FGCC Federal Geodetic Control Committee

Report on Test and Demonstration of Macrometer™ Model V-1000 Interferometric Surveyor

FGCC Report: FGCC-IS-83-2

May 1983

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ABSTRACT

In January 1983, the Federal Geodetic Control Committee (FGCC) conducted a test and demonstration of the Macrometer* interferometric surveying system. The system uses radio signals from the satellites of the Global Positioning System (GPS) to determine three-dimensional relative positions of survey stations without requiring interstation visibility. Macrometer model V-1000 receivers and the model P-1000 data processor were tested by the FGCC. In order to assess the accuracies of Macrometer determinations of base line lengths, azimuths, and ellipsoidal height differences, the FGCC used terrestrial surveys as standards for comparison. The coordinates for the test network were obtained from a special adjustment of the U.S. Transcontinental Traverse. The differences between the Macrometer and terrestrial determinations were consistent at a level that was significantly smaller than expected on the basis of prior estimates of the uncertainties of the terrestrial measurements. For lines with lengths ranging from 8 to 42 kilometers, the mean differences for the base line lengths, after adjustment for a scale difference of 1:455,000, were 0.2 cm with a standard deviation of 1.7 cm. The standard deviations about the mean differences in azimuth and ellipsoid heights were about 0.1 arc second and 4 cm, respectively. For a special test network with lines ranging in length of 0.2 to 0.8 km, the mean differences for the base line lengths were about 3 mm with an rms of 3 mm. The orientation and ellipsoid height differences were consistent at about the 1 arc second and 8 mm level, respectively. In summary, the test results indicated the Macrometer model V-1000 is a viable survey system that can be used successfully to establish geodetic control relative to the National Geodetic Reference System.

INTRODUCTION

During the period of January 14, 1983, to January 21, 1983, a test and demonstration were conducted with the Macrometer model V-1000

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* Macrometer is a trademark of Macrometrics, Inc., a subsidiary of Steinbrecher Corporation, 185 New Boston Street, Woburn, Massachusetts 01801.

Interferometric Surveyor. A public demonstration (see appendix A for copy of notice), hosted by the Instrument Subcommittee of the FGCC, was held on January 18, 1983, at the National Bureau of Standards test site at Gaithersburg, Maryland.

The test and demonstration were the first steps in a series of carefully controlled evaluations of portable geodetic receivers that use radio signals from the satellites of the Global Positioning System (GPS). The observed signals are processed to determine precise three-dimensional relative positions of survey stations. GPS geodetic receivers also have the capability for determining point positions. However, only relative positioning capability was evaluated in this test.

Eight stations of the FGCC test network, located in the vicinity of Washington, D.C., were occupied during the test. There were six observing sessions. Simultaneous observations were carried out with two Macrometer model V-1000 receivers and one older, proof-of-concept model (POCM). From the simultaneous GPS observations, relative positions between stations of the test network were determined by processing the observations with the Macrometer model P-1000 data processor. The evaluation and analysis focused on the operation of the receivers and the accuracy of the relative position determinations.

During each observing session, personnel from Macrometrics, Inc., and GEO/HYDRO, Inc., operated the receivers. Members of the FGCC Instrument Subcommittee supervised the test and monitored the field operation procedures at each station occupied. Subcommittee members were also present during the on-site data processing.

The public meeting and demonstration held on January 18, 1983, were attended by approximately 200 people representing government, industry and private survey firms. The agenda for the meeting included presentations on the Global Positioning System, information about the Macrometer receivers, results of processing for base lines measured before and on the day of the meeting, and finally, a demonstration of the V-1000 survey system. Appendix B shows a copy of the agenda for the meeting.

Postprocessing of the data was carried out independently by personnel of Macrometrics, Inc., and by the authors of this report. All processing was done with programs developed by Macrometrics, Inc. The results were analyzed by comparisons with coordinates derived from precise ground surveys. Differences in geodetic position, ellipsoid height, base line length, and azimuth determinations are presented in the report. Finally, comments and recommendations on the operational suitability of the Macrometer model V-1000 receivers are included.

BACKGROUND

Global Positioning System

The NAVSTAR Global Positioning System (GPS) has been under development since 1973 by the U.S. Department of Defense (DoD). GPS is now in Phase II of a three-phase development and deployment program (Wooden 1983; Remondi 1983).

The GPS is a space-based worldwide, all weather, radio position navigation system that has the potential of providing highly accurate three-dimensional positioning information. Present plans call for the system to be fully operational in 1989 with a minimum constellation of 18 satellites. Each satellite will be in an approximately 12-hour circular orbit inclined at about 55 degrees, and about 12,500 miles (20,000 km) above the Earth's surface. The full 18-satellite system will allow a receiver located anywhere on the Earth's surface to track the signals of a minimum of four satellites simultaneously and continuously.

Each satellite continuously transmits information on two frequencies, L1 at 1575.42 MHz and L2 at 1227.6 MHz. The two frequencies allow users, with appropriate receivers, to correct for ionospheric delays in signal propagation. Both frequencies are modulated with a precision code (P-code) for precise ground to satellite range measurements and with a coarse acquisition code (S-code) for initial signal acquisition and coarse measurements. Encoded on each of the transmitted signals are orbit ephemeris, time information, and almanac data for the balance of the constellation. The Macrometer, however, uses none of the encoded information.

The control system for GPS consists of a ground-based monitor and master stations. The monitor and control stations, located in Alaska, Hawaii, Guam and Vandenberg Air Force Base in California, track and provide updated information for the satellite navigation messages. This is transmitted to the master control station, located at Vandenberg, that periodically uploads updated information to individual satellites as required.

Users with appropriate equipment can process GPS signals to compute position, velocity, and Coordinated Universal Time (UTC). Three-dimensional position and time determinations require measurements from four satellites observed simultaneously or sequentially. If one of the four parameters is known, only three satellites need to be tracked simultaneously.

Presently, the GPS satellite constellation is limited to five operational satellites. A sixth, seventh, and possibly an eighth satellite are to be launched by the end of 1983. The limited coverage is 2 to 4 hours per day for four-satellite visibility and 4 to 6 hours per day for three-satellite visibility. The sixth and seventh satellites will improve four-satellite visibility for approximately 6 to 8 hours in the United States. The period of limited satellite coverage changes to an earlier time each day by about 4 minutes.

Testing and development carried out during Phase II of the GPS program schedule are expected to continue well into 1984, after which a decision will be made whether to approve the system for operational deployment. If production is continued, satellites will be launched by the space shuttle. By 1987, a 12-satellite constellation could be available, providing continuous worldwide availability of three to four satellites. The 18-satellite constellation could be available by the end of 1989.

Macrometer Survey Equipment and Processor

Receivers developed for the purpose of performing geodetic surveys may or may not require access to the P-code and S-code data. If the receivers cannot decode the GPS signals, ephemeris and timing data must be obtained from alternate sources. A receiver system that does not require knowledge of the GPS codes is the Macrometer model V-1000 Interferometric Surveyor.

With two or more receivers observing simultaneously, the Macrometer system is used to determine relative geodetic positions. Satellite orbital position information, required for processing the data, is obtained from some agency, such as is the case for the "precise" ephemerides for the Transit satellite system. Alternately, ephemerides may be determined by using the receiver systems as continuous trackers and computing ephemerides from the received data. Macrometrics, Inc., has implemented its own tracking network with stations in Massachusetts and Arizona, which will offer users an alternate source of orbital information (Counselman 1983).

Data from the model V-1000 receiver may be processed in the point positioning mode (single receiver operations); however, software was not available for processing the FGCC test data.

The model V-1000 units are designed for vehicle mounting. Each system includes an antenna, an electronics package, and a control/display unit. The V-1000 requires 12 VDC from the vehicle's electrical system, and 120 VAC which may be drawn from the vehicle via an inverter or from a separate gasoline-powered generator. Both sources were used at various times during the FGCC test. The V-1000 receiver and antenna weigh 45 kg and 19 kg, respectively.

Figures 1 and 2 show a vehicle-mounted V-1000 receiver with the antenna set up on stations of the FGCC test network. Figure 3 is a close-up view

Figure 1. -- Occupation of station OPTRACK 1966 with Macrometer model V-1000 Interferometric Surveyor.

Figure 2. -- Occupation of station NORTH GEOS GORF located at Goddard Optical Research Facility, NASA, Greenbelt, Md., with the Macrometer model V-1000.

Figure 3. -- Macrometer Model V-1000 Antenna.

of the antenna elements, ground plane, and dome that protects the antenna elements. Figure 4 shows the Macrometer mounted in the back of a jeep vehicle. Detailed information about the Macrometer receiver systems and principles of operation may be found in articles by Counselman and Steinbrecher (1982) and Counselman et al. (1983).

Figure 4. -- Macrometer receiver installed in a jeep vehicle. Equipment accessories shown include the antenna, tripod, and generator.

To support the field operations and process the data, the model P-1000 interferometric data processor is used with the Macrometer receiver system. This portable desk-top system uses the DEC LSI-11/23 microcomputer. The system includes a video terminal, printer, floppy and Winchester disk drives, tape cassette reader/recorder, modem, and all necessary software.

An almanac tape of data that is required to control automatically the field operation of the Macrometer receiver is prepared with the P-1000 and loaded into the receiver before commencing observations at a station. The almanac data control the start and stop time of the predetermined observing span and the sequential tracking of the GPS satellite signals. The P-1000 also produces a table which shows the azimuths and elevations of the satellites as functions of time for each observing station. The raw data acquired in the field are stored in the V-1000 internal bubble memory. After the observations are terminated, the observed data are transferred to a cassette tape, and are hand carried or transmitted either by mail or telephone modem to an office for processing.

