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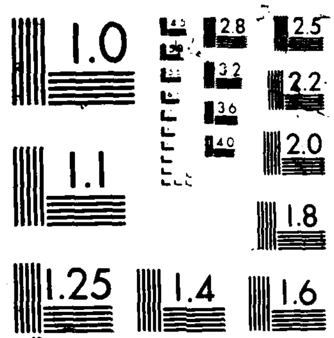
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A Consistent Geodetic Reference System for GPS

A. S. LIU
Systems and Computer Engineering Division
Engineering Group
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El Segundo, CA 90245-4691

AD-A191 415

27 February 1987

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Independent evaluation of the new GPS Operational Control System (OCS) is an Air Force objective. For this purpose, continuous counted, carrier tracked phase data of the six Navstar satellites from the Air Force Geophysics Laboratory's (AFGL) MIT receivers was requested. These data are combined with conventional GPS pseudo-range data to estimate the Navstar orbits and the GPS Intermediate Control System (ICS) station locations. It was discovered that the ICS station net was inconsistent with the AFGL/MIT receiver locations. The difference between the two reference systems is about 10 meters in longitude.

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I. INTRODUCTION

The ability to maintain a reliable and accurate Operational Control System (OCS) is a prerequisite for successful Global Positioning System (GPS) navigation performance. The OCS processes GPS Navstar pseudo-range data obtained from a network of monitor stations in order to make predictions of each GPS Navstar satellite position and clock, and formats these predictions into navigation messages which are then loaded into and broadcast by the Navstar satellites. A user desiring to navigate obtains Navstar position and clock information from these broadcasts which, together with measured pseudo-range to a number of Navstars, suffice to determine user position.

The analysis reported in this paper is part of a continuing effort on the part of the Air Force and The Aerospace Corporation to assure successful OCS performance. A most useful means of verifying OCS accuracy is the Very Long Baseline Interferometry (VLBI) technique, by which differenced range data are processed using the Aerospace TRACE program, independently of OCS software. The VLBI data are independent data, not derived from GPS monitor station pseudo-range data. To perform an initial evaluation of the potential of this procedure, appropriate data were requested from Air Force Geophysics Laboratory (AFGL) by the GPS Program Office.

Before meaningful assessments can be made, the GPS monitor station locations and the independent AFGL receiver locations must be in a consistent reference coordinate system. The coordinates of the current set of GPS monitor stations have been determined by the Defense Mapping Agency (DMA) using Transit satellites and other techniques. The AFGL receiver coordinates are referenced to the Polar Motion Analysis by the Radio Interferometric Surveying (POLARIS) network whose coordinates were determined by astronomical observations of natural radio sources such as quasars. The time reference (UT1) as well as the two small earth crustal rotational angles (x,y) of these observations are based upon U.S. Naval Observatory (USNO) and Bureau International des l'Heure (BIH) determinations of time and polar motion.

In combining the AFGL data with the GPS pseudo-range measurements of the Navstars, an inconsistency of about 20 meters between the GPS station network and the AFGL network was observed. Three possible causes of this inconsistency are discrepancies in UT1, (x,y), and station coordinates. Because GPS uses the same UT1 and (x,y) as is used by the POLARIS network, we conclude that the GPS station coordinates are referenced to a different geodetic reference system than the AFGL network. This report discusses the basis for this conclusion.

This 20-meter discrepancy was largely or entirely produced by the difference between the WGS-72 coordinate systems and the "VLBI" or AFGL coordinate system, which is the present basis of the current OCS reference system, WGS-84*.

*Private Communication, Dr. William Stein, Defense Mapping Agency

II. DATA CHARACTERISTICS AND PROCESSING

The Macrometers used are patented Aero Service Corp. receivers with six independent channels tied into a single, common cesium-based reference frequency. The original Macrometer design was improved upon by MIT under AFGL sponsorship and is now called MITES/Macrometers. The MITES are dual-band receivers which track both L-band signals from the Navstar satellites. In addition, the MITES use a hydrogen maser as a frequency reference. These receivers track the Navstar's L-band carrier frequencies (approximately 1542 and 1231 MHz) and continuously count the phase crossings of each carrier signal.

The AFGL data are Macrometer and MITES/Macrometer observations of Navstar satellites 1,3,4,6,8,9 during the period February 11 to 21, 1985. The measurements are referenced or "time tagged" to the USNO broadcast time standard. All receivers have a common reception time and are sampled every 608 seconds. As a result, when the so-called VLBI data are formed by differencing the phase measurements from two receivers at a common time point, the actual transmission times from the satellite for the two measurements are slightly different. In order to distinguish this type of data from true VLBI where the transmission time is common, but the reception times at the two ground stations are distinct, JPL has termed the former as DOR or differenced one-way range data. In this note, the terms VLBI and DOR are used synonymously and denoted as interferometric data.

In addition to the phase and DOR measurements, doubly differenced (DDOR) measurements are formed. These measurements are obtained by differencing DOR measurements from one satellite with DOR measurements from another satellite. These DDOR data, which are the difference of phase measurements between pairs of receivers (DOR) and also between pairs of satellites (DDOR), are free from clock effects (with the exception of constant phase offsets between receivers), and thus afford a possibly useful method to separate clock effects from ephemeris effects.

The Aero Service receivers are located at Woburn, Mass., and Phoenix, Arizona, and by virtue of being single band receivers, their data are uncorrected for time delays caused by the ionosphere. The MITES receivers are located at the POLARIS sites at Richmond, Florida; Fort Davis, Texas; and Haystack, Massachusetts. The difference in the delay times between the two L-band channels is used to correct one of the L-band signals for ionospheric time dilation effects. Unfortunately, only one pass of Haystack data was obtained, this station having failed after February 13.

In the case of the AFGL phase data, the receivers have an arbitrary offset at the beginning of each pass. As a result individual biases for each station and pass have to be taken into account. All time tags were decreased by 3 seconds to change the time base from USNO to GPS, and the cycle counts were scaled into units of meters. With the exception of the dual band correction of the ionosphere, the data received are essentially uncorrected. Therefore, tropospheric and general relativistic delays were added to the data, and the space signal delay (i.e., light time correction) was iteratively computed by TRACE.

For the GPS pseudo-range data, the measurements are derived from cross correlating the received code with a receiver-generated replica of the transmitted code. The cross correlation yields a time delay including a clock bias which defines the measurement. These measurements are time tagged with the GPS time reference system and then corrected and smoothed at the GPS master control station with a computer preprocessor called PREP/SMOOTH. Figure 1 shows the functions performed by PREP/SMOOTH. As seen in this figure, the space signal delay is estimated and subtracted from the observed receive time to yield an estimated transmission time. Further corrections for general relativistic effects, tropospheric and ionospheric delays are applied and the station aberrational effect is included. The station aberrational effect accounts for the earth rotation during light time transit of the signal. Thus no light transit solution during data processing is required. These smoothed, corrected, and re-time-tagged observations are used by TRACE for orbital and

