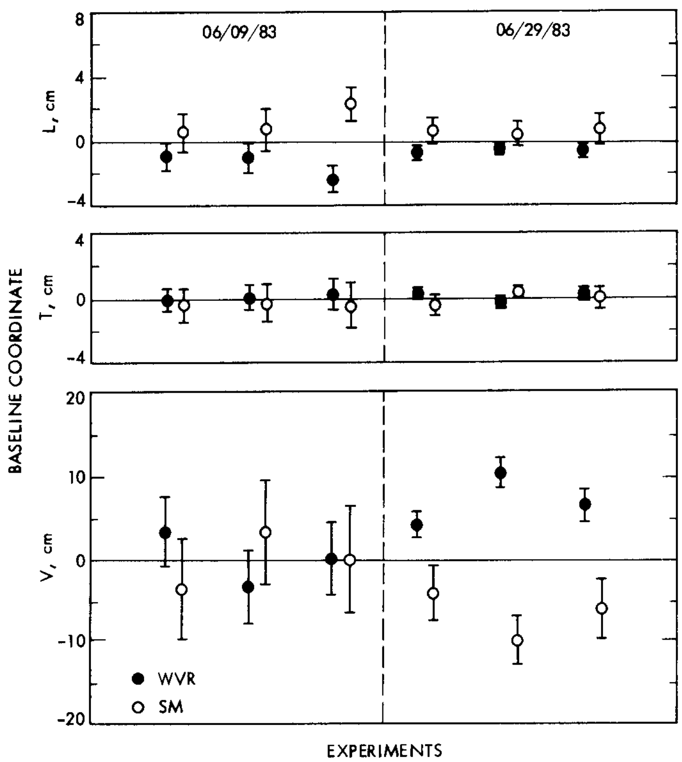

Fig. 1. The effect of different wet troposphere calibrations on estimated baseline parameters is illustrated for 6 baselines from two mobile VLBI experiments completed in June 1983. Estimated values of the length, transverse, and vertical baseline components for both WVR and surface meteorological calibrations are shown. See Table 2 for station names and baseline lengths.

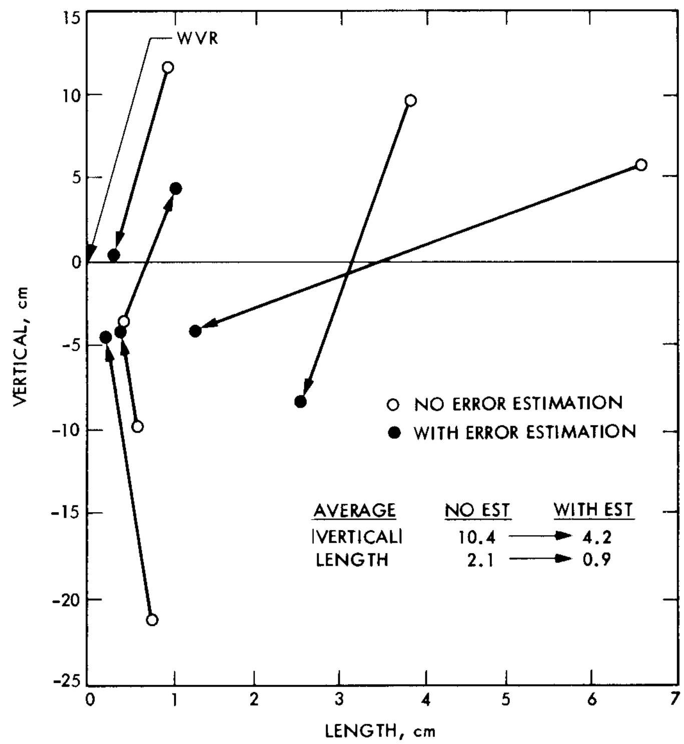

Fig. 2. The effect of the estimation of zenith troposphere error on length and vertical coordinates is shown. The difference between the WVR and SM values is substantially reduced by estimating an error in the SM calibration.

