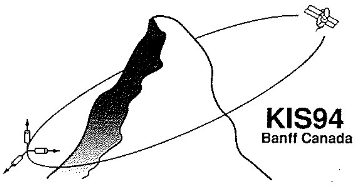

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Kinematic rail-track survey by GPS

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BIOGRAPHIES

Dr. Herbert Lichtenegger is geodesist and received his doctoral degree from the University of Technology at Graz with a thesis on earth tides. Since his habilitation with a textbook on GPS, he holds an appointment as docent for surveying including satellite geodesy at Graz university. He is author of some 70 scientific papers; he is also coauthor of three textbooks on GPS.

Eng. Željko Bačić received his diploma degree in geodesy at the University of Zagreb. At present, he is on leave to perform postgraduate studies on GPS at the University of Technology at Graz.

Prof. Bernhard Hofmann-Wellenhof studied geodesy at the University of Technology at Graz. His doctoral thesis delt with relative orientation in photogrammetry, and his habilitation thesis covered the theory of the gravitational potential. Since 1986, he holds an appointment as professor for surveying at his home university at Graz. He is author of some 80 scientific papers; he is also coauthor of three textbooks on GPS.

ABSTRACT

High-speed railway technology requires track survey on a regular basis with millimeter accuracy. In principle, GPS may be an economical alternative to traditional surveying methods in railway engineering. However, three limiting factors must be considered: (1) loss of signal lock will often occur because of topography or trains passing by, and, thus, on-the-fly ambiguity resolution techniques are required, (2) the highly reflective environment will often cause multipath which limits the achievable accuracy, and (3) some of the antennas are very sensitive against vertical dynamics (i.e., vertical shocks while tracking) leading to cycle slips which decreases the reliability of GPS for railway engineering.

1. INTRODUCTION

The objective of a cooperation between Plasser & Theurer Company at Linz (one of the world's leading manufacturers of track construction machinery) and the University of Technology at Graz is to prove GPS for real-time kinematic applications in the field of rail-track maintenance and correction where accuracies in the subcentimeter range are required. Because of frequent loss of GPS signal lock on the track, the project includes the development of software which allows for real-time ambiguity resolution. The known track geometry facilitates this task.

At present, millimeter accuracy in track survey is routinely achieved by a sophisticated survey car named EMSAT^{TM}. This car consists of two components, one is the main machine EM and the other is a small car called SAT. The two parts of the machine are first located at two control points of the track (with a separation of some 100 m). Between these two points, a reference chord is established by means of a laser beam. Subsequently, the main machine drives along the track and measures the offsets of the track relative to the reference chord by monitoring the position of the laser beam on a CCD camera mounted on the EM.

In the future, both parts of the EMSAT^{TM} will comprise GPS equipment to enable kinematic relative positioning of the roving vehicle with respect to the resting one. A first report on this concept and on the results of practical test series was presented at the General Meeting of IAG at Beijing, cf. Lichtenegger et al. (1993). In the meanwhile, additional theoretical and practical investigations have been conducted. Some of them are presented here. First, a report on interesting results of a – as it was considered! – routine measurement is given, then the results from antenna-acceleration tests are presented, and, finally, a miniature rail-track is described which serves to test hardware and software. The description includes some results of kinematic test measurements.

2. RAIL-TRACK SURVEY BY GPS

Measurements were performed on day 171 and 172 of 1994 and were considered as routine measurements to test once more GPS hardware and software for the capability of rail-track survey. The data was collected in the relative kinematic mode by Ashtech P-XII receivers. The fixed antenna was mounted on a tripod beside the track and the rover antenna was mounted on a small wheeled platform which was moved along a 500 m track section. In 5-meter intervals, points were marked on the track to allow for the reoccupation precisely. The track section was surveyed in the real kinematic mode as well as in the stop and go mode, cf. Hofmann-Wellenhof et al. (1994). For each investigation, the data sampling rate was one second whereas the satellite configuration varied from test to test.

When processing the data with Ashtech software GPPS (version 5.0), many of the jobs failed because the double-difference phase residuals became too large (e.g., some decimeters). Jumps of this size in the residuals happened to occur suddenly, although in most cases more than five satellites were tracked. Correlated to this are jumps in the calculated coordinates. An example of the effect is presented in Fig. 1.

