FGCC

Test and Demonstration of Three Dual-frequency (L_1/L_2) GPS Satellite Survey Systems

FGCC Report: FGCC-IS-90-2

MODELS and MONTH OF TEST

MINIMAC 2816	- MAY 1989
TRIMBLE 4000SST	- OCTOBER 1989
ASHTECH LD-XII	- NOVEMBER 1989

US Army Corps of Engineers

Larry D. Hothem
Instrument Subcommittee
Federal Geodetic Control Committee
Rockville, Maryland

June 1990

TVA Tennessee Valley Authority

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1. REPORT ON TEST AND DEMONSTRATION OF

MINI-MAC™ MODEL 2816, 1816, and 1616 GPS SURVEYOR SYSTEMS

AND ASSOCIATED PROCESSING SOFTWARE

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September 15, 1990

In May 1989 the Federal Geodetic Control Committee (FGCC) conducted a test and demonstration of the MINI-MAC™ models 2816, 1816, and 1616 GPS Surveyors developed by Aero Service, Western Atlas International, Houston, TX. The model 2816 is a dual-band (L_1 and L_2) eight satellite tracking receiver. Models 1816 and 1616 are the same as the model 2816 except the receivers track L_1 only, and the 1616 model tracks up to six satellites. This was the twelfth in a series of comprehensive tests by FGCC to evaluate the performance of GPS (Global Positioning System) geodetic satellite survey systems and associated vector processing software.

The test and demonstration were conducted over a 5-day period beginning Monday, May 1 (day 121), and ending Friday, May 5 (day 125), 1989, on stations of the FGCC test network located in the vicinity of Washington, DC. The measured vectors ranged in lengths of: short from 183 to 1322 m, medium from 7 to 19 km, and long from 35 to 105 km. Each observing day, four model 2816 receivers were operated for a single continuous session where the scheduled observing span was about 230 minutes. During the 5-day period, 20 independent station-occupation-sessions were scheduled and successfully observed which resulted in the measurement of 30 vectors (trivial and nontrivial).

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The MINI-MAC™ 2816 dual-band GPS Surveyor consists of two major components: a portable receiver and an external antenna. The receiver unit is in a waterproof case measuring about 19 by 33 by 51 cm (7.5 by 13 by 20 in.) and weighing about 20 kg (44 lb). It is powered by either an internal or external 12VDC power supply with a power consumption of approximately 40 W. The removable internal battery pack will operate the unit for 1 to 2 hours. Because the scheduled observing session lasted more than 2 hours, an external battery supply was used with all receivers during the test survey. The receivers are designed to operate in temperatures of -20°C to +50°C, with relative humidity up to 100 percent.

The model 2816 receiver can simultaneously track L_1 and L_2 signals from eight GPS satellites. Observing up to eight GPS satellites gives the surveyor the capability of tracking all available satellites in view at the present time and most, if not all, that will be in view for the next few years. The L_1 (1575.42 MHz) signal is acquired through use of fast-sequencing coarse/acquisition (C/A) code correlation technology where one analog channel is almost instantaneously divided into eight digital channels. Eight independent L_2 channels also acquire phase data by use of proprietary codeless techniques developed by Aero Service. The codeless L_2 channels obviate the need for access to the precise code (P-code) in order to make phase measurements on the L_2 carrier.

Other features of the receiver include: a self-contained data logger, built-in complete typewriter keyboard, an 80-column by 24-row backlit liquid-crystal display, 1-pps output, input for external 10-MHz frequency standard, and an RS232C interface. Data are initially recorded on an internal 64-Kb RAM (random access memory) and then transferred to one of two built-in 3.5-inch 720 Kb disk drives. Each disk is capable of storing more than 4,000 complete dual-frequency data samples or epochs, employing eight satellites (e.g., 66 minutes at 1-second sampling or 1,000 minutes at 15-second sampling).

Data are normally sampled at the default rate of 60 seconds, with higher and lower sampling rates available for selection. The data recorded for each sample consists of: day/year; time of day, L_1 phase; L_1 signal/noise ratio (SNR); L_2 phase; L_2 SNR; and L_1 pseudorange (one set for satellite tracked). Additionally, the once-per-hour predicted ephemerides (satellite coordinate data) included in the broadcast message for each satellite are recorded. The pseudorange data are processed with the broadcast (predicted) satellite orbital coordinates to determine in real-time, time-tags for the carrier phase measurements.

Aero Service offers two dual-frequency antenna models with the model 2816 system. The first model is a lightweight portable microstrip configuration weighing about 3.5 kg (7 lb) with a specified capability of better than 1-cm phase resolution. The second model is a patented nondirectional cross-dipole antenna with a specified phase-center stability at the 1-mm level. The cross-dipole antenna with a ground plane attached is specified to be uniquely insensitive to multipath problems. However, it is considerably larger and heavier (16 kg or 35 lb) than the portable microstrip antenna. Additionally, signals from the satellites cannot be received below about 12.5° above the horizon. During the FGCC test survey, the portable microstrip antenna was used the first 4 observing days and the cross-dipole antenna was used on the last observing day.

The MINI-MAC™ GPS Surveyor system are configured to operate in either the static (fixed site) or kinematic mode of surveying operations. During the FGCC test survey, data were collected only in the static mode.

The phase data collected simultaneously with one or more other receivers are processed to determine relative positions ($\Delta X, \Delta Y, \Delta Z$) between the occupied station points.

Aero Service's specified estimates for static survey relative positioning accuracies (1 σ) in any component are: 1 to 2 mm + 1 to 2 mm/km. The accuracy estimates assumed at least five satellites were tracked continuously for the appropriate time span, the cross-dipole antenna was used, L_1/L_2 carrier phase measurements were recorded and processed, and the accuracy of the orbital coordinate data was 1 mm/km (1 ppm) or better.

Aero Service's GPS processing package for production vector post-processing is called AIMS™ (Automatic Interferometric Mini-Mac™ Software). In use since 1985, AIMS™ processes single- and/or dual-band GPS phase data collected at up to 10 stations in a single simultaneous observational session. Optionally, single or individual vectors can be processed. The observing data can be processed in the batched mode and analyzed sequentially through the network for a project.

The AIMS™ package is designed to operate on an IBM PC or 100-percent compatible computer with 640K RAM, a hard disk having at least a 20-Mb capacity, a math-coprocessor, and a serial interface port. Aero Service specifies that 1-hour of static data for a single vector determination can be processed in less than 2 minutes with a 20 MHz 386 PC. With the same computer and a 10-station observing session, an hour of data can be processed in about 5 minutes.

Other features of the AIMS™ software package includes:

1. Automatic cycle-slip fixing (specified nearly 100 percent effective).
2. Once data are cycle-slip free, an ambiguity search can be performed to identify correct integer values of the intersatellite phase bias parameters.
3. Optional input for surfaced measured meteorological data or default to standard atmospheric values (T_{dry} = 20.0°C, RH (Relative Humidity) = 50 %, and $P_{sea\ level}$ = 1013 mb).
4. Selectable atmospheric propagation delay models.
5. Triple and double difference (float and fixed) processing techniques.
6. Graphics capability for display of residuals.
7. Input of precise ephemeris data in the standard distribution format.
8. Covariance and correlation data in output.
9. Capability to process data collected in the kinematic survey mode.
10. Full interactive data processing mode option.

Surface meteorological data were recorded during most of the station occupations. However, in the results received for analysis, only the default atmosphere values were used in the vector solutions.

Other software available from Aero Services for use as an aid in site selection and in planning observations include utilities to generate information on satellite visibility and geometry (i.e., skyplots where obstruction survey information can be overlaid to show masking of satellites; Position Dilution of Position (PDOP) tables; and Relative DOP (RDOP) tables).

This report is based on analysis of vector results produced with the AIMS™ software, version 1.00, dated February 1988. The software CAPS™, version 1.00, February 1988, was also used during post-processing for L_1 only data. Significant factors selected in the vector processing were:

1. Integer ambiguities were either fixed or floated in the double-difference solution (depending on length of vector).
2. Observation epoch processing interval (sampling rate): 60 sec
3. Elevation angle cutoff (above horizon): 20°
4. Residual editing criteria: 3.5 σ
5. Assumed standard deviation of measurement error: 4.0 mm + 1 mm/km
6. Tropospheric model: Modified Hopfield

The output for the AIMS™ vector processing software lists:

1. Initial coordinates for the station held "fixed."
2. Starting and ending, and total number of epochs (measurement counts) used in the solution.
3. Total number of double-difference observations.
4. Results of integer bias search.
5. Normalized RMS estimates.
6. Results for the vector components (ΔX, ΔY, ΔZ, and length).
7. Computed coordinates (latitude, longitude, and ellipsoidal height) for the "free" stations in the solution.
8. Covariance and correlation matrices.

The accuracy for the predicted (broadcast) satellite orbital coordinate data used in the solutions was estimated to be about 1 mm/km (1 ppm) at the 1 σ level.

Vector solutions requested by FGCC for analysis included:

1. L_1 only, "session" and "single nontrivial selected lines."
2. L_2 only, for short base lines only (i.e., within 2 km), "single" vector processing.
3. L_1 and L_2 ionospheric free linear combination for appropriate length vectors, "session" and "single nontrivial selected lines."
4. Selected subsets of about 1- and 2-hour spans processed as specified under 1, 2, and 3 above.

For each session, table 1.1 summarizes the approximate starting and ending time in UTC (Coordinated Universal Time), number of stations occupied, the PRN (pseudorandom noise) code for the satellites tracked, number of satellites at beginning/maximum/end of each session, and number of vector measurements (trivial and nontrivial) attempted compared to number submitted for evaluation.

