



Test Measurements using the WM 101

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Abstract

The principal features of the WM 101 GPS Satellite Surveying Equipment are: C/A code use, simultaneous phase measurements of the reconstructed carrier signals of the L1 frequency from GPS satellites, and recording of the compacted data on tape cassette in the field unit. Precise position differences are calculated using the post-processing software package PoPS™. The performance of the WM 101 was evaluated in three different tests. These were the zero-baseline test, the short-baseline test, and the small network test. Results of these tests show that the repeatability of the determinations of short baselines using the WM 101 is 4 mm (rms).

1. Introduction

1.1 Known GPS Accuracies in Relative Positioning

In the past few years it has become clear that using the Navstar-GPS satellites will have a significant and perhaps even revolutionary impact on surveying. GPS satellite surveying offers many advantages over conventional surveying methods. The most significant points are: 3D vector components are determined directly, line-of-sight between ground stations is unnecessary, sites are selected independent of network configuration, and gives high accuracy for relative positioning. Information about GPS and basic facts about surveying with GPS are presented in (1).

In order to assess the accuracy attained by GPS receivers, we found it useful to plot the absolute differences between results from GPS and terrestrial-geodetic measurements, ΔS , gathered in the past few years (see Figure 1). The sources of the results are given in Table 1.

Six different campaigns, listed in Table 1, were used to create Figure 1. The campaign identification numbers in Table 1 are also shown in Figure 1. Circles indicate data points obtained using Macrometer™, and triangles indicate data points obtained using T14100 equipment. The only selection principles applied to the data used in Figure 1 were clarity of the published results and the availability of terrestrial control measurement.

Figure 1 gives a remarkably coherent picture considering the diverse sources of the measurement results. Some of the results are direct comparisons of GPS baseline measurements with EDM observations (indicated in Figure 1 by heavy symbols), whilst the remaining results are comparisons of baselines indirectly calculated from GPS with conventional geodetic network adjustment results. Note that the plotted results show the sum of the error components from GPS as well as those from terrestrial measurements.

The dashed line in Figure 1 represents the absolute differences between GPS measurement and the "ground-truth" of the order of 10 mm + 2 ppm. Almost all data points are located below the dashed line. The dotted line sketches an approximate average over all data points shown in the figure. This curve represents absolute differences of the order of 3 mm + 1 ppm. The constant error term is related to the receiver performance and the length-dependent error term represents the GPS-related errors, such as propagation effects, orbit errors, etc.

