FGCC Federal Geodetic Control Committee

REPORTS ON TEST AND DEMONSTRATION OF GPS SATELLITE SURVEY SYSTEMS

MODELS and MONTH OF TEST

TRIMBLE 4000ST - APRIL 1989

NORSTAR 1000 - NOVEMBER 1988

ASHTECH L-XII - AUGUST 1988

SERCEL NR52 - JUNE 1988

MOTOROLA EAGLE - APRIL 1988

WILD-MAGNAVOX 101 - JANUARY 1987

TRIMBLE 4000SX - NOVEMBER 1986

ISTAC 2002 - JUNE 1986

TRIMBLE 4000S - FEBRUARY 1986

TEXAS INSTRUMENTS TI4100 - DECEMBER 1985

JUNE 1990

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DRAFT

FGCC TEST NETWORK

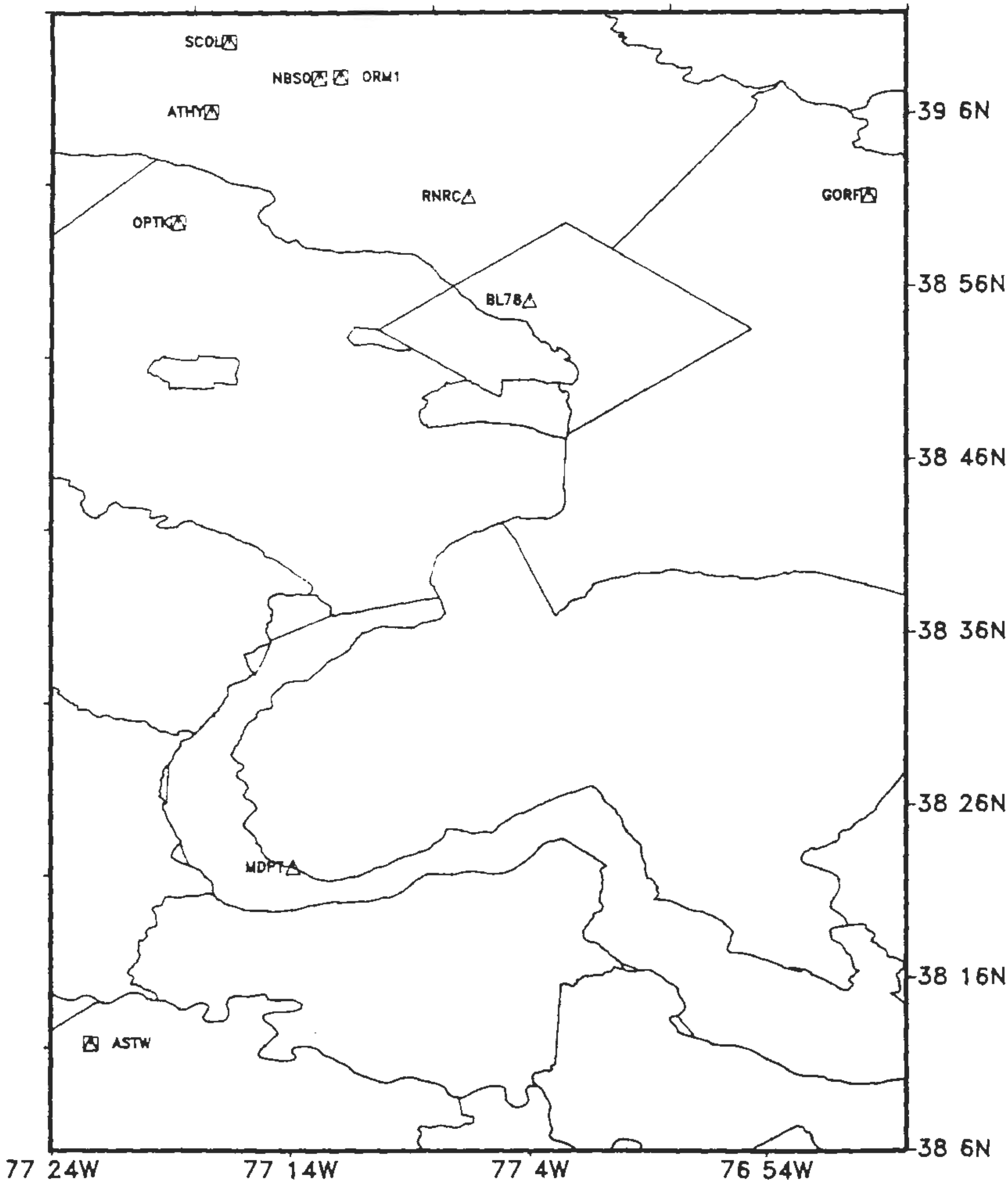
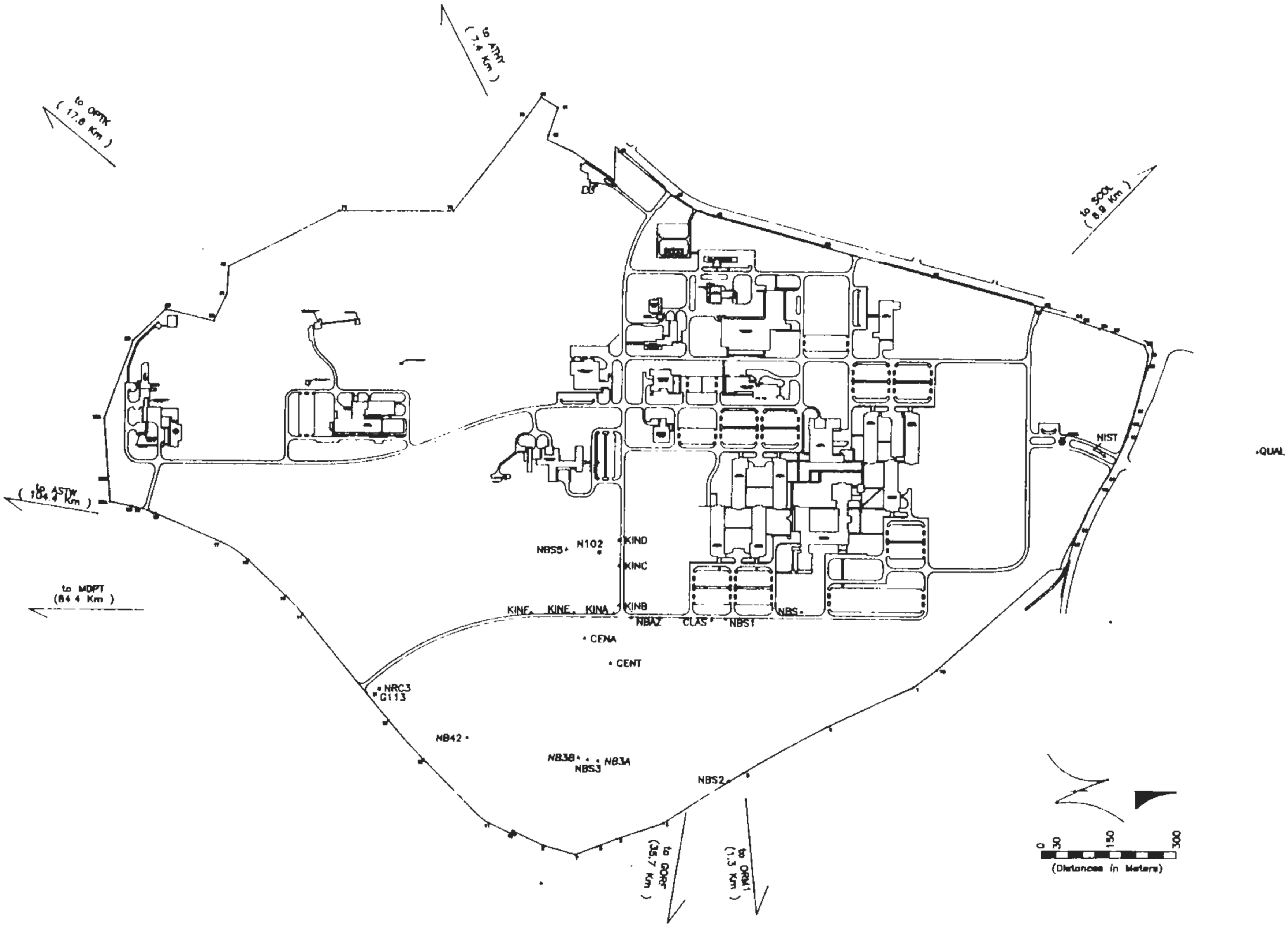


Figure 2. -- portion of FGCC test network - vicinity of Gaithersburg, Maryland



Federal Geodetic Control Committee

REPORT ON TEST AND DEMONSTRATION OF THE

TRIMBLE 4000ST GPS FIELD SURVEYOR

AND ASSOCIATED PROCESSING SOFTWARE

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June 7, 1990

In April 1989, the Federal Geodetic Control Committee (FGCC) conducted a test and demonstration of the Trimble Navigation, Ltd. model 4000ST GPS Field Surveyor eight-channel L_1 only, satellite survey system. This was the eleventh in a series of comprehensive tests by FGCC to evaluate the performance of GPS geodetic survey systems and associated vector processing software.

The test was conducted over a three-day period beginning Saturday, April 8 (day 098) and ending Monday, April 10 (day 100), 1989, on 12 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. Each observing day, ten 4000ST receivers were operated for one continuous simultaneous session where the scheduled observing span was about 245 minutes. Thirty 30 independent station-occupation-sessions were scheduled and successfully observed which resulted in the measurement of 135 vectors (trivial and non-trivial).

The 4000ST GPS Field Surveyor is a self-contained package consisting of a receiver, an internal antenna, and computer/data logger with a key board, data display, and non-volatile mass memory data storage unit. It can be mounted directly on a tripod and includes in the base of the case, a built-in tape for measuring the height of the antenna phase center above the station mark. External

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to the receiver is a battery protected in a hard case equipped for mounting on the tripod leg and includes a short cable for connecting to the 4000ST. An optional antenna for remote operation is available.

Eight independent single frequency L_1 only (1575.42 MHz) code correlation channels are a standard specification with an option for expanding to 12 independent L_1 only channels. Additionally, Trimble specifies the unit can be upgraded with an equal number of independent L_2 carrier phase channels for dual frequency observations. The 8 channel feature 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 4000ST operates with the coarse acquisition code (C/A code) or SPS (Standard Positioning Service) to make phase measurements on the reconstructed L_1 carrier signals. C/A code pseudo range, integrated Doppler, code phase, and L_1 carrier phase measurement data are sampled at the default rate of 15 seconds, with higher and lower sampling rates available for selection.

The pseudo range (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).

Trimble specifies that the receiver precision of measured data are:

Carrier phase:	0.1	mm rms	(2 second averaging)
Code phase:	0.3	m	(1 second averaging)
Code phase smoothed:	5	cm	(2 minutes averaging)
Doppler:	0.015	Hz	(1 second averaging)
Integrated Doppler:	3	mm	(3 hour integration time)

and accuracy of computed data are:

Position (navigation fix):	5-20	m	(Given: No selective availability (S/A), i.e. 1 ppm broadcast orbit accuracy and no dithering; and Geometric Dilution of Precision (GDOP)<6)
Velocity:	1	cm/sec	(≈5 knot) when GDOP<6

In the 4000ST operation manual, Trimble specifies estimates for the static survey relative positioning accuracies (1σ). The accuracy estimates assumed at least five satellites were tracked continuously for the appropriate time span and L_1 carrier phase measurements were recorded. The accuracy estimates were:

horizontal	- 10 mm + 2 ppm,
vertical (ellipsoid height differences)	- 20 mm + 2 ppm, and
azimuth	- 1 sec + 5/vector length in km.

The 4000ST receiver/datalogger/antenna system is enclosed in a waterproof aluminum case 30 × 35 × 13 cm (12 × 13.9 × 5.2 in) that weighs (excluding external battery) 16 lbs (7.2 kg). The system operates on about 8 watts of power from the external 10.5 to 20 VDC source, such as the six-pound (2.7 kg) sealed lead battery provided by Trimble. The specified receiver/antenna unit operating temperature range is -20°C to +55°C.

The standard built-in antenna supplied is a microstrip type design that is tuned to 1575.4 MHz. Although it is indicated in the operation manual that antenna orientation is not required, a common reference point on each antenna was oriented to North during the FGCC test survey to help ensure against any possible phase center bias that could affect the test survey results, particularly for the baselines of less than 2 km. The optional remote antenna has the same specifications as for the internal antenna, except for operating temperature range of -40 to 65°C.

The operation of the 4000ST is controlled and monitored by a display on the front panel. There 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 × 4.9 mm character size) against a yellow background make the display easy to read, particularly during the nighttime operations as experienced during the test survey. (To reduce the power that the backlighting feature consumes, there is a "sleep" mode feature that can be enabled.)

To operate and control the unit, there are six groups of alpha-numeric keys for activating the 4000ST's functions and to enter information in response to the receiver firmware prompts.

The standard internal recording medium is a random access memory (RAM) unit with a capacity of 0.5 mb. Trimble indicates the RAM unit can store in access of an 8-hour 5-satellite L_1 data set collected at a 15-second sampling rate. Optional upgrade to either a 1.0 or a 4.0 mb RAM unit is available.

There is one RS232C port for connecting external devices for real-time data recording and downloading of data stored in the MMU. It takes about 2 minutes to download at 19,200 baud one hour of five-satellite L_1 data sampled at the 15-second rate.

The Trimble 4000ST features 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 about 60 seconds. To lock on all available satellites and compute the first position (provided three or more satellites are in view) it will take about 120 seconds. Data displayed includes: satellite message information, details on satellite tracking and health status, three-dimensional pseudo range position (navigation fix), GPS time, and velocity.

The operator, for 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 4000ST can be left at a station in the unattended mode to operate automatically.

Other operational features or characteristics of the 4000ST system include: (1) automatic and continuous testing of CPU, MMU, and RF processor, to ensure proper operation, (2) satellite in one channel can be swapped with another satellite without affecting lock on other channels, (3) the system does not need a reference position for input to lock on the GPS signals, and (4) capability to operate in the kinematic or dynamic mode.

Some particular characteristics that users may desire but which were not incorporated in the version of the 4000ST tested in April 1989, include: (1) two input power plugs to permit adding and removing external power source without interruption of power, (2) an input port for external reference frequency standard, and (3) output port for a 1 pps (pulse per second) signal.

In the kinematic or dynamic mode, the Trimble 4000ST 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 3 G's. For navigation operation, the internal software processes the pseudo range data in a real-time mode.

Trimble's software package TRIMVEC-PLUS™ operates on an IBM PC or 100% compatible computer with 640K RAM, a hard disk having at least 20-Mb capacity, a math-coprocessor, and a serial interface port. Trimble specifies that one-hour of static data for a single vector determination can be processed in less than two minutes with a 20 MHz 386 PCs.