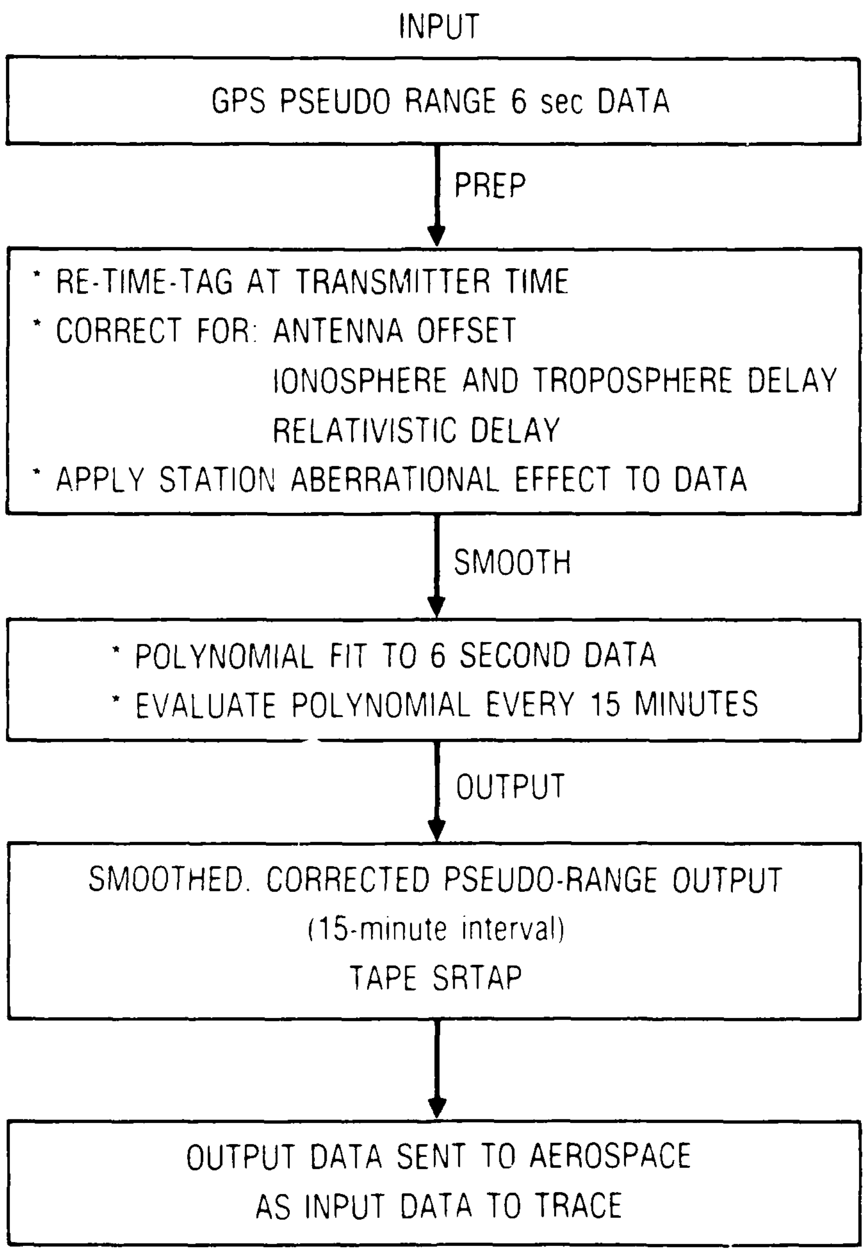

Fig 1. NSWC PREP/SMOOTH Program Functions

clock estimations. Because the GPS data are derived from code correlation, range bias offsets from pass to pass are not needed, and only one constant bias associated with one station need be considered.

The GPS pseudo-range data were combined first with AFGL phase data, then with DOR data and finally with DDOR data. NSWC bulletin values were used as starting conditions for the initial Navstar orbits, with timing and polar motion correction coefficients from the BIH bulletin. The AFGL station locations were given to us by MIT. For the DOR data, all phase differences are taken relative to Richmond, Fla. For the DDOR data all station phase differences are taken relative to Richmond and differences are taken between Navstar satellites as (NAV8-NAV3), (NAV6-NAV3) and (NAV4-NAV3). The input station locations are listed in Table 1. Figure 2 illustrates the geographic locations of the GPS and AFGL receivers. We see that the stations are widely distributed throughout the northern part of the western hemisphere. The GPS stations are the Intermediate Control System (ICS) stations. At the time the present analysis was undertaken, the new GPS Operational Control Systems (OCS) monitor stations and software were not yet operational.

Table 1. Tracking Stations Coordinates As Given by AFGL and GPS

STATION COORDINATES

AFGL stations	Latitude(deg)	Geocentric Longitude(deg)	Radius(km)
Richmond	25.464115	-80.384183	6374.1513
Ft. Davis	30.467022	-103.94738	6374.2055
Haystack	42.430623	-71.488149	6368.4685
Phoenix	33.230149	-111.89519	6372.0279
Woburn	42.321758	-71.143490	6368.4131

ICS GPS stations	Latitude(deg)	Geodetic Longitude(deg)	Altitude above Geoid (m)
Vandenberg	34.793460	-120.50821	154.950
Guam	13.616964	144.85916	208.960
Hawaii	21.522755	-157.99548	410.018
Alaska	61.283254	-149.82530	76.070

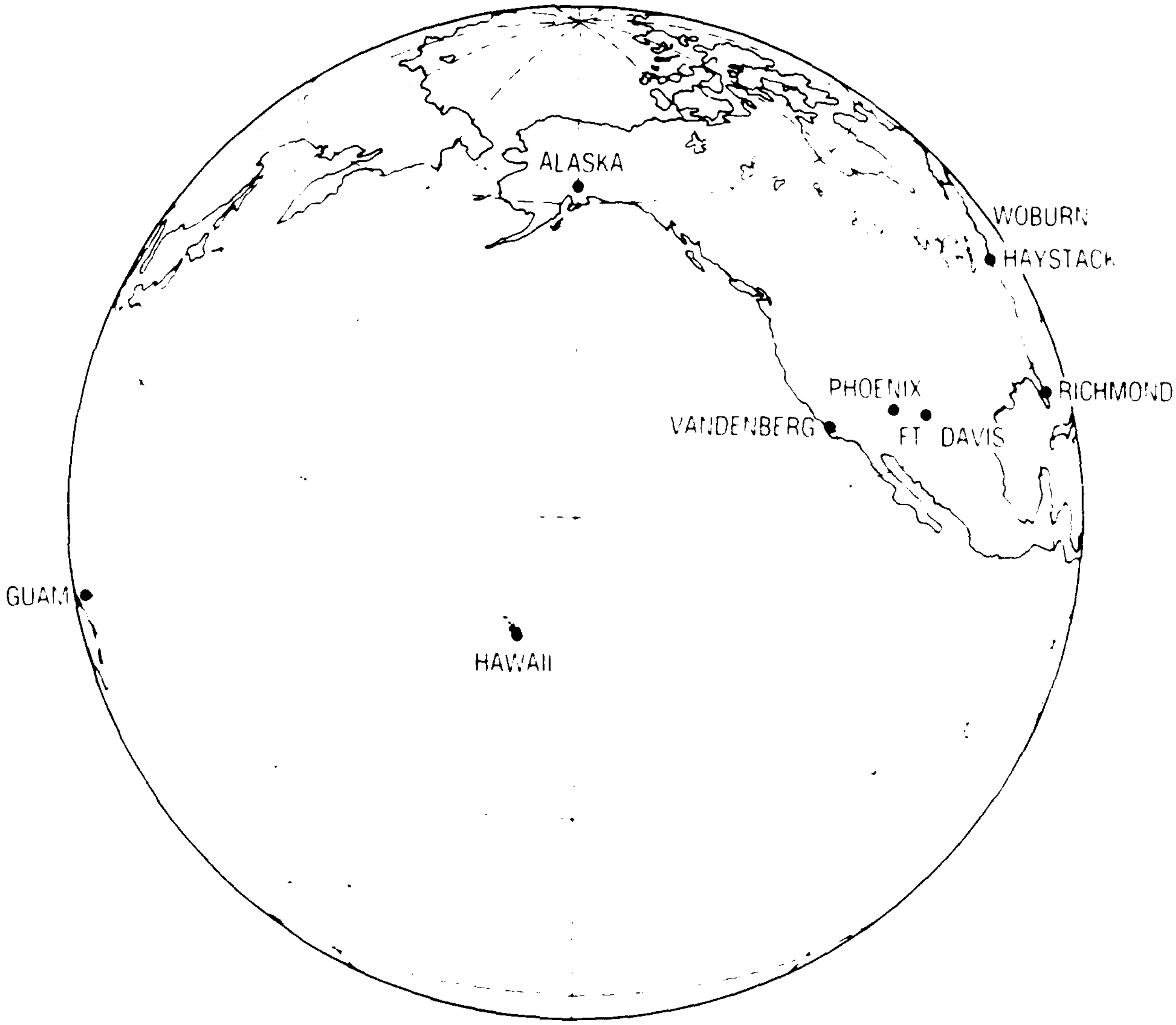

Fig. 2. ICS and AFGL Receiver Locations

III. SUMMARY OF RESULTS

A. DATA RESIDUALS

Examination of data residuals gives credibility to the resulting estimated parameters. We combined psuedo-range data with phase data and estimated the parameters listed in Table 2 for the Navstar satellites 3,4,6, and 8. In the following figures, ICS range refers to the pseudo range and MIT range refers to the AFGL phase data. MIT singly differenced range refers to the DOR data, and doubly differenced range to the DDOR data.

Table 2. Estimated Parameters

1. Six orbital initial conditions.
2. Solar radiation pressure constant for each Navstar satellite.
3. Y-axis acceleration constant for each Navstar satellite.
4. Phase bias for each station for each MITES pass.
5. Phase bias rate for each station.
6. Phase bias, rate, aging for each Navstar satellite clock.
7. GPS station longitude, latitude and altitude.

The ICS pseudo-range and MIT phase residuals for Navstar 3 are shown in Figures 3a and 3b. (The other Navstar residuals are essentially comparable). Figure 3a, labelled ICS range residuals, displays the residuals of the ICS pseudo range. From Figure 3a, we see that the ICS range residuals are on the order of 2 m or less. The MIT phase residuals shown in Figure 3b are on the order of 30 cm with the exception of Woburn. Woburn is a single frequency receiver and lacks ionospheric corrections and a hydrogen maser reference.

