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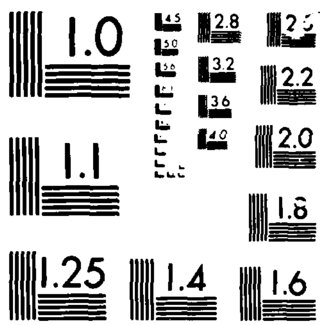

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19 ABSTRACT (Continue on reverse if necessary and identify by block number) Absolute positioning software written at the Defense Mapping Agency Hydrographic/Topographic Center (DMAHTC) was designed to process Texas Instruments 4100 (TI4100) geodetic receiver phase and range observations. This paper will describe absolute positioning solutions obtained by processing data collected during the Spring 1985 High Precision Baseline Test [1].

The positioning software can accept phase or range observations and test them as either psuedoranges or range differences thus allowing four different processing modes. The software estimates receiver position, scaling for the tropospheric correction, clock bias, drift, and aging parameters, and biases to the scaled phase measurement.

Data from the Spring 1985 Baseline Test have been reduced and position offsets relative to given reference positions have been tabulated. Comparisons have been made between solutions computed using different ephemerides, processing methods, observation types, clock (Over)

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19. Continued

treatments, and initial station offsets. Means and standard deviations of the differences between the position solutions and the reference positions are presented. Results show that the positioning software is computationally stable but that significant day to day variations of the solution are present due to the data.

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DMAHTC GPS POINT POSITIONING SOFTWARE: INITIAL RESULTS

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SUMMARY

Absolute positioning software written at the Defense Mapping Agency Hydrographic/Topographic Center (DMAHTC) was designed to process Texas Instruments 4100 (TI 4100) geodetic receiver phase and range observations. This paper describes absolute positioning solutions obtained by processing data collected during the Spring 1985 High Precision Baseline Test [1].

The positioning software can accept phase or range observations and treat them as either pseudoranges or range differences, thus allowing four different processing modes. The software estimates receiver position, scaling for the tropospheric correction, clock bias, drift, and aging parameters, and biases to the scaled phase measurement.

Data from the Spring Baseline Test have been reduced and position offsets relative to given reference positions have been tabulated. Comparisons have been made between solutions computed using different ephemerides, processing methods, observation types, clock treatments, and initial station offsets. Means and standard deviations of the differences between the position solutions and the reference positions are presented. Results show that the positoning software is computationally stable but that significant day to day variations of the solution are present due to the data.

1.0 INTRODUCTION

Absolute positioning software written at DMAHTC was designed to process TI 4100 receiver phase and range observations. Section 2 of this paper is a discussion of the processing software and methods used at DMAHTC to produce absolute positions using GPS data collected with the TI 4100 receiver.

Section 3 presents the results of processing 13 data sets collected at two sites during the Spring 1985 High Precision Baseline Test. Various processing options were used to produce solutions for these data sets. Results are tabulated and compared to demonstrate the consistency of the different processing options. Recoveries of station postion are shown when the initial position is offset by varying amounts in latitude, longitude, and height. Several data sets are edited to restrict the satellite geometry and the results of processing with these data sets are presented.

2.0 DMA GPS ABSOLUTE POSITIONING SOFTWARE

2.1 OVERVIEW

A flow chart of the GPS absolute point positioning process at DMA is shown in Figure 1. The TI 4100 receiver records raw data collected from up to four satellites at a time onto a cassette tape. The data on the cassette are transferred to a 9-track tape in exchange tape format [2] which is then read into a mass storage file on a mainframe computer. The STARPREP (Preprocessor and Correction) program reads this mass storage file and creates a number of files including the Corrected Measurement File and the Satellite Transaction File. These files and ephemeris data are combined in the PTPREP program to create the input file for the GPEST program. GPEST solves for the absolute point position among other parameters.

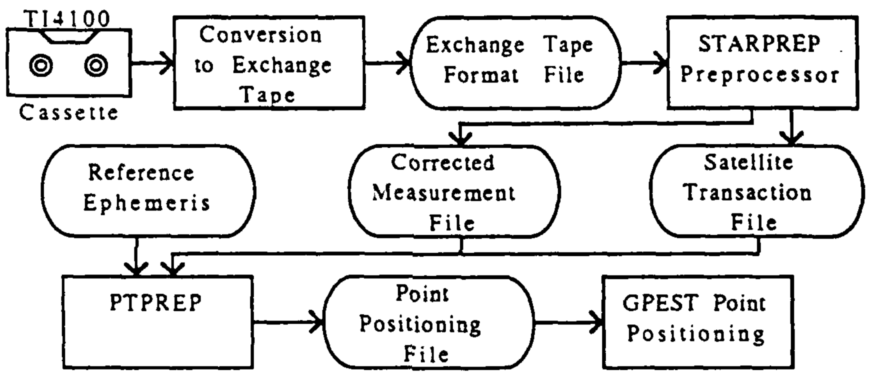


Figure 1 - GPS Absolute Positioning Data Flow

All the code is written in modular, structured form using ANSI FORTRAN 77 and includes error recovery and execution trace features, restart capability for each major section, optional computation and application of each of the measurement corrections in STARPREP, optional output of selected data, and diagnostic plots.

2.1.1 STARPREP PREPROCESSOR

The STARPREP preprocessor was designed specifically to process GPS tracking data obtained from the TI 4100 receiver. The current version of the program requires input data in 9-track exchange tape format and thus assumes that the original cassette tapes from the TI 4100 have already been converted to exchange tape format. It is also implicitly assumed that the GESAR navigation processor [3] was used in the receiver to collect the data.

STARPREP is structured to handle one data set (one tracking session for one receiver) at a time and leaves the function of matching or combining related data sets from multiple receivers to applications programs. There are three major sections in the program - edit, time tag corrections, and data corrections - which are executed sequentially. The net result is a data file containing measurements corrected for known sources of error and the associated corrected time tags. All of the computations are done in an earth-centered earth-fixed (ECEF) reference system (WGS-72).

