Positioning by an Active GPS System: Experimental Investigation of the Attainable Accuracy

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Key words: GPS, active GPS system, field test, positioning accuracy, local accuracy.

ABSTRACT

In two Austrian regions, active GPS networks have been installed by the respective energy companies. The GPS networks are continuously operated and provide online positioning capability with a precision of a few centimeters. The user needs only to be equipped with a single GPS receiver, a radio link and a special software. The use of an active GPS system might also be promising for surveying tasks of large scale engineering projects.

We present the results of experimental investigations of the attainable absolute and local positioning accuracy using an active GPS system. The measurements were performed at a distance of about 8 km from the nearest control station which also serves as transmitter of reference station data and corrections. The results show the main critical requirements: (i) a high data integrity rate of the radio link, (ii) the successful resolution of the carrier phase integer ambiguity, and (iii) the elimination of all outliers.

In this paper we propose an outlier detection scheme which eliminates outliers already in the field. In the absence of outliers, the precision of the plane positions and heights of single stations is batter than 3 cm. The local positioning accuracy for short baselines (< 2 km) is about 1 to 2 cm if the two sites are occupied within one hour and about 3 cm otherwise.

We conclude that the current active GPS systems cannot generally be used for high precision control surveys and setting-out of a construction project. However, they are well suited for cadastral surveying, GIS applications, and for general surveying tasks.

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1. INTRODUCTION

An active GPS reference system consists of a number of active GPS control stations which are operated in a network mode and linked to a computing center (Van der Marel, 1998). The active GPS control stations (reference stations) are continuously operated, and data and area correction parameters are sent to an unlimited number of users. Area correction parameters (ACP) are used to model error influences of the satellite orbit data and atmospheric effects. Wübbena et al. (2002) give a detailed description of the calculation of ACP. The major advantage of an active GPS system is that an accuracy of a few centimeters can be obtained with only a single GPS receiver, a radio link and a field computer with special software. This reduces equipment and staff costs compared to traditional GPS real time kinematik (RTK) positioning using a specially set up reference station.

In this paper we present experimental results of the attainable precision and accuracy of single point positioning with the active GPS system of Burgenland, Austria. These results are compared to other active GPS systems and to previous measurements with the same active GPS system made by Titz and Weber (1998).

We also focus on the achievable local accuracy, which – to our knowledge – has not been experimentally investigated so far. Here local accuracy ("Nachbarschaftsgenauigkeit" in German) is defined as the positional accuracy between two adjacent stations. In many engineering applications, like setting-out of the tracks for high speed railways, the absolute accuracy is of minor importance but the local accuracy is crucial. Therefore, we present investigations on the attainable local accuracy with an active GPS system and its time dependency.

2. ACTIVE GPS SYSTEM AND TEST SITUATION

2.1 Test Site

The active GPS system used for our experiments is located in Burgenland, a federal state in the south-eastern part of Austria. Compared to other active GPS systems with several hundreds of reference stations, like SAPOS in Germany (Seeber, 2000), the SATVB (German acronym for "surveying system for Burgenland using satellites") is a rather small system. It consists of 4 permanent GPS reference stations with inter-station distances between 40 and 106 km (fig. 1).

The test area is located about 8 km south-west of the town Neusiedl and consists of five points, see fig. 1. Starting with point B0, four other points with distances of 189 m (B200), 604 m (B600), 1036 m (B1000) and 2014 m (B2000) from B0 were marked. These distances where used to study a possible distance dependency of the local accuracy between two points as described in section 4.