Preliminary results from the observations may be obtained by reduction with extrapolated or predicted satellite orbital coordinates or ephemerides. However, the most accurate results are obtained by processing with "precise" ephemerides, which are orbital coordinates computed from tracking data observed at the same time as the GPS satellite survey observations are being made. The "precise" ephemerides may be available within a couple of days after the survey observations were made or they can take as long as a couple of weeks, depending on the source for the data.

TEST OBJECTIVES

The objectives of the test survey were:

(1) To introduce GPS geodetic receiver technology to the surveying community by demonstrating a portable satellite survey system.

(2) To evaluate the operational suitability of the Macrometer model V-1000 as a viable survey system.

(3) To determine if short base lines (approximately 1 km long) can be resolved for each of the three-dimensional coordinates to within 1 cm of the test standard (coordinates determined from conventional ground survey procedures) from about 2 hours of GPS observations.

(4) To determine if longer base lines (5 to 45 km) can be measured to one part in 100,000 or better.

(5) To demonstrate the ability to process raw field data in near-real-time with a desk-top microcomputer system.

TEST SURVEY NETWORK

The eight stations occupied during the test survey are part of the FGCC test network located within the vicinity of Washington, D.C. The stations were located at five sites. Figure 5 is a sketch of the FGCC test network. Three of the eight stations (NBS 1966, ATHEY, and OPTRACK 1966) are part of the original U.S. Transcontinental Traverse (TCT) network. The remaining five stations were tied to the TCT by precise traverse methods. Figure 6 shows the relationship of the FGCC test network to the TCT.

The distances between the stations occupied ranged from 186 meters to 1.3 km for the short base lines and 8.7 to 42.1 km for the medium length base lines.

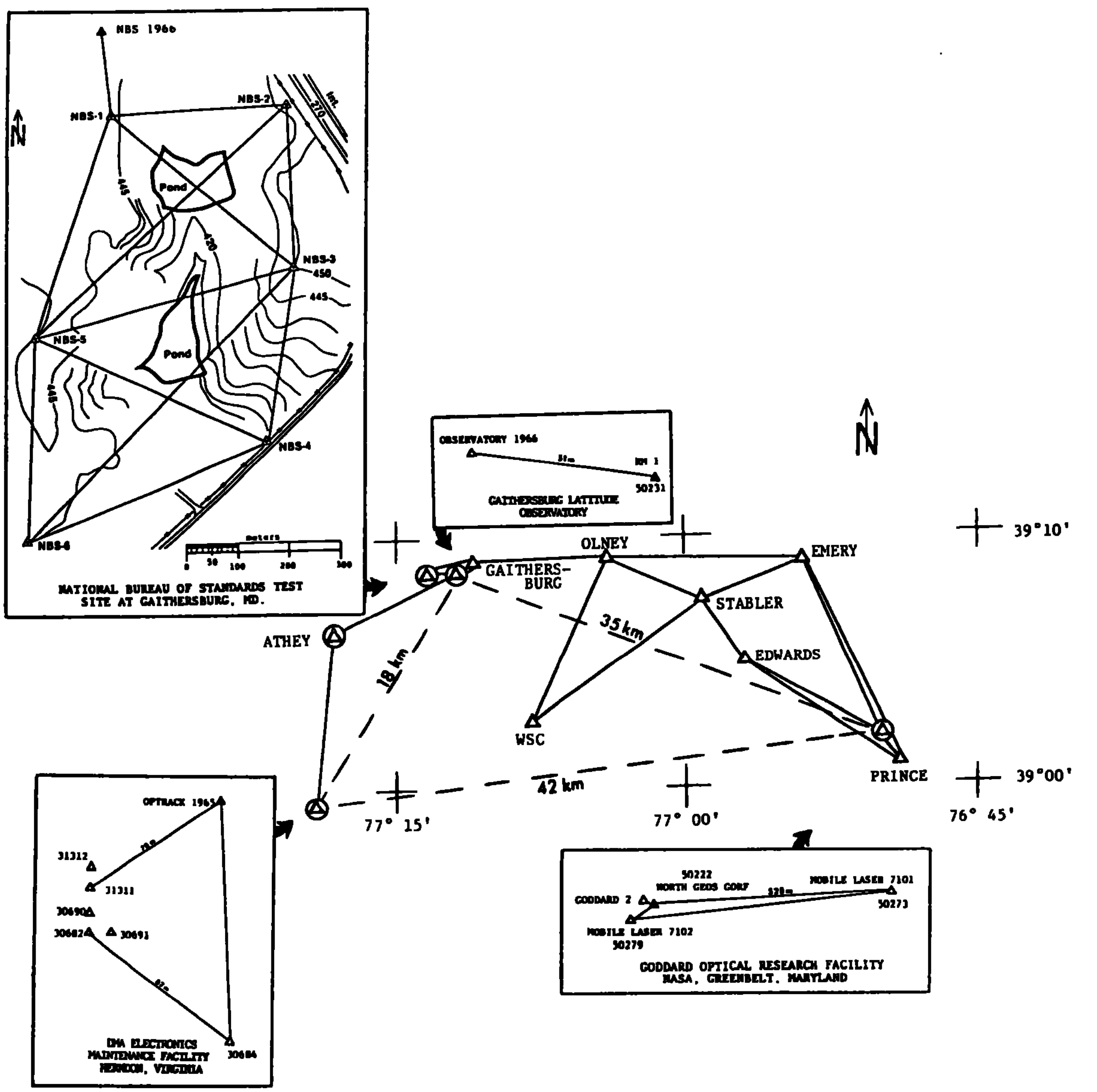

Figure 5. -- FGCC test network within metropolitan area of Washington, D.C.

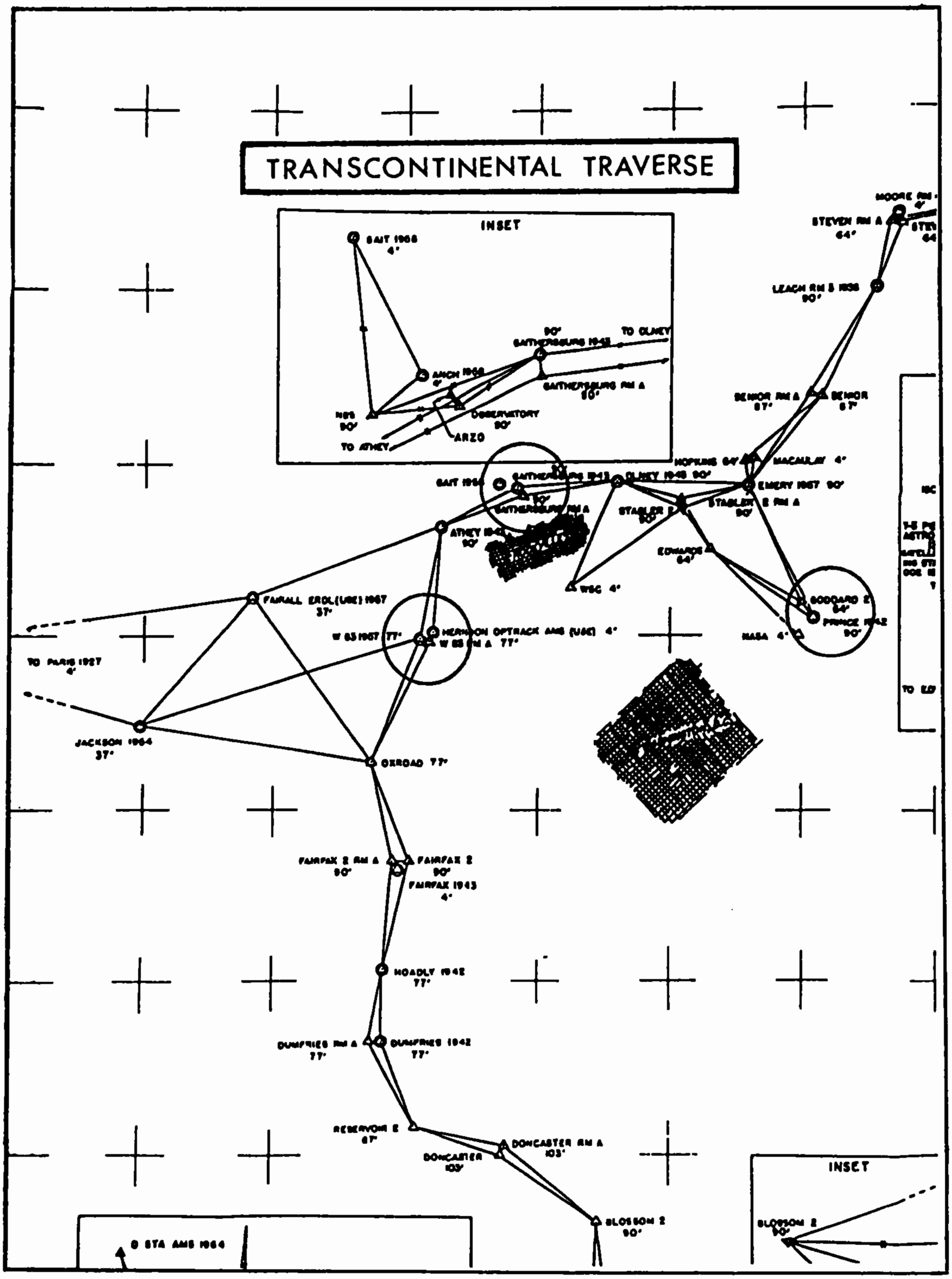

Figure 6. -- Relationship of U.S. Transcontinental Traverse to FGCC Test Network.