2.1.1.1 EDIT SECTION

Tracking data and related information are read into the computer from the exchange tape in the edit section of STARPREP. Two types of measurements are processed - pseudorange and biased accumulated Doppler phase for both L1 and L2 carrier frequencies. Pseudorange measurements are assumed to be based on the P-code and are scaled from the time units of the original measurement to distance units by multiplying the uncorrected pseudoranges by the speed of light. The phase measurement is the continuous accumulated cycle count recorded by the receiver, starting from the time the receiver successfully "locks on" to a given satellite. The phase measurements include an initial cycle ambiguity (bias) representing the existing receiver cycle count at the moment the local receiver clock is synchronized with GPS time. The phase measurements must be corrected for an accumulating count due to the fixed frequency bias purposely incorporated in the receiver. To make this correction, the nominal frequency offset is multiplied by the elapsed time from the start of the first good observation after receiver synchonization with GPS time. After applying this term to each phase measurement and multiplying the resulting quantity by the ratio of the speed of light to the carrier frequency, the phase measurement is scaled from units of cycles to units of distance. This "biased Doppler range" value is then used for the rest of the preprocessing.

The edit section checks the data for loss of signal or loss of phase lock, carrier signal-to-noise ratio less than input threshold value, missing L1 or L2 measurements (time gaps), gross discontinuities in range or phase, and verification of station position and receiver equipment used.

L1 and L2 measurements are combined to compute two-frequency ionospheric corrections for both the pseudorange and biased Doppler range data. Only the corrected L1 data are processed in the rest of STARPREP.

In addition to the measurement data, the edit section saves meteorological data, station information, receiver equipment information, and the satellite navigation message ephemeris and clock correction terms for later use by the preprocessor.

2.1.1.2 TIME TAG CORRECTION SECTION

The uncorrected time tag to each measurement is the receiver time at the time of reception. This time tag must be corrected to the time of transmission. This is accomplished by dividing the measured pseudorange by the velocity of light and subtracting this value from the reception time. (Propagation delay and the receiver clock offset from the satellite clock are accounted for by this simple process.)

An additional time tag correction to account for the satellite clock offset from GPS time is made using the navigation message values for the satellite clock parameters. This references the measurements to very nearly GPS time.

2.1.1.3 DATA CORRECTIONS SECTION

In addition to the ionospheric correction that was computed in the edit section, five other corrections are computed and applied to the measurements. These corrections account for tropospheric delay, relativity, satellite clock, earth rotation, and satellite antenna offset. The Hopfield model [4] was used for the tropospheric correction in conjunction with weather data recorded at the site. Periodic relativistic effects [5] and the offset of the center of mass of the satellite from the satellite antenna electrical center are accounted for. Measurements are adjusted for satellite clock offset and drift using parameters obtained from the navigation message. Further residual corrections are estimated in GPEST. Since STARPREP uses an ECEF reference system, an earth rotation correction is applied to the data as well. No correction is made for the receiver clock in the preprocessor. For computing these corrections, either the navigation message ephemeris or the Naval Surface Weapons Center's (NSWC) reference ephemeris [6] can be used as a source of satellite positions.

2.1.1.4 STARPREP OUTPUT

The *Satellite Transaction File* contains the sets of orbital elements that are included in the navigation message for the satellites observed during the time period of the data collection.

The Corrected Measurement File contains the corrected observations and the value of each of the corrections as described in Section 2.1.1.1.

2.1.2 PTPREP

The PTPREP (Point File Preparation) Program uses the Corrected Measurement File and the Satellite Transaction File to create a Point File which is used as the primary input to GPEST. The Point File consists of a series of records containing the observation time, the corrected observation, the corrections that were applied, and a satellite position. The satellite position may be computed using the navigation message elements from the Satellite Transaction File or interpolated from the NSWC reference ephemeris.

2.1.3 GPEST ABSOLUTE POSITIONING

GPEST is an interactive absolute positioning program designed to accept data files which have been processed by the STARPREP and PTPREP programs. GPEST consists of a driver (GPEST/B1) and 41 subroutines. The program size is about 60k words but can be expanded if more parameters are used.The program can use either the pseudorange (PR) or the accumulated Doppler phase (AD) data type collected from the TI 4100 receiver. These can be processed using two methods; range (R), or range difference (RD). This option allows GPEST to run in four modes: pseudorange processed as range (PR/R), pseudorange processed as range difference (PR/RD), accumulated Doppler processed as range (AD/R), and accumulated Doppler processed as range difference (AD/RD).

The primary outputs are the adjusted tracking station coordinates in WGS-72. Other outputs include corrections to the satellite clock parameters, receiver clock parameters, a scale factor for the tropospheric refraction correction, and the bias to the phase count for each span of data.

Clock terms may be determined in a global (gl) mode or in a satellite-specific (sv) mode. "Global" means that only one set of clock parameters (bias, drift, and aging) occur in the state vector and that the terms represent the receiver clock behavior with respect to GPS time. This assumes that the satellite clock parameters in the navigation message correct each satellite clock exactly to GPS time. "Satellite-specific" means that a set of clock parameters appear in the state vector for each satellite. A satellite-specific term will represent the relation between the receiver clock and the preprocessor corrected satellite clock .

To account for biases introduced into the phase data due to the initial phase ambiguity in the TI 4100 or losses of lock, GPEST divides each data set into "spans." A new span is defined after each discontinuity (loss of lock or cycle slip). GPEST uses the PR measurements as a check for large changes in bias in the AD measurements. In the AD/R mode an intial difference is computed between the PR and AD measurements for a satellite. All subsequent measurements are likewise differenced and compared to the intitial difference. If the absolute value of the difference of these values exceeds a maximum value input by the user, then GPEST assumes that a phase discontinuity has occurred and a new "span" is defined. A new range-bias term is then added to the state vector. The range bias terms are not needed in the AD/RD, PR/R, or PR/RD mode.

