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GPS ORBIT ESTIMATION AND STATION COORDINATE IMPROVEMENT USING A 1992 IGS CAMPAIGN DATA SET

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FOREWORD

This report is a compilation of Global Positioning System (GPS) orbit estimation and station coordinate improvement study results obtained under sponsorship of the Defense Mapping Agency (DMA). Most of these results have been previously reported on in several DMA quarterly progress reports, a study report, and a paper presented at the Institute of Navigation's GPS-94 conference.

This work was performed in the Space and Geodesy Branch of the Space and Surface Systems Division of the Strategic and Space Systems Department.

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ABSTRACT

Extensive orbit estimation and station coordinate improvement studies have been conducted using 3 weeks of Global Positioning System (GPS) pseudorange and carrier phase data from 34 globally distributed stations collected during the 1992 International GPS Geodynamics Service Test Campaign (IGS'92). The stations consisted of the 10 Defense Mapping Agency (DMA) and Air Force GPS tracking sites and 24 IGS Rogue receiver sites. In all orbit fits that included the IGS Rogue receiver data, eight globally distributed fiducial sites were used to define the International Earth Rotation Service (IERS) Terrestrial Reference Frame 1991 (ITRF91). Orbits computed in the World Geodetic System 1984 (WGS 84) reference frame using the DMA and Air Force data were compared against orbits computed in ITRF91 using the IGS Rogue receiver data. The data sets were used simultaneously to derive GPS-realized WGS 84 coordinates for the 10 DMA and Air Force sites. These coordinates were evaluated using both the 3 weeks of data used in their derivation and an independent data span of 6 weeks from early 1993. The assumptions and results from all these studies are detailed in this report.

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INTRODUCTION

Several studies have been done at the Naval Surface Warfare Center, Dahlgren Division (NSWCDD) related to GPS orbit estimation and station coordinate improvement based on data collected during the 1992 International GPS Geodynamics Service Test Campaign (IGS'92) held 21 June through 23 September. This campaign was coordinated by the IGS Oversight Committee representing the international GPS community. The Defense Mapping Agency (DMA) was represented on this committee. During the campaign, seven organizations routinely computed GPS orbits and Earth orientation estimates.

NSWCDD did not participate directly in this campaign but took advantage of a small part of the data set collected for a series of studies. Tracking data consisting of both pseudorange and carrier phase data collected at twenty-four sites during this campaign along with similar data collected at the ten DMA and Air Force tracking sites were used in these studies. Orbit and Earth orientation estimates were generated first using each network separately. Then the studies shifted to the derivation and evaluation of GPS-realized World Geodetic System 1984 (WGS 84) station coordinates for the DMA and Air Force tracking sites. The final set of coordinates were put into operational use at DMA starting the first full week in 1994 (GPS week 730). These coordinates were provided to the Air Force Space Command in May 1994 with a recommendation for their implementation as soon as practical. Reference 1 discusses the status of DMA's current WGS 84 maintenance and enhancement efforts and future plans. Reference 2 contains a subset of the station coordinate improvement results presented in this report and preliminary results from the operational use of the final GPS-realized WGS 84 coordinates by DMA.

A special 18-satellite and 32-station version of the OMNIS Multisatellite Filter/Smoother system of programs was used for these studies (References 3 and 4). OMNIS is the software system developed for DMA by NSWCDD for GPS orbit and clock estimation and has been in production use at DMA since mid-1989. The software system has extensive capabilities beyond those needed for the GPS precise orbit production work. The purpose of this report is to document the technical details of the orbit estimation and station coordinate improvement studies completed using the IGS'92 Campaign data set and the OMNIS software system.

TRACKING DATA SETS

The primary data set used in these studies was 3 weeks of GPS pseudorange and carrier phase data from 34 sites and 17 satellites collected during the IGS'92 campaign. These weeks consisted of GPS weeks 653 and 654 in July 1992 (designated spans A and B) and a 7-day span in September involving weeks 660 and 661 (designated span C). Each span had the usual half day added to both ends to allow overlapping fit spans for consecutive weeks. The 17 satellites consisted of four Block I satellites, PRNs 11, 13, 12, and 3, and all Block IIs through PRN28, which was launched in April of 1992. The secondary data set used in these studies consisted of 6 weeks of pseudorange data collected at the five DMA and five Air Force tracking sites during GPS weeks 680-685, 17 January - 27 February 1993. This was an independent data set used for additional evaluations of the final coordinates. Twenty-one satellites were available during this time span. For all spans, observations taken below 10-deg elevation angle were deleted.

DMA AND AIR FORCE DATA

The DMA and Air Force data set consisted of 15-min smoothed pseudorange and carrier phase data from the ten sites. The 10 sites are globally distributed as indicated in Figure 1. Each DMA site had dual TI 4100 four-channel receivers for which the data were adjusted to make them appear as if they came from one receiver. Therefore, only seven satellites could be tracked simultaneously. Each Air Force site had twelve Stanford Telecommunications Incorporated receivers and could track all satellites in view. All receivers operated using external Hewlett-Packard cesium frequency standards. The original dual-frequency antenna phase center coordinates are given in Table A-2 in Appendix A. They are the Transit-realized WGS 84 coordinates derived by DMA. These coordinates have been in use since the beginning of 1987 and plate motion corrections were first applied at the beginning of 1991. At that time the coordinates were assigned an epoch of 1988.0 for the plate motion model, since the International Earth Rotation Service (IERS) uses this epoch for reporting coordinates.

Consecutive carrier phase observations were converted to units of km and differenced to obtain range differences for further processing. The pseudorange and range difference observations were processed in three partitions through the OMNIS Corrector/Editor system of programs. Corrections for vacuum signal propagation time, relativity effects, GPS antenna offset effects, plate motion effects on the station coordinates, solid Earth tide effects on the station coordinates, and tropospheric refraction effects were applied. The weather data on the uncorrected and unedited observation files were plotted.

FIGURE 1. DMA AND AIR FORCE STATIONS

Bad weather values were corrected and some of the default data were replaced by monthly average weather data compiled by DMAAC. The NUVEL NNR-1 plate motion model was implemented in a special version of the OMNIS Corrector program and was used in place of the AM0-2 model that had been used in production for this time span. The NUVEL NNR-1 model is now the IERS recommended model (Reference 5). In using this model both Diego Garcia and Australia are assumed to be on a newly defined Australian plate instead of the Indian plate. For the plate motion correction, the observations were adjusted to make them appear as if they were measured by a station with the starting 1988.0 coordinates. The GPS antenna offsets used to make the antenna offset corrections are given in Table 1.

TABLE 1. GPS BODY-FIXED ANTENNA OFFSETS (M)

Satellite type	x	y	z
Block I	.2100	0.	.8540
Block II/IIA	.2794	0.	.9519

Seven satellite clock events were identified with three in span A (PRNs 12, 21, and 24), two in span B (PRNs 11 and 15), and two in span C (PRNs 11 and 3). For the DMA and Air Force stations there were six clock events identified in span A, seven in span B, and four in span C. Ascension was chosen as the master station for clock estimation for all cases involving just the DMA and Air Force data.

IGS ROGUE RECEIVER DATA

The starting IGS Campaign data set consisted of 1-min pseudorange and carrier phase data from 24 Rogue receiver sites in RINEX format. Table 2 lists the stations used including the site name, four-character abbreviation, NASA's Crustal Dynamics Project (CDP) number (800X sites are not part of the CDP), type of clock used, and the zenith dry tropospheric refraction correction. The Usuda site was apparently moved in August 1992 and so a new abbreviation was used after that time.

TABLE 2. IGS ROGUE RECEIVER SITE INFORMATION

Site Name	Abbrev.	CDP#	Clock*	Zenith corr.(cm)
Algonquin	ALGO	7282	H	225
Kokee	KOKB	1311	H	201
Fairbanks	FAIR	7225	H	222
Matera	MATE	7939	Cs	216
Tromso	TROM	7602	Rb	226
Santiago	SANT	1404	H	211
Yarragadee	YAR1	7090	Cs	224
Hartebeesthoek	HART	7232	Rb	192
Goldstone	GOLQ	7288	H	205
Penticton	DRAO	7283	Cs	216
Yellowknife	YELL	7285	Cs	225
Madrid	MADR	1565	H	209
Wettzell	WETT	7224	H	213
Kootwijk	KOSG	8833	Rb	227
Onsala	ONSA	7213	H	229
Metsahovi	METS	7601	Rb**	227
Canberra	CANB	1545	H	213
St. Johns	STJO	8004	Rb**	226
Masapalomas	MASP	8007	Rb**	225
Ny Alesund	NYAL	8001	Rb	228
Pamatai	PAMA	8008	Rb	221
McMurdo	MCMU	8003	Rb	230
Usuda	USUD,3	7246	H	193
Taipei	TAIW	8005	Rb	229

* H = hydrogen maser, Cs = cesium, Rb = rubidium
** Type of clock unknown, Rb assumed

During the IGS'92 Campaign all but two of these sites, Metsahovi and St. Johns, were designated IGS "core" sites. "Core" sites had to have precision P-code receivers and the communications capability to send data to a designated Data Center within 48 hr after the fact. These sites are globally distributed as indicated in Figure 2.

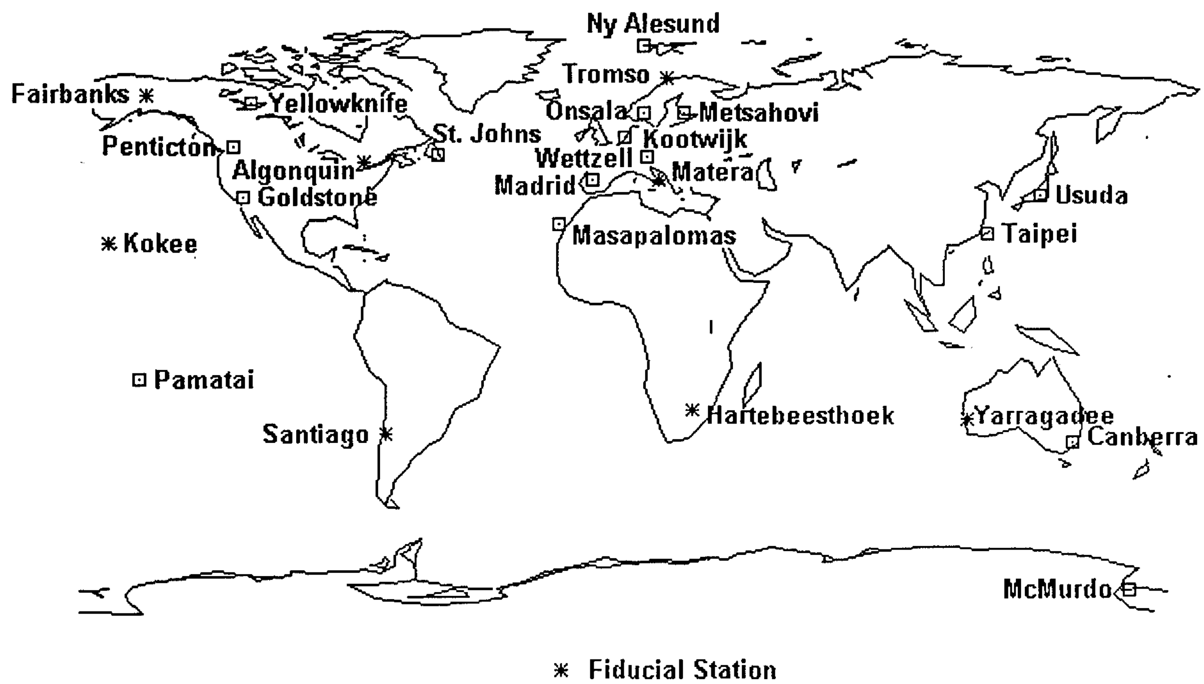

FIGURE 2. IGS ROGUE RECEIVER STATIONS

IERS estimates of the ITRF91 coordinates for all sites were obtained from IGS Electronic Mail Message No. 263 dated 27 May 1993. Table 3 gives the Earth-fixed Cartesian coordinates for the 24 Rogue receiver tracking sites in the ITRF91 reference frame at the 1992.6 epoch. All heights corresponded to the base of the antenna choke ring. Therefore, .050 m was added to each height to get to the antenna phase center for the two-frequency ionospherically corrected data.

