The March 1985 Demonstration of the Fiducial Network Concept for GPS Geodesy: A Preliminary Report

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The first field tests in preparation for the NASA Global Positioning System (GPS) Caribbean Initiative were conducted in late March and early April of 1985. GPS receivers were located at the POLARIS VLBI stations at Westford, Massachusetts; Richmond, Florida; and Ft. Davis, Texas; and at the Mojave, Owens Valley, and Hat Creek VLBI stations in California. Other mobile receivers were placed near Mammoth Lakes, California; Pt. Mugu, California; Austin, Texas; and Dahlgren, Virginia. These sites were equipped with a combination of GPS receiver types, including SERIES-X, TI-4100 and AFGL dual frequency receivers. The principal objectives of these tests were the demonstration of the fiducial network concept for precise GPS geodesy, the performance assessment of the participating GPS receiver types, and to conduct the first in a series of experiments to monitor ground deformation in the Mammoth Lakes-Long Valley caldera region in California. Other objectives included the testing of the water vapor radiometers for the calibration of GPS data, the development of efficient procedures for planning and coordinating GPS field exercises, the establishment of institutional interfaces for future cooperative ventures, the testing of the GPS Data Analysis Software (GIPSY, for GPS Inferred Positioning SYstem), and the establishment of a set of calibration baselines in California. Preliminary reports of the success of the field tests, including receiver performance and data quality, and on the status of the data analysis software are given.

I. Introduction

The development of geodetic surveying systems based on the Global Positioning System (GPS) satellites is motivated by the promise of high performance, mobility and low cost. The large number of measurements which can be economically made using GPS-based systems will enable the resolution of many geophysical questions which are inaccessible to the more costly VLBI or laser techniques. However, the use of GPS receivers for high-precision geodesy is still in its infancy, and much work remains in assessing system performance and understanding sources of error. Two major system components are still in the developmental or validation stage. These are the water vapor radiometers (WVRs) and the GPS receivers themselves. A third system element, the fiducial network, has received considerable investigation via covariance analysis (e.g.,

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Ref. 1[2]) but has not yet been tested in the field. The WVRs are currently undergoing extensive testing.

In this article, we report the results of recent field tests of the GPS receivers and of the fiducial network concept. These tests took place between March 28 and April 4, 1985. GPS receivers were placed at the NOAA/NGS POLARIS VLBI stations (Ref. 2) in Westford, Massachusetts; Richmond, Florida; and Ft. Davis, Texas; and at the Mojave, Owens Valley, and Hat Creek stations in California. Additional GPS receivers located near Mammoth Lakes, California, Austin, Texas, and Dahlgren, Virginia (Fig. 1) also recorded data during the test. The sites were equipped with a combination of GPS receiver types, including SERIES-X, TI-4100 and Air Force Geophysical Laboratory (AFGL) dual-frequency receivers. Three of the sites in California were equipped with WVRs (Table 1). In all, seventeen different institutions made contributions to this test (Table 2).

II. The Fiducial Network Concept

The accuracy of GPS-based baseline measurements depends in part on the accuracies with which the GPS satellite orbits are known. For baselines of 100 km length, simple geometric arguments show that orbit accuracies of the order 2.5 m are required to attain a baseline accuracy of 1 cm (Fig 2). For baselines lengths of several hundred km or more, orbit accuracies of better than 50 cm are required. Currently available GPS ephemerides are in error at the level of ten meters or more. Hence, results of geodetic quality are limited to baselines of no more than a few tens of km, unless a method of improving satellite ephemerides is devised.