The tropospheric refraction correction, which is obtained from the Point File for each observation, is multiplied by a scale factor (α) and then added to the corrected observation supplied by STARPREP. Thus, if the correction is adequate, and other error sources are adequately modeled, this factor should be close to zero.

GPEST utilizes a simple batch least squares fit. The state vector is given by:

$$\underline{X} = (X_{sta}, Y_{sta}, Z_{sta}, \alpha, bias_{sv}, drift_{sv}, aging_{sv}, range\text{-}bias_{sv,sp}) \qquad (1)$$

or by

$$\underline{X} =(X_{sta}, Y_{sta}, Z_{sta}, \alpha, bias_{gl}, drift_{gl}, aging_{gl}, range\text{-}bias_{sv,sp}) \qquad (2)$$

depending upon the clock model (gl or sv) used. Any of these terms are optional.

For equations 1 and 2:

X_{sta}, Y_{sta}, Z_{sta}......... Station position in a north, east, up (NEU) system

α......................... Scale factor for the tropospheric refraction correction

$bias_{sv}$,$drift_{sv}$,$aging_{sv}$... Clock parameters for receiver/satellite clock combination

$bias_{gl}, drift_{gl}, aging_{gl}$.... Clock parameters for receiver time with respect to GPS time

$range\text{-}bias_{sv,sp}$.......... Phase offsets for each satellite (sv) and span (sp)

The observation-state relation is given by the equation:

$$Obs = Range + (\alpha)\, Trop + c(bias + drift\,(\Delta t) + aging(\Delta t)^2) + (range\text{-}bias) \quad (3)$$

where:

$$Range = [\, (x_{sv} - x)^2 + (y_{sv} - y)^2 + (z_{sv} - z)^2 \,]^{1/2} \quad (4)$$

and

x, y, z.................. Station position in an ECEF system

x_{sv}, y_{sv}, z_{sv}........... Satellite position (ECEF)

Δt........................ Time from data set epoch

c.......................... Speed of light

Trop..................... Tropospheric refraction correction

When the RD mode of processing is used, both sides of equation 3 are differenced between two consecutive observations for the same satellite.

3.0 OVERVIEW OF PROCESSING RESULTS

The data sets from two stations included in the Spring 1985 High Precision Baseline Test will be discussed in this paper. The Ft. Davis, Texas and Richmond, Florida data sets comprised the most complete sequences available to the authors at the time of processing. The data were collected on days 89 through 95, 1985 (Saturday, 30 March 1985 through Friday, 5 April 1985). Figures 2 and 3 show elevation angle-azimuth plots for the data collection interval on day 94 at the Richmond site and day 93 at the Ft. Davis site. These plots illustrate typical geometry for most of the data sets. Data from day 93 were not available for the Richmond site. Each data set comprises from five to nine hours of tracking or from 1900 to 3000 observations at 30-second intervals. Almost all data sets include observations from six satellites. Day 92 at the Ft. Davis site includes observations from only five satellites. This data set consists of only 1319 observations and does not span the same daily time period as the other data sets.

For the processed data sets, PR measurements were generally on the order of from 20000 to 25000 kilometers. AD measurements scaled in STARPREP consisted of values that ranged from 50000 to -1470000 kilometers. Using the RD processing method, these observations ranged from 0.01 to 58 kilometers per 30-second observation interval. The noise on these measurements, which is shown in residual plots produced by GPEST, ranges from 1 to 10 meters for PR observations and from 5 to 15 centimeters for the AD observations. Thus, noise to measurement ratios varied in GPEST from approximately 10^{-9} for the AD/RD mode to 10^{-4} for the PR/RD mode.

The positions used as initial estimates for computing corrections will be referred to as reference positions. The WGS-72 positions used as initial estimates were transformed from published NAD values [7] and geodetic ties to the GPS sites. Richmond's initial WGS-72 coordinates were 25°.6140657N latitude, 279°.615796E longitude, and -0.022663 kilometers in height. Ft. Davis' initial WGS-72 coordinates were 30°.6359547N latitude, 256°.052905E longitude, and 1.58238 kilometers in height.

Tables 1 through 6 and 8 through 10 show the approximate offsets in latitude, longitude, height, and radial distance (in meters) between the reference positions and the positions computed by GPEST . If the solution failed to converge after 12 iterations, "NC" is shown. If data were not available, the table entry contains "-----." The table columns represent subsequent days at a site and the rows represent the four processing modes. Tables 1 through 6 show the offsets produced using various options in processing. These options include processing mode, ephemeris type, and clock parameters. Table 7 shows means and standard deviations computed for each coordinate in each mode for the series of days at each site. Tables 8 and 9 show only the AD/R and AD/RD modes and represent the offsets produced when using initial positions that have been perturbed in latitude and longitude or in height. Table 10 shows offsets computed from subsets of several of the original data sets.

3.1 PROCESSING OPTIONS

3.1.1 PROCESSING MODES (AD/R, AD/RD, PR/R, PR/RD)

Data sets collected over 7 consecutive days were processed in the four modes to test the repeatability of each of the methods. These results are shown in Tables 1 through 6 and resulting statisics are presented in Table 7.

Two measurements types, PR and AD, were collected at 30-second intervals by the TI 4100. These data types were described in Sections 2.1.1.1 and 2.1.3. Both types are treated in much the same manner by GPEST. However, the AD type requires the estimation of an additional bias (see Section 2.1.3) for each "span" of satellite data. Tables 1 through 6 show the results of processing using both types of observations.

