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Accuracy of Global Positioning System Broadcast Orbits for Relative Surveys

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ABSTRACT. How accurate are the Global Positioning System (GPS) broadcast orbits? This question is important to the GPS community for both military and civilian applications. Surveyors, for example, would like to know if field processing of GPS baselines can be considered final. There is widespread belief that for accurate surveys (e.g., 1 ppm), post-processing with precise ephemerides is required.

Precise versus broadcast comparisons are given in terms of along-track, cross-track, and radial plots and statistics based on hundreds of actual broadcast orbit comparisons. The proper use of the broadcast orbits is discussed. A strong measure of orbital accuracy is the effect of orbit errors on baseline vector computations. Numerous baseline vector solutions, using both precise orbits and broadcast orbits, are given.

1. INTRODUCTION

In the so-called "operative" satellite geodesy, it is assumed that the satellite position is known for any arbitrary epoch. This presupposes known orbits for the satellites. In an ideal case, an undisturbed orbit may be represented by, for example, the six Keplerian elements. The orbits in the real world, however, are perturbed by many different influences. Therefore, apart from the six Keplerian elements, their corresponding perturbations are also needed.

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For GPS, the broadcast message substantially fulfills the requirements for the determination of satellite positions at arbitrary epochs. A part of the broadcast message contains the broadcast ephemerides which are extrapolated values of the above mentioned orbital elements (Rockwell International Corporation 1984). These data are gathered in a block and modulated on the satellite signal (50 bits per second) after being uploaded by the master control station. Thus the user has the advantage of having them available during field work (permitting, for example, real-time point positioning and navigation). An update of the broadcast message exists on an hourly basis. The broadcast message comprises 1,500 bits which require 30 seconds to send. Although some of this information changes from one cycle to the next, the broadcast orbit parameters will simply be repeated every 30 seconds until they change after an hour.

In addition to the broadcast ephemerides, there are the precise ephemerides. The distinction between the two is important. The precise ephemerides are fitted orbits from observations of several stations (Swift 1985). At present, the user does not have access to the precise ephemerides in real time. Typically, the precise ephemerides are available 4 to 8 weeks after tracking data are collected.

Comparing the two kinds of ephemerides, the precise ephemerides are, as the name indicates, more precise because fitting is more accurate than extrapolation. On the other hand, a real-time application is (currently) restricted to the broadcast ephemerides. An interesting question is how the two kinds of ephemerides compare. This is done extensively in this paper where the precise ephemerides are considered to be the truth and the broadcast results are displayed in relation to this truth.

Sometimes the broadcast message has been misused. Opportunities for misuse resulted from an earlier period when receiver manufacturers recorded only one broadcast message per session, and some users were not aware of this potential problem. One broadcast message cannot be used for arbitrarily long observation periods. A tutorial example shows the effect of misusing the broadcast message.

As a final introductory note, we have specifically and intentionally avoided consideration of the intentional degradation of broadcast orbital data (i.e., Selective Availability or S/A) throughout this paper.

2. BACKGROUND

GPS has entered its final stage of deployment where 21 satellites and 3 additional spare satellites will be placed in orbit. Currently, the progression from Block I satellites to Block II satellites is underway. Based on the assumption of successful launches, all satellites should be in their appropriate orbits by 1993. The "heart" of each of these navigation and timing satellites is its clock. Actually three different types are in use in the current Block I satellites: quartz, rubidium, and cesium. The corresponding stabilities are roughly 10^{-9} seconds/second for quartz, 10^{-11} to 10^{-12} seconds/second for rubidium, and 10^{-12} to 10^{-13} seconds/second for cesium. Table 1 lists the satellite numbers (PRN) and the corresponding clocks (oscillators).

Table 1.--Clocks presently in use for GPS satellites

PRN	Clock
2	cesium
3	rubidium
6	rubidium
8	quartz
9	rubidium
11	cesium
12	cesium
13	cesium
14	cesium

PRN 3 used a cesium clock before January 1989. In addition, PRNs 2 and 14 were launched recently, and no data are reported here. Note that a satellite has more than a single clock. A Block II satellite is equipped with two cesium and two rubidium clocks (Wells 1987). Reviewing table 1, it can be expected that PRN 8 data should, in general, be of lower quality than data from other PRNs. This is mostly due to the fact that orbits herein compared were reduced with pseudoranges so that clocks and orbits are intertwined. In double-difference carrier phase processing, this would be less of a factor.

This paper deals primarily with orbital errors. A well-known rule of thumb states that the proportional (i.e., relative) baseline error is the same proportionally as the orbit error. More specifically, for a desired baseline accuracy of 0.001 m, an orbit error dr (m) can be computed approximately from dr = 20,000/b, where the baseline length b must be inserted in meters. This means, according to this rule, that for a 20,000 m baseline, the orbit error should not exceed 1 m to yield an accuracy of 0.001 m for the baseline determination.

The orbital errors have been obtained by considering the precise ephemerides as the truth and by comparing those values to broadcast ephemerides for a certain time span. In most cases maximum error values are given; this represents a relatively severe measure for the orbit errors. In some cases the mean of many samples, all taken as positive values, with its standard deviation (rms), is shown. To be able to cover many periods, a cumulative distribution function has been generated which allows a statement such as "80 percent of the precise-minus-broadcast difference comparisons have maxima smaller than 15 m." More details are given below.

3. ORBITAL ERRORS: BROADCAST VERSUS PRECISE

The choice of comparing broadcast data with precise data is easily understood because each user has access to broadcast data. Therefore, our goal was to investigate the broadcast message using numerous cases. The following results are based on data covering August 1987, and May 1988 to March 1989. For the latter period, apart from September 1988, at least one data set was available each month, in many cases more than one. It was of particular importance to include the last and the current year, since sunspot activities are near a maximum, causing strong effects on the ionosphere and, possibly, on the orbit computation accuracy. The broadcast messages were collected by four different receivers: Ashtech XII, MINIMAC 2816, TI 4100, Trimble 4000 SX (10-channel). They were recorded in Australia, Europe, Japan, and North America.

The precise ephemerides, the data of the Naval Surface Warfare Center (NSWC), were available in the form of three-dimensional coordinates in the WGS 84 (World Geodetic System 1984) at 15-minute intervals (Swift 1985).

The broadcast ephemerides were generated by a computation based on each broadcast message, which is related to the time of ephemeris (TOE), i.e., the time for which the broadcast message has been calculated. The broadcast computation was performed at the same 15-minute epochs so as to coincide with the precise ephemerides. Each broadcast message was used to compute orbital positions from -2 hours to +2 hours with respect to the TOE. With precise ephemerides and broadcast ephemerides now available at 15-minute epochs, a ninth-order polynomial was used to interpolate between epochs.

The precise ephemerides are considered to be true and were taken as reference. The differences between the corresponding broadcast ephemerides and the precise are the primary object of the investigation. The resulting difference vector (precise-minus-broadcast) for each epoch is split into three components: along-track, cross-track, and radial with respect to the plane and velocity of the satellite orbit. The results are given in appendix A. The columns of the tables in appendix A show the satellite number; the rows show the result for one broadcast orbit.

In detail, the first TOE in appendix A is August 17, 1987, 20:00 hours. For this epoch a broadcast message was available for the PRNs 6, 8, and 11. For each of the three satellites, the above mentioned 4-hour computation (-2 hours and +2 hours with respect to the TOE) was performed. Thereafter, for precise ephemerides and broadcast ephemerides, as well, a sufficiently smooth curve was interpolated for these 4 hours and the corresponding values compared. This yielded along-track, cross-track, and radial components. In either case, the maximum value was taken as reported in the tables of appendix A. This means that for PRN 6, the maximum discrepancy between precise and broadcast ephemerides expressed in the along-track component is 9 m for the time span -2 hours to +2 hours with respect to the TOE, i.e., in this case, August 17, 1987, 20:00. The corresponding value for the cross-track component for PRN 6 is 4 m, and 3 m for the radial component. Analogously, the results for PRNs 8 and 11 are given.

In the same way, all other rows have to be interpreted. Dashes in a satellite column indicate that either no broadcast message was available for the corresponding satellite, or it was identical to one given elsewhere.

Investigating all appendix A results for each satellite, some outliers interrupt the consistent behavior of the orbital errors: PRN 11 on August 1, 1988, and August 2, 1988; and PRN 8 on February 23, 1989, Session A, and on February 23, 1989, Session B. The latter two are clearly correlated.

Table 2 gives statistics in accordance to the clock accuracies. (See also table 1.) It shows the arithmetic mean of all entries in appendix A and the rms (standard deviation) in meters for each satellite. Note that PRN 3 appears twice because the clock was changed from cesium to rubidium in January 1989. (See sec. 2.) It is interesting to compare two clocks of the same satellite. The higher stability of the cesium clock is reflected by about 50 percent smaller orbital errors.

It must be stressed that the results of table 2 are computed without the above mentioned outliers for PRN 11 and PRN 8. Including the outliers, the results for PRN 11 are: along-track mean = 6.7, rms = 11.3, cross-track mean = 4.5, rms = 5.2, radial mean = 2.1, rms = 1.2; and for PRN 8: along-track mean = 28.4, rms = 37.3, cross-track mean = 24.1, rms = 21.3, radial mean = 10.8, rms = 6.0.

