Utilization of Mobile VLBI for Geodetic Measurements

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Three mobile VLBI systems have been fabricated under the direction of JPL for the NASA Crustal Dynamics Project. These systems include the 9-meter-diameter MV-1 telescope, the 3.7-meter-diameter MV-2 telescope and the 5-meter-diameter MV-3 telescope. Since 1980, mobile systems have been operated in conjunction with several fixed base stations in the western United States as part of a geodetic survey program to determine relative motions and regional strain fields near the tectonic plate boundaries in California and Alaska. In this article, we present a description of the three mobile systems and the environment in which they must function. The inherent accuracy of mobile VLBI measurements is assessed, based on a consideration of major sources of error. Some recent results are presented which serve to illustrate various aspects of the error model and are of geodetic interest as they span the broad region surrounding the surface trace of the San Andreas Fault. These results indicate that baseline measurements utilizing the current mobile VLBI systems have attained an accuracy of 2 cm or better in the horizontal plane. Since average geological rates of horizontal motion are on the order of 5 cm/yr across the plate boundary regions being studied, it is likely that crustal motions will be detected within the next few years, provided they are presently occurring at the geological rates.

I. Introduction

Over the past fifteen years, considerable progress has been made in the application of very long baseline interferometry (VLBI) to the measurement of Earth orientation and global crustal motion (see, e.g., Refs. 1, 2, 3, and 4). However, in order to study crustal motion on a regional scale (baselines of lengths less than 1000 km), mobile systems are required for spatial densification. To meet this need, MacDoran and others (Refs. 5, 6, and 7), beginning in the early 1970s, undertook the development of a 9-meter-diameter mobile VLBI system (now known as MV-1). Tests of this mobile system were conducted from 1974 to 1979 in order to demonstrate the feasibility of the mobile VLBI concept and to initiate a program of regional deformation studies in the western United States. The success of this effort subsequently led to the construction of two additional mobile VLBI systems. These were fabricated under the direction of JPL for the Crustal Dynamics Project (CDP; see Ref. 8) of the NASA Geodynamics Program. These newer MV (for mobile VLBI) systems include the 3.7-meter MV-2 telescope, which began data collection in 1980, and the 5-meter MV-3 telescope, which began data collection in 1982. The newer systems are smaller, are more easily transportable and take advantage of the technological insights gained in the experience with MV-1 (Refs. 9 and 10). These three MV units are presently being operated in conjunction with several fixed based stations in the western United States as part of a geodetic surveying program, to determine relative motions and regional strain fields near tectonic plate boundaries in California and Alaska. All data and results from this observing program are regularly archived in the CDP Data Information System (DIS) located at the Goddard Space Flight Center (GSFC), Greenbelt, Maryland (Refs, 11 and 12), where it is in the public domain. All results presented herein are available in the DIS (Ref. 13).

In this article, we present a description of the three mobile VLBI systems and the difficult environment in which they must function. The inherent accuracy of the mobile VLBI measurements is assessed for the example of the 883-km baseline between Monument Peak and Quincy in California, based on a consideration of major sources of error and on the internal consistency of the mobile VLBI results. Some recent results are presented which serve to illustrate various aspects of mobile system's inherent accuracy and are of geodetic interest as they span the broad region surrounding the surface trace of the San Andreas Fault. The current single-measurement (24 hours of data collection) accuracy in the length and horizontal transverse components of baselines of lengths 500 km or less appears to lie in the range of 1-2 cm. For baselines of lengths 500–1000 km, the accuracy of the transverse component degrades to the 2-3 cm range, because of uncertainties in currently available Earth orientation calibrations. The accuracy in the baseline vertical component is considerably worse than this, falling in the range of 8-10 cm. Anticipated improvements by 1986 in troposphere and earth orientation calibration (M. A. Janssen and J. O. Dickey, private communication) will improve single-measurement accuracies to 1-2 cm and 3-4 cm for the transverse and vertical components, respectively. Since average geological rates of horizontal motion are on the order of 5 cm/yr across the plate boundary regions being studied (Ref. 14), it is likely that crustal motions will be detected within the next few years, provided they are presently occurring at the geological rates.

II. The Mobile VLBI Systems

A. The Interferometry Technique

In interferometry measurements, the random broad-band emission of an extra-galactic radio source (usually a quasar) is simultaneously recorded on a magnetic medium at two widely separated radio antennas (Ref. 4). Subsequent cross-correlation of the recorded data at a centrally located special-purpose computer (known as a "correlator") leads to a determination of the difference in arrival time of the radio wavefront at the two antennas. This difference (or delay) depends on, among other things, the direction of the source and the vector separation of the two antennas. Hence, it is possible to estimate these and other quantities by measuring the delays and their rates of change for many different sources, preferably on several baselines simultaneously, and then passing these delays and delay rates through a multiparameter least-squares fitting code in which geophysical and astrometric quantities are adjustable parameters. For a complete description of the interferometry techniques, see, e.g., Refs. 15 and 16.

B. The Mobile Environment

It has long been foreseen that interferometric baseline measurements using large, permanent radio telescopes would eventually attain an accuracy in length of two centimeters or better. However, it was not clear that mobile systems were capable of this same level of performance. The reasons for this reservation are simple, having to do with the environment in which mobile systems operate. In this subsection, we present a description of these environmental conditions.

The most severe penalty imposed by the requirement of high mobility is the reduction of the quasar signal-to-noise ratio (SNR). This is a simple consequence of the small aperture size of the transportable telescopes. The smaller SNR lowers the inherent system precision and limits the number of sources usable for mobile VLBI interferometry. For observations in North America, the available number of sources of adequate strength is only about a dozen. The small size of this catalogue tends to distort the experimental geometry and observing strategy and may lead to high correlations between estimated geodetic and other parameters. This latter problem becomes especially serious in the event of poor behavior of the time and frequency standards.

Of almost equal importance is the lack of such strict environmental control as is routinely available in permanent radio observatories. This may have serious consequences in regard to the performance of the MV stations' hydrogen masers and other electronics, which are particularly sensitive to thermal, magnetic and mechanical perturbations. Further, the electronic equipment in an MV unit must withstand vibrations from hundreds of miles of highway driving and many miles of driving on rough off-highway roads. Dust and grit are pervasive under field conditions, in stark contrast to the conditions for in-house data collection, where even cigarette smoke is considered a hazard to computer magnetic tape and disk drives.

When a remote site is reoccupied, the mobile antenna is parked as near as possible (usually within 10 cm of horizontal displacement) to a monumented ground reference point, the official CDP "location" of that site. The survey tie vector between the antenna intersection of axes and the monument is measured using conventional surveying techniques. The error in this measurement further degrades the quality of mobile VLBI baseline results. (This is discussed further in Section III.)

There are important personnel or "human" considerations that are unique to the mobile environment. For example, the field crews often do not have convenient access to normal eating, sleeping and sanitary facilities. The nature of field work tends to be fatiguing. Mobile VLBI field exercises (or "bursts") may last up to two weeks and involve several thousand miles of driving and considerable heavy physical labor. In addition, field crews may have to contend with dense swarms of mosquitoes, rattlesnakes and even bears in the course of data collection. Although these human factors are impossible to include explicitly in the computation of formal uncertainties, they may strongly affect the quality, and quantity, of data taken in the field and thus may in effect lower mobile VLBI accuracy.

Several other problems unique to the mobile environment pose challenges, albeit indirectly, to the goal of two-centimeter accuracy. For example, the remote sites often do not have electricity and telephone service. Hence, the MV units must provide their own power and communications capability. Catastrophic station failures may require the hurried shipment by air of a particular part (or technician) to the scene of a disabled MV unit. Validation of remote station operation by quick correlation of a test tape may be difficult or impossible. Magnetic tape logistics in the field are a major problem, as the tapes for one MV unit for a single burst may weigh several thousand pounds. Special highway permits are required for the heavy vehicles that make up an MV "caravan," and travel restrictions in certain local areas may present problems. For example, on one occasion a field crew's unfamiliarity with heavy-vehicle regulations led to the arrest of the MV-2 antenna in Northern California, resulting in the loss of over twelve hours of geodetic data.