The following are estimated accuracies (2 sigma) for the conventional terrestrial survey determinations of the distances and azimuths between the stations measured during the test survey:

Stations	Estimated Accuracy	
	Distance	Azimuth
Test network at National Bureau of Standards	3 mm	5 sec
NBS 1966 to OBSERVATORY RM 1	1 cm	2 sec
NBS 1 to OBSERVATORY RM 1	1 cm	3 sec
ATHEY to OPTRACK	2 cm	1 sec
ATHEY to OBSERVATORY RM 1	2 cm	1 sec
OPTRACK to NORTH GEOS	8 cm	0.5 sec
OBSERVATORY RM 1 to NORTH GEOS	7 cm	0.5 sec
OPTRACK to OBSERVATORY RM 1	4 cm	0.5 sec

The estimated accuracies for the lengths of the short base lines at the NBS test network were derived from the formal statistics of a special three-dimensional adjustment of the site survey. Although the scale of the network is extremely well determined, the orientation of the network relative to the rest of the FGCC test network is not well known. This is because the orientation of the network was determined only from an angle measured between the azimuth mark of NBS 1966 and NBS-1. It is expected that the orientation of the network will be improved once there has been an opportunity to observe an astronomic azimuth.

The estimated accuracy for the horizontal ties between the other stations of the FGCC test network is based on the estimated accuracy of the TCT. The current estimate for the accuracy of the TCT is 1 ppm (1 sigma). This estimate, in terms of two sigma (90% confidence level), would be 1:500,000.

The estimated accuracy (1 sigma) of the vertical ties (differences in elevations above mean sea level) between the stations of the test network is:

NBS test network	3 mm
ATHEY, OPTRACK and NORTH GEOS	1 cm
OBSERVATORY RM 1	3 cm

Except for OBSERVATORY RM 1, the vertical ties were determined from spirit leveling. The elevation at OBSERVATORY RM 1 was determined by trigonometric leveling methods. The elevations for the stations of the test network ranged from 50 m at NORTH GEOS to 152 m at OBSERVATORY RM 1.

Since the station-to-station height differences determined from GPS observations are ellipsoid height differences, one must know the values for geoid heights or geoid height differences that were determined with respect to the reference ellipsoid used for the terrestrial survey network in order to compare with orthometric height differences. Presently, the best geoid heights available for analyzing the GPS determined ellipsoid height differences between stations of the test network are from the NGS

Astrogeodetic Geoid of 1975. The NGS Astrogeodetic Geoid was determined from an adjustment of astrogeodetic deflections for approximately 3000 stations located in the conterminous United States (Carroll and Wessells 1975).

The geoid height values used in analyzing the test results were taken directly or interpolated from a listing of heights determined from the 1975 adjustment. The estimated one-sigma accuracy for the absolute geoid heights is about 80 cm. However, the one-sigma accuracy for geoid height differences should be significantly better, perhaps less than a decimeter between stations in regions where there was a very good distribution of astronomic stations and where the slope of the geoid is relatively small. Such a region is the location of the Washington, D.C., FGCC test network where there were over 50 astro stations and a geoid slope of under 1 m per 50 km.

The estimated accuracy of the geoid height differences between stations ATHEY, OBS. RM 1, OPTRACK, and NORTH GEOS is 5 cm (1 sigma). The geoid height differences between the stations at the NBS test site were assumed to be zero because no localized geoid slope information was available for this area. However, consistent with the estimated accuracies above, the uncertainty for the zero geoid height difference at the NBS test site is estimated to be 4 mm (1 sigma). Combining the uncertainties for the geoid height differences and elevation differences between stations of the test network, the estimated accuracies for the ellipsoid height differences are:

Stations of NBS test network	5 mm
OPTRACK, ATHEY, NORTH GEOS	5 cm
OBSERVATORY RM 1	6 cm

The difficulty in having a sufficiently accurate standard for analyzing ellipsoid height differences computed from a satellite based geocentric coordinate system is a common worldwide problem. Due to the nonexistence of or sparseness of data for some areas, errors for geoid height differences may be as much as several meters. Thus, while it is possible to determine precise ellipsoid height differences from satellite observations, converting these ellipsoid height differences to accurate elevation differences (or differences in mean-sea-level heights) cannot be done unless the shape of the geoid is known to an accuracy that is equal to or better than the accuracy for the satellite derived ellipsoid height differences.

OBSERVATIONS

Eight observing sessions were scheduled, one each day beginning January 14 and ending January 21, 1983. Three Macrometer receivers were deployed during the survey. This included two model V-1000 receivers and one proof-of-concept model (POCM) that had been used by Macrometrics, Inc., during the past two years for experiments and testing. The POCM was not available until January 17 due to a severe winter storm which delayed its arrival from Massachusetts.

The observing sessions, scheduled for January 15 and January 16, had to be canceled due to a component malfunction in receiver V1000-44. This malfunction was the only receiver hardware failure that occurred during the test.

Table 1 is a summary of station occupation information taken from the GPS Station Observation Log (see appendix C for copy of log used during the test). Summarized in table 1 are information for time arrived at site, time setup completed, time observations began and ended, and time of departure. Additional information for each station occupied includes the equipment model and serial number, and height of antenna phase center above mark.

The observing period for each session of observations was 2 hours for the short lines and 3 hours for the longer lines. These observing spans were selected to obtain the best results possible. Due to the limited overall period of the test, it was not possible to perform observations for shorter observing spans.

The time required to set up the equipment after arriving at a station was generally less than 15 minutes. During the test, the almanac data files that are required to control the Macrometer were loaded into the receiver's memory before departing for the station site. Thus, the only major task required after arriving at the site and before starting the observations was setting up the antenna. The amount of setup time required depended on the experience of the observer in setting up antennas, plumbing, measuring the antenna height, etc. As table 1 shows, the setup was occasionally completed within 5 minutes.

The V-1000 antenna was stably located to within 1 mm over the station mark. The height difference between the station mark and the antenna's phase center was measured to the nearest millimeter. The horizontal eccentricity was zero for all antenna setups. However, due to possible plumbing error, the estimated error in the zero horizontal eccentricity is 1 mm (1 sigma). The error in the height measurement is also estimated to be 1 mm (1 sigma).

All observations began just before dawn and ended after the sun was above the horizon. Thus, the path of the satellite signals through the ionosphere changed from darkness to daylight during the period of the observations. It should be noted that the ionosphere changes most rapidly in this postdawn period.

Obstructions presented no significant problems at the sites. Although trees and overhead wires at stations OBSERVATORY RM 1, NBS 1966, and ATHEY were potential obstructions, there were no serious loss-of-signal problems. The other stations were generally clear of obstructions 20 degrees or more above the horizon.

No attempt was made to record any meteorological data at any of the stations occupied. During the test periods, the weather varied from clear to mostly cloudy. Although Macrometrics data processing programs can accept station weather data, all processing was done using only standard default values. In hindsight, the authors believe station weather should have been

Table 1. -- Station site occupation information

Observ. Session Number	Date	Station Name	Macrometer		Arrived at Site (1)	Complete Setup (1)	Begin Observ. (1)	End Observ. (1)	Depart Station (1)	Antenna Cable(4)		Height Antenna above mark
			Model Number	Serial Number	(GMT)	(GMT)	(GMT)	(GMT)	(GMT)	No. of 10-meter lengths	Total Length (m)	(cm)
1	1-14-83	NBS-4	V-1000	44	1134	1145	1216	1414	1500	2	20	133.8
		NBS-1	V-1000	32	1115	1130	1216	1414	1436	2	20	146.0
4	1-17-83	NBS-1	V-1000	44	1120	1133	1154	1430	1440	1	10	144.5
		OBS. RM 1	V-1000	32	1115	1120	1149	1432	1437	1	10	143.6
		NBS 1966	POCM	2	1120	1145	1154	1429	1500	2	20	18.5
5	1-18-83	NBS-4	V-1000	44	1120	1130	1200	1358	1404	1	10	131.7
		NBS-1	V-1000	32	1115	1130	1202	(2)	(2)	1	10	142.0
		NBS-3	POCM	2	1130	1155	1200	1400	1418	2	20	15.7
6	1-19-83	OPTRACK	V-1000	44	1138	1149	1150	1500	1510	1	10	137.8
		ATHEY	V-1000	32	1121	1140	1152	1459	(2)	1	10	174.3
		OBS. RM 1	POCM	2	1130	1150	1245(3)	1500	1530	2	20	17.8
7	1-20-83	OPTRACK	V-1000	44	1144	1153	1159	1454	1503	1	10	145.0
		NORTH GEOS	V-1000	32	1145	1150	1154	1455	1500	1	10	85.0
		OBS. RM 1	POCM	2	1120	1150	1157	1457	1510	2	20	17.9
8	1-21-83	OPTRACK	V-1000	44	1128	1138	1150	1454	1505	1	10	146.6
		NORTH GEOS	V-1000	32	1135	1148	1152	1455	1510	1	10	79.1
		OBS. RM. 1	POCM	2	1110	1125	1154	(2)	(2)	2	20	17.8

Notation: GMT - Greenwich Mean Time.
(1) Subtract 5 hours to convert GMT to local time (Eastern Standard Time); (2) Time not recorded; (3) Late start due to error in almanac data file; (4) The number of 10-meter cable lengths is given only to complete the summary of station occupation information. The number of lengths had no apparent effect on the results. Tests have shown that up to at least three 10-meter lengths will have no significant effect on the Macrometer observations.

recorded, particularly for the long base lines, and results compared with results based on default weather data. Future tests will include records of station weather data.

The V-1000 and POCM receivers contain a clock, referenced to a quartz crystal standard, which governs the timing of the satellite observations. It is specified in the Macrometer Field Manual that the clocks should be set to within 10 milliseconds of Coordinated Universal Time (UTC). Further, the manual specifies that before the Macrometers are taken to the observing station, the clocks of each receiver should be synchronized exactly, that is, within 1 microsecond of each other.