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 AE used during the test and version AE 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 multi-vector mode for up to 10 stations,
(3) automatic cycle slip fixing,
(4) triple and double difference (float and fixed) processing techniques,
(5) input of precise ephemeris data in the standard distribution format,
(6) covariance and correlation data in output, and
(7) capability to process data collected in the kinematic survey mode.

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.

Data collection during the test survey was carried out without any significant problems. There was no loss od data for any of the scheduled station occupations. Some of the data was affected by ionospheric disturbances which were most evident during the the first two nights of observations. After the first day, the data collection rate was increased from 15 seconds to 10 seconds to aid in the data processing of the noisy data.

Surface meteorological data were recorded during most of the station occupations. However, in the results received for analysis, only the default atmosphere values (T_{dry} = 20.0°C, RH (Relative Humidity) = 50 %, and $P_{sea\ level}$ = 1013 mb) were used in the vector solutions.

The data were initially processed with an early version of TRIMVEC-PLUS™ using the predicted orbital coordinate data contained in the broadcast message to produce single vector results. Processing of most of the data was completed during the test week with solutions provided for analysis and presentation at a public meeting held on Friday, April 14, 1988. Options selected in the processing were:

a.) Integer ambiguities were either fixed or floated in the double-difference solution depending on length of vector.	
b.) Observation epoch interval (sampling rate):	15 or 10 sec
c.) Elevation angle cutoff (above horizon):	20 deg
d.) Residual editing criteria:	3.5σ
e.) Tropospheric model:	Modified Hopfield

The accuracy for the predicted (broadcast) satellite orbital coordinate data used in the solutions was expected to be about 1 ppm (1σ). In processing the data with the broadcast ephemrides, the data closest to the middle of the observing span was used in the vector processing. Some of the solutions may have been affected by the uncorrected effects of ionospheric refraction and less-than-optimum satellite geometry.

The output for the TRIMVEC-PLUS™ vector processing software includes:

(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, and
(9) covariance and correlation matrices.

For each session, the approximate starting and ending time in UTC (Coordinated Universal Time), number of stations occupied, the PRN (pseudo-random-noise) code for the satellites tracked, number of satellites at beginning/maximum/end of each session, and number of vector measurements (trivial and non-trivial) scheduled, observed, and processed are summarized in table 1. As indicated, all observations were conducted during night conditions. Based on the single daily data set collected at each station occupied, the total number of vector measurements attempted (trivial and non-trivial) was 135. Subsets of the complete data set were also processed: a 2-hour and a 1-hour.

Table 1 -- Observation summary, Trimble 4000ST FGCC test survey

Session (Day of Year)	Starting and Ending Time (UTC)*	Num. of Stations	Satellites Observed (PRN Code)	Number of Sat. at Start/ Maximum /End	Vectors Trivial & Non-trivial Scheduled/Observed/ Processed (Excluding Subsets)
97	02:25-06:31	10	3,6,8,9,11,12,13,14	4/6/4	45/45/45
98	02:21-06:27	10	3,6,8,9,11,12,13,14	4/6/4	45/45/45
99	02:17-06:23	10	3,6,8,9,11,12,13,14	4/6/4	45/45/45
TOTALS		30			135/135/135

* Subtract 4 hours to convert UTC to local time.

During and immediately after completion of the field survey work, processing of about 50 vectors was done for the presentation at the public meeting on Friday, April 14. Eight loop closures and six repeat vector measurments were evaluated and presented.

Of the 135 possible vectors (trivial and non-trivial), final post-processed results were received for all lines. The double difference fixed solution method was used for vectors up to 43 km in length and the best triple difference solutions for the longer lines. All results were produced with the TRIMVEC PLUS™ automatic batch processing mode. No interactive processing was required. However, Trimble indicated thatmanual interactive processing might have generated better accuracy for the longer lines by using of the double difference float solition method.

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 past precise GPS vector baseline measurements. The analyses were carried out using the vector baseline components, baseline lengths, ellipsoidal height differences, and baseline azimuths.

Table 2 compares the results for a sample of the repeat measurements. It can be seen the spread in any component for baselines of under 2000 m is less than 6 mm. For the NBS1-ATHY line of 7.4 km, the difference between the repeat measurements ranged within 4.1 cm. In the case of the NBS1-OPTK line of 17.6 km, the component differences ranged within 3.0 cm. In the last three entries in table 3, baselines NBS1-GORF (35.7 km), NBS1-MDPT (84.4 km), and NBS1-ASTW (104.4 km), the component differences ranged within 0.6 cm, 22.7 cm, and 46.1 cm, respectively. As noted in the table, most of the solutions were based on the complete 240 minute data sets. The larger variation in the results for baselines NBS1-MDPT and NBS1-ASTW are typical for triple-difference solutions.

Table 2. -- Comparison of repeat vector measurements.

From /To	Day	Span (mn)	RMS (cm)	DX (m)	DY (m)	DZ (m)	Length (m)	Dh (m)	Azi (sec)	Rmk
									354-02	
NBS1	98	240	0.3	-43.883	107.144	142.992	183.990	1.668	48.11	1
NBS0	99	240	0.3	.883	.144	.992	.990	1.668	.11	1
	100	240	0.3	.883	.145	.991	.990	1.666	.38	1
	98	120	0.3	-43.885	107.141	142.997	183.992	1.673	.54	1
	99	120	0.3	.883	.144	.992	.990	1.668	.37	1
	100	120	0.4	.882	.145	.991	.991	1.666	.89	1
									76-05	
NBS1	98	240	0.4	1209.310	467.736	255.999	1321.644	15.492	49.60	1
ORM1	99	240	0.4	.306	.740	6.002	.642	.491	.92	1
	100	240	0.4	.307	.740	6.003	.644	.492	99	1
									242-44	
NBS1	98	240	0.5	-5936.260	-3532.484	-2629.346	7391.284	-2.141	52.17	1
ATHY	99	240	0.9	.268	.523	.305	.295	.106	.03	1
	100	240	0.9	.267	.521	.342	.306	.112	1.89	1
									209-21	
NBS1	99	240	1.3	-6264.863	-11280.516	-11895.403	17549.905	-25.823	55.67	1
OPTK	100	240	1.2	.862	.543	.421	.934	.813	.54	1
									110-25	
NBS1	99	240	2.9	34297.677	-123.398	-9771.484	35662.694	-86.286	34.26	1
GORF	100	240	2.2	.682	.397	.487	.700	.287	.27	1
									181-04	
NBS1	98	240	7.1	10126.553	-51773.466	-65902.835	84416.956	-131.234	27.85	3
MDPT	100	240	5.5	.226	.503	.821	.929	.254	8.66	3
									187-43	
NBS1	98	240	4.8	614.787	-66044.519	-80793.124	104354.134	-70.847	11.15	3
ASTW	99	240	8.8	.326	.586	2.998	.076	.796	2.10	3
	100	240	6.7	.328	.722	2.968	.139	.674	1.97	3

Solution method: (1) SB-DDFX-BE-L1; (2) SB-DDFL-BE-L1; (3) SB-TRP-BE-L1
Legend: SB - Single baseline solution; DD - Double difference; FX - Fixed integers; FL - Integer float; BE - Broadcast ephemerides.

In table 3, 8 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 8 loops were: 1.8, 3.7, 39.6, 97.6, 45.8, 243.9, 214.2, and 205.0 km. Each loop had four sides with 2 or 3 independently determined vectors. Absolute misclosures for the loops with the short length vectors ranged from 1 to 14 mm. Those loops with a combination of short and medium lengths, the absolute misclosures ranged from 0.2 to 8.7 cm (0.04 to 2.3 ppm). In the over 200 km loops which included vectors as long as 104 km, the absolute misclosure in the three vector components ranged between 3.9 and 46.8 cm (0.2 to 2.3 ppm).

All baselines were previously surveyed by three-dimensional precise terrestrial survey methods. Two-sigma accuracy estimates for the terrestrial relative positional measurements are: horizontal - 2 ppm and vertical - 3 ppm. Additionally, all lines measured with the Trimble 4000ST

Table 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	1.8	-0.2	1.4	-0.1	1.4	-1.2	
3	4	3.7	0.1	-0.5	0.1	0.5	0.5	
3	4	39.6	1.4	8.7	1.7	9.0	-5.3	
3	4	97.6	-1.3	0.5	1.3	1.9	0.2	
3	4	45.8	-1.3	6.1	0.2	6.2	-4.7	
3	4	243.9	6.6	9.8	-11.3	16.3	-13.4	
3	4	214.2	30.8	-30.3	-3.9	43.4	25.7	

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

systems 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 4000S and SX, Wild Magnavox WM-101, and SERCEL NR52. Overall, the estimated 1-sigma vector component uncertainties achieved from the 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 baseline 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 "base" (e) and the line-length dependent (p) values. The value for e should be comparable to the component uncertainty for "zero" length baselines, provided that the antenna set up error (centering and antenna phase center height measurement error) is insignificant.

When 4000ST L_1 data are collected for a span of 60 minutes (at least 120 minutes is recommended) and processed with the broadcast (BE) or predicted orbital elements, the empirically derived 1-sigma estimate for e is 10 mm and for p is 2 ppm or 2 mm/km. Combining these estimates statistically, the total 1-sigma and 2-sigma estimates for each vector component is given by:

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

and,

$$E_{2\text{-sigma}} = \pm 2 \cdot (\sqrt{[(20\ \text{mm})^2 + (d \cdot 4\ \text{mm/km})^2]_{BE}}),$$

where, d = length of the vector in km.

Overall, the results from the "broadcast" ephemeris solutions indicated that the 4000ST L_1 survey system will produce useful measurements that can meet a wide range of applications provided that: (1) quality observations are collected for an adequate period of time during good satellite geometry, (2) the point position for the station fixed in the vector solution is accurately referenced (e.g. 5-meter level) to the GPS orbital coordinate system (e.g. WGS 84), (3) the orbital coordinate accuracy is 2 ppm or better, and finally, (4) ionospheric refraction is not a significant problem, or, if it is, dual frequency phase observations are available.

The trees, buildings, and nearby power transmission lines at some of the FGCC test stations sites may have effected 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 21-24 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.

In table 4, the proposed FGCC accuracy standards for orders III through AA are summarized. Based on analysis of the results achieved from the FGCC test survey, assuming the accuracies for the broadcast and precise ephemerides are about 1 ppm and 0.1 ppm, respectively, and that "selective availability" can be effectively overcome, the capability of the 4000ST system to achieve the various orders are indicated. In the remarks are given certain conditions that the capabilities are based on. To achieve the high orders of A and AA, it was assumed that either the TRIMVEC 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 orders A and AA, 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 April 1989 on the Trimble Navigation, Inc. model 4000ST GPS Surveyor system, indicates that carrier phase data (L_1 only) collected on four or more satellites with an acceptable geometric configuration during a period of about 120 minutes or more, and processed with double difference software using orbital coordinate data accurate to 2 ppm or better will yield accuracies that should meet requirements for most control survey needs.

Table 4. -- FGCC accuracy standards and capability of the Trimble 4000ST.

FGCC Accuracy standards (2-sigma or 95% confidence level) (Reference: FGCC Version 5.0, May 11, 1988, reprinted August 1, 1989)		Trimble model 4000ST 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
2II	$\pm\sqrt{[(30\ mm)^2 + (d \cdot 50\ mm/km)^2]}$	Yes, with BE; L1 only
2I	$\pm\sqrt{[(20\ mm)^2 + (d \cdot 20\ mm/km)^2]}$	Yes, with BE; L1 only
1	$\pm\sqrt{[(10\ mm)^2 + (d \cdot 10\ mm/km)^2]}$	Yes, with BE; provided no significant ionospheric disturbances
B	$\pm\sqrt{[(8\ mm)^2 + (d \cdot 1\ mm/km)^2]}$	Should with BE provided no significant orbit error due to SA; Should with PE
A	$\pm\sqrt{[(5\ mm)^2 + (d \cdot 0.1\ mm/km)^2]}$	No with BE; should with PE; only assured with L1/L2 linear combination.
AA	$\pm\sqrt{[(3\ mm)^2 + (d \cdot 0.01\ mm/km)^2]}$	Not sure? If possible, requires use of orbital adjustment method; only with L1/L2 linear combination

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

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Mention of a commercial company or product does not constitute an endorsement by the Federal Geodetic Control Committee.

Federal Geodetic Control Committee

SUMMARY REPORT ON TEST AND DEMONSTRATION OF THE

NORSTAR 1000 GPS SATELLITE SURVEYING SYSTEM

AND ASSOCIATED PROCESSING SOFTWARE

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September 12, 1989

In November 1988, the Federal Geodetic Control Committee (FGCC) conducted a test and demonstration of the Norstar Instruments Ltd. model 1000 (NS1000) Global Positioning System (GPS) satellite survey system and associated processing software. This was the tenth in a series of tests of survey systems that use signals from GPS.

Norstar, a division of Nortech Surveys Inc., Calgary, Canada, developed the model 1000 in a joint arrangement with the electronics firm, Stanford Telecommunications Inc., California. The NS1000 is distributed in the US by Del Norte Technology, Inc. as model DNTI 1005.

The Norstar 1000 is a single-frequency (L_1 - 1575.42 MHz) GPS receiver system with five independent code correlation parallel channels that operates with the coarse acquisition code (C/A code) or SPS (Standard Positioning Service) to make phase measurements of the reconstructed L_1 carrier signals. An option is available to increase the number of channels to 7. C/A code pseudo range, L_1 integrated Doppler, and L_1 carrier phase measurement data are sampled at a 1-second rate or a multiple of 1 second. Norstar specifies that the pseudo range resolution is 6 cm and the accumulated carrier phase resolution is better than 1 mm.

The pseudo range 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

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relative positions ($\Delta X, \Delta Y, \Delta Z$) between the occupied station points. All test survey data were collected in the static mode of operations (fixed site).

The Norstar 1000 system includes two primary components: receiver and an antenna/preamplifier. The receiver unit, housed in a case 18 x 45 x 55 cm (7 x 8 x 22 in), weighs about 15 kg (33 lbs). It is powered by a 11 to 32 VDC nominal source such as a car battery and requires about 70 watts for operation and 3 watts for standby. An internal battery provides power while external batteries are being switched. The operating temperature is -40°C to +60°C. The standard antenna supplied, a quadrifilar helix or volute configuration that is tuned to 1575.4 MHz, is the Chu model 3224.

The receiver has a four by forty character display and a 20 key keypad. The recording medium is a mass memory unit (MMU) with a capacity of 512Kb. It can store in excess of an eight hour 5-satellite data set collected during a phase measurement sampling rate of 30 seconds. If the sampling rate is 1 sec, about 20 minutes of 5-satellite data can be stored. There was no indication that more than one MMU could be used to increase data storage capacity during high rates of phase measurements.

There are four serial input/output RS232C ports, each 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, and/or for a remote operation terminal. There is also an input port for an external reference frequency.