C. Mobile Station Description

Three mobile VLBI stations have been fabricated and are currently involved in the ongoing collection of data for the Crustal Dynamics Project. These are the 9-meter-diameter MV-1 station, the 3.7-meter MV-2 station and the 5-meter MV-3 station. The MV-1 and MV-2 antennas, but not electronics, were initially obtained as U.S. Army surplus equipment. All MV-3 components were designed and built specifically for the Crustal Dynamics Project. MV-1 was developed as a proof-of-concept effort, with high mobility as a lesser priority. It requires four men and fourteen working days (not including transit time) to relocate. MV-2 was developed to establish the concept of high mobility; this MV station has, in the course of actual field exercises, been relocated in 5 hours, plus transit time, using a crew of four (although more typical relocation times range from 24 to 48 hours in consideration of field crew fatigue and safety). MV-3 can also be relocated in five hours, plus transit time, with only a minimum crew of two needed. Station calibration equipment includes water vapor radiometers (WVRs) and surface meteorology sensors, recording temperature, barometric pressure, and relative humidity. The water vapor radiometers are attached to the telescopes themselves and point with the telescopes in the direction of the quasar line-of-sight.

Many aspects of MV station design have taken into account the mobile environmental factor discussed in the previous subsection. To optimize the SNR, all three of these stations are equipped to operate in a standard CDP configuration. That is, data are recorded using a computer-controlled Mark III terminal (up to 112 Mbits/s record rate), with dual-frequency (X-band and S-band) recording. This is a substantial improvement over the 4 Mbits/s rate of the Mark II recording system (X-band only) that was used through 1980, and reduces the penalty imposed by the small aperture diameters. (Indeed, the need to optimize SNR in the mobile systems was a major justification for the development of the Mark III system.) Spanned bandwidths are approximately 400 MHz at X-band (approximately 8.4 GHz) and 100 MHz at S-band (approximately 2.4 MHz). The broad-banding of the receivers also improves precision of the delay measurements. The hydrogen masers, used as time and frequency standards in all the MV units, are housed in double-walled environmental control enclosures, within which the temperature is regulated to within 0.1 Kelvin. The walls of this enclosure are lined with magnetic shielding. Each MV unit is equipped with a radio telephone and 50-kVA electric generator; MV-3 has two such generator units. Each unit has a walk-in trailer housing the station electronics. These electronics have been hardened against damage from highway vibrations so that data loss from in-transit equipment damage is minimal with the current systems. The trailer for MV-3 also contains cooking, sleeping and sanitary facilities for the field crews.

An MV station in transit between sites consists of a convoy or "caravan" of vehicles. The MV-1 caravan includes a crane for telescope assembly. The MV-1 and MV-2 caravans include a pick-up truck site-vehicle. The transit configurations of the three mobile stations are shown schematically in Fig. 1. MV-3 is shown in both its in-transit and deployed configurations in Fig. 2.

D. Field Operations

In their normal operating modes, the mobile VLBI units are deployed in observing campaigns or bursts, which may last from one to two weeks. MV-1 operates as a quasi-fixed station, while MV-2 and MV-3 tour the mobile VLBI sites which have been scheduled. From one to four fixed base stations may operate in conjunction with the MV-units to strengthen network geometry and SNR. Typical site occupation times range from 24 to 36 hours. Current deployment plans, as set up by the Crustal Dynamics Project, call for four bursts per year, three in the western United States and one in Alaska. From the present through 1988, MV-1 will be stationed semi-permanently at Vandenberg Air Force Base, California, while MV-2 and MV-3 will occupy about thirty sites in California and Alaska on an annual basis.

III. Sources of Error

In this section, we discuss the major sources of error in mobile VLBI measurements. These sources include: Earth orientation calibration, propagation media calibration, mobile survey tie, source positions, system noise, processing scatter, and other (unmodeled) error sources. A summary of the error model inputs is given in Table 1 for the mobile systems of 1980, for the current (1984) mobile systems and as anticipated for the mobile systems of 1986. The impact of these inputs on baseline accuracy, in all three components, is illustrated in Figs. 3, 4, and 5 for the example of the Monument Peak to Quincy baseline. Although the impact of calibration errors varies considerably as a function of baseline length and orientation and other factors, such as local meteorology, the example of this baseline is chosen as illustrative of many features of the mobile VLBI sources of error.

A. Earth Orientation

The VLBI technique provides a very accurate measurement of a baseline vector within the reference frame of the quasi-stellar radio sources (Refs. 17, 18, and 19). However, expression of the baseline in an Earth-fixed frame requires an accurate knowledge of the orientation of the Earth in space, that is, in the quasar frame. In principle, this calibration could be extracted from the mobile VLBI data themselves. However, the relatively short length of the mobile VLBI baselines would provide calibrations inferior to those which are now available from a number of external sources. Over the past several years, several different sources have been used. Initially, calibrations based primarily (although not exclusively) on classical astrometry (Ref. 20 and M. Feissel, private communication) were used. In the past several years, calibrations from a number of other sources (R. W. King, private communication) have been applied, with greatly improved results. In the current processing of mobile VLBI data, calibrations for UT1-UTC are those of Eubanks et al. (Ref. 21), in which data from Lunar Laser Ranging (LLR; see Ref. 22), VLBI-based data from the POLARIS project of the National Geodetic Survey (Ref. 23), DSN observations (Ref. 4), and data from the TEMPO project at JPL (Ref. 24) were combined with a Kalman filter based upon studies of atmospheric angular momentum. Within the next two years, improved calibrations based on Kalman filter combinations for all components of Earth orientation will be available (Ref. 21) as additional LLR stations come on-line and more frequent VLBI-based measurements are made. With these new calibrations, Earth orientation errors will become a negligible component in the mobile VLBI error budget (see Table 1 and Figs. 4 and 5).

B. Propagation Media

The total observed delay contains contributions due to the propagation media traversed by the radio waves. For individual stations, the total contributions for sources near the zenith may be as large as 120 cm for the ionosphere for X-band data recording, 220 cm for the dry troposphere at sea level and 30 cm for atmospheric water vapor; for sources at low elevations, these effects may be larger by factors of three or more. Clearly, the careful calibration of propagation media effects is one of the most challenging and important tasks requisite to attaining two-cm accuracy in mobile VLBI measurements.

Calibration of the ionosphere with the current mobile systems is obtained from simultaneous recording of data at S-band and X-band frequencies and combining of the separate delay (and delay rate) observables, based on an assumed inverse-squared frequency dependence for ionosphere dispersion. To the extent that higher-order terms in the dispersive relation are negligible, this approach provides an exact calibration of ionosphere effects. Prior to the implementation of the dual-frequency recording capability, data were recorded at X-band only. For these data, corrections to baseline solutions and covariances were determined empirically using data from a number of recent experiments with dual-frequency data recording (see Table 1 and Figs. 3, 4, and 5).

Calibration of the dry troposphere at the local zenith is obtained directly from the surface barometric pressure, corrected to the intersection of axes of the antenna. Mapping of the dry air mass from the zenith of the quasar line-of-sight is done using the mapping function of Chao (Ref. 25). Although the impact of error from mapping is minimized because of the relatively high (17 degrees) elevation angle cutoff used in mobile VLBI observations, the line-of-sight error may be as large as 1 cm for the Chao model (G. A. Lanyi and R. N. Treuhaft, private communication). This may cause shifts in the baseline vertical on the order of 1 cm. The combined error from the pressure measurement, the presence of horizontal pressure gradients, dynamic contributions to the barometric pressure, and from the mapping is approximately 1.5 cm for regional baselines.

Calibration of the atmospheric water vapor is obtained from water vapor radiometer (WVR) data. These data are used to extract the additional sky brightness along the quasar line-of-sight due to microwave emission from free water molecules. The WVR data are currently reduced using an algorithm developed by Claflin, Wu and Resch (Ref. 26). These calibrations, corrected to zenith, are accurate to about 2 cm (G. M. Resch, private communication). When WVR data are unavailable, calibrations are derived from an atmospheric model with surface meteorology (SM) data as input (Ref. 25). The SM-based calibrations are taken to be accurate to one-half the mean total value at zenith, which is typically in the range from 5 to 10 cm. The atmospheric water vapor dominates the error budget for the baseline vertical component, particularly when SM calibrations are used, as they were routinely in 1980.