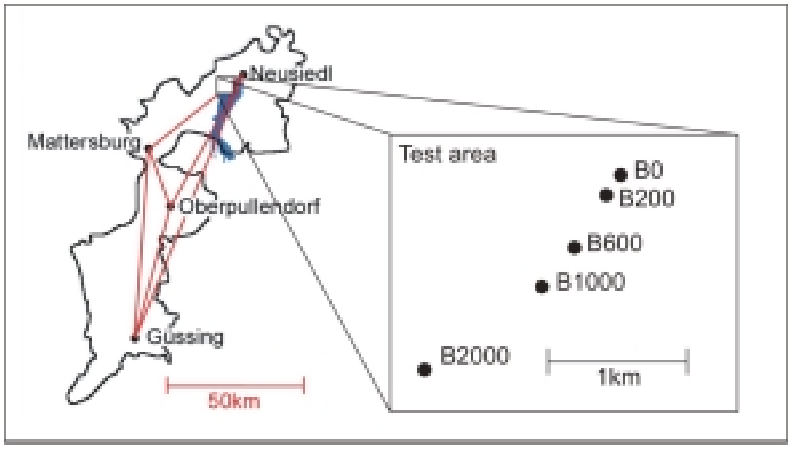

Figure 1: SATVB – reference station configuration and test area

The experiments were designed to evaluate the attainable precision of the active GPS system without any influences of incorrect handling of the field equipment. Therefore, carefully set up tripods were used (fig. 2), in order to eliminate error sources like stability of a surveying pole and vibrations due to wind. Furthermore, all measurements with the active GPS system and the terrestrial and static GPS surveys were carried out with forced centering. All measurements were done during the time period 19. to 20.12.2001.

Figure 2: Experimental setup

2.2 Ground Truth Measurements

Titz and Weber (1998) reported of systematic effects of SATVB in latitude in the order of 5 cm. To detect these or other systematic errors it was decided to determine ground truth values for the 5 stations by two independent techniques. Static GPS measurements were carried out and terrestrial measurements were made to independently check the GPS results.

2.2.1 Static GPS Measurements

In order to obtain ground truth data, it was decided to survey all stations by static GPS measurements using long observation times. For the static GPS measurements 2 Ashtech Z-FX CORS and 2 Ashtech Z-Surveyor receivers with 4 Ashtech choke ring antennas were used. The coordinates of the five points were determined in two GPS sessions of more than 7 hours with a sampling interval of 15 s. During the first night the stations B0, B200, B1000 and B2000, and on the following day the stations B600 and B2000 were occupied. Thus B2000 served as link point between the two sessions.

The RINEX data were processed with BERNESE 4.2 post-processing software. For the direct comparison of the coordinates from the static GPS measurements with those of the active GPS system, both results have to be in the same coordinate system. Therefore, the RINEX data of the active reference station Neusiedl were used to calculate coordinates of B2000 for both sessions in ITRF94, which is the reference system used by SATVB. With baselines from B2000, coordinates of all other points were computed by a network adjustment.

2.2.2 Terrestrial Measurements

High precision terrestrial surveys were used to partially check the static GPS results, especially the baseline lengths. Results of the terrestrial measurements were calculated in a local coordinate system. Atmospheric corrections were not applied during the measurements but separately taken into account in the subsequent analysis.

The quality of the static GPS results (stGPS) can be assessed by comparison with the spatial distances determined by the terrestrial measurements. From table 1 it is evident that the spatial distances differ by maximal 1.5 mm.

Due to the long observation times of the static GPS surveys and their good agreement with the terrestrial measurements, the results of the static GPS measurements were used as reference values for the evaluation of the accuracy of the active GPS system.

Table 1: Spatial distances derived from static GPS and terrestrial measurements

distance	d_{terr} [m]	d_{stGPS} [m]	difference [mm]
B0-B200	188.9573	188.9575	0.2
B0-B600	604.3922	604.3907	-1.5
B200-B600	417.7415	417.7411	0.4

2.3 Measurement Procedure

We decided to use two rovers for the investigation of the achievable local accuracy with the active GPS system. The equipment of both rovers was identical and consisted of radio link, field computer, JAVAD Legant antenna and JAVAD Legacy receiver. Unfortunately different versions of the software from Geo++ were installed in the rovers. In the following, the rover with the software dating from May 1999 is called rover A. In the second rover, rover B, the software dating from November 2000 was installed. For both receivers the same software settings were used, which included a cut-off elevation of 10°.