During the test survey, the day number, hours, minutes, seconds, and fraction of seconds (to within 10 milliseconds) for the clock of one of the receivers were set to UTC by using a GOES satellite timing signal received with a commercially built receiver provided with the Macrometer systems. After the clock for one of the receivers was set, it became the reference clock for synchronizing the other receiver clocks. Table 2 summarizes the clock settings relative to UTC and synchronization measurements.

It was the practice during the test survey to attempt a clock synchronization check before and after each observing session. Synchronization measurements were made with a Hewlett Packard time interval counter supplied with the Macrometer system. It is important to have available accurate measurements of the clock offsets as a priori estimates during processing of the data. Using a measured value for the clock offset, rather than having it be an unknown in the solution, can improve the results for the base line vectors, particularly for base lines longer than 10 to 20 km. In any case, the information is useful as a check. The measured value can be compared with the value determined from the satellite observations as a check against blunders.

Although measurements were always made before beginning each observing session, sometimes it was not possible to make another check after returning from the station occupied. This did not seriously affect the estimates for the clock offsets and drift rates except on January 19 when the stability of the POCM clock was affected by a loss of vehicle 12-volt power that occurred before the observing session. The vehicle had a dead battery.

The drift rate for the V-1000 clock should be, as specified in the Macrometer Field Manual, less than 10 microseconds/hour with respect to Coordinated Universal Time (UTC). The drift rates between the frequency standards used by the Macrometer clocks are specified to be under 1 microsecond/hour. If the magnitude of the drift rate is this small, then the drift can be completely neglected in the processing of the observations. Otherwise, it may be necessary to account for the drift in order to avoid loss of geodetic accuracy. The processing program includes provisions to account for clock drift. During the test, as indicated in table 2, the drift rates between the clocks were about 1 microsecond/hour.

Table 2. -- Macrometer clock offset measurements

Observ. Session Number	Date	Station Name	Receiver Clock (A)	Time Differences (+ ahead, - behind) Reference (B)	Time (GMT)	(B-A) (µs)	Reference (B)	Time (GMT)	(B-A) (µs)	Reference (B)	Time (GMT)	(B-A) (µs)
1	1-14-83	NBS-4	V1000-44			(2)	V1000-32	1030	1	V1000-32	1825	-3
		NBS-1	V1000-32			(2)	V1000-44	1030	-1	V1000-44	1825	+3
4	1-17-83	NBS-1	V1000-44	GOES-1	1030	+1030	V1000-32	1045	0	POCM-2	1451	-4
		OBS. RM 1	V1000-32	GOES-1	1030	+1030	V1000-44	1042	0			
		NBS 1966	POCM-2	GOES-1	1325	+1005	V1000-44	1045	0	V1000-44	1451	+4
			POCM-2	GOES-2	1325	- 900	GOES-2	1435	-924			
5	1-18-83	NBS-4	V1000-44	GOES-1	1025	+1025	V1000-32	1010	-18	V1000-32	1018	0
		NBS-1	V1000-32				V1000-44	1010	+18	V1000-44	1018	0
		NBS-3	POCM-2	GOES-1	1034	+1034	V1000-32	1032	+ 1			
			POCM-2	GOES-2	1239	- 937	GOES-2	1312	-947	GOES-2	1358	-906
6	1-19-83	OPTRACK	V1000-44			(2)	V1000-32	1025	-27	V1000-32	1030	0
		ATHEY	V1000-32			(2)	V1000-44	1030	0	V1000-44	1922	+ 6
		OBS. RM 1	POCM-2	GOES-1	1235	- 330	V1000-44	1030	0(3)	V1000-32	1927	+577
			POCM-2	GOES-2	1350	- 310	GOES-2	1423	-306			
7	1-20-83	OPTRACK	V1000-44			(2)	V1000-32	1018	- 22	V1000-32	1025	+ 2
		N. GEOS	V1000-32			(2)	V1000-44	1018	+ 22	V1000-44	1025	- 2
		OBS. RM 1	POCM-2	GOES-2	1200	-900	V1000-32	1037	+602	V1000-32	1040	0
			POCM-2	GOES-2	1457	-810						
8	1-21-83	OPTRACK	V1000-44			(2)	V1000-32	1008	- 27	V1000-32	1018	0
		N. GEOS	V1000-32			(2)	V1000-44	1018	0	V1000-44	1640	+35(4)
		OBS. RM 1	POCM-2	GOES-2	1130	-900	V1000-32	1010	0	GOES-2	1458	-777

Notation: ms - millisecond, µs - microsecond, GMT - Greenwich Mean Time, UTC - Coordinated Universal Time (1) Clocks were set to UTC time signal transmitted by GOES satellites and then synchronized to each other; GOES-1 satellite time signal receiver appeared to have a propagation delay of about 2 ms different from the GOES-2 receiver; The V1000-32, V1000-44, and POCM-2 are the model and serial numbers of the Macrometers; The accuracy of the offset measurements relative to the GOES time signal is + or - 50 µs, and relative to each clock is + or - 1 µs; (2) Clock offsets relative to GOES were not recorded; (3) At about 10:00 GMT, the reference oscillator for the POCM receiver was found to be cold due to a battery failure for the vehicle. Power was reapplied at 10:30 GMT. Since there was insufficient time for oscillator to stabilize, drift rate was high during observations. (4) Offset measured on 1/22/83 at 1640 GMT.

DATA PROCESSING

Data processing was carried out in two phases. The first phase involved processing a portion of the data on-site to demonstrate the capability for processing raw field data to obtain relative position coordinates of survey marks in near-real-time with a desk-top microcomputer system. Results of the on-site processing using predicted ephemerides were presented at the public meeting held on January 18.

The second phase, completed at a later date, involved processing the data with precise ephemerides using two slightly different versions of software developed by Macrometrics, Inc. Macrometrics and FGCC personnel processed the data independently. The on-site processing by Macrometrics and postprocessing by the FGCC used only the P-1000 processor supplied by Macrometrics. For part of the postprocessing by Macrometrics, a mainframe computer and some additional software were also used, as described in appendix E. The results from Macrometrics were delivered to FGCC on February 8, 1983.

Processing the data is done in two steps. In the first step, the data are processed with a program called INTERF. Final reduction is carried out with a least-squares adjustment program called LSQ. The computer system and software versions used during the on-site and postprocessing work are summarized in table 3.

Table 3. -- Ephemeris data and software versions used during data processing

Processing Phase	Processed By	Processor Used	Ephemeris Used	INTERF Version	LSQ Version
On-site	Macrometrics	P-1000	EX and H1	V01.01A1	V01.01A2
Post	FGCC	P-1000	F1	V01.02A2	V01.01A4
Post	Macrometrics	P-1000 and mainframe	F1	V01.02A2 and PEP*	V01.01A4

Notation:

EX - Extrapolated or predicted orbit based on 10-day old orbit data.

H1 - Hybrid orbit that was based on a combination of 3-day and 10-day data.

F1 - Final precise orbit data derived from tracking data acquired during the GPS satellite surveys.

* See appendix E.

After receiving initial instructions in use of the software, the authors were able to process the base lines with little additional assistance. Generally it took less than 30 minutes to process each base line. The software versions required a fair amount of human interaction, particulary during use of the least squares adjustment program called LSQ. However, Macrometrics has recently delivered new versions of the software which are more streamlined so that human interaction with the processing is reduced and less time is needed to process a base line.

In order that near-real-time processing can be performed within a few hours after a set of data has been observed, the data must be processed with predicted or extrapolated satellite orbital coordinate data. The predicted orbit may have to be derived from orbital data that may be a few days or more than a week old.

Precise orbital data are derived from tracking data acquired independently and at the same time as the observations are acquired during a GPS satellite geodetic survey. Presently, the orbital data are computed from 7-day periods of tracking data. Thus, it can take a week or more to obtain a final set of "precise" orbital coordinate data, depending on which part of the 7-day period the satellite survey was performed. Table 3 gives the ephemerides used during the on-site and postprocessing activities.

Macrometrics personnel were provided known station coordinates for only two of the eight stations occupied during the test survey. These coordinates, derived from a special adjustment of the U.S. Transcontinental Traverse, were for stations OPTRACK 1966 and NBS-1. For the remaining stations, approximate coordinates to the nearest second of arc were provided. It should be noted that it was not necessary to use precisely known coordinates for any of the stations during processing. Coordinates scaled from a topographic map would have provided acceptable estimates.

All terrestrial coordinates were referenced to the NAD 1927 datum and CLARKE 1866 reference ellipsoid. The ellipsoid height was computed by adding the elevations to geoid heights extrapolated from the National Geodetic Survey Astrogeodetic Geoid of 1975.

The output of program LSQ gives the coordinates for the unknown end of the base line. These coordinates, expressed in terms of latitude, longitude, and ellipsoid height, and the a priori coordinates for the known station can be converted back to Cartesian coordinates (X,Y,Z values) and differenced to compute the base line vector components and length. The geodetic coordinates can also be inversed to determine the azimuth of the base line. A sample output of LSQ for the final solution for base line NBS-1 to NBS-4 is shown in appendix D.

ANALYSIS OF RESULTS

The results for three groups of base line solutions were analyzed by comparison with the terrestrial standard. Differences in geodetic coordinates, heights, base line lengths, azimuths, and z-axis rotations were computed.

Short Base Line Analysis (under 2 km)

Figure 7 is a sketch of the base lines for the stations which were spaced less than 2 km apart. Table 4 summarizes comparisons of on-site and postprocessed GPS survey results with the terrestrial coordinates. The coordinate differences in centimeters for the unknown station are given in terms of northing, easting, and up. Additionally, differences in the satellite-derived and terrestrial azimuths for the base lines are summarized.

Each base line was reduced independently. For each solution, the coordinates were held fixed for one station and allowed to be free for the other end of the base line. The station held fixed is indicated in table 4.