The calibration of water vapor is expected to improve substantially in the next two years as new WVRs, developed by a CDP team made up of members from JPL, GSFC and the Bendix Corporation, become available (M. A. Janssen, private communication). Using these new WVRs, the calibration of atmospheric water vapor, corrected to zenith, will be accurate to about 0.5 cm, and this error source will no longer dominate the error budget for any one baseline component.

C. Mobile Survey Tie

The locations reported (see, e.g., Ref. 13) for the mobile VLBI sites are monumented ground reference points. The offset vector from the monument to the antenna intersection of axes (usually less than 10 cm in the horizontal plane) is measured using conventional surveying techniques. The consistency of repeated measurements of these vectors indicates that their accuracy is approximately 2 mm.

D. Source Positions

The positions of the radio sources that are used in the mobile VLBI observations in principle may be estimated from the mobile VLBI data itself. However, this source catalogue would be inferior in accuracy to several available catalogues which are based on larger data bases accumulated from large, fixed observatory antennas. Moreover, the estimation of source coordinates from the mobile VLBI data would weaken the solutions for the baseline coordinates.

The radio source positions and uncertainties adopted in the processing of the mobile VLBI data were derived from ten years of NASA DSN intercontinential VLBI data (Refs. 18 and 19). Positional uncertainties in the current DSN catalogue are on the order of 5 milliarcsec; these are expected to decrease by about a factor of five over the next two years (O. J. Sovers, private communication).

E. System Noise

The theoretical precision of the raw delay and delay rate observables is dependent on a combination of factors (see, e.g., Ref. 3), including telescope diameter, system temperature and receiver spanned bandwidth. As discussed earlier, the aperture sizes of the mobile systems may be smaller by an order of magnitude than that of fixed observatory telescopes used in geodetic measurements, resulting in decreased SNR and baseline measurement precision. To mitigate this problem, the CDP has provided two important system improvements to enhance the SNR of the mobile stations. One of these is the computer-controlled Mark III data recording system, which provides an increased bandwidth of up to 56 MHz, compared to 2 MHz for the Mark II system. The other is the installation of cooled field-effect transistor (FET) receivers to replace the traveling wave maser (TWM) receivers at the antenna feed. The FET receivers permit a spanned bandwidth at X-band of 400 MHz, whereas the TWM receivers were generally limited to 40 MHz. These two upgrades in principle can reduce system noise errors by greater than an order of magnitude, and in fact the improvement realized is about a factor of ten.

F. Other Random Errors

After parameter estimation, the RMS scatter of the delay residuals (i.e., observed delay minus theoretical delay) is invariably found to be substantially larger than expected based on system noise errors. This phenomenon is normally accommodated in the routine processing by addition in quadrature of white noise to the system noise errors of the individual observations, such that the normalized chi-square after parameter adjustment is one. Clearly, there are significant contributions to the total delay which are not represented in the theoretical delay model. Although it is for the present largely conjectural, it seems likely that these unmodeled random errors arise from high frequency instabilities in the time and frequency distribution (and other instrumental) systems and in the troposphere. In addition, there may be contributions from the effects of ocean loading, and radio source structure, which are not fully modeled in the current software, although mismodeling of these may lead to a mixture of random and systematic errors.

G. Processing Scatter

It has long been known that, in the course of routine data processing of VLBI data, there exist problems with repeatability in the cross-correlation process and in the estimation of geodetic parameters from a given set of observables. Both of these have historically come to be viewed as sources of random error. However, recent investigations by R. N. Treuhaft (private communication) and A. E. E. Rogers (private communication) indicate that the first of these phenomena is a simple consequence of random data loss during input to the correlator, attributable to the poor quality of the magnetic tapes used, and that once the data have been successfully read from the tapes, the cross-correlation and observable extraction processes proceed without error. Hence, correlator nonrepeatability is not an error source; rather, it is in effect a loss of signal-to-noise ratio, but one which is properly modeled in the extraction of observables and for which no additional error modeling is necessary or even appropriate. In the case of geodetic parameter estimation, as with correlation, there is data loss, in this case resulting from analysts' subjective decisions in the deletion of spurious data points. (In addition, the analyst may make decisions regarding modeling of station clock behavior.) Although the character of this data loss depends somewhat on the skill of the analysts and on the quality of the data, it would appear for the current mobile systems that this process too is effectively random. Hence, nonrepeatability in parameter estimation, as with correlation, is not an error source and no additional error modeling is necessary. Both of these problems have been reduced substantially by improvements in the quality of magnetic recording tapes available for use in mobile VLBI experiments and by overall improvements in quality of data produced by the mobile systems, reducing the need for human intervention in the processing of data.

H. Other Systematic Errors

Systematic errors are more difficult to detect than random errors, because they generally have no first-order effect on the size of the residual scatter. Further, they may have no effect on the consistency of repeated measurements made using the same technique, at least over short time spans. Moreover, systematic errors which vary on annual, or longer, time scales may be indistinguishable from actual tectonic motions. One way of testing for systematic errors is by comparing measurements made using different techniques of comparable precision. A preliminary comparison of VLBI (mobile and observatory-based) results with results from collocated satellite laser ranging (SLR) measurements (J. Ryan, private communication) shows consistency between the two techniques at about the level of the quadratically summed formal errors. Since there are few error sources common to both techniques, it is unlikely that there are unmodeled systematic errors in either technique which are as large as the formal errors themselves. Nevertheless, there are several mechanisms which may give rise to systematic errors on the order of one centimeter in the mobile VLBI results. These include: incomplete phase calibration, antenna flexure effects, interaction of the Earth's magnetic field with the receiver, the effects of ocean loading, radio source structure and mapping of the zenith dry troposphere to quasar elevation. To acknowledge the presence of these error sources, and in lieu for the time being of a more concise estimate of their significance, we have included these in Table 1 and in Figs. 3, 4, and 5 for the current mobile VLBI systems as 1 centimeter for the baseline length and horizontal transverse components and 2 centimeters for the baseline vertical component.

IV. Comparison to Results

In this section, we examine current baseline results (Ref. 13) for the Owens Valley Radio Observatory (OVRO)–JPL (335 km) and OVRO–Quincy (383 km) baselines and evaluate them for internal consistency. Based on these results, we conclude that the repeatability of multiple baseline measurements is consistent with the uncertainties derived from the error model presented in the previous section. This is consistent with the claim that the current estimates are realistic and that the mobile VLBI systems have attained an accuracy in the horizontal plane of better than 2 cm, overcoming the challenge posed by the mobile environment.

A. The OVRO—JPL Baseline

The mobile VLBI site at JPL has been occupied fifteen times between January of 1980 and the present. These occupations have resulted in eighteen separate measurements of the baseline between JPL and the 40-meter-diameter radio telescope of the OVRO, Big Pine, California. As has been pointed out in preceding sections of this paper, the mobile systems have undergone a substantial evolution in terms of system engineering over this period. Thus, the JPL–OVRO baseline is a good case in point to illustrate the effect of system improvements and to test consistency for the mobile VLBI baseline results.

Results from the current Mobile VLBI data base (Ref. 13) for the JPL–OVRO baseline are presented in Figs. 6a to 6c. These figures show error ellipsoids (one standard deviation) in the horizontal plane. The temporal history of this baseline is divided into three periods. The first is from January of 1980 through May of 1981 (shown in Fig. 6a). All of those data were collected using the "original" mobile VLBI system of 1980, that is, using Mark II data recording; 40-MHz, narrow-passband TWM receivers; and single-frequency X-band data recording. The second period is from August through November of 1981 (shown in Fig. 6b). These data were collected using Mark III data recording, and 400-MHz, passband, cooled FET receivers; however, only X-band data were recorded. In the third period, from October 1982 through February 1983, we show examples of data recorded using the fully upgraded, current mobile VLBI systems, including Mark III data recording; 400-MHz, passband, cooled FET receivers; and dual-frequency (S-X) data recording.

These figures contain several features which illustrate the effect of system improvements. First, it is clear from inspection that there is a considerable decrease in the size of the formal errors from 1980 to 1983. Moreover, there is a corresponding decrease in the scatter of these repeated measurements. To assess the consistency of the scatter and the formal errors, chi-square has been calculated for each coordinate of each figure. The results of these calculations are presented in Table 2, along with the probabilities for obtaining chi-square of that size or larger.