Since the attainable accuracy with the active GPS system should be investigated, only those satellite signals where used, for which area correction parameters were provided. This requires that these satellites must at least be visible at three reference stations and at the rover. Therefore, at certain times the number of satellites used was clearly below the number of satellites observed at the rover. Occasionally the ambiguities could not be fixed due to a poor satellite configuration. Especially between 10:15 and 14:00 UTC almost no positions could be stored. GLONASS satellites were not used for the experiments.

For the whole test period, rover A recorded positions at station B0. Simultaneously with the measurements at B0, the points B200, B600, B1000 and B2000 were occupied for more than two hours each, using rover B.

The following measurement procedure was adopted:

1. wait until the ambiguities are fixed
2. determine position by averaging over 5 s
3. save position
4. re-initialize the rover and continue with (1)

The software used, stores the coordinates in the system ITRF94, epoch 1993.0. In order to separate horizontal and vertical components, all coordinates were transformed into local horizon systems. The Cartesian coordinates from the static GPS analysis of the respective point served as origin for the single point analysis. For the baseline analysis the center of the baseline was used as origin.

2.4 Outlier Detection

To eliminate outliers, all measurements calculated by the software with standard deviations larger than 3 σ were removed from the data. In a subsequent “robust cleaning” step, all realizations with larger deviations than 3 σ from the median were also eliminated, see table 2. For the threshold value of 3 σ, σ was set to 3 cm because Titz and Weber (1998) reported the attainable accuracy for SATVB with 1 to 3 cm in horizontal position and height.

Thus, between 1 (rover B, at B1000) and 48 (rover A, at B0 on 20.12.01) observations have been eliminated using the threshold of 9 cm, see table 2.

Table 2: Number of outliers and measurements

point	measurement		rover	number of outliers		number of realizations without outliers
	date	UTC		identified by software	detected with the median	
B0	19.12.01	08:39 – 10:38	A	1	25	41
	19.12.01	13:47 – 16:46	A	2	0	127
	20.12.01	07:39 – 11:55	A	5	43	87
B200	19.12.01	13:46 – 16:46	B	4	0	141
B600	19.12.01	08:38 – 10:38	B	3	1	50
B1000	20.12.01	07:34 – 09:23	B	0	1	55
B2000	20.12.01	09:52 – 11:52	B	0	1	8

We suspect that the large number of outliers associated with rover A results from the older software version where sometimes ambiguities are falsely fixed. Every day around 10:15 UTC the satellite configuration started to become poor and the number of outliers increased using rover A, whereas for rover B the times to fix ambiguities increased considerably. Therefore, at station B2000 only 9 observations could be made. Due to this small number of observations B2000 is not considered in the following investigations.

Unfortunately, in most practical applications, the user has only a small number of measurements available. Table 3 lists that 3 outliers were not detected by the software of rover B, two of them had values of more than 4 m. Therefore, the detection of outliers is crucial and needs to be done already in the field. For this purpose we propose the following procedure:

(1) initialize and wait until ambiguities are fixed
(2) store coordinates; if standard deviations calculated by the software exceed 3 σ go back to (1)
(3) re-initialize and wait until ambiguities are fixed again
(4) store coordinates; if standard deviations calculated by the software exceed 3 σ go back to (1)
(5) compare stored coordinates; if any coordinate component differs more than 6 σ repeat the process beginning with (1); as soon as the coordinates of two consecutive measurements agree within 6 σ, store these values
(6) move to next point

Thus, final coordinates of a point are only obtained if the standard deviations (calculated by the software) of two consecutive measurements are less than 3 σ and their difference in all coordinate components is below 6 σ. With the proposed procedure all outliers of rover B, and 57 outliers of rover A can be eliminated.

3. RESULTS OF SINGLE POINT POSITIONING

3.1 Precision

As described in section 2.4, all realizations with larger deviations than 9 cm from the median were eliminated. The remaining data were used to calculate standard deviations (std) in local horizon systems, see table 3.