A fiducial network approach has been proposed by JPL for improving satellite orbit accuracy (Ref. 3; J. L. Fanselow and J. B. Thomas, 1983, private communication). In the fiducial network approach, three or more GPS receivers are placed at sites, called fiducial stations, whose positions are well established by an independent geodetic technique, such as VLBI or satellite laser ranging (SLR). Other receivers, called mobile receivers, are placed at sites of geodetic interest. During a GPS geodetic experiment, the fiducial receivers record data jointly with the mobile receivers (Fig. 3), enabling the simultaneous determination of accurate GPS satellite orbits and geodetic baselines. The effectiveness of the fiducial approach depends strongly on the locations of the fiducial receivers and on the accuracy with which the fiducial baselines are known a priori. Covariance analysis has shown that orbit accuracies of better than 3 meters are attainable using current systems, involving the POLARIS VLBI sites as fiducial stations and integrated GPS carrier doppler as the data type. Orbit accuracies of better than 50 cm could be attainable using a system which delivers unambiguous carrier ranging data and which may include a fiducial station located in the northern part of South America (Refs. 4, 1). The feasibility of such a system is currently being investigated at JPL (Ref. 5). If it proves feasible, and if planned receiver developments proceed smoothly, such a system could be operational by 1989.

It should be noted that the location of the fiducial receivers at VLBI stations has the advantage of automatically placing the GPS satellite orbits in the coordinate frame of the quasi-stellar radio sources. This has the aesthetic appeal of tying the GPS results to an absolute frame of reference. Further, it unifies the VLBI and GPS geodetic frames, enabling simultaneous display and easy intercomparison of GPS and VLBI three-dimensional baseline results.

III. Test Site Selection

The relative locations of the fiducial stations must be known to a few centimeters. Practical considerations limit the choices to locations which have some past history of VLBI (or SLR) measurement. For this reason, the VLBI stations of the POLARIS Project at Westford, MA, Richmond, FL, and Ft. Davis, TX, were chosen. (Fiducial stations for future GPS experiments may include additional sites which presently at least have the facilities available for making these measurements.)

The selection of the mobile sites was done to establish a set of calibration baselines and initiate a series of measurements to monitor ground deformation in the Long Valley caldera region of California. The stations at Mojave, Owens Valley and Hat Creek were selected as the endpoints for the calibration baselines. These stations were selected because of their easy access from JPL and from most of the participating organizations and because they involve colocations with VLBI and SLR geodetic systems. Hence, high geodetic quality intercomparison data are available. Further, baselines between these three sites are approximately colinear. For this case, errors in the baselines due to orbit uncertainties will be similar in character, but will scale with baseline length (Fig. 2) and should be separable from other error sources.

The Mammoth Lakes site was established as part of a JPL-Caltech program designed to supplement ongoing geodetic measurements by the U.S. Geological Survey. Part of this program consists of leveling surveys, designed to monitor

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vertical motion associated with the uplift of a resurgent dome in the Long Valley caldera. This is thought to be due to an intrusion of magma into a shallow (< 10 km) crustal reservoir, and represents a potential volcanic hazard. Because leveling surveys are expensive and error prone, it is desirable to develop supplemental techniques to monitoring vertical motion.

IV. Test Results

A. Receiver Performance

Three receiver types were involved in these field tests: the SERIES-X, the TI-4100 and the AFGL dual-frequency receivers. The SERIES-X receivers were built at JPL under the sponsorship of the Oceanic Processes Office of NASA's Office of Space Science and Applications; the TI-4100 receivers were developed by the Texas Instruments Corporation; and the AFGL dual-frequency receivers were developed by Macrometrics Incorporated for the Air Force Geophysical Laboratory (AFGL). Each of the ten participating stations in the test was equipped with one or more of these receivers (Table 1). All three receivers recorded data at both L-band frequencies (1.57542 GHz and 1.22760 GHz) broadcast by the GPS satellites, thus enabling reduction of ionosphere corruption of the data. Data were recorded each day by all receivers throughout a six-hour viewing window when the current constellation of seven usable GPS satellites was visible over North America. This six-hour window extended from approximately 5:00 to 11:00 GMT (9:00 P.M. to 3:00 A.M. PST). The TI-4100 receivers recorded data for two hours more than the others, beginning at 3:00 GMT. During this window, the TI-4100 and the AFGL receivers recorded data from six GPS satellites; the SERIES-X receivers recorded data from all visible satellites. Throughout the eight days of the test, WVRs at Mojave, Owens Valley and Hat Creek recorded data continuously, with no data loss. A map of the Western Hemisphere, showing fiducial and mobile stations, satellite ground tracks for the full eight-hour viewing period, and 15-deg horizon masks is presented in Fig. 4. In all, 106 station days of data recording were scheduled. Of these, only six station days of data were not recorded for various reasons. In general, the receivers operated smoothly and without technical problems. Tape changes were required only once every six hours with all receivers. Hence, tape changes were required only once a day. The acquisition of new satellites as they rose was fully automated by the field system computers, as was the deacquisition of setting ones. It was particularly noted by the authors, all of whom have experience with VLBI systems, that the operation of the GPS receiver systems seemed relatively uneventful, even dull.

