AD-A261 011

BRIDGING THE GAP BETWEEN TRANSIT AND GPS POINT POSITIONING – IMPLICATIONS OF HIGHER-ORDER IONOSPHERIC REFRACTION ON THE REALIZATION OF THE WGS 84 REFERENCE FRAME

BY PATRICK FELL   EVERETT SWIFT   JAMES CUNNINGHAM
STRATEGIC AND SPACE SYSTEMS DEPARTMENT

STEPHEN MALYS
DEFENSE MAPPING AGENCY

OCTOBER 1992

DTIC
ELECTE
MAR 0 8 1993
S E D

NAVAL SURFACE WARFARE CENTER
DAHLGREN DIVISION
Dahlgren, Virginia 22448-5000

93-04882

93 3 8 021

BRIDGING THE GAP BETWEEN TRANSIT AND GPS POINT POSITIONING – IMPLICATIONS OF HIGHER-ORDER IONOSPHERIC REFRACTION ON THE REALIZATION OF THE WGS 84 REFERENCE FRAME

BY PATRICK FELL   EVERETT SWIFT   JAMES CUNNINGHAM
STRATEGIC AND SPACE SYSTEMS DEPARTMENT

STEPHEN MALYS
DEFENSE MAPPING AGENCY

OCTOBER 1992

FOREWORD

This document examines the source of the scale difference between Transit and GPS satellite point positioning and infers the relationships in scale between the WGS 84 frame, as realized by its implementations through Transit and GPS satellite data reductions, and other terrestrial reference frames. The work was performed in the Space and Surface Systems Division of the Strategic and Space Systems Department and at the Defense Mapping Agency.

The authors would like to acknowledge C. Harris Seay for providing several of the simulated Doppler point positioning results used in this analysis and Bonnie Cannon for providing monthly readjustments of the Doppler network from 1987 to 1989.

This document has been reviewed by J. L. Sloop, Head, Space and Surface Systems Division.

Approved by:

R. L. SCHMIDT, Head
Strategic and Space Systems Department

DTIC QUALITY INSPECTED 1

Accesion For		
NTIS CRA&I		☑
DTIC TAB		☐
Unannounced		☐
Justification		
By		
Distribution /		
Availability Codes		
Dist	Avail and / or Special	
A-1		

ABSTRACT

This report examines the source of the scale difference between Transit and Global Positioning System (GPS) satellite point positioning and infers the relationships in scale between the World Geodetic System 1984 (WGS 84) frame, as realized by its implementations through Transit and GPS satellite data reductions, and other terrestrial reference frames. The results clearly illustrate the important distinction between the definition of a coordinate system and the realization of a reference frame.

CONTENTS

ILLUSTRATIONS

TABLES

INTRODUCTION

The World Geodetic System 1984 Conventional Terrestrial System (WGS 84 CTS)[1] was defined by modifying the Navy Navigation Satellite System or Transit System reference frame, known as 9Z-2, in scale (−0.6 ppm), in orientation (0.814 arcsec westward rotation) and by shifting the origin 4.5 m along the negative z-axis. Analogous to the previously defined Bureau International de l'Heure (BIH) CTS, the origin of the WGS 84 coordinate system is the center of mass of the Earth; the WGS 84 z-axis is parallel to the direction of the Conventional Terrestrial Pole (CTP) for polar motion as defined by the BIH; the x-axis is the intersection of the WGS 84 reference meridian and the plane of the CTP's equator; and the y-axis completes a right-handed system.

The operational implementations of this coordinate system were accomplished by either of two procedures, depending on requirements: The first consisted of geometrically transforming previously established NSWC 9Z-2 (or WGS 72) Doppler coordinates according to the definition of the WGS 84 CTS; the second consisted of estimating coordinates from Doppler data using precise Transit satellite ephemerides provided in the WGS 84 frame. This latter procedure required that the global Doppler network of satellite tracking stations be known in the WGS 84 reference frame prior to orbit estimation. The development of these tracking station coordinates was based on an iterative procedure of successive orbit determination and point positioning with the goal of producing a self-consistent 60 station network using Transit. The resulting coordinates, chosen as the official WGS 84 station coordinate set, were consistent to within 1 m in scale and z-axis parameter and consistent in longitude, with tracking station coordinates geometrically transformed from NSWC 9Z-2.[2] An independent evaluation of the difference between transformed NSWC 9Z-2 positions and the official WGS 84 Doppler coordinates for the stations provided a mean scale difference of 78 cm.[3] This second study, however, was not based on an identical station set (50 of the original 60 Doppler stations) and used slightly different 9Z-2 starting coordinates.

The estimated coordinates for the Doppler network were adopted by the Defense Mapping Agency (DMA) for the production of precise ephemerides for the Transit satellite system on 1 January 1987.[2] Notationally, this reference frame implementation, based on Doppler data collected during 1985, will be denoted as WGS 84 D85.

As part of an operational transition from Transit to the Global Positioning System (GPS) for point positioning, the DMA adopted WGS 84 coordinates for the GPS network whose tracking data are the basis for its precise GPS ephemerides. These tracking stations were surveyed, then positioned within WGS 84, using Transit Doppler. The Doppler data survey reductions were based on Transit ephemerides produced at DMA and therefore might be expected to be on WGS 84 D85. Table 1 provides the resulting coordinates for the Air Force Operational Control Segment (OCS) stations and the DMA stations comprising the 10-station GPS network. The date of each Doppler survey is provided in the table and represents the epoch when the data were collected. Although many of the stations were surveyed prior to 1 January 1987 (as early as October 1985), Doppler data reductions for all of these stations were based on recomputed Transit orbits estimated using the WGS 84 gravity model and WGS 84 D85 tracking station coordinates. GPS satellite ephemerides estimated with pseudorange data from this network support point positioning using either accumulated phase or pseudorange observations.[4, 5]

The above circumstances, therefore, would imply that GPS point positioning results are with respect to WGS 84 D85. However, over the past several years, comparisons of GPS and Transit point positioning results have revealed systematic height differences at a number of stations.[5, 6, 7] The mean of these differences for any group of stations generally exceeds 1 m, implying that a systematic scale difference exists between WGS 84 D85 and any WGS 84 realization based on GPS.[5, 6, 7]

TABLE 1. WGS 84 DOPPLER DERIVED COORDINATES FOR
OCS AND DMA GPS STATIONS

	DMA Station No.	Location	Longitude (deg)	Latitude (deg)	Height (km)	Survey Date
OCS	85128	Colorado Springs	255.4754142	38.8030569	1.91296	Oct 85
	85129	Ascension	345.5878714	−7.9513322	0.10784	Nov 85
	85130	Diego Garcia	72.3631217	−7.2665514	−0.06153	Feb 86
	85131	Kwajalein	167.7305353	8.7225006	0.04136	Apr 86
	85132	Hawaii	201.7606878	21.5614897	0.42972	Apr 86
DMA	85262	Australia	138.6547978	−34.6739325	0.03692	Sep 86
	85263	Argentina	301.4807053	−34.5737014	0.04947	Nov 85
	85264	England	358.7159244	51.4537958	0.16907	Dec 85
	85265	Bahrain	50.6081392	26.2091350	−0.01211	May 87
	85266	Ecuador	281.5064000	−0.2151528	2.92475	Feb 87