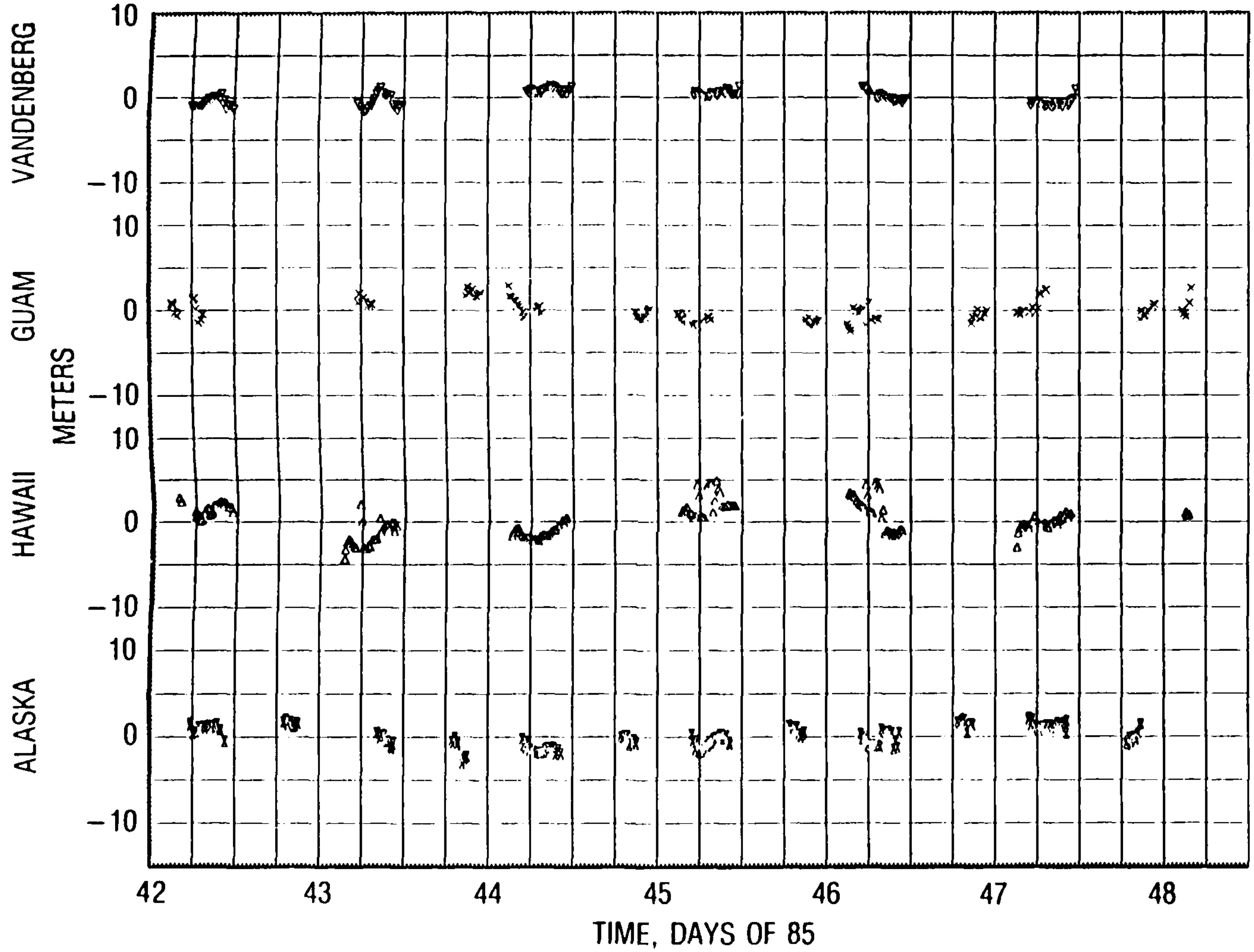

Fig. 3a. ICS Pseudo-range Residuals - Navstar 3

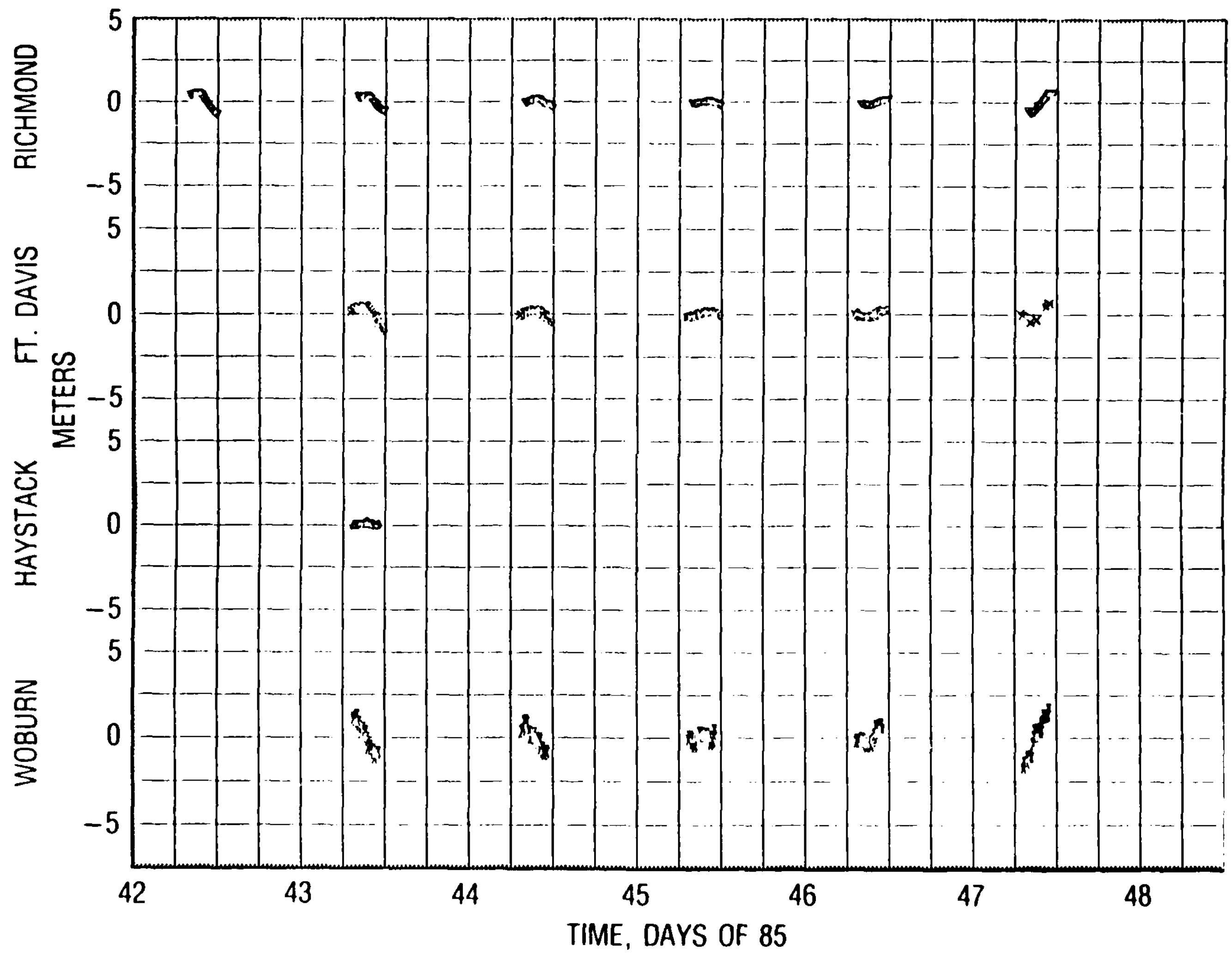

Fig. 3b. AFGL/MITES Macrometer Phase Residuals - Navstar 3

The results of combining ICS pseudo-range with MIT DOR data for Navstar 3 are shown in Figures 4a and 4b. (The other Navstar residuals are essentially comparable.) Figure 4a, labelled ICS range residuals, displays the residuals of the ICS pseudo range. Figure 4b shows the residuals of the DOR data. We see that the ICS range residuals are on the order of 2 m or less and the same as in Figure 3a. Because of the cancellation of common systematic errors, the MIT DOR residuals are on the order of 10 cm or less. Richmond is the reference station for the DOR data so no residuals are possible. Woburn has residuals of about 1 meter. Note again that Woburn is a single frequency receiver, lacks ionospheric corrections and a hydrogen maser reference.