Table 2.--Statistics for precise-minus-broadcast ephemerides (maximum differences in meters)

Quartz clock	PRN 8	Rubidium	PRN 3	PRN 6	PRN 9
Along-track mean	21.0		10.8	15.1	14.0
rms	10.9		6.1	6.5	8.1
Cross-track mean	20.0		5.3	9.8	7.0
rms	8.3		1.9	5.7	3.2
Radial mean	10.0		5.3	7.0	6.4
rms	4.8		1.9	2.2	2.3

Cesium	PRN 3	PRN 11	PRN 12	PRN 13
Along-track mean	5.9	5.3	5.6	4.4
rms	2.2	2.2	2.3	2.2
Cross-track mean	2.6	3.7	3.5	3.4
rms	1.2	2.0	1.7	1.8
Radial mean	2.6	2.0	2.0	1.3
rms	0.8	0.8	0.9	0.6

Still more insight into the orbital errors can be gained by looking at cumulative distribution functions that are given for each satellite and for each component in appendix B. This means that for each arithmetic mean of table 2 or, equivalently, for each column of the tables in appendix A the corresponding cumulative distribution function can be found. (Since PRN has used both rubidium and cesium clocks, two plots are included.) The first three plots in appendix B cover the cumulative distribution function for PRN 3 while using a cesium clock. The ordinates show the percentage, the abscissae show the along-track, cross-track and radial orbital errors in meters. Thus it can be read (e.g., from the along-track plot) that 40 percent of all calculated along-track orbital errors of PRN 3 have maxima less than or equal to 5 m while using the cesium clock. Note that the last point of each plotted curve is the 100 percent level. Consider also that the scale is not always the same for the plots in appendix B.

The results, especially of the satellites with cesium clocks, are impressive. Considering, e.g., PRN 11 and asking for 80 percent, then it can be seen that 80 percent of the along-track maxima are less than 6 m, for the cross-track maxima less than 5 m, and for the radial maxima less than 2 m.

4. USE AND MISUSE OF BROADCAST MESSAGES

Encouraged by the results of the previous section, it may be tempting to use broadcast ephemerides in all situations. This could lead to some surprises. The most important point is the TOE. A broadcast message may be accurately used only around its TOE, where ±2 hours is prescribed. Using it beyond these limits would lead to ever-growing ephemeris errors. This can be shown best by the tutorial example in figure 1.

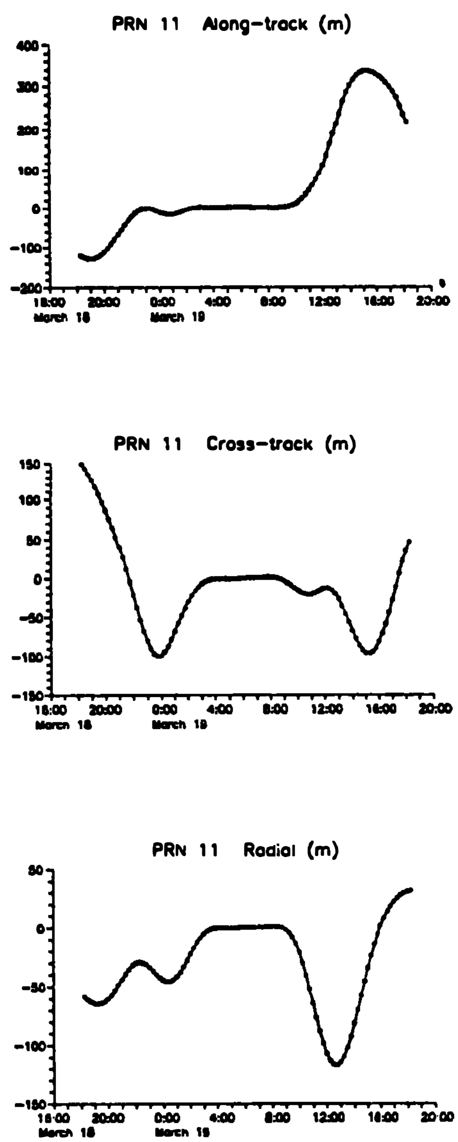

Figure 1.--Demonstration of the misuse of broadcast ephemerides. The ordinates show the residuals of precise-minus-broadcast ephemerides.

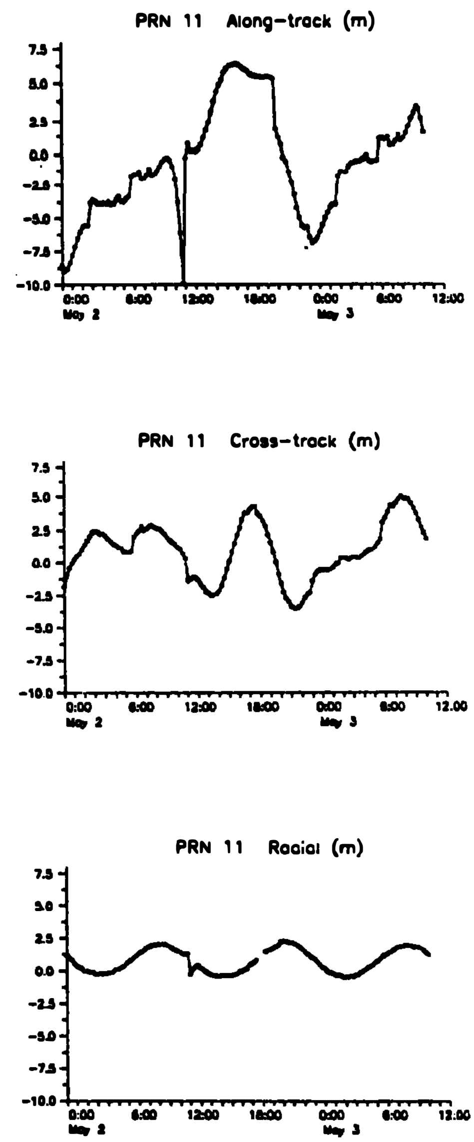

Figure 2.--Ensemble of broadcast messages. The ordinates show the residuals of precise-minus-broadcast ephemerides.

The three plots show the orbital errors for PRN 11 where one broadcast message is used for about 24 hours. The abscissae show the time and the ordinates show the along-track, cross-track, and radial error in meters when comparing broadcast and precise ephemerides. Attention should be paid to the different scales in figure 1. The broadcast message with a TOE of March 19, 6:00 hours was used. Figure 1 indicates that the broadcast message is good for a time period of approximately ±2 hours with respect to the TOE. Surpassing these limits leads to degraded results. By a combination of several messages, it is possible to cover a longer time span than 4 hours. Nominally, at each hour a new broadcast message is transmitted. To cover a longer time span, messages can be concatenated. For a better understanding, an illustrative example is provided in table 3, where 24 PRN 11 TOEs are concatenated.

Table 3.--Time of ephemeris broadcast messages for PRN 11, in 1989

May 2, 01:00	May 2, 14:00	May 3, 01:00
May 2, 02:00	May 2, 15:00	May 3, 02:00
May 2, 03:00	May 2, 16:00	May 3, 03:00
May 2, 04:00	May 2, 17:00	May 3, 04:00
May 2, 05:00	May 2, 18:00	May 3, 05:00
May 2, 06:00	May 2, 19:00	May 3, 06:00
May 2, 07:00	May 2, 20:00	May 3, 07:00
May 2, 08:00	May 2, 21:00	May 3, 08:00

Note that table 3 has two gaps: a 6-hour gap from 1989, May 2, 08:00 to 14:00, and a 4-hour gap from 1989, May 2, 21:00 to 1989, May 3, 01:00. According to the previous considerations, one uses a broadcast message for ±2 hours around its TOE. This means that the 4-hour gap should not show any adverse effect because it can be bridged from May 2, 21:00 to May 3, 01:00. In contrast, the 6-hour gap cannot be completely bridged; there remains a 2-hour gap even after extending the corresponding messages by +2 hours and by -2 hours, respectively. The results for PRN 11 are shown in figure 2, again separated in along-track, cross-track, and radial errors and displayed with respect to time.

The impact of the larger gap can clearly be seen in the plot for the along-track errors, although in this case it does not generate much degradation. In this example, the broadcast messages of May 2, 08:00, and May 2, 14:00, are used for ±3 hours each (thus closing the gap).

The statistics corresponding to figure 2 are given in table 4. These values are computed from the actual 15-minute samples (taken as absolute values) of the plot and not of maxima as in table 2. One can relate the values in tables 2 and 4, approximately, by maximum equals mean plus 1.5 times the rms.

Table 4.--Statistics derived from comparing precise and broadcast ephemerides for PRN 11 in the May 1989 example of figure 2

Satellite	Along		Cross		Radial		Comparison time	
	mean	rms	mean	rms	mean	rms	begin	end
PRN 11	3.2	2.4	1.9	1.3	0.9	0.7	May 1, 23:00	May 3, 10:00

Note that the broadcast messages of table 3 were not smoothed. Each message was used independently. A smoothing of the broadcast messages is therefore not required in any case. Furthermore, smoothing is not the point of this paper. We want to evaluate the orbits as they are actually used in the field.

So far we have demonstrated how the broadcast message can be used and misused. Probably the most interesting question is: how is the processing of baselines affected if broadcast ephemerides are taken instead of precise ephemerides? The next section deals with this topic.