EFFECT OF IONOSPHERIC REFRACTION ON
SATELLITE POINT POSITIONING

Ionospheric induced refraction, affecting observations made from orbiting satellites, has been traditionally reduced by combining measurements made at two coherent frequencies. This two-frequency measurement technique removes the greater part of this effect and provides, for instance, Doppler range differences that are significantly closer to the geometric range differences between the satellite and observing station over the observation interval, all other errors being ignored. However, residual error in range (or Doppler) measurements due to the ionosphere may have a significant effect on satellite point positioning accuracy, depending on the frequency of the satellite signal and other factors. For Transit satellite frequencies of 150 and 400 MHz, various authors have examined the structure[8,9] of this error or its impact[9,10] on Transit point positioning. Figure 1, for instance, provides examples of ellipsoidal height variations (up to 300 cm) due to higher order ionospheric effects. These results were based on simulations of point positioning, using Doppler data collected over 6-day spans.[10] It is evident from the figure that the impact of the ionosphere will depend on several factors including solar activity and location relative to the geomagnetic equator. Other factors effecting the results are the satellite's radiated frequencies and the orientation of the orbit plane to the Earth-Sun line. The correlation between time dependent variations in Doppler derived ellipsoidal heights and smoothed sunspot numbers has been examined in North America,[11] and methods have been derived to provide partial compensation for these effects.[9,11]

As a particular example of these effects, ionospheric residual range errors at Transit frequencies (computed by ray tracing through an ionospheric model at eight geographic locations) were considered.[8] The model for the ionosphere was typical of the world at 1800 UT with a Zurich sunspot number of 50. Trends in the resulting two-frequency corrected ionospheric residual range errors were functionalized with elevation angle α as the independent variable. The chosen form for the function was the simple exponential

$$r(\alpha) = ae^{-b\alpha} \quad (\alpha \text{ in degrees})$$

providing the residual range error $r(\alpha)$ in units of meters. The parameters of the model for three of the evident trends in the residual range errors were

$$r_1(\alpha): \quad a = 4.94 \quad b = 0.0689$$
$$r_2(\alpha): \quad a = 2.73 \quad b = 0.0623$$
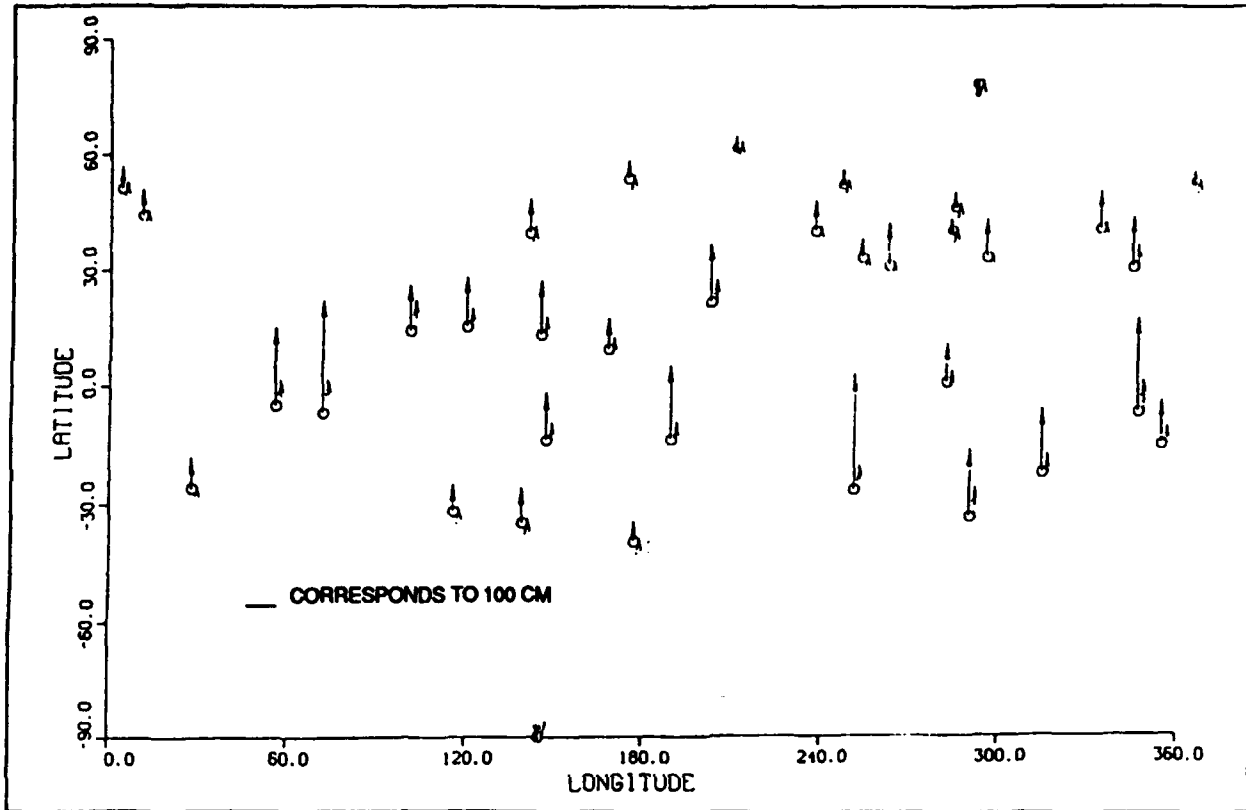$$r_3(\alpha): \quad a = 1.10 \quad b = 0.0523$$

FIGURE 1. THIRD-ORDER IONOSPHERIC EFFECT ON COMPUTED STATION
HEIGHTS FOR SOLAR FLUX LEVELS OF 100 AND 200

Application of this model to generate residual range difference errors for simulated Doppler data is dependent on location and local time at an observation site and on the distribution of the vertical columnar electron content within this simulated ionosphere.[8] For the two station locations chosen for this evaluation (0- and 45-deg North latitude, 280-deg East longitude), the selection of the particular model parameters a and b at any observation time was based on the global contour of total electron content for the simulated ionosphere, assuming this distribution remained fixed with respect to inertial space during the observation period. Model 1 was selected for use during hours when electron content above the station was highest; Model 3 was chosen during ionospherically quiet periods.

These residual errors were applied to Doppler range differences simulated over a 7-day interval using ephemerides for Transit Satellite 115 as computed by DMA. As a result of these errors, adjustments to the stations geodetic coordinates occur as provided in Table 2.

4

TABLE 2. GEODETIC COORDINATE ADJUSTMENT DUE TO HIGHER
ORDER IONOSPHERIC REFRACTION

Station	Latitude (cm)	Longitude (cm)	Height (cm)
A	−6.4	18.3	149.9
B	−12.2	1.8	154.4

This example again illustrates that coordinates derived from Doppler data subject to typical higher order ionospheric refraction are systematically higher, in this case by 150 cm, than their true ellipsoidal height. These results are consistent with those previously reported, based on simulations[10] and on actual data reductions.[9]

It is particularly interesting to consider the gross effect of residual ionospheric refraction on the realization of a geodetic reference frame established using Transit Doppler. During the period from January 1987 to October 1989, coordinates for stations comprising the DMA Doppler network were individually readjusted on a monthly basis using tracking data from the last 2 weeks of each month. This readjustment served solely as a diagnostic test as the official coordinates for the network were held fixed in WGS 84 D85 for orbit production at DMA. The Transit precise ephemerides used in these adjustments were therefore in the WGS 84 D85 system by virtue of the adopted Doppler station coordinates and other WGS 84 parameters. The number of stations adjusted each month varied from an initial group of around 50 stations to a reduced set of approximately 35 stations mainly because several stations were relocated, thus breaking continuity for some of the stations in the original 1985 solution. This primarily impacted a subset of those stations not used for Transit orbit determination.