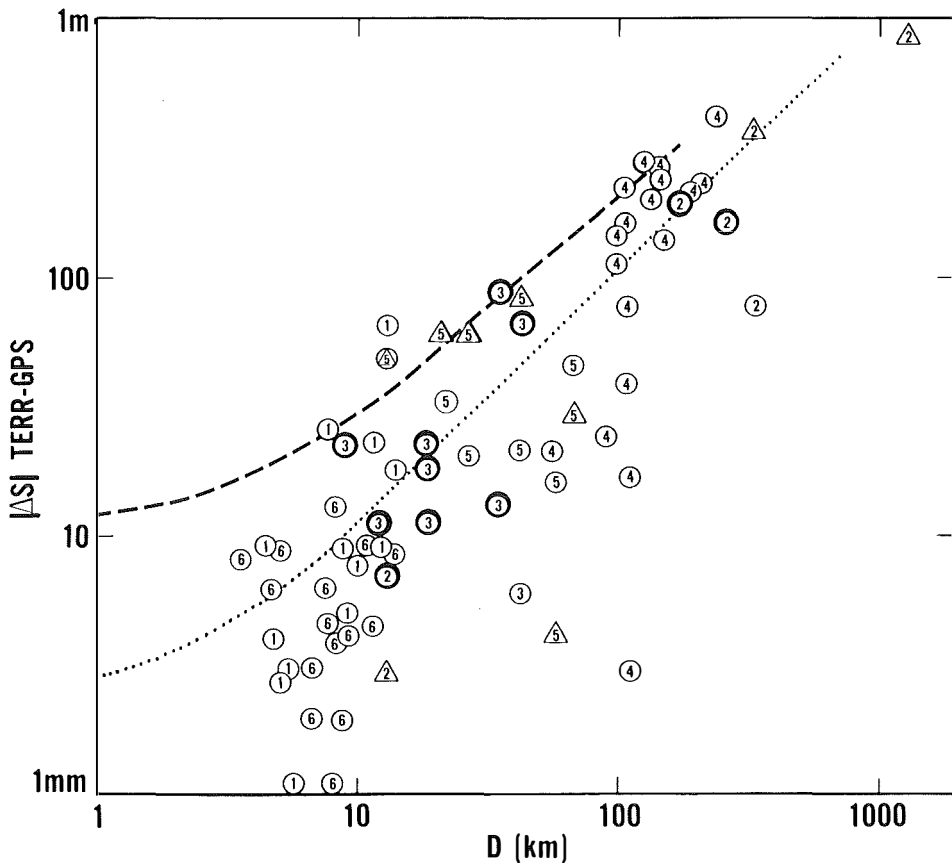


Figure 1
 Typical GPS accuracy in geodetic applications. The dotted line represents 3 mm + 1 ppm and the dashed line 10 mm + 2 ppm of the baseline separation distance.

No.	Place	Remarks	Reference
1	Inntal	Network, Scale factor removed	(3)
2	Barstow-1984	Baselines	(4)
3	FGCC-1983	Network	(5)
4	Niedersachsen	Network	(6)
5	Ottawa-1985	Network	(7)
6	CERN	Network, Scale factor removed	(8)

Table 1: Baseline comparison results

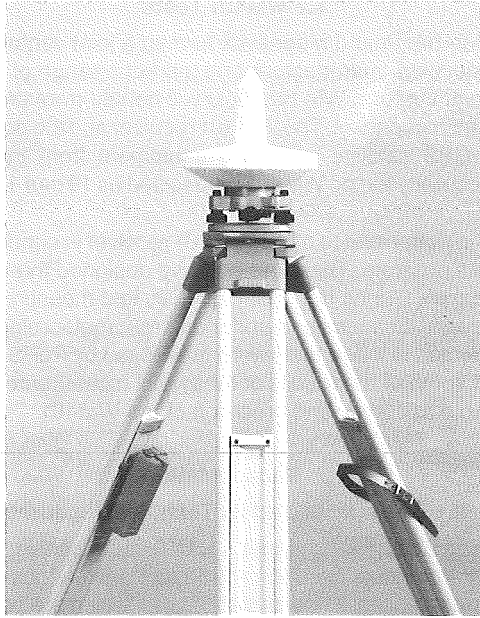


Figure 2: The WM101 GPS Satellite Surveying Equipment.

1.2 WM 101 Tests

Recently, Wild Heerbrugg and Magnavox formed a joint venture (WM Satellite Survey Company) in order to develop, manufacture and market a range of GPS satellite surveying equipment. With this joint venture, WM products will benefit from the resources and unique experience of both parent companies. The WM 101 receiver and the post-processing software, PoPS™, are the first GPS satellite surveying equipment from the WM Satellite Survey Company (WM). The accuracy for the WM 101 is specified as 10 mm + 2 ppm of the separation distance.

We want to test the performance of the WM 101 receiver in conditions as free from general GPS error sources as possible. Therefore we have designed three different test procedures, described in this paper. During the past half year, test measurements were carried out using the WM 101 at several locations and under different meteorological and environmental conditions. All data collected in these tests were processed by PoPS™. The main purpose of this paper is to present some of the results of these test measurements and to draw conclusions about the attainable accuracy and precision of the WM 101.

2. Recapitulation

2.1 The WM 101 and its Technical Features

The WM 101 (Figure 2) is a four channel, L1, C/A code receiver. The four channels provide satellite message information, pseudo-range and simultaneous carrier phase measurements (L1) from up to six satellites. It has all the features which are considered essential for a "true" field instrument: internal, rechargeable battery to power the unit for about 3 to 4 hours of operation, built-in tape-deck, operational temperature range from -25°C to $+55^{\circ}\text{C}$, water-proof and buoyant. The WM 101 antenna is shown in Figure 2. It is an omnidirectional antenna which maintains its right-hand circular polarization over the entire sphere in order to reduce multipathing effects. A cable of up to 120 m (RG 214) can be used to connect the receiver with the antenna. The operational temperature range for the antenna is from -40°C to $+70^{\circ}\text{C}$.