Table 3: Precision (1 σ) of single point positioning

point	measurement		rover	std_E	std_N	std_h
	date	UTC		[mm]	[mm]	[mm]
B0	19.12.01	08:39 – 10:38	A	10	13	34
	19.12.01	13:47 – 16:46	A	4	5	8
	20.12.01	07:39 – 11:55	A	6	19	28
B200	19.12.01	13:46 – 16:46	B	4	7	11
B600	19.12.01	08:38 – 10:38	B	5	8	14
B1000	20.12.01	07:34 – 09:23	B	5	12	17

Table 3 shows the high precision of the single point positioning results using the active GPS system when outliers are removed. The standard deviation (1 σ) of the plane position is generally better than 20 mm. In height the standard deviation increases up to 34 mm. As expected, the standard deviation in plane position is a factor 2 to 3 better than in height.

Our results confirm the precision of 1 to 3 cm as stated by Titz (1999) and Titz and Weber (1998). However, a general precision in horizontal position of 1 cm as reported by Wübbena et al. (2002) could only be achieved with rover B.

The measurements of B0 on 19.12.2001 were divided into a morning and afternoon session, since the measurements had a significantly higher dispersion in the morning than in the afternoon, see fig. 3. The reason for the larger dispersion during the morning hours is the worse satellite configuration during that time, which is responsible for the experienced longer times to fix ambiguities, sometimes more than two minutes. Similar experiences were already reported by Titz and Weber (1998).

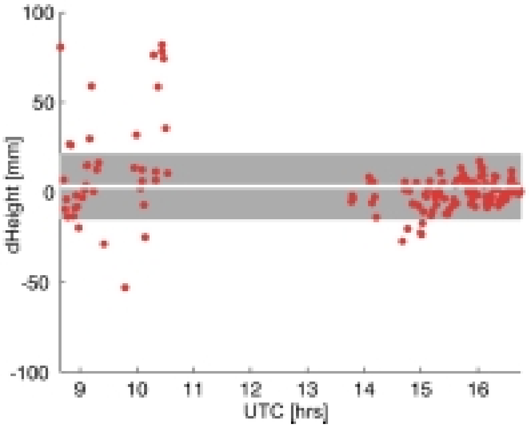

Figure 3: Height results for B0 using the active GPS system on 19.12.01, plotted with respect to the reference height; shaded area corresponds to ±σ = 18 mm

3.2 Accuracy

Systematic errors like offsets can only be detected if the measurements are compared to reference values. As described in section 2.2, ground truth values were established by static GPS and terrestrial measurements. Therefore, root mean square (rms) values for the different coordinate components could be calculated, see table 4.

Table 4: Accuracy (1 σ) of single point positioning

Point	measurement		ground truth - mean value [mm]			rms_E [mm]	rms_N [mm]	rms_h [mm]
	date	UTC	dE	dN	dh			
B0	19.12.01	08:39 – 10:38	-8	6	-14	13	14	38
	19.12.01	13:47 – 16:46	-4	3	1	5	6	8
	20.12.01	07:39 – 11:55	-14	12	-3	15	22	28
B200	19.12.01	13:46 – 16:46	-4	2	-9	6	10	15
B600	19.12.01	08:38 – 10:38	-3	8	-11	6	11	17
B1000	20.12.01	07:34 – 09:23	-16	5	-9	16	13	19

Table 4 shows that the rms values are only slightly larger than the std values (table 3) because of the small deviations of the mean values from ground truth. It is noteworthy that all east deviations are negative while the contrary is true for the north deviations. One reason could be unknown differences of the JAVAD Legacy antennas of the active GPS system and the Ashtech choke ring antennas used for the static GPS measurements, although all antennas were oriented to the North and phase center variation (PCV) values from NGS were applied. However, no offset of 5 cm in the north direction as reported by Titz and Weber (1998) could be found.

Fig. 4 shows the precision and accuracy of SATVB. All measurements are plotted against their ground truth values. The difference of more than 500 single point positioning solutions from the ground truth value exceeds 5 cm in five cases only. The precision can be best described by the 95% confidence ellipses, fig. 4.