After each monthly network adjustment, a seven-parameter transformation was determined between the official WGS 84 D85 coordinates and the readjusted station coordinates. Figure 2 provides the scale changes between the WGS 84 D85 coordinates and the readjusted network every month during this period except for November 1987. The annotations are the total number of stations from the original 1985 set that were readjusted each month. These results demonstrate that subsequent adjustments of the network produced systematic scale variations in the coordinates when compared to the original scale of WGS 84 D85. The cause is unknown for the initial offset of approximately 80 cm in these results from WGS 84 D85, but is not due to ionospheric refraction, since solar activity in early 1987 was not significantly different from that during 1985 (see Figures 3 and 4).
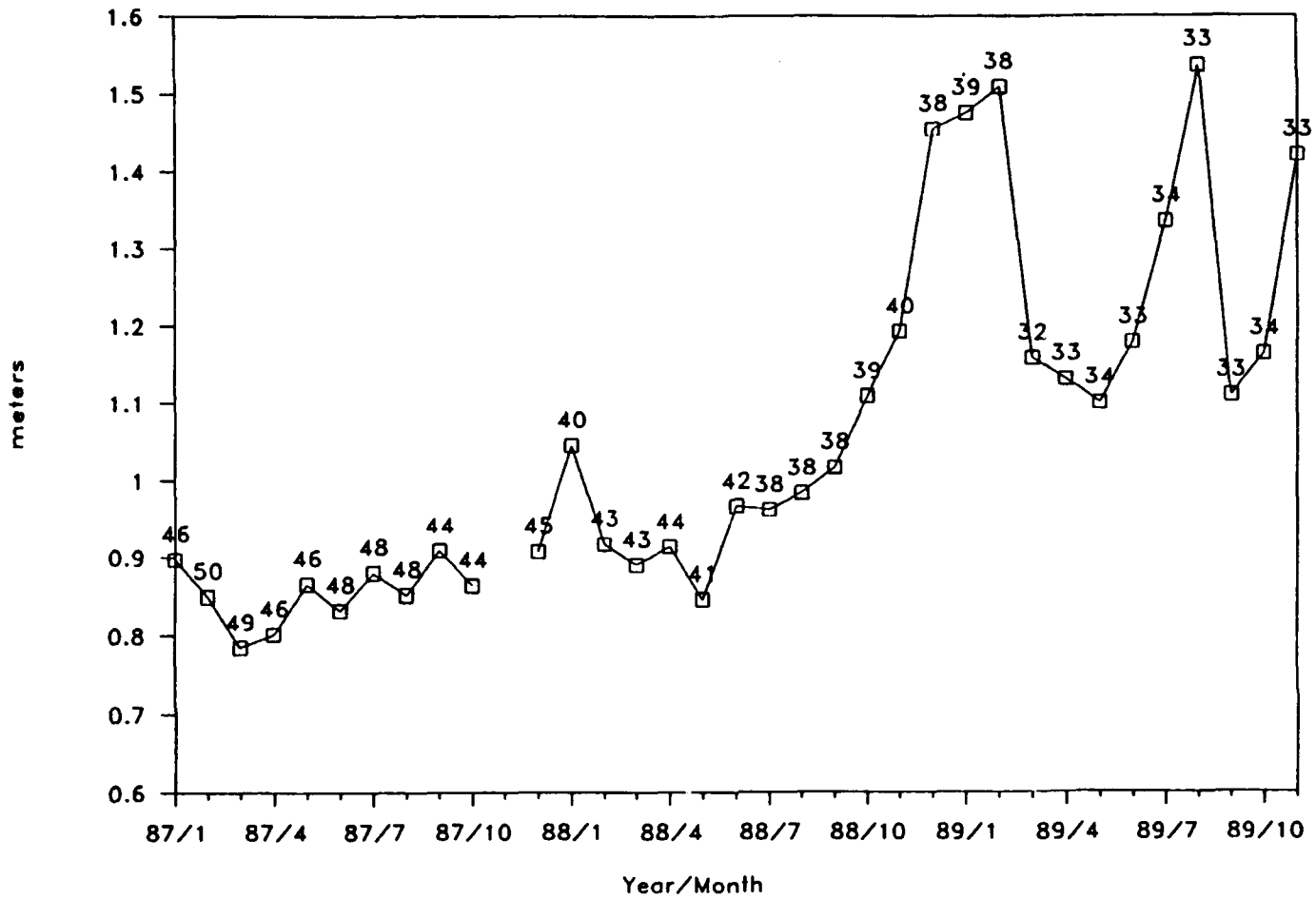
FIGURE 2. IMPLIED DOPPLER NETWORK SYSTEMATIC SCALE DIFFERENCES
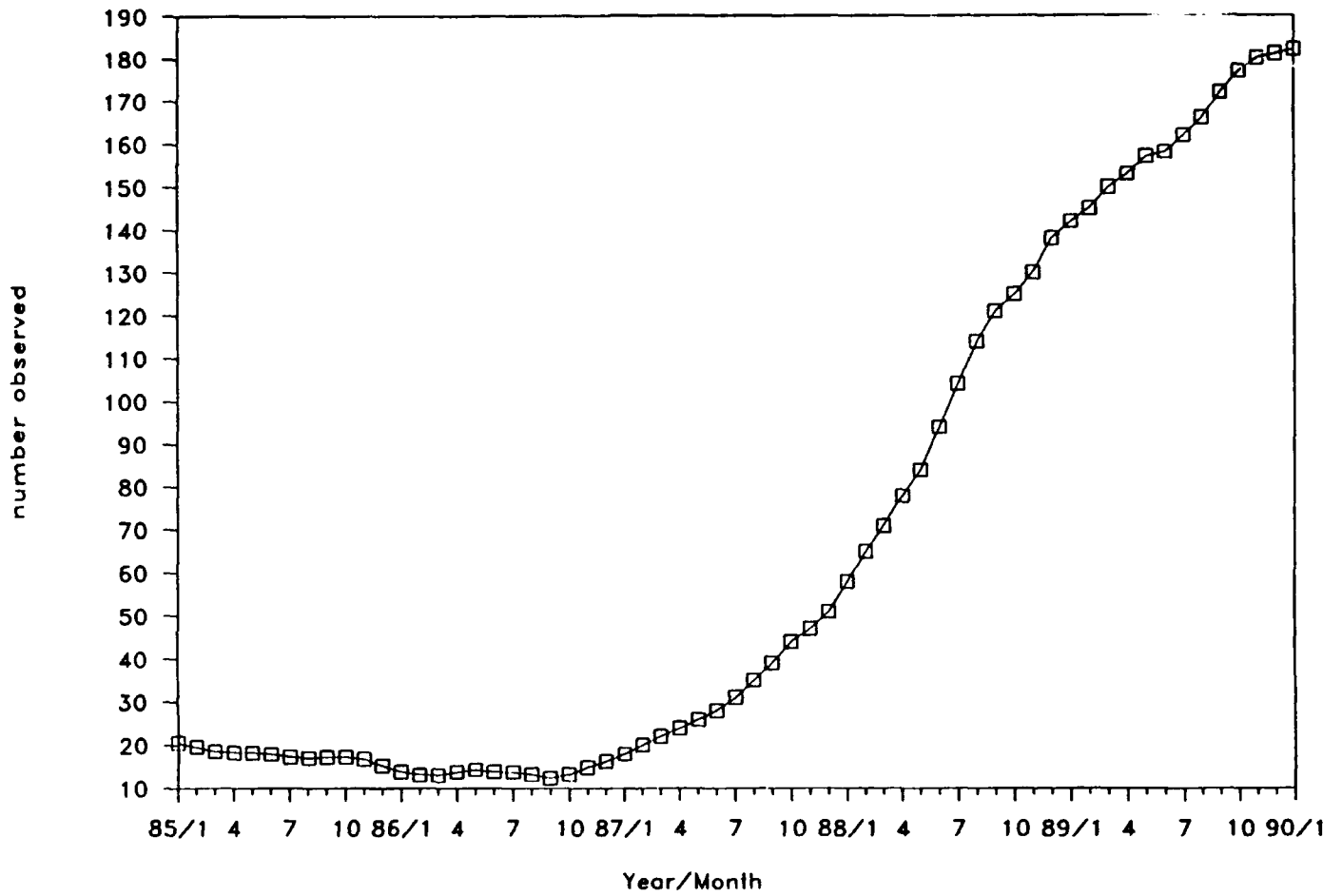JANUARY 1987 TO OCTOBER 1989