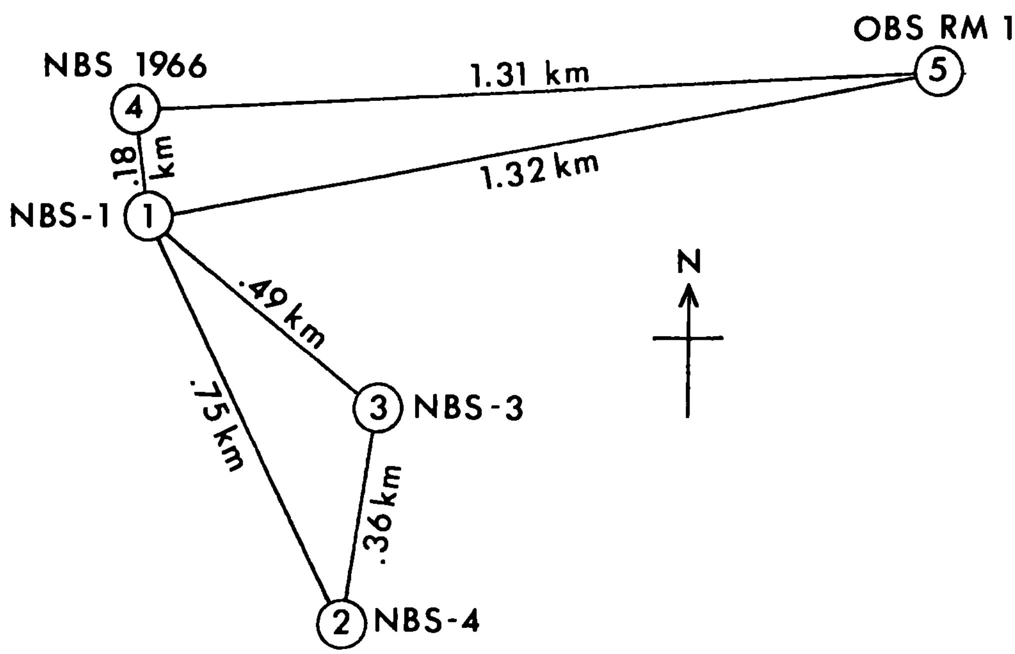

Figure 7. -- The short base lines observed during the FGCC test survey.

The differences in the coordinates at the unknown station were generally less than 1.5 cm. The larger differences of 3 to 4 cm in the Up component for station OBSERVATORY RM 1 relative to NBS-1 and NBS 1966 are consistent with the large uncertainty for the terrestrially determined elevation at OBSERVATORY RM 1, which, as noted earlier in the report, was estimated to be about 6 cm (1 sigma).

The differences for the azimuths between stations of the NBS test network were quite consistent. For the Macrometrics post results, the unweighted mean was -6.8 seconds with a standard deviation of 1.4 seconds. However, the unweighted mean for the azimuth of the base lines to OBSERVATORY RM 1 was +1.9 with a standard deviation of 0.4 seconds. Thus, the difference between the azimuth of the NBS test network and the base lines to

Table 4. - Comparison of satellite determined coordinates and the azimuth of the base line with terrestrial survey standard for stations spaced less than 2 km apart

Obs. Sess.	From Known (Fixed) station	To Unknown station	Obs. Date	Differences in Coordinates at "Unknown" Station and Azimuth of Base line (Terrestrial minus Satellite Derived) — On-site Results N (cm)	On-site E (cm)	On-site U (cm)	On-site Azi (sec)	Macrometrics Post Results N (cm)	Macrometrics E (cm)	Macrometrics U (cm)	Macrometrics Azi (sec)	FGCC Post Results N (cm)	FGCC E (cm)	FGCC U (cm)	FGCC Azi (sec)
1	NBS-1	NBS-4	1-14	1.2	-2.2	0.4	-7.1	1.0	-2.3	0.9	-6.9	1.0	-2.4	0.7	-7.1
4	NBS-1	NBS 1966	1-17	-0.2	0.4	0.2	-4.5	0.3	0.4	0.0	-4.5	0.0	0.6	0.0	-6.2
5	NBS-1	NBS-4	1-18	1.2	-1.5	-1.2	-5.3	0.7	-2.4	-1.0	-6.7	0.6	-2.4	-0.9	-6.7
	NBS-1	NBS-3		1.1	-0.9	-0.1	-5.9	1.4	-1.2	-0.1	-8.0	1.2	-1.0	-0.1	-6.5
	NBS-3	NBS-4		(1)	(1)	(1)	(1)	-0.6	-1.1	-0.9	-7.8	-0.6	-1.5	-0.7	-8.9
		Unweighted Mean								-0.2	-6.8			-0.2	-7.1
		Standard Deviation					(n=5)			0.8	1.4			0.6	1.1
4	NBS-1	OBS RM 1	1-17	-0.8	-1.5	3.1	1.8	-0.7	-1.3	3.7	1.6	-0.6	-1.1	4.0	1.3
	NBS 1966	OBS RM 1		-0.7	-1.9	3.0	1.4	-1.2	-1.8	3.8	2.1	-0.6	-1.5	3.9	1.1
		Unweighted Mean								3.8	1.9			4.0	1.2
		Standard Deviation					(n=2)			0.1	0.4			0.1	0.1

Notation: N - Northing, E - Easting, U - Up

(1) Base line was not processed on-site.

Note: The terrestrial survey is known to be uncertain up to 5 arcsec in azimuth. Thus, the N and E coordinate differences shown above are not significant except to show that if there were an adjustment to minimize the orientation and scale differences, the N and E coordinate differences would be reduced to less than 1 cm.

OBSERVATORY RM 1 was about 8 seconds. This is within 2 sigma of the estimated uncertainty for the orientation of the NBS test network relative to the rest of the FGCC test network. (See section on Test Survey Network.)

Table 5 is a comparison of the three independently determined lengths for the short base lines. Differences are given in millimeters. Differences were not given in proportional error because errors for lines this short are not expected to be proportional to base line length. The unweighted mean differences for the base lines of the NBS test network were less than 4 mm with standard deviations of 3 mm or less. For the 1.3 km base lines from NBS-1 and NBS 1966 to OBSERVATORY RM 1, the unweighted mean differences ranged from 12 to 14 mm with standard deviations of 4 to 5 mm. The differences were about equal to or less than the 2 sigma estimates for the accuracies of the terrestrially determined base line lengths.

No attempt was made to adjust for the rather large orientation difference between the terrestrial and satellite-derived coordinates. The scale difference is considered insignificant. If an adjustment had been made to minimize the orientation difference between the terrestrial and satellite coordinates, the values for the northing and easting differences would have reduced to a few millimeters. Likewise, an adjustment of the orientation difference for the lines to OBSERVATORY RM 1 would have reduced the northing and easting values to about 1 cm.

Finally, the differences between the on-site and postprocessed results were very small. As expected, short base lines (less than 2 km) processed with either predicted or precise orbital coordinates yielded essentially the same results.

Medium Length Base Line Analysis (8 to 42 km)

Figure 8 is a sketch of the base lines for the stations spaced 8 to 42 km apart. The coordinates determined from the Macrometer data for the unknown station of each base line were differenced from the terrestrial coordinates and summarized in table 6. The differences in the base line azimuths are also shown.

The results of on-site processing for two base lines observed on January 19 are not included in the summary. As expected for data processed with predicted satellite orbit coordinates for base lines longer than a few kilometers, the results were considerably degraded in accuracy compared to data reduced with the precise ephemerides. For example, the differences in the N, E, U, and azimuth for station ATHEY relative to OPTRACK from the on-site satellite-derived coordinates were -10.9, -17.2, 11.3 cm, and 3.20 second, respectively. This is not consistent with the results derived from postprocessing with the precise ephemerides.

The differences given in table 6 were computed before consideration of possible scale and orientation biases between the GPS and terrestrial coordinate systems. The unweighted mean azimuth difference for the Macrometrics post results was +0.41 second with an rms of 0.08 second. For the FGCC post results, the unweighted mean azimuth difference was

Table 5. -- Comparison of "short" base line length

Observ. Session	From Known (Fixed) Station	To Unknown Station	Observ. Date	Base Line Length (km)	Differences in Base Line Lengths (Terrestrial minus Satellite Derived)		
					On-site Results Difference (mm)	Macro. Post Results Difference (mm)	FGCC Post Results Difference (mm)
1	NBS-1	NBS-4	1-14-83	0.75	- 2	0	1
4	NBS-1	NBS 1966	1-17-83	0.18	- 1	4	0
5	NBS-1	NBS-4	1-18-83	0.75	- 4	4	5
	NBS-1	NBS-3		0.49	- 1	0	0
	NBS-3	NBS-4		0.36	(1)	6	4
		Unweighted Mean			- 2	3	2
		Standard Deviation			1	3	2
4	NBS-1	OBS RM 1	1-17-83	1.32	13	12	9
	NBS 1966	OBS RM 1		1.31	18	18	14
		Unweighted Mean			16	15	12
		Standard Deviation			4	4	4

(1) Base line was not processed on-site.