The NS1000 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 2 to 5 minutes. Data displayed includes satellite message information and reduced satellite data such as information on satellite health status, position (fixes), and range corrections.

The operator, for 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 NS1000 can be left at a station in the unattended mode to operate automatically.

Other operational features or characteristics of the NS1000 system include: (1) automatic swapping a satellite with another satellite in a channel without affecting lock on other channels, (2) display on the CDU, satellite tracking status, GPS time, and frequency information, (3) automatic and continuous testing of CPU, MMU, and RF processor, to ensure proper operation, and (4) high level capability to operate in the kinematic and/or dynamic mode.

In the kinematic or dynamic mode, the NS1000 operates either independently as a point positioning (i.e. navigation fix) system or a differential configuration where data are collected simultaneously with two or more systems. It can be configured to handle accelerations ranging between 0.6 G to a high of 4.0 G. For navigation operation, the internal software processes the pseudo range data in a real-time mode. Navigation data displayed includes estimated time of arrival at waypoints, travel distance, steering right/left with course corrections, and azimuth.

Norstar's software package NOVAS runs on an IBM PC or 100% compatible computer. The package includes a utility to generate satellite visibility and GDOP (Geometrical Dilution of Precision) tables. Using this information, the user can select the best available satellite constellation for a given location and date.

This report is based solely on analysis of vector results obtained from the NOVAS software version that was in use on November 8 and 9, 1988. NOVAS 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, (3) double differenced float and fixed vector solutions, (4) graphics capability for display of residuals, and (5) processing of data collected in the kinematic survey mode. The carrier phase data can be processed by NOVAS with either recorded broadcast or precise ephemeris data. As of the date of this report, the FGCC test data were processed with only the broadcast ephemerides.

The test was conducted over a period of 4 days beginning Monday, November 7, and ending Thursday, November 10, on stations of the FGCC test network located in the vicinity of Washington, DC. Base lines measured ranged in length from about 183 to 1322 m for short base lines, 7 to 19 km for moderate lengths, and 35 to 105 km for the longest lengths.

Two sessions were observed on the first day (observing sessions 312A-312B) for durations ranging from approximately 13 to 61 minutes. Three receivers were scheduled and used. Three sessions were scheduled on the second, third, and fourth days of the test (observing sessions 313A-313B-313C, 314A-314B-314C, and 315A-315B-315C) for durations ranging from approximately 44 to 61 minutes. It was planned to use 5 receivers, however, because of a hardware malfunction with one of the five receivers, only four stations were occupied during observing day 313. On the third day, all five scheduled receivers were used. Using a spare receiver received on day 314, six receivers were used on the last observing day (day-of-year 315). Thus, there were a total of 54 station-occupation-sessions attempted.

Surface meteorological data were recorded during each station occupation. However, in the results received for analysis, only the default accepted standard atmosphere values (T_{dry} = 20.0°C, T_{wet} = 13.9°C, and $P_{sea\ level}$ = 1013 mb) were used in the vector solutions.

The data were processed with the NOVAS software using the predicted orbital coordinate data contained in the broadcast message to produce single vector results. Processing of all data was attempted during the test week with solutions provided for analysis and presentation at a public meeting on Monday, November 14, 1988. Options selected in the processing were:

a.) Integer ambiguities were either fixed or floated in the double-difference solution depending on length of base line.
b.) Observation time interval (sampling rate): 15 sec
c.) Elevation angle cutoff (above horizon): 15 deg
d.) Cycle slip tolerance: 0.40 cycle

The output for the NOVAS 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, (6) indication whether the integer ambiguities were fixed or floated, (7) results for the vector components ($\Delta X, \Delta Y, \Delta Z$), base line length, forward and back azimuths, and ellipsoidal height differences, and (8) covariance matrix and standard deviations in terms of vector components and latitude-longitude-ellipsoidal height differences.

The accuracy for the predicted (broadcast) satellite orbital coordinate data was expected to be within the range of 1 to 2 ppm. Although for some of the solutions, the impact of the uncorrected effects of ionospheric refraction and less-than-optimum satellite geometry could have been a serious problem, generally the orbital coordinate data has been the most significant distant-dependent error source.

For each session, the approximate starting and ending time in UTC (Coordinated Universal Time), number of stations occupied, the PRN (pseudo-random-noise) code for the satellites tracked, number of satellites at beginning/end of each session, and number of vector measurements (trivial and non-trivial) attempted compared to number submitted for evaluation are summarized in the table on page 5. The total number of vector base line measurements attempted (trivial and non-trivial) was 99. All observations were conducted during daylight conditions. To convert UTC time to local time, subtract 5 hours.

Of the 99 possible vectors (trivial and non-trivial), results were received for only 36 lines. The 36 vectors received were limited to lines of short and medium length where the longest line was 18.5 km. Of the 63 vectors which were not successfully processed, 31 vectors were from session C. All data collected during session C (days 313, 314, and 315) produced poorly determined vectors. Probable explanations for the poor session C solutions were: (1) insufficient observations since only 3 to 4 satellites were available, (2) poor geometry even during periods of four-satellite availability, (3) perhaps large errors due to uncorrected effects of ionospheric refraction, and (4) possibly problems with the broadcast orbital data.

The remaining 32 vectors that were not processed successfully were from sessions A and B for lines ranging in length between 32 and about 104 km. Several attempts were made to compute valid vectors, but all were unsuccessful. As of the date of this report, Norstar officials have not been able to come up with a definite cause for the poor results. Two possible factors that could be the cause for the unresolved problem are: (1) major ionospheric disturbances that produced unusually large refraction errors, and (2) unusually large biases in the predicted orbital coordinate data, perhaps worse than 10 ppm. Norstar is continuing to investigate this problem and should a resolution be found, it will be included in an update of this report.

Session	Starting and Ending Time (UTC)	Num. of Stations	Satellites Observed (PRN Code)	Number of Satellites at Start/End	Vectors (Trivial and Non-trivial) Attempted/Analyzed*
312A	14:30 - 15:07	3	6, 9, 11, 12, 13	5/5	3/3
312B	15:14 - 16:10	3	8, 9, 11, 12, 13	5/5	3/3
313A	14:00 - 15:01	4	6, 9, 11, 12, 13	4/5	6/6
313B	15:01 - 16:05	4	8, 9, 11, 12, 13	5/5	6/6
313C	16:06 - 16:50	4	3, 8, 11, 12, 13	4/3	6/0
314A	13:56 - 14:57	5	6, 8, 9, 11, 12	4/5	10/3
314B	14:58 - 15:58	5	8, 9, 11, 12, 13	5/5	10/3
314C	16:02 - 16:50	5	3, 8, 11, 12, 13	4/3	10/0
315A	13:52 - 14:53	6	6, 8, 9, 11, 12	4/5	15/6
315B	14:53 - 15:57	6	8, 9, 11, 12, 13	5/5	15/6
315C	15:57 - 16:41	6	3, 8, 11, 12, 13	4/3	15/0
TOTALS		54			99/36

* Analyzed are the number of vectors that were successfully processed and available for evaluation.

The 36 vectors furnished by Norstar 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.

All base lines were previously surveyed by three-dimensional precise terrestrial survey methods. Two-sigma accuracy estimates for the terrestrial relative positional measurements are: horizontal - 2 ppm and vertical - 3 ppm. Additionally, all lines measured with the Norstar 1000 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 4000S and SX, Wild Magnavox WM-101, SERCEL NR52, and Ashtech XII. The 1-sigma base line component uncertainties achieved from the GPS test surveys conducted before the Norstar test were about $\pm\sqrt{[1 \text{ cm}^2 + (0.1d\cdot(1\text{-to-}2 \text{ ppm}))^2]}$, where d is the base line length in kilometers.

In the table on page 6, six loop misclosure computations are summarized. All loops were formed using vectors that were independently determined. The total distance around each of the six loops were: 2.9, 2.9, 17.4, 39.3, 39.2, and 40.1 km. Two three-sided loops were formed with base lines each less than 2 km in length. The misclosure in any of the three components ranged between

3 and 28 mm. Four additional loops were formed with base lines ranging in length between 0.18 and 18.48 km. The absolute minimum and maximum misclosure for any component in terms of distance were 0 and 5.5 cm, respectively. The worst misclosure in proportion to the total length of the loop was 1.4 ppm.

After an appropriate adjustment for any 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 uncertainties for the base line components. For base line lengths of

SUMMARY OF LOOP MISCLOSURE COMPUTATIONS

Number of Lines		Length of Loop	Misclosure									
			DX		DY		DZ		Resultant		Dh	
Inde-pendent	Total	(km)	(cm)	(ppm)	(cm)	(ppm)	(cm)	(ppm)	(cm)	(ppm)	(cm)	(ppm)
3	3	2.9	-0.3	-	-1.5	-	1.4	-	2.2	-	1.9	-
3	3	2.9	0.4	-	2.8	-	-1.1	-	3.0	-	-2.8	-
4	4	17.4	-0.8	-0.5	-1.0	-0.6	2.5	1.4	2.8	1.6	2.2	1.3
4	4	39.3	1.4	0.4	-3.9	-1.0	4.6	1.2	6.2	1.6	6.1	1.6
3	3	39.2	-0.8	-0.2	1.5	0.4	0.0	-	1.7	0.4	-1.1	-0.3
6	6	40.1	2.4	0.6	-4.8	-1.2	5.5	1.4	7.7	1.9	7.4	1.8

less than 2 km and data collection periods of 37 to about 60 minutes, the estimated 1-sigma uncertainty was about 12 mm. For lines longer than 2 km, but less than 20 km, the 1-sigma accuracy estimate for each base line component was about $\pm\sqrt{[(1.2\text{ cm})^2 + (0.1d \cdot 2\text{-to-}4\text{ ppm})^2]}$.

Since there were no results available for the longer base lines (32 to 104 km), it was not possible to provide estimated uncertainties that might be obtained for lines longer than about 20 km.

Overall, the results were slightly worse than results from past FGCC GPS measurements produced with double difference software. The cause was probably related to the same problem in getting valid results from the longer base line observations. Even with the limited results, there is a reasonably good indication that useful measurements are possible provided that: (1) at least 1 hour of observations are collected during good satellite geometry, (2) time tags for the phase measurements can be estimated reliably, (3) the point position for the station fixed in the vector solution is accurately referenced (5-meter level) to the GPS orbital coordinate system (e.g. WGS 84), (4) the orbital coordinate accuracy is 1-2 ppm, and finally, (5) ionospheric refraction is not significant or dual frequency observations are available.

The unsuccessful attempt to obtain valid vector solutions for the longer base lines might be overcome if the data were reprocessed with the precise ephemerides (1 to 0.1 ppm). But if most of the problem is due to severe ionospheric conditions, or a combination of ionosphere and orbital accuracy, it may not be possible to get valid solutions.

The trees, buildings, and nearby power transmission lines at some of the FGCC test stations sites may have effected 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 21-24 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.

Given the estimated uncertainties (i.e. $\pm\sqrt{[(1.2\ \text{cm})^2 + (0.1\text{d}\cdot 2\text{-to-}4\ \text{ppm})^2]}$) for line lengths up to 18 km from the Norstar 1000 test survey results and the current defined accuracy standards (FGCC 1988) for connecting control points horizontally and vertically to stations of the National Geodetic Reference System, the table on page 7 gives minimum distances between stations for

Accuracy standard (95% confidence level) (FGCC Ver. 5.0, May 11, 1988)		Minimum spacing (B) between stations to achieve specified order (km)
Order	Definition	
3I	$\pm\sqrt{[(5\ \text{cm})^2 + (0.1\text{d}\cdot 100\ \text{ppm})^2]}$	0
2II	$\pm\sqrt{[(3\ \text{cm})^2 + (0.1\text{d}\cdot 50\ \text{ppm})^2]}$	0
2I	$\pm\sqrt{[(2\ \text{cm})^2 + (0.1\text{d}\cdot 20\ \text{ppm})^2]}$	0.7
1	$\pm\sqrt{[(1\ \text{cm})^2 + (0.1\text{d}\cdot 10\ \text{ppm})^2]}$	2.5
B	$\pm\sqrt{[(0.8\ \text{cm})^2 + (0.1\text{d}\cdot 1\ \text{ppm})^2]}$	(1)

(1) Since the line-length portion of the accuracy estimate is 2 ppm or worse for Norstar 1000 data reduced with the predicted orbital coordinate data, a value for the minimum station spacing is not applicable for order B, A, and AA accuracy standards.

corresponding orders. It can be seen that unless order of 1 or higher is specified, the minimum spacing between adjacent stations is not a factor that requires consideration in planning for the location of GPS stations in a project when using the Norstar system.

In conclusion, analysis of the results from the FGCC test survey conducted in November 1988 on the Norstar model 1000 GPS survey system, indicates that carrier phase data (L_1 only) collected on four or more satellites with an acceptable geometric configuration during a period of about 60 minutes and processed with double difference software using orbital coordinate data accurate to 2 ppm or better will yield accuracies that should meet requirements for most control survey needs.

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FGCC Federal Geodetic Control Committee

REPORT ON TEST AND DEMONSTRATION OF THE

ASHTECH XII GPS SATELLITE SURVEY SYSTEM

AND ASSOCIATED PROCESSING SOFTWARE

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In August 1988, the Federal Geodetic Control Committee (FGCC) conducted a test and demonstration of the Ashtech Inc. models L-XII and S-XII Global Positioning System (GPS) satellite geodetic survey, navigation, and time transfer system. This was the ninth in a series of comprehensive tests by FGCC to evaluate the performance of GPS geodetic survey systems and associated vector processing software.

The test was conducted over a period of 5 days beginning Monday, August 14, and ending Friday, August 18, on stations of the FGCC test network located in the vicinity of Washington, DC. Baselines measured ranged in length from about 183 to 1322 m for short baselines, 7 to 19 km for moderate lengths, and 35 to 105 km for the longest lengths. One continuous session of 180 to 210 minutes in duration was observed each day. Ten receivers were used on the first three observing days, seven receivers on the fourth day, and five receivers on the last observing day for a total of 42 station-occupation-sessions.

The L-XII and S-XII models are two different versions of the ASHTECH XII survey system. The S-XII system operates in conjunction with an external laptype computer that controls the data collection and stores the data on the computer diskette. The L-XII is a self-contained package with a key board, data display, and non-volatile mass memory data storage unit. During the test about an equal number of S and L models were used to collect data. Ashtech has indicated that the S model

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is an interim lower cost system that eventually will be phased out of production for the self-contained L package.

Both models (L-XII and S-XII) are single frequency, L_1 only (1575.42 MHz) GPS receiver systems with 12 independent code correlation parallel channels. The 12 channel feature gives the surveyor the capability of tracking all available satellites in view at the present time and for the foreseeable future.