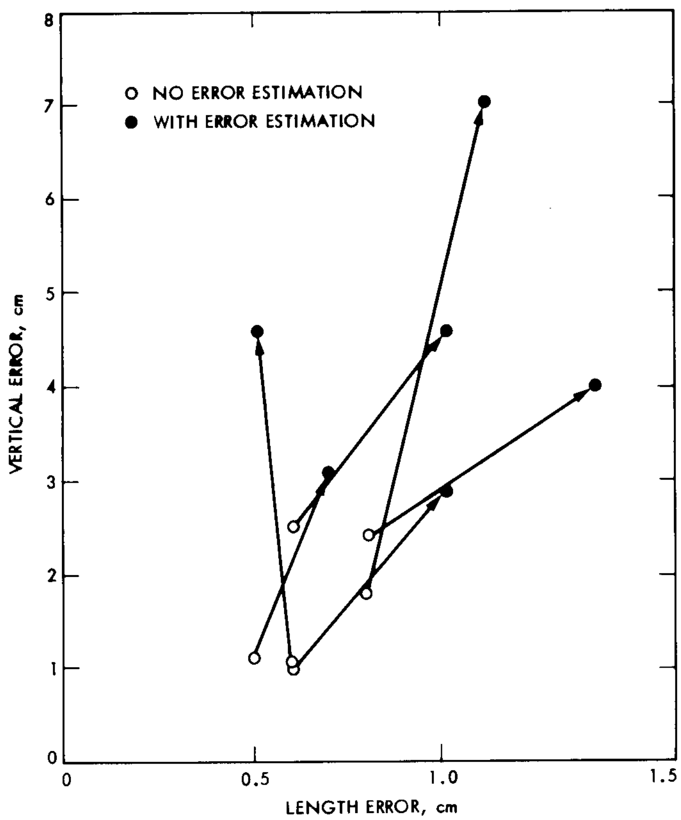

Fig. 3. The effect of the estimation of zenith troposphere error on formal uncertainties in the length and vertical coordinates is shown. The accuracy of these components is substantially increased by the estimation of an error in the calibration.

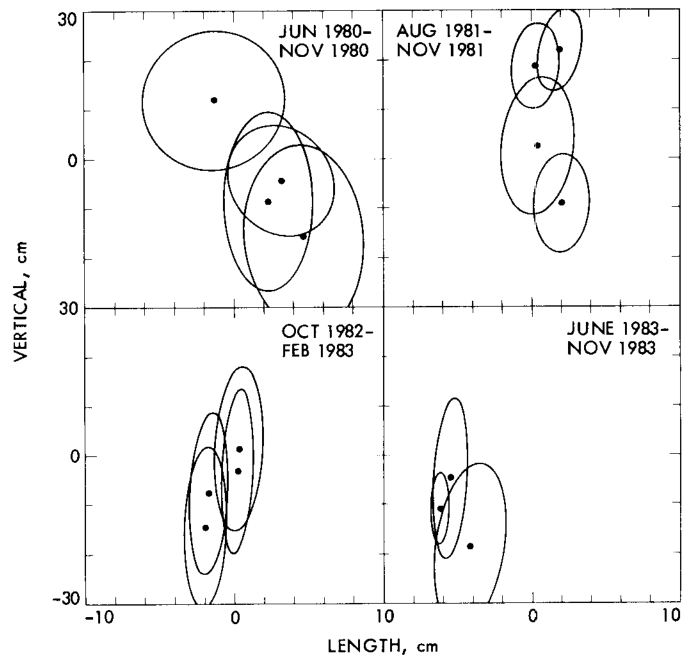

Fig. 4. Length and vertical coordinates of baselines from Big Pine, CA to Pasadena, CA are shown as shifts from a nominal reference baseline. Note how the rms scatters and the formal errors decrease with time (see Table 3).

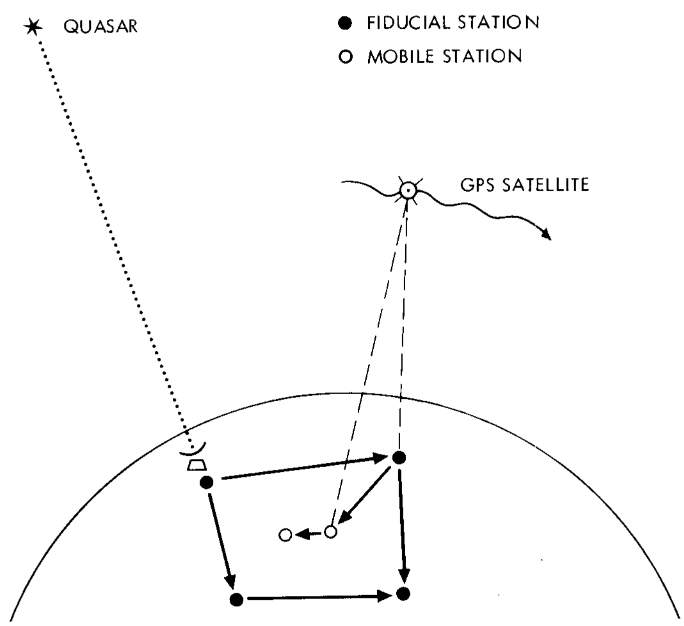

Fig. 5. The use of a fiducial network for GPS baseline measurements is shown. The fiducial station data enable the accurate estimation of the GPS satellite orbits. This, in turn, enables the accurate determination of the mobile station locations. VLBI observations establish the fiducial station baselines and tie the GPS results to the inertial frame of the quasars.