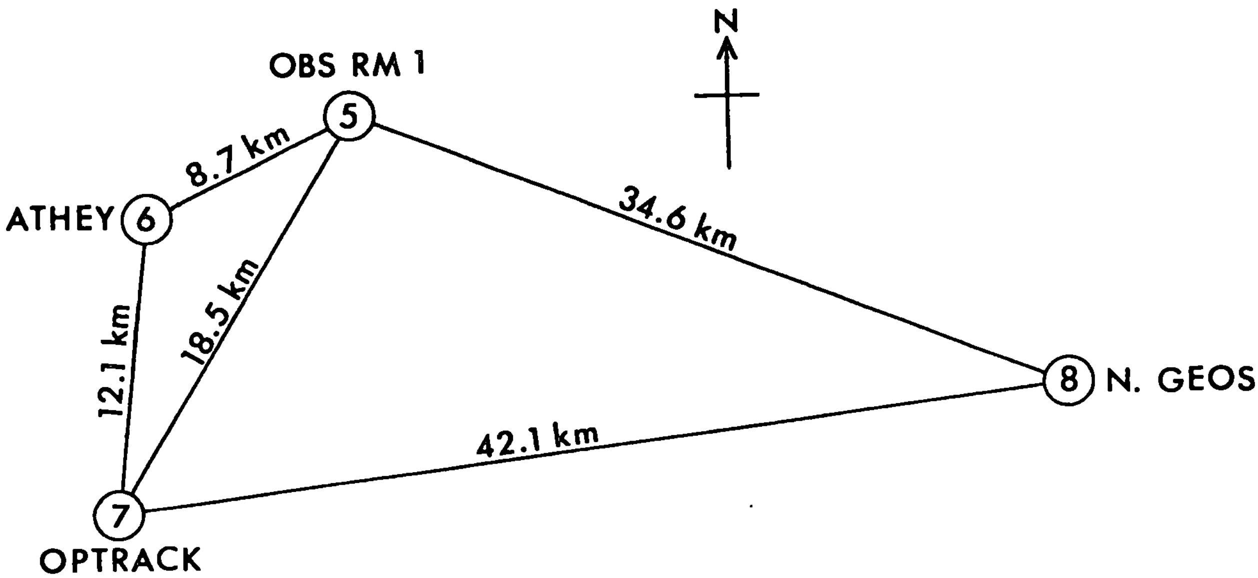

Figure 8. -- The 8- to 42-km base lines observed during the FGCC test survey.

+0.47 second with a standard deviation of 0.22 second. All values for the mean differences were well within the 2-sigma estimate for the uncertainties for the terrestrial base line azimuths.

Other interesting statistics from table 6 are the mean differences for the Up or ellipsoid height values. The unweighted mean from the Macrometrics results was -2.8 cm with an rms of 3.7 cm. For the FGCC processed results, the mean was 0.0 cm with an rms of 4.4 cm. These results indicate that perhaps the estimated errors in the terrestrially determined elevations and geoid heights for the stations were too large. Although a portion of the 4 cm rms value is probably due to the uncertainties in the terrestrial standard, there is evidence of an uncertainty of several centimeters in the satellite-derived height determinations for the 35 and 42 km base lines. The differences between the height measurements made on January 20 and 21 ranged from 2 to 12 cm. These differences are thought to be mostly the result of uncorrected effects of ionospheric refraction. Since the model V-1000 is a single channel receiver, it is not possible to compute a first-order correction directly from the observed data.

Nevertheless, the results of the relative ellipsoid height determinations indicate that for stations spaced less than 50 km apart, it is possible to determine ellipsoid heights from the Macrometer V-1000 observations that are sufficiently precise for many useful applications. When accurate differences in elevations or orthometric heights are known between stations, one could determine geoid height differences, perhaps to a few-centimeter level of accuracy. Conversely, if the slope of the geoid

Table 6. -- Comparison of satellite determined coordinates and the azimuth of the base line with terrestrial survey standard for stations spaced 8 to 42 km apart

Observ. Session	From Known (Fixed) Station	To Unknown Station	Observ. Date	Differences in Coordinates at Unknown Station and Base line Azimuth (Terrestrial minus Satellite Derived)							
				Macrometrics Post Results				FGCC Post Results			
				N (cm)	E (cm)	U (cm)	Azi (sec)	N (cm)	E (cm)	U (cm)	Azi (sec)
6	OPTRACK	ATHEY	1-19-83	1.3	-2.6	-2.0	0.39	0.7	-2.4	3.6	0.38
	OPTRACK	OBS RM 1		1.3	-4.9	-4.8	0.39	-1.7	-5.9	6.3	0.65
	OBS RM 1	ATHEY		0.4	2.8	1.4	0.37	2.5	3.7	-4.4	0.92
7	OPTRACK	N. GEOS	1-20-83	-8.4	-11.4	-6.0	0.45	-4.3	-0.9	-2.5	0.21
	OPTRACK	OBS RM 1		1.2	-5.1	-4.1	0.41	0.3	-3.6	2.5	0.32
	OBS RM 1	N. GEOS		-7.1	-2.8	-8.5	0.33	-4.0	3.0	-8.4	0.29
8	OPTRACK	N. GEOS	1-21-83	-10.7	-11.4	-0.3	0.55	-11.3	-7.1	0.9	0.57
	OPTRACK	OBS RM 1		1.4	-4.0	-4.3	0.30	-0.9	-3.3	0.7	0.37
	OBS RM 1	N. GEOS		-11.3	-7.4	3.4	0.46	-11.7	-4.7	1.1	0.54
	Unweighted Mean					-2.8	0.41			0.0	0.47
	Standard Deviation (n=9)					3.7	0.08			4.4	0.22

Notation: N - Northing, E - Easting, U - Up

Note: The N and E differences were computed without any consideration of the systematic difference in base line azimuths.

is well known relative to a station with a known elevation, an elevation at the unknown station of a base line could be determined accurately enough to meet a wide range of applications.

Differences for the base line lengths are given in table 7. The unweighted mean for the proportional values between the Macrometrics results and terrestrial lengths was 2.2 ppm with an rms of 0.6 ppm. This clearly indicates a scale difference between the base line lengths. The mean for the proportional values derived from the FGCC post results was 1.1 ppm with an rms of 1.0 ppm, but for reasons discussed earlier and in appendix E, results from the Macrometrics solutions are believed to be more reliable.

To illustrate the significance of the scale bias present between results computed by Macrometrics and the terrestrial standard, the mean proportional error of 2.2 ppm was applied as an adjustment to the base line differences. The results of these computations are given in table 8. The base line length differences that remain after adjustment ranged from +3.5 to -2.3 cm or 1 ppm or better for all lines. The mean difference was 0.2 cm with an rms of 1.7 cm or 0.6 ppm. These results are consistent with the uncertainty of 1 ppm (1 sigma) for the terrestrial base line lengths.

Overall, the results from the solutions by Macrometrics were significantly better than the results computed by the authors using a less accurate version of the processing software (see appendix E). However, in the near future, the differences should be insignificant. The software version used by the authors to process the data will be replaced by an upgraded version that is expected to be compatible with the version used by Macrometrics.

RECOMMENDATIONS

Based on the experiences gained by the authors during the test survey and from more recent test surveys, certain enhancements are desirable to ensure that data of highest quality are collected, to improve data handling, and to maximize the self-sufficiency of the operators using the Macrometers.

Except for the audible alarm and jack for external frequency signal input, all of the recommended enhancements involve software modifications or extensions. The Macrometer receiver contains an LSI-11 computer with both random-access memory and "mass" storage (bubble and tape) devices.

The recommended enhancements are:

1. Before starting the observations, the operator should be prompted for the measurement of the height of antenna phase center above the mark. It should also be possible to enter the antenna height measurement made after the end of the observations.

2. Operator should be prompted to enter other important information such as timing offset data.

Table 7. -- Comparisons for 8- to 42-km base lines

Obs. Sess.	From Known (Fixed) Station	To Unknown Station	Observ. Date	Base Line Length (km)	Differences in Base Line Length and Orientation (Terrestrial minus Satellite Derived)			
					Macrometrics Post Results Difference Proportion		FGCC Post Results Difference Proportion	
					(cm)	(ppm)	(cm)	(ppm)
6	OPTRACK	ATHEY	1-19-83	12.08	1.7	1.4	1.1	0.9
	OPTRACK	OBS RM 1		18.48	3.7	2.0	1.8	1.0
	OBS RM 1	ATHEY		8.68	2.4	2.7	2.3	2.6
7	OPTRACK	N. GEOS	1-20-83	42.12	10.8	2.6	0.6	0.1
	OPTRACK	OBS RM 1		18.48	3.8	2.0	2.2	1.2
	OBS RM 1	N. GEOS		34.58	5.3	1.5	-1.3	-0.4
8	OPTRACK	N. GEOS	1-21-83	42.12	10.7	2.5	6.3	1.2
	OPTRACK	OBS RM 1		18.48	3.3	1.8	1.1	0.6
	OBS RM 1	N. GEOS		34.58	11.1	3.2	8.7	2.5
	Mean					2.2		1.1
	Standard Deviation					0.6		1.0

Table 8. -- Comparison of base line lengths determined by Macrometrics, Inc., after adjustment for a scale factor computed in table 7

Observ. Session	From Known (Fixed) Station	To Unknown Station	Observ. Date	Base Line Length (km)	(Terrestrial minus Satellite Derived) Base Line Difference Before Adjustment (cm)	Base Line Adjustment Value for Base Line Diff. (cm)	Base Line Difference After Adjustment (cm)	Base Line Difference After Adjustment Proportion
6	OPTRACK	ATHEY	1-19-83	12.08	1.7	-2.7	-1.0	-0.8 ppm
	OPTRACK	OBS RM 1		18.48	3.7	-4.1	-0.4	-0.2 ppm
	OBS RM 1	ATHEY		8.68	2.4	-1.9	0.5	0.6 ppm
7	OPTRACK	N. GEOS	1-20-83	42.12	10.8	-9.3	1.5	0.4 ppm
	OPTRACK	OBS RM 1		18.48	3.8	-4.1	-0.3	-0.2 ppm
	OBS RM 1	N. GEOS		34.58	5.3	-7.6	-2.3	-0.7 ppm
8	OPTRACK	N. GEOS	1-21-83	42.12	10.7	-9.3	1.4	0.3 ppm
	OPTRACK	OBS RM 1		18.48	3.3	-4.1	-0.8	-0.4 ppm
	OBS RM 1	N. GEOS		34.58	11.1	-7.6	3.5	1.0 ppm
						Mean	0.2	0.0 ppm
						Standard Deviation	1.7	0.6 ppm

3. The operator should be able to enter an optional command that would result in display of a menu for entry of weather data.