Before discussing the results of these calculations, it should be noted that there are three assumptions implicit in the way these tests were made:

(1) First, we assume that there is no significant contribution to the scatter in the repeated measurements arising from actual short-term (or episodic) tectonic motions within any of the three time periods. Although there is no a priori reason to make this assumption, we note that such motions would tend to make chi-square anomalously large, whereas it actually tends to be somewhat smaller than expected. Further, there is no evidence for significant long-term motion on this baseline (see Section V).

(2) A second implicit assumption is that a meaningful chi-square may be calculated separately for each baseline coordinate, thus assuming, in effect, that there is no correlation between their errors.

(3) A third assumption is that there is no correlation between Earth orientation errors in separate experiments. This assumption is almost certainly incorrect for experiments separated by periods of less than a week. Hence we issue the caution that assumptions (2) and (3) may make chi-square anomalously small.

With the above in mind, we now consider the results of these tests. In Table 2, we see that for most cases, the scatter in the repeated solutions is reasonably representative of the formal errors, although there is some indication (in the length in Fig. 6a and the transverse in Fig. 6c) that the scatter is smaller than expected. (Possibly this is a breakdown of either or both of assumptions (2) and (3).) Hence, we conclude that the realistic uncertainties (one standard deviation) in horizontal components of the OVRO–JPL baselines are no worse (and possibly better) than the current formal errors, which are on the order of 1.5 cm in the horizontal plane. Similar plots for the baseline vertical coordinate (not included here because of space constraints) show essentially the same agreement with the error model.

B. The OVRO—Quincy Baseline

The mobile VLBI remote site at Quincy in Northern California has been occupied by the Mobile VLBI stations in October 1982 and June 1983. (An additional occupation occurred in April of 1984, but those data are not yet available from the Crustal Dynamics Data Information System (Ref. 11).) The monitoring of crustal motions involving the Quincy site is of particular interest because of its reported southward motion of 6.5 ± 1.5 cm/yr with respect to the Monument Peak site, some 883 km away in the extreme south of California, based on SLR measurements made between 1970 and 1979 (Ref. 27). Although the mobile VLBI surveying history for these two sites as of this writing is too short to make a confirmation of the published SLR result, it is nevertheless of great interest to examine the first-epoch measurements to evaluate their accuracy.

Results from the current mobile VLBI data base (Ref. 13) for the OVRO–Quincy baseline are presented in Fig. 6d for the October 1982 occupation (experiments 82E and 82G) and the June 1983 occupation (experiment 83F). As inspection of this figure shows, the three measurements have formal errors on the order of 1 cm in the horizontal plane. Chi-square calculations for these data (Table 2) lead to the same basic conclusion as in the case of the OVRO–JPL baseline. First-epoch measurements of the OVRO–Monument Peak baseline (not shown) give results of similar accuracy. Thus, if the motion reported from observations between 1970 and 1979 in the SLR-based measurements (Ref. 27) is still occurring, then it will be easily detected within the next two years, as current CDP observing plans (R. J. Coates, private communication) call for annual reoccupations of both of these sites.

V. Discussion

In this article, we have presented a description of the mobile VLBI systems and the engineering and technical steps that were taken to optimize their performance under field conditions. An error model was presented and its predictions were found to be consistent with the observed scatter in repeated measurements. This suggests that the error model is realistic and that the accuracy in the horizontal plane of mobile VLBI measurements has reached the level of 2 cm or better.

This accuracy should improve further within the next two years as improved calibrations for Earth orientation and atmospheric water vapor become available. The anticipated accuracy at that time for regional baselines (up to 1000 km in length) will be approximately 1.5 cm in the length and horizontal transverse and 3.5 cm in the baseline vertical. The most important remaining error sources at that time will be random errors, probably from unmodeled troposphere and station clock (and other instrumental) behavior. These problems are currently being studied at JPL and other VLBI centers; however, they may ultimately prove to be difficult to eliminate entirely from the mobile VLBI error budget.

One possible means of increasing mobile system precision by possibly an order of magnitude, in effect circumventing the problems described above, lies in the use of the phase delay observable, rather than the presently used group delay, as the input to parameter estimation. Preliminary results for very short baseline (length < 20 km) phase-delay measurements (K. M. Liewer, private communication, and Ref. 28) are extremely encouraging. However, it remains to be seen whether the phase delay data type can be used routinely on regional baselines, using the small-diameter mobile VLBI telescopes.

These remaining problems notwithstanding, it should be emphasized that the current mobile systems have a sensitivity to crustal motion, over a four-year period of monitoring, of about 0.5 cm/year (one standard deviation), assuming even a rather modest observing scenario of only one site occupation per year. More frequent monitoring will lead to even higher sensitivity. Since the geological rates of horizontal motion are on the order of 5 cm/yr across the plate boundary regions being studied in California and Alaska (Ref. 14), it seems likely that crustal motions will be detected using the mobile systems within the next few years, provided they are presently occurring at the geological rates.

Acknowledgment

This article consists partially of materials representing the personal accomplishments of the authors, both of whom have been involved in the mobile VLBI project at JPL for many years. However, the bulk of the materials and results presented herein represent the multi-year efforts of dozens of individuals, some of whom we list here. The mobile VLBI project was initially founded at JPL under the name of Project ARIES by Peter F. MacDoran, George M. Resch and Arthur E. Niell. Development of the MV-3 mobile VLBI system, initially known by the name of Project ORION, was led by Charles J. Vegos and Gary S. Parks. The mobile VLBI field operations were coordinated and directed by Charles J. Vegos. The extensive software system, containing Earth model and matrix inversion routines, used in the reduction of mobile VLBI data was conceived and written by John L. Fanselow. Considerable physical insight into the workings of mobile VLBI systems and understanding of error sources was provided by a number of analysts, including Arthur E. Niell, John L. Fanselow, J. Brooks Thomas and Steven L. Allen. The Mobile VLBI Project is a part of the JPL Geodynamics Project, managed by Dr. Nicholas A. Renzetti.

References

1. J. W. Ryan, T. A. Clark, R. J. Coates, B. E. Corey, W. D. Cotton, C. C. Counselman, III, H. F. Hinteregger, C. A. Knight, C. Ma, D. S. Robertson, A. E. E. Rogers, I. I. Shapiro, A. R. Whitney, and J. J. Wittels, "Precision Surveying Using Radio Interferometry," J. Surveying and Mapping Div., Proc. ASCE, vol. 104, no. SU1, pp. 25-34, 1978.

2. T. A. Herring, B. E. Corey, C. C. Counselman, III, I. I. Shapiro, B. O. Ronnang, O. E. H. Rydbeck, N. R. Vandenberg, H. F. Hinteregger, C. A. Knight, A. E. E. Rogers, A. R. Whitney, D. S. Robertson, and B. R. Schupler, "Geodesy by Radio Interferometry: Intercontinental Distance Determinations with Subdecimeter Precision," J. Geophys. Res., 86, pp. 1647-1651, 1981.

3. A. R. Whitney, A. E. E. Rogers, H. F. Hinteregger, C. A. Knight, J. I. Levine, S. Lippincot, T. A. Clark, I. I. Shapiro, and D. S. Robertson, "A Very-Long-Baseline Interferometer System for Geodetic Applications," Rad. Sci., 11, pp. 421-432, 1976.

4. O. J. Sovers, J. B. Thomas, J. L. Fanselow, E. J. Cohen, G. H. Purcell, Jr., D. H. Rogstad, L. J. Skjerve, and D. J. Spitzmesser, "Radio Interferometric Determination of Intercontinental Baselines and Earth Orientation Utilizing Deep Space Network Antennas," J. Geophys. Res. (in press).

5. J. B. Thomas, J. L. Fanselow, P. F. MacDoran, L. J. Skjerve, D. J. Spitzmesser, and H. F. Fliegel, "A Demonstration of an Independent-Station Radio Interferometry System with 4-cm Precision on a 16-km Baseline," J. Geophys. Res., 81, pp. 995-1005, 1976.

6. A. E. Niell, K. M. Ong, P. F. MacDoran, G. M. Resch, D. D. Morabito, E. S. Claflin, and J. F. Dracup, "Comparison of a Radio Interferometric Differential Baseline Measurement with Conventional Geodesy," Tectonophysics, 52, pp. 49-58, 1979.