5. SURVEY EXAMPLES - PROCESSING BASELINES WITH BROADCAST AND WITH PRECISE EPHEMERIDES

We now want to compare baselines processed with broadcast and with precise ephemerides. The following results are taken from a measurement campaign covering August 17, 1987, 18:00 to 23:45. The experimenter was Dr. Al Evans at the Naval Surface Warfare Center (NSWC). Table 5 shows differences of the broadcast and the precise orbits expressed again, as in the earlier sections, as along-track, cross-track, and radial components. In table 5 the values for along-track, cross-track, and radial components for each satellite were obtained from 1-minute samples in the comparison time indicated. The comparison times reveal when each satellite was visible. Taking PRN 12 as an example, table 5 shows that it was visible from 20:57 to 23:25. Table 6 gives the results of data taken on August 17, 1987, from four short baselines by TI 4100 receivers. PRN 11 is the reference satellite in all cases. The remaining PRNs, sorted according to their appearance, are: 6, 8, 13, 12, 3, where PRN 3 was not observed for the baseline MBRE-CHUR. For the other baselines, PRN 3 was visible for about 45 minutes.

Table 5.--Comparison of precise and broadcast ephemerides on August 17, 1987

Satellite	Along		Cross		Radial		Comparison time	
	mean	rms	mean	rms	mean	rms	begin	end
PRN 03	6.7	1.0	2.5	0.1	2.6	0.2	23:20	24:05
PRN 06	3.9	2.7	0.7	0.4	2.6	0.6	18:44	21:20
PRN 08	13.9	5.5	8.9	4.9	11.0	2.0	18:44	22:34
PRN 11	1.5	1.2	2.3	1.1	1.1	0.8	18:44	24:05
PRN 12	2.1	0.9	0.9	0.5	2.1	0.3	20:57	23:25
PRN 13	3.3	0.9	0.5	0.2	1.8	0.4	20:41	24:05

Table 6.--Comparison of baselines and their components computed either with precise (P) or with broadcast (BC) orbits using all available satellites

From-To	Orbit	Baseline (m)	dx (m)	dy (m)	dz (m)
MBRE-NSWC	P	1478.9198	-1402.2738	48.6680	467.4005
	BC	1478.9196	-1402.2737	48.6686	467.4005
	P-BC	-0.0002	-0.0001	-0.0006	0.0000
	ppm	0.14	0.07	0.41	0.00
MBRE-BOM2	P	3604.6640	464.9020	2318.1235	2720.9874
	BC	3604.6648	464.9022	2318.1239	2720.9881
	P-BC	-0.0008	-0.0002	-0.0004	-0.0007
	ppm	0.22	0.06	0.11	0.19
MBRE-CHUR	P	4771.0078	-4668.2497	-368.7751	913.2166
	BC	4771.0067	-4668.2490	-368.7728	913.2154
	P-BC	0.0011	-0.0007	-0.0023	0.0012
	ppm	0.23	0.15	0.48	0.25
MBRE-RAD9	P	8372.7136	5708.9626	-3003.1820	-5337.6940
	BC	8372.7148	5708.9618	-3003.1846	-5337.6952
	P-BC	-0.0012	0.0008	0.0026	0.0012
	ppm	0.14	0.10	0.31	0.14

Table 6 shows the precise-minus-broadcast differences in baseline lengths and baseline components. In addition, these differences are also expressed in parts per million (ppm) with respect to the baseline length. An increase of the differences with respect to the baseline length can be seen. The largest difference appears for the longest baseline, i.e., the 8 km baseline. Demanding an accuracy of 0.001 m, for the example in table 6, it may be stated that for baselines up to about 4 km there appears to be no significant difference in taking either broadcast or precise ephemerides. Note that this statement is restricted to the special campaign mentioned above. Many effects can influence the result, e.g., satellite geometry.

According to table 5, the orbit errors of PRN 8 are by far the largest ones, as expected, based on the discussion in section 2. Do the results of table 6 change if this satellite is omitted from the computations? Before looking at the results, a warning should be stressed. Omitting a satellite will weaken the geometry. This means that the subsequent baseline vector results are not necessarily better than those of table 6. This is not as important in this investigation since sensitivity to orbit errors is the objective.

Table 7.--Comparison of baselines and their components computed either with precise (P) or with broadcast (BC) orbits without PRN 8

From-To	Orbit	Baseline (m)	dx (m)	dy (m)	dz (m)
MBRE-NSWC	P	1478.9184	-1402.2724	48.6817	467.3991
	BC	1478.9185	-1402.2724	48.6815	467.3994
	P-BC	-0.0001	0.0000	0.0002	-0.0003
	ppm	0.07	0.00	0.14	0.20
MBRE-BOM2	P	3604.6633	464.9020	2318.1223	2720.9874
	BC	3604.6635	464.9018	2318.1219	2720.9881
	P-BC	-0.0002	0.0002	0.0004	-0.0007
	ppm	0.06	0.06	0.11	0.19
MBRE-CHUR	P	4770.9920	-4668.2414	-368.7376	913.1923
	BC	4770.9922	-4668.2413	-368.7386	913.1931
	P-BC	0.0002	-0.0001	0.0010	-0.0008
	ppm	0.04	0.02	0.21	0.17
MBRE-RAD9	P	8372.7140	5708.9630	-3003.1804	-5337.6951
	BC	8372.7153	5708.9635	-3003.1787	-5337.6975
	P-BC	-0.0013	-0.0005	-0.0017	0.0024
	ppm	0.16	0.06	0.20	0.29

The comparisons shown in table 7 are similar to those in table 6. There is a slight improvement for baselines MBRE-CHUR and MBRE-RAD9, but it is so small that it would be adventurous to conclude that this results from the decrease of the orbital errors by omitting PRN 8.

However, the examples of short baselines show how the results are affected by different ephemerides. The effect increases with increasing baseline length.

Table 8 gives the orbit errors for the displayed comparison times of February 17, 1989. The baselines in the range of 37 km and 75 km, based on Trimble data, are shown in table 9. For station VAN5 to station LOFT and VAN5 to EVEL, two comparison tests were performed between precise and broadcast ephemerides: (1) all available satellites were used, and (2) all satellites except PRN 6 were used. The influence of omitting satellites becomes apparent now.

Table 8.--Comparison of broadcast and precise ephemerides on February 17, 1989

Satellite	Along		Cross		Radial		Comparison time	
	mean	rms	mean	rms	mean	rms	begin	end
PRN 03	6.3	1.2	3.9	0.2	3.9	0.5	8:50	9:42
PRN 06	18.1	5.4	0.4	0.2	7.2	2.0	6:40	8:40
PRN 09	6.4	3.8	1.8	0.4	7.3	1.1	6:40	9:42
PRN 11	3.5	1.5	3.8	1.1	1.0	0.7	6:40	9:52
PRN 12	2.7	0.6	0.9	0.6	0.5	0.2	7:15	9:42
PRN 13	2.3	1.5	2.1	1.4	0.5	0.4	6:40	9:42

Table 9.--Comparison of baselines and their components computed either with precise (P) or with broadcast (BC) orbits for different numbers of PRN on February 17, 1989

1989/02/17		PRNs: 11(ref.),6,9,13,12,3		Rec. type: Trimble	
From-To	Orbit	Baseline (m)	dx (m)	dy (m)	dz (m)
VAN5-LOFT	P	37897.2634	-9905.9584	-19207.7935	-31130.9368
	BC	37897.2581	-9905.9636	-19207.7869	-31130.9328
	P-BC	0.0053	0.0052	-0.0066	-0.0040
	ppm	0.14	0.14	0.17	0.11

(Table continued on next page)

1989/02/17		PRNs: 11(ref.), 9,13,12,3		Rec. type: Trimble	
From-To	Orbit	Baseline (m)	dx (m)	dy (m)	dz (m)
VAN5-LOFT	P	37897.2702	-9905.9523	-19207.7945	-31130.9465
	BC	37897.2718	-9905.9534	-19207.7967	-31130.9467
	P-BC	-0.0016	0.0011	0.0022	0.0002
	ppm	0.04	0.03	0.06	0.01

1989/02/17		PRNs: 11(ref.),6,9,13,12,3		Rec. type: Trimble	
From-To	Orbit	Baseline (m)	dx (m)	dy (m)	dz (m)
Van5-EVEL	P	75112.2254	24148.9267	-39108.1932	-59407.2805
	BC	75112.2037	24148.9150	-39108.1782	-59407.2677
	P-BC	0.0217	0.0117	-0.0150	-0.0128
	ppm	0.29	0.16	0.20	0.17

1989/02/17		PRNs: 11(ref.), 9,13,12,3		Rec. type: Trimble	
From-To	Orbit	Baseline (m)	dx (m)	dy (m)	dz (m)
VAN5-EVEL	P	75112.2222	24148.9248	-39108.1963	-59407.2750
	BC	75112.2185	24148.9216	-39108.1945	-59407.2729
	P-BC	0.0037	0.0032	-0.0018	-0.0021
	ppm	0.05	0.04	0.02	0.03

Table 10 provides another comparison study based on data taken with Ashtech receivers. The orbital errors (precise-minus-broadcast) for the appropriate time span of observation for each satellite use the baseline information given in table 11. For these two baselines, two comparisons were performed: (1) all available satellites were used, and (2) all satellites except PRN 8 were used.