The XII receivers operate with the coarse acquisition code (C/A code) or SPS (Standard Positioning Service) to make phase measurements of the reconstructed L_1 carrier signals. The C/A code pseudo range, L_1 integrated Doppler, and L_1 carrier phase measurement data are sampled at a 1-second rate or a multiple of 1 second. Ashtech specifies that the resolution and accuracy of measured and computed data are:

Carrier phase:	0.1 mm rms
Code phase:	1 meter
Code phase smoothed:	few centimeters
Doppler:	0.001 Hz
Integrated Doppler:	3 mm
Position:	20 m (depends on broadcast orbit accuracy and having a Geometric Dilution of Precision (GDOP)<6)
Velocity:	1 cm/sec (0.02 knot) when GDOP<6

The pseudo range (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).

The Ashtech L-XII system includes two primary components: a receiver and an antenna/preamplifier. The receiver unit is housed in a case 12 x 22 x 32 cm (4.6 x 8.5 x 12.5 in). 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 1575.4 MHz.

The XII receiver has a eight by forty character display and 16 key keypad. The recording medium is a mass memory unit (MMU) with a capacity of 2 mb. It can store in excess of an twenty-hour 8-satellite data set collected during a phase measurement sampling rate of 30 seconds. If the sampling rate is 1 sec, about 40 minutes of 8-satellite data can be stored.

There are two serial input/output RS232C ports, each 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, and/or for a remote operation terminal. 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 L-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 includes satellite message information and reduced satellite data such as information on satellite health status, position (fixes), and range corrections.

The operator, for 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 Ashtech XII can be left at a station in the unattended mode to operate automatically.

Other operational features or characteristics of the Ashtech 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 L-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 is configured to handle accelerations up to about 2 G. For navigation operation, the internal software processes the pseudo range data in a real-time mode. Navigation data displayed includes estimated time of arrival at waypoints, travel distance, steering right/left with course corrections, and azimuth.

Ashtech's software package GPPS (GPS Post Processing Software) runs on an IBM PC or 100% compatible computer. In addition to vector processing, GPPS includes utilities 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 software version that was in use during August 15-19, 1988. GPPS can be operated either in the manual (user interface) or automatic (batch) mode. Other important features of the vector baseline processing software include:

1. single vector processing only,
2. automatic cycle slip fixing,
3. double differenced float and fixed vector solutions,
4. graphics capability for display of residuals, and
5. processing of data collected in the kinematic survey mode.

The carrier phase data can be processed by GPPS using either the recorded broadcast or precise ephemeris data in the standard format.

Surface meteorological data were recorded during most of the station occupations. However, in the results received for analysis, only the default accepted standard atmosphere values (T_{dry} = 33.0°C, RH (Relative Humidity) = 50%, and $P_{sea\ level}$ = 1013mb) were used in the vector solutions.

The data were initially processed 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 on Friday, August 18, 1988. Options selected in the processing were:

a. Integer ambiguities were either fixed or floated in the double-difference solution depending on length of vector.	
b. Observation epoch interval (sampling rate):	20 sec
c. Elevation angle cutoff (above horizon):	15 or 20 deg
d. Residual editing criteria:	3σ
e. Apply tropospheric delay correction:	No

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 (ΔX, ΔY, ΔZ), baseline length, forward and back azimuths, and ellipsoidal height differences, and
9. covariance matrix and standard deviations in terms of vector components and latitude-longitude-ellipsoidal height differences.

The accuracy for the predicted (broadcast) satellite orbital coordinate data was expected to be within the range of 1 to 2 ppm. Although for some of the solutions, the impact of the uncorrected effects of ionospheric refraction and less-than-optimum satellite geometry could have been a serious problem, generally the orbital coordinate data has been the most significant distant-dependent error source.

For each session, the approximate starting and ending time in UTC (Coordinated Universal Time), number of stations occupied, the PRN (pseudo-random-noise) code for the satellites tracked, number of satellites at beginning/end of each session, and number of vector measurements (trivial and non-trivial) attempted compared to number submitted for evaluation are summarized in the table 1. The total number of vector baseline measurements attempted (trivial and non-trivial) was 166. All observations were conducted during daylight conditions. To convert UTC time to local time, subtract 5 hours.

Of the 166 possible vectors (trivial and non-trivial), results were received for only 71 lines. Ashtech attempted to obtain viable solutions for the other 95 vectors, but the efforts were unsuccessful. Possible reasons for the unsatisfactory solutions are: (1) insufficient phase observations, (2) poor geometry even during periods of four-satellite availability, (3) perhaps major ionospheric disturbances that produced large refraction errors, and (4) possibly problems with the broadcast orbital data.

The 71 vectors furnished by Ashtech were evaluated by comparison of repeat measurements, computation of loop misclosures, comparison with test network terrestrial coordinate differences, and comparison with past precise GPS vector baseline measurements. The analyses involved the use of vector baseline components, baseline lengths, ellipsoidal height differences, and baseline azimuths.

Table 1 -- Observation summary, Ashtech L-XII FGCC test survey

Session	Starting and Ending Time (UTC)*	Num. of Stations	Satellites Observed (PRN Code)	Number of Satellites at Start/End	Vectors (Trivial and Non-trivial) Attempted/Analyzed**
227	18:15 - 22:35	10	3,6,8,9,11,12,13	4/4	45/21
228	18:00 - 22:16	10	3,6,8,9,11,12,13	4/4	45/15
229	18:12 - 22:12	10	3,6,8,9,11,12,13	4/4	45/23
230	18:02 - 22:50	7	3,6,8,9,11,12,13	4/4	21/2
231	18:35 - 22:04	5	3,6,8,9,11,12,13	4/4	10/10
TOTALS		42			166/71

* Subtract 4 hours to convert UTC to local time.
** The number of vectors analyzed are that which were successfully processed and available for evaluation.

Table 2 compares the results for a sample of the repeat measurements. The span for the observations used in the solutions ranged between 33 and 115 minutes. Hence, results might be expected to be less precise than what has been achieved from previous FGCC test data sets with observing spans of 100 to 200 minutes. Also, for this test there appeared to be an unusual number of possible blunders due to operator error or inexperience in antenna setup procedures.

In the case of the shortest baseline, NBS1-NBS0, the spread in the vector components ranged between 2 and 11 mm, But as shown, while the length only differed by 3 mm, the height difference was 16 mm, indicating either a blunder in the antenna height measurement or the software was not capable of producing optimal results. It is unlikely there would be a significant bias in the observations due to either tropospheric or ionospheric effects.

There appears to be a blunder in the height measurements for the NBS0-ORM1 baseline (1.3 km) since the spread in the height differences is 45 mm while the spread in the length is only 5 mm. This is also a characteristic of the repeat measurements for the NBS3-ATHY baseline (7.6 km) where the spread in the length is 3 mm while the spread in the height is 42 mm. These results for the repeat measurements indicate a height measurement error occurred during one of the setups on station NBS3.

Good agreement in the results was not achieved for the vector ATHY-OPTK where the difference in the length was 13.4 cm. On the other hand, the lengths for the baselines of NBS3-GORF (35.2 km), NBS3-MDPT (84.1 km), and NBS3-ASTW (104.1 km) agree to better than 1 mm/km (1 ppm). The height differences are nearly comparable.

Table 2. -- Comparison of repeat vector measurements

From /To	Day	Span (mn)	RMS (cm)	DX (m)	DY (m)	DZ (m)	Length (m)	Dh (m)	Azi (sec)	Rmk
									354-02	
NBS1	229	73	0.4	-43.884	107.154	142.984	183.989	1.655	49.96	4
NBS0	231	111	0.5	.886	.143	.995	.992	1.671	54.24	4
									84-05	
NBS0	227	114	1.1	1253.191	360.597	113.010	1308.927	13.828	57.98	1
ORM1	228	33	1.1	.193	.588	.017	.926	.839	8.06	1
	229	47	1.0	.190	.621	2.986	.931	.794	8.60	4
									246-09	
NBS3	227	44	1.2	-6342.420	-3419.946	-2382.494	7589.374	-1.245	59.83	1
ATHY	228	61	2.1	.417	.928	.539	.377	.287	.15	1
									189-38	
ATHY	229	77	1.7	-328.605	-7747.987	-9266.143	12083.074	-23.783	57.48	4
OPTK	230	58	2.4	.555	8.162	.173	.208	.661	6.90	4
									110-09	
NBS3	229	53	1.9	33891.587	-10.814	-9524.675	35204.534	-85.285	20.48	4
GORF	231	115	4.5	.620	.820	.665	.563	.269	.41	1
									181-20	
NBS3	228	83	2.9	9720.123	-51661.122	-65656.185	84107.592	-130.373	3.66	4
MDPT	229	81	3.1	.022	.215	.181	.633	.316	.95	5
									187-56	
NBS3	227	78	1.5	207.963	-65932.463	-80546.281	104090.519	-69.768	56.29	2
ASTW	228	89	3.1	8.235	.379	.435	.586	.881	.55	4

Solution method: (1) SB-DDFX-BE-L1; (2) SB-DDFL-BE-L1; (3) SB-TRP-BE-L1; (4) SB-DDFX-PE-L1; (5) SB-DDFL-PE-L1

Legend: SB - Single baseline solution; DD - Double difference; FX - Fixed integers; FL - Integer float; BE - Broadcast ephemerides; PE - Precise ephemerides.

The mixed results for the repeat measurements indicate that numerous problems occurred during the test, due to inexperience in operation of the equipment and setup of the tripods, software that was less than optimal, or noisy data caused by ionospheric and tropospheric disturbances. For example on the second observing day (228), a major thunderstorm moved into the area of the test network during the last half of the observing session.

In table 3, four 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 four loops were: 2.0, 17.7, 96, and 249 km. The first loop has three sides where each side is less than 2 km in length. The misclosure in the three vector components ranged between 1 and 8 mm. In a second loop that was formed using five vectors ranging in lengths of 0.5 to 7.5 km, the absolute component misclosures were between 1.7 cm (1.0 ppm) and 4.8 cm (2.7 ppm). The third loop was formed with three vectors 18 to 42 km long that gave absolute misclosures of 4.8 cm (0.5 ppm) to 8.2 cm (0.86 ppm). Finally, the last loop formed has six vectors 1 to 100 in length. The absolute component misclosure was between 8.1 cm (0.3 ppm) and 13.7 cm (0.6 ppm).

Table 3. -- Summary of loop misclosure computations

Number of Lines		Length of Loop	Misclosure									
			DX		DY		DZ		Resultant		Dh	
Inde-pendent	Total	(km)	(cm)	(ppm)	(cm)	(ppm)	(cm)	(ppm)	(cm)	(ppm)	(cm)	(ppm)
2	3	2.0	-0.1	-	0.8	-	-0.3	-	0.9	-	-0.8	-
2	5	17.7	2.4	1.4	-1.7	-1.0	4.8	2.7	5.6	3.2	4.7	2.7
3	3	96	-4.8	-0.5	6.6	0.7	8.2	0.9	11.6	1.2	2.2	1.3
4	6	249	-8.1	-0.3	12.7	0.5	-13.7	-0.6	20.4	0.8	-24.4	-1.0

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

All baselines were previously surveyed by three-dimensional precise terrestrial survey methods. Two-sigma accuracy estimates for the terrestrial relative positional measurements are: horizontal - 2 ppm and vertical - 3 ppm. Additionally, all lines measured with the ASHTECH XII systems 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 4000S and SX, Wild Magnavox WM-101, and SERCEL NR52. Overall, the estimated 1-sigma vector component uncertainties achieved from the 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 baseline 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 "base" (e) and the line-length dependent (p) values. The value for e should be comparable to the component uncertainty for "zero" length baselines, provided that the antenna set up error (centering and antenna phase center height measurement error) is insignificant.

Overall, the results from the "broadcast" ephemeris solutions indicated that the Ashtech XII L_1 survey system will produce useful measurements that can meet a wide range of applications provided that: (1) quality observations are collected for an adequate period of time during good satellite geometry, (2) the point position for the station fixed in the vector solution is accurately referenced (e.g. 5-meter level) to the GPS orbital coordinate system (e.g. WGS 84), (3) the orbital coordinate accuracy is 2 ppm or better, and finally, (4) ionospheric refraction is not a significant problem, or, if it is, dual frequency phase observations are available.

The results of the analyses indicated that for the first-generation Ashtech XII receiver and software, it was possible to achieve values comparable with results from other late model GPS survey systems. When L_1 data were collected for a span of least 60 minutes and processed with the broadcast (BE) (predicted orbital elements), the empirically derived 1-sigma estimate for the site-dependent error "e" is better than 10 mm and for the distance-dependent error "p" is 2 mm/km (2 ppm). Combining these estimates statistically, the total 1-sigma and 2-sigma estimates for each vector component is given by:

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

and,

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

where, d = length of the vector in km.

The trees, buildings, and nearby power transmission lines at some of the FGCC test stations sites may have effected 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 21-24 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.

In table 4, the proposed FGCC accuracy standards for orders III through AA are summarized. Based on analysis of the results achieved from the FGCC test survey, assuming the accuracies for the broadcast and precise ephemerides are about 1 ppm and 0.1 ppm, respectively, and that "selective availability" can be effectively overcome, the capability of the 4000ST system to achieve the various orders are indicated. In the remarks are given certain conditions that the capabilities are based on. To achieve the high orders of A and AA, it was assumed there was very little ionospheric disturbances and that 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. To achieve reliably the orders A and AA, it will be necessary to collect data with a very low noise level which can be processed to produce vectors while adjusting the orbital coordinate data.

Table 4. -- FGCC accuracy standards and capability of the Ashtech L-XII

FGCC Accuracy standards (2-sigma or 95% confidence level) (Reference: FGCC Version 5.0, May 11, 1988, reprinted August 1, 1989)		Ashtech model L-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
2II	$\pm\sqrt{[(30\ mm)^2 + (d \cdot 50\ mm/km)^2]}$	Yes, with BE; L1 only
2I	$\pm\sqrt{[(20\ mm)^2 + (d \cdot 20\ mm/km)^2]}$	Yes, with BE; L1 only
1	$\pm\sqrt{[(10\ mm)^2 + (d \cdot 10\ mm/km)^2]}$	Yes, with BE; provided no significant ionospheric disturbances.
B	$\pm\sqrt{[(8\ mm)^2 + (d \cdot 1\ mm/km)^2]}$	Should with BE, but may need PE, and provided there is no significant ionospheric disturbances nor orbit error due to SA.
A	$\pm\sqrt{[(5\ mm)^2 + (d \cdot 0.1\ mm/km)^2]}$	No with BE; should with PE; only assured with L1/L2 linear combination. May need to adjust to adjust orbit.
AA	$\pm\sqrt{[(3\ mm)^2 + (d \cdot 0.01\ mm/km)^2]}$	Not sure? Due to limited accuracy of present precise orbit, will require use of orbital adjustment method; must have L1/L2 data for ionospheric free solution.

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

In conclusion, analysis of the results from the FGCC test survey conducted in August 1988 on the Ashtech models L-XII and S-XII GPS survey system, indicates that carrier phase data (L_1 only) 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 control survey needs.