Table 1.1.--Observation summary, MINI-MAC™ model 2816 FGCC test survey

Session	Starting and ending time (UTC)(1)	Number of stations	Satellites observed (PRN code)	Number of satellites at start/maximum/end	Vectors (trivial and nontrivial)	
					Primary set possible/analyzed(2)	Subsets possible/analyzed(2)
121	00:55-04:44	4	6,8,9,11,12,13	4/6/4	6/6	12/12
122	00:51-04:40	4	6,8,9,11,12,13	4/6/4	6/6	12/12
123	00:47-04:36	4	6,8,9,11,12,13	4/6/4	6/6	12/12
124	00:43-04:32	4	6,8,9,11,12,13	4/6/4	6/6	12/12
125	00:39-04:28	4	6,8,9,11,12,13	4/6/4	6/6	12/12
TOTALS		20			30/30	60/60

(1) Subtract 4 hours to convert UTC to local time.
(2) The number of vectors analyzed are those which were successfully processed and available for evaluation.

As indicated in table 1.1., all observations were conducted from dusk through about midnight local time. Based on the single daily data set collected at each station occupied, the total number of vector measurements attempted (trivial and nontrivial) was 30. Subsets of the complete data set were also processed at 1- and 2-hour intervals.

Table 1.1 also summarizes the results obtained for each of all possible vectors (trivial and nontrivial). The vector results were evaluated by comparison of repeat measurements, the computation of loop misclosures, comparison with the test network terrestrial coordinate differences, and comparison with precise GPS vector base line measurements determined from previous FGCC test surveys. The analyses were carried out using the vector base line components, base line lengths, ellipsoidal height differences, and base line azimuths.

Table 1.2 compares the results for repeat measurements. The spread in any component for base lines under 1,000 m is less than 10 mm for the solution using the complete data sets and less than 15 mm for data sets of 60- or 90-minute spans. For the ORM1-ATHY line of 8.6 km, the difference between the repeat measurements ranged from 0 to 16 mm. In the last line shown in table 1.2, ATHY-GORF, the spread for the L_1 only solution ranged from 4 to 67 mm, whereas, for the L_1 ionospheric free solution, the differences ranged from 1 to 8 mm. In this example for a base line of about 41.0 km, benefits of having dual frequency measurements are clearly demonstrated.

Table 1.2.--Comparison of repeat vector measurements

From	To	Day	Span (min)	RMS (cm)	DX (m)	DY (m)	DZ (m)	Length (m)	Dh (m)	Remarks
NBS0	NBS1	121	229	1.1	43.883	-107.145	-142.992	183.990	-1.667	(1)
		125	229	1.3	.884	.146	.989	.988	.665	(1)
		121	90	0.8	.880	.149	.989	.989	.663	(3)
		125	90	1.5	.889	.140	.993	.989	.671	(3)
NBS0	NBS3	121	229	1.3	450.017	-219.756	-389.822	634.641	-2.525	(5)
		125	229	1.3	.026	.754	.824	.647	.526	(5)
NBS1	NBS3	121	229	1.3	406.135	-112.612	-246.830	488.418	-0.857	(5)
		122	229	2.8	.141	.606	.835	.424	.864	(5)
		125	229	1.3	.142	.607	.836	.426	.863	(5)
		121	60	1.2	.134	.605	.836	.418	.867	(3)
		122	60	1.1	.138	.597	.836	.420	.872	(3)
		125	60	1.0	.140	.611	.833	.423	.859	(3)
ORM1	ATHY	122	229	1.7	-7145.563	-4000.285	-2885.346	8682.544	-17.616	(3)
		123	229	1.8	.579	.279	.355	.557	.616	(3)
ATHY	GORF	123	229	9.6	40234.022	3409.094	-7142.196	41004.993	-84.018	(5)
		124	229	9.5	.026	.056	.137	.983	.951	(5)
		123	229	1.8	.014	.086	.118	.971	.964	(8)
		124	229	1.2	.022	.094	.112	.978	.965	(8)

Solution method: (1) SB-DDFX-BE-L1; (2) SB-DDFL-BE-L1; (3) SB-DDFX-BE-L1/L2; (4) SB-DDFL-BE-L1/L2; (5) MB-DDFX-BE-L1; (6) MB-DDFL-BE-L1; (7) MB-DDFX-BE-L1/L2; (8) MB-DDFL-BE-L1/L2

Legend: SB - Single base line solution; MB - Multiple base line or session solution; DD - Double difference; FX - Fixed integers; FL - Integer float solution; BE - Broadcast ephemerides.

In table 1.3, nine sample loop misclosure computations are summarized. The loops were formed using independently determined vectors that were selected arbitrarily from double difference solutions which used the predicted orbital elements. The total distance around each of the nine loops ranged from 3.7 to 246.5 km. The number of base lines in each loop ranged from three to six with two to four independently determined vectors.

The resultant misclosure for the loop with short length vectors was 12 mm. For those loops with a combination of short and medium length vectors determined from L_1 only solutions, the resultant misclosures ranged from 3.9 to 7.4 cm. When the same vectors were determined from ionospheric free data (L_1/L_2 solutions), the resultant loop misclosure was 1.2 to 2.6 cm. In the loop formed with vectors as long as 104 km with a total distance around the loop of 247 km, the resultant misclosure was 3.7 cm for the L_1 only solutions. The resultant misclosure for the L_1/L_2 vectors was 1.5 cm. Again as noted earlier for the repeat base line measurements, results are significantly improved when L_2 phase data are available.

All base lines were previously surveyed by three-dimensional precise terrestrial survey methods. Two-sigma accuracy estimates for the terrestrial

Table 1.3--Summary of loop misclosure computations

Number of lines		Length of loop	Misclosure					REMARKS
Independent	Total		DX	DY	DZ	Resultant	Dh	
		(km)	(cm)	(cm)	(cm)	(cm)	(cm)	(1)
3	5	3.7	-0.8	-0.8	0.4	1.2	0.7	L1 only solutions
3	4	18.1	-2.5	-2.0	6.6	7.4	5.3	L1 only solutions
3	4	18.1	-0.7	0.3	-2.5	2.6	-0.6	L1/L2 solutions
2	3	95.2	-0.4	3.8	-6.0	7.1	0.1	L1 only solutions
2	3	95.2	-0.8	-0.8	-0.5	1.2	0.1	L1/L2 solutions
3	4	97.5	-3.6	0.8	1.2	3.9	6.4	L1 only solutions
3	4	97.5	-1.1	-0.2	-0.1	1.5	-0.7	L1/L2 solutions
4	6	246.5	-3.4	0.7	1.2	3.7	-0.4	L1 only solutions
4	6	246.5	-0.7	-0.2	-1.3	1.5	-0.7	L1/L2 solutions

(1) Vectors from double difference float or fixed solutions using the predicted (broadcast) ephemerides.

relative positional measurements are 2 mm/km (2 ppm) for horizontal and 3 mm/km for vertical. Additionally, all lines measured with the MINI-MAC™ 2816 system were surveyed during previous FGCC GPS test surveys. Test survey results have been accumulated in a database from the models: Macrometer™ V1000, Texas Instrument TI4100, Trimble 4000S, 4000SX, and 4000ST, Wild-Magnavox WM-101, SERCEL NR52, Ashtech L-XII, and Norstar 1000. Overall, the estimated 1-sigma vector component uncertainty achieved from the earlier GPS test survey data processed with broadcast ephemerides is about $\pm\sqrt{[10\ mm + (d\cdot(2\ mm/km))^2]}$, where d is the base line length in kilometers.

After an appropriate adjustment for significant systematic differences due to differences between WGS84, WGS72, and NAD83 coordinate systems, the comparisons with terrestrial and past GPS measurements were evaluated to estimate 1-sigma vector component uncertainties for the "site" dependent (e) and the "distance" dependent (p) values. The value for e should be comparable to the component uncertainty for "zero" length base lines, provided that the antenna setup error (centering and antenna phase center height measurement error) is insignificant.

When model 2816 L_1 data (comparable to a data set collected with model 1816 when eight satellites are in view and to model 1616 when only six satellites are in view) for a span within the range of about 60 to 90 minutes are processed with the broadcast (BE) or predicted orbital elements, the empirically derived 1-sigma estimate for e is 5 mm and for p is 2 mm/km (2 ppm). Combining these estimates statistically, the total 1-sigma and 2-sigma estimates for each vector component are given by:

$$E_{1\text{-sigma}} = \pm \sqrt{[(5\ \text{mm})^2 + (d \cdot 2\ \text{mm/km})^2]}_{BE},$$

and

$$E_{2\text{-sigma}} = \pm 2 \cdot (\sqrt{[(5\ \text{mm})^2 + (d \cdot 2\ \text{mm/km})^2]}_{BE}),$$

where

d = length of the vector in kilometers.

When the same data are processed using the L_2 data ("ionospheric-free" L_1 observable), the empirically derived 1-sigma estimate for e is 5 mm and for p is 1 mm/km (1 ppm). Combining these estimates statistically, the total 1-sigma and 2-sigma estimates for each vector component is given by:

$$E_{1\text{-sigma}} = \pm \sqrt{[(5\ \text{mm})^2 + (d \cdot 1\ \text{mm/km})^2]}_{BE},$$

and

$$E_{2\text{-sigma}} = \pm 2 \cdot (\sqrt{[(5\ \text{mm})^2 + (d \cdot 1\ \text{mm/km})^2]}_{BE}),$$

where

d = length of the vector in kilometers.

Overall, the results from the "broadcast" ephemeris solutions indicated that the 2816 L_1/L_2 GPS Surveyor will produce effective results that meet or exceed manufacturer's specifications.

The trees, buildings, and nearby power transmission lines at some of the FGCC test stations sites may have affected the test data. However, these are about the same conditions that could have affected or had a negative influence on previous test surveys. Furthermore, these are factors which frequently characterize the conditions at operational GPS survey stations. Thus, the less than optimal conditions found at some of the FGCC stations are useful in the tests to help determine the design effectiveness and capabilities of the GPS survey instruments and processing software.