7. K. M. Ong, P. F. MacDoran, J. B. Thomas, H. F. Fliegel, L. J. Skjerve, D. J. Spitzmesser, P. D. Batelaan, and S. R. Paine, "A Demonstration of a Transportable Radio Interferometric Surveying System with 3-cm Accuracy on a 307-m Base Line," J. Geophys. Res., 81, pp. 3587-3593, 1976.

8. "Application of Space Technology to Crustal Dynamics and Earthquake Research," NASA Technical Paper 1464, GSFC, Greenbelt, MD, August 1979.

9. D. W. Trask, M. L. Brunn, E. J. Cohen, J. M. Davidson, J. L. Fanselow, P. F. MacDoran, R. B. Miller, A. E. Niell, G. S. Parks, G. M. Resch, L. J. Skjerve, C. J. Vegos, and K. S. Wallace, "Mobile VLBI Surveying: Instrumentation, Operating Procedures, and Survey Results of ARIES," Proceedings of Symposium No. 5: Geodetic Applications of Radio Astronomy, ed. William Carter, U. S. Department of Commerce, National Oceanic and Atmospheric Administration, Washington, D.C., pp. 120-133, 1982.

10. D. W. Trask, M. L. Brunn, J. M. Davidson, J. L. Fanselow, A. E. Niell, G. M. Resch, and K. S. Wallace, "Response of the Mobile VLBI Design to Error Sources," Proceedings of Interferometry, Centre National d'Etudes Spatiales, Toulouse, France, pp. 88-108, 1982.

11. H. G. Linder, and C. E. Noll, "Crustal Dynamics Data Information System User's Guide," NASA/GSFC Document X-931-82-14, GSFC, Greenbelt, MD, October 1982.

12. C. E. Noll, E. A. Creamer, R. J. Allenby, H. G. Linder, and G. D. Mead, "Crustal Dynamics Catalogue of Site Information (Review Copy)," NASA/GSFC Document X-904-83-14, GSFC, Greenbelt, MD, September 1983.

13. P. M. Kroger, S. L. Allen, B. C. Beckman, J. M. Davidson, J. E. Patterson, M. A. Slade, J. S. Spitler, and F. P. Wieland, "Current Mobile VLBI Data Base Submitted to the NASA Crustal Dynamics Data Information System," GSFC, Greenbelt, MD, 4 July 1984.

14. J. B. Minster and T. H. Jordan, "Present-Day Plate Motions," J. Geophys. Res., 83, pp. 5331-5354, 1978.

15. J. B. Thomas, "An Analysis of Long Baseline Radio Interferometry," DSN Progress Report, JPL Technical Report 32-1526, Vol. VII, pp. 37-50, Vol. VIII, pp. 29-38, and Vol. XVI, pp. 47-64, Jet Propulsion Laboratory, Pasadena, California, 1972.

16. I. I. Shapiro, "Estimation of Astrometric and Geodetic Parameters from VLBI Observations," Methods of Experimental Physics, ed. M. L. Meeks, Academic Press, New York, pp. 261-276, 1976.

17. S. L. Allen, "Earth Orientation Effects on Mobile VLBI Baselines," TDA Progress Report 42-78, pp. 202-215, Jet Propulsion Laboratory, Pasadena, California, 1984.

18. J. B. Thomas, O. J. Sovers, J. L. Fanselow, E. J. Cohen, G. H. Purcell, Jr., D. H. Rogstad, L. J. Skjerve, and D. J. Spitzmesser, "Radio Interferometric Determination of Source Positions, Intercontinental Baselines, and Earth Orientation with Deep Space Network Antennas–1971 to 1980," TDA Progress Report 42-73, pp. 128-155, Jet Propulsion Laboratory, Pasadena, California, 1983.

19. J. L. Fanselow, O. J. Sovers, J. B. Thomas, G. H. Purcell, Jr., E. J. Cohen, D. H. Rogstad, L. J. Skjerve, and D. J. Spitzmesser, "Radio Interferometric Determination of Source Positions Utilizing Deep Space Network Antennas–1971 to 1980," Astron. J. (in press).

20. M. Feissel, BIH (Bureau International de l'Heure) Annual Report, 1982.

21. T. M. Eubanks, J. A. Steppe, and M. A. Spieth, "The Accuracy of Radio Interferometric Measurements of Earth Rotation," TDA Progress Report 42-80, Jet Propulsion Laboratory, Pasadena, California, 1984.

22. J. O. Dickey and J. G. Williams, "Earth Rotation from Lunar Laser Ranging," Astron. Astrophys. Suppl. Ser., 54, pp. 519-540, 1983.

23. W. E. Carter, D. S. Robertson, J. E. Pettey, B. D. Tapley, B. E. Schutz, R. J. Eanes and M. Lufeng, "Variations in the Rotation of the Earth," Science, 224, pp. 957-961, 1984.

24. T. M. Eubanks, M. G. Roth, P. B. Esposito, J. A. Steppe and P. S. Callahan, "An Analysis of TEMPO Earth Orientation Results," Proceedings of Symposium No. 5: Geodetic Applications of Radio Astronomy, ed. William Carter, U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Washington, D.C., pp. 152-162, 1982.

25. C. C. Chao, "A New Method to Predict Wet Zenith Range Correction from Surface Measurements," DSN Progress Report 32-1526, Vol. XIV, pp. 33-41, Jet Propulsion Laboratory, Pasadena, California, 1973; and A. L. Berman, "The Prediction of Zenith Range Refraction from Surface Measurements of Meteorological Parameters," JPL Technical Report 32-1602, Jet Propulsion Laboratory, Pasadena, California, 1976.

26. E. S. Claflin, S. C. Wu, and G. M. Resch, "Microwave Radiometer Measurement of Water Vapor Path Delay: Data Reduction Techniques," DSN Progress Report 42-48, pp. 22-30, Jet Propulsion Laboratory, Pasadena, California, 1978; and S. C. Wu, "Optimum Frequencies of a Passive Microwave Radiometer for Tropospheric Path Length Correction," IEEE Transactions on Antennas and Propagation, Vol. AP-27, No. 2, pp. 233-239, 1979.

27. D. E. Smith, R. Kolenkiewicz, P. J. Dunn, and M. H. Torrence, "The Measurements of Fault Motion by Satellite Laser Ranging," Tectonophysics, Vol. 52, pp. 59-67, 1979.

28. A. E. E. Rogers, C. A. Knight, H. F. Hinteregger, A. R. Whitney, C. C. Counselman, III, I. I. Shapiro, S. S. Gourevitch, and T. A. Clark, "Geodesy by Radio Interferometry: Determination of a 1.24 km Baseline with ~5-mm Repeatability," J. Geophys. Res., 83, pp. 325-334, 1978.

Table 1. Error model inputs[a]

Error Source	Assumed Uncertainty in Year		
	1980[b]	1984	1986
Earth Orientation			
UT1-UTC	2 milliseconds	0.2 milliseconds	0.07 milliseconds
X-pole	10 milliarcsec	7 milliarcsec	2.0 milliarcsec
Y-pole	10 milliarcsec	7 milliarcsec	1.5 milliarcsec
Transmission Media			
Water Vapor (Zenith)	5 cm	2 cm	0.5 cm
Dry Air (Zenith)	1 cm	1 cm	1 cm
Dry Air (Mapping)[c]	1 cm	1 cm	1 cm
Ionosphere[d,e]			
Length	1.1 cm/500 km	0 cm	0 cm
Transverse	2.4 cm	0 cm	0 cm
Vertical	6.2 cm	0 cm	0 cm
Mobile Survey Tie	0.5 cm	0.2 cm	0.2 cm
Source Positions	20-50 milliarsec	5 milliarcsec	1 milliarcsec
System Noise	300 picoseconds	50 picoseconds	50 picoseconds
Other Random (Clocks, troposphere, other)	150 picoseconds	50 picoseconds	50 picoseconds
Other Systematic[d]			
Length, Transverse	2 cm	2 cm	1 cm
Vertical	5 cm	5 cm	2.5 cm

[a] Except where otherwise indicated (see footnote c), the quoted value denotes the error in the calibration or error source, not the resulting error in the baseline component.