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FGCC Federal Geodetic Control Committee

SUMMARY REPORT ON TEST AND DEMONSTRATION OF THE

SERCEL MODEL NR 52 GPS SATELLITE SURVEYING SYSTEM

AND ASSOCIATED PROCESSING SOFTWARE

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In June 1988, the Federal Geodetic Control Committee (FGCC) conducted a test and demonstration of the SERCEL (Societe d'Etudes, Recherches et Constructions Electroniques) model NR 52 GPS satellite survey system and associated processing software. SERCEL is a major manufacturer in France of electronic field survey and positioning equipment. This was the eighth in a series of tests of portable satellite survey systems that use radio signals from satellites of the Global Positioning System (GPS).

The SERCEL NR 52 is a single-frequency, L_1 (1575.42 MHz) only, GPS receiver system with five independent code correlation parallel channels that operates with the coarse acquisition code (C/A code) or SPS (Standard Positioning Service) to make phase measurements of the reconstructed L_1 carrier signals. Using the 5 dedicated channels, the system can simultaneously acquire and track up to 5 satellites. Pseudo range and carrier phase measurement data are sampled at a 0.6-second rate or a multiple of 0.6 seconds. As specified by SERCEL, the measurement resolution for the pseudo ranges and carrier phase measurements are 12 cm and 1.5 mm, respectively.

The NR 52 carrier phase measurements are performed with reference to the GPS satellite transmission time rather than to the receiver clock time. More precisely, in each independent channel, the phase measurements are made upon receipt of a particular state of the GPS data stream. Thus, the phase measurements on the GPS signals are not synchronous, but are exactly referenced to the satellite transmission time. In differencing the phase data between receivers for the same satellites, the satellite clock offset is zero. Carrier phase data collected simultaneously with one or more other receivers are processed to determine relative positions between the occupied station points. All test survey data were collected in the static mode of operations (fixed site).

The NR 52 system includes three primary components: receiver, portable laptype computer, and an antenna/preamplifier. The receiver unit, housed in a case 33 x 38 x 33 cm (13 x 15 x 13 in.), weighs about 18.6 kg (41 lbs). It is powered by a 12 VDC source such as a car battery and requires about 96 watts. The frequency standard is a crystal oscillator with a stability rated at 1×10^{-10}/day (Boucher and Nard 1985).

The portable laptype computer (PC DOS compatible), which is connected to the NR 52 RS232 output, serves as the control and display unit (CDU). The CDU is used to control the data acquisition, tracking, interchannel calibration functions, and the recording of the raw data. The operator, for single or multiple sessions, programs the start and stop times and assigns the appropriate satellite to each channel. Once these initial programming steps are completed, the NR 52 system can be left at a station in the unattended mode to operate automatically. It will take approximately 90 seconds between when system is turned on and there is successful lock on the first satellite.

The remaining major component of the NR 52 system is the antenna which is a helix configuration tuned for 1575.4 MHz. It is housed in a weather-tight case weighing about 3 kg (6.6 lbs) that can be mounted on a standard tripod. The L_1 signal is passed to an internal preamplifier and then sent via cable to the receiver. The standard cable is 20 m (61 ft) of RG 223. The maximum cable length is dependent on maximum tolerable loss in signal strength. SERCEL specifies that the loss can reach 15dB with no degradation of the quality of measurements. Higher losses will yield a degradation in signal/noise ratio, although data may remain usable. For the RG 223 cable, the limit in loss of 15dB corresponds to maximum length of 27 m (82 ft).

Other operational features or characteristics of the NR 52 system include: (1) a satellite can be swapped with another satellite in a channel without affecting lock on other channels, (2) the carrier phase measurement collection rate is selectable, (3) during the satellite tracking, the CDU displays satellite tracking status, GPS time, and frequency information, and (4) system design includes capability to operate in the kinematic mode.

Some aspects of other GPS survey systems that were not features on the NR 52 system: (1) as discussed earlier, because the NR 52 is configured only as a raw data sensor there can be no display of pseudo range point position or navigation fix results, (2) there is no internal memory or RAM for storage of data before writing to the diskette, and (3) to lock on to the GPS signals, a reference position within about 2 degrees of the coordinates for the point occupied is required.

SERCEL's "GPS Mission" software package runs on IBM PC or 100% compatible computers. GPS Mission includes a utility to generate satellite visibility and

GDOP (Geometrical Dilution of Precision) tables. Using these information, the user selects the best available satellite constellation for a given location and date.

The post-processing vector base line solution software of the GPS Mission package that was used to process the preliminary and final results was version V1.2, January 1, 1988. It can be operated either in the manual (user interface) or automatic (batch) mode. Some features of the base line processing software: (1) automatic cycle slip fixing, (2) double difference float and fixed solutions, and (3) graphics capability for display of residuals. The software uses the recorded broadcast ephemeris data in the vector solutions. Presently, the software cannot input the precise ephemeris data.

The test was conducted over a period of 4 days from June 26 through 29, 1988, (dates based on local time) with three 82- to 86-minute observing sessions scheduled each day. Ten stations of the FGCC test network located in the vicinity of Washington, DC, were occupied. It was planned to use 5 receivers each day, however, on the second and third days, four were used. The fifth receiver could not be used due to a minor hardware problem that was corrected by the fourth day (Barboux 1988).

The approximate starting and ending time in UTC (Coordinated Universal Time), daylight/darkness status, PRN (pseudo-random-noise) code for the satellites tracked, and number of satellites at beginning/end of each session were:

[1] 21:30 (daylight) - 22:56 (daylight) PRN's 6, 8, 9, 11, 12, 4/5
[2] 23:04 (daylight) - 00:25 (dusk) PRN's 6, 9, 11, 12, 13, 4/5
[3] 00:38 (dusk) - 02:00 (darkness) PRN's 8, 9, 11, 12, 13, 5/2

As indicated, satellite PRN 3 of the seven-satellite Block I system was not observed. Also, during the first session PRN 12 was rising and although data was collected, it was not used in the solutions because it did not rise above 20° before the end of the session. During the eight-minute gap between sessions, system calibration and initialization was performed. To convert time in UTC to local time, subtract 4 hours.

During each observing day at three or four stations, meteorological data (i.e. temperature, pressure, and relative humidity) were recorded before and after each session. These measurements were collected to help improve the results if the GPS observations had been collected during periods when major weather fronts were passing through. Otherwise, during stable weather conditions it was not expected the measured data would give results that were better than the solutions based on default values (accepted standard atmosphere values, i.e. T_{dry} = 20.0°C, T_{wet} = 13.9°C, and $P_{sea\ level}$ = 1013 mb). This was because the instruments used were not designed for reliable high quality measurements, nor were they calibrated to help optimize the accuracy of the measurements.

The first observing session each day was begun with a GDOP of about 60, peaking at about 300 during the session. During the second and third sessions, if there was a successful lock on the four or five available satellites at the beginning of the session, GDOP was less than 10. During the third session, even if signals were not obstructed, four or more satellites were available for less than

15 minutes. The cutoff angle above the horizon for the observations was 20°. The phase measurement sampling rate was 15 seconds.

Based on analysis of premission predictions for GDOP and number of satellites observed, the second of the three daily observing sessions was expected to give the best base line results while the third session was expected to give the worst values. The success of the observations was further complicated by the fact that trees obstructed crucial signals at some of the sites. This problem was most significant during the third observing session. Under normal field operations with the Block I constellation, some of the stations with critical obstructions would not have been occupied during the third session.

In addition to the trees, nearby buildings and power transmission lines at some of the FGCC stations may have effected the test results. These were the same conditions that could have 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 considered important factors in the tests to help determine the design effectiveness and capabilities of the GPS survey instruments and processing software.

Once the 21-24 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.

There was one serious cause for concern during the four-day test period. During the second observing day a major magnetic storm warning due to the largest solar flare in four years was issued by the NOAA Space Environment Laboratory. By the third day it had ebbed into a minor magnetic storm. Since the NR 52 is an L_1 only system, it was expected the magnetic storm would have a significant impact on the base line results for the second day's observations due to the uncorrected delay effects of ionospheric refraction.

Of 60 station-occupation-sessions (5 receivers × 3 sessions each day) scheduled during the four observing days, 6 were not observed due to the hardware problem mentioned earlier. For the 54 station-occupation-sessions, the number of independent (non-trivial) vectors was 42 and dependent (trivial) vectors was 54 for a total of 96. Results were received from SERCEL for all 96 lines.

Base lines measured ranged in length from about 183 to 1322 m for short base lines, about 7 to 19 km for moderate lengths, and about 35 to 105 km for the longest lengths. All base lines were previously surveyed by precise three-dimensional terrestrial survey methods and all were measured during previous FGCC GPS test surveys conducted on systems that included: Macrometer™ V1000, TI4100, Trimble 4000S and SX, WM-101, and Motorola Eagle. Two-sigma accuracy estimates for the terrestrial relative positional measurements are: horizontal - 2 ppm and vertical - 3 ppm. The 1-sigma base line component uncertainties achieved for the past FGCC GPS relative positional measurements were about $\pm\sqrt{[1\ \text{cm} + (0.1B\cdot(1\text{-to-}2\ \text{ppm}))^2]}$, where B is the base line length in kilometers.

The GPS Mission software offers two methods for combining the carrier phase measurements to develop the double differences. One method is called "chaining" and the other is called "pivoting". Pivoting is the classical and most common approach that involves using a "reference" satellite. In this method, the satellite selected should be one that was continuously observed during the session. In the chaining method, it is characterized by differences PRN_1-PRN_2, PRN_2-PRN_3, ... $PRN_{(n-1)}$-PRN_n. Since FGCC test data were generally different in quality, SERCEL selected the pivoting method. Generally, PRN 6 was selected as the reference satellite for the first session, and PRN 11 for the second and third sessions (Barboux 1988).

The output for the SERCEL GPS Mission base line processing software included: initial coordinates, antenna height offsets, measurement counts, what double differences were formed, integers before and after fixing, which station was held fixed in the solution, results in terms of cartesian and geodetic coordinates referenced to the coordinate system for the orbital data (WGS 84), rms of the fit, and sigmas and correlations for the components.

The complete data set for the test survey was processed during the test week with preliminary solutions made available for analysis and presentation at a public meeting held on Friday, July 1, 1988. Final solutions were provided in August 1988. The observations were processed in the batch mode using the "session" method where data collected simultaneously during each observing session were processed in multiple base line solutions. The predicted (broadcast) satellite orbital coordinate data with an expected accuracy of 1 to 2 ppm, were used in the solutions.

The base line data 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.

As noted earlier, there were several factors that could have had a significant effect on the results. As was predicted, the best results were achieved during the second of three daily observing sessions. The third session yielded results that were fair at best. The first session gave mixed results. All data on the second day were more noisy than any other of the four days. This was attributed to the expected effects of the severe magnetic storm mentioned earlier. Even on the third and fourth days, the data were of poorer quality (i.e. noisier) than the data collected on the first day. However, the results during the second daily session did not seem to be severely impacted by the effects of the magnetic storm. On the other hand, because of the poorer satellite geometry and fewer observations collected during sessions one and three, the effects of the magnetic storm quite likely contributed to the poorer results achieved.

All data were processed with and without recorded meteorological data. In the solutions that did not use the recorded meteorological data, standard atmosphere values were used. Close analysis of the results for the second daily session indicated that use of the measured meteorological data did not appear to improve the results, rather, the results sometimes were significantly degraded. While the differences in the base line lengths were not meaningful, the differences in the vector components were significant. A possible reason the base line results were not improved might have been due to the fact that standardized instrumentation, and calibration and observing procedures were not used.

After an appropriate adjustment for significant systematic differences (due to differences between WGS 84, WGS 72, and NAD 27 coordinate systems), the results, with particular attention given to the second daily session, were evaluated to estimate 1-sigma uncertainties for the base line components. For base line lengths of less than 2 km and data collection periods of about 80 minutes, the estimated 1-sigma uncertainty was 1.0 cm. For lines longer than 2 km, the 1-sigma accuracy estimate for each vector component was about $\pm\sqrt{[1 \text{ cm} + (0.1B \cdot 2.0 \text{ ppm})^2]}$, where B is the base line length in kilometers. The results for sessions one and three were, in general, substantially worse by an estimated factor ranging between 2 to 5.

The results for the second daily session are typical of what one can expect to achieve from double difference integer-fixed or integer-float solutions when using: about 1 hour of observations, good satellite geometry, four or more satellites, accurate time tags for the phase measurements, a point position for the base (fixed) station that is accurately referenced (5-meter level) to GPS orbital coordinate system (e.g. WGS 84), and orbital coordinate data with an estimated accuracy that is 1-2 ppm. The relative positioning accuracies achieved were comparable to results of previous GPS test surveys where the observable was the L_1 carrier phase measurement.

The accuracy for the longer base lines may have been limited by the accuracy of the predicted (broadcast) orbital coordinate data. If the data were reprocessed with the precise ephemerides, the proportional component in the above accuracy estimate could be smaller, provided the results are not significantly influenced by the uncorrected effects of atmospheric (i.e. tropospheric and ionospheric) refraction and satellite geometry.

Clearly, if a different observation strategy had been chosen during the test survey to optimize the quantity and quality of the observations, two sessions rather than one session each day should have given very good results. An optimized observing schedule might have involved deleting the third observing session while lengthening the observing span for the first session to perhaps 100 minutes or so. However, the span during the second session which was observed during an optimal configuration for the satellites could perhaps have been shortened to 50-60 minutes without a significant degradation in the vector results.

To illustrate how the best results ($\pm\sqrt{[1 \text{ cm} + (0.1B \cdot 2.0 \text{ ppm})^2]}$) achieved from the SERCEL NR 52 test survey could meet current defined accuracy standards (FGCC 1988) for connecting control points horizontally and vertically to stations of the National Geodetic Reference System, the table on page seven gives minimum distances between stations for corresponding orders. It can be seen that unless order B or higher is specified, the minimum spacing between adjacent stations is not a factor that must be considered in planning for the location of the stations.

Order:Definition (95% confidence level) (FGCC Ver. 5.0, May 11, 1988)	Minimum spacing (B) between stations to achieve specified order (km)
3I : $\pm\sqrt{[(5\ cm)^2 + (0.1B \cdot 100\ ppm)^2]}$	0
2II: $\pm\sqrt{[(3\ cm)^2 + (0.1B \cdot 50\ ppm)^2]}$	0
2I : $\pm\sqrt{[(2\ cm)^2 + (0.1B \cdot 20\ ppm)^2]}$	0
1 : $\pm\sqrt{[(1\ cm)^2 + (0.1B \cdot 10\ ppm)^2]}$	0
B : $\pm\sqrt{[(0.8\ cm)^2 + (0.1B \cdot 1\ ppm)^2]}$	6

In conclusion, analysis of the results from the FGCC test survey conducted in June 1988 on the SERCEL model NR 52 GPS survey system, carrier phase data (L_1 only) collected on four or more satellites with an acceptable geometric configuration during a period of about 80 minutes and processed with double difference software using orbital coordinate data accurate to 2 ppm or better will yield accuracies that should meet requirements for most control survey needs.