Once the 21 to 24 block II satellite constellation is operationally available, users will have more flexibility in dealing with obstructions. It is expected that most stations with marginal obstruction problems today will in the near future have adequate signals of good quality passing through clear areas of the sky. Hence, confidence in achieving desired accuracies at stations with substantial problems with obstructions will improve significantly during the next few years.

Table 1.4 summarizes the FGCC accuracy standards for orders III through AA. Based on analysis of the results achieved from the FGCC test survey and assuming the accuracies for the broadcast and precise ephemerides are about 1 ppm and 0.1 ppm, respectively, the capability of the MINI-MAC™ model 2816 to achieve the various orders is indicated. The remarks specify certain conditions upon which the capabilities are based.

To achieve the high orders of A and AA, it was assumed that the AIMS™ software is capable of producing results from fixed orbital coordinate data solutions that are limited only by the accuracy of the precise orbit data. To achieve the accuracy standards of orders A and AA, it may be necessary to process the vectors while adjusting the orbital coordinate data. However, when data are processed with Aero Service's alternate software package called

SONAP™, GPS vectors are determined while adjusting the orbit. The accuracies achieved should approach 3 mm + 0.01 mm/km (0.01 ppm).

Table 1.4.--FGCC accuracy standards and capability of the MINI-MAC™ 2816

FGCC accuracy standards (2-sigma or 95% confidence level) (Reference: Version 5.0, May 11, 1988, reprinted with corrections August 1, 1989)		MINI-MAC model 2816 capability of meeting FGCC accuracy standards
Order	Definition	Remarks
3I	$\pm\sqrt{[(50\ mm)^2 + (d \cdot 100\ mm/km)^2]}$	Yes, with BE; L1 only or L1/L2.
2II	$\pm\sqrt{[(30\ mm)^2 + (d \cdot 50\ mm/km)^2]}$	Yes, with BE; L1 only or L1/L2.
2I	$\pm\sqrt{[(20\ mm)^2 + (d \cdot 20\ mm/km)^2]}$	Yes, with BE; L1 only or L1/L2.
1	$\pm\sqrt{[(10\ mm)^2 + (d \cdot 10\ mm/km)^2]}$	Yes, with BE; should with L1 only; more confidence with L1/L2.
B	$\pm\sqrt{[(8\ mm)^2 + (d \cdot 1\ mm/km)^2]}$	Possibly with BE; more confidence with PE; possibly with L1 only data, but more confidence with L1/L2 data.
A	$\pm\sqrt{[(5\ mm)^2 + (d \cdot 0.1\ mm/km)^2]}$	No with BE; should with PE of 0.1 ppm or better and L1/L2 data in linear combination to reduce effects of ionospheric disturbances; if PE not accurate enough, solutions must be done with orbital adjustment method. It is assumed that SA would not have a major impact on quality of observations.
AA	$\pm\sqrt{[(3\ mm)^2 + (d \cdot 0.01\ mm/km)^2]}$	Fixed orbit solutions with PE may not produce acceptable results; then must use orbital adjustment method; L1/L2 data essential for combining linearly to reduce effects of ionospheric disturbances. It is assumed that SA would not have a major impact on quality of observations.

Legend: BE - Broadcast (predicted) ephemerides; PE - Precise ephemerides; SA - Selective availability; d - length of vector in Km

In conclusion, it was found from analysis of the FGCC test survey results obtained in May 1989 from the MINI-MAC™ model 2816 GPS Surveyor that this system can produce accuracies that will meet a wide range of geodetic and engineering survey requirements. This conclusion is valid only when dual frequency carrier phase data (L_1 and L_2) are collected on four or more satellites with an acceptable geometric configuration and processed with double difference software using orbital coordinate data accurate to 1 mm/km (1 ppm) or better. Data spanning a period of about 60 minutes should yield accuracies that meet accuracy requirements for FGCC orders of 1 or lower. Data spanning periods of 2 to 5 hours may be required to ensure that higher accuracy orders (i.e., FGCC orders B, A, and AA) can be achieved. When only the L_1 data of the model 2816 are processed, the results should be comparable to when the L_1 only MINI-MAC™ models 1816 and 1616 are used in a GPS survey.

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2. REPORT ON TEST AND DEMONSTRATION OF

TRIMBLE 4000SST GPS SURVEYOR

AND ASSOCIATED PROCESSING SOFTWARE

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September 16, 1990

In October-November 1989 the Federal Geodetic Control Committee (FGCC) conducted a test and demonstration of the Trimble Model 4000SST GPS Surveyor, a dual-band (L_1 and L_2) receiver developed by Trimble Navigation, Ltd., Sunnyvale, CA. This was the thirteenth in a series of comprehensive tests by FGCC to evaluate the performance of GPS (Global Positioning System) geodetic satellite survey systems and associated vector processing software.

The test and demonstration were conducted over a 5-day period beginning Monday, October 30 (day 303), and ending Friday, November 3 (day 307), 1989, on stations of the FGCC test network located in the vicinity of Washington, DC. Vectors measured ranged in lengths of: short from 183 to 1322 m, medium from 7 to 19 km, and long from 35 to 105 km. Five Trimble 4000SST receivers were tested by GPS surveying in static and kinematic modes.

During days 303, 304, and 305, phase measurements in the static mode were collected during a single continuous session of approximately 240 minutes. On day 306, three of the five receivers were operated in the kinematic mode on stations of the FGCC test network located at the National Institute of Standards and Technology, Gaithersburg, MD. During the final observing day, phase measurements were collected in the static mode for a span of about 120 minutes. Twenty-two independent station-occupation-sessions in the static mode were scheduled. The stations were successfully observed resulting in the measurement of 41 vectors (trivial and nontrivial). Nineteen stations were occupied repeatedly with the three roving receivers during the kinematic test survey on day 306.

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The Trimble 4000SST dual-band GPS surveyor consists of three major components: a portable receiver/datalogger, an external antenna, and battery supply. The receiver unit is in a waterproof case measuring about 30 by 35 by 13 cm (12 by 13.9 by 5.2 in) and weighing about 7.2 kg (16 lb). The system operates on about 8 W from an external 10 to 35 VDC power source, such as the 6-pound (2.7 kg) sealed lead battery provided by Trimble. The specified receiver/antenna unit operating range for temperature is -20°C to +55°C.

The 4000SST can simultaneously track L_1 and L_2 signals from eight GPS satellites. Observing up to eight GPS satellites gives the surveyor the capability of tracking all available satellites in view at the present time and most, if not all, that will be in view for the next few years. The L_1 (1575.42 MHz) signal is acquired through use of independent channel coarse/acquisition (C/A) code correlation technology. Eight independent L_2 channels also acquire phase data. The L_2 channels do not require the P-code in order to make phase measurements on the L_2 carrier.

Data collected include time-tagged phase measurements, C/A code pseudorange, and integrated Doppler. The carrier phase measurements are sampled at the default rate of 15 seconds, with lower sampling rates available for selection. Additionally, the once-per-hour predicted ephemerides (satellite coordinate data) included in the broadcast message for each satellite are recorded. The pseudorange data are processed with the broadcast (predicted) satellite orbital coordinates to determine time-tags for the carrier phase measurements in real-time.

Other features of the receiver include: a self-contained data logger with built-in keyboard, data display, non-volatile mass memory data storage unit, input for external frequency standard, and an RS232C interface.

The operation of the model 4000SST is controlled and monitored by a display on the front panel. The unit is controlled through six groups of alpha-numeric keys where data are entered in response to receiver firmware prompts. The monitor is an adjustable backlighted liquid crystal display (LCD) located in the upper center of the front panel that features four lines of forty alpha-numeric characters. Black images (2.8 mm by 4.9 mm character size) against a yellow background make the display reasonably easy to read, particularly during nighttime operations as experienced during the test survey. To minimize power consumption between sessions, there is an auto-timer with "sleep" mode.

The RS232C port provides for connection of external devices for real-time data recording and downloading of data stored in RAM.

The antenna unit is a microstrip type design that is tuned to both the L_1 and L_2 frequencies. With the ground plane, the antenna unit weighs about 3.5 kg (7 lb) with a specified capability of better than 1 cm phase resolution.

The 4000SST GPS Surveyor is configured to operate in either the static (fixed site) or kinematic mode of surveying operations. The operation and control of the unit is relatively simple. When power is applied, the unit displays the most recently entered values or the factory set default values and automatically begins a sky-search for available satellites. Acquisition of the first satellite will generally take about 60 seconds. To lock on all available satellites takes about 120 seconds. Data displayed include satellite message information, details on satellite tracking and health status, three-dimensional pseudorange position (navigation fix), GPS time, and velocity.

The operator performing single or multiple sessions can program the start and stop times and assign the appropriate satellite to each channel. Once these initial steps are completed, the 4000SST can be left at a station in the unattended mode to operate automatically.

In the kinematic survey mode, the 4000SST operates either independently as a point positioning (i.e., navigation fix) system or in a differential configuration where data are collected simultaneously with two or more other receivers. It is configured to handle accelerations up to 2 G's. For navigational operation, the internal software processes the pseudorange data in real-time mode. Navigation data displayed include waypoints, travel distance, and bearing.

The phase data collected simultaneously with one or more other receivers are processed to determine relative positions ($\Delta X, \Delta Y, \Delta Z$) between the occupied station points.