[b] Current (1984) uncertainties for Earth orientation and source positions permit reprocessing of 1980 data with improved accuracy. The values presented here serve to illustrate improvements in the quality of mobile VLBI results in a historical perspective.

[c] This is the error in the Chao mapping function at 17 degrees, which is the elevation angle cutoff for the mobile systems.

[d] The quoted value is not the error in the calibration or error source itself; it is the empirically determined error in the baseline resulting from this error source.

[e] An average level of 1.0×10^{17} electrons/cm^2 is assumed for the zenith columnar ionosphere content.

Table 2. Chi-square calculations[a]

Baseline	Dates	Degrees of Freedom	Chi-square		Probability[b]	
			Length	Transverse	Length	Transverse
OVRO–JPL	1/80–5/81	6	1.3	5.9	97	56
OVRO–JPL	8/81–11/81	3	0.84	1.8	83	62
OVRO–JPL	10/82–2/83	3	2.4	0.12	49	99
OVRO–Quincy	10/82 6/83	2	1.3	0.24	52	89

[a]The data from which these are calculated are graphically displayed in Fig. 6.

[b]The listed values give probability (units of percentage) of obtaining chi-square that large or larger.

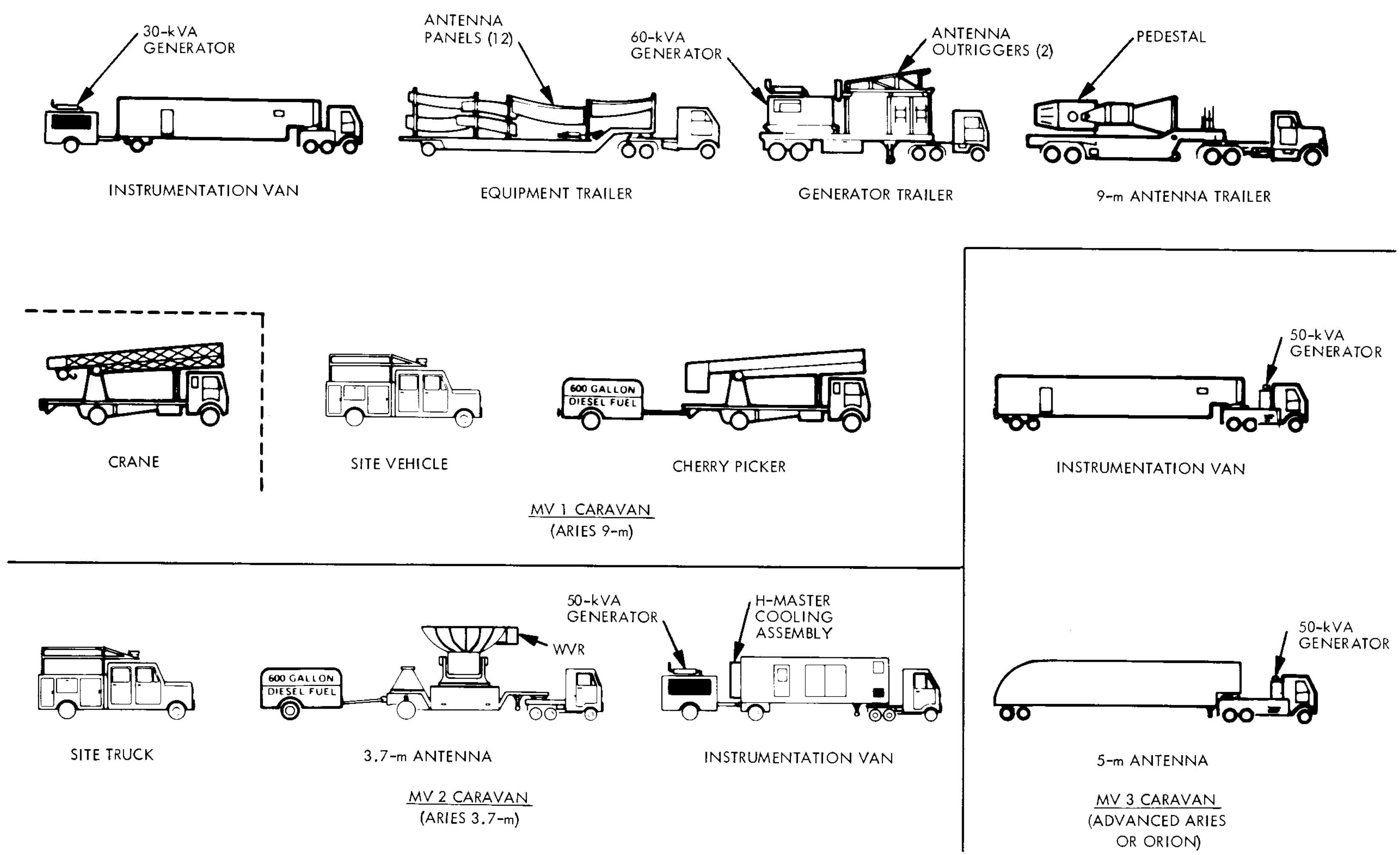

Fig. 1. Schematic depictions of the transit configurations of the three mobile VLBI stations

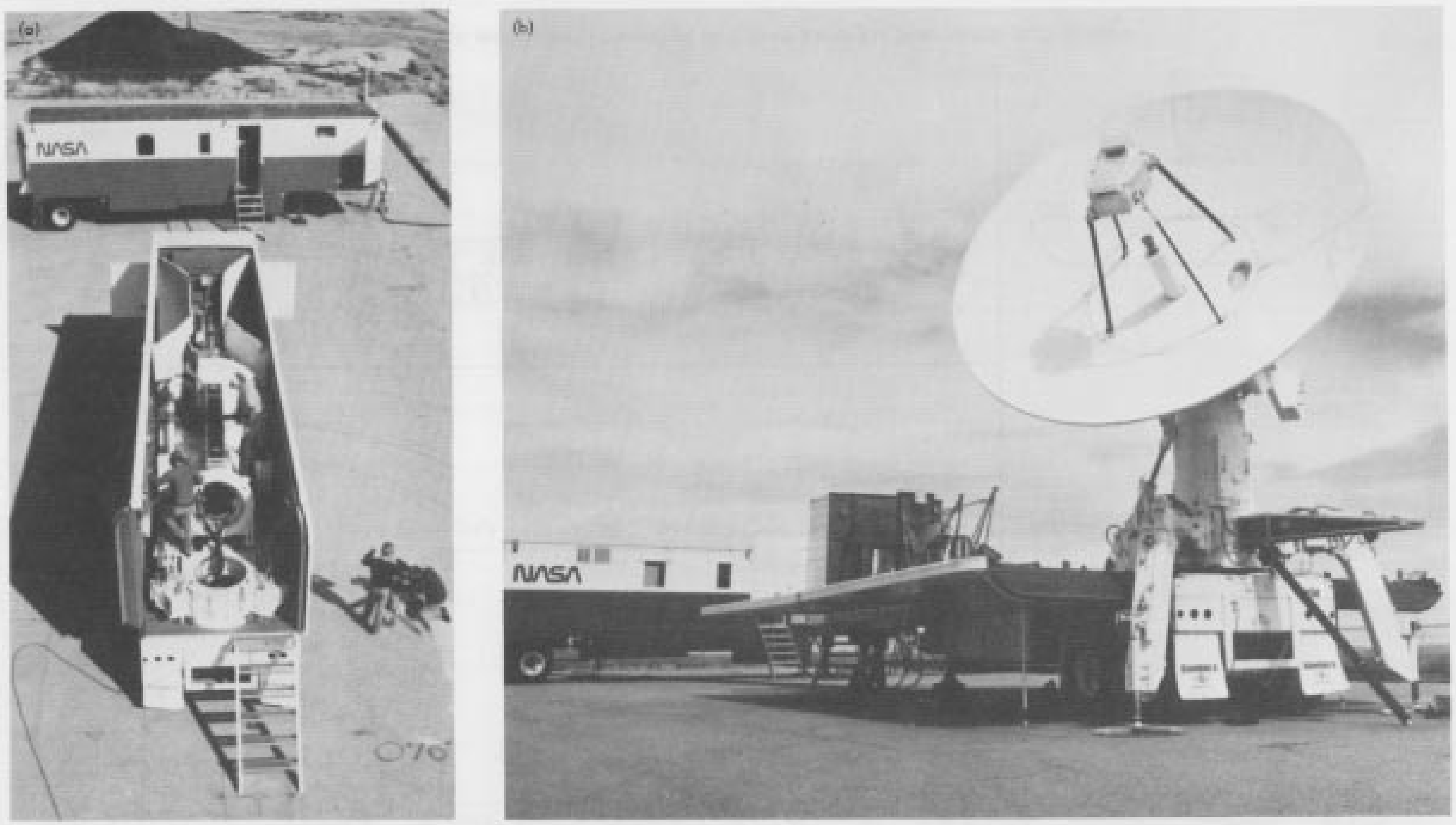

Fig. 2. MV-3 in: (a) its transit configuration and (b) its deployed configuration