Table 10.--Comparison of broadcast and precise ephemerides on August 15, 1988

Satellite	Along		Cross		Radial		Comparison time	
	mean	rms	mean	rms	mean	rms	begin	end
PRN 06	2.1	1.5	2.4	0.8	5.2	0.8	19:09	20:15
PRN 08	11.7	7.1	13.5	7.6	12.9	0.9	19:09	21:10
PRN 09	9.6	3.4	1.9	0.8	3.9	0.4	19:09	21:15
PRN 11	1.0	0.5	1.0	0.4	0.9	0.5	19:09	22:00
PRN 12	5.5	1.1	1.0	0.8	3.0	0.4	20:00	22:00
PRN 13	1.9	0.5	2.4	0.1	1.0	0.4	20:00	22:00

Table 11.--Comparison of baselines and their components computed either with precise (P) or with broadcast (BC) orbits for different numbers of PRN

1988/08/15		PRNs: 11(ref.),6,8,9,12,13		Rec. type: Ashtech	
From-To	Orbit	Baseline (m)	dx (m)	dy (m)	dz (m)
MDPT-ASWP	P	22712.6398	-9511.8947	-14271.2410	-14890.2500
	BC	22712.6440	-9511.8913	-14271.2522	-14890.2479
	P-BC	-0.0042	-0.0034	0.0112	-0.0021
	ppm	0.18	0.15	0.49	0.09

1988/08/15		PRNs: 11(ref.),6, 9,12,13		Rec. type: Ashtech	
From-To	Orbit	Baseline (m)	dx (m)	dy (m)	dz (m)
MDPT-ASWP	P	22712.6358	-9511.8893	-14271.2315	-14890.2566
	BC	22712.6369	-9511.8824	-14271.2377	-14890.2566
	P-BC	-0.0011	-0.0069	0.0062	0.0000
	ppm	0.05	0.30	0.27	0.00

1988/08/15		PRNs: 11(ref.),6,8,9,12,13		Rec. type: Ashtech	
From-To	Orbit	Baseline (m)	dx (m)	dy (m)	dz (m)
NSBO-MDPT	P	84599.8354	10170.1485	-51880.8162	-66046.0532
	BC	84599.8588	10170.1460	-51880.8895	-66046.0260
	P-BC	-0.0234	0.0025	0.0733	-0.0272
	ppm	0.28	0.03	0.87	0.32

1988/08/15		PRNs: 11(ref.),6, 9,12,13		Rec. type: Ashtech	
From-To	Orbit	Baseline (m)	dx (m)	dy (m)	dz (m)
NSBO-MDPT	P	84599.8338	10170.1608	-51880.7892	-66046.0704
	BC	84599.8474	10170.1984	-51880.7851	-66046.0853
	P-BC	-0.0136	-0.0376	-0.0041	0.0149
	ppm	0.16	0.44	0.05	0.18

Tables 9 and 11 clearly show the sensitivity to orbit errors. With regard to sensitivity, omitting the PRN with the biggest orbit error is more important than the weakening of the geometry. However, this cannot be stated generally for all cases, because it depends on the inter-relationship of the size of the excluded orbital error (by omitting a PRN), the degradation with respect to geometry, and possibly by the orientation of the baseline with respect to the orbit error vectors.

Appendix C contains additional examples as well as more information on the examples discussed, e.g., the ambiguities.

6. SUMMARY

From the surveyor's point of view, the satellite positions must be known at any arbitrary epoch when using GPS. There are several methods that can be used to obtain the necessary satellite coordinates: they can be computed (e.g., broadcast), estimated (e.g., orbit relaxation), or received from other sources (e.g., NSWC/DMA or NGS). For GPS, the most common and convenient approach is to use the broadcast message that is transmitted via the satellite signal. These ephemerides are extrapolated. The most accurate approach is to use the precise ephemerides which are calculated based on a least-squares fit of the tracking data from permanent tracking stations. The difference between the generation of broadcast and precise ephemerides is important, as discussed in section 1.

Since the broadcast ephemerides are available while carrying out field observations, they are extrapolated values. Values exist on an hourly basis for each satellite. Updating and uploading are performed by the GPS control-segment master station one or more times per day.

The precise ephemerides used here were generated by NSWC. They are based on the data of many tracking stations and are computed for the time passed, i.e., the time while the observations were taken. These precise ephemerides are considered to be the most accurate operational GPS satellite orbital data available at this time. Other institutions, e.g., Jet Propulsion Laboratory (Lichten and Border 1987), have claimed achievement of even higher accuracy, but not yet on an operational basis.

Since the broadcast ephemerides are accessible to any user at the time of observation, whereas not everyone may have access to the precise ephemerides, a comparison of these two ephemerides was made and the effect on relative positioning with GPS was shown.

7. CONCLUSION

Considering the precise ephemerides as true values, comparisons with broadcast ephemerides were performed. The broadcast ephemerides were calculated from -2 hours to +2 hours around the corresponding TOE. For many of those 4-hour intervals the maximum residual values of broadcast and precise ephemerides, expressed as along-track, cross-track and radial component, have been reported. Taking the mean of these maximum values, it has been shown that the broadcast ephemerides are good for a quartz clock (PRN 8) to about 20 m for the along-track and cross-track, and 10 m for the radial component; for a rubidium clock (PRN 3 since January 1989, PRNs 6, 9) to 10-15 m for along-track, 5-10 m for cross-track, and 5-7 m for the radial component; and for a cesium clock (PRN 3 before January 1989, PRNs 11, 12, 13) to about 4-6 m for along-track, 3-4 m for cross-track, and 2-3 m for the radial component. These results are based on a wide range of data that cover a time span greater than a year, various geographic regions, and different receiver types (the latter only reflects the correctness of the data received and decoded by the manufacturers). In addition, most of the data were taken in a period of high sunspot activities.

For several results, precise-minus-broadcast comparisons were also given in terms of mean and standard deviation. This is a more familiar and a more meaningful orbit error definition than the maxima. Had this definition been used, the values in the previous paragraph would naturally be smaller.

Besides the extensive comparisons of broadcast and precise ephemerides, the effect on baseline processing is of interest. For short baselines in the range of 1.5 km to 8.4 km, it has been shown for one observation campaign, that with increasing baseline length, an effect of the ephemerides used becomes visible. Taking a measure of 1 mm, a significant difference between broadcast and precise ephemerides then appears for baselines longer than about 4 km. For shorter baselines no significant difference can be seen.

For longer baselines, up to about 85 km, variations due to using different orbital data never exceeded 0.3 ppm with respect to the baseline length, and 0.1 ppm to 0.2 ppm variations were typical.

8. REFERENCES

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APPENDIX A.--NSWC/DMA PRECISE-VERSUS-BROADCAST EPHEMERIDES (COMPONENT DIFFERENCES)

Maximum values of orbital errors, precise-minus-broadcast for various epochs. The displayed errors are valid from -2 hours to +2 hours with respect to the shown date.

	PRN 03	PRN 06	PRN 08	PRN 09	PRN 11	PRN 12	PRN 13	
Aug 17	-	9	23	-	3	-	-	Along
1987	-	4	17	-	4	-	-	Cross
20h	-	3	13	-	3	-	-	Radial
Aug 17	-	9	16	-	2	-	-	Along
1987	-	7	25	-	4	-	-	Cross
21h	-	3	13	-	3	-	-	Radial
Aug 17	-	10	22	-	7	3	5	Along
1987	-	5	24	-	3	3	2	Cross
22h	-	4	13	-	2	2	2	Radial
Aug 17	-	7	-	-	5	4	5	Along
1987	-	5	-	-	3	3	3	Cross
23h	-	5	-	-	1	2	2	Radial
Aug 13	-	-	22	-	6	10	5	Along
1987	-	-	23	-	3	3	1	Cross
00h	-	-	11	-	1	2	2	Radial
Aug 18	7	-	-	-	6	5	5	Along
1987	3	-	-	-	3	1	1	Cross
01h	3	-	-	-	1	2	2	Radial
Aug 18	9	-	-	-	7	-	5	Along
1987	3	-	-	-	3	-	1	Cross
02h	2	-	-	-	1	-	1	Radial
Aug 18	-	-	14	-	-	-	-	Along
1987	-	-	7	-	-	-	-	Cross
18h	-	-	13	-	-	-	-	Radial
Aug 18	-	11	21	-	3	-	-	Along
1987	-	8	6	-	4	-	-	Cross
19h	-	4	13	-	2	-	-	Radial
Aug 18	-	12	27	-	3	-	-	Along
1987	-	4	13	-	4	-	-	Cross
20h	-	4	14	-	2	-	-	Radial
Aug 18	-	11	28	-	7	-	-	Along
1987	-	12	18	-	4	-	-	Cross
21h	-	4	14	-	2	-	-	Radial
Aug 18	-	13	32	-	6	2	1	Along
1987	-	5	25	-	3	2	8	Cross
22h	-	4	14	-	2	2	2	Radial
Aug 18	-	12	-	-	5	3	1	Along
1987	-	3	-	-	2	2	8	Cross
28h	-	5	-	-	1	2	2	Radial
Aug 19	-	-	24	-	6	3	1	Along
1987	-	-	19	-	2	2	3	Cross
00h	-	-	10	-	1	2	2	Radial

NSWC minus Broadcast (meters)