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SUMMARY REPORT ON TEST AND DEMONSTRATION OF THE

MOTOROLA MINI-RANGER GOLDEN EAGLE GPS GEODETIC SYSTEM

AND ASSOCIATED PROCESSING SOFTWARE

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In April 1988, the Federal Geodetic Control Committee (FGCC) conducted a test and demonstration of the Motorola Mini-Ranger Golden Eagle GPS geodetic system, and associated geodetic postprocessing software. This was the seventh in a series of tests of portable satellite survey systems that use radio signals from satellites of the Global Positioning System (GPS).

The Motorola Golden Eagle system is a single-frequency (L_1 only) four parallel channel receiver that operates with the coarse acquisition code (C/A code) to make carrier phase measurements. The receiver collects pseudorange data for point position determination and time-tagging of the carrier phase measurements. Each receiver, as tested, is connected to a laptop personal computer. Software loaded in the computer is used to control the data collection and for recording the data on 3-1/2 inch diskettes. Carrier phase data collected simultaneously with one or more other receivers are processed to determine relative positions between the occupied station points. All test survey data were collected in the static mode of operations (fixed site).

The test was conducted over a period of 5 days from April 4 through 8, 1988. Using four receivers, nine stations of the FGCC test network located in the vicinity of Washington, DC, were occupied. Three sessions (A, B, and C) were observed each day for a total of 15 observing sessions. The observing spans for each session were about 75, 60, and 60 minutes, respectively. Since the A-session began at about 11:00 PM and the C-session ended at about 3:45 AM local time (Eastern Daylight Saving time), all observations were during total darkness. Base lines ranging in length from 186 meters to about 105 km were measured. Six

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of the seven Block I GPS satellites were observed during the test. Satellites observed during sessions A, B, and C were PRN numbers 6-8-9-11, 6-8-11-12, and 9-11-12-13, respectively, except during session C of the first day (day 095) when PRN numbers 8-9-11-12 were observed.

In addition to the vector base line processing program GEOBASE, Motorola's software package (part 98-P20572Y, version B, (C) 1987) contains utilities for compiling satellite visibility tables, position dilution of precision (PDOP) tables, files for initialization of the system in preparation for automatic data collection, and systems testing. The version of software used to control the data collection was configured to record single-differenced phase data (between satellites) with time tags, a single point position (i.e., initial "fix"), and the broadcast (predicted) ephemerides. In computing the differenced phase data, the satellite with the lowest PRN is used as reference. The raw undifferenced phase measurements and pseudo-range data were not recorded.

GEOBASE, the vector base line solution software, uses the triple differencing method for processing the recorded "differenced" carrier phase data in a "single" base line mode with the broadcast ephemerides. For the fixed position, the point position, or "fix", determined at the start of the data collection is used. The accuracy of the point position is dependent on how good the geometric configuration of the satellites (i.e., low PDOP) is at the time the "fix" was computed. Since the pseudorange data were not recorded, it was not possible to improve the accuracy of the point position used in the base line solution.

Within a few hours after the end of each day's observing sessions, all data were processed to obtain preliminary solutions. These results were made available for analysis and presentation at a public meeting held on Friday, April 8, 1988. In operating the software, it was found to be very simple to use. Using the pull-down menus, it is possible to operate the software with very little need to refer to a manual or set of guidelines. After a small amount of time is spent in compiling the data files, GEOBASE is started and thereafter, computations are performed with essentially no interaction required (typical for the triple differencing base line processing technique).

Overall, the Motorola Eagle receivers, including the data loggers (Zenith personal computer laptops), operated with no hardware related problems. Nor were there any significant power supply problems. The only data loss during the test were due to an operator's error when the wrong initialization file was used for all three sessions of a station-occupation. Thus, of 60 station-session-occupations attempted, only 3 were unsuccessful. The total number of base line measurements attempted (trivial and non-trivial) was 90; of these, results were provided by Motorola for 81 base lines, where the 9 missing base lines were due to the operator's error.

The base line data 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. Accuracy estimates were determined after adjusting for systematic differences.

The most accurate and consistent results from the test survey data came from the 27 vector base lines measured during the B session. The results achieved were consistent with what could be expected when a triple differencing processing method is used to process about an hour's worth of data with the broadcast ephemerides. Good satellite geometry, as would be reflected in low PDOP values, is required when attempting to obtain on-site (i.e., near-real-time) accurate estimates for the phase time tags and point position.

The B sessions were characterized by very good satellite geometry throughout most of the observing period. The PDOP values were generally within Motorola's recommended range of 4 to 6. In contrast with the B session, the A and C sessions produced substantially poorer results. This was because the PDOP values, particularly at the start of the session, were much higher (i.e., poor satellite geometric configuration) than recommended for reliable on-site estimates for the time tags and the point position. At the start of the A and C sessions, the PDOP values were typically in the 20 to over 100 range.

Since the pseudorange data were not recorded, it was not possible to recompute the point position and revise the phase data time tags. Thus, to provide a fair evaluation of the hardware independent of the acquisition software characteristics, the results given in this summary report are based solely on the B-session data. The results for the A and C sessions will be included in the full report.

The results of the test showed that when Eagle carrier phase measurements are collected during recommended PDOP conditions and processed with "triple differencing" software using the broadcast ephemerides, relative positioning accuracies were consistent with Motorola's specifications. When data are collected for about 60 minutes over base line lengths of less than 1 km, the estimated 1-sigma accuracy for each base line component is about 1 cm. For lines longer than about 1 km, the 1-sigma accuracy in centimeters for each vector base line component was about $\pm\sqrt{[(1\ \text{cm})^2 + (0.1B \cdot 3\ \text{ppm})^2]}$, where B is the base line length in kilometers. These accuracy estimates are typical of what can be expected from triple difference solutions using at least 1 hour of observations when accurate time tags for the phase measurements and an accurate point position are available for use in the base line solutions.

Trees, buildings, and nearby power transmission lines at some of the FGCC test stations sites may have affected the results of the test survey. These were the same conditions that could have had a negative impact on previous test surveys. Furthermore, these were conditions which sometimes characterize the situation at operational GPS survey stations. Thus, it is important in the design of GPS survey instruments and processing software that appropriate features are available to deal effectively with such problems.

In conclusion, provided observing sessions are started with PDOP values that are within the range specified by the manufacturer, it was demonstrated that these data processed with triple difference software will yield results that are within the manufacturer's specifications (order 1). However, as found with the April 1988 test data, reliable results will not be achieved when sessions are started with poor PDOP values. Thus, when using the Eagle survey system with the April 1988 acquisition software, there is the following limitation. To obtain base line measurements with the specified accuracy, select observing periods that offers four satellites with starting PDOP values that are within the recommended range of 4 to 6. This will ensure an optimal point position determination and accurate time tags for the phase measurements.

Finally, depending on location of the survey team and other logistical constraints, Eagle system users may find that the present Block I GPS satellite configuration offers only a single opportunity each day to collect valid data. However, as the number of satellites in the GPS constellation are increased with deployment of the Block II satellites, this limitation will be of less importance. In the meantime, when the Eagle survey system is used to connect points to stations of the National Geodetic Reference System, the results should meet standards for the lower orders of accuracy (i.e. order 1 or less).

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SUMMARY REPORT ON TEST AND DEMONSTRATION OF THE

WM101 GPS SATELLITE SURVEYING SYSTEM

AND ASSOCIATED PROCESSING SOFTWARE

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August 11, 1989

In January 1987, the Federal Geodetic Control Committee (FGCC) conducted a test and demonstration of the Wild-Magnavox (WM) Satellite Survey Company's model WM101 satellite survey system and associated postprocessing software. This was the sixth in a series of tests of portable satellite survey systems that use radio signals from satellites of the Global Positioning System (GPS).

The WM101 is a single-frequency (L_1 only) system with four independent code correlation channels that operates with the coarse acquisition code (C/A code) to make phase measurements of the reconstructed carrier signals. Three of the four independent channels are sequenced so that up to six satellites can be tracked. The receiver collects pseudorange data that are processed with the broadcast (predicted) satellite coordinates to determine in real-time point positions and time-tags for the carrier phase measurements. The briefcase style receiver unit which weighs about 32 lbs (14.5 kg) contains a processor, control panel, display unit, and a digital tape cassette reader/recorder. The recording unit is used to record both raw satellite data and internally computed position results.

Power for the WM101 is supplied by an internal, rechargeable, nickel cadmium battery pack or by an external source. The internal battery pack is rated to supply power for 4 hours. The remaining major component of the WM101 system is the antenna which can be mounted on a standard tripod. The 2.75 lb (1.2 kg)

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volute antenna with a height of about 7.1 in. (0.18 m) and maximum horizontal width of 8.3 in. (0.21 m) receives the 1575.42 MHz L_1 signal which is passed to an internal preamplifier and then sent via cable to the receiver/processing unit.

Carrier phase data collected simultaneously with one or more other receivers are processed to determine relative positions between the occupied station points. All test survey data were collected in the static mode of operations (fixed site).

The test was conducted over a period of 4 days from January 26 through 29, 1987, where 5, 7, 8, and 5 receivers were used during each observing day, respectively. Twelve stations of the FGCC test network located in the vicinity of Washington, DC, were occupied. Each observing day consisted of a single session where the scheduled observing period was about 3.5 hours. The approximate starting and ending time for each session were 08:30 UTC (3:30 AM local time) and 12:00 UTC (7:00 AM local time), respectively. Thus, all observations were during total darkness.

Base lines ranging in length from about 9 meters to about 105 km were measured. Six of the seven Block I GPS satellites (PRN numbers 6, 8, 9, 11, 12, and 13) were observed during the test.

Wild-Magnavox's software, called PoPS™ (Post Processing Software), is designed to process carrier phase data collected simultaneously from as many as 10 stations. PoPS™ operates on a personal computer (e.g., PC XT, AT, or 386 system) to compute coordinate differences between station points. The software includes a data base management system and automated data screening facilities. The PoPS™ software (version 1.04) used to process the data was the version that was being used operationally in February 1987. That version is presently superseded by version 2.02. All observations were processed with the predicted satellite orbit data incorporated in the broadcast message.

PoPS™ uses the double-difference method for processing the carrier phase observations to compute relative positions. Included in the preprocessing step is a subroutine designed to perform automatic cycle-slip detection and a user interface for interactive data editing. The output consists of cartesian coordinates in the GPS coordinate system (i.e., World Geodetic System 1984), ambiguity values and clock corrections (if resolved), and residuals of the double-difference observations.

All data were processed during the test week with preliminary solutions made available for analysis and presentation at a public meeting held on Thursday, January 29, 1987. A second set of solutions, with a minor improvement in results, was provided later.

During the test survey, there was one hardware related problem that caused a complete loss of observations. This occurred during observing day 2. Portions of other data sets were also lost due to minor power supply problems. Adequate power supply was of particular concern on the first day because there were only a few hours between when the equipment finally arrived at the airport for pickup and before it was transported to the observing stations. During this short period of time for the presurvey preparations, it was not possible to ensure all batteries were adequately charged in preparation for the first observing day.

During the first observing session, the observations were carried out while a severe winter snow storm was underway. Although the blizzard conditions were a problem for the observers, the receivers at all stations were operated while sitting in the snow with outside temperatures ranging as low as about 20°F (-7°C). Three of the five operating units failed to collect the complete 3.5 hour data set because the battery supply was exhausted before the end of session. During the next three observing days, temperatures during the sessions ranged as low as -17° F (-27° C). Before sessions began on days 2, 3, and 4, extra precautions were taken to ensure the batteries were fully charged. Thus, no significant amount of data was lost due to power failure on test days 2, 3, and 4.

Other than some data lost at a few of the stations due to masking by obstructions, no other significant problems were experienced during the data collection.

Of 26 station-session-occupations scheduled, only 1 was unsuccessful. The total number of base line measurements attempted (trivial and non-trivial) was 76; of these, results were received from WM for 69 base lines, where the 7 missing base lines were due to the hardware failure on day 2.

The data set for each observing session was subdivided into approximately two 60-minute subsets which then doubled the total possible number of base lines to 138. Of the 138 base lines, WM provided solutions for 124 vectors (90%). Those base line results which were not received were from a sub-session containing data for a period that was too short for a reliable solution.

The base line data 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.

The results of the test showed that WM101 carrier phase measurements processed with double differencing software using the broadcast (predicted) ephemerides would give relative positioning accuracies that were well within WM's specifications of 1 cm + 2 ppm (2 sigma). These estimates were determined after adjusting for systematic differences.

The comparisons were evaluated to determine 1-sigma accuracy estimates for the base line components. For base line lengths of less than 2 km and data collection periods of 50 minutes or more, the 1-sigma accuracy estimate was 1 cm. For lines longer than 2 km, the 1-sigma accuracy estimate for each base line component was about $\pm$ $[(1\ \text{cm})^2 + (0.1d \cdot 1.0\ \text{ppm})^2]$, where d is the base line length in kilometers. These accuracy estimates are typical of what can be expected from double difference solutions using at least 1 hour of observations. To ensure these accuracies are achievable, the time tags for the phase measurements and the point position for the base station used in the base line solutions must have been accurately determined.

The accuracy for the longer base lines are affected by the accuracy of the predicted (broadcast) orbital coordinate data. If the data were reprocessed with the precise ephemerides, it is expected the proportional component in the above accuracy estimate would be smaller.

Trees, buildings, and nearby power transmission lines at some of the FGCC test stations sites may have affected the results of the test survey. These were the same conditions that could have had a negative impact on previous test surveys. Furthermore, these were conditions which sometimes characterize the situation at operational GPS survey stations. Thus, it is important in the design of GPS survey instruments and processing software that it be capable of dealing with such problems as effectively as possible.

In conclusion, the results achieved from the WM101 test survey data were well within the manufacturer's specifications. The test results demonstrated that for sessions of about 60 to 180 minutes, the carrier phase data can be processed with double difference software to yield very good accuracies for the relative positioning measurements. The accuracies of these measurements should meet accuracy standards for most "dependent" surveys that involve connection of control points relative to stations of the National Geodetic Reference System.

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SUMMARY REPORT
on
TEST AND DEMONSTRATION
ON THE

TRIMBLE 4000SX SATELLITE SURVEY SYSTEM

AND
ASSOCIATED PROCESSING SOFTWARE

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January 1988

The test was conducted over a 3-day period in November 1986. Seven to nine receivers were operated simultaneously on stations of the FGCC test network located in the Washington, DC area. The 10-station network has base lines ranging in length from 186 m to 105 km. Two observing sessions with a span of 120 to 175 minutes were scheduled each day for a total of six sessions. Generally, the sessions were successfully observed. No significant data losses occurred due to 4000SX hardware problems. However, several sessions were either unsuccessfully observed or only a partial data set was obtained due to power supply or cable problems related to the data collectors (Kaypro 2000 or Grid laptop computers).