All Rogue receiver data were time-tagged with GPS time of reception. The data were converted from RINEX to OMNIS format and the carrier phase data were converted to units of km and used to smooth the pseudorange data to even 15-min intervals. The carrier phase data were then sampled at 15-min intervals and converted to range differences. The observations were processed through the OMNIS Corrector/Editor system of programs in six partitions (three satellite partitions for each of two station partitions) using standard techniques with some changes. All data were corrected for vacuum signal propagation time, relativity effects, GPS antenna offset effects, solid Earth tide effects on station coordinates, and tropospheric refraction effects. Since the coordinate epoch was within a few weeks of

TABLE 3. IGS ROGUE RECEIVER STATION COORDINATES (M)

CDP#	x	y	z	Antenna ht.
7282	918129.608	-4346071.220	4561977.798	.114
1311	-5543838.081	-2054587.527	2387809.575	.093
7225	-2281621.322	-1453595.773	5756961.966	.116
7939	4641949.815	1393045.211	4133287.265	.135
7602	2102940.446	721569.369	5958192.076	2.473
1404	1769693.251	-5044574.115	-3468321.155	.094
7090	-2389025.339	5043316.833	-3078530.933	.073
7232	5084625.425	2670366.519	-2768494.036	9.754
7288	-2353614.083	-4641385.417	3676976.478	0
7283	-2059164.597	-3621108.392	4814432.426	.118
7285	-1224452.378	-2689216.072	5633638.284	.117
1565	4849202.516	-360329.182	4114913.006	0
7224	4075578.676	931852.630	4801569.982	0
8833	3899225.338	396731.759	5015078.287	.105
7213	3370658.758	711876.987	5349786.823	.995
7601	2892571.038	1311843.300	5512634.036	0
1545	-4460996.083	2682557.150	-3674443.967	0
8004	2612631.340	-3426807.001	4686757.745	.162
8007	5439189.186	-1522054.848	2953464.161	.122
8001	1202430.741	252626.641	6237767.500	5.216
8008	-5245195.204	-3080472.425	-1912825.530	8.410
8003	-1310695.242	310468.883	-6213363.477	4.990
7246*	-3855262.628	3427432.203	3741020.952	0
7246**	-3855263.049	3427432.526	3741020.437	0
8005	-3024781.867	4928936.916	2681234.520	1.766

* Coordinates for spans A and B
** Coordinates for span C

the data spans, no plate motion correction was needed. No ocean loading corrections to station position were included. Since no weather data were available for these sites, nominal zenith tropospheric refraction corrections (see Table 2) were obtained from the Jet Propulsion Laboratory (JPL) and used along with a dry mapping function to compute the tropospheric refraction correction at a given elevation angle. The function used was obtained by C.C. Chao in 1974 through ray tracing (Reference 6) and is given by

$$1/(\sin E + A/(\tan E + B))$$

where E = elevation angle, A = .00143 and B = .0445. The zenith correction was multiplied by this factor and then subtracted from the measurement.

There were 14 Rogue receiver station clock events identified in span C, 42 in span B (at least three stations had one event per day), and 27 in span A. Due to problems associated with clock jumps, the data from Ny Alesund was not used in span A. Only three stations had no events for all spans - Algonquin, Fairbanks, and Penticton. Algonquin was chosen as the master station for clock estimation for all cases that included IGS Rogue receiver data.

SA STATUS

Selective Availability (SA), in the form of satellite clock dither, was on during the July spans but was off during the September span. The DMA pseudorange data and the Air Force pseudorange and carrier phase data from the July spans had the SA effects removed. However, SA effects had not been removed from the DMA carrier phase data collected in July. Data sets without SA effects removed cannot be processed simultaneously with data sets with SA removed. As a consequence, the DMA carrier phase data collected during all three spans could be used simultaneously with the IGS Rogue receiver data. However, only span C could be used for the DMA and Air Force carrier phase data analysis part of these studies. Table 4 summarizes the data sets and whether SA effects were removed or were still present. Orbit fits using the singly differenced mode of processing were used for those data sets which did not have SA removed to do final editing.

TABLE 4. SA STATUS FOR DATA SETS

	Rogue		DMA		Air Force	
Span	R*	RD*	R	RD	R	RD
A	On	On	Removed	On	Removed	Removed
B	On	On	Removed	On	Removed	Removed
C	Off	Off	Off	Off	Off	Off

* R = range, RD = range difference

REFERENCE TRAJECTORIES

For all orbit fits involving the IGS Rogue receiver data, reference trajectories were generated that conformed closely to the adopted IGS analysis standards (Reference 5). The IERS GM value of 398600.4418 km^3/sec^2 was used along with the GEM-T3 gravity field truncated to eighth degree and order with the coefficients scaled by 398600.4418/398600.436 to account for the GM difference and with $C_{2,1} = -.17x10^{-09}$ and $S_{2,1} = 1.19x10^{-09}$.

A solid Earth tidal potential model with Love's number = .29 was used but no ocean tidal potential effects were included. The DE200/LE200 Sun and Moon ephemerides were used. For radiation pressure forces the ROCK4 and ROCK42 models (References 7 and 8) were used along with a y-axis bias acceleration in integrating the reference trajectories. The assumed satellite masses used in the radiation pressure models are given in Table 5. No Earth albedo model was used. There was only one satellite that required a thrust to be present in the reference trajectory and this was PRN25 for span A. The starting Earth orientation values used were the IERS final values for these spans as reported in the IERS Bulletin B.

TABLE 5. SATELLITE MASSES

Satellite type	Mass (kg)
Block I	440.89
Block II	890.00
Block IIA	973.00

For the orbit fits involving just the DMA and Air Force data, separate reference trajectories were integrated using the IERS GM value to remove any effects from the use of the older WGS 84 GM value of 398600.5 km^3/sec^2. Also, the WGS 84 gravity field model truncated to eighth degree and order was used. All other force models were identical to those used for the IGS Rogue receiver data processing. The standard DMA Earth orientation coefficient sets used in production were used as starting values for these fits.

ORBIT ESTIMATION

Each data set was used separately to derive orbits under different assumptions. Several sets of orbits were compared to determine relative accuracy, to determine the effects of these different assumptions, and to determine systematic differences between the Transit-realized WGS 84 reference frame and the ITRF91 reference frame. The accuracy of the resulting Earth orientation estimates was also examined.

Only measurements taken above 10 deg in elevation (defined as the instantaneous elevation at the associated observation time tag) were included in the orbit fits. For all orbit estimation cases involving the IGS Rogue receiver data, eight sites were chosen as fiducial sites; i.e., their coordinates were held fixed while all other coordinates were estimated. These sites were Algonquin, Kokee, Fairbanks, Matera, Tromso, Santiago, Yarragadee, and Hartebeesthoek (see Figure 2). These eight sites were identical to what JPL started using in late July 1992 for their routine IGS processing, except Matera was substituted for Madrid because of some questionable residuals for Madrid. Algonquin was designated the master station for clock estimation. For all orbit estimation cases involving just the DMA and Air Force tracking data, Ascension was designated the master station for clock estimation. Table 6 contains the assumed a priori statistics for all possible parameters estimated in any case.

TABLE 6. A PRIORI STATISTICS ON ESTIMATED PARAMETERS

Orbit

A priori sigmas	Radial	Along-track	Cross-track
Position (km)	.01	.03	.03
Velocity (km/sec)	$2.\times10^{-06}$	$6.\times10^{-06}$	$6.\times10^{-06}$

Radiation pressure scale (Gauss-Markov process)
A priori and steady-state sigma = .1 (unitless)
Decorrelation time = 4 hr

Y-axis acceleration (Gauss-Markov process)
A priori and steady-state sigma = $1.\times10^{-12}$ km/sec^2
Decorrelation time = 4 hr

Clocks (Linear systems with white noise inputs)

	Time offset	Frequency offset	Frequency drift
A priori sigmas	(nsec)	(parts in 10^{12})	(parts in 10^{12}/day)
Satellites	100.	1.	.1
Stations (except master)	100.	1.	-

White noise spectral densities

	(μsec^2/sec)	(ppm^2/sec)	((ppm/sec)^2/sec)
PRN3	$.2250\times10^{-08}$	2.8120×10^{-15}	0.
PRNs 11,13,12	$.4000\times10^{-08}$	$.5556\times10^{-15}$	0.
All Block IIs	$.4000\times10^{-08}$	$.1200\times10^{-15}$	0.
Station H & Cs	$.7397\times10^{-10}$	$.5708\times10^{-19}$	-
Station Rb	$.6250\times10^{-10}$	$.4875\times10^{-16}$	-

Tropospheric refraction
A priori sigma = 50 cm
Gauss-Markov
Steady-state sigma = 10 cm
Decorrelation time = 6 hr
Random walk
Variance rate = 1.44 cm^2/hr

Earth orientation	a priori sigma
x and y	50 cm
x and y rates	5 cm/day
UT1-UTC rate	1 msec/day
UT1-UTC acceleration	.1 msec/day^2

Station Coordinates (non-fiducial)

A priori sigma = 1.5 m in east, north, and vertical directions

Extensive orbit comparisons were completed for these three spans. Table 7 defines the cases that will be discussed below. Under the difference method column, SD stands for singly differenced (two stations/one satellite) and DD stands for doubly differenced (two satellites/two stations). The data were not explicitly differenced but the a priori statistics on the clock parameters were used to implement an approximately equivalent technique. The various minimum observation sigmas for range difference data are due to the fact that the appropriate accumulated clock noise over 15 min has to be accounted for in weighting the measurements. This consists of both the satellite and station clock contributions for non-differenced cases and the station clock only contribution for the singly differenced cases.