At this writing, most of the data recorded appears to be of very high quality. Initial processing is currently under way at JPL. Data from all satellites has been successfully recovered for the first few days of the test and the receivers appear to have operated properly.

B. Fiducial Network Performance

The principal objective of the March 1985 field test was the demonstration of the feasibility of the fiducial network concept. The proof will lie in the degree to which the accuracy of the mobile station baselines is improved over that attainable in the absence of a fiducial network. Considerable analysis remains before this question can be answered. In the mean time, it is instructive to describe the improvement expected based on covariance analysis. Figure 5 presents results for the Mojave/Owens Valley baseline, based on the actual observing scenario for the March field tests. The error model assumptions made in this analysis were as follows. Data noise was taken to be 2 cm; zenith troposphere calibration was taken to be 2 cm at stations where there were WVR's and 5 cm otherwise; fiducial baseline accuracy was taken to be 3 cm in all coordinates; a priori satellite position and velocity at epoch were taken to be 10 meters and 1 mm/sec, respectively; uncertainty in geocenter location was taken to be 20 cm in all coordinates; modeling of solar radiation pressure on the GPS spacecraft was assumed to be accurate to within 5% of the total effect; the product of GM was taken to be accurate to a part in 1.E+08; and the error in the gravity model was taken to be 10% of the difference between the GEM6 and APL5.0 models; the elevation angle cutoff at each station was taken to be 15 degrees; and the data type used was carrier phase. These error model assumptions are standard ones for the current systems and are justified in detail elsewhere (Ref. 6). Two analyses of the March scenario were run, one in which the satellite epoch states were estimated (i.e., using the fiducial network) and one in which they were fixed at their a priori values (i.e., as if it were a two-station experiment with no fiducial network). An intermediate case in which there are ten GPS stations in the network and in which satellite orbits are estimated, but in which none of the GPS receivers have a priori known relative locations, gives results between the two extremes shown in Fig. 5. As Fig. 5 shows for the case of the Mojave/Owens Valley baseline, the use of a fiducial network is expected to improve accuracy for this baseline by factors of from five in the vertical to forty in the north. This improvement is dependent on baseline length and orientation and in general increases with baseline length.

C. Other Test Objectives

As outlined earlier, it was also among the objectives of the March field tests to develop efficient procedures for conducting large-scale GPS field operations and to establish institutional interfaces for future cooperative ventures. We feel that these objectives were attained.

Data from the field test are being used to test the GIPSY Software. The software tests began several months ago.

D. Delivery of Data

The raw data (observables, uncertainties and time tags) from this test has been made available to all participating organizations. In addition, important ancillary information (WVR and meteorology data, site eccentricities and fiducial baseline vectors) are available. Processed results (calibrated observables, ionosphere data, GPS satellite orbits and station locations and observables) will also be available to the test participants, but the delivery of these will lag the raw data delivery by several months.

V. Conclusions

The March 1985 field tests described in this article were conducted as preparation for the NASA GPS Caribbean Initiative. It would be premature at this time to make any definitive evaluation of the data quality or of the feasibility of GPS as a geodetic technology. However, as of now, the overall effort seems to have been a success, indicating the possibility of an initial deployment to one of the Caribbean countries. Re-occupation of most of the sites involved in the March test, as well as deployment to Baja California and mainland Mexico, took place in November 1985. As with the recently completed test, their efforts were collaborative.