Approximately 40 independent (non-trivial) base lines were measured. There was one other significant problem external to the hardware that had a negative influence on obtaining optimal results. This problem, which effected the data only during the first session each day, was caused by a malfunction of NAVSTAR GPS satellite SV 8. The satellite malfunction was characterized by an unstable reference frequency which effected the accuracy of clock offset determinations. However, it was possible to circumvent this problem by processing simultaneous data sets with time spans of 90 minutes or more and deleting SV 8 from these solutions. In these solutions, the results were comparable to those obtained from the second session of each observing day.

The results of the test showed that the 4000SX met or exceeded the test accuracy objectives of ±(1 cm + 2 ppm) (one-sigma). Carrier phase measurement data sets of 1-2 hours duration processed with the TRIMVEC software in the single base line mode produced relative positioning measurements with one-sigma "base" uncertainties in each base line component (dX,dY,dZ) of less than 1 cm plus a

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"line-length" dependent uncertainty of about 1 ppm. Most of the error sources found in the "base" uncertainties occurred mostly during antenna setup (centering and height measurement errors). But also, it is expected there were significant error contributions in some of the data sets due to antenna phase center variations and signal multipath effects.

Most of the "line-length" dependent uncertainty was caused by error in the broadcast (predicted) orbit used in the data processing. There may have also been some significant error contributed by uncorrected effects of the ionospheric refraction on the signal. Because the 4000SX is only a single frequency (L1) receiver, corrections for the ionospheric refraction were not computed.

The special 4000SL data set, which had been collected simultaneously with 4000SX receivers by Trimble Navigation, was also processed with TRIMVEC software. The 4000SL results were compatible with those obtain from the 4000SX systems. No significant differences at the ±(1 cm + 2 ppm) level were found.

In conclusion, the Trimble 4000SX and 4000SL systems are considered to be viable geodetic satellite survey systems capable of meeting accuracy standards for a wide range of land and engineering surveying requirements. Survey data sets observed simultaneously an hour or more that includes observations of four or more 'healthy' satellites and processed with the broadcast (predicted) orbital data should meet or exceed the one-signa geometric accuracy of ±(1 cm + 2 ppm). The ppm (parts-per-million) component is limited primarily by the accuracy of the orbital data.

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SUMMARY REPORT
ON
TEST AND DEMONSTRATION
OF THE

ISTAC SERIES GPS POSITIONER MODEL 2002

AND
ASSOCIATED PROCESSING SOFTWARE

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September 8, 1989

In June 1986, the Federal Geodetic Control Committee (FGCC) conducted a test and demonstration of the ISTAC (International SERIES Technology Applications Corporation) SERIES (Satellite Emission Range Inferred Earth Surveying) GPS Positioner Model 2002 satellite survey system and associated processing software. This was the fourth in a series of tests of portable satellite survey systems that use radio signals from satellites of the Global Positioning System (GPS). Also, it was the second "codeless" system to be tested, the first being the Macrometer™ model V1000 in January 1983 (Hothem and Fronczek 1983).

The ISTAC model 2002 is a single frequency codeless system that operates independent of any knowledge of either the C/A (course/acquisition) code or P (precise) code transmissions. It incorporates simultaneous multiple satellite signal reception of all visible satellites with up to 35 software-assignable channels available. Because the system cannot decode the GPS signals, satellite orbital coordinate and timing data must be obtained from alternate sources. By processing of the phase measurements made on either the L_1-band C/A or P channel signals in a codeless mode, three-dimensional relative positional coordinates can be determined.

The ISTAC 2002 system with a combined weight of about 32 kg (70 lbs), consists of a three-piece configuration including an antenna/receiver (A/R) unit, a battery powered clock interface unit (CIU), and a lap-portable data analyzer/recorder (DA/R). The operating temperature is 0 to 50°C (32 to 122°F) (Whitcomb 1986).

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The A/R unit, weighing 7 kg (15 lbs) and housed in a 23 cm (9 in) high, 42 cm (17 in) diameter, weather-tight dielectric beam-shaping case, mounts on a standard tripod. The antenna is a flat microstrip configuration tuned for 1575.4 MHz. The signal from the antenna is fed to an amplifier, a double conversion receiver, and a codeless, spectral-compression processor that operates without knowledge of the satellite orbits. The compressed spectral output of the A/R unit is an 80 Hz baseband analog signal that contains all the positioning physics from the C/A and P-code modulations.

The CIU, housed in a 28 x 26 x 42 cm (11 x 10 x 17 in) weather-tight case weighing 18 kg (40 lbs), contains a rubidium frequency reference standard, self-testing features, signal-conditioning and timing electronics. Battery power is provided by the CIU for up to 8 hours for the entire 2002 system. The power supply includes a 100 to 240 VAC battery charger and batteries.

The DA/R unit is a battery-powered laptype PC compatible computer that performs in-the-field real-time data quality analysis, individual satellite identification, and data recording. Combined with a weather-tight 46 x 33 x 13 cm (18 x 13 x 5 in) briefcase, the DA/R weighs about 7 kg (15 lbs). The laptype computer with a 3 1/2 inch diskette (730 kb) has a capacity for storing about 6 1/2 hours of data (based on four-satellite data sets). The DA/R computer can also be used as a field-office computer for preliminary base line processing.

Operation of the ISTAC 2002 is relatively easy. Synchronization of the clocks is optional as the associated processing software is capable of solving for the absolute time and clock offset between receivers. Once the system is setup at the observing station, the 2002 can be turned on, time set by wrist watch, and data acquisition begun within 4 minutes. However, to ensure reliable achievement of the specified accuracies, elimination of the absolute time and clock offset parameters as unknowns by synchronization of the CIU's with an accurate external time standard is recommended (ISTAC 1986).

The minimum number of satellites required for effective base line solutions is four. All must be above the antenna/receiver's effective reception region of about 20° above the horizon. Because the receivers do not use the code, satellites are distinguished by use of the induced Doppler shift of the transmitted signals. For proper operation during the DA/R processing, differences in the Doppler-shifted frequency must be sufficient to avoid conflicts. Typically, the station sites should be relatively free of trees, buildings, or other obstructions that might block the satellite signals. The manufacturer also indicates that system performance may be affected if the A/R unit is located near (less than 20 m) metal or dense objects such as poles, fences, buildings, etc.

During the field observing session, the DA/R software processes in real-time the data received from the CIU to display the identification of all satellites visible in the sky, the signal-to-noise ratio for each satellite, and the time-tagged doppler shift and phase for both C/A and P channels. This information, which is recorded, is used as an instantaneous field verifier of the total system operational health. Another function of the DA/R software is to produce satellite visibility and Geometrical Dilution of Precision (GDOP) tables.

All GPS satellites transmit on the same two L-band center frequencies: L_1 at 1575.42 MHz and L_2 at 1227.6 MHz. The L_1 carrier signal is modulated by two pseudo-random noise codes: a 10.23 MHz clock rate "P-code" signal and a 1.023 MHz "C/A-code" signal. The P-code modulation has a wavelength of 29.3 m compared to the L_1 carrier wavelength of 0.19 m. Consequently, the technical problem of solving for the correct integer cycle, i.e. ambiguity resolution, can be done easier and more reliably for the 29.3 m signal wavelength then for the 0.19 m carrier wavelength. However, there is a tradeoff in potential accuracy for the vector base line solutions.

Using 1% as the general rule-of-thumb for estimating phase measurement uncertainty (system measurement capability), the uncertainty associated with each P-code signal phase measurement is 29 cm compared to the L_1 carrier phase measurement of only 1.9 mm. Thus, P-code signal phase measurements have about 153 times less precision than the L_1 carrier phase measurements. Consequently, it can be expected the "base" errors will be substantially greater for base line results derived from P-code signal phase data then when compared to results achieved from L_1 carrier phase observations.

In addition to the P-code signal phase measurement "base" error associated with system capability, systematic errors, possibly multipath induced, may have been significant in some base line measurements and contributed to base error of 5 to 15 cm. Furthermore, the base error uncertainty reflects instrument performance combined with error associated with antenna/receiver setup over the station marks. The base error is independent of line-length dependent error sources due to factors such as orbital coordinates (ephemerides) uncertainty and atmospheric refraction effects.

In the post-processing step for the ISTAC 2002 DA/R software, the recorded data is evaluated by spectral analysis techniques to extract time dependent amplitude, phase and frequency for each GPS satellite observed. The initial cycle count or ambiguity resolution for each satellite is uniquely resolved within 100 seconds of data acquisition initiation (Whitcomb 1986). These P-code phase measurements are then differenced to remove or minimize clock offset and distance dependent uncertainties (i.e. correlated effects of atmospheric and satellite orbital errors).

Since the 2002 is a codeless system, information on the broadcast (predicted) ephemerides (BE) is not available from the observation data. The BE data, or alternatively, the precise ephemerides (PE), must be obtained from an independent source. Once either the BE or PE data are available, the DA/R software is used to solve 3-D relative positions from the frequency and phase measurements for each satellite extracted from the compressed spectral output of the CIU. Because the 2002 is an L_1 only system, it was not possible in this test to extract directly the ionospheric delay data, thus in the base line processing there was no correction applied for the effects of ionospheric refraction.

As specified by the manufacturer, when given reasonable satellite geometry (GDOP<5), the estimated overall accuracies (1-sigma) for the ISTAC 2002 survey system are (Whitcomb 1986): 100-second observations yield sub-meter accuracies; 15-minute observations yields 8 cm horizontal, 10 cm vertical, and 3 cm length;

and, 60-minute observations yields 5 cm horizontal, 7 cm vertical, and 2 cm length. These accuracies are generalized since for a particular base line length, the total uncertainty requires taking the root square sum (RSS) of the base error (i.e. system uncertainty) and distance dependent uncertainty. When the distance-dependent uncertainty contribution is better than 2 ppm, the above estimates are reasonable. For this test, the dominant distance-dependent uncertainty source was the orbital data which was estimated to be 2 ppm or better.

The test was conducted over a period of 5 days from June 16 through 20, 1986, (dates based on local time) with three 60-minute observing sessions scheduled each day. Nine stations of the FGCC test network located in the vicinity of Washington, DC, were occupied. It was planned to use four receivers each day, however, on the first observing day only three systems were used because one system had a A/R unit that was not properly configured. The problem with the A/R unit was corrected before the start of the second observing day. The approximate starting time for the first session and ending time for the last session were 22:20 UTC (6:20 PM local time) and 3:00 UTC (11:00 PM local time), respectively. Thus, the observations started during daylight and ended during total darkness (session A during daylight, session B during dusk, and session C during darkness).

Base lines measured ranged in length from about 183 to 1322 m for short base lines, about 7 to 19 km for moderated lengths, and about 35 to 105 km for the longest lengths. All base lines were previously surveyed three-dimensionally by precise terrestrial survey methods and the TI-4100 GPS satellite survey system (December 1985). Also, a portion of the lines were measured in January 1983 with the Macrometer™ model V1000 and in February 1986 with the Trimble model 4000S. Two-sigma accuracy estimates for the terrestrial relative positional measurements are: horizontal - 2 ppm and vertical - 3 ppm. The 1-sigma uncertainties achieved for the past FGCC GPS relative positional measurements were about $\pm\sqrt{[1 \text{ cm} + (0.1d \cdot (1\text{-to-}2 \text{ ppm}))^2]}$, where d is the base line length in kilometers.

All seven Block I GPS satellites available in June 1986 (PRN numbers 3, 6, 8, 9, 11, 12, and 13) were observed during the test. For each individual session, the PRN numbers represented in the data sets included: A-3,6,8,11, B-6,8,9,11,13, and C-6,8,9,11,12,13. The range of GDOP values for each session A, B, and C, were: 4.1 to 4.6, 4.9 to 6.8, and 3.2 to 3.8, respectively. Consequently, session C was expected to yield the best results.

All observations were processed in the single base line mode with the predicted satellite orbit data that is incorporated in the broadcast message. These BE data were obtain from an independent source.

The output of the ISTAC base line processing software consists for each base line, cartesian coordinates in the GPS coordinate system (i.e., World Geodetic System 1972), geodetic coordinates (latitude, longitude, and ellipsoid height) referenced to North American Datum 1927, cartesian coordinate differences, base line azimuth, and ellipsoidal height differences. Additionally, displayed in the output are the height of antenna measurements, and cartesian coordinate difference error and correlation estimates.

On Friday morning, June 20, 1986, a public forum was held to discuss the results for the preliminary solutions based on observations obtained from the first four days of the five-day test period. Solutions for about one-half of the observed data were available for evaluation. In this report, the test results were based on evaluation of a final set of solutions provided on January 16, 1987.

Of 60 station-session-occupations scheduled, only 3 were not observed, which as mentioned earlier, occurred during the first observing day. The number of possible single base line solutions for each observing session in the 3-receiver operation is 3; for the 4-receiver operation it is 6. Therefore, the total number of base lines (independent [non-trivial] and dependent [trivial]) observed was 81. Of the 81 possible single base line solutions, 42 (52%) were received from ISTAC (MacDoran 1987). Those not provided could not be processed due to: bad satellite geometry - 19; unresolved clock jump while occupying station ATHY during observing sessions 168C and 169A - 9; and, base line solutions based on a data set that combined session B with data for session C - 11 (Whitcomb 1987).

Although GDOP was somewhat higher for session B compared to the other sessions, it was still within tolerable limits. However, it was reported that the ISTAC GDOP integration software predicted unstable results for the 60-minute period of session B (Whitcomb 1987). The poorer results were predicted due to bunching of PRN 12 and PRN 13 in the same NW part of the sky. Session A was also predicted to yield results poorer than for session C because of the bunching of PRN 6, 9 and 11 in the same WNW part of the sky.

In comparing the predicted integrated GDOP accuracies from the 60-minute session C data set with a following session that was 120 minutes long indicated an accuracy that was about 2 times better than what was expected for session C. To obtain results equivalent to what was expected for session C, data for session A were concatenated with data for session B for 7 of the 42 submitted base lines. In other cases, since it was not possible to obtain reliable results by any optimal strategy, the sessions were not processed.

Trees, buildings, and nearby power transmission lines at some of the FGCC test stations sites may have affected the results of the test survey. Although, these were the same conditions that could have had a negative impact on previous test surveys, they are factors which frequently characterize the situation at operational GPS survey stations. Thus, these factors are considered important in the FGCC tests to determine the effectiveness or capability of the GPS survey instruments and processing software to deal with such problems.

Other than some data lost at a few of the stations due to masking by obstructions, an unexplained clock jump for one of the systems during the second day of observing sessions, no other significant problems were experienced during the data collection.