More information about the design principles and features of the WM 101 is given in (2, 9).

2.2 The Post-processing Software PoPS™

As an integral part of the WM 101 GPS Satellite Surveying Equipment, WM offers the post-processing software package, PoPS™. This highly integrated software product analyses observations from networks of up to ten stations on a personal computer. It uses modern data processing techniques, including a data base management system, and its computational method is an advanced development of the well-known "Bernese GPS Software". The innovative techniques and approaches used in PoPS™ are described in detail in (10).

3. Test procedures and results

3.1 Preamble

Three different tests were designed and carried out to check the performance of the WM 101 receiver and its associated post-processing software package, PoPS™. These three tests were:

- (i) Zero-baseline test
- (ii) Short-baseline test
- (iii) Small network test

Each test procedure was designed to fulfil specific test criteria. The first test procedure, the zero-baseline test, is a commonly-used hardware test configuration. Due to the fact that two receivers are connected to the same antenna element, the computed baseline length should be zero. Deviations from zero are caused by differences in the receivers.

The antenna performance cannot be tested with the zero-baseline test. Therefore a short-baseline test is needed to check the antenna performance in addition to the receiver hardware. Assuming that the two antenna locations are not too widely separated, propagation and orbit effects should be negligible. Unfortunately, the distance between the two antenna locations is no longer a true value, as it would be in the zero-baseline test. Thus the so-called "ground-truth" must be measured with sufficient accuracy using other equipment, e. g. EDM.

The short-baseline test configuration is a very simple use of GPS equipment in surveying practice. Therefore a third test procedure, the small network test, is proposed. This general test covers not only hardware related error sources but also external sources as already mentioned. If a network of more than two stations is observed several times, vector closures of the independent vector elements between the stations can be formed. This allows an unbiased assessment of the precision attained since the true value of the closure is zero.

The next three sections will deal with these three tests. Descriptions of the tests, their purposes, summaries of the measurements and the results will be given in detail.

3.2 Zero-baseline Test

Test Design

Figure 3 sketches the design of the zero-baseline test. Two WM101 receivers are connected to the same antenna element. Due to the special design of the receivers two preamplifier/downconverter units are used to connect the receivers with the antenna element. Each receiver/preamplifier set gets identical signals. Therefore this specific test configuration suppresses atmospheric propagation effects, orbit errors, multipath and antenna imperfections. Any electronic differences between the two receiver/preamplifier units are thus thoroughly tested.

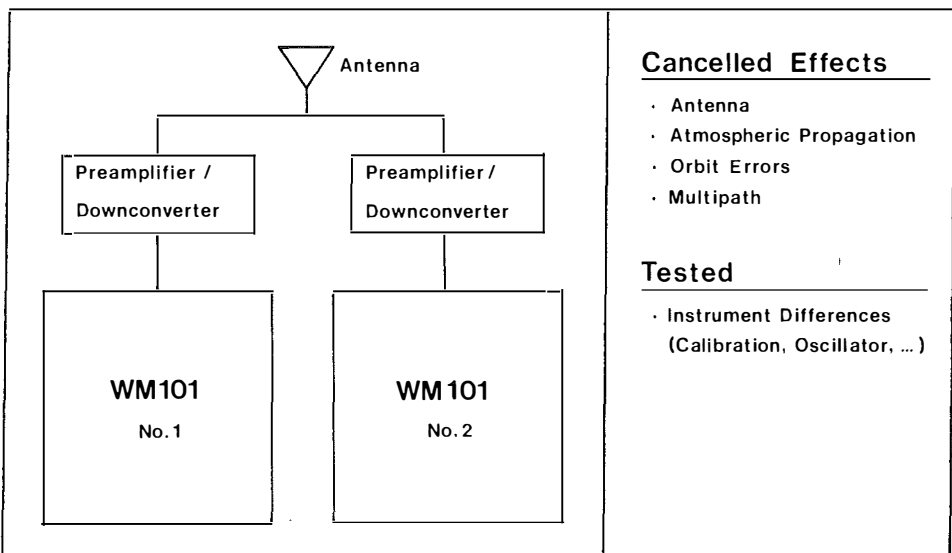


Figure 3: Configuration for the zero-baseline test.

