Demonstration of the Fiducial Concept Using Data From the March 1985 GPS Field Test

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The first field test of NASA's GPS Geodetic Program took place in March of 1985. The principal objective of this test was the demonstration of the feasibility of the fiducial station approach to precise GPS-based geodesy and orbit determination. Other objectives included an assessment of the performance of the several GPS receiver types involved in these field tests and the testing of the GIPSY Software for GPS data analysis. In this article, we describe the GIPSY (GPS Inferred Positioning SYstem) software system and examine baseline solutions for consistency with independent measurements made using very long baseline interferometry.

I. The Fiducial Network Concept

The accuracy of GPS-based baseline measurements depends in large part on the accuracies with which the GPS satellite orbits have been determined. Currently available post-fit ephemerides define a self-consistent frame of reference at the level of approximately 1 part per million (ppm). Since expected values of crustal motion are on the order of 1–10 cm/yr, or less, a geodetic measurement program relying on post-fit ephemerides, and requiring temporal resolution of less than a decade, would be sensitive to such motions over distances of no more than several tens of km. On the other hand, a reference system based on very long baseline interferometry (VLBI) or satellite laser ranging (SLR) measurements is potentially self-consistent at a level of better than 0.01 ppm. Hence, a GPS-based geodetic network tied to the VLBI reference system could be utilized for geodetic measurements on a worldwide basis.

A means of establishing this frame tie and improving the GPS ephemeris has been developed at JPL and other institutions, and is referred to as the fiducial network approach (Ref. 1 and a private communication with J. L. Fanselow and J. B. Thomas, 1983). In this approach, three or more receivers are placed at sites, called fiducial sites, whose positions have been well-established by an independent technique, such as

VLBI. Additional receivers, known as mobile receivers, are placed at sites of geodetic interest. During a GPS measurement, the fiducial receivers record data jointly with the mobile receivers, enabling simultaneous determination of accurate GPS satellite orbits and geodetic baselines. It should be noted that by locating the fiducial receivers at VLBI stations, the GPS orbit and baseline solutions are inherently expressed in the coordinate frame of the quasi-stellar radio sources. This has the aesthetic appeal of unifying the GPS and VLBI results in an inertial, or absolute, frame of reference, enabling simultaneous display, direct comparison and simultaneous use in geophysical interpretation. A schematic illustration of the fiducial network method for precision GPS-based geodesy is shown in Fig. 1.

Covariance analysis has shown that orbit accuracies on the order of 0.1 ppm (or about 3 m) are attainable using currently available systems, involving the NOAA/NGS POLARIS VLBI sites as fiducial stations and carrier phase as the data type (Ref. 2). GPS orbit estimation using data from the March Test has verified this projection (Ref. 3). Anticipated improvements in the next generation systems, including improved models of orbital dynamics, widespread availability of 0.5 cm accurate water vapor radiometers, improved knowledge of fiducial station locations, the availability of a fiducial station in the Northern part of South America (for Caribbean geodesy), and the availability of 1–2 cm accurate absolute range as a data type will lead to orbit and baseline accuracies of order 0.01 ppm by 1989 (Ref. 4).

II. The March 1985 Field Tests

The March 1985 Field Test took place between March 28 and April 4, 1985. Receivers were placed at the NOAA/NGS POLARIS VLBI stations (Ref. 5) in Westford, MA, Richmond, FL, and Ft. Davis, TX; and at the Mojave, Owens Valley and Hat Creek VLBI stations in California. Additional GPS receivers located near Mammoth Lakes, CA, Austin, TX, Dahlgren, VA and Point Mugu, CA (Fig. 2) also recorded data during the test. These 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. In all, seventeen different institutions made substantial contributions to this test (Ref. 1). A more detailed description of the March 1985 test can be found in Refs. 1 and 4.

III. The GIPSY Software System

The GIPSY (for GPS Inferred Positioning System) software for GPS data analysis was developed between January 1985 and the present at JPL and is still undergoing significant modification to improve observable models and the user interface. It consists of approximately 70,000 lines of code, approximately one third of which was adapted from preexisting software systems, such as the VLBI data analysis code MASTERFIT (Ref. 6) and the satellite orbital dynamics modeling code PATH VARY[1] (see also Ref. 9). The remaining two-thirds consist of newly written code, a good portion of which is also used in the OASIS (*O*rbit *A*nalysis *SI*mulation *S*ystem) error analysis software (Ref. 10). It is written in FORTRAN and resides on a VAX 11/785, running under the VMS Version 4.3 operating system.