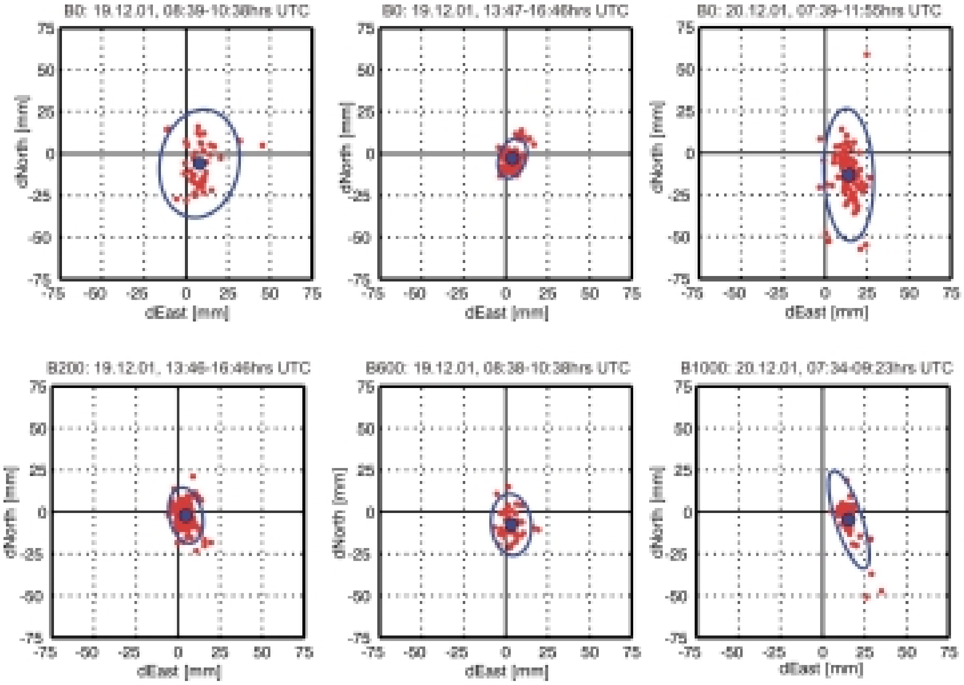

Figure 4: Precision and accuracy of single point positioning with the active GPS system; the ground truth value has the coordinates (0,0) in all subplots; the 95% confidence ellipses are shown

The difference in precision between good and poor satellite configurations can be seen in the upper three subplots of fig. 4. These subplots show the measurements of B0 at different times. The good satellite configuration on 19.12.01 p.m. results in small coordinate variations (upper middle subplot) compared to the coordinate variations on 19.12.01 a.m. and 20.12.01 a.m.

4. RESULTS OF LOCAL ACCURACY

4.1 Preamble

For several engineering applications the accurate positioning of two points relative to each other is of greater importance than their accurate absolute positioning in a coordinate system. This holds true especially for high speed railway surveys where e.g. two points have to be set out with an accuracy of better than e.g. 10 mm at a distance of 150 m. For shorter distances an even higher accuracy is required. It is of great practical interest whether an active GPS system can be used for the survey of such demanding accuracy requirements. However, to our knowledge no related experiments have been carried out so far. Therefore, in the following we investigate the attainable local accuracy and take a look at its time and distance dependency.

The Federal Geographic Data Committee (1998) defines local accuracy as “a value that represents the uncertainty in the coordinates of the control point relative to the coordinates of other directly connected, adjacent control points at the 95-percent confidence level”. Another useful measure of local accuracy is the relative error ellipse, as described by Cooper (1987).

4.2 Simultaneous Measurements

It is commonly known, that GPS measurements are highly time correlated. Due to this correlation common errors at two stations can be reduced by subtraction. However, it is expected that this correlation decreases with time and baseline length. Therefore, it would appear that simultaneous measurements at two stations using the active GPS system would yield a higher local accuracy.