	PRN 03	PRN 06	PRN 08	PRN 09	PRN 11	PRN 12	PRN 13	
Aug 19 1987 01h	- - -	- - -	- - -	- - -	6 2 1	5 2 2	4 2 1	Along Cross Radial
Aug 19 1987 02h	6 3 2	- - -	- - -	- - -	8 3 1	- - -	3 2 1	Along Cross Radial
May 31 1988	4 1 2	13 9 7	- - -	8 8 6	2 3 2	8 2 2	5 3 1	Along Cross Radial
Jun 23 1988	6 4 3	12 9 7	31 28 6	12 7 6	4 4 2	6 3 1	3 3 1	Along Cross Radial
Jul 7 1988	- - -	16 4 5	13 21 11	11 7 4	5 3 2	4 4 2	2 2 1	Along Cross Radial
Aug 1 1988	7 2 4	12 9 8	30 11 13	9 3 6	102 43 10	8 2 1	10 5 2	Along Cross Radial
Aug 2 1988	9 2 4	9 4 8	- - -	5 3 6	24 21 3	7 2 1	6 4 2	Along Cross Radial
Aug 8 1988	5 3 4	9 10 7	30 40 21	4 2 5	8 3 2	7 4 3	4 4 1	Along Cross Radial
Aug 14 1988	3 1 2	12 4 8	38 40 11	6 1 5	4 3 2	7 2 3	3 1 2	Along Cross Radial
Aug 15 1988	- - -	9 1 6	23 32 10	7 3 6	6 3 2	7 1 3	4 3 1	Along Cross Radial
Aug 16 1988 SessionA	- - -	14 4 9	30 31 12	10 2 7	11 6 2	2 3 2	2 3 1	Along Cross Radial
Aug 16 1988 SessionB	2 6 2	- - -	- - -	18 7 8	12 8 2	5 3 2	2 3 1	Along Cross Radial
Aug 17 1988	- - -	14 7 9	7 28 9	- - -	9 3 2	7 2 2	4 5 1	Along Cross Radial
Aug 18 1988	- - -	11 8 10	10 32 3	- - -	9 4 1	5 4 2	1 6 1	Along Cross Radial

NSWC minus Broadcast (meters)

	PRN 03	PRN 06	PRN 08	PRN 09	PRN 11	PRN 12	PRN 13	
Oct 20	3	13	7	6	5	8	1	Along
1988	2	14	16	4	4	3	1	Cross
	2	6	4	4	1	3	1	Radial
Oct 24	8	14	6	15	6	6	5	Along
1988	2	14	17	7	1	2	3	Cross
	8	7	4	5	1	3	1	Radial
Oct 27	8	15	4	20	7	4	3	Along
1988	2	15	13	6	4	7	1	Cross
	3	7	3	6	2	3	1	Radial
Nov 5	6	17	4	11	4	3	2	Along
1988	3	13	12	4	4	3	6	Cross
	2	7	3	6	1	2	1	Radial
Dec 9	7	13	14	16	3	5	7	Along
1988	3	10	5	7	2	3	2	Cross
	3	5	8	4	1	3	1	Radial
Dec 12	8	11	10	8	2	7	3	Along
1988	2	10	9	4	4	8	2	Cross
	1	5	6	4	1	8	1	Radial
Dec 13	5	6	12	7	4	8	5	Along
1988	1	9	9	7	8	8	1	Cross
	2	4	7	5	1	3	1	Radial
Dec 14	3	-	12	6	4	5	5	Along
1988	8	-	12	7	8	5	8	Cross
	2	-	7	4	2	2	1	Radial
Dec 15	-	9	10	7	2	3	5	Along
1988	-	10	11	4	2	5	3	Cross
	-	5	7	4	2	3	1	Radial
Dec 16	-	10	20	8	5	8	6	Along
1988	-	11	19	3	8	7	4	Cross
	-	5	7	4	2	2	1	Radial
Dec 20	7	10	22	7	4	8	2	Along
1988	3	7	15	4	5	3	2	Cross
	3	6	3	5	1	2	1	Radial
Jan 9	26	10	-	10	10	8	3	Along
1989	9	9	-	5	7	5	5	Cross
	7	3	-	2	8	3	1	Radial
Jan 18	21	12	-	10	5	11	2	Along
1989	8	7	-	4	8	5	3	Cross
	7	4	-	3	2	2	1	Radial
Jan 24	10	14	50	12	4	3	7	Along
1989	8	2	29	5	6	5	7	Cross
SessionA	9	6	23	5	8	1	2	Radial

NSWC minus Broadcast (meters)

	PRN 03	PRN 06	PRN 08	PRN 09	PRN 11	PRN 12	PRN 13	
Jan 24	-	15	52	14	5	4	5	Along
1989	-	3	33	5	8	5	5	Cross
SessionB	-	5	20	4	3	1	1	Radial
Jan 24	17	9	-	9	8	3	8	Along
1969	10	10	-	14	9	5	8	Cross
SessionC	9	8	-	5	3	3	2	Radial
Jan 25	20	7	22	12	9	2	5	Along
1969	8	15	20	8	12	5	7	Cross
	9	7	19	3	3	2	2	Radial
Jan 26	-	18	20	11	7	4	9	Along
1989	-	4	22	4	7	2	4	Cross
	-	8	15	5	8	0	1	Radial
Jan 27	19	13	22	8	5	4	8	Along
1989	7	5	27	7	8	6	9	Cross
	8	7	15	4	3	1	1	Radial
Jan 30	[illegible]	11	38	7	5	5	5	Along
1989	[illegible]	6	27	7	5	3	5	Cross
SessionA	8	5	13	4	3	2	1	Radial
Jan 30	-	-	38	7	6	4	3	Along
1989	-	-	27	9	8	4	7	Cross
SessionB	-	-	13	3	4	2	2	Radial
Jan 30	8	-	-	-	5	2	3	Along
1989	8	-	-	-	8	5	7	Cross
SessionC	8	-	-	-	3	2	2	Radial
Jan 30	23	12	-	-	-	7	6	Along
1989	5	6	-	-	-	6	7	Cross
SessionD	8	6	-	-	-	3	3	Radial
Feb 9	-	7	23	14	9	-	11	Along
1989	-	17	18	13	3	-	4	Cross
	-	6	8	5	3	-	3	Radial
Feb 10	21	24	25	11	4	5	8	Along
1989	3	13	18	12	4	2	3	Cross
SessionA	5	6	7	7	3	2	1	Radial
Feb 10	-	11	21	10	6	-	7	Along
1989	-	12	20	11	4	-	4	Cross
SessionB	-	6	5	5	2	-	2	Radial
Feb 12	13	34	23	20	6	10	3	Along
1989	5	30	20	16	8	3	5	Cross
	5	6	6	4	8	4	3	Radial
Feb 12	-	18	24	14	4	-	-	Along
1989	-	23	19	9	2	-	-	Cross
SessionA	-	8	8	4	4	-	-	Radial

NSWC minus Broadcast (meters)

	PRN 03	PRN 06	PRN 08	PRN 09	PRN 11	PRN 12	PRN 13	
Feb 13	-	18	23	14	4	11	4	Along
1989	-	22	18	9	3	4	5	Cross
SessionB	-	6	6	4	3	4	2	Radial
Feb 13	15	17	21	14	4	8	4	Along
1989	4	21	16	9	3	4	5	Cross
SessionC	7	8	8	7	2	4	2	Radial
Feb 13	15	-	-	11	9	5	3	Along
1989	4	-	-	8	3	1	3	Cross
SessionD	5	-	-	8	2	3	2	Radial
Feb 17	10	25	-	16	5	4	2	Along
1989	5	10	-	6	5	2	4	Cross
	5	10	-	8	3	1	1	Radial
Feb 22	7	34	-	15	7	10	7	Along
1989	3	18	-	6	7	2	7	Cross
Session1	4	10	-	9	1	2	1	Radial
Feb 22	14	38	11	15	7	8	4	Along
1989	5	26	21	10	3	2	6	Cross
Session2	5	9	6	8	1	3	1	Radial
Feb 23	7	18	-	16	5	8	6	Along
1989	4	14	-	7	4	3	4	Cross
Session1	5	10	-	9	2	2	2	Radial
Feb 23	5	14	185	14	2	6	6	Along
1989	7	12	115	7	3	2	2	Cross
SessionA	6	10	23	8	3	3	2	Radial
Feb 23	-	-	210	-	-	-	-	Along
1989	-	-	120	-	-	-	-	Cross
SessionB	-	-	29	-	-	-	-	Radial
Feb 24	9	25	-	16	2	4	5	Along
1989	5	12	-	8	2	3	2	Cross
	5	10	-	9	1	2	1	Radial
Feb 27	6	15	-	26	9	8	5	Along
1989	4	5	-	4	5	6	3	Cross
	5	8	-	8	1	2	0	Radial
Feb 28	5	25	-	32	4	8	8	Along
1989	6	9	-	6	4	5	2	Cross
	5	10	-	8	1	2	1	Radial
Mar 1	3	20	-	52	7	5	7	Along
1989	2	12	-	15	5	3	3	Cross
	4	10	-	8	1	1	1	Radial
Mar 3	7	20	-	35	5	5	7	Along
1989	5	7	-	8	3	4	8	Cross
	4	10	-	10	1	1	0	Radial