FIGURE 3. SMOOTH SUNSPOT NUMBERS
JANUARY 1985 TO JANUARY 1990
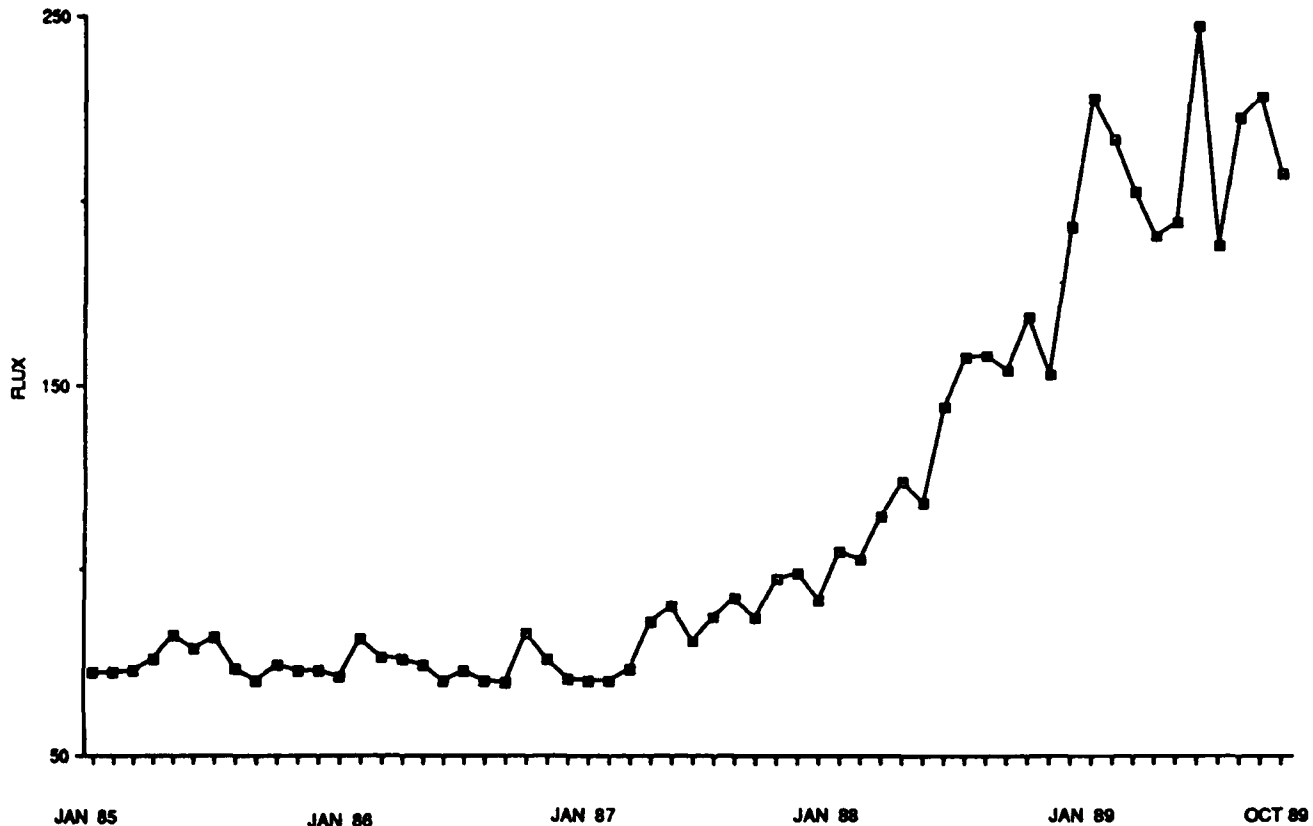
FIGURE 4. SOLAR FLUX AT 2800 MHZ—MONTHLY MEANS
JANUARY 1985 TO OCTOBER 1989

What is important is the scale variation after January 1987, ranging to 70 cm, which is highly correlated with changes in solar activity. Figure 3 provides smoothed sunspot numbers covering this period, taken from the *Solar Indices Bulletin* published monthly by the National Geophysical Data Center in Boulder, Colorado. The mean observed solar flux measured at 2800 MHz is plotted in Figure 4 for the period from January 1985 to October 1989. A comparison of Figures 2, 3, and 4 shows that there is significant correlation between changes in solar activity and the mean scale change of a readjusted Doppler network. This correlation is 0.79 with solar flux during December 1987 to October 1989 and 0.80 with smoothed sunspot numbers during January 1987 to October 1989. This, and the examples cited above, demonstrate the impact on scale of uncompensated ionospheric refraction, thus, directly limiting the fidelity of a WGS 84 CTS implementation established through Doppler techniques.

IMPACTS ON THE REALIZATION OF THE
WGS 84 REFERENCE FRAME

With uncompensated ionospheric refraction impacting the heights of Doppler point positions, it is of interest to determine to what extent the scale of the WGS 84 reference frame has been impacted by such errors. This question leads to a comparison of three reference frame concepts: The first is the definition of the WGS 84 CTS; the second and third relate to attempts to realize the WGS 84 CTS through the use of the Transit System and GPS, respectively. Notations (such as WGS 84 D__ and WGS 84 G__) will be used to express such reference frame realizations. For example, WGS D85 was already defined as a particular Doppler implementation based on data collected in 1985.

The notations of Table 3 are adopted for comparisons discussed below. The designation WGS 84 D85/87 refers to the coordinates for the Air Force and DMA GPS tracking sites provided in Table 1, which were developed in the time period spanning October 1985 to May 1987. Although determined using Transit satellite ephemerides that were estimated from data collected at Doppler tracking sites whose coordinates were in WGS 84 D85, these GPS station coordinates, as a set, are biased in scale. The value for this bias was determined indirectly and is presented below.