4. The processor in the Macrometer receiver should be programmed to display an error code and perhaps turn on a beeping alarm, whenever certain critical numbers are not within the range of normal values. This would be very helpful in alerting the operators for possible irregularities or malfunctions.

5. The Macrometer receiver's processor should include more software to perform self-diagnostic routines to test components and modules. Test routines would be initiated after appropriate entry of a command. This feature would help to ensure the system was functioning normally before commencing observations. It would also be used to troubleshoot a system when there might be an indication of a malfunction.

6. Add a new feature providing the capability to review (as soon as observations are terminated) the quality, completeness, and acceptability of the observations. This could be done by playing back the data recorded on the cassette before departing from the station. This feature would make it possible for the operator to determine whether the station observations were acceptable for postprocessing. If not acceptable, the operator could contact other units and advise that an additional observing session is required. As the window or time-span of satellite availability increases, this feature will be important for efficient field operations.

7. Add a new feature providing the capability of using the Macrometer receiver's processor to compute almanac files. This would be very useful to reduce dependence of operators on an office for generating the almanac data or so-called "A" files. This is also necessary to support the feature recommended in item 6.

8. Future models like the V-1000 should have a jack for connecting an external frequency standard. The receiver should be able to accept as input a 5 MHz reference signal. The use of an external frequency standard would improve the accuracy of point positioning. Additionally, this feature enables the receiver to be used for satellite orbit and very long base line determinations.

SUMMARY

The results achieved from the FGCC test and demonstration of the Macrometer model V-1000 Interferometric Surveyor agreed very well with the terrestrial coordinate standard. Although the horizontal accuracy of the 8- to 42-km lines of the test network is estimated to be about 1 ppm (1 sigma), it appears the estimated uncertainties may have been too large. The results also indicated the need for improving the azimuth determinations for the short lines (under 2 km) of the test network.

Base lines determined from the Macrometer observations for distances of

0.4- to 1.3-km agreed to within a few millimeters of the terrestrial derived lengths. Comparison of the satellite and terrestrial base line lengths for the 8- to 42-km lines yielded a scale difference of 2.2 ppm with an rms value of 0.6 ppm. After adjusting for the scale difference, the satellite-derived and terrestrial base lines agreed to better than 1 ppm.

Differences in the orientation of the 8- to 42-km base lines were consistent to within 0.1 arc second (rms). The unweighted mean difference was about 0.4 arc second. For the short lines of 0.1 to 1.3 km, the orientation differences were not meaningful since the terrestrial orientation was not well known.

There was no significant difference between the satellite- and the terrestrial-derived ellipsoid height differences. The rms of the differences was about 4 cm for the base lines 8 to 42 km long. At the NBS test network, where the orthometric height differences for the under 1-km base lines are accurate to 3 mm (rms) and the geoid undulation is assumed to be zero with an rms of about 4 mm, the rms of the differences between the satellite- and terrestrial-derived ellipsoid heights was less than a centimeter.

The consistency of the differences in base line lengths and azimuths between the satellite- and terrestrially-derived relative positions indicate very clearly that the coordinates of one system can be adjusted to be compatible with the other system to within a few tenths of an arc second in orientation and better than 1 ppm in scale. It should be noted that this conclusion is based only on the limited results of the FGCC test and apply, in general, only to that network. It is not unreasonable to expect to find different orientation and scale values for other parts of the present NAD 1927 reference system. Additional tests will need to be conducted to investigate the long-term consistency of relative positions derived from Macrometer observations. Furthermore, to refine the understanding of the relationship between the GPS and terrestrial coordinate systems, extensive comparisons will be required.

Overall, the Macrometer receivers functioned very well. However, a component malfunction on January 15 prevented data being acquired on that day and the following day. The unit with the failed component had been delivered from the factory only a few days before the FGCC test. Thus, an opportunity did not exist before the FGCC survey to test the unit adequately in an operational environment.

Trees, buildings, and overhead wires at some of the sites were potential obstructions, but did not significantly affect the results of the survey. Thus, loss of observations due to obstructions was insignificant.

The ability to process raw field data in near-real-time in the field with a desk-top microcomputer system was successfully demonstrated. Data for base lines of under 2 km that were reduced on-site with the predicted ephemerides did not differ significantly from the results of processing the data later with the precise ephemerides. The accuracy of results processed in near-real-time will depend on the accuracy of the orbit and the length of the base lines. Postprocessing with the precise ephemerides, which is generally possible within a couple of weeks after the observations are performed, will give the most precise results.

The model V-1000 Macrometer must be vehicle-mounted to transport between stations. The maximum length of cable between the receiver and antenna is specified as 30 m, thus survey stations must be accessible within 30 m of the survey vehicle. The time required to setup and initialize the is generally less than 15 minutes. Since setup of the equipment is simple and operation of the receiver is automatic, one person for each Macrometer can easily handle a station occupation.

To summarize, the results of the test showed that the Macrometer model V-1000 is a viable survey system that can be used successfully to establish geodetic control relative to stations of the National Geodetic Reference System. The relative positional accuracies for stations separated by less than 1 km should be at the 2- to 3-millimeter level (1 sigma) in all three coordinates. For medium length base lines or stations separated by several tens of kilometers, the accuracies in the base line lengths would certainly be better than 1:100,000 and very likely approach 1 ppm. The orientation of the medium length base lines should be consistent to within 0.1-second level. Since it appeared from the test results that ellipsoid height differences were accurate at the 1- to 4-centimeter level, it is possible that differences in elevations-above-MSL could be very well determined. The accuracy of the elevation differences will depend on how accurate the geoid height differences are known. While these accuracy estimates are based on the results of the FGCC test, it is expected that they are reasonable estimates for distances of up to at least 100-km station spacings. It will be necessary to conduct additional tests to determine reliable uncertainty estimates for stations separated by more than a 100 km.

ACKNOWLEDGMENTS

On behalf of the FGCC, we would like to express our thanks for the excellent assistance and liaison support provided by Mr. Ron Hartsock of the National Bureau of Standards. The support that Mr. Hartsock gave in making arrangements for the auditorium facilities, a room for operating the processing equipment, and access to the NBS test survey network during the night and weekend hours was greatly appreciated.

REFERENCES

Carroll, Dennis and Wessells, C. W., 1975: A 1975 Astrogeodetic Geoid for the United States. Collected Reprints 1975, National Ocean Survey, NOAA, Rockville, Md, June 1976, pp. 22-32.

Counselman, C. C., III, 1983: MACROMETER Development - Present and Future. Presented at FGCC Meeting on Test and Demonstration of Macrometer Model V-1000 Survey System, Gaithersburg, Md., January 18.

Counselman, C. C., III, and Steinbrecher, D. H., 1982: The MACROMETER: A Compact Radio Interferometry Terminal for Geodesy with GPS. Proceedings of the Third International Doppler Symposium, Las Cruces, N.M., February 8-12, pp. 1165-1172.

Counselman, C. C., III, Abbot, R. I., Gourevitch, S. A., King, R. W., and Paradis, A. R., 1983: Centimeter-Level Relative Positioning with GPS. Journal of Surveying Engineering (ASCE), August (in press).

Remondi, Benjamin W., 1983: GPS Geodetic Receivers - A Status Update Report. Proceedings of the ACSM-ASP Convention, Washington, D.C., March 14-18, pp. 441-448.

Wooden, William, 1983: An Overview on the Global Positioning System - Current and Future Status. Presented at FGCC Meeting on Test and Demonstration of Macrometer Model V-1000 Survey System, Gaithersburg, Md., January 18.

FGCC Federal Geodetic Control Committee

December 27, 1982

MEMBERSHIP:

Department of Agriculture

Department of Commerce

Department of Defense

Department of Energy

Department of Housing and Urban Development

Department of Interior

Department of Transportation

National Aeronautics and Space Administration

Tennessee Valley Authority

N O T I C E

TEST AND DEMONSTRATION OF MACROMETER GPS SATELLITE SURVEY SYSTEM

Beginning on the morning of Tuesday, January 18, 1983, the Instrument Subcommittee of the Federal Geodetic Control Committee (FGCC) and representatives of MACROMETRICS, INC., will conduct a test of the MACROMETER GPS Satellite Survey System. The test will be carried out over a 4-day period on the FGCC test network located in the area of Washington, D.C.

At 9:00 a.m., Tuesday, January 18, MACROMETRICS, INC. will conduct a special demonstration with two MACROMETER survey systems at the National Bureau of Standards (NBS) test site at Gaithersburg, Maryland. The NBS test site is part of the FGCC test network.

The demonstration, hosted by the Instrument Subcommittee, will focus on the operation of the MACROMETER, on-site processing capabilities, and comparisons of preliminary test results with adjusted terrestrial survey data.

After setup of the equipment and while the observations are being made, representatives of MACROMETRICS, INC. will provide briefings on the equipment. These briefings will be held in the Third Floor Conference Room (A346) in the Metrology Building, Number 220, at the National Bureau of Standards. Attached are directions to the National Bureau of Standards and a map of the NBS complex.

The other stations of the FGCC test network that will be occupied during the 4-day test are located near Herndon, Virginia, Greenbelt, Maryland, and Darnestown, Maryland. The baseline lengths vary from a few hundred meters to about 42 kilometers, including several lines that are 5 to 10 km long.

A written report on the test and demonstration will be published by FGCC by about April.