Therefore, two rovers were used in the field work, to compute coordinate differences of nearly simultaneous measurements. The standard deviations of the individual coordinate components of all baselines were calculated, see table 5. The results suggest a dependency of the std on baseline length. However, this is difficult to assess because the influence of the baseline length is drowned by the detrimental effect of the satellite configuration. As table 3 indicates, the std of the single point positioning of B600 is larger than that of B200. Obviously this also maps into a larger std of the baseline B0-B600.

Table 5: Std (1 σ) of coordinate differences from simultaneous measurements

Baseline	length [m]	$std_{\Delta E}$ [mm]	$std_{\Delta N}$ [mm]	$std_{\Delta h}$ [mm]
B0-B200	189	4	5	8
B0-B600	604	5	14	23
B0-B1000	1036	5	23	24

Simultaneous measurements with the active GPS system are correlated due to common propagation effects and ACP at both rover stations. However, the coordinate differences were derived from the coordinates of the end stations and not from double differenced phase ($\Delta\nabla\Phi$) observations as used by RTK.

With the software GRAZIA (Gassner et al., 2002) the data of the static GPS $\Delta\nabla\Phi$ measurements were calculated in a RTK mode with B0 as reference station. After each ambiguity fixing, the mean of two point position solutions was stored and the ambiguities were re-initialized. Thus more than 4000 fully independent positions of B200, B1000 and B2000 were calculated. Their std indicate a dependency of the precision on the baseline length, but are significantly smaller than the std of the coordinate differences derived with the active GPS system, see fig. 5.

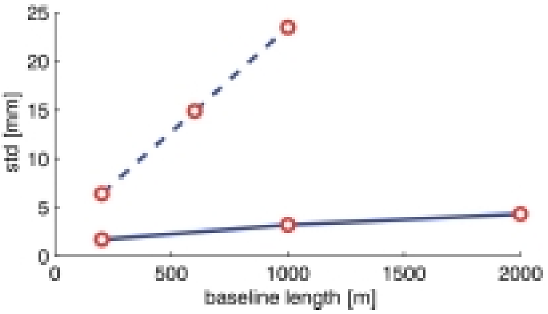

Figure 5: Std of simultaneous horizontal positioning with the active GPS system (dashed line) and

RTK (continuous line) for different baseline lengths

4.3 Time Dependency

The results in table 5 show that relative positioning with the active GPS system yields a quite useful precision for certain surveying tasks. However, a great practical and economical advantage would be achieved if the measurements do not need to be carried out exactly simultaneously. Therefore, the time dependency of the local accuracy was investigated.

If the end point measurements are not made simultaneously, the rms values slowly increase with time difference for baseline B0-B200. Fig. 6 shows a clear trend in the north component. There the rms value is smaller than 5 mm in case of simultaneous measurements and almost 10 mm if the time difference is about 1.5 hours.

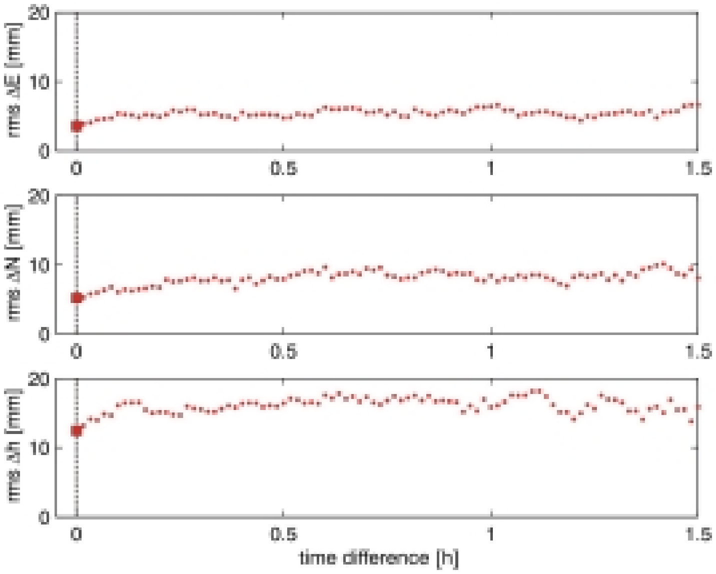

Figure 6: Dependency of rms values on the time difference for baseline B0-B200; squares represent simultaneous measurements