Measurements

All of the zero-baseline tests were carried out in Torrance, California. The single antenna was tripod-mounted on the roof of Building Three of the Magnavox plant (33°50' N, 118°20' W). The receivers were operated in the laboratory. For this report we have selected the measurements which were recorded on March 22nd, 1986. Measurements were compacted by the receiver to one-minute data points. The available data span the time period from 0400 to 1100 GMT, during which the signals of the space vehicles number, 3, 6, 8, 9, 11, 12, 13 were recorded. A cut-off angle of 15° elevation was selected in the receiver and in the post-processing.

Processing

The total data volume was separated into three sessions as the period of one session is limited in PoPSTM to 200 data points. Figure 4 shows the three sessions in a satellite tracking plot for this particular day. The screening of the double-differenced phase observations (DDPO) by PoPSTM led to the elimination of all data from space vehicle 11, because of unexpected high phase noise. Therefore DDPO were formed using all possible combinations of phase observations from the six remaining satellites.

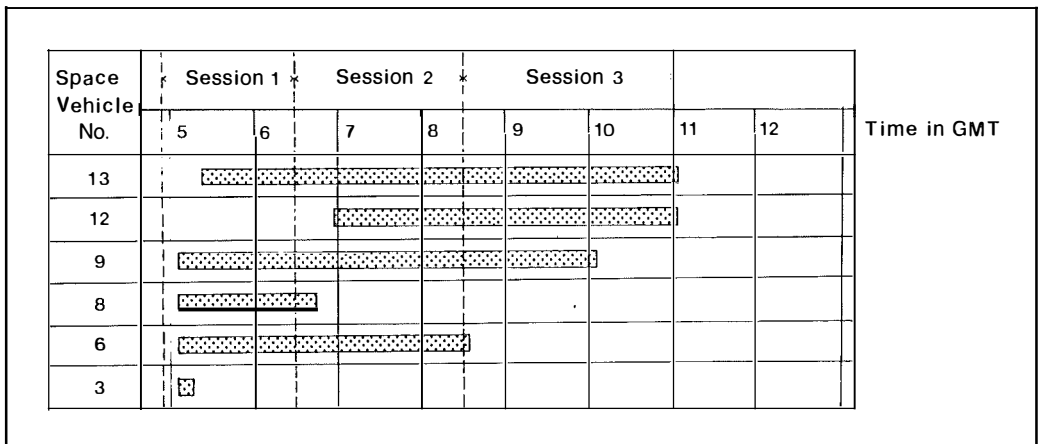


Figure 4:
Satellite tracking plot for the zero-baseline test of March 22nd, 1986.
The periods of the three sessions are shown. Space vehicle 11 is not shown, see text.

Results

Table 2 lists the results of each individual session as well as the results of all three sessions combined in one adjustment. Applying the law of propagation of variances, the rms of one individual phase observation is half the value of the rms value of a double-differenced phase observation. As shown in Table 2, the rms value for one DDPO was 2 mm, yielding an rms for a single phase measurement of 1 mm.

The computed baseline-length varied for the three individual sessions from 2 mm to 5 mm. The combined adjustment of all sessions yielded a length of 2 mm. For rather long periods there were only three satellites above the horizon. The results indicate that the WM101 receivers perform with an inherent accuracy which is much better than stated by the constant term in the accuracy specification (10 mm). However, we realize that this term should also account for error terms which are suppressed by the special configuration of the zero-baseline test. There was good agreement between the results (coordinate differences and lengths) as calculated for the individual sessions.

SESSION	DATA			RESULTS			
	TIME INTERVAL (min)	NO. OF DDPO	RMS OF DDPO (mm)	LENGTH OF BASELINE (mm)	ΔX (mm)	ΔY (mm)	ΔZ (mm)
1	93	228	2	5	4	1	-2
2	120	336	2	2	1	0	-1
3	150	226	2	3	2	2	-2
ALL SESSIONS	363	790	2	2	2	0	-1

Table 2: Results of the zero-baseline test (March 22nd, 1986).

