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Accuracy of Global Positioning System Broadcast Orbits for Relative Surveys

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CONTENTS

Abstract.....	1
1. Introduction.....	1
2. Background.....	2
3. Orbital errors: broadcast versus precise.....	4
4. Use and misuse of broadcast messages.....	7
5. Survey examples - processing baselines with broadcast and with precise ephemerides.....	9
6. Summary.....	15
7. Conclusion.....	15
8. References.....	16
Appendix A. NSW/C/DMA precise-versus-broadcast ephemerides (component differences).....	17
Appendix B. NSW/C/DMA precise-versus-broadcast ephemerides (according to clock).....	23
Appendix C. NSW/C/DMA precise-versus-broadcast ephemerides (baseline case studies).....	25

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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.

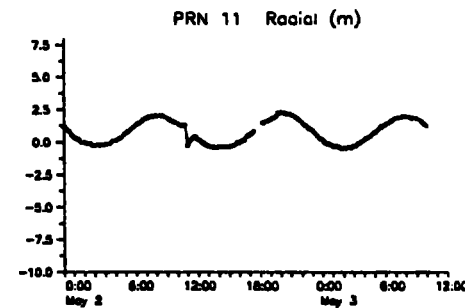
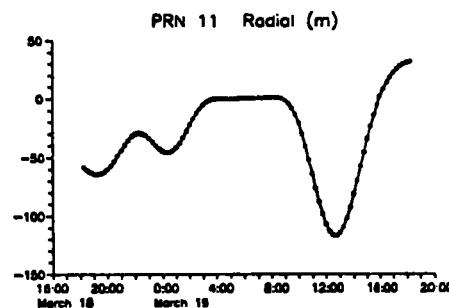
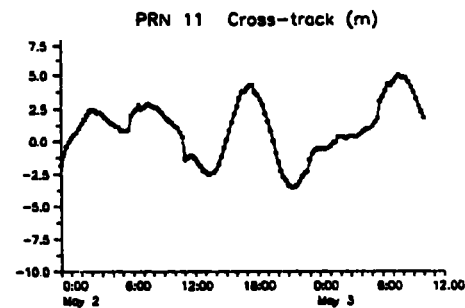
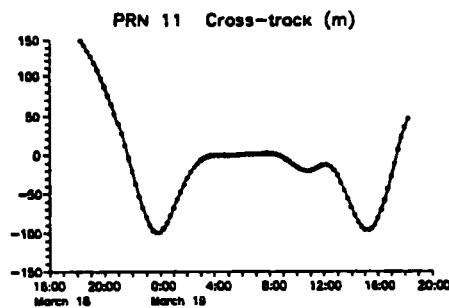
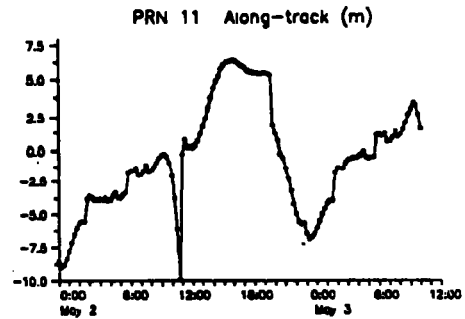
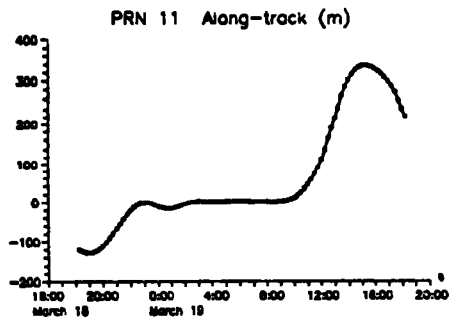


Figure 1.--Demonstration of the misuse of broadcast ephemerides. The ordinates show the residuals of precise-minus-broadcast ephemerides.

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 mean	rms	Cross mean	rms	Radial mean	rms	Comparison time 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 mean	rms	Cross mean	rms	Radial mean	rms	Comparison time 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)
NSB0-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)		
NSB0-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., NSWCDMA 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 NSWCDMA. 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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- Wells, D. (editor), 1987: Guide to GPS positioning. Canadian GPS Associates, Fredericton, Canada, chapter 5.