Trimble specifies that the resolution and accuracy of measured and computed data are:

Carrier phase:	0.1	mm rms	(2 sec. averaging)
Code phase:	0.3	m	(1 sec. averaging)
Code phase smoothed:	5	cm	(2 min. averaging)
Doppler:	0.015	Hz	(1 sec. averaging)
Integrated Doppler:	3	mm	(3 hour integration time)
Point-position (pseudorange):	15	m (depends on broadcast orbit accuracy and having a Geometric Dilution of Precision (GDOP)<4, URE<4, and no SA)	

Trimble's specified estimates for static survey relative positioning accuracies at the one-sigma (1 σ) level in any component are:

horizontal:	10 mm + 2 mm/km
vertical (ellipsoid height differences):	20 mm + 2 mm/km
azimuth:	1 sec + 5/d

where, d is the vector length in kilometers.

The accuracy estimates assumed that at least five satellites were tracked continuously for the appropriate time span, L_1/L_2 carrier phase measurements were recorded and processed, and the accuracy of the orbital coordinate data was 1 mm/km (i.e., 1 ppm) or better.

Trimble's GPS processing package for production vector post-processing is called TRIMVEC-PLUS. In use since 1988, TRIMVEC-PLUS processes either single or dual-band GPS phase data on an IBM PC or a 100 percent compatible computer with 640K RAM, a hard disk having at least a 20-Mb capacity, a math-coprocessor, and a serial interface port. Trimble specifies that 1 hour of static data for a single vector determination can be processed in less than 2 minutes with a 20 MHz 386 PC.

The TRIMVEC-PLUS package includes a utility to generate information for planning GPS surveys, such as details on satellite visibility and geometry (i.e., skyplots with obstruction survey information overlaid to show masking of satellites, Position Dilution of Position (PDOP), and Relative DOP (RDOP) tables). Using this information, the best satellite constellation available for a given location, date, and starting-ending times can be selected.

This report is based solely on analysis of vector results obtained from the TRIMVEC-PLUS software version used during the test and version used during post-processing. TRIMVEC-PLUS can be operated either in the manual (interactive) or automatic batch mode to process L_1 only or dual frequency (L_1 and L_2) carrier phase data. Other important vector processing features of TRIMVEC-PLUS include:

1. Single vector processing mode.
2. Simultaneous multivector mode for up to 10 stations.
3. Automatic cycle slip fixing.
4. Triple and double difference (float and fixed) processing techniques.
5. Graphics capability for display of residuals.
6. Input of precise ephemeris data in the standard distribution format.
7. Covariance and correlation data in output.
8. Capability to process data collected in the kinematic survey mode.
9. Optional input for surfaced measured meteorological data or default to standard atmospheric values (T_{dry} = 20.0°C, RH (Relative Humidity) = 50 percent, and $P_{sea\ level}$ = 1013 mb).

In addition to GPS planning and vector processing attributes, TRIMVEC-PLUS includes utilities for performing quality control (e.g. loop misclosure, computations, and summaries), coordinate conversion computations, archiving survey results, and management of data base files.

Surface meteorological data were recorded during most of the station occupations. However, in the results received for analysis, only the default atmosphere values were used in the vector solutions.

This report is based on analysis of vector results produced during the test week with TRIMVEC-PLUS software version BC, dated October 1989, and results from post-processing with version BD, dated January 1990. The following significant factors were selected in the vector processing:

1. Integer ambiguities were either fixed or floated in the double-difference solution (depending on length of vector).
2. Some of the results were derived only from triple differencing processing.
3. Observation epoch processing interval (sampling rate): 15 sec
4. Elevation angle cutoff (above horizon): 20 deg
5. Residual editing criteria: 3.5 σ
6. Tropospheric model: Modified Hopfield

The TRIMVEC-PLUS vector processing software provides the following output:

1. Initial coordinates for the station held fixed.
2. Antenna height offsets.
3. Total number of epochs (measurement counts) available for processing.
4. Graphical indication of satellites and corresponding data that are available.
5. Number of outliers rejected.
6. Results of integer bias search.
7. RMS and RDOP estimates.
8. Results for the vector components (ΔX, ΔY, ΔZ), length, azimuths, and ellipsoidal height differences.
9. Covariance and correlation matrices.

The accuracy for the predicted (broadcast) satellite orbital coordinate data used in the solutions was estimated to be about 1 mm/km (1 ppm) at the 1 σ level.

FGCC requested vector solutions for:

1. L_1 only, "session" and "single nontrivial selected lines."
2. L_2 only, for short base lines only (i.e., within 2 km), "single" vector processing.
3. L_1 and L_2 ionospheric free linear combination for appropriate length vectors, "session" and "single nontrivial selected lines."
4. Selected subsets of about 1 and 2-hour spans processed as specified under 1, 2, and 3 above.

For each session, table 2.1 summarizes the approximate starting and ending time in UTC (Coordinated Universal Time), number of stations occupied, the PRN (pseudorandom noise) code for the satellites tracked, number of satellites at beginning/maximum/end of each session, and number of vector measurements (trivial and nontrivial) attempted compared to number submitted for evaluation.

As indicated in table 2.1, all observations began around dawn (7 a.m.) and continued through noon local time. Based on the single daily data set collected at each station occupied, the total number of vector measurements attempted (trivial and nontrivial) was 41. This does not include the vectors measured during the kinematic test survey. Subsets of the complete data set were also processed at 1- and 2-hour spans.

Table 2.1.--Observation summary, Trimble 4000SST FGCC test survey

Session	Starting and ending time (UTC)(1)	Number of stations	Satellites observed (PRN code)	Number of satellites at start/ maximum/end	Vectors (trivial and nontrivial Primary set (excluding subsets) scheduled/observed/processed
303	12:22-16:22	5	2,3,6,9,11,12,13,14,16	4/6/4	10/10/10
304	12:18-18:18	5	2,3,6,9,11,12,13,14,16	4/6/4	10/10/10
305	12:14-16:14	5	2,3,6,9,11,12,13,14,16	4/6/4	10/10/10
306	12:00-18:30	21	2,3,6,9,11,12,13,14,16	4/6/4	1/ 1/ 1 (2)
307	14:46-16:00	5	2,3,6,9,11,12,13,14,16	4/6/4	10/10/10
TOTALS		41			41/41/41

(1) Subtract 5 hours to convert UTC to local time.
(2) The kinematic vectors are excluded in this figure.

Results were received for each of all possible vectors (trivial and nontrivial) that could be processed. These vectors were evaluated by comparison of repeat measurements, the computation of loop misclosures, comparison with the test network terrestrial coordinate differences, and comparison with precise GPS vector base line measurements determined from previous FGCC test surveys. The analyses were carried out using the vector base line components, base line lengths, ellipsoidal height differences, and base line azimuths.

Table 2.2 compares the results for repeat measurements. It can be seen the spread in any component for base lines under 2,000 m is ≤9 mm. For the ATHY-OPTK line of 12.1 km, the difference between the repeat measurements is ≤6 mm. In the last entry, line OPTK-GORF of 42.1 km, the difference is ≤11 mm.

In table 2.3, nine sample loop misclosure computations are summarized. The loops were formed using independently determined vectors that were selected arbitrarily from double difference solutions which used the predicted orbital elements. The total distance around each of the nine loops ranged from 3.7 to 246.5 km. The number of base lines in each loop ranged from three to six with two to four independently determined vectors.

The resultant misclosure for the loop with short length vectors was 12 mm. For those loops with a combination of short and medium length vectors determined from L_1 only solutions, the resultant misclosures ranged from 3.9 to 7.4 cm. When the same vectors were determined from ionospheric free data (L_1/L_2 solutions), the resultant loop misclosure was 1.2 to 2.6 cm. In the loop formed with vectors as long as 104 km with a total distance around the loop of 247 km, the resultant misclosure was 3.7 cm for the L_1 only solutions. For the same loop, the resultant misclosure when using the L_1/L_2 vectors improved to 1.5 cm. The significant improvement in precision for ionospheric free solutions indicates the value of have dual frequency receivers.

Table 2.2.--Comparison of repeat vector measurements

From	To	Day	Span (min)	RMS (cm)	DX (m)	DY (m)	DZ (m)	Length (m)	Dh (m)	Remarks
NBSO	NBS1	303	240	0.5	43.886	-107.152	-142.989	183.992	-1.659	(1)
		307	92	0.4	.884	.146	.992	.991	.666	(1)
NBS1	ORM1	303	240	0.6	1209.303	467.747	255.995	1321.641	15.480	(1)
		304	240	0.6	.302	.747	.992	.646	.471	(1)
		303	240	1.6	.307	.756	.991	.639	.478	(3)
		304	240	1.3	.301	.750	.983	.638	.471	(3)
ATHY	OPTK	304	240	1.1	-328.589	-7748.022	-9266.054	12083.028	-23.698	(1)
		305	240	2.2	.594	.028	.058	.035	.696	(3)
OPTK	GORF	304	240	1.5	40562.605	11157.152	2123.951	42122.656	-60.290	(3)
		305	240	1.4	.606	.162	.946	.654	.301	(3)

Solution method: (1) SB-DDFX-BE-L1; (2) SB-DDFL-BE-L1; (3) SB-DDFX-BE-L1/L2; (4) SB-DDFL-BE-L1/L2; (5) MB-DDFX-BE-L1; (6) MB-DDFL-BE-L1; (7) MB-DDFX-BE-L1/L2; (8) MB-DDFL-BE-L1/L2; (9) SB-TRP-BE-L1/L2

Legend: SB - Single base line solution; MB - Multiple base line or session solution; DD - Double difference; FX - Fixed integers; FL - Integer float solution; BE - Broadcast ephemerides.