The scale difference between WGS 84 D85 and D85/87 is due to several factors, but not primarily the ionosphere. The amount of bias due to the ionosphere would depend on the dates of survey, which are listed in Table 1, and on the variations in solar activity from that occurring during 1985 when WGS 84 D85 was established. For instance, the monthly average solar flux during 1985 varied from 72.1 in January to 72.4 in December, with a 3-month high period during May through July of 82.0, 78.5, and 81.3. Smoothed monthly sunspot numbers for 1985 showed a decreasing trend ranging from 20.5 in January to 15.3 in December. For the GPS stations positioned by Doppler, the average flux was 75.3 during data collection periods. The average sunspot number was 16.5. These averages fit within the corresponding range of values for 1985. The largest individual difference was during May 1987 when the flux and sunspot values were 89.8 and 26.5, respectively. Considering the results in Figure 2 and Figures 3 and 4, it is likely that scale variations due to solar activity were far below the changes implied by major solar variations after May 1987. Since no large variations in solar activity were present at these times, other factors must be considered to completely understand the scale difference. This is discussed further below.

Also in Table 3, WGS 84 G89 refers to a determination of coordinates for the same OCS and DMA stations using GPS tracking data[6] rather than Transit Doppler. The WGS 84 G91 is a similar GPS data solution[12] developed in 1991 at Naval Surface Warfare Center Dahlgren Division (NSWCDD). SV5 and ITRF 90 are reference frames controlled through VLBI and SLR.

TABLE 3. NETWORK REFERENCE NOTATIONS AND DEFINITIONS

Notation	Definition	Reference/Source
WGS 84 D85	Doppler Network (50 Stations), 1985 Solution using Doppler Observations	Cunningham, 1987 (Reference 2)
WGS 84 D85/87	GPS Network (10 Stations) Doppler Surveys during 1985-1987	Defense Mapping Agency
WGS 84 G89	GPS Network (10 Stations) GPS Survey	Swift, 1989 (Reference 6)
WGS 84 G91	GPS Network (10 Stations) GPS Survey	Cunningham, 1991 (Reference 12)
SV5	GPS Frame developed by MIT	Murray, 1991 (Reference 13)
ITRF 90	IERS Terrestrial Reference Frame, 1990	Boucher, 1991 (Reference 14)

From these WGS position determinations and related studies over the past several years, the question noted above regarding the impact of ionospheric refraction on reference frame development has been partially answered. Figure 5 serves to highlight what is known at this point. First, comparison of the GPS tracking station coordinates WGS 84 D85/87 with a self-consistent GPS determined WGS 84 G89 reveals that a mean height difference of 120 cm exists between the two sets of coordinates.[6] Since GPS measurements are far less susceptible to higher order ionospheric refraction, the height bias between these two systems is most likely due to height variations in Doppler positioning, from late 1985 to early 1987, caused by uncompensated ionospheric effects.[15] A similar result of 130 cm has been reported after comparison of WGS 84 D85/87 and the WGS 84 G91 coordinate set.[12] Assuming that variations in the scale of the reference frame, as evidenced by Doppler comparisons (Figure 2), are applicable to the 10-station OCS/DMA network, then the GPS-based WGS 84 implementations are more consistent with the definition of the WGS 84 CTS than are either WGS 84 D85 or D85/87. An initial comparison between WGS 84 D85/87 and SV5[16,17], using 3 weeks of GPS data collected during the International Earth Rotation Service GIG 1991 campaign, indicates that the former system has an average height bias of 141 cm with respect to the SV5 reference frame designed by the Massachusetts Institute of Technology for monitoring crustal deformation.[13] The SV5 reference frame has been tied to the VLBI/SLR frame through a number of local ties between GPS Rogue receivers and VLBI instrumentation. Another comparison between the VLBI/SLR network and the five DMA GPS tracking stations in WGS 84 D85/87 gives 140 cm for the mean scale bias.[18]
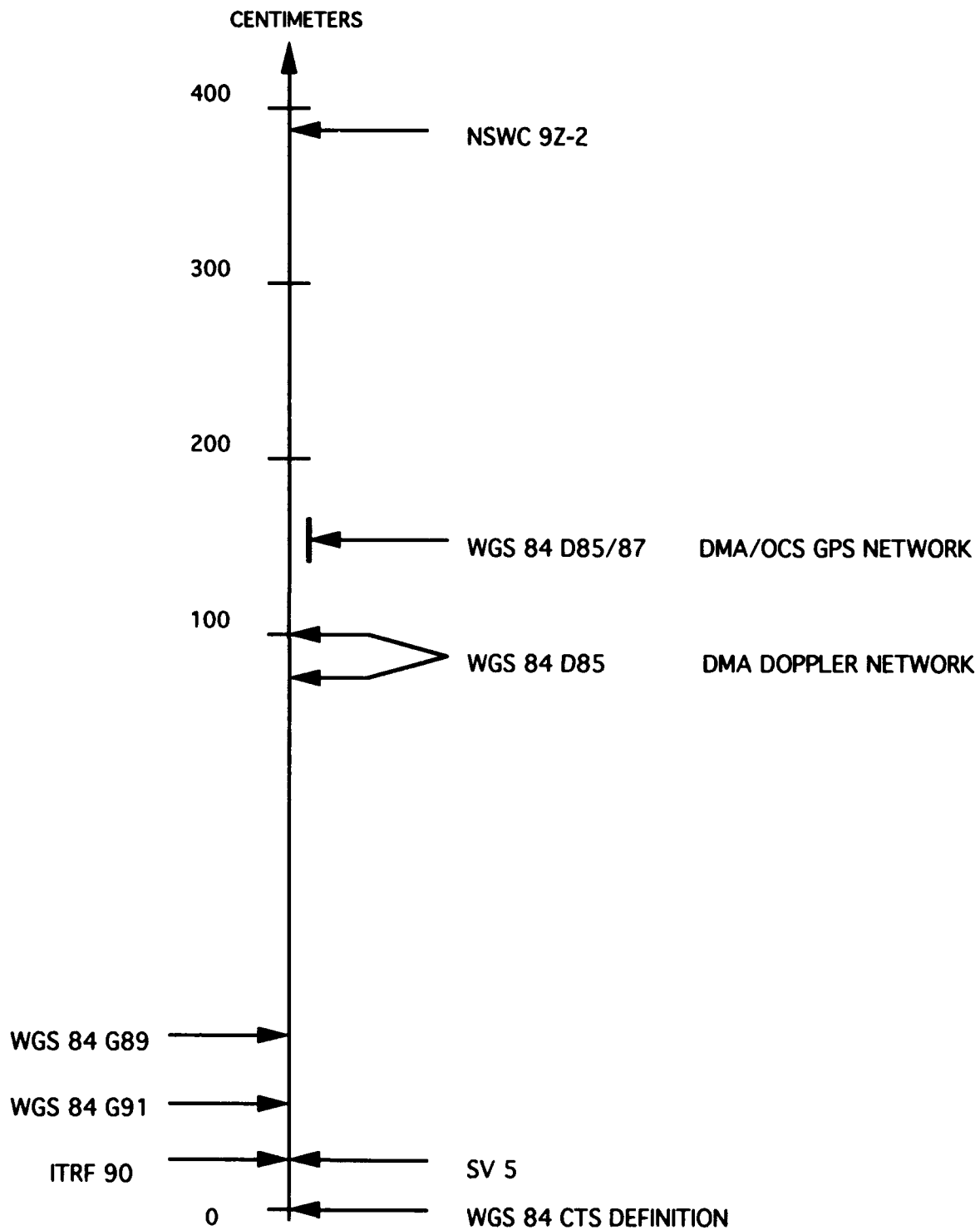
CENTIMETERS

400 — NSWC 9Z-2

300

200

WGS 84 D85/87   DMA/OCS GPS NETWORK

100 — WGS 84 D85   DMA DOPPLER NETWORK

WGS 84 G89

WGS 84 G91

ITRF 90   SV 5

0   WGS 84 CTS DEFINITION

FIGURE 5. REFERENCE FRAME SCALE RELATIONSHIPS

11

To further assess the nature of the systematic differences between Transit and GPS implementations of WGS 84, a set of 16 globally distributed stations were positioned using both Transit Doppler[19] and GPS carrier phase[20] point positioning techniques. Standard DMA precise Transit and GPS ephemerides were held fixed in the point positioning estimation processes. In the GPS case, the precise satellite clock states were also held constant. The Transit positions were estimated from data collected during the period 1985 to 1992. The GPS positions were estimated from data especially collected for this purpose during the period 1988 to 1992. The GPS ephemerides and clocks used in the data reductions were estimated with the WGS 84 D85/87 Doppler-derived coordinates of the 10 tracking stations held fixed. Therefore, the GPS positions derived from these estimates are not statistically independent from errors in this particular realization of WGS 84.