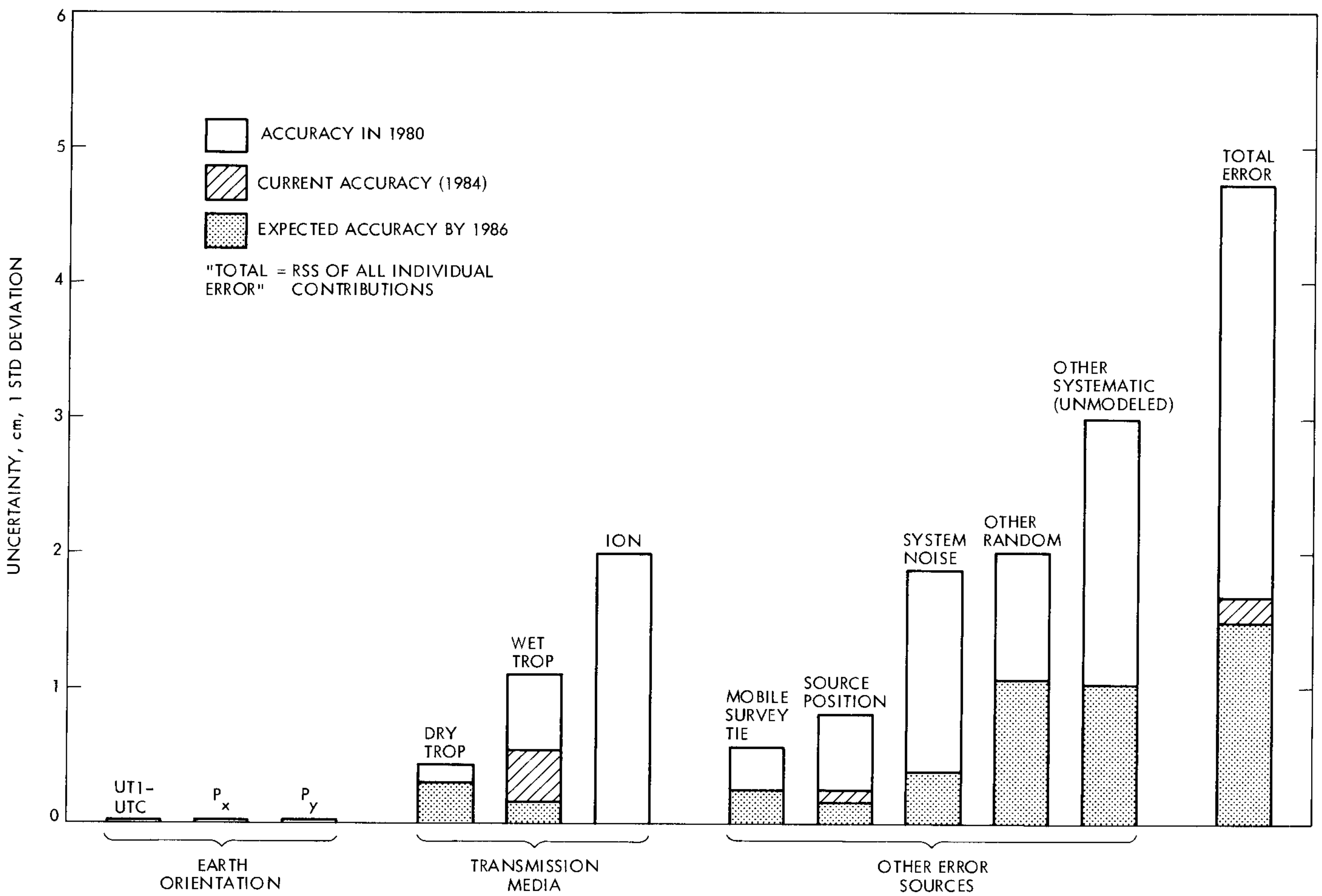

Fig. 3. The error budget for the length component for the example of the Monument Peak—Quincy baseline

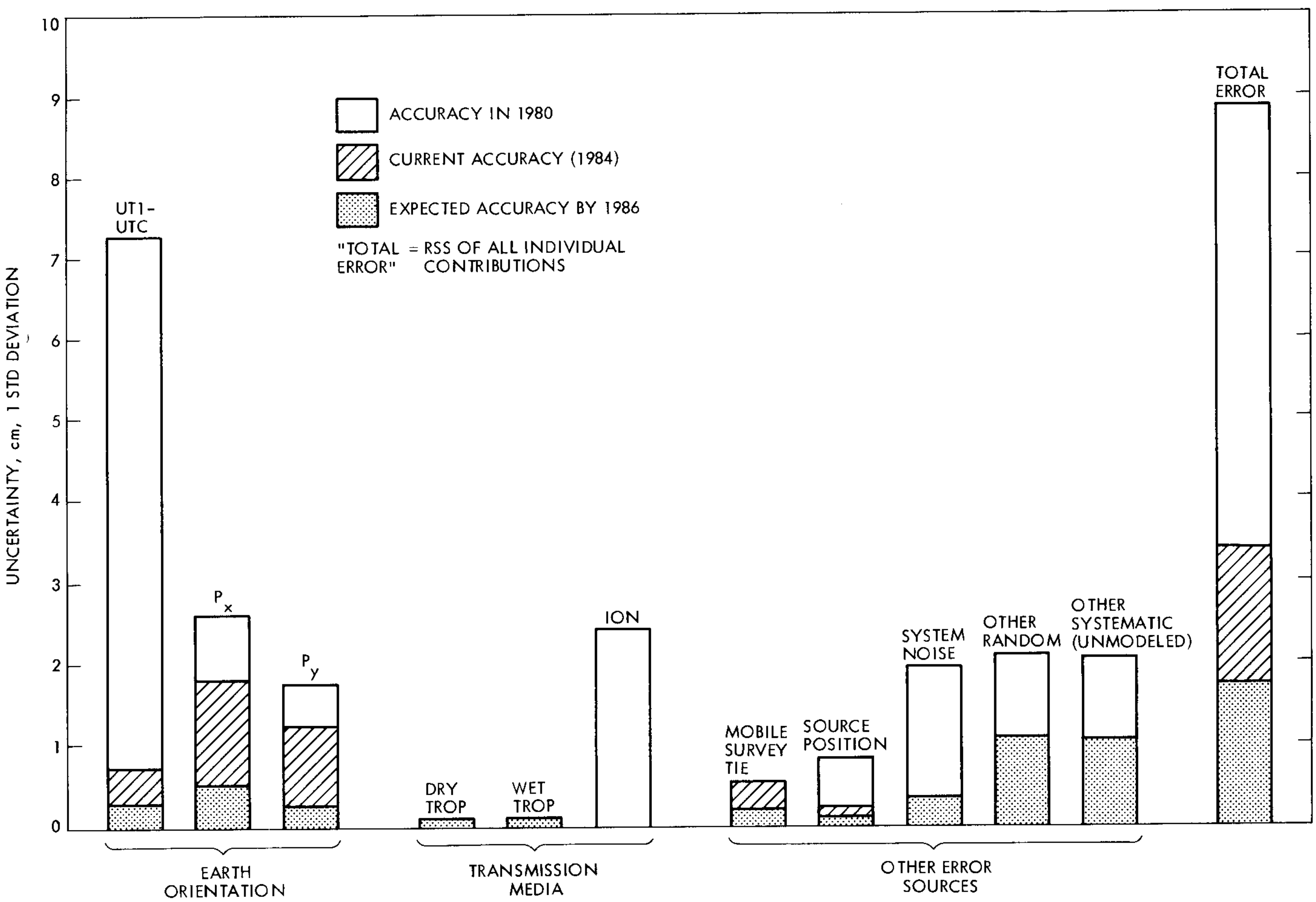

Fig. 4. The error budget for the horizontal transverse component for the example of the Monument Peak—Quincy baseline