Table 2.3.--Summary of loop misclosure computations

Number of lines		Length of loop	Misclosure					REMARKS
Independent	Total	(km)	DX (cm)	DY (cm)	DZ (cm)	Resultant (cm)	Dh (cm)	(1)
3	3	2.8	-0.4	0.8	-0.5	1.0	-1.6	L1 only solutions
2	4	18.1	0.4	-0.5	0.4	0.8	-2.6	L1 only solutions
2	4	18.1	1.6	-1.1	2.6	3.2	-0.6	L1/L2 solutions
3	6	122.3	-3.9	5.5	-4.7	8.2	-5.3	L1 only solutions
3	6	122.3	-4.5	8.2	-6.6	11.4	-8.7	L1/L2 solutions
2	4	236.9	-13.4	6.4	-6.8	16.3	-17.3	L1 only solutions
2	4	236.9	0.1	-5.9	4.0	7.1	1.1	L1/L2 solutions
4	7	233.6	1.0	5.1	-0.4	5.2	-4.2	L1/L2 solutions

(1) Vectors from double difference float or fixed solutions using the predicted (broadcast) ephemerides.

All base lines were previously surveyed by three-dimensional precise terrestrial survey methods. Two-sigma accuracy estimates obtained for the terrestrial relative positional measurements were 2 mm/km (2 ppm) for horizontal and 3 mm/km (3 ppm) for vertical. Additionally, all lines measured with the Trimble 4000SST survey system have been measured during previous FGCC GPS test surveys. GPS survey systems used to make these measurements included the: Macrometer™ V1000, Texas Instrument TI4100, Trimble models 4000S, 4000SX, and 4000ST, Wild Magnavox WM-101, SERCEL NR52, and MINIMAC™ 2816. Overall, the estimated 1-sigma vector component uncertainties achieved from the earlier GPS test survey data processed with broadcast ephemerides are about $\pm\sqrt{[10 \text{ mm} + (d\cdot(2 \text{ mm/km}))^2]}$, where d is the base line length in kilometers.

After an appropriate adjustment for significant systematic differences due to differences between WGS 84, WGS 72, and NAD 83 coordinate systems, the comparisons with terrestrial and past GPS measurements were evaluated to estimate 1-sigma vector component uncertainties for the "site" dependent (e) and the "distance" dependent (p) values. The value for e should be comparable to the component uncertainty for "zero" length base lines, provided that the antenna setup error (centering and antenna phase center height measurement error) is insignificant.

When model 4000SST L_1 data for a span within the range of about 60 to 90 minutes are processed with the broadcast (BE) or predicted orbital elements, the empirically derived 1-sigma estimate for e is 10 mm and for p is 3 mm/km (3 ppm). Combining these estimates statistically, the total 1-sigma and 2-sigma estimates for each vector component are given by:

$$E_{1\text{-sigma}} = \pm\sqrt{[(10 \text{ mm})^2 + (d\cdot 3 \text{ mm/km})^2]}_{BE},$$

and

$$E_{2\text{-sigma}} = \pm\, 2\cdot(\sqrt{[(10 \text{ mm})^2 + (d\cdot 3 \text{ mm/km})^2]}_{BE}),$$

where

d = length of the vector in kilometers.

When the same data are processed using the L_2 data ("ionospheric-free" L_1 observable), the empirically derived 1-sigma estimate for e is 5 mm and for p is 1 mm/km (2 ppm). Combining these estimates statistically, the total 1-sigma and 2-sigma estimates for each vector component are given by:

$$E_{1\text{-sigma}} = \pm\sqrt{[(5 \text{ mm})^2 + (d\cdot 1 \text{ mm/km})^2]}_{BE},$$

and

$$E_{2\text{-sigma}} = \pm\, 2\cdot(\sqrt{[(5 \text{ mm})^2 + (d\cdot 1 \text{ mm/km})^2]}_{BE}),$$

where

d = length of the vector in kilometers.

Overall, the results from the "broadcast" ephemeris solutions indicated that the 4000SST L_1/L_2 GPS Surveyor will produce accurate results that meet or exceed manufacturer's specifications.

The trees, buildings, and nearby power transmission lines at some of the FGCC test stations sites may have affected the test data. However, these are about the same conditions that could have affected or had a negative influence on previous test surveys. Furthermore, these are factors which frequently characterize the conditions at operational GPS survey stations. Thus, the less than optimal conditions found at some of the FGCC stations are useful in the tests to help determine the design effectiveness and capabilities of the GPS survey instruments and processing software.

Once the 21 to 24 block II satellite constellation is operationally available, users will have more flexibility in dealing with obstructions. It is expected that most stations with marginal obstruction problems today will in the near future have adequate signals of good quality passing through clear areas of the sky. Hence, confidence in achieving desired accuracies at stations with substantial problems with obstructions will improve significantly during the next few years.

Table 2.4 summarizes the FGCC accuracy standards for orders III through AA. Based on analysis of the results achieved from the FGCC test survey and assuming the accuracies for the broadcast and precise ephemerides are about 1 mm/km (1 ppm) and 0.1 mm/km (0.1 ppm), respectively, the capability of the 4000SST to achieve the various accuracy standards is indicated. The remarks contain certain conditions upon which the capabilities are based.

Table 2.4.--FGCC accuracy standards and capability of the Trimble 4000SST2

FGCC accuracy standards (2-sigma or 95% confidence level) (Reference: Version 5.0, May 11, 1988, reprinted with corrections August 1, 1989)		Trimble model 4000SST capability of meeting FGCC accuracy standards
Order	Definition	Remarks
3I	$\pm\sqrt{[(50\text{ mm})^2 + (d\cdot 100\text{ mm/km})^2]}$	Yes, with BE; L1 only or L1/L2.
2II	$\pm\sqrt{[(30\text{ mm})^2 + (d\cdot 50\text{ mm/km})^2]}$	Yes, with BE; L1 only or L1/L2.
2I	$\pm\sqrt{[(20\text{ mm})^2 + (d\cdot 20\text{ mm/km})^2]}$	Yes, with BE; L1 only or L1/L2.
1	$\pm\sqrt{[(10\text{ mm})^2 + (d\cdot 10\text{ mm/km})^2]}$	Yes, with BE; should with L1 only; more confidence with L1/L2.
B	$\pm\sqrt{[(8\text{ mm})^2 + (d\cdot 1\text{ mm/km})^2]}$	Possibly with BE; more confidence with PE; possibly with L1 only data, but more confidence with L1/L2 data.
A	$\pm\sqrt{[(5\text{ mm})^2 + (d\cdot 0.1\text{ mm/km})^2]}$	No with BE; should with PE of 0.1 ppm or better and L1/L2 data in linear combination to reduce effects of ionospheric disturbances; if PE not accurate enough, solutions must be done with orbital adjustment method. It is assumed that SA would not have a major impact on quality of observations.
AA	$\pm\sqrt{[(3\text{ mm})^2 + (d\cdot 0.01\text{ mm/km})^2]}$	Fixed orbit solutions with PE may not produce acceptable results; then must use orbital adjustment method; L1/L2 data essential for combining linearly to reduce effects of ionospheric disturbances. It is assumed that SA would not have a major impact on quality of observations.

Legend: BE - Broadcast (predicted) ephemerides; PE - Precise ephemerides;
SA - Selective availability d - length of vector in Km

To achieve the high accuracy orders of A and AA, it was assumed that TRIMVEC-PLUS software is capable of producing results from fixed orbital coordinate data solutions that are limited only by the accuracy of the precise orbit data. To achieve accuracy orders A and AA, it may be necessary to process the vectors while adjusting the orbital coordinate data. Reports indicate that data can be processed while adjusting the orbit to achieve accuracies approaching 0.01 mm/km (0.01 ppm).

In conclusion, analysis of the results from the FGCC test survey conducted in October 1989 on the Trimble model 4000SST GPS Surveyor indicates that carrier phase data (L_1 and L_2) collected on four or more satellites with an acceptable geometric configuration during a period of 60 minutes or more, and processed with double difference software using orbital coordinate data accurate to 2 mm/km (2 ppm) or better, will yield accuracies that should meet requirements for most geodetic and engineering survey needs.

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FGCC Federal Geodetic Control Committee

3. REPORT ON TEST AND DEMONSTRATION OF

ASHTECH LD-XII GPS SATELLITE SURVEY SYSTEM

AND ASSOCIATED PROCESSING SOFTWARE

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September 17, 1990

In November 1989 the Federal Geodetic Control Committee (FGCC) conducted a test and demonstration of the Ashtech LD-XII GPS Satellite Survey System, a dual-band (L_1 and L_2) receiver developed by Ashtech Inc., Sunnyvale, CA. This was the fourteenth in a series of comprehensive tests by FGCC to evaluate the performance of GPS (Global Positioning System) geodetic satellite survey systems and associated vector processing software.

The test and demonstration were conducted over a 4-day period beginning Monday, November 6 (day 310), and ending Friday, November 9 (day 313), 1989, on stations of the FGCC test network located in the vicinity of Washington, DC. The measured vectors ranged in lengths of: short from 183 to 1322 m, medium from 7 to 19 km, and long from 35 to 105 km. Up to eight Ashtech LD-XII receivers were tested by GPS surveying in static and kinematic mode.

During days 310, 311, and 312, phase measurements in the static mode were collected during a single continuous session of approximately 240 minutes. On day 311, one of the eight receivers was operated at a special site for a non-FGCC experiment. Data for this special experiment are excluded from the FGCC data set. During day 312, two of the eight receivers were used on a non-FGCC experiment, thus only the data collected with the remaining six receivers are part of the FGCC test.

On day 313, three of the eight receivers were operated in the kinematic mode on stations of the FGCC test network located at the National Institute of Standards and Technology, Gaithersburg, MD. The remaining five receivers were operated on day 313 in the static mode throughout the duration of the kinematic test of approximately 6 hours. In the static mode of operations, 27 independent station-occupation sessions were scheduled. The stations were successfully observed resulting in the measurement of 79 vectors (trivial and nontrivial). Nineteen stations were occupied repeatedly with the three roving receivers during the kinematic test survey on day 313.