Table 1- Solution Offsets for Richmond Site Using
NSWC Reference Ephemeris and Satellite-Specific Clock

Meters from Reference Position

			Day 89	Day 90	Day 91	Day 92	Day 93	Day 94	Day 95
AD	R	Δφ	+3.59	+2.13	+3.41	+03.37	--------	+2.63	+0.57
		Δλ	+5.89	+4.41	+9.82	+11.70	--------	+3.74	+4.39
		Δh	-5.99	-2.35	+0.63	-01.93	--------	+1.50	+5.66
		Rad	+9.11	+5.44	+10.43	+12.34	--------	+4.82	+7.19
AD	RD	Δφ	+2.10	+1.75	+0.74	+01.55	--------	+2.48	+2.14
		Δλ	+8.08	+6.92	+8.66	+07.99	--------	+3.43	+4.59
		Δh	+0.03	-0.54	+1.61	-00.28	--------	-1.56	-0.62
		Rad	+8.37	+7.17	+8.86	+08.17	--------	+4.52	+5.12
PR	R	Δφ	+3.58	+3.56	NC	NC	--------	+2.81	+0.15
		Δλ	+7.65	+5.23	NC	NC	--------	+4.77	+6.52
		Δh	-0.62	+2.03	NC	NC	--------	+4.64	+5.43
		Rad	+8.48	+6.65	NC	NC	--------	+7.23	+8.50
PR	RD	Δφ	+9.97	-0.55	-8.85	+23.85	--------	+7.37	+7.12
		Δλ	+9.41	+12.35	-1.98	+42.11	--------	+11.10	+29.67
		Δh	+0.42	-9.59	-14.38	-35.26	--------	+7.06	+13.10
		Rad	+13.69	+15.65	+16.98	+48.34	--------	+15.08	+33.23

As described in Section 2.1.3, processing can also be done using two methods, R and RD. The R processing method treats both measurement types as biased pseudoranges. The RD method differences consecutive measurements for a satellite, eliminating biases which are common to a satellite. This processing method eliminates the need to solve for the individual span biases and other unmodeled biases. Tables 1 through 6 compare the results of processing using both methods. Tables 1 and 2 show comparisons of results from the four modes of processing for the Richmond and Ft. Davis sites. The NSWC reference ephemerides and satellite-specific clock parameters were used to produce these two tables.

Table 1 shows PR and AD measurements processed in the R mode produce similar results. For the six sets of data processed from the Richmond site, the AD/R mode produced mean offsets of 2.62 meters for the latitude (φ), 6.66 meters for the longitude (λ), and -0.41 meters for the height (h) as shown in Table 7. This compares closely in φ and λ to the PR/R mode offset means computed from only four solutions as shown in Table 7. For PR/R mode means of 2.53, 6.04, and 2.87 meters for φ, λ, and h, respectively, were produced. The AD/RD mode shows similar results with offset means of 1.79, 6.61, and -0.85 meters for φ, λ, and h, respectively. The R/RD mode shows the largest differences producing station offset means of 6.49, 17.11, and -2.96 meters for φ, λ, and h, repectively.

Table 2 - Solution Offsets for Ft. Davis Site Using
NSWC Reference Ephemeris and Satellite-Specific Clock

Meters From Reference Position

			Day 89	Day 90	Day 91	Day 92	Day 93	Day 94	Day 95
AD	R	Δφ	+3.08	-0.84	+1.11	-0.11	-0.03	-0.43	+3.14
		Δλ	+7.70	+12.93	+12.15	+6.11	+11.92	+12.20	+22.64
		Δ h	+1.64	+2.91	+0.05	-0.30	+0.77	+1.69	-0.35
		Rad	+8.44	+13.27	+12.19	+6.11	+11.93	+12.31	+22.88
AD	RD	Δφ	+1.32	+0.60	-0.39	+1.32	+0.37	+0.71	+1.35
		Δλ	+6.55	+13.25	+12.79	+7.56	+13.32	+12.99	+13.75
		Δ h	+0.31	+1.14	+0.94	+0.96	+0.46	+0.69	+0.46
		Rad	+6.68	+13.31	+12.82	+7.72	+13.33	+13.02	+13.83
PR	R	Δφ	+3.31	NC	+1.44	+1.66	+0.32	-0.31	+1.47
		Δλ	+7.55	NC	+13.54	+19.52	+12.32	+14.57	+21.35
		Δ h	+2.13	NC	-1.45	+3.62	+0.21	+3.42	+1.94
		Rad	+8.50	NC	+13.68	+19.92	+12.32	+14.97	+21.51
PR	RD	Δφ	+6.48	-1.04	+2.71	+3.60	+0.59	+6.68	+11.11
		Δλ	+9.65	+18.15	+2.01	-4.25	+13.18	+31.74	+23.56
		Δ h	-3.97	+1.84	+0.26	-23.42	+4.46	+1.02	+1.57
		Rad	+12.26	+18.26	+3.37	+24.07	+13.93	+32.45	+26.09

The Ft. Davis site offsets are shown in Table 2. Means and standard deviations for the 7 solutions are shown in Table 7. The Ft. Davis site shows internal consistency similar to the Richmond site among the offsets produced by the AD/R, AD/RD, and PR/R modes. The PR/RD mode again shows the largest divergence from the other modes.

The AD/RD mode produced the smallest standard deviations in φ, λ, and h for both the FT. Davis and the Richmond sites in all but one case. The standard deviaton in latitude resulting from the PR/R mode for the Richmond site is smaller than that for the AD/RD mode. However, only four solutions were used to produce this statistic due to the inability of the PR/R mode to converge for several data sets. In every case the PR/RD mode produced the highest standard deviations.

3.1.2 EPHEMERIS (NAVIGATION MESSAGE/NSWC REFERENCE)

Processing was done for the Ft. Davis and Richmond sites using the two ephemeris types available to the STARPREP and PTPREP programs. The navigation message ephemeris was computed using the algorithm described by Van Dierendonck [8]. The reference ephemeris was produced by NSWC and was evaluated using a Lagrange 8-point interpolator. The reference ephemeris has a resolution of 15 minutes.