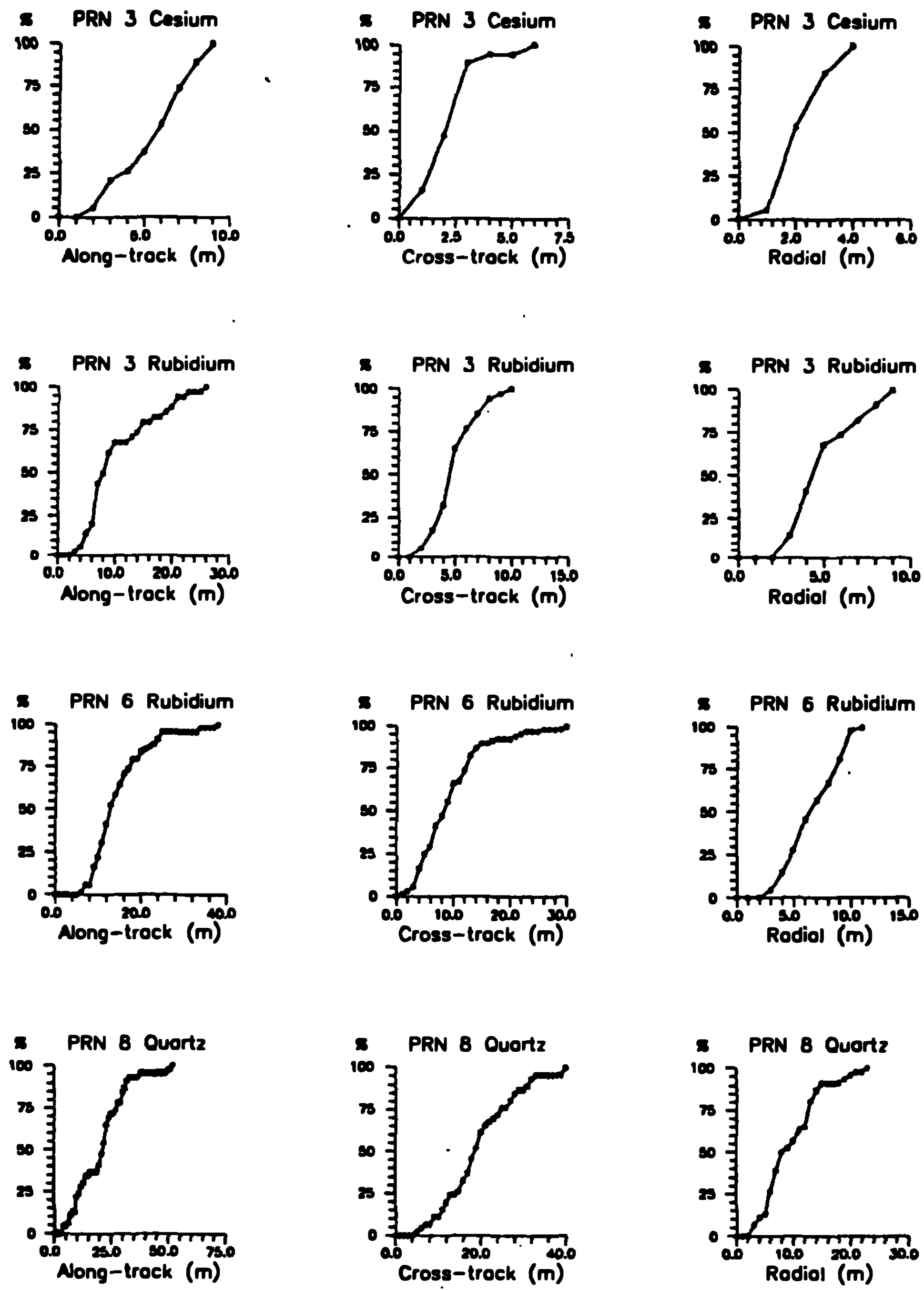
NSWC minus Broadcast (meters)

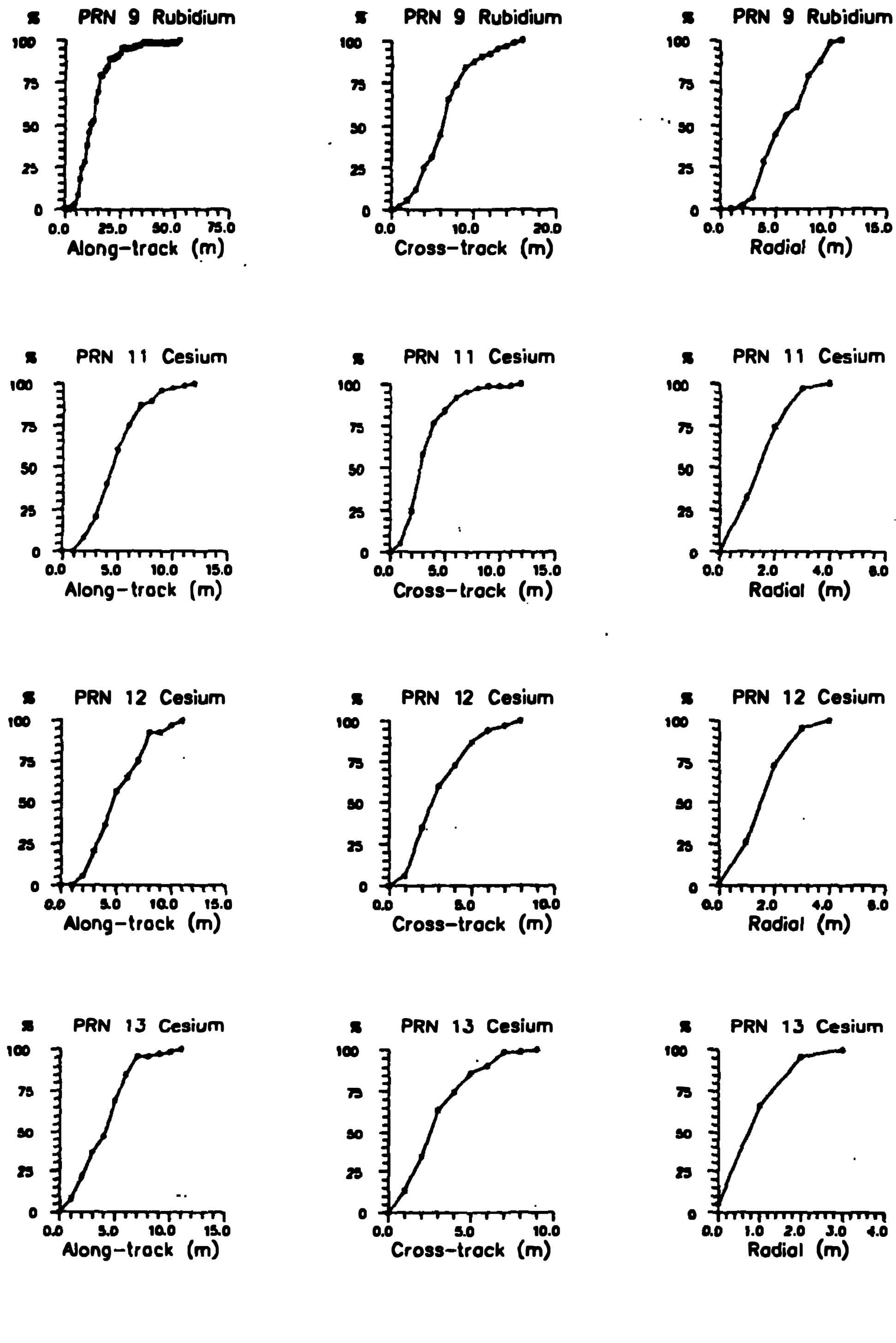
	PRN 03	PRN 06	PRN 08	PRN 09	PRN 11	PRN 12	PRN 18	
Mar 2	6	21	8	18	5	5	7	Along
1989	5	18	20	8	8	4	2	Cross
SessionA	4	10	6	9	2	1	0	Radial
Mar 2	7	22	10	10	6	4	6	Along
1989	5	18	16	10	1	2	1	Cross
SessionB	4	7	7	8	2	2	1	Radial
Mar 2	8	-	-	10	5	5	6	Along
1989	5	-	-	7	2	2	1	Cross
SessionC	4	-	-	10	2	2	1	Radial
Mar 3	7	23	-	20	3	3	2	Along
1989	5	13	-	11	1	1	3	Cross
SessionA	4	11	-	11	2	1	1	Radial
Mar 3	-	24	-	19	4	-	3	Along
1989	-	7	-	8	1	-	2	Cross
SessionB	-	10	-	10	2	-	1	Radial
Mar 6	7	13	-	16	6	6	2	Along
1989	3	10	-	7	2	2	5	Cross
	3	8	-	10	8	1	1	Radial
Mar 7	4	20	-	18	3	5	2	Along
1989	2	5	-	9	2	3	8	Cross
	8	9	-	10	2	2	1	Radial
Mar 8	9	18	-	23	3	4	4	Along
1989	6	8	-	13	2	6	3	Cross
	3	9	-	10	2	1	2	Radial
Mar 9	9	16	-	25	2	5	7	Along
1969	6	6	-	9	2	6	2	Cross
	3	9	-	9	2	1	1	Radial
Mar 10	7	16	-	20	4	3	5	Along
1989	6	7	-	6	2	4	2	Cross
	4	-9	-	10	2	1	1	Radial
Mar 13	5	13	-	14	3	6	1	Along
1989	8	7	-	6	2	8	1	Cross
	3	9	-	6	1	1	0	Radial
Mar 18	7	15	-	12	4	8	6	Along
1989	4	6	-	5	2	2	2	Cross
	4	9	-	8	1	1	1	Radial
								Along
								Cross
								Radial
								Along
								Cross
								Radial

NSWC minus Broadcast (meters)

APPENDIX B.--NSWC/DMA PRECISE-VERSUS-BROADCAST EPHEMERIDES (ACCORDING TO CLOCK)

Cumulative distribution functions based on the results of appendix A.