The results of combining ICS pseudo-range with MIT DDOR data are shown in Figures 5, 6a, 6b, 7a, 7b, 8a and 8b for Navstar satellites 3, 4, 6, and 8. These residuals are a result of doing a simultaneous multi-vehicle solution for Navstar pairs (8-3),(6-3) and (4-3). Navstar 3 is the reference vehicle for the DDOR data, so no residuals are possible for this vehicle.

Figures 5 and 6a, labelled ICS range residuals, display the residuals of the ICS psuedo-range from Navstar 3 and 4. In Figure 6a, we see that the ICS range residuals for Navstar 4 have a noticeable sine wave pattern for all four GPS stations which is not present for Navstar 3 (Figure 5). Navstar 4 is periodically eclipsed by the earth and causes the sinusoid. The vehicles that are not periodically eclipsed do not have a sinusoid pattern in their residuals (Fig. 4a). The sinusoid is a clock effect and not due to a dynamical radiation pressure perturbation. This sinusoid can be removed by a simple clock correction without affecting any of the dynamical parameters.

Figure 6b shows the residuals of the DDOR data for the Navstar pair (4-3). The vehicle pair (4-3) is labelled as vehicle 4. Richmond is the reference station for the DDOR data so no residuals are possible. Because of the cancellation of common systematic errors, the MIT DDOR residuals are on the order of 8 cm or less.

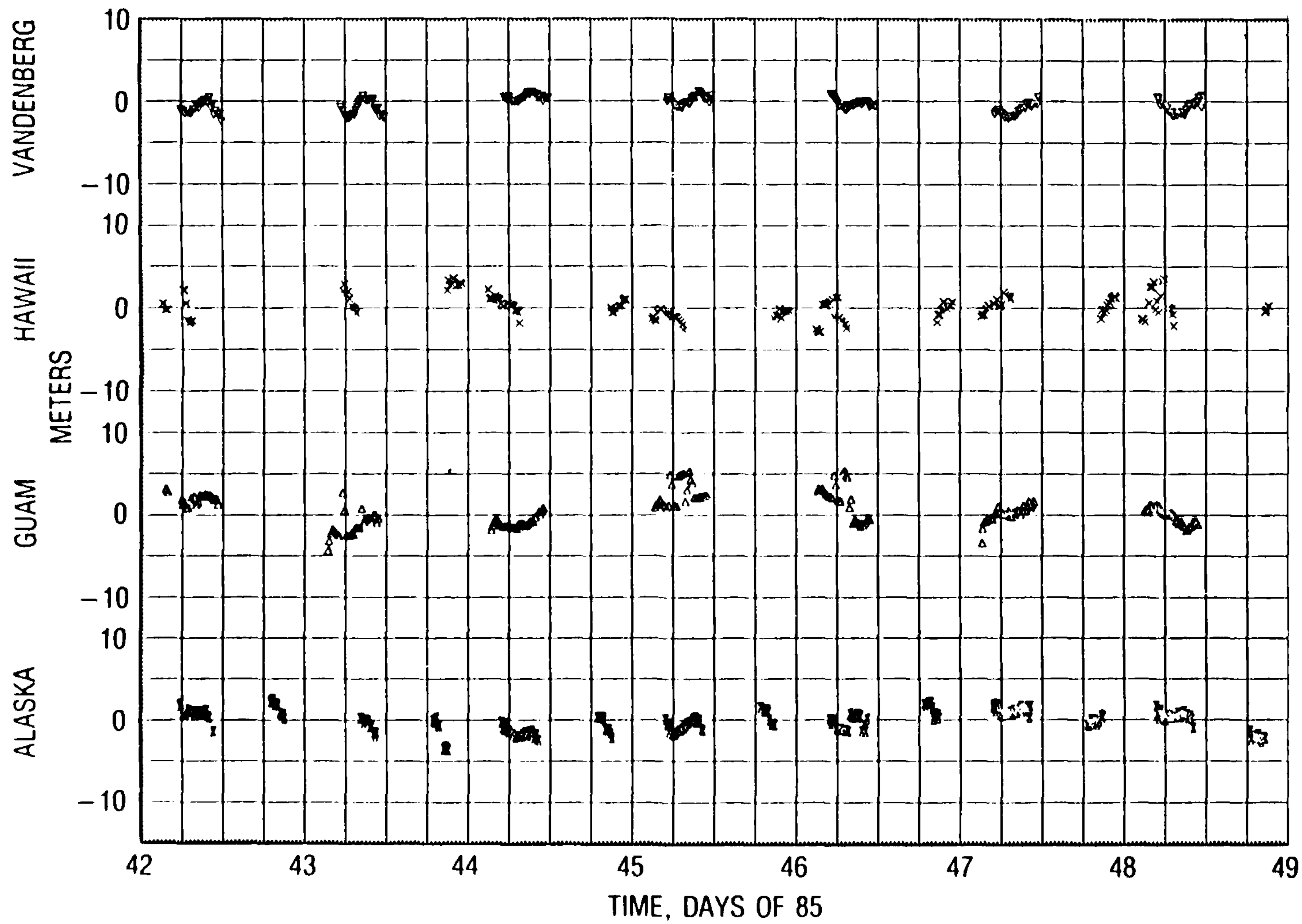

Fig. 4a. ICS Pseudo-range Residuals, Combined ICS/MIT DOR Data - Navstar 3

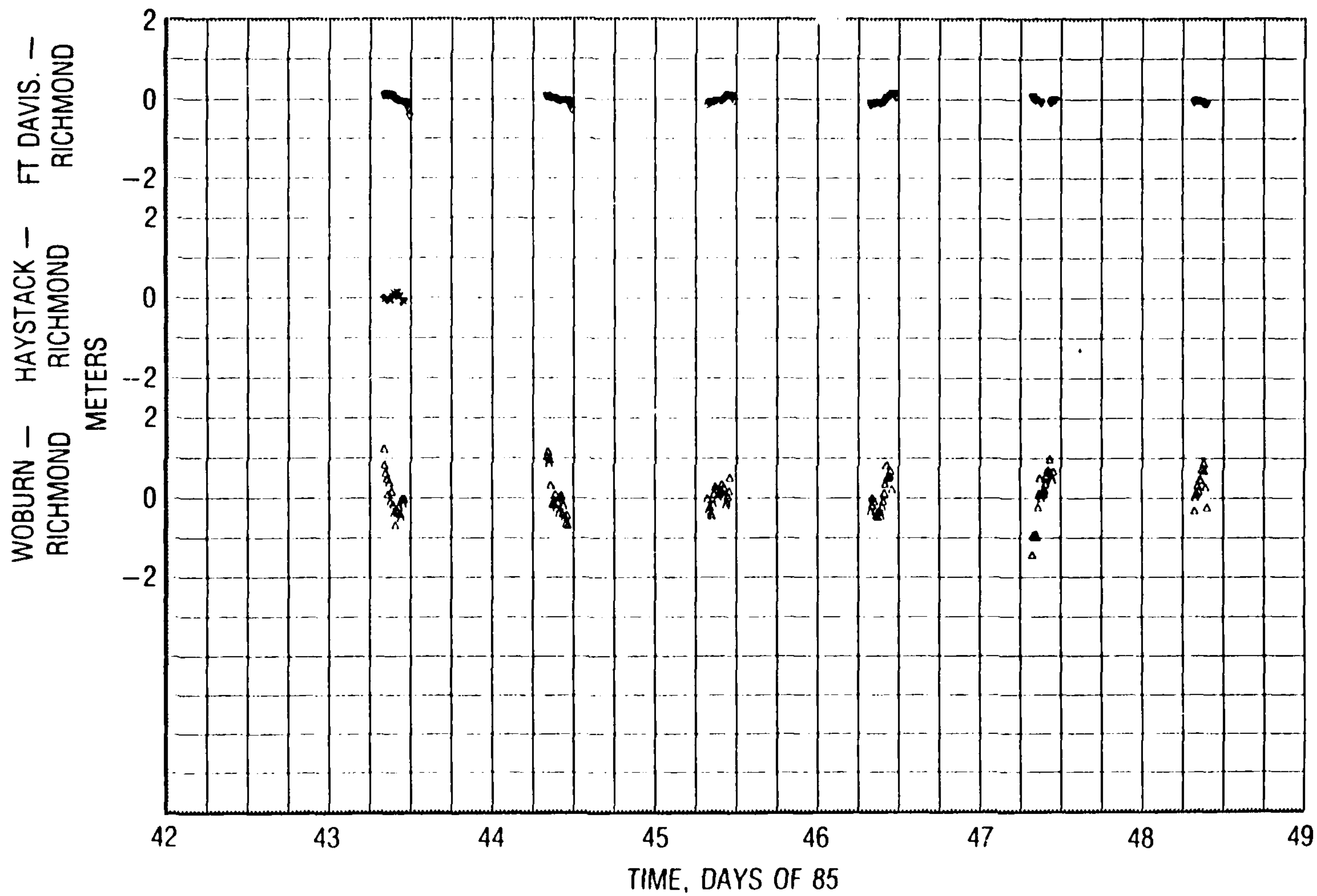

Fig. 4b. AFGL/MITES Macrometer DOR Phase Residuals - Navstar 3
Singly Differenced Data