The GIPSY software system consists of a series of eight principal modules. These perform various operations, including translation of data to the VAX, interactive editing, calibration and compression, computation of an a priori ephemeris and theoretical observables, generation of differenced data types, least-squares parameter estimation and post-processing. This software is capable of combining data from all receiver types and of processing different data types (e.g., carrier phase and pseudo-range) simultaneously. The modeling and calibrations implemented in these modules are sufficient to support 0.01 ppm accuracy and better.

Estimated parameters may include satellite position and velocity at epoch, station position and velocity, station and satellite clocks, range biases (for carrier phase data), two solar radiation pressure coefficients and a y-bias factor for each satellite, zenith tropospheric delay at each station, earth orientation parameters, geocenter coordinates, solid earth tide parameters, corrections to precession and nutation, and general relativity gamma. (It should be noted that in normal data processing, only a subset of these parameters are estimated.) Options for clock modeling include constant, linear, quadratic and stochastic clocks for undifferenced and single differenced observables. Clocks may also be removed altogether using double differencing.

Typical throughput times are approximately 15 min of VAX central processing unit time per station day of GPS data (assuming observations recorded at 6-min intervals), excluding the time required for meteorology data reduction. A schematic flow chart illustration of the GIPSY software system is shown in Fig. 3.

IV. Analysis and Results

In this initial investigation of the fiducial approach, a subset of the March test data was selected as representative of the

[1]S.-C. Wu, et al., 1986, *OASIS Programmer's Guide, Version 1.0*, JPL Internal Document D-3140, Jet Propulsion Laboratory, Pasadena, Calif.

overall network. This subset consisted of the carrier phase data from April 3, 1985 from the AFGL dual-frequency GPS receivers located at the POLARIS VLBI sites at Westford, MA, Richmond, FL and Ft. Davis, TX and from the SERIES-X receivers located at the Mojave and Owens Valley VLBI sites in California. GPS satellites included in this subset were GPS 1, GPS 3, GPS 4, GPS 6, GPS 8 and GPS 9 (launch sequence numbers).

Tropospheric calibration was done using water vapor radiometer data for the stations in California and surface meteorology data as input to atmospheric models for all other stations. Ionospheric calibration was achieved using an appropriate linear combination of the phase observables from the separate L-band channels (1.57542 GHz and 1.22760 GHz) based on an assumed inverse frequency-squared dispersive relationship. Differences in measurement epochs for the two receiver types were reconciled by "compressing" the Series-X data, which have observation epochs occurring at 14-s intervals, to match the epochs of the AFGL receiver data, which occur at 6-min intervals. Compression was achieved by fitting the difference between the data and a computed observable to a second order polynomial over the 6-min interval.

Estimated parameters included satellite positions and velocities, station positions, station and spacecraft clocks and range biases. Fiducial station locations were given a priori constraints of 1 cm in each coordinate; mobile stations were given constraints of 2 km. Clocks were treated as stochastic bias parameters, having time constants of zero, which has the same effect as removing clocks by explicitly double-differencing. A priori station locations were derived from several sources, including both VLBI (Ref. 7) and local survey (Ref. 8) data and a combination of these with correction to the geocenter, using SLR data (C. C. Counselman and R. W. King, 1985, private communication). A priori ephemerides were those of the U.S. Naval Surface Weapons Center (NSWC), rotated and scaled to correct for known differences in orientation and GM for the coordinate systems in current use at NSWC and JPL. Data weights were adjusted to make chi-square per degree of freedom equal to unity.