The collocated station sets used in this direct comparison are given in Tables 4 and 5. A similarity transformation between the two sets of coordinates yielded the seven parameters shown in Table 6. A comparison of these parameters with their standard deviations indicates that scale is the one of the seven parameters that can be considered the most statistically significant. This scale parameter (−0.164 parts per million) corresponds to 1.05 m at mean Earth radius. The standard deviation on the determination of this parameter corresponds to 17 cm. When the estimation of this similarity transformation was performed, the adopted uncertainties (1 sigma) for the station coordinates were 45 cm for all components except the GPS z-components that were assigned an uncertainty of 30 cm. A smaller standard deviation on the z-coordinates derived from phase data has been empirically demonstrated[20] and is believed to be a result of the predominate north-south motion of the GPS satellites relative to a fixed terrestrial point. The resulting standard error of fit (the *a posteriori* variance of unit weight) was 1.01. The 16 stations used resulted in 41 degrees-of-freedom in this adjustment.

As corroborated by other results presented herein, the sign of the scale difference places the Transit determined ellipsoid heights above those determined by GPS. This can also be seen by a simple inspection of the height components in Tables 4 and 5. A straightforward difference of the height components in these tables yields a mean value of 1.08 m, with a standard deviation of 66 cm. This result is less than the 120 to 130 cm scale differences obtained previously; however, those solutions were a result of simultaneous adjustments of GPS orbits, clocks, station coordinates, and other parameters, such as zenith tropospheric delays. The 12 to 22 cm disparity between these point positioning results and other results presented herein could certainly be explained by these significant differences in estimation algorithms. It is also noteworthy that, when orbits are held fixed, only a fraction of any radial orbit error propagates into an estimated point position.

TABLE 4. WGS 84 TRANSIT POINT POSITIONING RESULTS USING DOPPLER

Location	Longitude (deg)	Latitude (deg)	Height (km)
Albrook	280.44170917	8.98786306	0.073460
Smithfield	138.65479780	− 34.67393250	0.036690*
Argentina	301.48070530	− 34.57370140	0.049240*
England	358.71592440	51.45379580	0.168840*
Bahrain	50.60813920	26.20913500	− 0.012340*
Ecuador	281.50640000	− 0.21515280	2.924520*
Pueblo	255.70806528	38.43652583	1.501730
Albuquerque	253.34695972	35.05620778	1.485674
Dodge City	259.99250028	37.75115250	0.732922
Falcon AFB	255.47541694	38.80311750	1.911650
Platt	255.27366333	40.18279444	1.503180
Portugal	332.90967890	38.77533056	0.108937
Oman	57.45144250	19.03830861	0.004016
Ascension	345.59792100	− 7.90784700	0.040715
Kinshasa	15.25513600	− 4.37043400	0.453526
Sheyma	174.10109556	52.72878722	0.078560

* Height to antenna base, not electrical center, as in Table 1.

TABLE 5. WGS 84 GPS POINT POSITIONING RESULTS USING PHASE

Location	Longitude (deg)	Latitude (deg)	Height (km)
Albrook	280.44170667	8.98786389	0.072010
Smithfield	138.65479500	− 34.67393139	0.035523
Argentina	301.48070694	− 34.57369861	0.049086
England	358.71592444	51.45379028	0.167742
Bahrain	50.60814028	26.20913833	− 0.013810
Ecuador	281.50639722	− 0.21515389	2.923127
Pueblo	255.70806556	38.43651833	1.500867
Albuquerque	253.34695889	35.05619972	1.485436
Dodge City	259.99250528	37.75114361	0.732775
Falcon AFB	255.47539581	38.80311903	1.910677
Platt	255.27366320	40.18279398	1.501560
Portugal	332.90967189	38.77534075	0.106671
Oman	57.45143422	19.03831714	0.002995
Ascension	345.59792111	− 7.90785111	0.040521
Kinshasa	15.25514306	− 4.37044028	0.451354
Sheyma	174.10110083	52.72878472	0.077538

TABLE 6. SIMILARITY TRANSFORMATION BETWEEN WGS 84 TRANSIT AND
GPS POINT POSITIONING RESULTS FROM TABLES 4 AND 5

	X (cm)	Y (cm)	Z (cm)	L (x10⁻⁶)	ω ψ ε (marcsec*)		
Parameter	− 21	− 11	− 7	− 0.164	1.3	2.7	− 7.5
Sigma	18	18	16	0.027	6.7	7.2	6.4

* The angles ω, ψ, and ε are around the Z-, Y-, and X- axes, respectively.

CONCLUSIONS

The results presented in this report clearly illustrate the important distinction between the definition of a coordinate system and the realization of a reference frame.[21] The WGS 84 coordinate system was adopted in both Transit and GPS point positioning techniques, yet these techniques yield two distinct realizations of the WGS 84 reference frame due to ionospheric refraction and other factors, such as the propagation of orbit error into station positioning.

The relationships in scale between the various frames discussed above are summarized in Figure 5. Based on two studies, the metric scale difference between the WGS 84 CTS definition and the WGS 84 D85 frame is on the order of from 78 to 100 cm (in the figure, refer to the two arrows associated with the DMA Doppler network).[2,3] Second, since the GPS tracking stations were positioned by Doppler over a period spanning October 1985 to May 1987, height errors at individual stations have led to a WGS 84 D85/87 system with a mean scale above that of WGS 84 D85. One factor in this difference is sample size. The GPS network consists of only 10 stations. Thus, the effect of random positioning errors (1 to 1.5 m in each component for Doppler positioning) on the mean scale may be much greater than on that of a Doppler network with 50 to 60 stations. Third, based on adjustments comparing WGS 84 D85/87 with a reference frame closely tied to VLBI/SLR (References 17 and 18), using data from either all or from a partial (5-station) set of OCS/DMA GPS stations, it is probable that WGS 84 D85/87 lies 50 to 60 cm in scale above WGS 84 D85 or 150 to 160 cm above the WGS 84 CTS definition, as illustrated in Figure 5. Fourth, comparisons of GPS positioning solutions for the OCS/DMA stations with WGS 84 D85/87 imply that a GPS-based implementation of the WGS 84 reference frame would result in scale consistency with VLBI/SLR to within 10 to 20 cm. In Figure 5, ITRF 90 and SV5 are considered equivalent in scale.