The Ashtech LD-XII system includes two primary components: a receiver and an antenna/preamplifier. The receiver unit is housed in a case 12 by 22 by 32 cm (4.6 by 8.5 by 12.5 in) and weighs about 22 kg (10 lb). It is powered by a 9 to 32 VDC nominal source such as a car battery. An internal battery provides power while external batteries are being switched. The operating temperature is -20°C to +55°C. The standard antenna supplied is a microstrip design that is tuned to L_1 and L_2 frequencies. With the ground plane, the antenna unit weighs about 8.8 kg (4 lb) with a specified capability of better than 1 cm phase resolution.

The LD-XII can simultaneously track the L_1 and L_2 signals from up to twelve GPS satellites. Observing up to twelve GPS satellites gives the surveyor the capability of tracking all available satellites in view at the present time and for the foreseeable future. The L_1 (1575.42 MHz) signal is acquired through use of independent channel coarse/acquisition (C/A) code correlation technology. There are also 12 independent L_2 channels that acquire phase data by use of codeless techniques developed by Ashtech. The codeless L_2 channels obviate the need for access to the precise code (P-code) in order to make phase measurements on the L_2 carrier.

Data collected include time-tagged phase measurements, C/A code pseudorange, and integrated Doppler. The carrier phase measurements are sampled at the default rate of 20 seconds, with lower sampling rates available for selection. Additionally, the once-per-hour predicted ephemerides (satellite coordinate data) included in the broadcast message for each satellite are recorded. The pseudorange data are processed with the broadcast (predicted) satellite orbital coordinates to determine in real-time, time tags for the carrier phase measurements.

The model LD-XII receiver has an eight- by forty-character display and a 16-key keypad. The recording medium is a mass memory unit (MMU) with a capacity of 2 mb. It can store in excess of a 20-hour 12-satellite data set collected during a phase measurement sampling rate of 30 seconds. If the sampling rate is 1 second, about 40 minutes of 12-satellite data can be stored.

There are two serial input/output RS232C ports, each of which can be configured for connecting external devices for real-time recording of data, downloading data stored in the MMU, steering displays, differential positioning data, or for remote terminal operation. There is also an input port for an external reference frequency and an output port for a 1 pps (pulse per second) signal.

The ASHTECH LD-XII employs a user friendly menu for operation and control of the unit. When power is applied, the unit displays the most recently entered values or the factory set default values and automatically begins a sky-search for available satellites. Acquisition of the first satellite will generally take 30 to 45 seconds. Data displayed include satellite message information and reduced satellite data such as information on condition of satellite health status, position (fixes), and range corrections.

For single or multiple sessions, the operator can program the start and stop times and assign the appropriate satellite to each channel. Once these initial steps are completed, the Ashtech LD-XII can be left at a station in the unattended mode to operate automatically.

Other operational features or characteristics of the Ashtech LD-XII systems include:

1. display on the CDU, satellite tracking status, GPS time, and frequency information,
2. automatic and continuous testing of CPU, MMU, and RF processor, to ensure proper operation, and
3. high level capability to operate in the kinematic and/or dynamic mode.

In the kinematic or dynamic mode, the Ashtech LD-XII operates either independently as a point positioning (i.e., navigation fix) system or in a differential configuration where data are collected simultaneously with two or more other receivers. It can be configured to handle accelerations up to at least 2 G. For navigation operation, the internal software processes the pseudorange data in real-time. Navigation data displayed include estimated time of arrival at waypoints, travel distance, steering right/left with course corrections, and azimuth.

The phase data collected simultaneously with one or more other receivers are processed to determine relative positions ($\Delta X,\Delta Y,\Delta Z$) between the occupied station points.

Ashtech specifies that the resolution and accuracy of measured and computed data are:

Carrier phase:	0.1 mm rms
Code phase:	1 m
Code phase smoothed:	few centimeters
Doppler:	0.001 Hz
Integrated Doppler:	3 mm
Point-position (pseudorange:	20 m (depends on broadcast orbit accuracy and having a Geometric Dilution of Precision (GDOP)<4 and no SA)

The pseudorange (code phase) data are processed with the broadcast (predicted) satellite orbital coordinates to determine in real-time, point positions (navigation fixes) and time-tags for the carrier phase measurements. The phase data collected simultaneously with one or more other receivers are processed to determine relative positions ($\Delta X, \Delta Y, \Delta Z$) between the occupied station points. All test survey data analyzed for this report were collected in the static mode of operations (fixed site).

Ashtech's software package GPPS runs on an IBM PC or 100 percent compatible computer. The package includes a utility to generate satellite visibility tables. Using this information, the user can select the best available satellite constellation for a given location and date.

This report is based on analysis of vector results obtained from the GPPS (GPS Post Processing Software) software version that was in use during November 1989 and during post-processing of the data in late 1989 and early 1990. GPPS can be operated either in the manual (user interface) or automatic (batch) mode. Other important features of the vector base line processing software include:

1. Single vector processing only.
2. Automatic cycle slip fixing.
c. Double differenced float and fixed vector solutions.
d. Graphics capability for display of residuals.
e. Processing of data collected in the kinematic survey mode.
f. Process with either the recorded broadcast (predicted) ephemerides or the precise post-computed ephemerides in the standard format.

The data were processed by Ashtech with the GPPS software using the predicted orbital coordinate data contained in the broadcast message to produce single vector results. Processing of most of the data was attempted during the test week with solutions provided for analysis and presentation at a public meeting held Monday, November 13, 1989. Options selected in the processing:

1. Integer ambiguities were either fixed or floated in the double-difference solution depending on length of vector.
2. Observation epoch interval (sampling rate): 20 sec
3. Elevation angle cutoff (above horizon): 15 or 20 deg
4. Residual editing criteria: 3 σ
5. Apply tropospheric delay correction: Yes

The output for the GPPS vector processing software includes:

1. Initial coordinates for the station held fixed.
2. Antenna height offset.
3. Total number of epochs (measurement counts) available for processing.
4. Number of epochs below angle cutoff.
5. Number of outliers rejected.
6. Number of cycle slips detected.
7. Indication whether the integer ambiguities were fixed or floated.

8. Results for the vector components ($\Delta X, \Delta Y, \Delta Z$), base line length, forward and back azimuths, and ellipsoidal height differences.
9. Covariance matrix and standard deviations in terms of vector components and latitude-longitude-ellipsoidal height differences.

The Ashtech software package includes a utility to generate information for planning GPS surveys, such as details on satellite visibility and geometry (i.e., skyplots with obstruction survey information overlaid to show masking of satellites, Position Dilution of Position (PDOP), and Relative DOP (RDOP) tables). Using this information, the best satellite constellation available for a given location, date, and starting-ending times can be selected.

In addition to GPS planning and vector processing software support, Ashtech includes utilities for performing quality control (e.g., loop misclosure computations and summaries), three-dimensional adjustments, coordinate conversion computations, archiving survey results, and management of data base files. Software is also included for use in converting the raw observations to the standard international exchange format and the vector results and project information into the FGCC standard formats.

Surface meteorological data were recorded during most of the station occupations. However, in the results received for analysis, only the default atmosphere values were used in the vector solutions.

The accuracy for the predicted (broadcast) satellite orbital coordinate data used in the solutions was estimated to be about 1 mm/km (1 ppm) at the 1 σ level.

For each session, table 3.1 summarizes the approximate starting and ending time in UTC (Coordinated Universal Time), number of stations occupied, the PRN (pseudorandom noise) code for the satellites tracked, number of satellites at beginning/end of each session, and number of vector measurements (trivial and nontrivial) attempted compared to number submitted for evaluation.

The total number of vector base line measurements attempted (trivial and nontrivial) was 74. This does not include the vectors measured during the kinematic test survey. All observations were conducted during daylight hours. To convert UTC time to local time, subtract 4 hours. Of the 74 possible vectors (trivial and nontrivial), results were received for all lines. Subsets of the complete data set were also processed during 1- and 2-hour spans.

The vectors furnished by Ashtech were evaluated by comparison of repeat measurements, the computation of loop misclosures, comparison with the test network terrestrial coordinate differences, and comparison with past precise GPS vector base line measurements. The analyses were carried out using the vector base line components, base line lengths, ellipsoidal height differences, and base line azimuths.

Table 3.1.--Observation summary, Ashtech LD-XII FGCC test survey

Session	Starting and ending time (UTC)(1)	Number of stations	Satellites observed (PRN code)	Number of satellites at start/ maximum/end	Vectors (trivial and nontrivial) Primary set (excluding subsets) scheduled/observed/processed
310	11:50-15:50	8	2,3,6,9,11,12,13,14,16	4/6/4	28/28/28
311	11:46-18:00	7	2,3,6,9,11,12,13,14,16	4/6/4	21/21/28
312	11:42-15:42	6	2,3,6,9,11,12,13,14,16	4/6/4	15/15/15
313	11:38-17:44	25	2,3,6,9,11,12,13,14,16	4/6/4	10/10/10(2)
TOTALS		46			74/74/74

(1) Subtract 4 hours to convert UTC to local time.
(2) The kinematic vectors are excluded in this figure.

Ashtech's specified estimates for static survey relative positioning accuracies at the one-sigma (1σ) level in any component are:

horizontal:	10 mm + 2 mm/km
vertical (ellipsoid height differences):	20 mm + 2 mm/km
azimuth:	1 sec + 5/d

where d is the vector length in kilometers.

The accuracy estimates assumed that at least five satellites were tracked continuously for the appropriate time span, L_1/L_2 carrier phase measurements were recorded and processed, and the accuracy of the orbital coordinate data was 1 mm/km (i.e., 1 ppm) or better.