TABLE 7. ORBIT ESTIMATION CASES

Case	Data Types		Difference Method	Mini-batch step(sec)	Min. obs. sigma(cm) R	Min. obs. sigma(cm) RD
DMA/Air Force						
D	R		None	3600	55	
E	R		None	900	55	
F	R		SD	900	55	
Rogue						
Q		RD	DD	900		3
R	R		DD	900	30	
S		RD	SD	900		15
T	R		SD	900	30	
U	R	RD	SD	900	30	15
V	R	RD	DD	900	30	3
W(C only)	R		None	900	30	
X(C only)	R	RD	None	900	30	30
Y(C only)	R		None	3600	30	

Table 8 contains the after-fit RMS residuals for these cases combined over all stations, satellites, and applicable spans. These results indicate that the minimum observation sigmas used throughout these studies were appropriate.

TABLE 8. AFTER-FIT RMS RESIDUALS (CM)

	R	RD
DMA/Air Force		
D	55	
E	49	
F	47	
Rogue		
Q		3
R	19	
S		13
T	24	
U	23	13
V	23	3
W(C only)	23	
X(C only)	22	25
Y(C only)	26	

Since spans A and B were consecutive weeks and had the usual 24-hr overlap, the overlap differences for the middle twelve hours were computed to try to quantify the accuracy of the Rogue receiver orbit fits relative to the DMA/Air Force orbit fits. The RMS and peak orbit differences over all satellites for nine cases are given in Table 9. For all cases but the case involving singly differenced range difference (case S), the Rogue cases had smaller overlaps than the DMA/Air Force cases. The smallest overlaps were for the Rogue case in which both data types were processed in a doubly differenced mode (case V).

TABLE 9. OVERLAP ORBIT DIFFERENCES (CM)

Case	Radial		Along-track		Cross-track	
	RMS	Peak	RMS	Peak	RMS	Peak
D	49	115	104	308	79	280
E	54	130	115	348	77	278
F	63	146	132	388	80	291
Q	9	23	40	115	29	114
R	19	58	42	114	37	138
S	53	131	167	540	85	384
T	18	59	37	121	29	109
U	15	46	32	94	27	99
V	6	18	16	49	18	70

The RMS and peak orbit differences between several pairs of cases are given in Table 10. The RMS was taken over all satellites for the middle 7-day span of all three 8-day fit spans and the peak was the worst case for any satellite for any span. They are grouped as follows: the first set involves cases that use the DMA and Air Force data; the second set involves cases that use the Rogue receiver data; and the third set involves one from each of the first two sets. The comparisons involving just the DMA and Air Force data give the effects of decreasing the mini-batch interval and of singly differenced processing. All of the comparisons in the second set that have along-track RMS differences greater than 100 cm involve case S. The comparisons involving cases W, X, and Y are for span C only. The differences in the third set include reference frame differences that will be discussed later. The peak differences were not computed for this set. The along-track differences for all cases in this set include a mean bias of approximately -135 cm.

TABLE 10. ORBIT DIFFERENCES (CM)

Case	Radial		Along-track		Cross-track	
	RMS	Peak	RMS	Peak	RMS	Peak
E vs. D	9	70	25	228	11	52
F vs. D	19	158	49	384	17	91
F vs. E	12	119	32	287	8	39
R vs. Q	23	162	81	505	50	201
T vs. R	6	45	20	152	13	49
S vs. Q	30	130	129	673	40	255
S vs. T	33	158	145	732	61	247
Q vs. V	11	50	50	238	23	91
R vs. V	15	116	43	379	30	123
S vs. U	32	146	140	688	57	230
T vs. U	4	68	11	153	7	27
(Span C only for W, X, and Y)						
W vs. T	1	12	4	49	1	4
X vs. U	3	40	10	138	4	13
X vs. W	2	17	5	59	2	9
Y vs. W	3	24	10	102	5	22
Q vs. D	54		219		197	
R vs. D	56		213		200	
Q vs. E	56		222		199	
R vs. E	59		216		202	
S vs. D	60		260		202	
T vs. D	57		214		199	
U vs. D	56		214		199	
V vs. D	55		212		198	

Seven parameter similarity transformations (see Appendix B for the definition of the transformation) were computed to characterize the systematic differences between pairs of orbits in the third set for each span. Table 11 gives the transformation parameter values for the six comparison cases involving case D averaged over the three spans. The standard deviations varied from 2 to 16 cm for the translation parameters and from .2 to 1.6 mas for the rotation parameters. A rotation about z of -16 mas corresponds to -49 cm at the Earth's equator and -206 cm at GPS altitude.

TABLE 11. TRANSIT-REALIZED WGS 84-to-ITRF91 TRANSFORMATION PARAMETERS FOR ORBITS

Comparison / Parameter	D/Q	D/R	D/S	D/T	D/U	D/V	Units
x translation	-2	-1	-1	-2	-1	-1	cm
y translation	3	7	1	6	5	2	cm
z translation	-20	-23	-24	-24	-24	-22	cm
scale	.01	.00	.01	.01	.01	.01	parts in 10^8
rotation about x	2.9	2.1	4.3	2.2	2.3	3.1	mas
rotation about y	-8.0	-8.3	-8.2	-8.2	-8.2	-8.1	mas
rotation about z	-15.5	-15.5	-16.2	-15.6	-15.7	-15.8	mas

The RMS orbit differences still present after these systematic differences (slightly different for each span) were removed are given in Table 12. An along-track bias of approximately -28 cm remained and a cross-track bias of approximately +12 cm was now present.

TABLE 12. RMS ORBIT DIFFERENCES AFTER TRANSFORMATION APPLIED (CM)

Case	Radial	Along-track	Cross-track
Q vs. D	52	165	156
R vs. D	55	156	161
S vs. D	58	206	162
T vs. D	54	158	159
U vs. D	54	157	159
V vs. D	52	154	157

As discussed above, eight of the Rogue receiver sites were used as fiducials and the coordinates for the remaining 16 sites were estimated. Nine of these estimated sites were collocated with VLBI and/or SLR tracking sites and the other seven were not.

The RMS station coordinate adjustments grouped this way and combined based on all three spans are given in Table 13. The cases that included pseudorange data had larger vertical adjustments than the ones that involved range difference data only. The Q case coordinate adjustments by station and span are given in Table C-1 in Appendix C. The formal uncertaintes for the Q case were 1.8 cm in the east direction, 1.0 cm in the north direction, and 1.9 cm in the vertical direction. For the R case the uncertainties were 1.4, 1.6, and 6.8 cm, respectively.

TABLE 13. RMS ROGUE RECEIVER STATION COORDINATE ADJUSTMENTS (CM)

	9 Stations			7 Stations			Combined		
Case	E	N	V	E	N	V	E	N	V
Q	2	1	5	8	2	10	5	2	8
R	9	8	32	11	10	36	10	9	34
S	6	5	7	10	5	10	8	5	8
T	9	8	30	10	9	33	9	9	31
U	8	7	18	9	7	25	8	7	21
V	5	3	5	4	3	13	5	3	9

Six Earth orientation parameters were estimated in each orbit fit. Table 14 gives the means and standard deviations of the resulting estimates versus the IERS final values taken over all three spans. The UT1-UTC results for the first three cases that involve the DMA and Air Force data have the difference between the DMA predicted value and the IERS final value at the appropriate fit epoch subtracted from the differences. The x and y estimates for all cases involving the Rogue receiver data are much more accurate than for the cases involving the DMA and Air Force data. Table 15 gives the corresponding formal uncertainties except for UT1-UTC, for which the uncertainty in its estimated rate is given.

TABLE 14. EARTH ORIENTATION DIFFERENCES FROM IERS

	x(mas)		y(mas)		UT1-UTC(msec)	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
D	9.8	1.8	-5.3	2.0	-.02	.07
E	10.1	1.8	-5.5	2.2	-.03	.09
F	10.4	1.8	-5.7	2.3	-.02	.08
Q	.8	.6	1.6	.0	-.01	.10
R	.4	.4	-.4	.1	-.04	.09
S	.4	1.0	1.8	.6	.02	.20
T	.5	.5	-.4	.1	-.04	.07
U	.4	.5	-.3	.1	-.04	.06
V	.6	.4	.7	.1	-.01	.09

TABLE 15. FORMAL UNCERTAINTIES IN EARTH ORIENTATION

Cases	x and y(cm)	UT1-UTC rate(msec/day)
D-F	3.0	.06
Q-R,T-V	1.2	.04
S	5.2	.10

GPS-REALIZED WGS 84 STATION COORDINATES

Station coordinate adjustments to the starting Transit-realized WGS 84 coordinates for the ten DMA and Air Force sites were estimated using three basic methods.

1. Coordinate adjustments were estimated simultaneously with the orbit, satellite and station clocks, and Earth orientation parameters using both the DMA/Air Force and IGS Rogue receiver data with the eight Rogue fiducial sites held fixed,

2. Coordinate adjustments were estimated with the orbit and satellite clock estimates derived from the IGS Rogue receiver data held fixed, and

3. Coordinate adjustments were estimated iteratively. In this method the orbits and satellite clocks were first estimated using the DMA and Air Force tracking data with the starting coordinates held fixed. These fitted orbits and clocks were then held fixed and coordinate adjustments estimated. The updated coordinates were then used in the next orbit fit and this process was continued until the coordinate estimates converged.

The first two methods result in GPS station coordinates in the ITRF91 reference frame as realized by the eight fiducial sites, while the third method just provides more internally consistent GPS-realized WGS 84 coordinates. Variations on these methods in terms of the data sets used were required because sets with and without SA effects removed cannot be processed in the same fit. For instance, the range difference data for the DMA sites for spans A and B could be processed simultaneously with the IGS Rogue receiver data but not with the Air Force data or even the DMA pseudorange data. Stochastic zenith tropospheric refraction corrections were always estimated along with the station coordinates. The same a priori sigma of 1.5 m was used on all three estimated station coordinate components in all cases.

SENSITIVITY ANALYSES

Since SA was off during span C, this span was used to test the sensitivity of the station coordinate adjustments to various processing techniques. Tables 16-18 give the estimated adjustments to the starting coordinates for span C for the above three methods with separate and combined data types used for the first method. DD designates that the data were processed in a doubly differenced mode. For the last two methods only pseudorange data were used and no differencing was done. Stochastic zenith tropospheric refraction corrections were estimated as random walk processes with a variance rate of 1.44 cm^2/sec for all cases in these tables. The column labelled "Use" corresponds to the second method. The orbits and satellite clocks held fixed in this case were derived using both pseudorange and range difference Rogue receiver data processed in a doubly differenced mode (Case V in the ORBIT ESTIMATION section). The column labelled "Iter." corresponds to the third method. Since the iterative approach does not use any data that would improve the alignment between WGS 84 and ITRF91, there are no systematic east and north adjustments present. To compare the iterative adjustments with the "Use" adjustments, the mean correction over all ten stations was removed from the "Use" adjustments and the resulting adjustments are given in the column labelled "Use Adj."

For the east and north coordinate adjustments, the largest differences among the three cases involving the simultaneous method are 26 and 23 cm, respectively, for Colorado Springs. The adjustments for the "Use" case are similar to the simultaneous cases for these two coordinates also. The systematic differences between WGS 84 and IRTF91 are very consistent for the first four cases as indicated by the mean values over all stations. The RMS of the differences between the last two columns for the east coordinate adjustments is 17 cm and for the north coordinate adjustments is 25 cm. This is a measure of the consistency of these two sets of adjustments.