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 1987 20h	- - -	9 4 3	23 17 13	- - -	3 4 3	- - -	- - -	Along Cross Radial
Aug 17 1987 21h	- - -	9 7 3	16 25 13	- - -	2 4 3	- - -	- - -	Along Cross Radial
Aug 17 1987 22h	- - -	10 5 4	22 24 13	- - -	7 3 2	3 3 2	5 2 2	Along Cross Radial
Aug 17 1987 23h	- - -	7 5 5	- - -	- - -	5 3 1	4 3 2	5 3 2	Along Cross Radial
Aug 18 1987 00h	- - -	- - -	22 23 11	- - -	6 3 1	10 3 2	5 1 2	Along Cross Radial
Aug 18 1987 01h	7 3 3	- - -	- - -	- - -	6 3 1	5 1 2	5 1 2	Along Cross Radial
Aug 18 1987 02h	9 3 2	- - -	- - -	- - -	7 3 1	- - -	5 1 1	Along Cross Radial
Aug 18 1987 18h	- - -	- - -	14 7 13	- - -	- - -	- - -	- - -	Along Cross Radial
Aug 18 1987 19h	- - -	11 8 4	21 6 13	- - -	3 4 2	- - -	- - -	Along Cross Radial
Aug 18 1987 20h	- - -	12 4 4	27 13 14	- - -	3 4 2	- - -	- - -	Along Cross Radial
Aug 18 1987 21h	- - -	11 12 4	28 18 14	- - -	7 4 2	- - -	- - -	Along Cross Radial
Aug 18 1987 22h	- - -	13 5 4	32 25 14	- - -	6 3 2	2 2 2	1 3 2	Along Cross Radial
Aug 18 1987 23h	- - -	12 3 5	- - -	- - -	5 2 1	3 2 2	1 3 2	Along Cross Radial
Aug 19 1987 00h	- - -	- - -	24 19 10	- - -	6 2 1	3 2 2	1 3 2	Along Cross 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 19	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	33 40 11	6 1 5	4 3 2	7 2 3	3 1 2	Along Cross Radial
Aug 15 1988	- - -	9 1 8	29 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	- - -	- - -	16 7 8	12 6 2	6 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 8	- - -	9 4 1	5 4 2	1 3 1	Along Cross Radial

NSWC minus Broadcast (meters)

	PRN 03	PRN 06	PRN 08	PRN 09	PRN 11	PRN 12	PRN 13	
Oct 20 1988	3 2 2	13 14 6	7 16 4	6 4 4	5 4 1	8 3 3	1 1 1	Along Cross Radial
Oct 24 1988	8 2 3	14 14 7	6 17 4	15 7 6	6 1 1	6 2 3	5 3 1	Along Cross Radial
Oct 27 1988	8 2 3	15 15 7	4 13 3	20 6 6	7 4 2	4 7 3	3 1 1	Along Cross Radial
Nov 6 1988	6 3 2	17 13 7	4 12 3	11 4 6	4 4 1	3 3 2	2 6 1	Along Cross Radial
Dec 9 1988	7 3 3	13 10 5	14 5 8	16 7 4	3 2 1	5 3 3	7 2 1	Along Cross Radial
Dec 12 1988	8 2 1	11 10 5	10 9 6	8 4 4	2 4 1	7 8 3	3 2 1	Along Cross Radial
Dec 13 1988	5 1 2	6 9 4	12 9 7	7 7 5	4 3 1	8 8 3	5 1 1	Along Cross Radial
Dec 14 1988	3 3 2	- - -	12 12 7	6 7 4	4 3 2	5 5 2	5 3 1	Along Cross Radial
Dec 15 1988	- - -	9 10 5	10 11 7	7 4 4	2 2 2	8 5 3	5 3 1	Along Cross Radial
Dec 16 1988	- - -	10 11 5	20 19 7	8 3 4	5 3 2	8 7 2	6 4 1	Along Cross Radial
Dec 20 1988	7 3 3	10 7 6	32 15 3	7 4 5	4 5 1	3 3 2	2 2 1	Along Cross Radial
Jan 9 1989	26 9 7	10 9 3	- - -	10 5 2	10 7 3	8 5 3	3 5 1	Along Cross Radial
Jan 12 1989	21 8 7	12 7 4	- - -	10 4 3	5 8 2	11 5 2	2 3 1	Along Cross Radial
Jan 24 1989 Session A	10 8 9	14 2 6	50 29 23	13 5 5	4 6 3	3 5 1	7 7 2	Along Cross Radial

NSWC minus Broadcast (meters)