References

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Table 1. Receiver, WVR deployment

Austin, TX	ARL TI-4100
Dahlgren, VA	ARL TI-4100
Ft. Davis, TX	TDH TI-4100
Hat Creek, CA	TI TI-4100, DSN R04 WVR
Mammoth Lakes, CA	ARL TI-4100
Mojave, CA	SERIES-X, TI TI-4100, CDP Retrofit WVR
Owens Valley, CA	SERIES-X, TI TI-4100, CDP Prototype WVR
Pt. Mugu, CA	PMTC TI-4100
Richmond, FL	AFGL dual-frequency, ARL TI-4100
Westford, MA	AFGL dual-frequency, ARL TI-4100

Table 2. Participating institutions and organizations

NASA Geodynamics Program
Applied Research Laboratory
Air Force Geophysical Laboratory
Bendix Corporation
California Institute of Technology
Crustal Dynamics Project
Defense Mapping Agency
Goddard Space Flight Center
Haystack Observatory
Interferometrics Incorporated
Jet Propulsion Laboratory
National Geodetic Survey
Naval Surface Weapons Center
Pacific Missile Test Center
Texas Department of Highways
Texas Instruments Corporation
United States Geological Survey
University Navstar Consortium

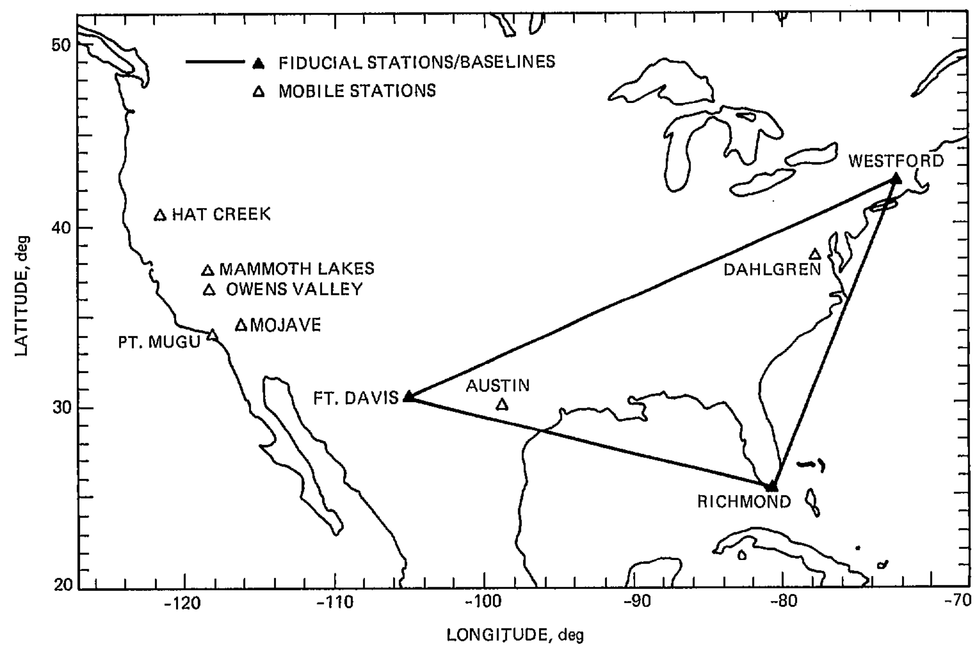

Fig. 1. The locations of the fiducial and mobile GPS receivers in the March 1985 demonstration