The vertical coordinate adjustments show the greatest variability. The largest difference between vertical adjustments for the range difference versus the range only case is 92 cm for Ascension. Even larger differences exist between the "Use" method and the iterative method. The mean of these differences is 39 cm and the standard deviation is 76 cm. The vertical adjustments for Colorado Springs varied from -122 to 42 cm with the range difference only case having the most negative adjustment.

TABLE 16. EAST COORDINATE ADJUSTMENTS FOR SPAN C (CM)

Station	Simultaneous DD RD	Simultaneous DD R+RD	Simultaneous DD R	Use R	Use Adj. R	Iter. R
Colorado Springs	-29	-46	-55	-52	-5	14
Ascension	-13	-14	-10	-15	32	16
Diego Garcia	-47	-49	-50	-56	-9	4
Kwajalein	-13	-11	-5	-10	37	41
Hawaii	-114	-118	-117	-116	-69	-46
Australia	-67	-68	-65	-68	-21	-32
Argentina	-36	-40	-40	-38	9	-4
England	-52	-44	-38	-41	6	-19
Bahrain	18	11	5	10	57	37
Ecuador	-89	-86	-84	-85	-38	-25
Mean	-44	-47	-46	-47	0	-1
S.D.	37	36	36	35	35	28

TABLE 17. NORTH COORDINATE ADJUSTMENTS FOR SPAN C (CM)

Station	Simultaneous DD RD	Simultaneous DD R+RD	Simultaneous DD R	Use R	Use Adj. R	Iter. R
Colorado Springs	-18	-15	5	9	33	5
Ascension	5	7	15	-6	18	39
Diego Garcia	-11	-17	-30	-17	7	-11
Kwajalein	-37	-36	-40	-39	-15	-3
Hawaii	-30	-28	-21	-18	6	9
Australia	-35	-39	-48	-47	-23	-8
Argentina	-26	-25	-24	-30	-6	31
England	-52	-49	-52	-46	-22	-65
Bahrain	15	12	4	10	34	7
Ecuador	-70	-65	-56	-59	-35	-21
Mean	-26	-26	-25	-24	0	-2
S.D.	24	22	24	23	23	27

TABLE 18. VERTICAL COORDINATE ADJUSTMENTS FOR SPAN C (CM)

Station	Simultaneous DD RD	Simultaneous DD R+RD	Simultaneous DD R	Use R	Use Adj. R	Iter. R
Colorado Springs	-122	-102	-80	-58		42
Ascension	-116	-129	-208	-218		-129
Diego Garcia	-216	-224	-241	-294		-86
Kwajalein	-135	-142	-212	-217		-180
Hawaii	-150	-146	-84	-100		-139
Australia	-121	-132	-184	-184		-228
Argentina	-53	-57	-44	-11		-53
England	-154	-161	-166	-208		-134
Bahrain	-144	-147	-173	-170		-160
Ecuador	-196	-203	-137	-95		-88
Mean	-141	-144	-153	-156		-117
S.D.	43	45	62	82		71

For the three "simultaneous" cases, coordinate adjustments for 14 Rogue receiver sites were also estimated. The RMS adjustments over all sites are given in Table 19. The east RMS adjustment for the range difference only case was dominated by a -27 cm adjustment for one site. The RMS of the other 13 sites was less than 4 cm. The largest vertical adjustment for the pseudorange only case was 94 cm with all others 44 cm or less in magnitude. These values indicate that the pseudorange data used by itself provide the worst coordinate estimates, since the accuracy of the ITRF91 starting coordinates for most of the Rogue receiver sites is a few centimeters. This is probably because the pseudorange data have a higher noise level and are subject to larger multipath effects than the range difference data. In addition, analysis of after-fit residuals indicates that the DMA and Air Force pseudorange data have a higher noise level than the Rogue receiver pseudorange data, 55 vs. 30 cm. Therefore, larger random variations in the vertical adjustments could be expected for these sites. Table C-2 in Appendix C contains the Rogue receiver station coordinate adjustments for these three cases by station.

TABLE 19. RMS ROGUE RECEIVER STATION COORDINATE ADJUSTMENTS FOR "SIMULTANEOUS" CASES (CM)

Case	East	North	Vertical
RD	8	2	7
R+RD	5	3	9
R	7	8	34

The above cases that involved pseudorange data (all except column one in Tables 16-18, which involved range difference data only) were also done with the zenith tropospheric refraction correction estimated as a first-order Gauss-Markov process with a steady-state sigma of 10 cm and a decorrelation time of 6 hr. The corresponding station coordinate adjustments are given in Tables 20-22. The results for the east and north coordinate adjustments changed only slightly from those obtained using the random walk tropospheric refraction correction model. The vertical adjustments were in general more varied and more negative with the worst case being the iterative case in which the mean adjustment became more negative by 19 cm.

TABLE 20. EAST COORDINATE ADJUSTMENTS FOR SPAN C USING GAUSS-MARKOV TROPOSPHERIC REFRACTION MODELING (CM)

Station	Simultaneous DD RD	Simultaneous DD R+RD	Simultaneous DD R	Use R	Use Adj. R	Iter. R
Colorado Springs	-29	-51	-54	-51	-4	14
Ascension	-13	-17	-10	-15	32	16
Diego Garcia	-47	-53	-51	-57	-10	5
Kwajalein	-13	-13	-5	-9	38	38
Hawaii	-114	-121	-115	-114	-67	-43
Australia	-67	-73	-64	-69	-22	-32
Argentina	-36	-45	-42	-39	8	-3
England	-52	-48	-38	-40	7	-18
Bahrain	18	4	2	7	54	34
Ecuador	-89	-89	-83	-84	-37	-26
Mean	-44	-51	-46	-47	0	-2
S.D.	37	35	35	35	35	26

TABLE 21. NORTH COORDINATE ADJUSTMENTS FOR SPAN C USING GAUSS-MARKOV TROPOSPHERIC REFRACTION MODELING (CM)

Station	Simultaneous DD RD	Simultaneous DD R+RD	Simultaneous DD R	Use R	Use Adj. R	Iter. R
Colorado Springs	-18	-16	3	8	32	4
Ascension	5	8	15	-6	18	36
Diego Garcia	-11	-16	-30	-18	6	-10
Kwajalein	-37	-37	-40	-38	-14	-3
Hawaii	-30	-28	-22	-19	5	9
Australia	-35	-40	-47	-46	-22	-5
Argentina	-26	-23	-21	-28	-4	31
England	-52	-48	-54	-47	-23	-68
Bahrain	15	14	6	10	34	5
Ecuador	-70	-64	-54	-58	-34	-30
Mean	-26	-25	-24	-24	0	-2
S.D.	24	23	24	22	22	28

TABLE 22. VERTICAL COORDINATE ADJUSTMENTS FOR SPAN C USING GAUSS-MARKOV TROPOSPHERIC REFRACTION MODELING (CM)

Station	Simultaneous DD RD	Simultaneous DD R+RD	Simultaneous DD R	Use R	Use Adj. R	Iter. R
Colorado Springs	-122	-97	-69	-44		37
Ascension	-116	-136	-202	-216		-133
Diego Garcia	-216	-232	-240	-284		-138
Kwajalein	-135	-145	-201	-208		-175
Hawaii	-150	-145	-97	-116		-149
Australia	-121	-136	-189	-193		-215
Argentina	-53	-55	-51	-40		-66
England	-154	-162	-169	-220		-160
Bahrain	-144	-151	-185	-199		-202
Ecuador	-196	-202	-170	-148		-155
Mean	-141	-146	-157	-167		-136
S.D.	43	47	60	75		69

The Rogue receiver coordinate adjustments corresponding to using the different tropospheric modeling are given in Table 23. There are small differences from Table 19 in the east and north components but the RMS adjustment to the vertical coordinates increased from 34 to 63 cm for the pseudorange only case.

TABLE 23. RMS ROGUE RECEIVER STATION COORDINATES ADJUSTMENTS FOR "SIMULTANEOUS" CASES USING GAUSS-MARKOV TROPOSPHERIC REFRACTION MODELING (CM)

Case	East	North	Vertical
RD	8	2	7
R+RD	6	4	12
R	8	8	63

To test the sensitivity to the gravity field model used, the doubly differenced range difference case (corresponds to column 1 in Tables 16-18) was repeated using the reference trajectories based on the truncated WGS 84 gravity field. The station coordinate adjustments differed by at most 1 cm in any component and the fitted orbits had worst case differences over all satellites of 3 cm in the radial direction, 6 cm in the along-track direction, and 8 cm in the cross-track direction.

To show the consistency of the adjustments from span to span, results for both the "simultaneous" method involving range difference data only processed in a doubly differenced mode and the iterative method involving pseudorange data only are given in the Tables 24 and 25. Since the Air Force range difference data had SA effects removed, only the DMA sites could be included in the simultaneous fits for spans A and B. The maximum deviation is the absolute value of the largest difference from the mean. The east coordinate adjustment for England had the largest maximum deviation for the "simultaneous" case. Span C was inconsistent with the other two spans for this case. Over all three spans the RMS station coordinate adjustments for the 14 estimated Rogue receiver sites were 6, 1, and 7 cm in the east, north, and vertical directions, respectively. The consistency in the "iterative" cases was much less, especially in the vertical direction. The "iterative" case for all spans was also done with the zenith tropospheric refraction correction modeled as a first-order Gauss-Markov process with a steady-state sigma of 10 cm and a decorrelation time of 6 hr. Table 26 contains the results for this case. The results for the east and north coordinate adjustments changed only slightly. The vertical adjustments were in general more varied and more negative with a mean adjustment over the three spans of -15 cm. The maximum deviations were about the same sizes.