Tables 3 and 4 show solutions computed using the navigation message ephemeris for the Richmond and Ft. Davis sites. These may be compared to Tables 1 and 2 which show solutions using the interpolated NSWC reference ephemeris. Tables 3 and 4 show results of processing with satellite-specific clock parameters as do Tables 1 and 2.

Table 3 - Solution Offsets for Richmond Site Using Navigation Message Ephemeris and Satellite-Specific Clock

Meters from Reference Position

			Day 89	Day 90	Day 91	Day 92	Day 93	Day 94	Day 95
AD	R	Δφ	+3.30	+2.04	+4.25	+0.76	--------	+2.69	+0.47
		Δλ	+9.59	+9.06	+12.67	+15.46	--------	+5.43	+4.98
		Δh	-8.72	-2.56	+0.33	+2.42	--------	+2.65	+3.75
		Rad	+13.37	+9.64	+13.37	+15.68	--------	+6.61	+6.25
AD	RD	Δφ	+1.15	+1.44	+0.52	-2.06	--------	+1.94	+1.59
		Δλ	+10.42	+10.03	+9.69	+7.46	--------	+4.13	+3.99
		Δh	+4.42	-2.27	+0.52	+4.11	--------	-1.32	-1.50
		Rad	+11.33	+10.39	+9.72	+8.77	--------	+4.75	+4.54
PR	R	Δφ	+1.61	+2.41	NC	NC	--------	+2.82	+0.08
		Δλ	+13.05	+7.38	NC	NC	--------	+5.90	+7.15
		Δh	+8.68	-1.97	NC	NC	--------	+4.21	+4.12
		Rad	+15.76	+8.01	NC	NC	--------	+7.77	+8.26
PR	RD	Δφ	+8.03	-0.88	-9.62	+20.20	--------	+6.63	+5.47
		Δλ	+11.96	+16.28	+0.27	+24.31	--------	+12.83	+29.08
		Δh	+4.52	-11.74	-14.78	-28.64	--------	+7.28	+13.46
		Rad	+15.08	+20.10	+17.62	+42.62	--------	+16.16	+32.52

Table 7 shows the means and standard deviations for the solutions produced using both ephemeris types. The latitude offsets produced using the navigation message ephemeris for both the Ft. Davis and Richmond sites were smaller than those produced using the NSWC reference ephemeris for all modes. The longitude offsets produced using the navigation message ephemeris for both the Ft. Davis and Richmond sites were larger for all modes. The mean heights were affected differently by the two ephemeris types. The Richmond mean heights were consistently higher using the NSWC reference ephemeris and the Ft. Davis mean heights were consistently lower.

For the Richmond site the ϕ, λ, and h standard deviations were smaller for the reference ephemeris in the AD/R and AD/RD modes. Ft. Davis shows higher standard deviations for the reference ephemeris for ϕ and λ in every mode except PR/R. In PR/R mode the standard deviaitons for ϕ and λ were smaller for the reference ephemeris and the standard deviations for the heights were smaller for the reference ephemeris in all modes.

Table 4 - Solution Offsets for Ft. Davis Site Using
Navigation Message Ephemeris and Satellite-Specific Clock

Meters from Reference Position

			Day 89	Day 90	Day 91	Day 92	Day 93	Day 94	Day 95
AD	R	Δφ	+2.75	-01.11	+1.17	-0.53	-0.05	-0.95	+2.24
		Δλ	+8.02	+13.80	+12.27	+8.21	+11.68	+12.46	+22.90
		Δh	-2.01	-00.79	-2.17	-4.47	-1.69	+0.01	-2.17
		Rad	+8.71	+13.87	+12.53	+9.37	+11.81	+12.50	+23.15
AD	RD	Δφ	+0.54	-00.22	-0.25	+0.94	+0.32	+0.59	+0.42
		Δλ	+7.44	+14.23	+13.29	+9.17	+12.75	+13.74	+12.80
		Δh	-2.43	-01.85	-1.42	-2.95	-1.10	-0.18	-0.70
		Rad	+7.85	+14.36	+13.38	+9.68	+12.81	+13.77	+12.85
PR	R	Δφ	+3.08	NC	+1.47	+1.26	-0.06	-0.87	+0.89
		Δλ	+7.82	NC	+13.59	+21.77	+12.07	+14.77	+21.61
		Δh	-1.62	NC	-3.82	-0.37	-2.34	+1.61	+0.69
		Rad	+8.56	NC	+14.20	+21.28	+12.31	+14.90	+21.68
PR	RD	Δφ	+6.12	-01.80	+2.30	+2.93	-0.01	+6.05	+9.90
		Δλ	+10.69	-19.63	+3.33	-2.03	+14.12	+33.09	+22.37
		Δh	-7.35	-01.41	-2.03	-26.92	+2.55	-0.11	+0.29
		Rad	+14.34	+19.78	+4.52	+27.15	+14.37	+33.67	+24.48

3.1.3 CLOCK TREATMENT (GLOBAL/SATELLITE-SPECIFIC)

GPEST can solve for clock parameters in the satellite-specific mode and in the global mode as described in Section 2.1.3. Aging was not estimated in any of the data sets discussed. STARPREP uses the navigation message clock parameters to correct the satellite clocks before any clock parameters are estimated in GPEST.