Two separate parameter estimations were made using this data set. The strategy employed in this initial effort was to designate a single mobile receiver and look at mobile-fiducial baselines. In the first, the GPS receiver at Mojave was designated as the "mobile" receiver; in the second, the receiver at Ft. Davis was taken to be the mobile receiver. Baseline length results from these two cases, excluding results for the fiducial-fiducial baselines, were compared to the independent results based on VLBI measurements (Refs. 7, 8 and C. C. Counselman and R. W. King, 1985, private communication). This comparison showed agreement between GPS and VLBI lengths at the level of 0.13 ppm. In a third parameter estimation, all GPS receivers were treated as mobile receivers, with no estimation of satellite orbit parameters. The agreement in baseline length between the GPS- and VLBI-based estimations for this third case was at the level of 0.72 ppm, a degradation of over a factor of five from the case in which fiducial stations were used for orbit estimation. A summary of these results is given in Fig. 4.

V. Conclusion and Summary

The GIPSY software system for GPS data analysis has been developed at the Jet Propulsion Laboratory. This software was used to process a portion of the data from the March 1985 precision baseline tests and to investigate the feasibility of the fiducial station approach to precision GPS geodesy. It was found that the use of fiducial stations for GPS orbit determination improved the RMS agreement in baseline length between collocated GPS and VLBI antennas by over a factor of 5, to a level of agreement of 0.13 ppm, a level of accuracy which is sufficient for regional geodesy (baselines up to 1000 km). Anticipated system improvements should further improve GPS-based geodetic measurements to a level of approximately 0.01 ppm, which will enable the utilization of GPS-based geodetic systems on a worldwide basis.

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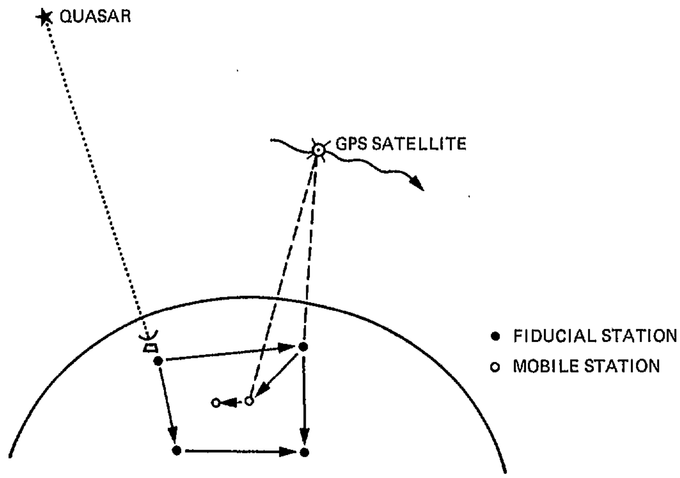

Fig. 1. A schematic illustration of the fiducial network method for precision GPS geodesy is shown

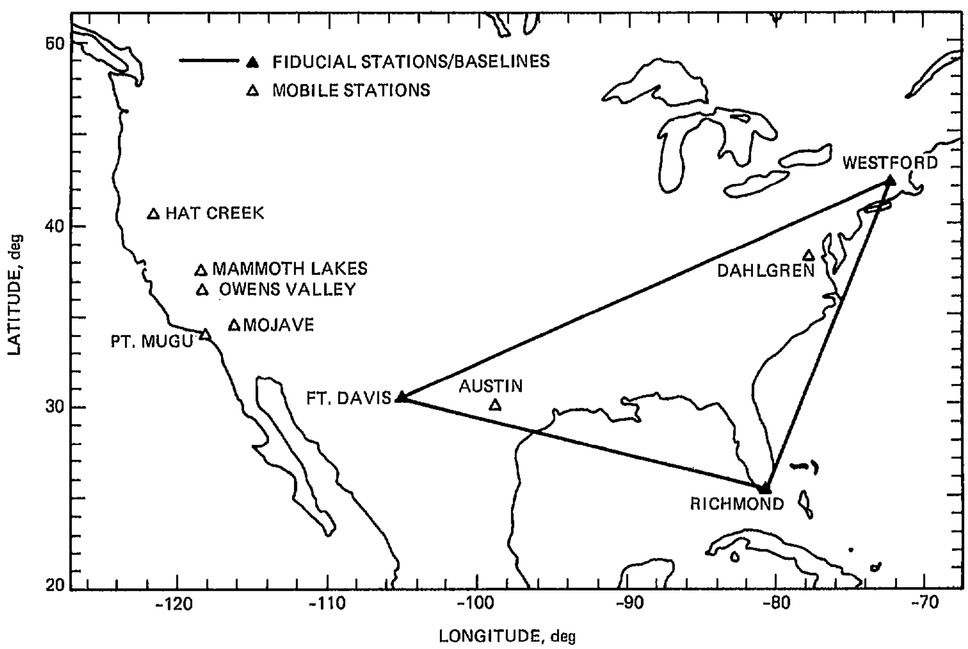

Fig. 2. The locations of the fiducial and mobile GPS receivers involved in the March 1985 demonstration of the fiducial network concept are shown