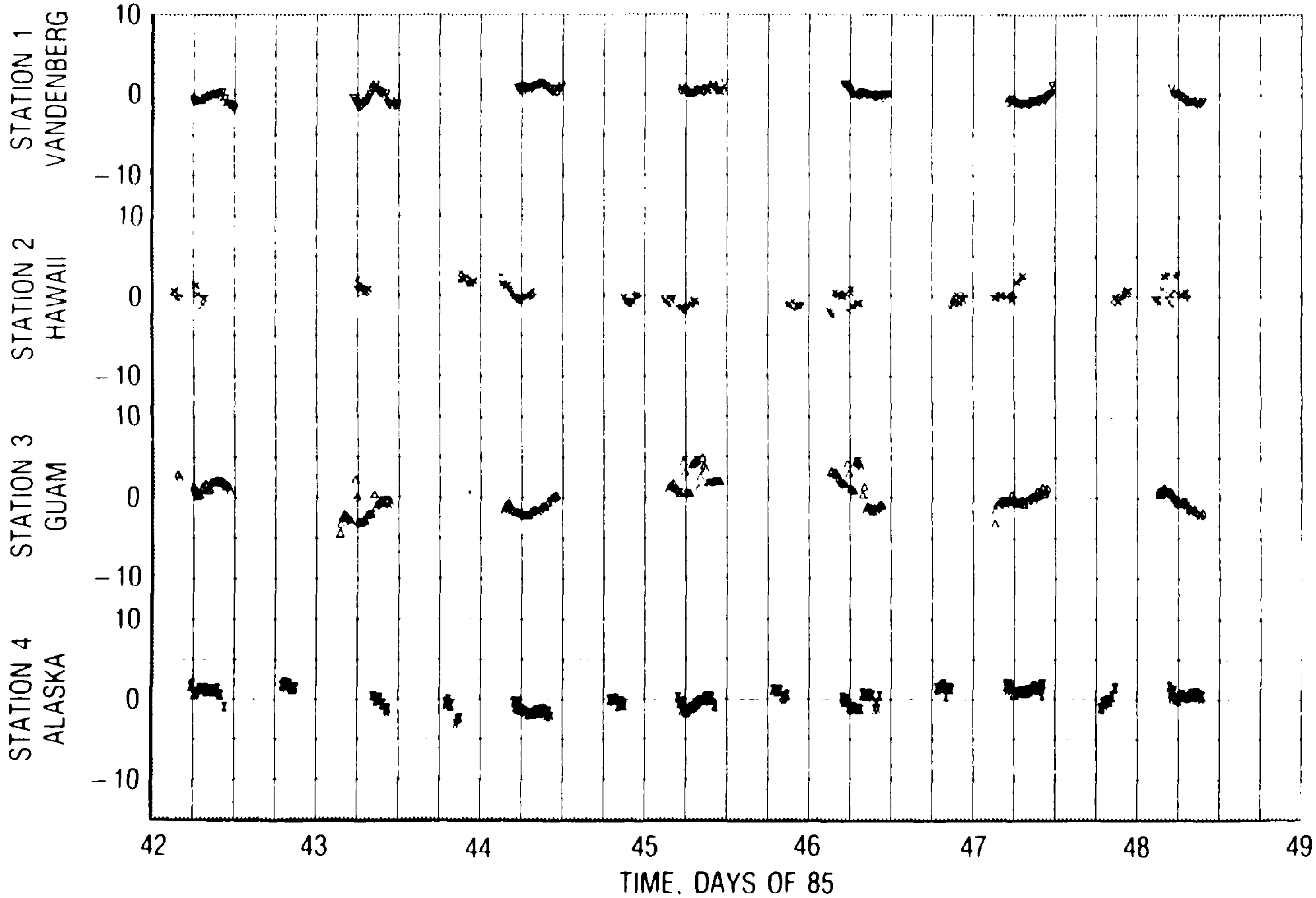

Fig. 5. ICS Pseudo-Range Residuals, Combined ICS/MIT DDOR Data – Navstar 3

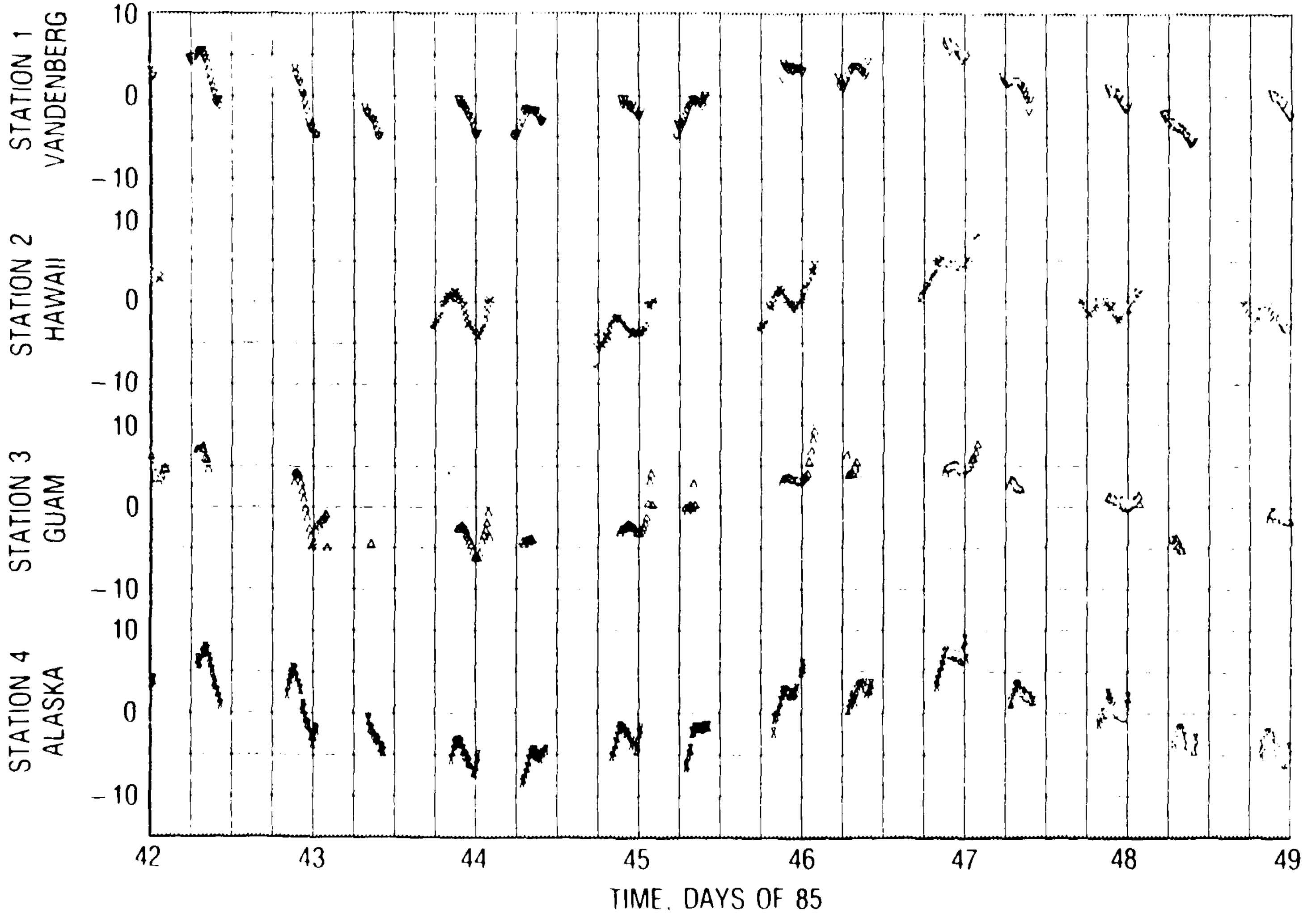

Fig. 6a. ICS Pseudo-range Residuals, Combined ICS/MIT DDOR Data - Navstar 4

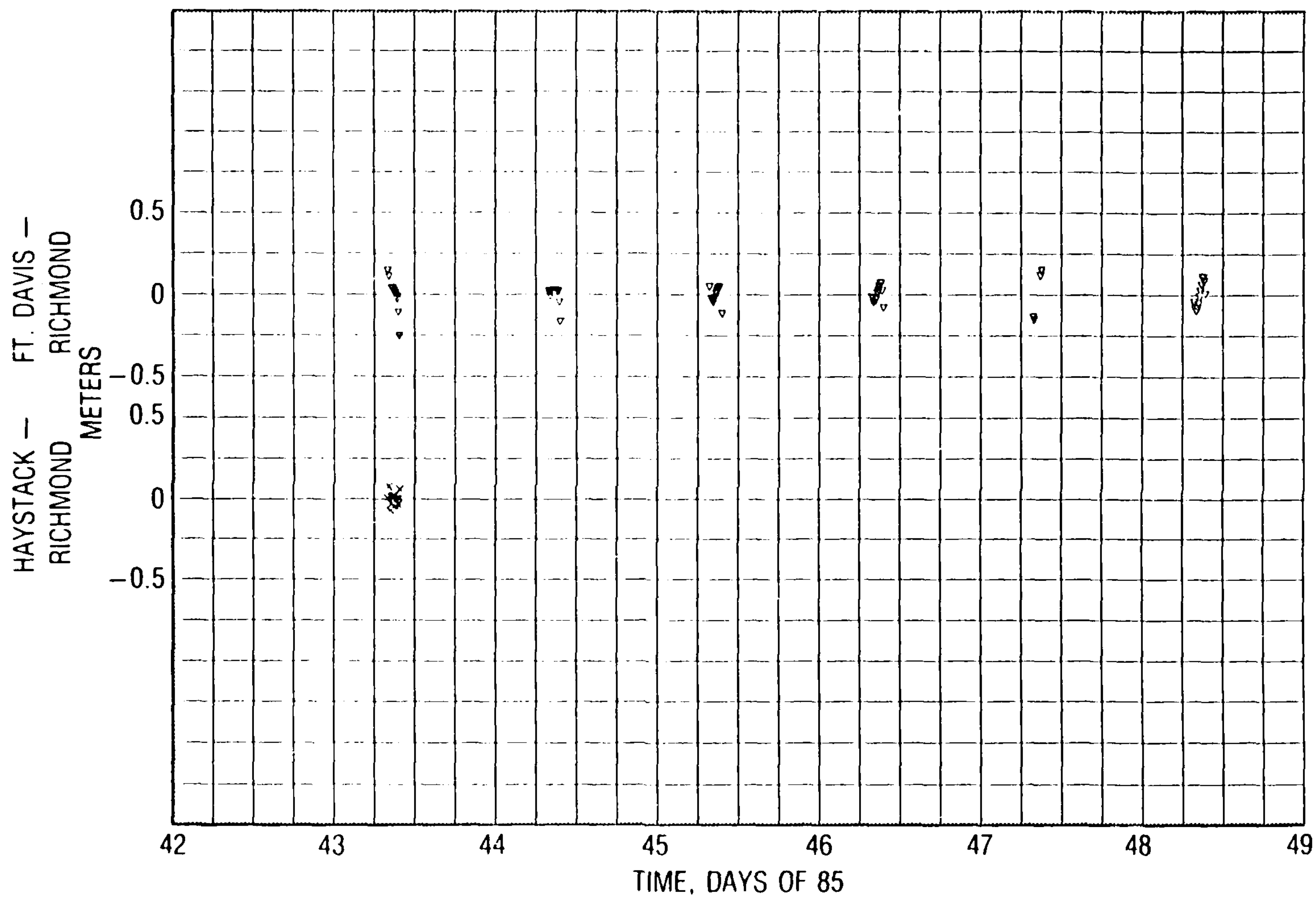

Fig. 6b. AFGL/MITES Macrometer DDOR Phase Residuals - Navstar 4 Doubly Differenced Data (NAV4 - NAV3)

Figures 7a and 7b are residuals of ICS pseudo-range and MIT DDOR data for Navstar 6 and Navstar pair (6-3).

Figures 8a and 8b are residuals of ICS pseudo-range and MIT DDOR data for Navstar 8 and Navstar pair (8-3). Because Navstar 8, like Navstar 4, is being periodically eclipsed by the earth, a sinusoid pattern in the pseudo-range residual appears in Figure 8a for all four GPS stations, like Navstar 4 in Figure 6a. The DDOR residuals in Figure 8b show a repetitive pattern for each pass. The cause for this pattern is not yet completely understood and is currently under investigation.

B. STATION LONGITUDE SOLUTION

The adjustments to the GPS ICS station longitudes are shown in Table 3. In the solution for these station locations, the reference system was chosen to be the AFGL network (i.e., the AFGL coordinates were held fixed). The AFGL network is tied to the VLBI reference system which in turn is based upon astronomical observations. The results presented here are interpreted as the necessary adjustments to bring the GPS network, which is based upon a DMA determined coordinate system, into alignment with the astronomically based VLBI system.

In using GPS pseudo-range data with MIT phase and DOR data, individual station estimates were obtained for each Navstar satellite separately. With the exception of the Navstar 4 solution, all values tended to be on the order of about 15 to 20 meters. The solution for Navstar 4 is distorted because of its clock being affected by the earth eclipses. The residuals for this solution are seen in Figure 6b. For the doubly differenced solution (DDOR), all vehicles are used for a common station location solution. The result is one set of values for each GPS station.

As can be seen, the station location solutions resulting from using pseudo-range and MIT phase, DOR and DDOR data, are all positive with a magnitude of about 15 to 20 meters, indicating that the GPS network should be shifted eastward by that amount.