TABLE 24. STATION COORDINATE ADJUSTMENTS FOR "SIMULTANEOUS" CASE (RANGE DIFFERENCE DATA ONLY) (CM)

	East		North		Vertical	
Station	Mean	Max.Dev.	Mean	Max.Dev.	Mean	Max.Dev.
Colo. Springs	-29		-18		-122	
Ascension	-13		5		-116	
Diego Garcia	-47		-11		-216	
Kwajalein	-13		-37		-135	
Hawaii	-114		-30		-150	
Australia	-66	1	-35	0	-121	1
Argentina	-36	0	-26	1	-52	1
England	-57	5	-51	1	-154	1
Bahrain	18	2	15	1	-142	2
Ecuador	-90	1	-70	1	-197	2
Mean	-45		-26		-141	
S.D.	37		24		43	

TABLE 25. STATION COORDINATE ADJUSTMENTS FOR "ITERATIVE" CASE (PSEUDORANGE DATA ONLY) (CM)

	East		North		Vertical	
Station	Mean	Max.Dev.	Mean	Max.Dev.	Mean	Max.Dev.
Ascension	19	3	36	5	-113	16
Diego Garcia	9	5	-9	2	-91	21
Kwajalein	44	3	-8	5	-180	11
Hawaii	-50	4	16	7	-162	23
Australia	-36	4	-13	5	-234	14
Argentina	-7	4	36	5	-90	37
England	-22	6	-61	8	-105	39
Bahrain	49	12	4	8	-189	39
Ecuador	-27	3	-26	5	-129	31
Mean	0	1	-2	0	-127	10
S.D.	32	4	28	2	68	11

TABLE 26. STATION COORDINATE ADJUSTMENTS FOR "ITERATIVE" CASE (PSEUDORANGE DATA ONLY, USING GAUSS-MARKOV TROPOSPHERIC REFRACTION MODELING) (CM)

	East		North		Vertical	
Station	Mean	Max.Dev.	Mean	Max.Dev.	Mean	Max.Dev.
Colo. Springs	21	7	6	2	26	33
Ascension	18	2	35	4	-129	6
Diego Garcia	9	4	-9	1	-138	16
Kwajalein	42	4	-8	5	-160	17
Hawaii	-48	5	15	6	-193	44
Australia	-34	3	-10	5	-226	14
Argentina	-7	5	38	7	-81	15
England	-21	4	-63	9	-128	35
Bahrain	45	11	4	7	-217	24
Ecuador	-27	2	-27	5	-175	20
Mean	0	2	-2	1	-142	6
S.D.	31	5	28	2	70	13

DERIVATION OF FINAL STATION COORDINATES

Based on the sensitivity analyses using weekly spans, the "simultaneous" case using range difference data only processed in a doubly differenced mode was chosen as the method for deriving the final coordinates. This is similar to the method being used in the IGS community to derive high-accuracy station coordinates for GPS sites. To provide station coordinate estimates based on more samples and to try to quantify their accuracy, eight 1-day fits were done for each span. This resulted in 8 samples for the Air Force sites (span C only) and 23 samples for the DMA sites (spans A and B overlap by one day). Table 27 gives the estimated adjustments and their standard deviations over the 8 or 23 samples. The repeatability using this approach was excellent. The east coordinate adjustments for England and Bahrain had the largest standard deviations of 5 cm. The formal uncertainties were typically 5, 3, and 6 cm in the east, north, and vertical directions, respectively.

To get the final GPS-realized WGS 84 coordinates, these adjustments with one more digit of precision were rotated to the Earth-fixed Cartesian system and added to the Cartesian coordinates derived from the original Transit-realized WGS 84 geodetic coordinates. These adjusted Cartesian coordinates were then converted back to geodetic coordinates. All of these coordinates and adjustments are associated with an epoch of

TABLE 27. FINAL STATION COORDINATE ADJUSTMENTS AT 1988.0 EPOCH BASED ON AVERAGING DAILY ESTIMATES (CM)

Station	Mean	S.D.	Mean	S.D.	Mean	S.D.
Colo. Springs	-30	3	-18	1	-124	3
Ascension	-13	2	5	2	-118	3
Diego Garcia	-47	2	-11	2	-219	3
Kwajalein	-12	3	-36	2	-136	2
Hawaii	-113	2	-29	1	-151	2
Australia	-65	2	-35	2	-123	3
Argentina	-36	2	-25	1	-52	3
England	-57	5	-51	2	-155	3
Bahrain	18	5	16	2	-144	3
Ecuador	-89	2	-71	1	-197	4
Mean	-44	2	-26	4	-142	4
S.D.	37		24		43	

1988.0. To get coordinates for 1994.0, the plate motion corrections based on the NUVEL NNR-1 model were applied to the Cartesian coordinates and then these coordinates were converted to geodetic coordinates. The plate motion corrections over this 6-year period are given in Table 28 in two ways - by east and north components and by magnitude and azimuth. The actual coordinates in both geodetic and Cartesian form for both epochs are given in Tables A-3 and A-4 in Appendix A along with the Cartesian coordinate rates due to plate motion in Table A-3. The coordinates for the DMA stations effective 14 December 1993, after the TI 4100 receivers and antennas were replaced with Ashtech Z-12 receivers and antennas, are also given in these tables. The heights of all DMA stations except for Argentina decreased by 18.6 cm due to the antenna change. Argentina's height decreased by 20.2 cm since this station was using a different model of the TI 4100 antenna.

A seven-parameter similarity transformation was estimated to characterize the systematic differences between the final GPS-realized WGS 84 and the starting Transit-realized WGS 84 station coordinates at the 1988.0 epoch. The transformation equations are defined in Appendix B. These transformation parameters are given in Table 29. A scale of -21.8 parts in 10^8 corresponds to -139 cm at the Earth's equator. A rotation about z of -15.6 mas corresponds to -48 cm at the Earth's equator. These parameter values are similar to those given for orbits in Table 11 in the ORBIT ESTIMATION section except for the scale parameter. For the orbit case the scale parameter primarily accounts for differences in GM, which was the same in all cases.

TABLE 28. PLATE MOTION CORRECTIONS FROM 1988.0 TO 1994.0 (CM)

Station	East	North	Magnitude	Azimuth(deg.)
Colo. Springs	-9	-5	10	243.0
Ascension	-4	7	8	331.1
Diego Garcia	29	24	37	50.4
Kwajalein	-41	18	45	293.3
Hawaii	-37	20	42	299.0
Australia	15	36	39	22.6
Argentina	-1	7	7	349.9
England	11	10	14	48.2
Bahrain	18	22	28	38.6
Ecuador	-4	5	6	326.7
Mean	-2	14	24	
S.D.	21	11	15	

TABLE 29. TRANSIT-REALIZED WGS 84-TO-GPS-REALIZED WGS TRANSFORMATION PARAMETERS

Parameter	Value	Units
x translation	-4	cm
y translation	-1	cm
z translation	-28	cm
scale	-21.8	parts in 10^8
rotation about x	4.2	mas
rotation about y	-4.0	mas
rotation about z	-15.6	mas

The RMS differences over all ten stations between both the Transit-realized WGS 84 and transformed coordinates and the GPS-realized WGS 84 coordinates are given in Table 30. The RMS differences between the transformed coordinates and the GPS-realized coordinates are almost identical to the standard deviations for the applied adjustments as expected.

TABLE 30. RMS DIFFERENCES BETWEEN TRANSIT-REALIZED AND TRANSFORMED COORDINATES VS. GPS-REALIZED WGS 84 COORDINATES (CM)

Component	Transit-Realized	Transformed
East	58	36
North	35	23
Vertical	148	41

EVALUATION OF FINAL STATION COORDINATES

The final GPS-realized WGS 84 station coordinates were evaluated in several ways. They were used to derive new DMA precise orbits using smoothed pseudorange data and these orbits were compared against the old DMA precise orbits and the JPL IGS orbits. This was done for both the data span used for their derivation and an independent 6-week data span. The Earth orientation solutions generated as a byproduct of deriving the new orbits were also compared against the IERS final values.

USING SAME DATA SET

For the span C data set used in deriving the coordinates an additional evaluation approach could be used. This involved using the 10 DMA and Air Force stations as fiducial sites while estimating coordinates for 22 IGS Rogue receiver sites.

Orbit Estimation Results

As a first step in evaluating the final coordinates, the standard precise orbit fits based on the DMA and Air Force smoothed pseudorange data were redone using these coordinates for the three spans. The overall RMS residuals decreased slightly from 55 to 52 cm. The overlap differences between spans A and B did not change significantly. Table 31 summarizes the clock and orbit differences between the estimates based on the Transit-realized coordinates (labelled "old") and the estimates based on the final GPS-realized coordinates (labelled "new") obtained for the three spans and overall. The IERS GM value was used in both sets of fits. The mean clock difference is due to the station height adjustment of -118 cm for the selected master station at Ascension.

TABLE 31. CLOCK AND ORBIT DIFFERENCES - NEW VS. OLD (CM)

	Clock			Radial		Along-track		Cross-track	
Span	Mean	RMS	Peak	RMS	Peak	RMS	Peak	RMS	Peak
A	112	116	203	28	105	151	354	181	486
B	109	114	209	29	125	147	348	177	498
C	108	112	207	27	103	145	375	179	507
All	110	114	209	28	125	148	375	179	507

Both the old and new orbits were compared against a set of orbits based on Rogue receiver range difference and pseudorange data combined (case V in Table 7). The RMS differences over the three spans are given in Table 32. The along-track component had a mean bias of -138 cm for the old case and -22 cm for the new case.

TABLE 32. RMS ORBIT DIFFERENCES VS. ROGUE (CM)

Case	Radial	Along-track	Cross-track
Old	55	212	198
New	47	135	97

Seven parameter similarity transformations were computed to characterize the systematic differences between each set of old and new orbits versus the Rogue orbits. The transformation parameters are given in Table 33. The column labeled Old/Rogue is the same as the last column in Table 11 in the ORBIT ESTIMATION section. The largest systematic differences for the old set (in z translation and rotation about z) were basically eliminated, indicating that the new orbits are essentially in the ITRF91 reference frame.

Table 34 contains the RMS orbit differences after the transformations were applied and show significant orbit improvement beyond accounting for systematic reference frame differences. The along-track component had a mean bias of -27 cm for the old case and -19 cm for the new case. The cross-track component had a mean bias of 11 cm for the old case and just -2 cm for the new case.

TABLE 33. TRANSFORMATION PARAMETERS FROM OLD AND NEW TO ROGUE ORBITS

Comparison Parameter	Old/Rogue	New/Rogue	Units
x translation	-1	-0	cm
y translation	2	-3	cm
z translation	-22	4	cm
scale	.01	.01	parts in 10^8
rotation about x	3.1	-2.6	mas
rotation about y	-8.1	-2.5	mas
rotation about z	-15.8	-.4	mas

TABLE 34. RMS ORBIT DIFFERENCES VS. ROGUE AFTER TRANSFORMATION APPLIED (CM)

Case	Radial	Along-track	Cross-track
Old	52	152	157
New	46	133	92

The Earth orientation differences from the IERS final values corresponding to these orbit fits are given in Table 35 for the old, new, and Rogue cases. The old and new cases involve only pseudorange data from the 10 DMA and Air Force stations and the Rogue case involves range difference and pseudorange data from 24 stations. The mean x and y differences for the new case decreased relative to the old case but were still not as good as the Rogue case. This is apparently a limitation on the quality of Earth orientation data that can be recovered using pseudorange data by itself and using a smaller station network.

TABLE 35. EARTH ORIENTATION DIFFERENCES FROM IERS FOR OLD, NEW, AND ROGUE CASES

	x(mas)		y(mas)		UT1-UTC(msec)	
Case	Mean	S.D.	Mean	S.D.	Mean	S.D.
Old	9.8	1.8	-5.3	2.0	-.02	.07
New	4.3	1.8	3.2	1.7	-.07	.09
Rogue	.6	.4	.7	.1	-.01	.09

Another indication of the self-consistency of the final coordinates was obtained by holding the new orbit and clock estimates fixed and estimating adjustments to all station coordinates, using the pseudorange data. Table 36 gives the means and absolute values of the maximum deviations from the means over all three spans for each station and combined. The vertical adjustments just indicate the weakness of determining heights using pseudorange data. The vertical adjustment for Colorado Springs was the largest in magnitude and was inconsistent with the other stations. This has been seen in previous studies and other analyses have indicated that multipath effects are large for this tracking site.