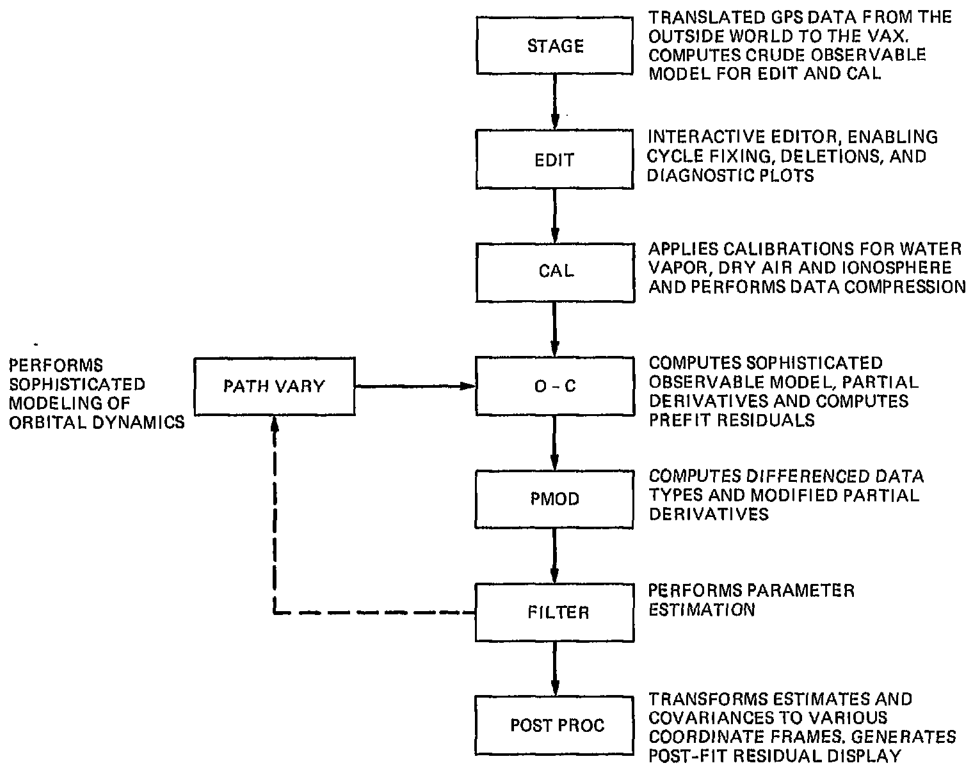

Fig. 3. A schematic flow chart of the GIPSY software system is shown

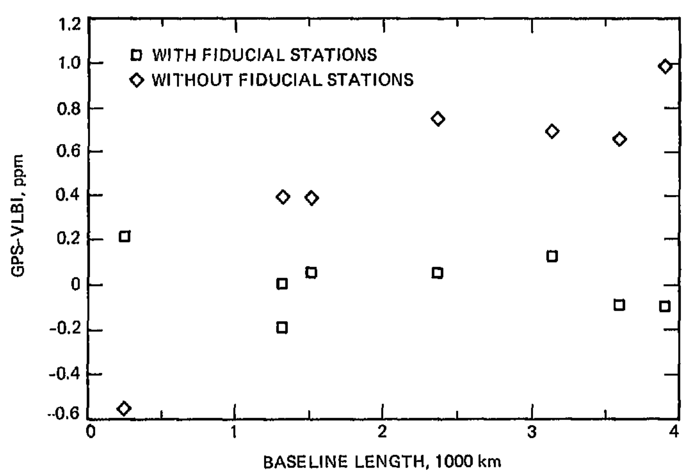

Fig. 4. A comparison of GPS- and VLBI-based geodetic measurements is shown