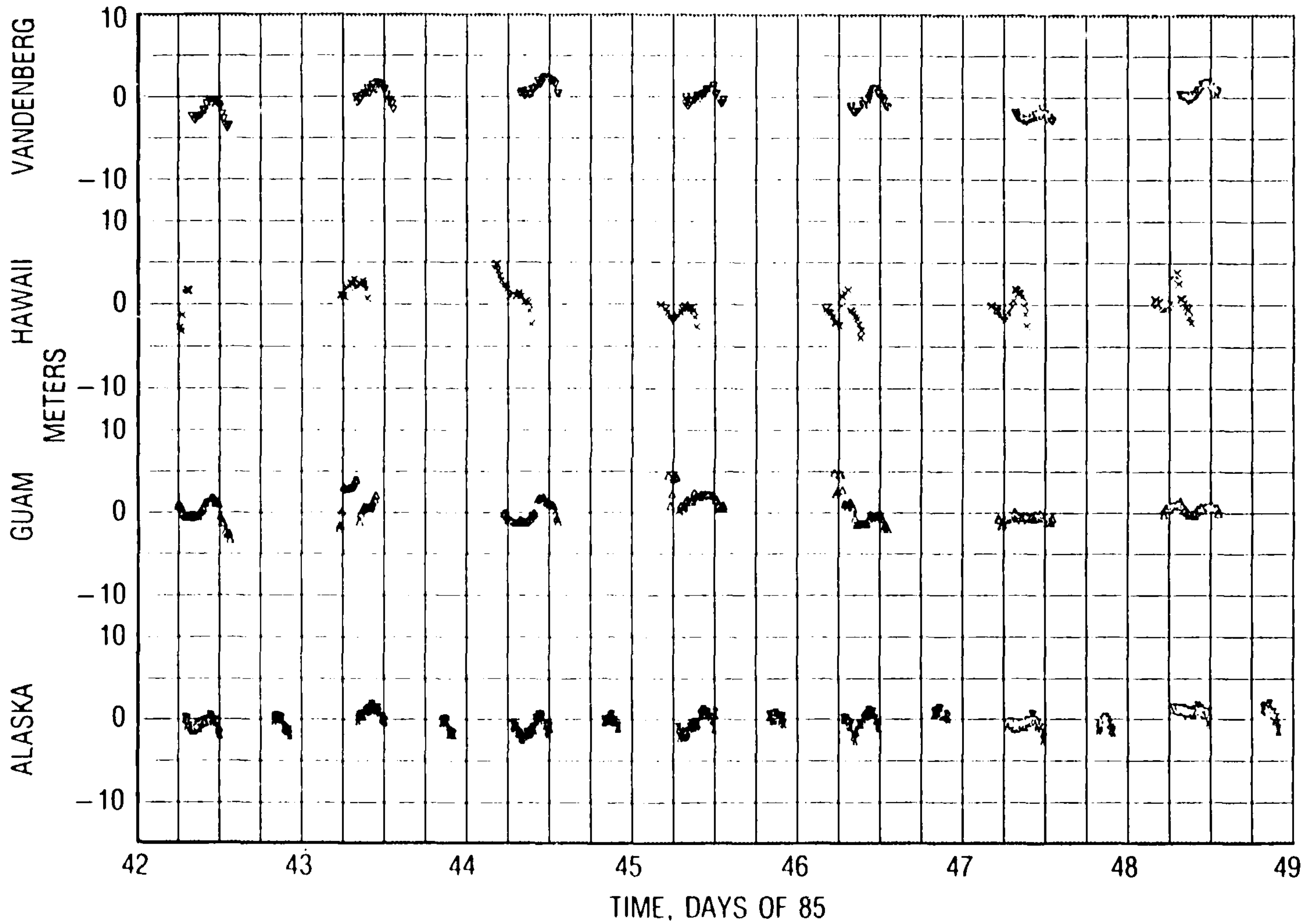

Fig. 7a. ICS Pseudo-range Residuals, Combined ICS/MIT DDOR Data - Navstar 6

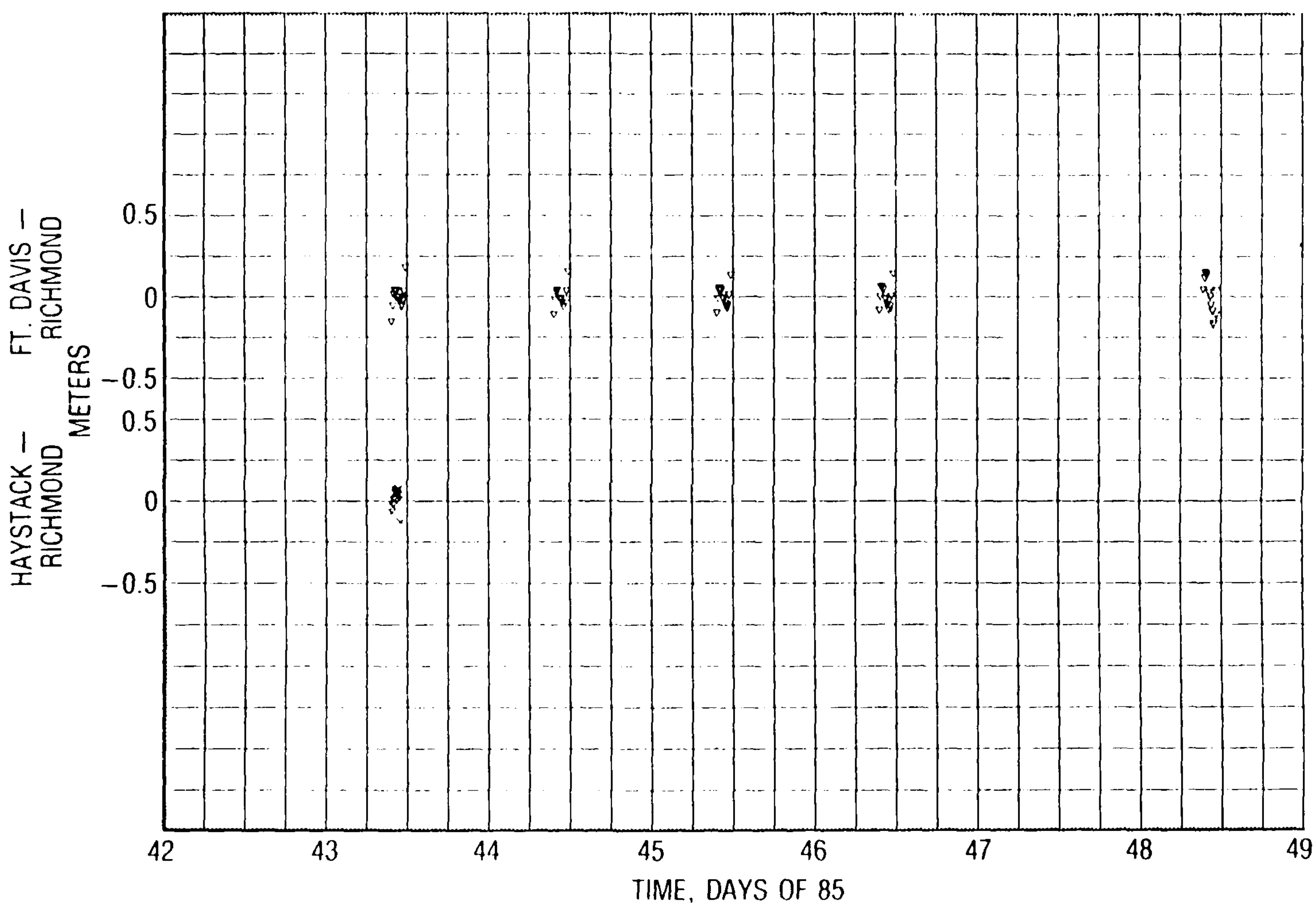

Fig. 7b. AFGL/MITES Macrometer DDOR Phase Residuals - Navstar 6 Doubly Differenced Data (NAV6 - NAV3)