TABLE 36. STATION COORDINATE ADJUSTMENTS BASED ON NEW ORBITS (CM)

	East		North		Vertical	
Station	Mean	Max.Dev.	Mean	Max.Dev.	Mean	Max.Dev.
Colo. Springs	-4	2	-1	1	90	22
Ascension	-1	1	2	2	-25	5
Diego Garcia	6	2	0	1	38	10
Kwajalein	4	4	-6	3	-11	11
Hawaii	1	3	2	3	-28	31
Australia	-5	1	3	1	-54	8
Argentina	-1	2	3	6	-38	13
England	3	2	-2	2	7	26
Bahrain	-8	4	-2	4	-58	17
Ecuador	5	2	-3	4	-4	18
Mean	-0	2	-0	3	-8	16
S.D.	4		3		43	

IGS Rogue Receiver Station Coordinate Adjustments

To test the quality of the final DMA and Air Force station coordinates using the Rogue receiver data, the weekly fit for span C based on range difference data only was redone with the DMA and Air Force sites used as the fiducial sites and the coordinates for 22 Rogue receiver sites estimated. These included the eight sites used as fiducial sites in deriving the final coordinates. Table 37 gives the station coordinate adjustment statistics for a group consisting of these eight original fiducial stations and seven other stations all collocated with either VLBI and/or SLR tracking sites, for the other seven stations, and combined. Two of the Rogue receiver sites in the non-collocated group have east coordinate adjustments of -10 and -27 cm. All of the vertical coordinate adjustments were positive except for -2 cm at one site and an unexplained overall bias of 6 cm was present. The eight original Rogue receiver fiducial sites had a mean vertical adjustment of 9 cm and a standard deviation of 6 cm. The adjustments for the individual Rogue stations are given in Table C-3 in Appendix C. These adjustments are consistent with the accuracy of the starting ITRF91 coordinates being from a few to 10 cm.

TABLE 37. IGS ROGUE RECEIVER STATION COORDINATE ADJUSTMENTS (CM)

	15 Stations			7 Stations			Combined		
	E	N	V	E	N	V	E	N	V
Mean	-1	-1	6	-7	-1	7	-3	-1	6
S.D.	3	2	6	9	2	6	6	2	6
RMS	3	2	8	11	2	9	7	2	8

Comparisons with JPL IGS Orbits

A subset of the orbits generated as part of this evaluation were compared against the JPL orbits done for the IGS. The JPL orbits were received in the adopted IGS format (NGS SP3 format), merged as required, and converted into OMNIS format to get week-long spans for comparison purposes. For the three spans (A-C) used in deriving the final coordinates, three sets of orbits were compared against the JPL orbits. The first set consisted of the orbits derived using the Transit-realized station coordinates but the IERS GM value (case labelled "old" in the Tables 38-40). The second set consisted of orbits derived using both the final GPS-realized coordinates and the IERS GM value (labelled "new"). The third set consisted of orbits derived using the 24 Rogue receiver smoothed pseudorange and carrier phase data (labelled "Rogue", case V in Table 7).

Table 38 gives the RMS orbit differences between each set and the available JPL orbits for the three 7-day spans combined over all satellites. Due to some satellites being missing in the JPL files for certain days, 15 satellites were used in these comparisons for span A and 13 for both the spans B and C. ,For the "old" cases, along-track biases ranging from -136 to -106 cm were present for each span. For span C both the "new" and "Rogue" cases have significantly smaller differences. This is due primarily to reference frame differences since JPL changed their selection of fiducial sites between spans B and C from three to eight sites. As discussed above the eight fiducials used in these studies were the same as those used by JPL except for one site. Therefore, the differences for span C for the "Rogue" case indicate the excellent agreement between orbits fits done by NSWCDD and JPL using a similar data set but entirely independent software.

TABLE 38. RMS ORBIT DIFFERENCES VS. JPL (CM)

Case	Span	Radial	Along-track	Cross-track
Old	A	48	248	202
	B	58	259	225
	C	56	215	200
New	A	44	235	196
	B	49	261	233
	C	48	140	110
Rogue	A	19	210	202
	B	19	233	220
	C	19	49	39

Seven parameter similarity transformations were computed to characterize the systematic differences between each set of orbits and the JPL orbits. The transformation parameters are given in Table 39. The x and y translations were small and the z translation changed by 21 to 26 cm in going from the "old" to the "new" case. All scale values were small. For span C all rotations were small except for the rotation about z for the "old" case. The largest rotation about z corresponding to the "new" case is equivalent to 12 cm at GPS altitude.

Table 40 contains the RMS orbit differences after the transformations were applied. Comparing the "new" vs. the "old" differences indicates the improvement in agreement beyond that due to just systematic reference frame differences. All three spans agree well for the "Rogue" case. The systematic differences for span C were small as indicated by the small changes in the differences from Table 38 to Table 40 for both the "new" and "Rogue" cases.

TABLE 39. TRANSFORMATION PARAMETERS FROM OLD, NEW, AND ROGUE TO JPL ORBITS

Parameter	Span	Old/JPL	New/JPL	Rogue/JPL	Units
x translation	A	-6	-4	6	cm
	B	3	5	-3	
	C	6	5	6	
y translation	A	13	6	9	cm
	B	5	2	8	
	C	8	1	-1	
z translation	A	2	23	11	cm
	B	-3	23	12	
	C	-41	-18	-4	
scale	A	-.02	-.02	-.01	parts in 10^8
	B	-.04	-.03	-.06	
	C	-.02	-.02	-.04	
rotation about x	A	-13.2	-18.9	-17.8	mas
	B	-17.3	-23.3	-22.3	
	C	1.4	-4.1	.5	
rotation about y	A	11.7	16.6	20.0	mas
	B	11.0	17.0	19.3	
	C	-7.5	-1.8	0.0	
rotation about z	A	-14.3	.9	.8	mas
	B	-14.6	.7	1.4	
	C	-14.2	.6	1.6	

TABLE 40. RMS ORBIT DIFFERENCES VS. JPL AFTER TRANSFORMATION APPLIED (CM)

Case	Span	Radial	Along-track	Cross-track
Old	A	48	151	150
	B	57	157	151
	C	52	158	177
New	A	46	127	78
	B	50	136	102
	C	47	137	101
Rogue	A	22	49	42
	B	22	50	46
	C	19	46	38

USING INDEPENDENT DATA SET

To further evaluate the final GPS-realized WGS 84 station coordinates and the use of the IERS GM value using an independent data set, six consecutive weeks from early in 1993 were selected - GPS weeks 680-685, 17 January - 27 February. Only DMA and Air Force smoothed pseudorange data were processed for this span.

Orbit Estimation Results

The standard precise orbit fits based on the DMA and Air Force pseudorange data for all 21 satellites available were redone with the final GPS-realized WGS 84 coordinates held fixed and using the IERS GM value. The first 2 weeks were also redone with the same coordinates but using the original WGS 84 GM value. Since the pseudorange data had already been corrected using the AM0-2 plate motion model instead of the more recent NUVEL NNR-1 model, a slight error was introduced. The peak errors for any site were 3.5 cm in longitude and 2.0 cm in latitude. The effect of changing just GM is shown in Table 41. The statistics were computed over all satellites. Both the mean radial orbit difference and the satellite clock difference were -129 cm, corresponding to the expected effect of the GM change. Small along-track and cross-track differences were present.

TABLE 41. CLOCK AND ORBIT DIFFERENCES - IERS GM VS. ORIGINAL WGS 84 GM (CM)

Week#	Clock			Radial		Along-track		Cross-track	
	Mean	RMS	Peak	RMS	Peak	RMS	Peak	RMS	Peak
680	-129	129	132	129	132	1	5	2	10
681	-129	129	132	129	132	1	5	2	9

For the full 6 weeks with both the station coordinates and GM changed, the overall RMS residuals decreased slightly from 60 to 58 cm. The overlap differences did not change significantly. Table 42 summarizes the clock and orbit differences obtained for these 6 weeks. The varying mean clock differences are due to a constant change of -129 cm due to the GM difference and changes due to using a refined station height for the selected master station for each week. The master changed from Colorado Springs to Hawaii starting week 682 and from Hawaii to Kwajalein starting week 685.

The Earth orientation differences from the IERS final values corresponding to these orbit fits for the 6 weeks are given in Table 43 for the old and new cases. The mean differences shifted and the standard deviations decreased only slightly.

TABLE 42. CLOCK AND ORBIT DIFFERENCES - NEW + GM CHANGE VS. OLD (CM)

Week#	Clock			Radial		Along-track		Cross-track	
	Mean	RMS	Peak	RMS	Peak	RMS	Peak	RMS	Peak
680	-39	50	177	132	234	141	384	168	480
681	-39	51	196	132	257	143	350	170	499
682	24	40	132	132	233	145	342	175	530
683	28	43	140	132	227	146	376	175	520
684	24	43	159	133	236	143	378	164	457
685	29	44	160	133	241	146	416	167	463
All	5	45	196	132	257	144	416	170	530

TABLE 43. EARTH ORIENTATION DIFFERENCES FROM IERS FOR OLD AND NEW CASES FOR INDEPENDENT DATA SET

	x(mas)		y(mas)		UT1-UTC(msec)	
Case	Mean	S.D.	Mean	S.D.	Mean	S.D.
Old	7.6	1.0	-1.8	.4	-.09	.08
New	1.4	.8	6.6	.4	-.12	.09

For each week the orbits were held fixed while estimating adjustments to the coordinates for all stations using pseudorange data. This was done using both the Transit-realized coordinates and original WGS 84 GM and the final coordinates and IERS GM. Tables 44 and 45 give the means and standard deviations over all six weeks of the station adjustments for each station and combined. The standard deviations of the east and north adjustments decreased from 15 to 6 cm and 16 to 4 cm, respectively. The mean vertical adjustment changed from -92 cm to 4 cm with a small decrease in the standard deviation. These are indications of the improved self-consistency of the final coordinates. The vertical adjustments for Colorado Springs based on pseudorange data continue to be inconsistent with the other nine stations.

TABLE 44. STATION COORDINATE ADJUSTMENTS BASED ON OLD ORBITS AND ORIGINAL WGS 84 GM (CM)

	East		North		Vertical	
Station	Mean	S.D.	Mean	S.D.	Mean	S.D.
Colo. Springs	7	1	14	2	82	10
Ascension	-1	2	10	1	-126	8
Diego Garcia	-9	1	-4	1	-113	5
Kwajalein	28	1	-11	1	-144	12
Hawaii	-24	2	7	1	-120	12
Australia	-12	1	4	2	-97	8
Argentina	2	2	17	2	-42	11
England	-4	0	-38	1	-103	10
Bahrain	23	2	15	1	-122	5
Ecuador	-13	3	-14	1	-136	15
Mean	-0	1	-0	1	-92	10
S.D.	15		16		64	

TABLE 45. STATION COORDINATE ADJUSTMENTS BASED ON NEW ORBITS AND IERS GM (CM)

	East		North		Vertical	
Station	Mean	S.D.	Mean	S.D.	Mean	S.D.
Colo. Springs	-7	1	1	2	147	9
Ascension	-3	2	0	1	-35	6
Diego Garcia	7	1	-2	1	62	6
Kwajalein	2	1	-7	1	-18	10
Hawaii	3	1	0	1	-3	10
Australia	-5	1	4	2	-43	5
Argentina	-2	2	-5	2	-18	11
England	5	0	-4	1	-10	9
Bahrain	-10	2	5	1	-43	5
Ecuador	9	2	1	1	-1	7
Mean	-0	1	-1	1	4	8
S.D.	6		4		56	

Comparisons with JPL IGS Orbits

The 6 independent weeks used to evaluate the final station coordinates were also used in these types of comparisons except that no Rogue-based orbits were derived for these weeks. Also, in the "old" case the original WGS 84 value of GM was used. Table 46 gives the RMS orbit differences combined over all 21 satellites (4 Block Is and 17 Block IIs) over all 6 weeks. The RMS radial difference for the "old" case reduces to 62 cm if the known effect (-129 cm mean radial adjustment) of the GM difference is removed.