In regards to aspects of processing phase measurement data, it should be noted that while the initial cycle determination (i.e. ambiguity resolution) for the ISTAC 2002 phase measurements is obtained by a relatively simple process because the P-code signal is used (29.2 m wavelength vs. 19.2 cm wavelength for the L_1 carrier), in all FGCC tests, manufacturers of L_1 carrier phase measurement systems are required to demonstrate their processing software is capable of making reliable ambiguity resolutions. This is done by demonstrating that base lines can be accurately determined using for initial station coordinate estimates the pseudo-range point position solutions. Generally the accuracy for the pseudo-range point positions is 5 to 20 meters (25 to 100 times the L_1 carrier wavelength of 19.2 cm).

Another aspect that may affect accuracy of base line solutions is the length of the observing session used in the base line solutions. In past FGCC tests of GPS survey systems, base line vectors have been determined from spans ranging from as few as 18 minutes (e.g. the TI4100 system test) to as long as about 3 hours. In the ISTAC 2002 data reduction, the data spanned periods ranging from about 60 to 120 minutes.

The base line data 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.

After an appropriate adjustment for significant systematic differences, the comparisons were evaluated to estimate 1-sigma uncertainties for the base line components. For base line lengths of less than 2 km and data collection periods of 60 to 120 minutes, the estimated 1-sigma uncertainty was about 5-8 cm. For lines longer than 2 km, the 1-sigma accuracy estimate for each base line component was about $\pm\sqrt{[(5\text{-}8 \text{ cm})^2 + (0.1B \cdot 2.0 \text{ ppm})^2]}$, where B is the base line length in kilometers. In terms of length, azimuth, ellipsoid height differences, at the 68% (1-sigma) confidence level, the estimates were:

Length: $\pm\sqrt{[(5 \text{ cm})^2 + (0.1d \cdot 1.5 \text{ ppm})^2]}$,

Azimuth: $\pm\sqrt{[(5 \text{ cm})^2 + (0.1d \cdot 1.5 \text{ ppm})^2]}$,

Ellipsoid Height Difference: $\pm\sqrt{[(8 \text{ cm})^2 + (0.1d \cdot 1.5 \text{ ppm})^2]}$

The accuracy for the longer base lines are affected by the accuracy of the orbital coordinate data. If the data were reprocessed with the precise ephemerides, it is likely the distance-dependent component would be smaller in the above estimates for the length and azimuth of a base line. However, because of less than optimal satellite geometry, it is not expected the accuracy for the height difference would improve.

The results achieved from the ISTAC 2002 test survey data were in reasonable agreement with the manufacturer's specifications for 60-minute data sets and GDOP values of less than 5, cited earlier in this report. The only significant difference was the base error (system uncertainty) estimate for base line length. ISTAC's 2 cm (1-sigma) estimate is considered too optimistic. To illustrate how the results achieved from the ISTAC 2002 test survey would meet current defined accuracy standards (FGCC 1988) for connecting control points horizontally and vertically to stations of the National Geodetic Reference System, the table on page 7 gives minimum distances between stations for corresponding orders. It can be seen that for all orders, the minimum spacing between adjacent stations is a factor that must be considered in planning for the location of the stations.

Order:Definition (95% confidence level) (FGCC Ver. 5.0, May 11, 1988)	Minimum spacing (d)	
	For horizontal ties (km)	For vertical ties (km)
1 : $\pm\sqrt{[(1\ cm)^2 + (0.1d \cdot 10\ ppm)^2]}$	10	18
2I : $\pm\sqrt{[(2\ cm)^2 + (0.1d \cdot 20\ ppm)^2]}$	5.0	8
2II: $\pm\sqrt{[(3\ cm)^2 + (0.1d \cdot 50\ ppm)^2]}$	1.9	3.0
3I : $\pm\sqrt{[(5\ cm)^2 + (0.1d \cdot 100\ ppm)^2]}$	0.8	1.5

In conclusion, analysis of the results from the FGCC test survey conducted in June 1986 on the ISTAC 2002 GPS Positioner survey system, data (L_1 only) collected on four or more satellites with an acceptable geometric configuration during a period of 1 to 2 hours and processed with orbital coordinate data accurate to 2 ppm or better should yield accuracies that would satisfy low accuracy control requirement provided the spacing between adjacent stations is greater than the minimum allowable distances given in the table above.

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FGCC Federal Geodetic Control Committee

SUMMARY REPORT ON TEST AND DEMONSTRATION OF THE

TRIMBLE 4000S SATELLITE SURVEY SYSTEM

AND ASSOCIATED PROCESSING SOFTWARE

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October 1986

In February 1986, the Federal Geodetic Control Committee (FGCC) conducted a test and demonstration of the Trimble Navigation 4000S GPS Surveyor satellite survey system and associated geodetic postprocessing software. This was the third in a series of tests of portable satellite survey systems that use radio signals from satellites of the Global Positioning System (GPS).

The Trimble 4000S system is a single-frequency receiver that operates with the Course Acquisition Code (C/A Code) or Standard Positioning Service (SPS). The model 4000S system features include carrier phase tracking, continuous and simultaneous tracking of up to 4 satellites (independent channels, parallel tracking), and automatic search and acquisition. Carrier phase measurements acquired by the 4000S can be processed to determine three-dimensional relative positions between survey stations. Although it is possible to use the 4000S code phase observations to determine point positions, only relative position determinations (based on carrier phase observations) were evaluated in this test. All test survey data were collected in the static mode of operations (fixed site).

During the six-day test period, February 24 through March 1, 1986, four Trimble 4000S receivers were used to occupy eight stations of the FGCC 3-D test network located in vicinity of Washington, DC. Base lines ranging in length from 186 meters to about 105 km were measured. Seven GPS satellites were available during the test.

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Three observing sessions (A, B, and C) were scheduled each of the six observing days. The satellites observed during each session were Space Vehicle (SV) numbers 3-6-8-11, 6-8-9-11, and 9-11-12-13, respectively.

The test objectives included evaluating the operation of the 4000S system and establishing whether the carrier phase data collected were of sufficient quality to produce relative positioning surveys results that would meet or exceed accuracy standards for acceptance into the National Geodetic Reference System.

From the four-satellite simultaneous carrier phase measurements, relative positions between stations of the test network were determined with single base line processing software TRIMVEC™. TRIMVEC™ software incorporates the double-differencing processing technique to compute vector base lines using the broadcast (predicted) ephemerides. The on-site processing of the data during the week of the test was open to the public. Preliminary results for a portion of the base lines measured were presented at a public meeting on Friday afternoon, February 28, 1986.

Overall, the Trimble 4000S receiver hardware, including the data loggers, functioned very well. Hardware related problems that did occur were due to insufficient battery supply. However, the percent of data lost due to battery failures was not significant.

Unfortunately, there was a non-hardware problem that occurred during the test that did have an impact on the quality of the data. The version of the 4000S firmware used during the test that controls the data collection operation, incorporates a control loop that corrects the oscillator frequency based on frequency measurements of the satellites. This firmware version was installed just before the test began. It was found that the firmware could not handle properly excessive phase noise problems caused by a malfunctioning clock system aboard GPS satellite SV 11. The SV 11 signal was used as the primary satellite to control the receiver's oscillator. Because of the SV 11 problem, the controlling signal for the receiver oscillator was highly unstable. The rapid change in oscillator frequency result in degraded tracking characteristics (frequent cycle slips) on all channels at various times.

Although the SV-11 problem affected the quality of the data, the base line software was able to effectively handle the frequent cycle slips well enough to produce very good results for most of the base lines observed. Of the 72 station-occupation or station-session data sets that were scheduled to be collected, only two were lost due to battery supply failures. Of the 70 remaining data sets, approximately 20 data sets have not been processed successfully because of excessive number of cycle slips. Of the data sets processed successfully, some had over 50 cycle slips. Most had at least 10 cycle slips.

Since the test was conducted, the status of satellite SV 11 has returned to normal operation (mid-May 1986) and Trimble firmware has been upgraded to handle correctly any satellites known to have excessive phase noise problems. No other significant problems were experienced during the test.

The base line data were evaluated by comparison of repeat measurements, analysis of loop misclosure computations, and by comparison with the coordinates of the test network previously determined by precise terrestrial survey methods. All analyses were based on defining the base line vectors in terms of the three-dimensional components of height differences, length, and azimuth.

The results of the test showed that even though the Trimble 4000S carrier phase measurements were not of optimum quality at all times, satisfactory results could be achieved with the TRIMVEC™ software using the broadcast ephemerides.

The relative positioning accuracy estimates (1-sigma) for baseline lengths of less than 2 km and data collection periods of about one hour were, in terms of length, azimuth and height differences, about 5 mm, 0.5 arc second, and 10 mm, respectively. For base line lengths of 2 to 45 km and similar data collection periods, the 1-sigma relative positioning accuracy estimates for length, azimuth, and height differences were 5 mm + 2 ppm, 0.2 arc second, and 10 mm + 4 ppm, respectively. It appeared that comparable accuracies were achieved for the few base line lengths of 45 to 105 km that could be computed. However, since most of the 45 to 105 km lines could not be processed successfully, the accuracy estimates for these length lines are tentative.

Trees, buildings, and nearby power transmission lines at some of the FGCC test station sites may have affected the results of the test survey. However, since these are conditions which may be typical at many proposed GPS survey stations, the GPS survey instrumentation and processing software should be capable of handling such potential problems.

In summary, although the data collected with the Trimble 4000S survey system during the FGCC test were of lesser quality than expected at times, it was still possible to obtain results that indicated that the 4000S system and associated relative positioning software is a viable relative positioning survey system. It was demonstrated that the 4000S system can be used successfully to establish coordinates for points that will satisfy most accuracy standards specified. The results also indicated that when optimal quality data are collected, the system has the potential for yielding accuracies consistent with other test results obtained on the FGCC test network with single frequency carrier phase GPS satellite survey systems.

ADDENDUM

An enhanced Trimble GPS satellite survey system, known as the model 4000SX, will be tested in November 1986. This system features one to five channels of simultaneous tracking, a micro-strip antenna for reduced multipath sensitivity, and more automated data logging capabilities.

Federal Geodetic Control Committee

SUMMARY REPORT
ON
TEST AND DEMONSTRATION
OF THE

TI4100 GPS NAVIGATOR SATELLITE SURVEY SYSTEM

AND
ASSOCIATED PROCESSING SOFTWARE

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July 1986

In December 1985, the Federal Geodetic Control Committee (FGCC) conducted a test and demonstration of the Texas Instruments (TI) model TI4100 GPS Navigator survey system, and associated geodetic postprocessing software. This was the second in a series of tests of portable satellite survey systems that use radio signals from satellites of the Global Positioning System (GPS).

The TI4100 system is a dual-frequency multiplexed four-satellite receiver that operates with the Precise Code (P-Code). If the P-code is not available it can use the Course Acquisition Code (C/A Code) in a single-frequency mode of operations. Carrier phase measurements acquired from the TI4100 observations can be processed to determine three-dimensional relative positions between survey stations. Although it is possible from the TI4100 observations to determine point positions, only relative positioning capability was evaluated in this test. All test survey data were collected in the static mode of operations (fixed site).

During the five-day test period, December 2-6, 1985, five TI4100 receivers were used to occupy ten stations of the FGCC 3-D test network located in the vicinity of Washington, DC. Base lines ranging in length from 186 meters to about 105 km were measured. Seven GPS satellites were available during the test. There were three observing sessions each of the first four days with observing spans

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of 60, 115, and 30 minutes, respectively, and one observing session of 120 minutes on the last day of the test.

In addition to evaluating the operation of the TI4100 system, the test objectives included evaluating the capability of the TI4100 system to collect data of sufficient quality to support relative positioning surveys with a high degree of accuracy. It would be determined whether the results met or exceeded the accuracy standards for acceptance into the National Geodetic Reference System. The results would be based on two-frequency observations, thus the data was corrected for ionospheric delay.

From the four-satellite simultaneous carrier phase measurements, relative positions between stations of the test network were determined with the TI GEOMARK™ single base line processing software and the Geophysical Services, Incorporated MAGNET 4100™ multi-base line processing software. Data were processed with the broadcast (predicted) ephemerides, some during the week of the test and all following the test. The on-site processing of the data was open to the public. Preliminary results for a portion of the base lines were presented at a public meeting on Friday afternoon, December 6.

Overall, the TI4100 receivers functioned very well. Only one hardware related problem occurred. On several occasions, static discharge caused the TI4100's to drop into the standby mode. This caused breaks in the data which gave results that were less than optimal. (Since the test was conducted, this problem in the TI4100 GPS Navigators has been corrected). Other problems experienced during the test were in general, very minor. Of the 65 station-session data sets that were scheduled to be collected, only two were lost completely (both due to human error). About 15 other data sets had significant amounts of data missing caused by either late starts, the static discharge problem, or obstructions blocking the satellite signals. There were also some problems with the broadcast ephemerides during the first day or two.

The base line data were evaluated in terms of length, azimuth and height differences by comparison with coordinates of the test network previously determined by precise terrestrial methods.

The results of the test showed that the TI4100 GPS Navigator carrier phase measurements processed with the broadcast ephemerides using either the GEOMARK™ or MAGNET 4100™ software will provide very high 3-D relative positioning accuracies. The accuracy estimates were determined after adjusting for systematic differences between the reference system for the terrestrial standard and the GPS relative positioning results.

The relative positioning accuracy estimates (1-sigma) for base line lengths of less than 2 km and data collection periods of 18 to 30 minutes were, in terms of length, azimuth and height differences, 5 mm, 0.5 arc second, and 10 mm, respectively. For base line lengths of 2 to 30 km and similar data collection periods, the 1-sigma relative positioning accuracy estimates for length, azimuth. and height differences were 5 mm + 1 ppm, 0.1 arc second, and 10 mm + 2 ppm, respectively. Comparable accuracies were found for base line lengths of 30 to 105 km for 15-30 minute data sets processed with MAGNET 4100™. However, because GEOMARK™ processes data by the triple difference technique for line lengths greater than 30 km, data collection periods of 1 to 2 hours were required to give relative positioning accuracies comparable to line lengths of less than 30 km processed with GEOMARK™.

Trees, buildings and nearby power transmission lines at some of the FGCC test stations sites may have affected the results of the test survey. However, since these are conditions which are often typical at operational GPS survey stations, the GPS survey instrument and processing software must be capable of dealing with such problems as effectively as is possible.

The ability of the GEOMARK™ and MAGNET 4100™ software to process raw carrier phase data in near-real time was successfully demonstrated. Accuracies obtained met or exceeded the claims for the expected 1-sigma accuracies that could be achieved from TI4100 carrier phase data. In particular, data collection periods of less than 30 minutes for base lines lengths of less than 30 km is all that may be required when processing with either software to give results with accuracies at the few centimeter level in any component. However, to obtain these results from short observing periods, you must have four-satellite simultaneous observations. The geometry of the satellites will also be an important consideration.

The results clearly demonstrated that the TI4100 and associated geodetic post-processing software is a viable and accurate relative positioning satellite survey system. This system can be used successfully to establish geodetic control relative to stations of the National Geodetic Reference System.