Table 5 - Solution Offsets for Richmond Site Using
NSWC Reference Ephemeris and Global Clock

Meters from Reference Position

			Day 89	Day 90	Day 91	Day 92	Day 93	Day 94	Day 95
AD	R	Δφ	+3.42	-3.04	+2.13	+2.81	--------	+1.68	+1.56
		Δλ	+6.10	-6.67	+9.49	+8.17	--------	+4.01	+6.90
		Δh	-3.41	-2.46	+1.56	+2.83	--------	+6.05	-1.19
		Rad	+7.78	+7.74	+9.87	+9.10	--------	+7.45	+7.19
AD	RD	Δφ	+2.24	-2.45	+1.76	+1.85	--------	+2.12	+1.96
		Δλ	+7.33	-6.88	+8.51	+7.58	--------	+3.09	+4.19
		Δh	-0.26	-2.47	+0.27	-0.87	--------	-1.14	-0.51
		Rad	+7.68	+7.72	+8.71	+7.87	--------	+3.92	+4.67
PR	R	Δφ	+3.27	-6.07	NC	NC	--------	+1.89	+3.92
		Δλ	-0.79	-1.61	NC	NC	--------	+2.01	+4.04
		Δh	-3.11	-7.35	NC	NC	--------	+9.44	+3.28
		Rad	+4.58	-9.66	NC	NC	--------	+9.84	+14.43
PR	RD	Δφ	+4.54	-4.49	-4.43	-1.42	--------	+9.76	+7.51
		Δλ	+8.79	-1.73	+12.54	+9.32	--------	+3.03	+6.15
		Δh	+6.74	-12.40	-10.47	-16.60	--------	-1.43	-4.53
		Rad	+13.10	+13.29	+16.95	+19.10	--------	10.29	+10.77

Solutions shown in Tables 1 through 4 were produced using the satellite-specific mode for the bias and drift terms in processing. Tables 5 and 6 represent processing done with the bias and drift terms determined globally.

The solution offsets presented in Table 5 produced statistics that show improvement of position consistency in every mode except PR/R when compared to Table 1. Table 7 shows that the global clock treatment produces lower standard deviations in all coordinate offsets and modes except for the PR/R mode and the λ offset in the AD/RD mode. In the case of the λ coordinate in the AD/RD, standard deviations are nearly equal (2.13 meters for the satellite-specific clock mode as opposed to 2.12 meters for the global clock mode).

Table 6 - Solution Offsets for Ft. Davis Site Using
NSWC Reference Ephemeris and Global Clock

Meters from Reference Position

			Day 89	Day 90	Day 91	Day 92	Day 93	Day 94	Day 95
AD	R	Δφ	+0.82	-0.02	+0.44	+0.30	+0.54	+0.39	+0.98
		Δλ	+8.05	+10.50	+8.25	+7.37	+8.01	+11.08	+9.51
		Δh	+2.87	+0.97	-2.70	+5.55	-2.91	+0.72	-6.54
		Rad	+8.61	+10.58	+8.71	+9.24	+8.56	+11.15	+11.60
AD	RD	Δφ	+0.75	+1.00	+0.52	+1.51	+0.67	+0.85	+0.91
		Δλ	+5.24	+9.85	+10.06	+7.52	+10.29	+9.90	+11.59
		Δh	+0.29	-0.54	-0.26	+0.50	-0.41	-0.18	+0.01
		Rad	+5.31	+9.95	+10.11	+7.70	+10.35	+9.97	+11.65
PR	R	Δφ	+0.79	NC	+0.40	+3.81	+0.36	-0.25	+3.92
		Δλ	+3.00	NC	-1.22	-3.13	-1.76	+2.19	+0.69
		Δh	+3.93	NC	-7.17	-1.18	-3.47	-5.66	-7.83
		Rad	+5.01	NC	+7.28	+5.07	+3.91	+6.07	+8.78
PR	RD	Δφ	+0.18	-1.38	+2.26	+6.58	+3.07	-0.69	+1.99
		Δλ	+6.72	+14.61	+3.61	-1.16	+13.58	+23.97	+15.70
		Δh	+0.07	+3.41	+0.33	-16.63	+2.31	+4.77	+6.53
		Rad	+6.74	+15.10	+4.28	+17.92	+14.15	+24.51	+17.16

Table 7 - Summary of Offset Statistics

			Δφ (Meters)			Δλ (Meters)			Δh (Meters)		
			Sv-Specific Clk		Gl Clk	Sv-Specific Clk		Gl Clk	Sv-Specific Clk		Gl Clk
			Nv Eph	Reference Eph		Nv Eph	Reference Eph		Nv Eph	Reference Eph	
Richmond	Mean	AD/R	+2.25	+2.62	+2.44	+9.53	+6.66	+6.89	-0.36	-0.41	+0.56
		AD/RD	+0.76	+1.79	+2.06	+7.62	+6.61	+6.26	+0.66	-0.85	-0.83
		PR/R	+1.73	+2.53	+3.79	+8.37	+6.04	+0.91	+9.95	+2.87	+4.24
		PR/RD	+4.97	+6.49	+1.91	+15.79	+17.11	+6.93	-4.98	-2.96	-6.45
	Std. Dev.	AD/R	1.46	1.15	0.76	4.07	3.31	1.86	4.67	3.97	3.58
		AD/RD	1.46	0.61	0.26	2.94	2.12	2.13	2.94	1.70	0.94
		PR/R	1.21	1.62	1.74	3.19	1.30	2.60	3.89	2.74	5.53
		PR/RD	9.91	10.95	6.20	10.14	15.91	4.09	16.01	11.61	8.46
Ft. Davis	Mean	AD/R	+0.50	+0.85	+0.49	+12.76	+12.24	+8.97	-1.90	+0.92	-0.29
		AD/RD	+0.33	+0.75	+0.89	+11.92	+11.46	+9.21	-1.52	+0.71	-0.08
		PR/R	+0.96	+1.32	+1.51	+15.27	+14.81	-0.04	-0.97	+1.65	-3.56
		PR/RD	+3.64	+4.30	+1.72	+14.46	+13.43	+11.00	-5.00	-2.61	+0.11
	Std. Dev.	AD/R	1.56	1.66	0.33	4.98	5.27	1.41	1.40	1.22	4.05
		AD/RD	0.43	0.64	0.32	2.57	3.04	2.12	0.97	0.31	0.38
		PR/R	1.36	1.25	1.86	5.50	5.01	2.39	2.01	1.95	4.41
		PR/RD	4.01	4.12	2.70	11.80	12.37	8.47	10.14	9.52	7.73

Table 6 shows offsets from processing for the Ft. Davis site using the global clock mode. For the Ft. Davis site, Table 7 shows consistently smaller standard deviations in φ and λ, often by a factor of two or more. The exception is the PR/R mode for the latitude offset, where the standard deviation is 1.25 meters for the satellite-specific clock mode and 1.86 meters for the global clock mode. The standard deviations of the heights are smaller using the satellite-specific mode.