3.3 Short-baseline Test

Test Design

The configuration for the short-baseline test is shown in Figure 5. Compared with the zero-baseline test this test configuration checks the differences between antennas, in addition to the two receivers. It can be assumed for an antenna separation of about 88 m that most GPS environmental effects are strongly correlated. The effects are mainly atmospheric propagation and orbit errors. In differencing phase measurements to compute the baseline, the common part of all error sources will be cancelled. The remaining errors will primarily be caused by differences in the receivers and in the antennas.

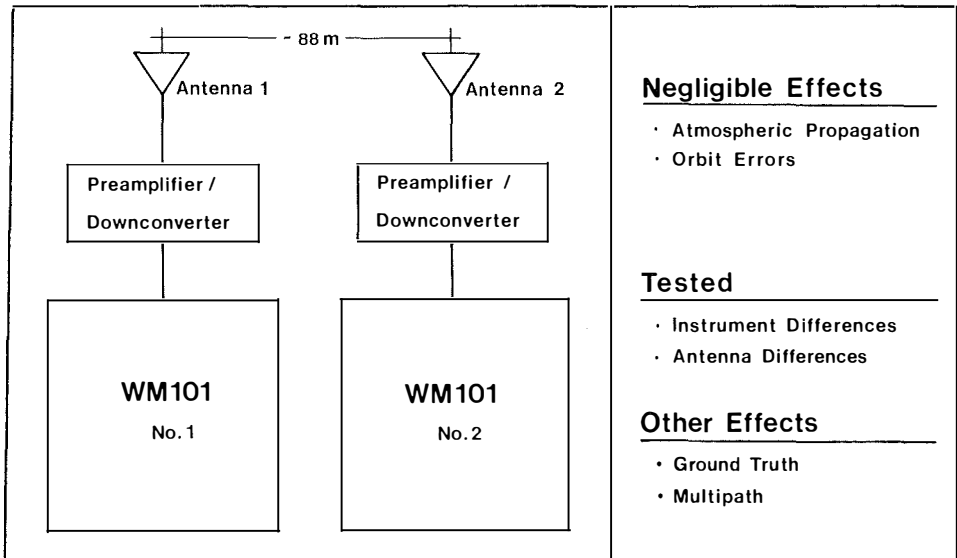


Figure 5: Configuration for the short-baseline test.

Measurement

Short-baseline tests have been carried out repeatedly during the last months at the Magnavox plant, Torrance California. the antennas were located on the same roof as the antenna for the zero-baseline test. It is known that the roof on Building Three at the Magnavox plant is likely to give multipath effects. Figure 6 shows the environmental conditions at this location. Two typical measurement periods are reported here. The first set of data was gathered on March 27th, 1986, and the second set on April 25th, 1986. For both sessions, measurements within each one minute interval, were computed to single data points by the receiver. See Table 3 for more information about the test data. The slope distance between the two antenna locations was measured using a WILD DI5 Distomat. The accuracy of this instrument is specified as 3 mm + 2 ppm.



Figure 6: The roof of Building Three at the Magnavox plant in Torrance.

Results

The results obtained are listed in Table 3. The differences between the two independently computed baseline lengths is 4 mm. The GPS results are in good agreement with the EDM-measured distance. The rms values for the distances were computed as 1 mm and 2 mm respectively. The rms value for a single DDPO was calculated as 6 mm, which yields 3 mm for a single phase observation.


SESSION	Station OCCUPATION TIME (min)	NO. OF DDPO	RMS OF DDPO (mm)	EDM SLOPE DISTANCE (m)	GPS SLOPE DISTANCE (m)	 (mm)
27. March 1986	150	344	6	87.882	87.882	0
25. April 1986	150	139	6	87.882	87.878	+4

Table 3: Results for the short-baseline test.

The difference between these totally independent estimates of baseline lengths is statistically insignificant. Considering that different receiver pairs were used, the agreement in the baseline lengths is excellent. The comparison of the short-baseline test shows no significant change in the results. This indicates that the antennas perform according to specification.