For additional information, you may contact:

Fred Wilson, Chairman, Instrument Subcommittee, FGCC
Phone: (202) 227-2213
Larry Hothem, (301) 443-8580
Chuck Fronczek, (301) 443-2196

for information write:
THE CHAIRMAN
FEDERAL GEODETIC CONTROL COMMITTEE
6001 Executive Boulevard • Room 305/C1 • Rockville, Maryland 20852

APPENDIX B. -- AGENDA FOR PUBLIC MEETING

FGCC Federal Geodetic Control Committee

MEMBERSHIP:

Department of Agriculture

Department of Commerce

Department of Defense

Department of Energy

Department of Housing and Urban Development

Department of Interior

Department of Transportation

National Aeronautics and Space Administration

Tennessee Valley Authority

1-17-83

AGENDA

for

Public Meeting: FGCC Test and Demonstration of MACROMETER
Tuesday, January 18, 1983
National Bureau of Standards
Gaithersburg, Maryland

9:15 a.m. Welcome and introductions by FGCC - Fred Wilson, Chairman, FGCC Instrument Subcommittee

9:30 a.m. Overview on GPS system - Current and Future Status. Bill Wooden, DMAHTC

10:15 a.m. Coffee break: NBS Cafeteria

10:45 a.m. Information about MACROMETRICS, INC.; MACROMETER development, present and future. Charles C. Counselman, III, MACROMETRICS, INC.

11:15 a.m. Brief description of FGCC Test Network and test objectives; Results for survey performed on Tuesday, January 18, 1983. Larry Hothem, FGCC Instrument Subcommittee.

11:45 a.m. Public demonstration of setup and take-down of MACROMETER systems; two groups. Location: Outside on walkway next to auditorium.

1:00 p.m. Lunch: NBS Cafeteria

2:00 - 3:00 p.m. Informal discussion

for information write:
THE CHAIRMAN
FEDERAL GEODETIC CONTROL COMMITTEE
6001 Executive Boulevard · Room 305/C1 · Rockville, Maryland 20852

(1-15-83) GPS STATION OBSERVATION LOG	PAGE	YEAR	STATION NAME	DOPPLER STATION NUMBER (IF ANY)	GPS STATION NUMBER (IF KNOWN)
	LOCATION		PROJECT		AGENCY OBSERVING

OCCUP. NUM.	DATE	ARRIVE AT SITE (UT Time)	COMPLETE SETUP (UT Time)	BEGIN OBSERV. (UT Time)	END OBSERV. (UT Time)	DEPART STATION (UT Time)	BASE STATION	EQUIPMENT TYPE	EQUIP. SERIAL NUMBER	ANTENNA CABLE LENGTHS		NAME OF OBSERVER
							YES NO					

TRIBACH USED	ANTENNA ECCENTRICITES (Relative to Station Mark)			WEATHER CONDITIONS (*) (i.e. Sky, Winds, Temp., precipitation, relative humidity, etc.)	
	North (m)	East (m)	Up (m)		
			+ + =		
			+ + =		

GPS RECEIVER CLOCK DELAYS			DIFFERENCES FROM OTHER RECEIVERS			REMARKS (*)
TIME (UT)	REFERENCE (GOES, TRANSIT, WWV, etc.)	DELAY (+ ahead) (- behind) (us)	TIME (UT)	REFERENCE Receiver Serial Number	DIFFERENCES (+ ahead) (- behind) (us)	(Operator comments, equipment failures, obstruction problems, report of any tracking loss and reaquisition time, voltage readings, etc.)

Subtract _____ hours to convert UT to local time.

* If additional space is required, use back of this form.

APPENDIX D. -- SAMPLE OUTPUT OF REDUCTION PROGRAM LSQ

Output of program LSQ. Final coordinates for station NBS-4 relative to station NBS-1. Coordinates are referenced to NAD 1927 datum and CLARKE 1866 reference ellipsoid.

```
EPHEMERIS AND SURVEY DATA FILES:
SITE 1) E13F13.014        RNBS13.014
SITE 2)                   RNBS43.014
INTERF FILE: IS1S41.014

CHI-SQUARE =  0.11774E+03 FOR   175 OBSERVATIONS  CUT AMP=   3.0  EPOCHS  1-60
ASSUMED STANDARD DEVIATION OF MEASUREMENT ERROR =        3. MILLIMETERS

ERROR CORRELATION MATRIX:
 1.0000
 0.5291  1.0000
-0.1485  0.0644  1.0000
```

LABEL (UNITS)	APRIORI	ADJUSTMENT	SIGMA	POSTFIT
1 SITE 1 LAT. (DMS)	039:08:01.22894	0.000000D+00		
2 SITE 1 LONG.(DMS)	077:12:49.28747	0.000000D+00		
3 SITE 1 HEIGHT (KM)	0.1363660000	0.000000D+00		
4*SITE 2 LAT. (DMS)	039:07:39.00000	0.896947D-04	0.48E-08	039:07:39.32290
5*SITE 2 LONG.(DMS)	077:12:36.00000	-0.384125D-04	0.50E-08	077:12:35.86171
6*SITE 2 HEIGHT (KM)	0.1270000000	-0.194919D-02	0.10E-05	0.1250508133
7 CLOCK 1 EPOCH (SECS)	0.0000000000	0.000000D+00		
8 CLOCK 1 RATE	0.0000000000	0.000000D+00		
9 CLOCK 1 ACCELERATION	0.0000000000	0.000000D+00		
10 CLOCK 2 EPOCH (SECS)	0.0000000000	0.000000D+00		
11 CLOCK 2 RATE	0.0000000000	0.000000D+00		
12 CLOCK 2 ACCELERATION	0.0000000000	0.000000D+00		
13 BIAS 1 (CYCLES)	0.0000000000	0.000000D+00		
14 BIAS 2 (CYCLES)	0.0000000000	-0.660000D+02		
15 BIAS 3 (CYCLES)	0.0000000000	-0.101000D+03		
16 BIAS 4 (CYCLES)	0.0000000000	0.851600D+04		
17 BIAS 5 (CYCLES)	0.0000000000	-0.118000D+03		
18 BIAS 6 (CYCLES)	0.0000000000	0.000000D+00		
19 ATMOSPHERE SITE 1	0.0000000000	0.000000D+00		
20 ATMOSPHERE SITE 2	0.0000000000	0.000000D+00		

APPENDIX E -- Differences Between Versions of Data processing Programs

by

Charles C. Counselman III*
Macrometrics, Inc.
185 New Boston Street
Woburn, Massachusetts 01801

In the processing of the field data from the FGCC test survey, slightly different versions of the computer programs INTERF and LSQ were used at different times and places. Also, some of the postprocessing by Macrometrics, Inc., used a "mainframe" computer in addition to the Macrometrics P-1000 processor. What were the differences between the different program versions, and what was done on the mainframe computer?

To answer these questions, let me first outline the steps in the processing of MACROMETER data. The processing begins when the raw field data from two survey sites have been received at the P-1000 processor. These data are input to the INTERF program, which analyzes them to determine the interferometric phase (the difference between the phases of the signals received simultaneously at the two sites) for each satellite as a function of time. The interferometric phases are the basic observables from which the position of the "unknown" station, relative to the position of the reference station, is estimated. The position estimation is performed with program LSQ, which employs a conventional least-squares adjustment procedure.

Program INTERF is completely automatic. That is, it requires no assistance from a human operator. The only manual inputs to INTERF are such things as station names and dates. Program LSQ is interactive. Its operator must choose, for example, which station coordinates are to be adjusted, and which observations are to be included. To guide its operator, LSQ presents graphs of residuals (differences between observed and theoretically computed phases) on the P-1000 video terminal, asks multiple-choice questions, asks the operator to move a cursor around the video screen to tag any observations that are to be deleted, and so on.

An essential part of the data processing, ordinarily performed by INTERF, is the computation of the positions of the satellites in their orbits. The starting point for this computation is a set of so-called "orbital elements" for the satellites at a particular time. This time should be chosen to be near the center of the time span of the observations that are being processed. For each satellite there are six orbital elements, and each element is a number with 6 to 8 digits. The

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usual means of getting the orbital elements is via telephone modem, from a computer at Macrometrics, Inc. However, since the amount of orbital data is small, verbal or written communication and manual entry would be possible.

From the orbital elements at the chosen time, INTERF computes the satellite positions for each observation time by means of formulas that account for some, but not all, of the dynamics of the problem. The differences between the different versions of INTERF that were used in the FGCC test were in the accuracies of their orbit formulas.

In the original INTERF, version 01.01A1, one approximation implicit in the orbital computation limited the accuracy to several parts per million. Version 01.02A1, used by the FGCC in their postprocessing, was somewhat better, and yielded accuracy of about two parts per million (one sigma). The two most serious errors in this version are that (i) lunar and solar perturbations of the satellite orbits are neglected, and (ii) the earth's polar motion is neglected.

We are testing, but are not ready to release, a version of INTERF that accounts for polar motion, lunar and solar perturbations, perturbations by terrestrial gravity field harmonics through fourth order, and perturbations by radiation pressure. This program runs on the P-1000 data processor and has accuracy of 0.5 part per million. The program was not ready in time for the FGCC test. Instead, for our own "postprocessing," we used the Massachusetts Institute of Technology, Planetary Ephemeris Program (PEP) for the earth rotation and satellite motion computations. A file of data written by PEP running on a mainframe computer was read by INTERF which ran on the P-1000; otherwise the MACROMETER data processing was done in the usual way, on a P-1000 system.

The versions of LSQ used in the FGCC test did not differ in any way that should have affected the results. Only such things as input/output labeling and formats were different.

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration

National Ocean Service
Charting and Geodetic Services
National Geodetic Survey (N/CG17x2)
Rockville, Maryland 20852

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