% PRN 9 Rubidium
Along-track (m)
% PRN 9 Rubidium
Cross-track (m)
% PRN 9 Rubidium
Radial (m)
% PRN 11 Cesium
Along-track (m)
% PRN 11 Cesium
Cross-track (m)
% PRN 11 Cesium
Radial (m)
% PRN 12 Cesium
Along-track (m)
% PRN 12 Cesium
Cross-track (m)
% PRN 12 Cesium
Radial (m)
% PRN 13 Cesium
Along-track (m)
% PRN 13 Cesium
Cross-track (m)
% PRN 13 Cesium
Radial (m)

APPENDIX C.--NSWC/DMA PRECISE-VERSUS-BROADCAST EPHEMERIDES (BASELINE CASE STUDIES)

Comparison of precise and broadcast ephemerides for several observation time spans and corresponding baseline results. Component differences and standard deviations are given in meters.

Comparison of precise and broadcast ephemerides on August 17, 1987:

Satellite	Along		Cross		Radial		Comparison time	
	mean	rms	mean	rms	mean	rms	begin	end
PRN 03	6.7	1.0	2.5	0.1	2.6	0.2	23:20	24:05
PRN 06	3.9	2.7	0.7	0.4	2.6	0.6	18:44	21:20
PRN 08	13.9	5.5	8.9	4.9	11.0	2.0	18:44	22:34
PRN 11	1.5	1.2	2.3	1.1	1.1	0.8	18:44	24:05
PRN 12	2.1	0.9	0.9	0.5	2.1	0.3	20:57	23:25
PRN 13	3.3	0.9	0.5	0.2	1.8	0.4	20:41	24:05

Comparison of precise and broadcast ephemerides on August 18, 1987:

Satellite	Along		Cross		Radial		Comparison time	
	mean	rms	mean	rms	mean	rms	begin	end
PRN 03	4.4	0.9	1.9	0.9	1.3	0.7	22:46	24:05
PRN 06	6.4	3.8	0.8	0.5	3.1	0.9	18:44	21:16
PRN 08	16.2	11.2	8.3	5.1	12.1	1.8	18:44	22:21
PRN 11	1.8	1.5	2.0	1.0	1.1	0.7	18:44	24:05
PRN 12	3.1	2.8	0.7	0.4	2.2	0.7	20:53	23:21
PRN 13	0.6	0.4	2.4	1.4	1.1	0.5	20:37	24:05

Comparison of broadcast and precise ephemerides on August 15, 1988:

Satellite	Along		Cross		Radial		Comparison time	
	mean	rms	mean	rms	mean	rms	begin	end
PRN 06	2.1	1.5	2.4	0.8	5.2	0.8	19:09	20:15
PRN 08	11.7	7.1	13.5	7.6	12.9	0.9	19:09	21:10
PRN 09	9.6	3.4	1.9	0.8	3.9	0.4	19:09	21:15
PRN 11	1.0	0.5	1.0	0.4	0.9	0.5	19:09	22:00
PRN 12	5.5	1.1	1.0	0.8	3.0	0.4	20:00	22:00
PRN 13	1.9	0.5	2.4	0.1	1.0	0.4	20:00	22:00

Comparison of broadcast and precise ephemerides on February 17, 1989:

Satellite	Along mean	Along rms	Cross mean	Cross rms	Radial mean	Radial rms	Comparison time begin	Comparison time end
PRN 03	6.3	1.2	3.9	0.2	3.9	0.5	8:50	9:42
PRN 06	18.1	5.4	0.4	0.2	7.2	2.0	6:40	8:40
PRN 09	6.4	3.8	1.8	0.4	7.3	1.1	6:40	9:42
PRN 11	3.5	1.5	3.8	1.1	1.0	0.7	6:40	9:52
PRN 12	2.7	0.6	0.9	0.6	0.5	0.2	7:15	9:42
PRN 13	2.3	1.5	2.1	1.4	0.5	0.4	6:40	9:42

Concerning the displayed integer ambiguities, only the fractional part is shown. These fractional parts are sorted according to the list of PRN numbers (which are sorted with respect to their appearance). They are based on double-differences; therefore for baseline MBRE to NSWC on 1987/08/17 with PRNs 11 (reference satellite), 6, 8, 13, 12, and 3 the fractional parts of the ambiguities for the precise orbit are to be understood as 6-11 = .080, 8-11 = .078, 13-11 = .922, 12-11 = .905, and 3-11 = .798.

Date: 1987/08/17 PRNs: 11(ref.),6,8,13,12,3 Receiver: TI 4100

MBRE -	NSWC	Baseline (m)	dx (m)	dy (m)	dz (m)
Orbit	P	1478.9198	-1402.2738	48.6680	467.4005
Orbit	BC	1478.9196	-1402.2737	48.6686	467.4005
	P-BC	-0.0002	-0.0001	-0.0006	0.0000
	ppm	0.14	0.07	0.41	0.00
Ambig.	P	.080 .078 .922 .905 .798			
Ambig.	BC	.077 .075 .925 .909 .804			

Date: 1987/08/17 PRNs: 11(ref.),6, 13,12,3 Receiver: TI 4100

MBRE -	NSWC	Baseline (m)	dx (m)	dy (m)	dz (m)
Orbit	P	1478.9184	-1402.2724	48.6817	467.3991
Orbit	BC	1478.9185	-1402.2724	48.6815	467.3994
	P-BC	-0.0001	0.0000	0.0002	-0.0003
	ppm	0.07	0.00	0.14	0.20
Ambig.	P	.072 .937 .921 .844			
Ambig.	BC	.073 .937 .921 .843			

Date: 1987/08/18 PRNs: 11(ref.),6,8,13,12,3 Receiver: TI 4100

MBRE -	NSWC	Baseline (m)		dx (m)		dy (m)	dz (m)
Orbit	P	1478.9163		-1402.2704		48.6629	467.4001
Orbit	BC	1478.9161		-1402.2703		48.6639	467.3999
	P-BC	0.0002		-0.0001		-0.0010	0.0002
	ppm	0.14		0.07		0.68	0.14
Ambig.	P	-.960	-.985	.949	.949	.822	
Ambig.	BC	-.960	-.989	.943	.950	.823	

Date: 1987/08/18 PRNs: 11(ref.),6, 13,12,3 Receiver: TI 4100

MBRE -	NSWC	Baseline (m)		dx (m)		dy (m)	dz (m)
Orbit	P	1478.9176		-1402.2709		48.6592	467.4033
Orbit	BC	1478.9177		-1402.2709		48.6592	467.4034
	P-BC	-0.0001		0.0000		0.0000	-0.0001
	ppm	0.07		0.00		0.00	0.07
Ambig.	P	-.967		.961	.961	.849	
Ambig.	BC	-.966		.962	.963	.850	

Date: 1987/08/17 PRNs: 11(ref.),6,8,13,12,3 Receiver: TI 4100

MBRE -	BOM2	Baseline (m)		dx (m)		dy (m)	dz (m)
Orbit	P	3604.6640		464.9020		2318.1235	2720.9874
Orbit	BC	3604.6648		464.9022		2318.1239	2720.9881
	P-BC	-0.0008		-0.0002		-0.0004	-0.0007
	ppm	0.22		0.06		0.11	0.19
Ambig.	P	.023	-.984	.952	.903	.853	
Ambig.	BC	.026	-.995	.958	.904	.861	

Date: 1987/08/17 PRNs: 11(ref.),6, 13,12,3 Receiver: TI 4100

MBRE -	BOM2	Baseline (m)		dx (m)		dy (m)	dz (m)
Orbit	P	3604.6633		464.9020		2318.1223	2720.9874
Orbit	BC	3604.6635		464.9018		2318.1219	2720.9881
	P-BC	-0.0002		0.0002		0.0004	-0.0007
	ppm	0.06		0.06		0.11	0.19
Ambig.	P	.030		.951	.895	.838	
Ambig.	BC	.032		.955	.895	.847	

Date: 1987/08/18	PRNs: 11(ref.),6,8,13,12,3			Receiver: TI 4100	
MBRE - BOM2		Baseline (m)	dx (m)	dy (m)	dz (m)
Orbit	P	3604.6666	464.9074	2318.1285	2720.9856
Orbit	BC	3604.6675	464.9074	2318.1300	2720.9855
	P-BC	-0.0009	0.0000	-0.0015	0.0001
	ppm	0.25	0.00	0.42	0.03
Ambig.	P	.048 -.917 .822 .823 .618			
Ambig.	BC	.054 -.917 .821 .817 .615			

Date: 1987/08/18	PRNs: 11(ref.),6, 13,12,3			Receiver: TI 4100	
MBRE - BOM2		Baseline (m)	dx (m)	dy (m)	dz (m)
Orbit	P	3604.6690	464.9067	2318.1241	2720.9927
Orbit	BC	3604.6700	464.9066	2318.1253	2720.9930
	P-BC	-0.0010	0.0001	-0.0012	-0.0003
	ppm	0.28	0.03	0.33	0.08
Ambig.	P	.057 .843 .828 .647			
Ambig.	BC	.063 .843 .823 .645			