3.4 Small Network Test

Test Design

The repeated observation of a small network allows the computation of independent vector closures, for which the true values should be zero in all three coordinates. Thus the number of independent vector closures, c , is given as

$$c = (n - 1) (s - 1)$$

where n is the number of stations in the network and s is the number of sessions during which all stations were observed simultaneously. Each vector misclosure is formed from the sum of independent baseline vectors derived from phase measurements. This fact can be used to estimate the rms of a single baseline determination, m_b , by applying the error propagation law for uncorrelated observations. The value obtained gives another estimate of the constant term of the accuracy specification for the WM 101 receivers. Scale errors, which nevertheless should be negligible for small networks, cannot be detected by this method.

An additional advantage is gained of the ground truth of the small network is known with high accuracy. This allows an absolute comparison of the GPS results for the baseline lengths with the related "ground-truth".

Measurements

The test measurements were carried out at the EDM calibration facility (47°20' N and 9°35' E) of Wild Heerbrugg. The baseline is on flat ground beside the River Rhine, see Figure 7. Four pillars (0, 3, 6 and 7) were occupied with prototype WM 101 receivers during three nights (20, 25, 28 February 1986). Thick snow covered the ground for the second and third nights. Each occupation period lasted 1.5 to 2.0 hours. For all observation periods, the data were compacted by the receivers to one minute data points. The same receiver/antenna pair was always used at each pillar. Throughout the three sessions, the antennas were oriented in the same direction in order to reproduce the test configuration. The satellite cut-off angle was set to 15° in the receiver.

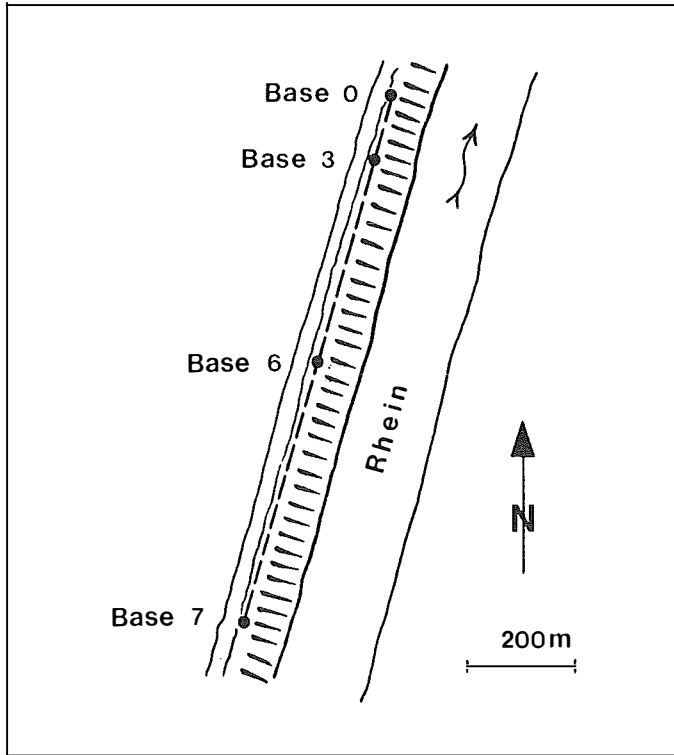


Figure 7: Sketch of the EDM calibration facility near Heerbrugg.
Only the occupied pillars are shown.

Processing

All processing was done using PoPS™. Details of the processing are described in (10). The data from the first three nights (sessions) were analysed. Identical baseline definitions were chosen for each session, with Base 0 as a reference point and the three baselines being

- Base 0 — Base 3,
- Base 0 — Base 6,
- Base 0 — Base 7.

As a first step, each session was treated as a network on its own. Finally, the data of all three sessions were used in a single adjustment. For each adjustment, the following model parameters and processing settings were selected:

- A priori sigma of observation 4 mm
- Minimum elevation of observations 15°
- Tropospheric correction model Saastamoinen
- Ionospheric correction model None
- Ephemerides Broadcast
- Ambiguities Resolved

Table 4 lists the number of DDPO remaining in each baseline in each session after data screening removed those measurements with gross errors. The sites were occupied for a shorter period in the first sessions; the shorter period for the third session resulted from a tape malfunction at site Base 7.