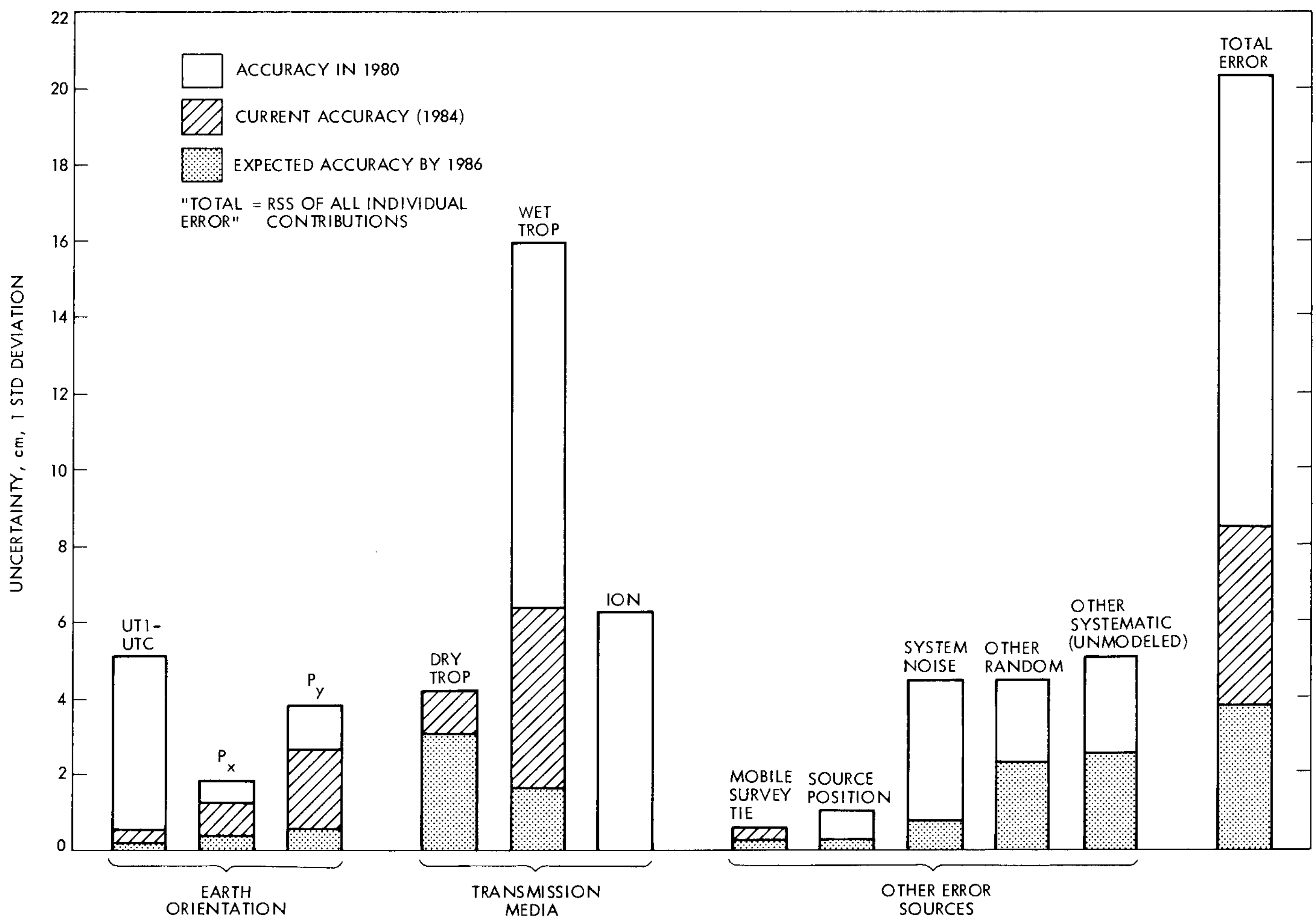

Fig. 5. The error budget for the baseline vertical component for the example of the Monument Peak—Quincy baseline

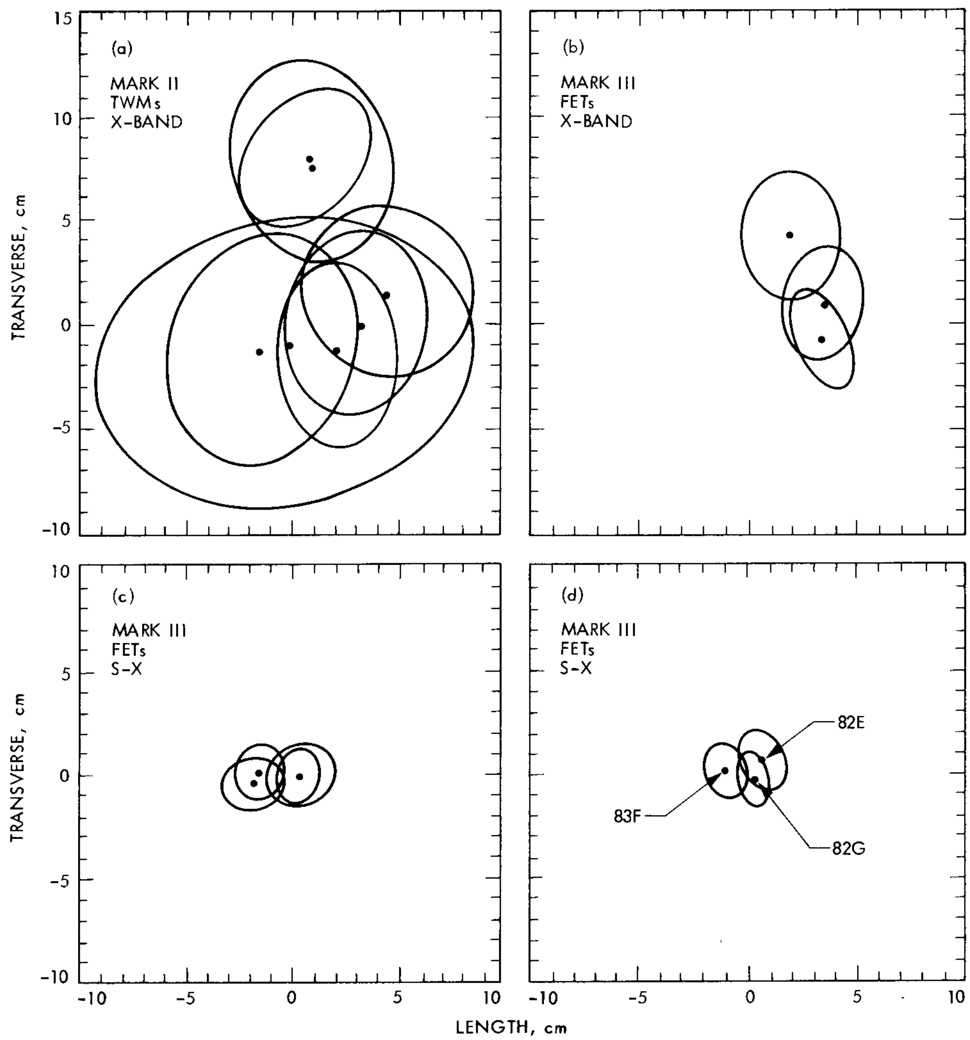

Fig. 6. Error ellipsoids in the horizontal plane for: (a) the OVRO—JPL baseline from January 1980 to May 1981, (b) the OVRO—JPL baseline from August 1981 to November 1981, (c) the OVRO—JPL baseline from October 1982 to February 1983, and (d) the OVRO—Quincy baseline from October 1982 to June 1983. These error ellipsoids illustrate various stages of mobile VLBI system development over the past four years. Consistency of the measurements made using the current system (see Figs. 6c and 6d) appears to be on the order of 2 cm or better.