3.2 RECOVERY OF SOLVED STATION POSITIONS

Three days of data for both sites were processed using initial position vectors that were offset from the reference postion in φ and λ. These perturbations of the initial position were done in order to test GPEST's ability to recover a position given an inaccurate initial position. This is, in one sense, a test of the computational stability of the positioning procedure. The offsets were on the order of 4 arcseconds or approximately 110 to 120 meters. The Richmond site is perturbed by approximately 110 meters in latitude and -110 meters in longitude. The Ft. Davis site is perturbed by approximately -110 meters in latitude and 110 meters in longitude. These figures might be typical of the accuracy of coordinates scaled from a map grid.

Table 8 presents offsets produced with these initially perturbed latitudes and longitudes. These offsets can be compared directly to results from Tables 1 and 2. Aside from the initial station coordinates, all modes and input parameters were the same for the results presented in both sets of tables. The differences in the solutions are minimal. As an example, the φ, λ, and h offsets for day 90 from Table 8 in the AD/RD mode are 1.75, 6.94, and -0.54 meters. Table 1 shows values of 1.75, 6.92, and -0.54 meters for the coordinates. The total difference is only 2 cm. The other data sets shown in Table 8 show similar small differences.

Table 3 - Solution Offsets with Initial Latitude and Longitude Perturbed
NSWC Reference Ephemeris - Satellite-Specific Clock - All Units are Meters

			Richmond Site			Ft. Davis Site		
			Day 90	Day 91	Day 92	092	093	094
AD	R	Δφ	-2.03	-3.16	-3.37	-0.11	-0.02	-0.43
		Δλ	-4.69	+9.23	+11.71	+6.10	+11.90	+12.18
		Δh	-3.35	-0.69	-1.93	-0.30	-0.77	+1.69
		Rad	-6.40	-9.78	+12.34	-6.11	-11.93	-12.30
AD	RD	Δφ	+1.75	-0.78	-1.54	+1.32	-0.37	+0.71
		Δλ	-6.94	-3.67	-3.01	-7.55	-13.31	+12.98
		Δh	-0.54	-1.53	-0.23	+0.96	-0.46	+0.69
		Rad	[illegible]	-3.35	-3.16	-7.73	-13.32	+13.02

Three days of data from both sites were processed using initial position vectors that were offset in h. The offsets were 10 meters for day 90, 30 meters for day 91, and 780 meters for day 92 at the Richmond station and -40 meters for day 92, 10 meters for day 93, and -100 meters for day 94 at the Ft. Davis site.

Table 9 presents offsets produced with these initially perturbed heights. Again, these offsets can be directly compared to results from Tables 1 and 2. As with the latitude and longitude offsets, the differences in the solutions are minimal. As an example, the ϕ, λ, and h offsets for day 90 from Table 9 in the AD/RD mode are 1.75, 6.94, and -0.54 meters. Table 1 shows values of 1.75, 6.92, and -0.54 meters for the coordinates for the same day and processing mode. As with the latitude and longitude offsets, the total difference is only 2 cm. The other data sets shown in Table 9 exhibit similar small differences when compared to Tables 1 and 2.

Table 9 - Solution Offsets with Initial Heights Perturbed

NSWC Reference Ephemeris - Satellite-Specific Clock - All Units are Meters

			Richmond Site			Ft. Davis Site		
			Dav 90	Dav 91	Dav 92	092	093	094
AD	R	$\Delta\phi$	+2.30	+3.16	+3.37	-0.11	-0.02	-0.43
		$\Delta\lambda$	+4.69	+9.23	+11.72	+6.10	+11.90	+12.18
		Δh	-3.85	-0.69	-1.93	-0.93	+0.77	+1.69
		Rad	+6.40	+9.78	+12.35	+6.11	+11.93	+12.30
AD	RD	$\Delta\phi$	+1.75	+0.74	+1.54	+1.32	+0.37	+00.71
		$\Delta\lambda$	+6.94	+8.68	+8.03	+7.54	+13.31	+12.98
		Δh	-0.54	+1.61	+0.28	+0.96	+0.49	+0.69
		Rad	+7.17	+8.86	+8.18	+7.72	+13.32	+13.02

3.3 EDITED DATA SETS (SPAN LENGTH AND SATELLITE GEOMETRY)

Two of the original data sets were edited to create subsets that could be used to test the effects of various factors on the station position solutions. Some of these factors are the amount of data, the time span of the data, the number of satellites from which observations are used, and the change in satellite geometry. Figures 2 through 7 illustrate the geometry of the data used for these sets. The outer ring in the figures represents an elevation angle of 0°. The inner circle represents 45°, and the crosshair represents the zenith point.