While uncompensated ionospheric refraction appears to be the primary factor responsible for the distinct realizations of scale seen in WGS 84, other factors may also play a significant role. For example, an error in the adopted value of GM will propagate into position estimates using either Transit or GPS ephemerides. Since Transit and GPS satellites are at significantly different altitudes, this error source affects the two satellite positioning methods differently. While quantification of this effect was not considered in this study, it helps underline the complexities of reference frame development and maintenance.

Other conclusions and recommendations that can be drawn from the analysis to date are as follows:

- The direct implementation of WGS 84, using its definition as applied to a network of NSWC 9Z-2 Doppler station coordinates, provided a system whose scale was less impacted by ionospheric refraction than the reestimated coordinates of the Doppler network, WGS 84 D85. It is assumed that the scale correction (-0.6 ppm) adopted for the WGS 84 CTS largely compensated for this effect, since that scale correction was indicated from comparisons with VLBI and SLR.

- The WGS 84 D85/87 system of GPS tracking station coordinates obtained with Doppler is not consistent with WGS 84 established by GPS, is biased in scale, and should be replaced based on a readjustment using GPS data alone. The systematic scale difference due to uncompensated ionospheric refraction of Transit Doppler is the primary reason for the observed height bias between Doppler and GPS positioning seen at many locations.

- The preliminary GPS solutions for the coordinates of the GPS tracking stations, WGS 84 G89 and G91, are much more consistent in scale with VLBI/SLR. These preliminary solutions are being refined. Additional comparisons between WGS 84 and VLBI/SLR based frames, using GPS observations, will further clarify systematic scale differences.

- The WGS 84 CTS definition appears to be consistent in scale with ITRF 90 to the 10-cm level.[14]

REFERENCES

1. Defense Mapping Agency Technical Report 8350.2, *Department of Defense World Geodetic System 1984, Its Definition and Relationship with Local Geodetic Systems*, Second Edition, Sep 1991.

2. Cunningham, J., *Determination of Tranet and SMTP Tracking Station Coordinates for Use in the WGS 84*, NSWC TR 87-61, NSWCDD, Dahlgren, VA, Jun 1987.

3. Malys, S., *Dispersion and Correlation Among Transformation Parameters Related to Satellite Reference Frames*, Report 392 of the Department of Geodetic Science and Surveying, The Ohio State University, Columbus, OH, Jul 1988.

4. Hermann, B., *Absolute Positioning Results from the Global Positioning System*, Final Report, prepared for the Defense Mapping Agency, Jan 1988.

5. Malys, S.; Bredthauer, D.; Hermann, B.; and Clynch, J., "Geodetic Point Positioning with GPS: A Comparative Evaluation of Methods and Results," in *Proceedings of the Sixth International Geodetic Symposium on Satellite Positioning*, The Ohio State University, Columbus, OH, Mar 1992.

6. Swift, E., "Determination of WGS 84 Station Heights for the Combined Air Force and DMA Tracking Networks Using GPS Data," in *Proceedings of the Fifth International Geodetic Symposium on Satellite Positionings*, New Mexico State University, Las Cruces, NM, Mar 1989.

7. Hermann, B., "Five Years of Absolute Positions at the Naval Surface Warfare Center," in *Proceedings of the Sixth International Geodetic Symposium on Satellite Positioning*, The Ohio State University, Columbus, OH, Mar 1992.

8. Clynch, J. and Altenburg, R., "Ionospheric Residual Range Error Model," in *Proceedings of the Second International Geodetic Symposium on Satellite Doppler Positioning*, University of Texas, Austin, TX, Jan 1979.

9. Clynch, J. and Renfro, B., "Evaluation of Ionospheric Residual Range Error Model," in *Proceedings of the Third International Geodetic Symposium on Satellite Doppler Positioning*, New Mexico State University, Las Cruces, NM, Feb 1982.

REFERENCES (CONTINUED)

10. Anderle, R., *Doppler Satellite Data Characteristics*, NSWC TR 83-353, NSWCDD, Dahlgren, VA, Oct 1983.

11. Tscherning, C. and Goad, C., "Correlation Between Time Dependent Variations of Doppler-Determined Height and Sunspot Numbers," *Journal of Geophysical Research*, Vol. 90, No. B6, May 1985.

12. Cunningham, J. and Curtis, V., *Estimating GPS Orbits, Clocks, and Covariances in Support of Satrack II*, NSWC TR 91-539, NSWCDD, Dahlgren, VA, Aug 1991.

13. Murray, M.; King, R.; and Morgan, P., "SV5: A Terrestrial Reference Frame for Monitoring Crustal Deformation with the Global Positioning System," *EOS Transactions of American Geophysical Union*, Vol. 71, Dec 1991.

14. Boucher, C., *Definition and Realization of Terrestrial Reference Systems*, Report 1987-1991 of the IAG Special Study Group 5.123, Presented during the XXth General Assembly of the IUGG, Vienna, Austria, Aug 1991.

15. Fell, P., *Geodetic Positioning using a Global Positioning System of Satellites*, Report 299, Department of Geodetic Science and Surveying, The Ohio State University, Columbus, OH, Jun 1980.

16. Swift, E., "Preliminary Comparison of the WGS 84 and SV5 Reference Frames Using GPS Pseudorange Data," in *Proceedings of the Sixth International Geodetic Symposium on Satellite Positioning*, The Ohio State University, Columbus, OH, Mar 1992.

17. Swift, E., personal communication.

18. Abusali, P.A.M.; Schutz, B.; Tapley, B.; and Bevis, M., "Transformation Between SLR/VLBI and WGS 84 Reference Systems," Submitted to *Bulletin Geodesique*, 1992.

19. Jenkins, R.E.; Merrit, B.; Messent, B.; and Lucas, J., "Refinement of Positioning Software (DOPPLR)," in *Proceedings of the Second International Geodetic Symposium on Satellite Positioning*, University of Texas, Austin, TX, Jan 1979.

20. Malys, S. and Jensen, P., "Geodetic Point Positioning with GPS Carrier Beat Phase Data from the CASA Uno Experiment," *Geophysical Research Letters*, Vol. 17, No. 5, Apr 1990.