TABLE 46. RMS ORBIT DIFFERENCES VS. JPL FOR INDEPENDENT DATA SET (CM)

Case	Radial	Along-track	Cross-track
Old	143	207	185
New	55	161	110

Seven parameter similarity transformations were computed to characterize the systematic differences between each set of orbits and the JPL orbits. The transformation parameters are given in Table 47. The use of the final coordinates reduced the mean translations with the largest decrease in the z direction. The rotation about z was also significantly reduced. These results indicate that the "new" orbits are essentially in the ITRF91 reference frame.

TABLE 47. TRANSFORMATION PARAMETERS FROM OLD AND NEW TO JPL ORBITS FOR INDEPENDENT DATA SET

Parameter	Comparison	Old/JPL	New/JPL	Units
x translation	Mean	12	11	cm
	S.D.	5	5	
y translation	Mean	7	4	cm
	S.D.	7	6	
z translation	Mean	-25	-1	cm
	S.D.	4	4	
scale	Mean	-4.86	-.03	parts in
	S.D.	.03	.03	10^8
rotation about x	Mean	1.5	-4.5	mas
	S.D.	.9	.8	
rotation about y	Mean	-6.9	-.8	mas
	S.D.	.5	.3	
rotation about z	Mean	-12.8	1.5	mas
	S.D.	.5	.3	

Table 48 contains the RMS orbit differences after the transformations were applied. Comparing the "new" with the "old" differences again indicates the improvement in agreement beyond that due to systematic reference frame differences.

TABLE 48. RMS ORBIT DIFFERENCES VS. JPL
AFTER TRANSFORMATION APPLIED
FOR INDEPENDENT DATA SET (CM)

Case	Radial	Along-track	Cross-track
Old	60	173	152
New	55	158	101

ORBIT ESTIMATION USING DMA/AIR FORCE CARRIER PHASE DATA

The data from span C were used to evaluate the effects of using carrier phase measurements (handled as range differences) on GPS orbit and clock estimation accuracy for the case involving just the 10 DMA and Air Force tracking stations. The final GPS-realized WGS 84 coordinates for these sites were used in this study. This evaluation was based on three criteria: orbit differences, Earth orientation estimates, and IGS Rogue receiver station coordinate adjustments.

The baseline orbit estimation case was defined as the solution resulting from using the final coordinates in the standard DMA GPS production processing mode--pseudorange data only with 1-hr mini-batch steps. Earth orientation parameters were always estimated in this mode. Four additional cases with other processing characteristics were considered:

Case	Processing Mode Characteristics
1	range difference data only, 1-hr mini-batch step
2	pseudorange and range difference data, 1-hr step
3	pseudorange and range difference data, 15-min step, singly differenced
4	pseudorange and range difference data, 15-min step, doubly differenced

For each processing mode, orbit and clock estimates were compared with the baseline case. The Earth orientation estimates from each case were compared with the IERS final values for the middle seven days of the span. An independent evaluation of the orbits and clocks generated in each mode was done by holding them fixed and estimating station coordinate adjustments for the 24 IGS Rogue receiver sites.

The orbit and clock differences versus the baseline case are given in Table 49. Range difference data used alone (Case 1) from 10 stations processed this way do not have the strength to precisely determine the orbit parameters. RMS differences of less than 25 cm were obtained when pseudorange data were combined with range difference data in the undifferenced mode. Somewhat larger differences resulted when the combined data were processed in a singly or doubly differenced mode.

TABLE 49. CLOCK AND ORBIT DIFFERENCES VS. BASELINE CASE (CM)

	Clock		Orbit					
			Radial		Along-track		Cross-track	
Case	RMS	Peak	RMS	Peak	RMS	Peak	RMS	Peak
1	-	-	70	259	377	1509	191	594
2	13	173	9	71	23	169	15	49
3	46	720	18	95	51	265	34	101
4	76	698	30	165	94	452	78	275

The Earth orientation differences from the IERS final values for the baseline and cases 2-4 are given in Table 50. Combining the pseudorange and range difference data resulted in a slight improvement over the baseline case in the Earth orientation estimates. In most components, the standard deviation of the Earth orientation differences over the seven days was smaller for the combined data cases than for the baseline pseudorange data case.

TABLE 50. EARTH ORIENTATION DIFFERENCES FROM IERS

	x (mas)		y (mas)		UT1-UTC (msec)	
Case	Mean	S.D.	Mean	S.D.	Mean	S.D.
Baseline	2.6	1.4	4.6	1.9	.01	.03
2	2.3	1.1	5.2	0.6	.01	.02
3	3.3	1.4	5.1	0.7	.04	.02
4	2.2	1.1	3.3	0.7	-.02	.04

The orbits and clocks from the various processing methods were used with the smoothed pseudorange data to compute coordinate adjustments for the 24 IGS Rogue receiver sites. In computing these adjustments, only station parameters (coordinates, clocks, and tropospheric refraction corrections) were estimated and the satellite orbit and clock estimates were held fixed. For each set of orbit and clock estimates, the mean station adjustments over all 24 sites and the standard deviations about the means are given in Table 51. The solutions were consistent among all processing methods evaluated--baseline pseudorange and combined pseudorange and range difference. Each set of orbits gave about the same result. However, these results did indicate that absolute positioning accuracies of 22 cm horizontally and 64 cm vertically are achievable with low noise pseudorange data.

TABLE 51. STATION COORDINATE ADJUSTMENTS FOR 24-SITE IGS ROGUE RECEIVER NETWORK (CM)

	East		North		Vertical	
Case	Mean	S.D.	Mean	S.D.	Mean	S.D.
Baseline	-2	15	-4	16	5	61
2	-1	15	-4	15	4	62
3	-1	15	-4	15	6	63
4	1	15	-5	15	9	64

Based on the above brief analysis, carrier phase data combined with pseudorange data does not appear to significantly improve GPS satellite orbit and clock estimates for this 10-station tracking network.

SUMMARY AND CONCLUSIONS

Extensive analyses have been conducted using three weeks of both pseudorange and carrier phase data from thirty-four stations collected during the IGS'92 Campaign. The DMA and Air Force data were processed using the standard procedures except that the IERS recommended value of GM and the IERS recommended plate motion model NUVEL NNR-1 were used. In all orbit fits that included the IGS Rogue receiver data, eight globally distributed fiducial sites were used to define the ITRF91 reference frame. The status of the data with regards to removal of SA effects dictated which data sets could be processed simultaneously. With SA effects not removed, singly or doubly differenced processing was required. Only by using doubly differenced processing could the full strength of the carrier phase data be exploited.

Prior to improving the DMA and Air Force station coordinates, orbits were determined with each data set independently. Orbits determined with the 24 IGS Rogue receiver sites were better than those determined with the ten DMA and Air Force sites except for the case involving Rogue receiver carrier phase data used with no differencing. The RMS differences were typically .5 m in the radial direction, 1.6 m in the along-track direction, and 1.6 m in the cross-track direction after removal of systematic reference frame differences.

Sensitivity analyses were conducted to determine the best way to derive GPS-realized WGS 84 coordinates for the DMA and Air Force sites. The approach adopted was to average daily solutions obtained using range difference data from the 10 sites processed simultaneously with the data from 22 IGS Rogue receiver sites in a doubly differenced mode. When compared against the Transit-realized WGS 84 starting coordinates, the resulting GPS-realized WGS 84 coordinates indicated three systematic errors based on the 10 stations involved. These are a z shift of approximately -.3 m, a scale change of -21.8 parts in 10^8 (corresponds to approximately -1.4 m at the Earth's equator), and a longitude change of -15.6 mas (corresponds to approximately -.5 m at the Earth's equator). Several previous investigations have identified a similarly sized scale bias in Transit-realized WGS 84 coordinates (References 9-13).

Two primary pieces of evidence support a claim of 10 cm, one sigma, accuracy for each GPS-realized WGS 84 station coordinate component. The first is the daily repeatabilities of 5 cm or less for each component for each station of the estimates as derived using range difference data processed in a doubly differenced mode. The second is the 8 cm or less RMS of the station coordinate adjustments estimated for twenty-two IGS Rogue receiver sites in an orbit fit in which the DMA and Air Force sites with final coordinates were treated as fiducial sites. A slight degradation in accuracy with time due to the limitations of the plate motion model should also be considered. If no plate motion model is used with the final coordinates, the uncertainty in the horizontal direction grows as a function of time relative to their epoch at a maximum rate of 7.5 cm/yr.

Based on a sample of nine weeks, the DMA precise orbits determined using the final GPS-realized WGS 84 coordinates differed from the JPL IGS orbits by approximately .5 m in the radial direction, 1.5 m in the along-track direction, and 1.1 m in the cross-track direction. These RMS differences indicate an improvement beyond that due to just removing the systematic differences between the original Transit-realized WGS 84 and ITRF91 reference frames.