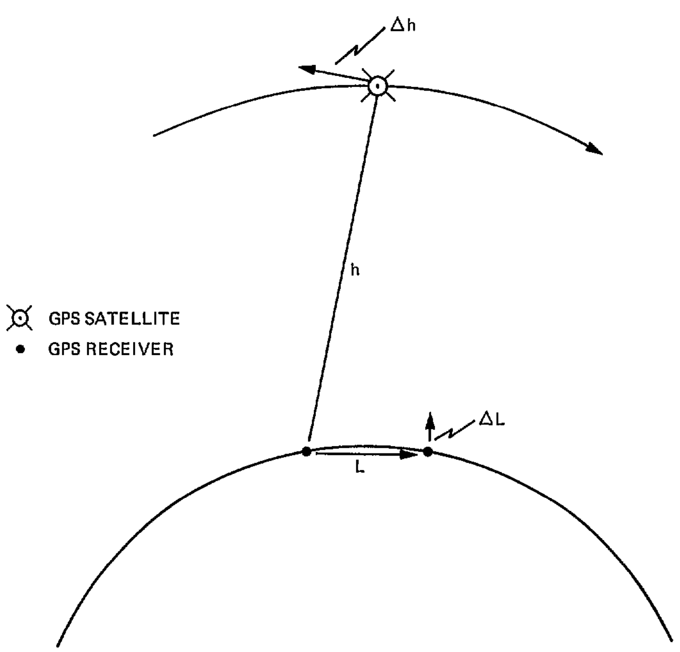

Fig. 2. The qualitative dependence of baseline accuracy on orbit accuracy is illustrated. Ground Stations track a GPS satellite. An error Δh in the satellite position results in an error ΔL in the baseline vector, such that $\Delta L \approx L/h * \Delta h$, where L is the baseline length and h is the satellite altitude. For L = 100 km, $\Delta L \approx \Delta h/250$.

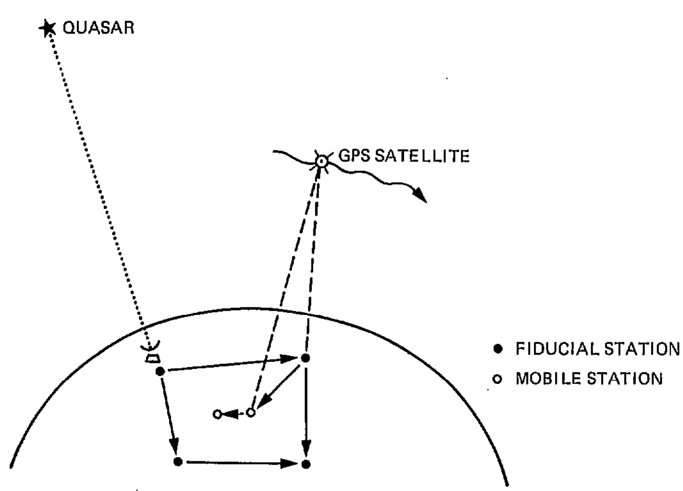

Figure 3. A schematic illustration of the fiducial network method for precision GPS geodesy is shown. Data from the fiducial stations enables accurate orbit determination, which in turn enables accurate mobile baseline determination. VLBI observations from the fiducial sites (not necessarily simultaneous with the GPS observations) determine fiducial baselines and tie the GPS results to the inertial frame of the quasistellar radio sources.