Table 10 - Solution Offsets for Edited Data Sets

NSWC Reference Ephemeris - Satellite-Specific Clock - All Units are Meters

			Richmond Site - Dav 94		Ft. Davis - Dav 93	
			North Quads	South Quads	North Quads	South Quads
AD	R	$\Delta\phi$	+2.91	+7.45	-0.65	-11.44
		$\Delta\lambda$	+1.85	+23.92	+16.92	-2.45
		Δh	+0.55	+6.36	-2.82	+14.00
		Rad	-3.48	+25.90	+17.21	+18.23
AD	RD	$\Delta\phi$	-2.90	+6.20	+0.75	-11.93
		$\Delta\lambda$	-1.39	+18.72	+21.28	+1.96
		Δh	-0.69	+4.39	+1.30	-9.84
		Rad	-3.52	+20.24	+21.39	+15.57

Figure 2-Richmond-Day94
Unedited

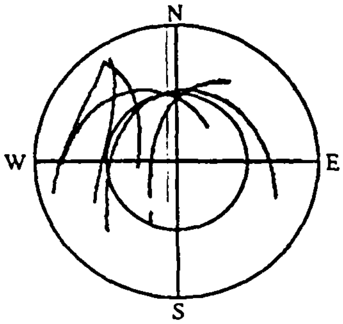


Figure 4-Richmond-Day94
Southern Quadrants

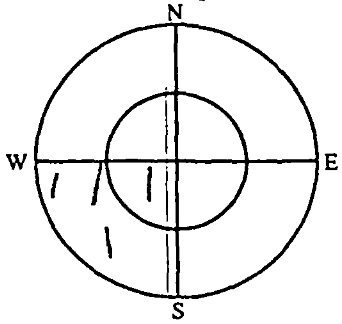


Figure 6-Richmond-Day94
Northern Quadrants

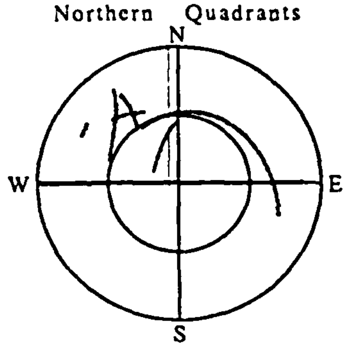


Figure 3-Ft.Davis-Day93
Unedited

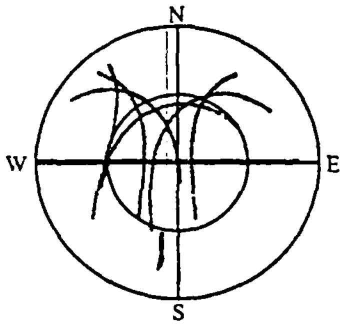


Figure 5-Ft.Davis-Day93
Southern Quadrants

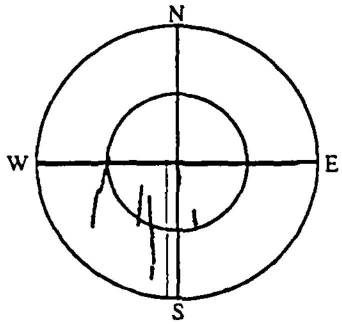
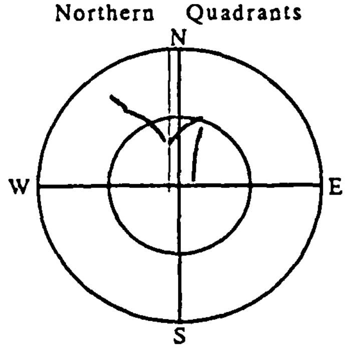


Figure 7-Ft.Davis-Day93
Northern Quadrants



The data set that was collected on day 94 at the Richmond site was edited twice to produce two smaller data sets, one with observations limited to those taken while the satellites being tracked were in the northern quadrants, and another with observations limited to the southern quadrants. The data set for day 93 at the Ft. Davis site was edited to produce two subsets in a similar manner. Figures 2 and 3 represent the unedited data sets. Figures 4 and 5 represent the data sets limited to the southern quadrants and Figures 6 and 7 represent the sets limited to the northern quadrants. Table 10 shows the offsets produced by reducing these data sets. These sets were processed using satellite-specific clock parameters and the reference ephemerides and may be compared to results shown in Tables 1 and 2.

In the AD/RD mode, the edited data set which most closely recovers the offsets computed from the Table 1 solutions is the set shown in Figure 6. This set contains 1051 observations as opposed to 251, 547, and 472 observations for the other three edited data sets. The solutions from the other three edited sets do not fall within one standard deviation of the solutions for the unedited sets.

4.0 CONCLUSIONS AND RECOMMENDATIONS

From the solutions presented, a systematic offset was detected in latitude, longitude, and height for each of the two stations in all modes. The source of this offset is unknown but may stem from several sources such as error in the reference positions, ephemeris error, or systematic error due to satellite geometry.

There was a significant amount of day-to-day variation in all coordinates and modes. However, as was shown in Table 7, the accumulated Doppler count observation type processed as range-differences, with global clock parameter solution and the reference ephemeris, produced standard deviations in ϕ, λ, and h which in the majority of cases were smaller than the other modes. The offsets for this mode show standard deviations over a week which were sub-meter in latitude and height and approximately 2 meters in longitude. The Doppler data processed as ranges and the pseudorange data processed as ranges generally produced standard deviations that were only slightly less consistent then the AD/RD mode. The pseudorange data processed as range differences produced the highest standard deviations for station position in every mode. This may be due to the measurement to noise ratio as described in Section 3.0. For the two sites longitude consistently shows the largest offsets in all modes.

The position estimation procedure in GPEST appears to be insensitive to perturbation in the initial estimates of the station coordinates of up to 780 meters. The results shown in Tables 8 and 9 demonstrate that the solution converges to the same position regardless of the initial offset of the a priori coordinates. More tests of this nature need to be conducted to determine the limit of this stability.

Satellite constellation configuration and the amount of data obviously affect the positioning solution. Editing the data sets to bias the geometry of the data processed by GPEST has an affect on the solution, but the few cases explored here are inconclusive as to any systematic effect. In the cases represented, the amount of data and the data interval may have been the determining factor rather than geometry. With short spans of data, periodic ephemeris errors, which are averaged out over longer periods, may become more dominant.

Further experimentaion with absolute positioning using the TI 4100 and the GPS system is necessary to ascertain the accuracy and precision with which solutions can be made. Further tests should be made to compare results obtained using varying collection span periods and observation intervals. Improvements in satellite ephemerides, satellite clocks, and satellite geometry that will be available when Block II GPS satellites are deployed may allow absolute positioning with sub-meter accuracies.

5.0 ACKNOWLEDGEMENTS

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