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APPENDIX A

DMA AND AIR FORCE STATION COORDINATES

TABLE A-1. AIR FORCE AND DMA STATION NAMES AND NUMBERS

Station Name	DMA Station #
Colorado Springs	85128
Ascension	85129
Diego Garcia	85130
Kwajalein	85131
Hawaii	85132
Australia	85262
Argentina	85263
England	85264
Bahrain	85265
Ecuador	85266

TABLE A-2. TRANSIT-REALIZED WGS 84 COORDINATES AT 1988.0 EPOCH

Station #	Longitude(deg)	Latitude(deg)	Height(km)	Plate
85128	255.4754142	38.8030569	1.91216	NOAM
85129	345.5878714	-7.9513322	.10784	SOAM
85130	72.3631217	-7.2665514	-.06153	INDI
85131	167.7305353	8.7225006	.04136	PCFC
85132	201.7606878	21.5614897	.42972	PCFC
85262	138.6547978	-34.6739325	.03692	INDI
85263	301.4807053	-34.5737014	.04947	SOAM
85264	358.7159244	51.4537958	.16907	EURA
85265	50.6081392	26.2091350	-.01211	ARAB
85266	281.5064000	-.2151528	2.92475	SOAM

Station #	x (km)	y (km)	z(km)
85128	-1248.59700	-4819.43412	3976.50113
85129	6118.52537	-1572.35096	-876.46444
85130	1917.03275	6029.78438	-801.37654
85131	-6160.88597	1339.85129	960.84327
85132	-5511.98296	-2200.25015	2329.48217
85262	-3942.24330	3468.85974	-3608.19773
85263	2745.49975	-4483.63689	-3599.05497
85264	3981.77547	-89.25190	4965.29299
85265	3633.91233	4425.27881	2799.86306
85266	1272.86864	-6252.77412	-23.80129

TABLE A-3. GPS-REALIZED WGS 84 COORDINATES AT 1988.0 EPOCH

Station #	Longitude(deg)	Latitude(deg)	Height(km)	Plate
85128	255.47541080	38.80305524	1.911725	NOAM
85129	345.58787026	-7.95133177	.106665	SOAM
85130	72.36311742	-7.26655238	-.063719	AUST
85131	167.73053418	8.72249735	.039997	PCFC
85132	201.76067694	21.56148704	.428207	PCFC
85262	138.65479074	-34.67393566	.035690	AUST
85263	301.48070138	-34.57370366	.048950	SOAM
85264	358.71591619	51.45379118	.167523	EURA
85265	50.60814100	26.20913643	-.013552	ARAB
85266	281.50639197	-.21515920	2.922779	SOAM
From 14 Dec 93 on				
85262	138.65479074	-34.67393566	.035504	AUST
85263	301.48070138	-34.57370366	.048748	SOAM
85264	358.71591619	51.45379118	.167337	EURA
85265	50.60814100	26.20913643	-.013739	ARAB
85266	281.50639197	-.21515920	2.922593	SOAM

Station #	x (km)	y (km)	z(km)
85128	-1248.597078	-4819.433222	3976.500215
85129	6118.524215	-1572.350791	-876.464232
85130	1917.032534	6029.782150	-801.376369
85131	-6160.884679	1339.851139	960.842711
85132	-5511.982171	-2200.248628	2329.481342
85262	-3942.241960	3468.859421	-3608.197320
85263	2745.499149	-4483.636590	-3599.054879
85264	3981.774894	-89.252453	4965.291463
85265	3633.911328	4425.277871	2799.862562
85266	1272.867371	-6252.772362	-23.801994
From 14 Dec 93 on			
85262	-3942.241846	3468.859320	-3608.197214
85263	2745.499062	-4483.636448	-3599.054764
85264	3981.774778	-89.252451	4965.291317
85265	3633.911221	4425.277741	2799.862480
85266	1272.867333	-6252.772180	-23.801993

Station #	x rate (km/yr)	y rate (km/yr)	z rate (km/yr)
85128	-.0000157	-.0000008	-.0000060
85129	.0000000	-.0000065	.0000113
85130	-.0000438	.0000192	.0000392
85131	.0000188	.0000658	.0000292
85132	-.0000112	.0000612	.0000313
85262	-.0000422	.0000037	.0000495
85263	.0000017	-.0000065	.0000092
85264	-.0000122	.0000182	.0000100
85265	-.0000328	.0000062	.0000328
85266	-.0000057	-.0000012	.0000088

TABLE A-4. GPS-REALIZED WGS 84 COORDINATES AT 1994.0 EPOCH

Station #	Longitude(deg)	Latitude(deg)	Height(km)
85128	255.47540977	38.80305483	1.911725
85129	345.58786991	-7.95133114	.106665
85130	72.36312000	-7.26655024	-.063719
85131	167.73053046	8.72249894	.039997
85132	201.76067341	21.56148887	.428207
85262	138.65479238	-34.67393241	.035690
85263	301.48070125	-34.57370306	.048950
85264	358.71591774	51.45379205	.167523
85265	50.60814276	26.20913841	-.013552
85266	281.50639166	-.21515872	2.922779
From 14 Dec 93 on			
85262	138.65479238	-34.67393241	.035504
85263	301.48070125	-34.57370306	.048748
85264	358.71591774	51.45379205	.167337
85265	50.60814276	26.20913841	-.013739
85266	281.50639166	-.21515872	2.922593

Station #	x (km)	y (km)	z(km)
85128	-1248.597172	-4819.433227	3976.500179
85129	6118.524215	-1572.350831	-876.464163
85130	1917.032272	6029.782265	-801.376134
85131	-6160.884566	1339.851534	960.842885
85132	-5511.982238	-2200.248261	2329.481530
85262	-3942.242214	3468.859444	-3608.197023
85263	2745.499159	-4483.636628	-3599.054824
85264	3981.774821	-89.252344	4965.291523
85265	3633.911130	4425.277907	2799.862759
85266	1272.867337	-6252.772369	-23.801941
From 14 Dec 93 on			
85262	-3942.242099	3468.859342	-3608.196917
85263	2745.499072	-4483.636486	-3599.054709
85264	3981.774705	-89.252341	4965.291377
85265	3633.911024	4425.277778	2799.862677
85266	1272.867300	-6252.772186	-23.801940

APPENDIX B

DEFINITION OF TRANSFORMATION EQUATIONS

The seven-parameter similarity transformation used throughout this report is defined by the following equation:

$$\begin{vmatrix} x' \\ y' \\ z' \end{vmatrix} = \begin{vmatrix} x \\ y \\ z \end{vmatrix} + \begin{vmatrix} T1 \\ T2 \\ T3 \end{vmatrix} + \begin{vmatrix} D & -R3 & R2 \\ R3 & D & -R1 \\ -R2 & R1 & D \end{vmatrix} \begin{vmatrix} x \\ y \\ z \end{vmatrix}$$

where

x,y,z = Earth-fixed coordinates in first system (km)
x',y',z' = Earth-fixed coordinates in second system (km)
T1,T2,T3 = three translation parameters (km)
D = scale parameter (unitless)
R1,R2,R3 = three rotation parameters (radians)

In computing the transformation parameters between two sets of orbits, each 15-min position for the middle 7 days of each 8-day span for all satellites was used. In computing the transformation parameters between two sets of station coordinates, positions for all 10 stations were used. Least squares fitting was used for both cases since they are both overdetermined. The same observation sigma was used for all three coordinate components for either satellite position or station position. Once the transformation parameters were determined, the mean, standard deviation, and root mean square of the differences between the starting coordinates and the transformed coordinates were computed. For orbits these were resolved in terms of the radial, along-track, and cross-track reference frame. For station coordinates these were resolved in terms of east, north, and vertical directions. All translations were converted to cm, the scale parameter was converted to parts in 10^8, and all rotations were converted to milliarcseconds.

APPENDIX C

IGS ROGUE RECEIVER STATION COORDINATE ADJUSTMENTS

TABLE C-1. IGS ROGUE RECEIVER STATION COORDINATE ADJUSTMENTS (CORRESPONDING TO CASE Q IN TABLE 13 IN MAIN BODY) (CM)

	East				North				Vertical			
Span	C	B	A	ALL	C	B	A	ALL	C	B	A	ALL
Sta.#												
7288	-2	-1	1		-2	-1	-3		1	3	2	
7283	-3	-2	0		-2	-1	-2		3	6	5	
7285	2	-1	-3		-4	-2	-2		4	8	7	
1565	-2	-2	-1		-1	-1	-1		3	0	3	
7224	-1	0	0		0	1	1		6	6	5	
8833	0	-1	1		-1	0	0		9	9	8	
7213	-2	1	1		-1	1	0		7	5	4	
7601	-1	1	2		-1	0	0		4	4	2	
1545	1	2	3		-1	1	0		-3	-4	-4	
Mean	-1	-0	0		-1	-0	-1		4	4	4	
S.D.	2	1	2		1	1	1		3	4	3	
RMS	2	1	2	2	2	1	1	1	5	6	5	5
8004	-9	-11	-12		-2	-2	-2		7	5	6	
8007	-1	-1	0		1	0	0		6	3	7	
8001	1	2			1	1			0	2		
8008	1	2	5		-3	-2	-3		-1	3	1	
8003	1	3	2		-2	1	0		0	0	0	
7246	-5	-2	-6		-1	-1	1		20	24	21	
8005	-29	-5	2		-1	2	2		11	16	-2	
Mean	-6	-2	-2		-1	-0	-0		6	8	6	
S.D.	0	5	6		1	1	2		7	8	8	
RMS	12	5	6	8	2	1	2	2	9	11	9	10
Overall												
Mean	-3	-1	-0		-1	-0	-1		5	6	4	
S.D.	7	3	4		1	1	1		5	6	6	
RMS	8	3	4	5	2	1	2	2	7	9	7	8

TABLE C-2. IGS ROGUE RECEIVER STATION COORDINATE ADJUSTMENTS (CORRESPONDING TO TABLE 19 IN MAIN BODY) (CM)

	East			North			Vertical		
Case Sta.#	RD	R+RD	R	RD	R+RD	R	RD	R+RD	R
7288	-1	-4	-4	-2	-5	-9	1	1	10
7283	(not used)								
7285	2	-2	-7	-4	-3	-1	4	3	-1
1565	-3	1	3	-1	1	4	2	9	44
7224	-2	-7	-11	1	1	5	5	8	18
8833	(not used)								
7213	-2	-4	-6	0	0	-5	5	2	-6
7601	-1	-3	-6	0	-2	-6	2	4	7
1545	1	1	8	0	1	0	-2	-1	41
Mean	-1	-3	-3	-1	-1	-2	2	4	16
S.D.	2	3	6	2	2	5	2	3	18
RMS	2	4	7	2	2	5	3	5	24
8004	-9	3	13	-1	0	8	7	4	-28
8007	-2	2	7	1	4	16	5	17	94
8001	1	0	-1	1	-7	-18	0	1	-8
8008	1	-8	1	-3	-2	-4	0	-1	-17
8003	0	3	13	-1	3	8	3	1	-32
7246	-3	-3	-5	-1	0	3	20	21	24
8005	-27	-10	-5	-1	-3	-9	12	14	25
Mean	-6	-2	3	-1	-1	1	7	8	8
S.D.	9	5	7	1	3	11	7	8	41
RMS	11	5	8	1	4	11	9	12	42
Overall									
Mean	-3	-2	0	-1	-1	-1	5	6	12
S.D.	7	4	7	1	3	8	5	7	32
RMS	8	5	7	2	3	8	7	9	34

TABLE C-3. IGS ROGUE RECEIVER STATION COORDINATE ADJUSTMENTS (CORRESPONDING TO TABLE 37 IN MAIN BODY) (CM)

Sta.#	East	North	Vertical
7282	-2	-2	11
1311	0	-1	6
7225	3	0	4
7939	-4	-1	7
7602	-2	1	6
1404	1	0	3
7090	1	2	7
7232	-3	0	24
Mean	-1	-0	9
S.D.	2	1	6
RMS	2	1	11
7288	0	-3	3
7283	(not used)		
7285	4	-6	6
1565	-5	-1	3
7224	-5	0	6
8833	(not used)		
7213	-5	0	6
7601	-4	0	3
1545	1	1	-2
Mean	-2	-1	4
S.D.	3	2	3
RMS	4	3	4
Mean	-1	-1	6
S.D.	3	2	6
RMS	3	2	8
8004	-10	-3	9
8007	-4	0	6
8001	-2	1	1
8008	0	-3	1
8003	-1	-1	1
7246	-2	1	18
8005	-27	1	10
Mean	-7	-1	7
S.D.	9	2	6
RMS	11	2	9
Overall			
Mean	-3	-1	6
S.D.	6	2	6
RMS	7	2	8

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