	Base 0-Base 3	Base 0-Base 6	Base 0-Base 7
Session 1	171	131	159
Session 2	272	249	268
Session 3	356	307	178

Table 4: Number of DDPO available for each baseline and session.

	Base 0-Base 3 (mm)	Base 0-Base 6 (mm)	Base 0-Base 7 (mm)
Session 1	5	8	6
Session 2	5	6	5
Session 3	5	6	6

Table 5: rms errors of one DDPO for each baseline and session.

	Base 0-Base 3 (m)	Base 0-Base 6 (m)	Base 0-Base 7 (m)
EDM Ref.	116.508	501.514	1001.519
Session 1	116.513	501.518	1001.515
Session 2	116.513	501.524	1001.508
Session 3	116.513	501.527	1001.510
3-session, 4-station network	116.513	501.523	1001.510

Table 6: Baseline lengths, computed values and EDM references.

Results

The rms errors for individual phase observations were half of the values for the double-differenced observations shown in Table 5, i. e. 2 to 4 mm. The results (Table 6) of the computed baseline lengths (slope distance) showed a repeatability within a range of up to 9 mm between sessions. The EDM reference values (see Table 6) are the weighted averages of a series of measurements using a variety of EDM equipment. The accuracy can be assumed to be 2 mm. Table 6 shows that the maximum deviation of the WM 101 results from the EDM reference is 13 mm. This is an excellent result considering the rather poor satellite geometry (as shown in Figure 8) for this test campaign.

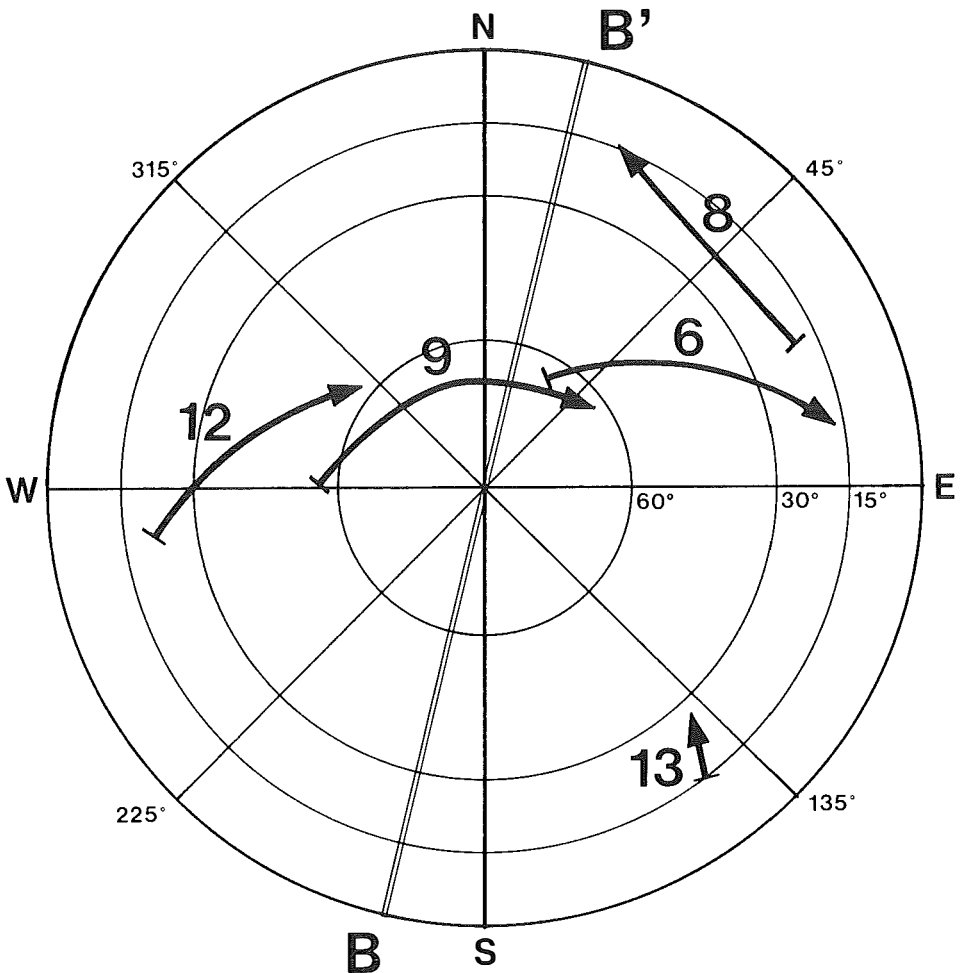


Figure 8:

Satellite availability diagramm for the data collected on February 25th, 1986. Observation period was from 1910 to 2112 (GMT + 1). The orientation of the EDM baseline is shown by the line B to B'.

In addition to the repeatability we would like to assess the attainable accuracy using an absolute test. This is done by computing the vector misclosures which are known to be zero in the absence of observational errors. A triangle represents the fundamental vector polygon, and therefore we have selected the three baselines:

- Base 0 – Base 3
- Base 3 – Base 7
- Base 7 – Base 0

for the computation of vector misclosures. The coordinate differences were computed for each session separately. The results are listed in Table 7. The coordinate system used is WGS-72. The vector polygons for each session show small misclosures since the baselines were computed in separate solutions rather than in one network adjustment for each session. These small “session” vector misclosures indicate that no gross errors were made. They are not measures of observational accuracy, since the three baseline results are not independent.

Baseline	Session	ΔX (m)	ΔY (m)	ΔZ (m)
0-3	1	- 86,693	16,802	76,008
3-7	1	- 658,613	127,560	577,223
7-0	1	745,305	- 144,363	- 653,233
$\Sigma 1$		- ,001	- ,001	- ,002
0-3	2	- 86,695	16,803	76,007
3-7	2	- 658,608	127,559	577,221
7-0	2	745,299	- 144,360	- 653,228
$\Sigma 2$		- ,004	,002	,000
0-3	3	- 86,690	16,805	76,011
3-7	3	- 658,606	127,558	577,220
7-0	3	745,300	- 144,361	- 653,231
$\Sigma 3$,004	,002	,000

Table 7: Computed coordinate differences (WGS-72) for the three baselines and sessions.

Session	1			2			3			ΔX	ΔY	ΔZ	f
	0-3	3-7	7-0	0-3	3-7	7-0	0-3	3-7	7-0				
No. 1	x				x				x	-1	0	-2	2,2
No. 2	x					x		x		0	0	0	0,0
No. 3		x		x					x	-8	2	-1	8,3
No. 4			x	x				x		4	-2	-6	7,5

Table 8: Independent vector closures for triangle Base 0 – Base 3 – Base 7.

As explained earlier, only four independent vector closures can be formed for the triangle (0–3–7) which was observed simultaneously by three receivers in three independent sessions. In Table 8 we show the formulation of the four different vector closures. The vector misclosures are calculated using the appropriate coordinate differences from Table 7, and are listed in Table 8 including the length $|f|$ of the misclosure.

Realizing that $|f|$ is the sum of the true errors of the baselines, we can calculate the rms value of one baseline determination m_b using the formula

$$m_b = \left(\frac{\sum_{k=1}^4 f_k^2}{s \cdot n} \right)^{1/2}$$

which yields for our data, $m_b = 3.3$ mm. Since the baselines are rather short, m_b may be compared with the constant term of the accuracy specification for the WM 101. This further confirms the excellent performance of the WM 101 receivers in practical field measurements. This result is in good agreement with the general accuracy picture of survey results as shown in Figure 1.

4. Conclusion

Recently the WM Satellite Survey Company has introduced their first products, the WM 101 and PoPS™. Three test configurations have been designed in order to verify the performance of the WM 101 receivers and antennas. The three configurations were a zero-baseline, a short-baseline and a small network test.

For all data sets processed, the rms for a single phase observation was calculated to be less than 3 mm. The zero-baseline and the short-baseline tests have shown that the receivers and the antenna perform much better than stated in the constant term of the accuracy specification for the Wm 101 receiver (10 mm).

The results from the small network test and especially the vector misclosures (3.3 mm rms for a independently determined baseline length), show the excellent performance of the WM 101 GPS Satellite Surveying Equipment.

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