Date: 1987/08/17	PRNs: 11(ref.),6,8,13,12			Receiver: TI 4100	
MBRE - CHUR		Baseline (m)	dx (m)	dy (m)	dz (m)
Orbit	P	4771.0078	-4668.2497	-368.7751	913.2166
Orbit	BC	4771.0067	-4668.2490	-368.7728	913.2154
	P-BC	0.0011	-0.0007	-0.0023	0.0012
	ppm	0.23	0.15	0.48	0.25
Ambig.	P	-.919 -.913 .889 -.158			
Ambig.	BC	-.919 -.916 .894 -.149			

Date: 1987/08/17	PRNs: 11(ref.),6, 13,12			Receiver: TI 4100	
MBRE - CHUR		Baseline (m)	dx (m)	dy (m)	dz (m)
Orbit	P	4770.9920	-4668.2414	-368.7376	913.1923
Orbit	BC	4770.9922	-4668.2413	-368.7386	913.1931
	P-BC	0.0002	-0.0001	0.0010	-0.0008
	ppm	0.04	0.02	0.21	0.17
Ambig.	P	-.926 .907 -.127			
Ambig.	BC	-.923 .907 -.126			

Date: 1987/08/18 PRNs: 11(ref.),6,8,13,12,3 Receiver: TI 4100

MBRE -	CHUR	Baseline (m)	dx (m)	dy (m)	dz (m)
Orbit	P	4771.0056	-4668.2480	-368.7721	913.2152
Orbit	BC	4771.0046	-4668.2474	-368.7690	913.2145
	P-BC	0.0010	-0.0006	-0.0031	0.0007
	ppm	0.21	0.13	0.65	0.15
Ambig.	P	-.006 -.034	.012 .990	.939	
Ambig.	BC	-.007 -.044	.013 .994	.939	

Date: 1987/08/18 PRNs: 11(ref.),6, 13,12,3 Receiver: TI 4100

MBRE -	CHUR	Baseline (m)	dx (m)	dy (m)	dz (m)
Orbit	P	4771.0102	-4668.2504	-368.7828	913.2224
Orbit	BC	4771.0103	-4668.2505	-368.7830	913.2228
	P-BC	-0.0001	0.0001	0.0002	-0.0004
	ppm	0.02	0.02	0.04	0.08
Ambig.	P	-.000	.037 .990	.975	
Ambig.	BC	-.007	.013 .994	.939	

Date: 1987/08/17 PRNs: 11(ref.),6,8,13,12,3 Receiver: TI 4100

MBRE -	RAD9	Baseline (m)	dx (m)	dy (m)	dz (m)
Orbit	P	8372.7136	5708.9626	-3003.1820	-5337.6940
Orbit	BC	8372.7148	5708.9618	-3003.1846	-5337.6952
	P-BC	-0.0012	0.0008	0.0026	0.0012
	ppm	0.14	0.10	0.31	0.14
Ambig.	P	.026 -.003	.014 .983	.017	
Ambig.	BC	.019 -.983	.014 .984	.020	

Date: 1987/08/17 PRNs: 11(ref.),6, 13,12,3 Receiver: TI 4100

MBRE -	RAD9	Baseline (m)	dx (m)	dy (m)	dz (m)
Orbit	P	8372.7140	5708.9630	-3003.1804	-5337.6951
Orbit	BC	8372.7153	5708.9635	-3003.1787	-5337.6975
	P-BC	-0.0013	-0.0005	-0.0017	0.0024
	ppm	0.16	0.06	0.20	0.29
Ambig.	P	.042	.995 .956	.968	
Ambig.	BC	.033	.992 .957	.965	

Date: 1987/08/18 PRNs: 11(ref.),6,8,13,12,3 Receiver: TI 4100

MBRE -	RAD9	Baseline (m)	dx (m)	dy (m)	dz (m)
Orbit	P	8372.7160	5708.9704	-3003.1943	-5337.6825
Orbit	BC	8372.7175	5708.9696	-3003.2013	-5337.6817
	P-BC	-0.0015	0.0008	0.0070	-0.0008
	ppm	0.18	0.10	0.84	0.10

Ambig.	P	-.030	.961	-.840	-.789	-.723
Ambig.	BC	-.038	.974	-.835	-.782	-.707

Date: 1987/08/18 PRNs: 11(ref.),6, 13,12,3 Receiver: TI 4100

MBRE -	RAD9	Baseline (m)	dx (m)	dy (m)	dz (m)
Orbit	P	8372.7121	5708.9704	-3003.1920	-5337.6777
Orbit	BC	8372.7138	5708.9707	-3003.1943	-5337.6787
	P-BC	-0.0017	-0.0003	0.0023	0.0010
	ppm	0.20	0.04	0.27	0.12

Ambig.	P	-.012		-.824	-.790	-.711
Ambig.	BC	-.024		-.828	-.788	-.709

Date: 1988/08/15 PRNs: 11(ref.),6,8,9,12,13 Receiver: Ashtech

MDPT -	ASWP	Baseline (m)	dx (m)	dy (m)	dz (m)
Orbit	P	22712.6398	-9511.8947	-14271.2410	-14890.2500
Orbit	BC	22712.6440	-9511.8913	-14271.2522	-14890.2479
	P-BC	-0.0042	-0.0034	0.0112	-0.0021
	ppm	0.18	0.15	0.49	0.09

Ambig.	P	-.945	-.939	.994	-.065	-.071
Ambig.	BC	-.953	-.910	.053	-.000	-.022

Date: 1988/08/15 PRNs: 11(ref.),6, 9,12,13 Receiver: Ashtech

MDPT -	ASWP	Baseline (m)	dx (m)	dy (m)	dz (m)
Orbit	P	22712.6358	-9511.8893	-14271.2315	-14890.2566
Orbit	BC	22712.6369	-9511.8824	-14271.2377	-14890.2566
	P-BC	-0.0011	-0.0069	0.0062	0.0000
	ppm	0.05	0.30	0.27	0.00

Ambig.	P	-.955		.994	-.052	-.061
Ambig.	BC	-.953		.051	-.000	-.022

Date: 1989/02/17 PRNs: 11(ref.),6,9,13,12,3 Receiver: Trimble

VAN5 -	LOFT	Baseline (m)	dx (m)	dy (m)	dz (m)
Orbit	P	37897.2634	-9905.9584	-19207.7935	-31130.9368
Orbit	BC	37897.2581	-9905.9636	-19207.7869	-31130.9328
	P-BC	0.0053	0.0052	-0.0066	-0.0040
	ppm	0.14	0.14	0.17	0.11
Ambig.	P	.035 -.006 -.964 .013 .126			
Ambig.	BC	.079 -.078 -.983 .993 .127			

Date: 1989/02/17 PRNs: 11(ref.), 9,13,12,3 Receiver: Trimble

VAN5 -	LOFT	Baseline (m)	dx (m)	dy (m)	dz (m)
Orbit	P	37897.2702	-9905.9523	-19207.7945	-31130.9465
	BC	37897.2718	-9905.9534	-19207.7967	-31130.9467
	P-BC	-0.0016	0.0011	0.0022	0.0002
	ppm	0.04	0.03	0.06	0.01
Ambig.	P	-.001 -.941 .054 .188			
Ambig.	BC	-.076 -.986 .989 .117			

Date: 1989/02/17 PRNs: 11(ref.),6,9,13,12,3 Receiver: Trimble

VAN5 -	EVEL	Baseline (m)	dx (m)	dy (m)	dz (m)
Orbit	P	75112.2254	24148.9267	-39108.1932	-59407.2805
	BC	75112.2037	24148.9150	-39108.1782	-59407.2677
	P-BC	0.0217	0.0117	-0.0150	-0.0128
	ppm	0.29	0.16	0.20	0.17
Ambig.	P	.918 -.016 -.978 -.961 .107			
Ambig.	BC	.019 -.137 -.027 -.006 .054			

Date: 1989/02/17 PRNs: 11(ref.), 9,13,12,3 Receiver: Trimble

VAN5 -	EVEL	Baseline (m)	dx (m)	dy (m)	dz (m)
Orbit	P	75112.2222	24148.9248	-39108.1963	-59407.2750
Orbit	BC	75112.2185	24148.9216	-39108.1945	-59407.2729
	P-BC	0.0037	0.0032	-0.0018	-0.0021
	ppm	0.05	0.04	0.02	0.03
Ambig.	P	-.026 -.976 -.960 .114			
Ambig.	BC	-.151 -.055 -.060 .979			

Date: 1988/08/15 PRNs: 11(ref.),6,8,9,12,13 Receiver: Ashtech

NBSO -	MDPT	Baseline (m)	dx (m)	dy (m)	dz (m)
Orbit	P	84599.8354	10170.1485	-51880.8162	-66046.0532
Orbit	BC	84599.8588	10170.1460	-51880.8895	-66046.0260
	P-BC	-0.0234	0.0025	0.0733	-0.0272
	ppm	0.28	0.03	0.87	0.32

Ambig.	P	.898	.046	-.060	.881	.962
Ambig.	BC	.904	.330	-.817	.054	.094

Date: 1988/08/15 PRNs: 11(ref.),6, 9,12,13 Receiver: Ashtech

NBSO -	MDPT	Baseline (m)	dx (m)	dy (m)	dz (m)
Orbit	P	84599.8338	10170.1608	-51880.7892	-66046.0704
Orbit	BC	84599.8474	10170.1984	-51880.7851	-66046.0853
	P-BC	-0.0136	-0.0376	-0.0041	0.0149
	ppm	0.16	0.44	0.05	0.18

Ambig.	P	.881		-.061	.909	.978
Ambig.	BC	.896		-.820	.063	.099