Of course, the rms values of the coordinate differences, are related to the rms values of the baseline length. The same trend as in fig. 6 is visible in the upper left subplot of fig. 7 for the rms values of the baseline length for B0-B200. However, the rms values of coordinate differences and thus baseline lengths from B0 to points B600 and B1000 do not show such a trend, see fig. 7. Again, we suspect that the reason for this, is the superposition of the satellite configuration on the time dependency. Nevertheless, it has to be mentioned that even with poor satellite configuration the rms of the baseline length is always better than 22 mm which is a useful precision for certain surveying tasks.

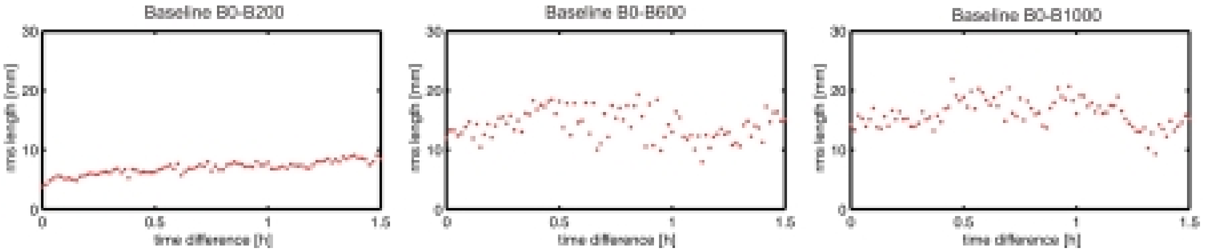

Figure 7: Time dependency of rms values of baseline lengths of different baselines

5. CONCLUSIONS

We experimentally evaluated the attainable accuracy with an active GPS system. Ground truth was provided by independent static GPS measurements and terrestrial measurements. To achieve highest precision only satellites with area correction parameters were used. However, this limits the useful survey time. In December 2001 between 10 a.m. and 2 p.m. almost no ambiguities could be fixed at our test site, due to poor satellite geometry.

The absolute accuracy of the active GPS system is generally better than 3 cm in plane position. The height accuracy is in the range of 1 to 4 cm. We want to emphasize that this accuracy can only be obtained if outliers are successfully eliminated. Therefore, we have proposed an outlier detection scheme which eliminates outliers already in the field.

Our investigations show that for the determination of precise coordinate differences, simultaneous measurements are not necessary. For a local accuracy of 1 to 2 cm it is sufficient to measure both points within one hour using the active GPS system. This yields significant practical and economical advantages compared to simultaneous measurements. Since the accuracy of single point positioning of our experiments corresponds to results reported by other authors it is reasonable to expect that the derived local accuracy is also valid for other active GPS systems.

We conclude that the current active GPS systems cannot generally be used for high precision control surveys and setting-out of a construction project. However, this highly efficient survey technique is well suited for cadastral surveying, GIS applications, and for general surveying tasks.

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BIOGRAPHICAL NOTES

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Fritz K. Brunner received the degrees Dipl.-Ing. and Dr. techn. from the Technical University of Vienna in 1967 and 1972, respectively. During 1969-1974, he was an assistant at the TU Vienna. From 1974 to 1982, he was a lecturer at the University of New South Wales, Australia. During 1981, he was an A. v. Humboldt fellow at the Geodetic Institute, University of Stuttgart. From 1982 to 1986, he headed the Advanced Products Group at Wild Heerbrugg Ltd., Switzerland. In 1986 he was appointed Professor and Head, School of Surveying, University of New South Wales. In 1994 he received an A. v. Humboldt Research Award. Since October 1994 he is Professor of Engineering Geodesy, Graz University of Technology. From 1995 to 1999 he was President of Section I "Positioning" of IAG. In 2001, he was elected President of the Austrian Geodetic Commission.