	PRN 03	PRN 06	PRN 08	PRN 09	PRN 11	PRN 12	PRN 13	
Jan 24 1989 SessionB	- - -	15 3 5	52 33 20	14 5 4	5 6 3	4 5 1	5 5 1	Along Cross Radial
Jan 24 1989 SessionC	17 10 9	9 10 6	- - -	9 14 5	6 9 3	3 5 3	6 6 2	Along Cross Radial
Jan 25 1989	20 8 9	7 15 7	22 20 19	12 8 3	9 12 3	2 5 2	5 7 2	Along Cross Radial
Jan 26 1989	- - -	16 4 6	20 22 15	11 4 5	7 7 3	4 2 0	9 4 1	Along Cross Radial
Jan 27 1989	19 7 8	13 5 7	23 27 15	8 7 4	5 8 3	4 6 1	6 9 1	Along Cross Radial
Jan 30 1989 SessionA	- - 8	11 6 5	38 27 13	7 7 4	5 5 3	5 3 2	5 5 1	Along Cross Radial
Jan 30 1989 SessionB	- - -	- - -	38 27 13	7 9 3	5 6 4	4 4 2	3 7 2	Along Cross Radial
Jan 30 1989 SessionC	8 5 6	- - -	- - -	- - -	5 6 3	2 5 2	3 7 2	Along Cross Radial
Jan 30 1989 SessionD	23 5 8	12 8 6	- - -	- - -	- - -	7 6 3	6 7 3	Along Cross Radial
Feb 9 1989	- - -	7 17 6	28 18 8	14 13 5	9 3 3	- - -	11 4 3	Along Cross Radial
Feb 10 1989 SessionA	21 3 5	24 13 6	25 18 7	11 12 7	4 4 3	5 2 2	6 3 1	Along Cross Radial
Feb 10 1989 SessionB	- - -	11 13 6	21 20 5	10 11 5	6 4 2	- - -	7 4 2	Along Cross Radial
Feb 12 1989	13 5 5	34 30 6	23 20 6	20 16 4	3 3 3	10 3 4	3 5 3	Along Cross Radial
Feb 13 1989 SessionA	- - -	18 23 6	24 19 8	14 9 4	4 2 4	- - -	- - -	Along Cross Radial

NSWC minus Broadcast (meters)

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

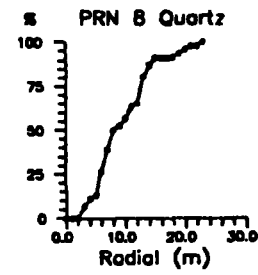
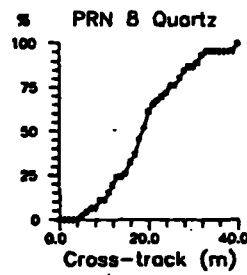
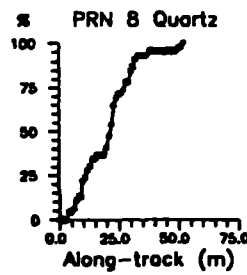
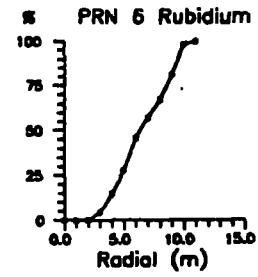
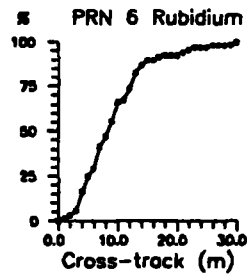
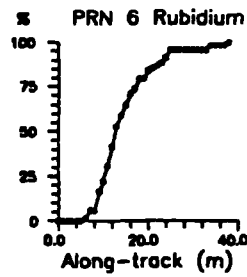
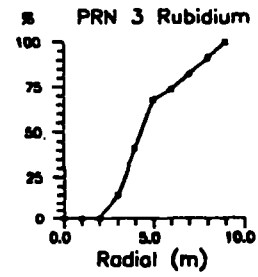
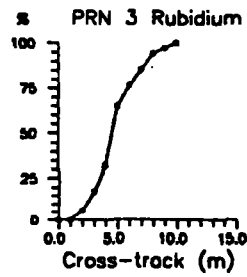
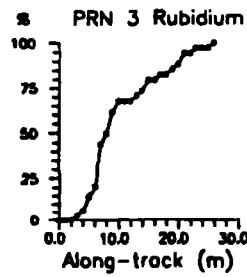
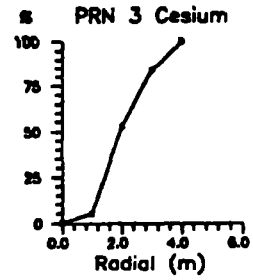
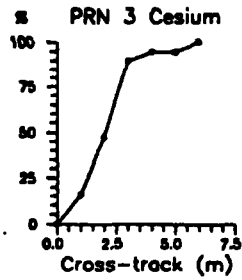
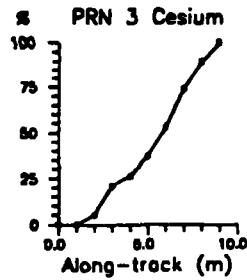
NSWC minus Broadcast (meters)