21. Mueller, I., "Reference Coordinate Systems and Frames: Concepts and Realizations," *Bulletin Geodesique*, 59, 1985.

DISTRIBUTION

	Copies		Copies
ATTN J BROZENA	1	ATTN GG (L DOTSON)	5
M PETERS	1	DIRECTOR	
P VOGT	1	DEFENSE MAPPING AGENCY	
NAVAL RESEARCH LABORATORY		AEROSPACE CENTER	
MAIL CODE 5110		3200 S SECOND ST	
4555 OVERLOOK AVE SW		ST LOUIS MO 63118-3399	
WASHINGTON DC 20375-5320			
		ATTN T SOLER	1
ATTN D McCARTHY	1	NGS/NOS/NOAA N/CG	
TIME SERVICE DIVISION		6001 EXECUTIVE BLVD	
U S NAVAL OBSERVATORY		ROCKVILLE MD 20852	
WASHINGTON DC 20392-5420			
		ATTN G MADER	1
ATTN (GG) S BARKER	1	NGS/NOS/NOAA N/CG114	
COMMANDING OFFICER		6001 EXECUTIVE BLVD	
NAVAL OCEANOGRAPHIC OFFICE		ROCKVILLE MD 20852	
STENNIS SPACE CENTER MS 39522-5001			
		ATTN I MUELLER	1
ATTN PPG (K BURKE)	1	C GOAD	1
PPG (J SLATER)	1	DEPARTMENT OF GEODETIC	
PRA (W WOODEN)	1	SCIENCE AND SURVEYING	
DIRECTOR		THE OHIO STATE UNIVERSITY	
DEFENSE MAPPING AGENCY		1958 NEIL AVE	
8613 LEE HIGHWAY		COLUMBUS OH 43210-1247	
FAIRFAX VA 22031-2137			
		ATTN B VANGELDER	1
ATTN DD (T HENNIG)	1	E MIKHAIL	1
SGC (R ZIEGLER)	1	DEPARTMENT OF CIVIL ENGINEERING	
SGC (M KUMAR)	4	PURDUE UNIVERSITY	
SGS (R RUSSMAN)	2	WEST LAFAYETTE IN 47907	
EG (S MALYS)	1		
SGC (J LAMONS)	1	ATTN (STOP 238-540) W MELBOURNE	1
DEFENSE MAPPING AGENCY		(STOP 238-625) S LICHTEN	1
SYSTEMS CENTER		JET PROPULSION LABORATORY	
8613 LEE HIGHWAY		4800 OAK GROVE DRIVE	
FAIRFAX VA 22031-2137		PASADENA CA 91109	

DISTRIBUTION (CONTINUED)

	Copies			Copies
ATTN T HERRING 54-618 MASSACHUSETTS INSTITUTE OF TECHNOLOGY CAMBRIDGE MA 02139	1	ATTN GIFT & EXCHANGE DIVISION LIBRARY OF CONGRESS WASHINGTON DC 20540		4
		INTERNAL DISTRIBUTION:		
		E231		3
ATTN C REIGBER	1	E232		2
DGF1 ABT 1		E281	(LIPSCOMB)	1
MARSTALLPLATZ 8		K10		1
8000 MINCHEN 22 FRG		K104	(FELL)	15
		K12		5
ATTN C BOUCHER	1	K12	(SWIFT)	15
INSTITUT GEOGRAPHIQUE NATIONAL		K12	(CUNNINGHAM)	15
2 AVENUE PASTEUR		K13		5
94160 SAINT-MANDE FRANCE		K14		5
		K40		1
ATTN G BEUTLER	1	K43		3
W GURTNER	1	N74	(GIDEP)	1
ASTRONOMICAL INSTITUTE OF BERNE SIDLER STRASSE 5 CH-3012 BERNE SWITZERLAND				
ATTN W SCHLUETER SATELLITENBEOBACHTUNGSSTATION WETTZELL TECHNISCHE UNIVERSITAT MUNCHEN D-8493 KOETZTING FRG	1			
ATTN B SCHUTZ CENTER FOR SPACE RESEARCH WRW402 UNIVERSITY OF TEXAS AT AUSTIN AUSTIN TX 78712	2			
DEFENSE TECHNICAL INFORMATION CENTER CAMERON STATION ALEXANDRIA VA 22304-6145	12			

REPORT DOCUMENTATION PAGE

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	October 1992	Final/October 1992

4. TITLE AND SUBTITLE

Bridging the Gap between Transit and GPS Point Positioning – Implications of Higher-Order Ionospheric Refraction on the Realization of the WGS 84 Reference Frame

5. FUNDING NUMBERS

6. AUTHOR(S)

Patrick Fell, Everett Swift, James Cunningham, Stephen Malys

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Surface Warfare Center (Code K10)
Dahlgren Division
Dahlgren, Virginia 22448-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

NSWCDD/TR-92/557

9. SPONSORING/MONITORING AGENCY NAME(S) AND

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

This report examines the source of the scale difference between Transit and Global Positioning System (GPS) satellite point positioning and infers the relationships in scale between the WGS 84 frame, as realized by its implementations through Transit and GPS satellite data reductions, and other terrestrial reference frames. The results clearly illustrate the important distinction between the definition of a coordinate system and the realization of a reference frame.

14. SUBJECT TERMS

Global Positioning System (GPS), Ionospheric Refraction, Satellite Point Positioning, WGS 84 Reference Frame

15. NUMBER OF PAGES

29

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

GENERAL INSTRUCTIONS FOR COMPLETING SF 298

The Report Documentation Page (RDP) is used in announcing and cataloging reports. It is important that this information be consistent with the rest of the report, particularly the cover and its title page. Instructions for filling in each block of the form follow. It is important to *stay within the lines* to meet *optical scanning requirements*.

Block 1. Agency Use Only *(Leave blank)*.

Block 2. Report Date. Full publication date including day, month, and year, if available (e.g. 1 Jan 88). Must cite at least the year.

Block 3. Type of Report and Dates Covered. State whether report is interim, final, etc. If applicable, enter inclusive report dates (e.g. 10 Jun 87 - 30 Jun 88).

Block 4. Title and Subtitle. A title is taken from the part of the report that provides the most meaningful and complete information. When a report is prepared in more than one volume, repeat the primary title, add volume number, and include subtitle for the specific volume. On classified documents enter the title classification in parentheses.

Block 5. Funding Numbers. To include contract and grant numbers; may include program element number(s), project number(s), task number(s), and work unit number(s). Use the following labels:

```
C   -  Contract       PR  -  Project
G   -  Grant          TA  -  Task
PE  -  Program        WU  -  Work Unit
       Element               Accession No.
```

BLOCK 6. Author(s). Name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. If editor or compiler, this should follow the name(s).

Block 7. Performing Organization Name(s) and address(es). Self-explanatory.

Block 8. Performing Organization Report Number. Enter the unique alphanumeric report number(s) assigned by the organization performing the report.

Block 9. Sponsoring/Monitoring Agency Name(s) and Address(es). Self-explanatory.

Block 10. Sponsoring/Monitoring Agency Report Number. *(If Known)*

Block 11. Supplementary Notes. Enter information not included elsewhere such as: Prepared in cooperation with...; Trans. of...; To be published in... . When a report is revised, include a statement whether the new report supersedes or supplements the older report.

Block 12a. Distribution/Availability Statement. Denotes public availability or limitations. Cite any availability to the public. Enter additional limitations or special markings in all capitals (e.g. NOFORN, REL, ITAR).

```
DOD   -  See DoDD 5230.24, "Distribution
         Statements on Technical Documents."
DOE   -  See authorities.
NASA  -  See Handbook NHB 2200.2
NTIS  -  Leave blank
```

Block 12b. Distribution Code.

```
DOD   -  Leave blank.
DOE   -  Enter DOE distribution categories from
         the Standard Distribution for
         Unclassified Scientific and Technical
         Reports.
NASA  -  Leave blank.
NTIS  -  Leave blank.
```

Block 13. Abstract. Include a brief *(Maximum 200 words)* factual summary of the most significant information contained in the report.

Block 14. Subject Terms. Keywords or phrases identifying major subjects in the report.

Block 15. Number of Pages. Enter the total number of pages.

Block 16. Price Code. Enter appropriate price code *(NTIS only)*

Block 17.-19. Security Classifications. Self-explanatory. Enter U.S. Security Classification in accordance with U.S. Security Regulations (i.e., UNCLASSIFIED). If form contains classified information, stamp classification on the top and bottom of this page.

Block 20. Limitation of Abstract. This block must be completed to assign a limitation to the abstract. Enter either UL (unlimited or SAR (same as report). An entry in this block is necessary if the abstract is to be limited. If blank, the abstract is assumed to be unlimited.