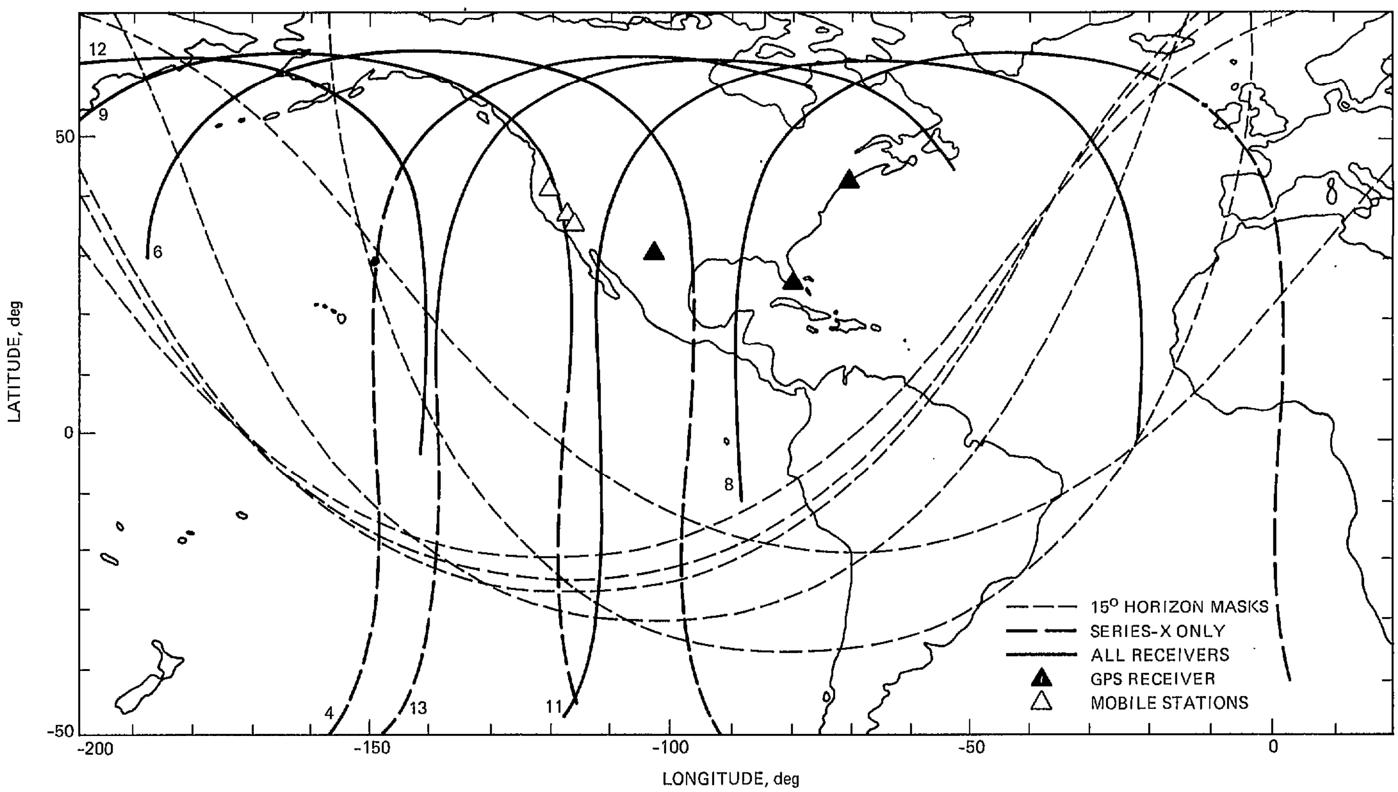

Figure 4. A map of the Western Hemisphere is shown, with stations at Westford, Richmond, Ft. Davis, Mojave, Owens Valley, and Hat Creek indicated. The short dashed lines denote the fifteen-degree horizon masks for these six stations. GPS satellite ground tracks are denoted by solid or long dashed lines. The solid lines indicate when the satellites were scheduled for viewing by all three receiver types; the dashed lines indicated where the satellites were viewed only by the SERIES-X receivers. The GPS satellite number is given at the beginning of each track.

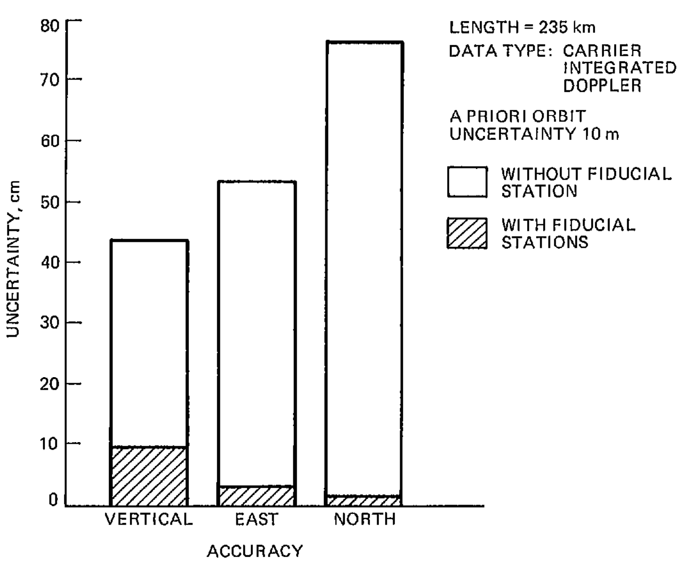

Figure 5. Covariance analysis results show expected baseline accuracies from the March 1985 field tests for the Mojave/Owens Valley baseline. Two scenarios are displayed, illustrating the improvement in accuracy expected as a result of the utilization of a fiducial station network.