Vector solutions requested by FGCC for analysis included:

1. L_1 only, "session" and "single nontrivial selected lines."
2. L_2 only, for short base lines only (i.e., within 2 km), "single" vector processing.
3. L_1 and L_2 ionospheric free linear combination for appropriate length vectors, "session" and "single nontrivial selected lines."
4. Selected subsets of about 1- and 2-hour spans processed as specified under 1, 2, and 3.

All base lines were previously surveyed by three-dimensional precise terrestrial survey methods. Two-sigma accuracy estimates for the terrestrial relative positional measurements are 2 mm/km (2 ppm) for the horizontal and 3 mm/km (3 ppm) for the vertical. Additionally, all lines measured with the Ashtech LD-XII system have been measured during previous FGCC GPS test surveys. GPS survey systems used to make these measurements included the: Macrometer^{TM} V1000, Texas Instrument TI4100, Trimble models 4000S, 4000SX, 4000ST, and 4000SST, Wild Magnavox WM-101, SERCEL NR52, MINIMAC^{TM} 2816, and Ashtech L-XII.

Overall, the estimated 1-sigma vector component uncertainties achieved from the earlier GPS test survey data processed with broadcast ephemerides is about $\pm\sqrt{[10 \text{ mm} + (d\cdot(2 \text{ mm/km}))^2]}$, where d is the base line length in kilometers.

Table 3.2 compares the results for repeat measurements. For the ATHY-OPTK line of 12.1 km, the difference between the L_1 only repeat measurements was ≤15 mm in any component. The differences were comparable for the L_1/L_2 solutions. The differences between repeat L_1 only measurements for the vector ATHY-GORF of 41.0 km was ≤17.4 cm, which reduced to ≤3.4 cm for the L_1/L_2 solutions. The repeat results for the OPTK-GORF vector of 42.1 km was also characterized by significant improvement in the L_1/L_2 solutions compared to the L_1 only solutions. The results clearly indicated the benefits of having dual frequency measurements.

Table 3.2.--Comparison of repeat vector measurements

From	To	Day	Span (min)	RMS (cm)	DX (m)	DY (m)	DZ (m)	Length (m)	Dh (m)	Remarks
ATHY	OPTK	310	241	2.5	-328.594	-7748.039	-9266.059	12083.044	-23.689	(1)
		312	241	2.1	.593	.048	.047	.040	.674	(1)
		310	241	0.8	.602	.059	.100	.087	.701	(4)
		312	241	0.8	.607	.072	.088	.087	.684	(4)
ATHY	GORF	310	238	6.7	40233.920	3409.130	-7142.117	41004.881	-84.013	(1)
		312	240	5.9	.746	.176	.106	.713	.072	(1)
		310	238	0.9	4.036	.062	.069	.982	-83.911	(4)
		312	240	1.2	.063	.063	.103	5.014	.928	(4)
OPTK	GORF	310	238	8.5	40562.368	11157.348	2123.961	42122.480	-60.473	(1)
		311	332	8.9	.424	.175	.924	.486	.357	(1)
		312	239	6.5	.341	.251	.911	.425	.436	(1)
		310	238	0.7	.695	.147	4.001	.743	.240	(4)
		311	375	0.6	.690	.118	.023	.733	.204	(4)
		312	239	0.9	.702	.096	.016	.737	.189	(4)

Solution method: (1) SB-DDFX-BE-L1; (2) SB-DDFL-BE-L1; (3) SB-DDFX-BE-L1/L2; (4) SB-DDFL-BE-L1/L2; (5) MB-DDFX-BE-L1; (6) MB-DDFL-BE-L1; (7) MB-DDFX-BE-L1/L2; (8) MB-DDFL-BE-L1/L2; (9) SB-TRP-BE-L1/L2

Legend: SB - Single base line solution; MB - Multiple base line or session solution; DD - Double difference; FX - Fixed integers; FL - Integer float solution; BE - Broadcast ephemerides.

Table 3.3 summarizes six loop misclosure computations. The loops were formed using independently determined vectors that were selected arbitrarily from double difference solutions that used the predicted orbital elements. The total distance around each of the 9 loops ranged from 95.3 to 247.2 km. The number of base lines in each loop ranged from three to six with three independently determined vectors.

For the loops with a combination of short and medium length vectors determined from L_1 only solutions, the resultant misclosures were 27.8 and 9.7 cm. When a similar loop was formed with vectors determined from ionospheric free data (L_1/L_2 solutions), the resultant loop misclosure was improved to 4.9 and 4.5 cm, respectively.

Table 3.3.--Summary of loop misclosure computations

Number of lines		Length of loop	Misclosure					REMARKS
Independent	Total		DX	DY	DZ	Resultant	Dh	
		(km)	(cm)	(cm)	(cm)	(cm)	(cm)	(1)
3	4	97.3	1.3	-26.8	7.4	27.8	25.1	L1 only solutions
3	4	97.3	4.6	-1.5	0.2	4.9	2.1	L1/L2 solutions
3	4	95.3	5.6	3.0	-7.4	9.7	-6.0	L1 only solutions
3	4	95.3	2.1	-2.3	3.4	4.5	4.2	L1/L2 solutions
3	6	247.2	-6.1	0.9	4.6	7.7	1.0	L1 only solution
3	6	247.2	-1.5	-1.5	-0.7	2.2	0.4	L1/L2 solutions

(1) Vectors from double difference float or fixed solutions using the predicted (broadcast) ephemerides.

In the loop formed with vectors as long as 104 km with a total distance around the loop of 247 km, the resultant misclosure was 7.7 cm for the L_1 only solutions. However, the resultant misclosure using the L_1/L_2 vectors decreased to 2.2 cm. Clearly, the precision for the vectors was significantly improved when the L_2 data were used in the solutions.

After an appropriate adjustment for significant systematic differences due to differences between WGS 84, WGS 72, and NAD 83 coordinate systems, the comparisons with terrestrial and past GPS measurements were evaluated to estimate 1-sigma vector component uncertainties for the "site" dependent (e) and the "distance" dependent (p) values. The value for e should be comparable to the component uncertainty for "zero" length base lines, provided that the antenna set up error (centering and antenna phase center height measurement error) is insignificant.

When model LD-XII L_1 data for a span within the range of about 60 to 90 minutes are processed with the broadcast (BE) or predicted orbital elements, the empirically derived 1-sigma estimate for e is 10 mm and for p is 3 mm/km (3 ppm). Combining these estimates statistically, the total 1-sigma and 2-sigma estimates for each vector component are given by:

$$E_{1\text{-sigma}} = \pm \sqrt{[(10\ \text{mm})^2 + (d \cdot 3\ \text{mm/km})^2]}_{BE},$$

and

$$E_{2\text{-sigma}} = \pm 2 \cdot (\sqrt{[(10\ \text{mm})^2 + (d \cdot 3\ \text{mm/km})^2]}_{BE}),$$

where

d = length of the vector in kilometers.

When the same data are processed using the L_2 data ("ionospheric-free" L_1 observable), the empirically derived 1-sigma estimate for e is 5 mm and for p is 1 mm/km (1 ppm). Combining these estimates statistically, the total 1-sigma and 2-sigma estimates for each vector component are given by:

$$E_{1\text{-sigma}} = \pm \sqrt{[(5\ mm)^2 + (d \cdot 1\ mm/km)^2]_{BE}},$$

and

$$E_{2\text{-sigma}} = \pm 2 \cdot (\sqrt{[(5\ mm)^2 + (d \cdot 1\ mm/km)^2]_{BE}}),$$

where

d = length of the vector in kilometers.

Overall, the results from the "broadcast" ephemeris solutions indicated that the LD-XII L_1/L_2 GPS survey system will produce accurate results that meet or exceed manufacturer's specifications.

The trees, buildings, and nearby power transmission lines at some of the FGCC test stations sites may have affected the test data. However, these are about the same conditions that could have affected or had a negative influence on previous test surveys. Furthermore, these are factors which frequently characterize the conditions at operational GPS survey stations. Thus, the less than optimal conditions found at some of the FGCC stations are useful in the tests to help determine the design effectiveness and capabilities of the GPS survey instruments and processing software.

Once the 21 to 24 Block II satellite constellation is operationally available, users will have more flexibility in dealing with obstructions. It is expected that most stations with marginal obstruction problems today will in the near future have adequate signals of good quality passing through clear areas of the sky. Hence, confidence in achieving desired accuracies at stations with substantial problems with obstructions will improve significantly during the next few years.

Table 3.4 summarizes the FGCC accuracy standards for orders III through AA. Based on analysis of the results achieved from the FGCC test survey and assuming the accuracies for the broadcast and precise ephemerides are about 1 ppm and 0.1 ppm, respectively, the capability of the LD-XII to achieve the various orders are indicated. The remarks contains certain conditions upon which the capabilities are based. To achieve orders A and AA, it was assumed that either the GPPS software is capable of producing results from fixed orbital coordinate data solutions that are limited only by the accuracy of the precise orbit data. If the precise orbital coordinate data are not accurate enough, it may be necessary to process the vectors while adjusting the orbital coordinate data.

In conclusion, analysis of the results from the FGCC test survey conducted in November 1989 on the Ashtech model LD-XII GPS survey system indicates that carrier phase data (L_1 and L_2) collected on four or more satellites with an acceptable geometric configuration during a period of about 60 minutes or more, and processed with double difference software using orbital coordinate data accurate to 2 mm/km (2 ppm) or better, will yield accuracies that should meet requirements for most geodetic and engineering survey needs.