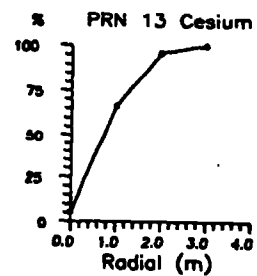
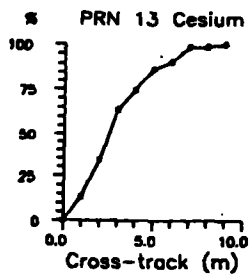
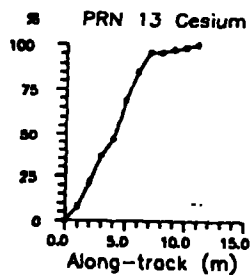
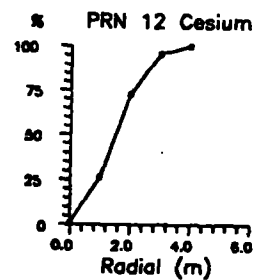
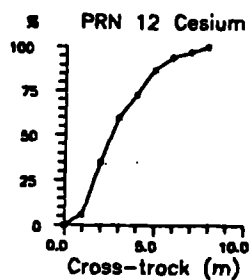
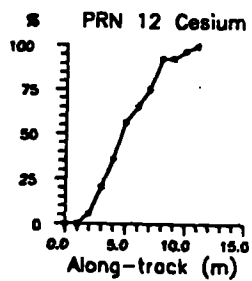
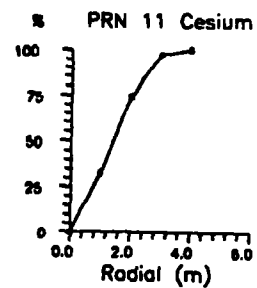
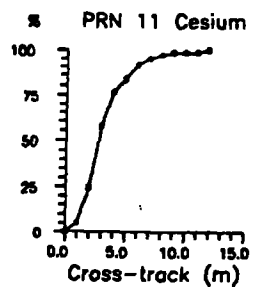
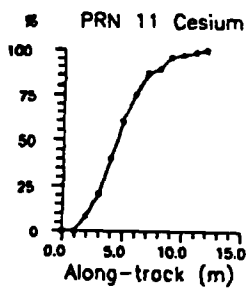
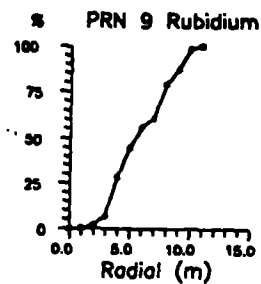
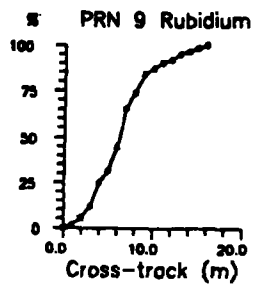
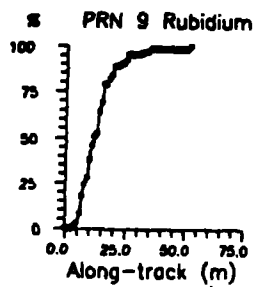
	PRN 03	PRN 06	PRN 08	PRN 09	PRN 11	PRN 12	PRN 13	
Mar 2 1989 SessionA	6 5 4	21 13 10	8 20 6	18 8 9	5 3 2	5 4 1	7 2 0	Along Cross Radial
Mar 2 1989 SessionB	7 5 4	22 13 7	10 16 7	10 10 8	6 1 2	4 2 2	6 1 1	Along Cross Radial
Mar 2 1989 SessionC	8 5 4	- - -	- - -	10 7 10	5 2 2	5 2 2	6 1 1	Along Cross Radial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





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	rms	Cross mean	rms	Radial mean	rms	Comparison time 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

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

NBS0 - 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
Ambig. BC	.904	.330	-.817	.054

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

NBS0 - 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