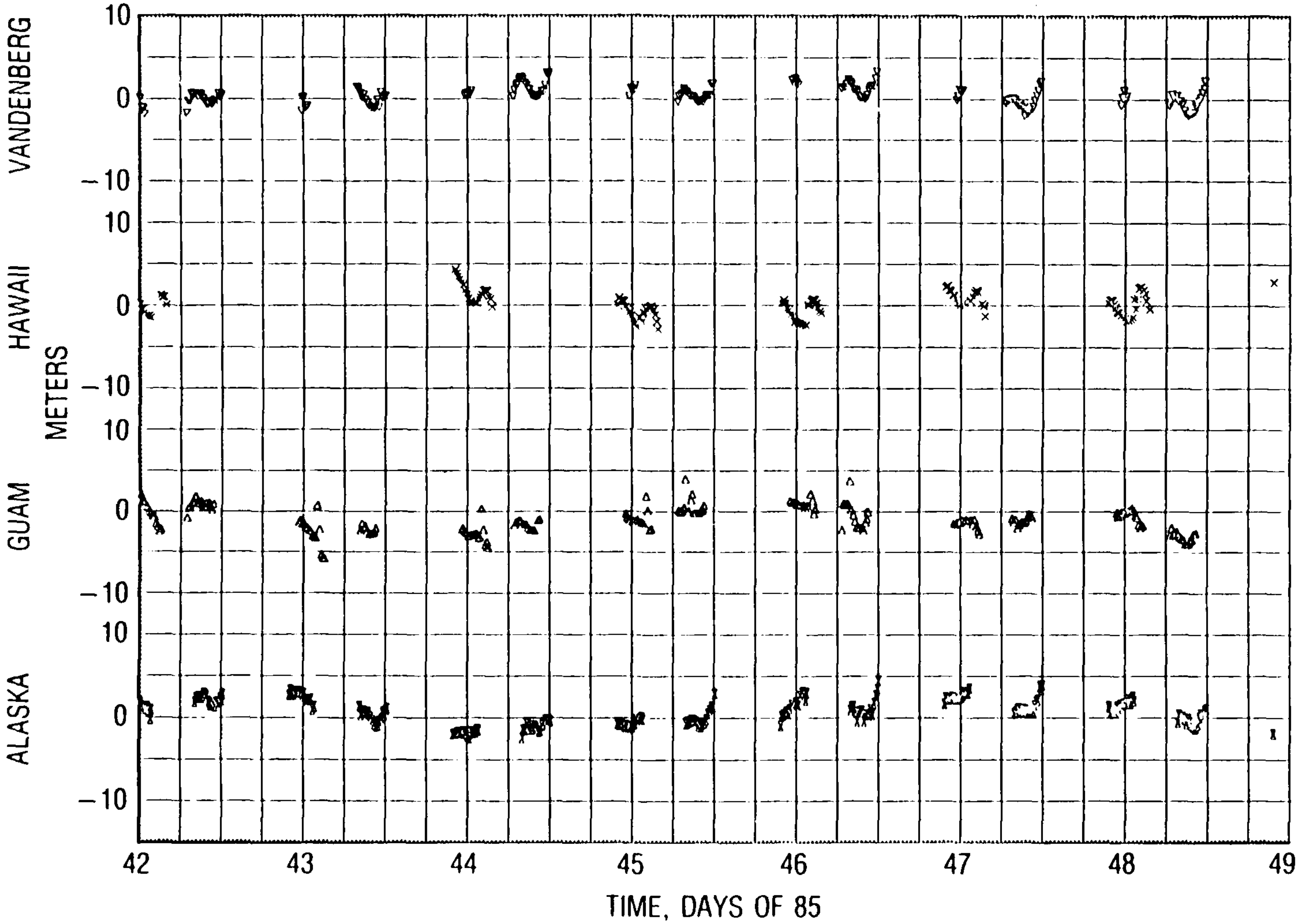

Fig. 8a. ICS Pseudo-range Residuals, Combined ICS/MIT DDOR Data – Navstar 8

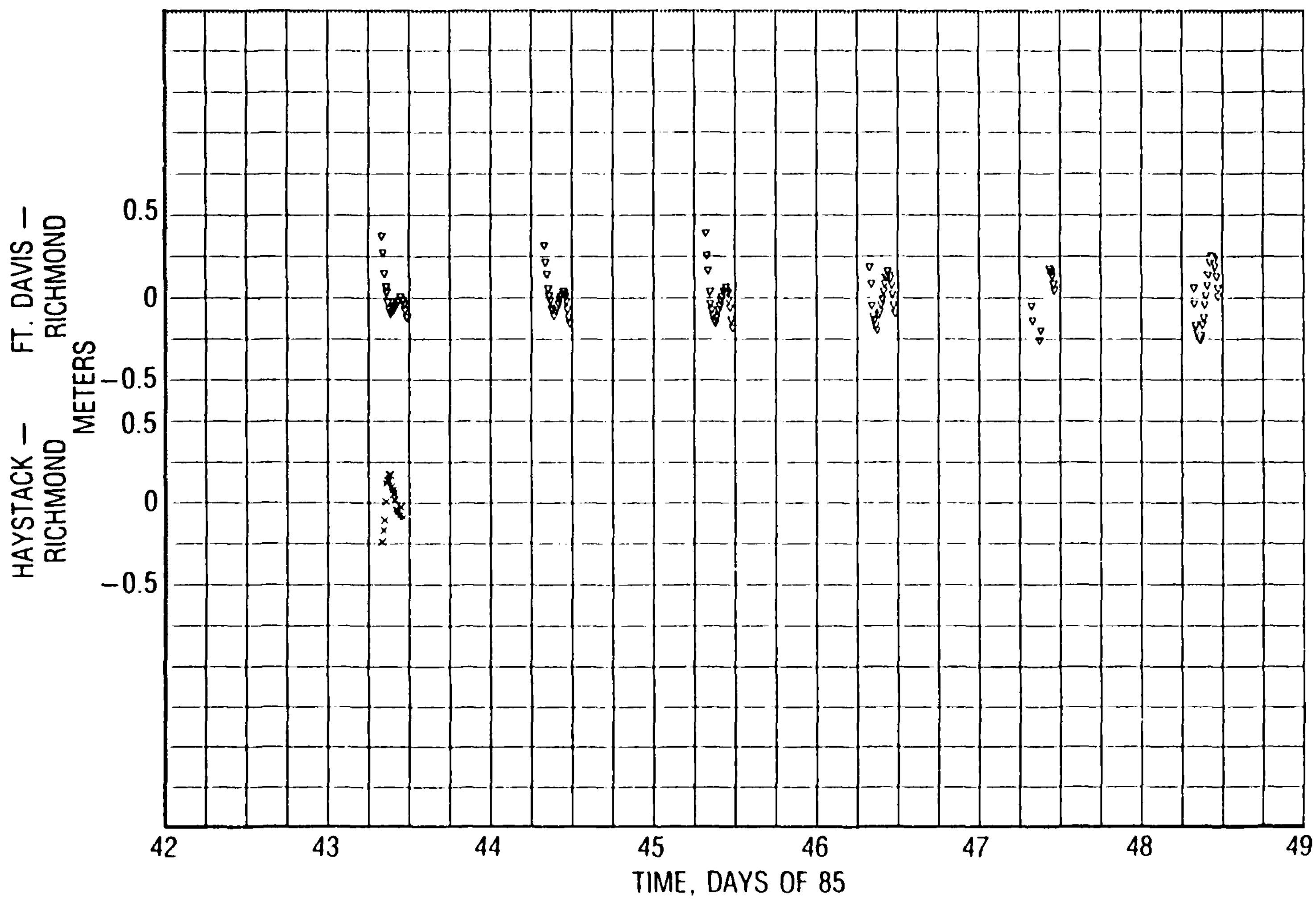

Fig. 8b. AFGL/MITES Macrometer DDOR Phase Residuals - Navstar 8
Doubly Differenced Data (NAV8 - NAV3)

Table 3. Longitude Shift in 10^{-5} Degrees

10^{-5} degs approx 1.1 meters

ONE WAY PHASE SOLUTION

STATION

NAV	Vandenberg shift	Vandenberg sig	Guam shift	Guam sig	Hawaii shift	Hawaii sig	Alaska shift	Alaska sig
3	15.6	2.	15.5	2.	20.6	2.	17.5	2.
4	23.2	3.	15.1	2.	25.7	2.	24.4	2.
6	10.5	2.	20.6	3.	16.7	2.	17.5	2.
8	13.0	1.	10.2	1.	14.1	1.	13.4	1.
Weighted Mean	13.7	1.	12.5	1.	17.1	1.	16.1	1.

INTERFEROMETRIC (DOR) SOLUTION

STATION

NAV	Vandenberg shift	Vandenberg sig	Guam shift	Guam sig	Hawaii shift	Hawaii sig	Alaska shift	Alaska sig
3	18.5	2.	17.1	2.	21.4	2.	19.0	2.
4	17.1	3.	9.7	3.	23.4	3.	21.4	3.
6	15.7	5.	23.6	5.	20.3	5.	19.0	5.
8	22.3	5.	18.4	4.	22.1	4.	21.7	4.
Weighted Mean	18.2	2.	17.6	1.	24.9	1.	25.8	2.

DOUBLE DIFFERENCE (DDOR) SOLUTION

NAV pairs (6-3,4-3,8-3)

STATION

Vandenberg shift	Vandenberg sig	Guam shift	Guam sig	Hawaii shift	Hawaii sig	Alaska shift	Alaska sig
15.9	1.	11.4	1.	17.9	1.	17.1	2.

IV. CONCLUSIONS

Our original goal was and remains the investigation of the value of independent data and software for checking the operational GPS orbit determination process. We discovered that the inconsistency of the GPS tracking station network with the AFGL network hampers a valid assessment. The problem is a longitude difference of about 20 meters between the GPS network and the astronomical system. When the appropriate station adjustments are made simultaneously with orbit parameters, radiation pressure constants, and data biases, the resulting residuals are about 2 meters for the GPS pseudo-range and about 30 cm or less for the AFGL phase, and less than 10 cm for singly differenced and doubly differenced phase data. The AFGL phase data, which is carrier tracked, is inherently less noisy (on the order of about 2 cm) than the GPS pseudo-range which is code tracked, and whose accuracy is on the order of about 1 meter. The AFGL phase data, however, suffer from the classical phase or cycle ambiguities from pass to pass, (i.e., the phase continuity is lost at the beginning of each pass). GPS pseudo-range only has a constant clock offset between the ground receiver and spacecraft transmitter. With this single exception, range (or phase) continuity is preserved from pass to pass.

At this level, many small effects must be considered and possibly reanalyzed. General relativistic effects, which could be approximated by a post-Newtonian theory, are not included. The post-Newtonian approximation could be in two parts: (a) a dynamical perturbation causing a perigee precession, and (b) a perturbation of the received signal. In TRACE, the first effect is ignored, and the second effect is included but needs to be re-examined. When data analysis approaches the accuracy of meters or sub-meters, refraction and differential (i.e., second order) refraction begin to have an important effect. For the AFGL phase, DOR, and DDOR data, refraction and differential refraction are computed in TRACE. These atmospheric refraction corrections should be reanalyzed to see if better methods for correction (e.g., in-situ measurements by water vapor radiometers, two color refractometers) exist, or if better atmospheric refraction calculations (e.g., complete ray tracing) than the current Hopfield algorithms used in TRACE are available.

This analysis exhibits an example of the benefits to be gained by using independent data (VLBI) to validate the operational system. Once the discrepancy was discovered, its cause could be identified: namely, the fact that the two networks are on different geodetic reference systems.

V. GLOSSARY AND DEFINITIONS

AFGL	Air Force Geophysics Laboratory
BIH	International Bureau of Longitude (Bureau International des l'Heure)
DMA	Defense Mapping Agency
DOR	Singly differenced (between stations) phase data
DDOR	Doubly differenced (between station pair and Navstar pair) phase data
GPS	Global Positioning System
MIT	Massachusetts Institute of Technology
MITES	MIT improved AFGL receivers
Navstar	GPS Navigation Satellite
NSWC	Naval Surface Weapons Center
OCS	GPS Operational Control System
POLARIS	Polar Motion Analysis by Radio Interferometric Survey
Pseudo-range data	Code tracked range data with arbitrary bias
Phase data	Carrier tracked, continuously counted zero phase crossing
USNO	U. S. Naval Observatory
VLBI	Very Long Baseline Interferometry

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