Table 3.4.--FGCC accuracy standards and capability of the Ashtech LD-XII

FGCC accuracy standards (2-sigma or 95% confidence level) (Reference: Version 5.0, May 11, 1988, reprinted with corrections August 1, 1989)		Ashtech model LD-XII capability of meeting FGCC accuracy standards
Order	Definition	Remarks
3I	$\pm\sqrt{[(50\ mm)^2 + (d\cdot 100\ mm/km)^2]}$	Yes, with BE; L1 only or L1/L2.
2II	$\pm\sqrt{[(30\ mm)^2 + (d\cdot 50\ mm/km)^2]}$	Yes, with BE; L1 only or L1/L2.
2I	$\pm\sqrt{[(20\ mm)^2 + (d\cdot 20\ mm/km)^2]}$	Yes, with BE; L1 only or L1/L2.
1	$\pm\sqrt{[(10\ mm)^2 + (d\cdot 10\ mm/km)^2]}$	Yes, with BE; should with L1 only; more confidence with L1/L2.
B	$\pm\sqrt{[(8\ mm)^2 + (d\cdot 1\ mm/km)^2]}$	Possibly with BE; more confidence with PE; possibly with L1 only data, but more confidence with L1/L2 data.
A	$\pm\sqrt{[(5\ mm)^2 + (d\cdot 0.1\ mm/km)^2]}$	No with BE; should with PE of 0.1 ppm or better and L1/L2 data in linear combination to reduce effects of ionospheric disturbances; if PE not accurate enough, solutions must be done with orbital adjustment method. It is assumed that SA would not have a major impact on quality of observations.
AA	$\pm\sqrt{[(3\ mm)^2 + (d\cdot 0.01\ mm/km)^2]}$	Fixed orbit solutions with PE may not produce acceptable results; then must use orbital adjustment method; L1/L2 data essential for combining linearly to reduce effects of ionospheric disturbances. It is assumed that SA would not have a major impact on quality of observations.

Legend: BE - Broadcast (predicted) ephemerides; PE - Precise ephemerides;
SA - Selective availability d - length of vector in Km

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Personnel representing the FGCC Instrument Subcommittee included: R. Anderson (test coordinator), S. Cofer, D. Crockett, C. Fronczek, L. Hothem, J. Love, J. Maloney, D. Minkel, and P. Spofford.

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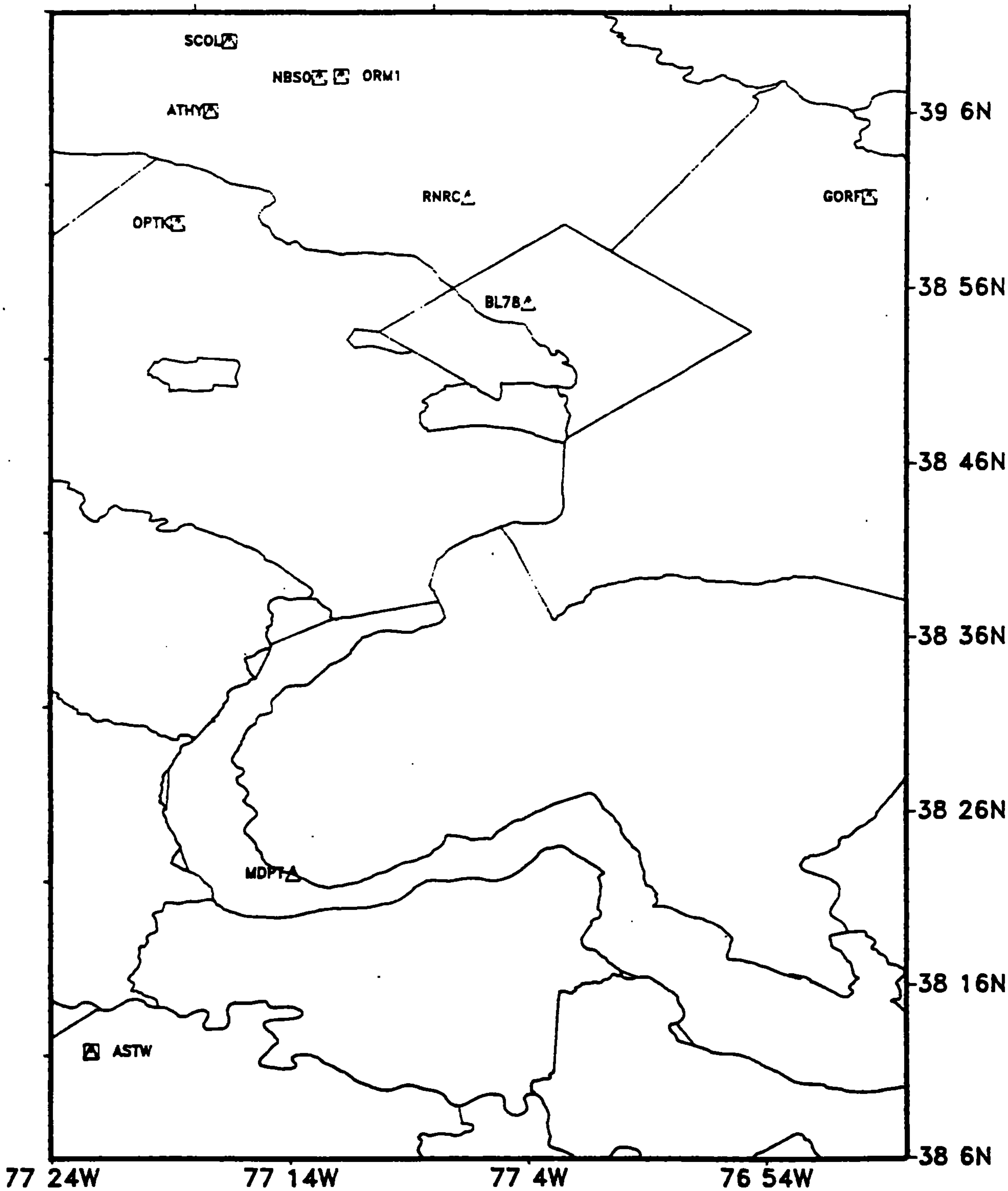

Figure 1.--FGCC test network in the vicinity of Washington, DC

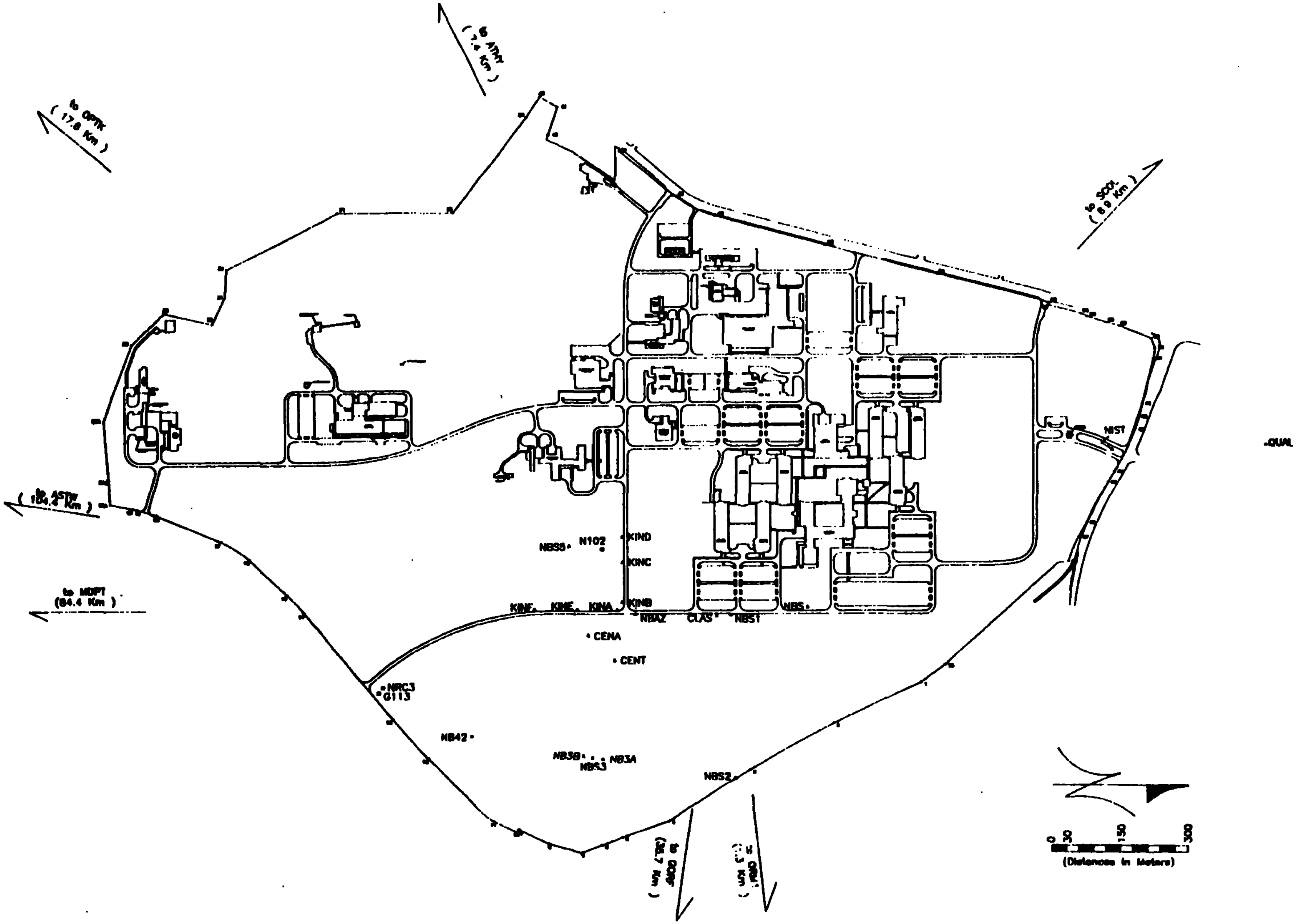

Figure 2.--Portion of FGCC test network located at National Institute of Standards and Technology, Gaithersburg, Maryland

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