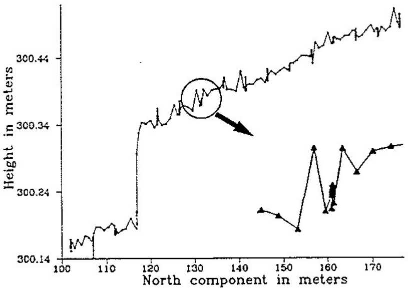

Figure 1: Kinematic survey plot

In Fig. 1, height is plotted versus northing (which nearly coincided with the direction of the antenna motion) for a short track section of 75 m. which was surveyed in the stop and go mode. In the graph, the stop points may easily be recognized as fuzzy "dots" where the heights vary in the range of 1 to 2 centimeters as usually. The variations of the heights are also in the expected range when the antenna was in motion on the slightly sloped track. Remarkable is the behavior of the resulting heights just before and after the stop points, cf. the zoomed and extracted detail in Fig. 1. In most of the cases, a distinct peak appears which seems to justify the assumption that accelerations or sudden shocks may cause irregularities in the measured phases. The figure is dominated by a jump in the height of about 17 cm at the fourth stop point.

To investigate this effect in more detail, the position of the start point and the end point of the track section have been determined. Thus, the initialization of the kinematic survey can be performed on both points, and the data can be processed forwards and backwards. The last digits of the initial ambiguities in cycles at both initialization track points are given in Table 1.

SV	Elevation	Ambiguities at	
#	e	Start point	End point
05	23°	77.04	25.03
17	22°	96.98	97.02
20	61°	03.97	03.96
24	22°	64.98	65.93
25	50°	37.01	36.99

Table 1: Ambiguities referring to SV 06, $e = 86°$

During the survey, there occurred a loss of signal lock for satellite SV 05. The resulting cycle slip was corrected by the software. For SV 24, a change of the ambiguity by one cycle can be recognized comparing the ambiguities based either on the track start point or the end point. This cycle slip was not detected by the software and is the reason for the jump in the heights. It should be mentioned that there is also an effect on position; however, as usual this effect is smaller by a factor of 2 or 3. Therefore, in the following only heights are considered. It is remarkable that this cycle slip amounting to one cycle occurred when the stop point was left which is again an indicator for the sensitivity of the antenna against accelerations or sudden shocks.

3. ACCELERATION TESTS

Artificial accelerations were applied to the antennas to unveil the reason of the effects in the aforementioned track survey. Tests were performed on the roof of the university building on day 193 and 194 of the current year. On both days, two sessions were observed where the fixed and rover antenna were interchanged. Each session consisted of 8 test series where after each series the roving antenna was relocated at its initialization site. In the first and last series, the roving antenna before and after the actual acceleration tests was checked by conventional kinematic surveys. In the second series, horizontal accelerations were applied to the rover antenna. The third series was a slow vertical movement of the antenna. In the fourth and fifth series, the antenna was subject to vertical accelerations of 1 g in form of free falls and sudden upward motions. The sixth series was a shake test in horizontal direction, and the seventh series covered shaking in vertical direction with different velocities.

The result of the tests confirmed the assumption that there is a strong sensitivity of Ashtech antennas against accelerations particular in vertical direction. As an example, the result of free-fall tests of one antenna is shown in Fig. 2.

In this figure, the height component and the horizontal distance of the rover antenna with respect to the initialization site are plotted. The antenna was moved from the initialization site to another location were five free-fall trials were performed. After these tests, the antenna was relocated on its initialization point.

From Fig. 2 it can be recognized that after the second and fourth trial a shift in the height of about 35 cm occurred. To a smaller amount, there appear also changes in the position. A total height change of about 70 cm and a total change in position of about 25 cm resulted as misclosures after repositioning the antenna on its intitialization site. It should be mentioned that the software did not detect any cycle slip. Only a warning message reported large double-difference phase residuals. However, the backward computation of the test has demonstrated that the phases of all five tracked satellites must be corrected by just one cycle because of cycle slips. To recover the phase corrections, an initialization was performed after each free-fall test. Therefrom one can conclude that the first jump in the heights was caused by cycle slips of one cycle on three satellites and the second jump was caused by cycle slips on the two remaining satellites. After correcting these cycle slips, the misclosures at the initialization points completely disappeared. The corrected result of the free-fall tests is represented in Fig. 3 which is otherwise analogous to Fig. 2.

It should be mentioned that the characteristic

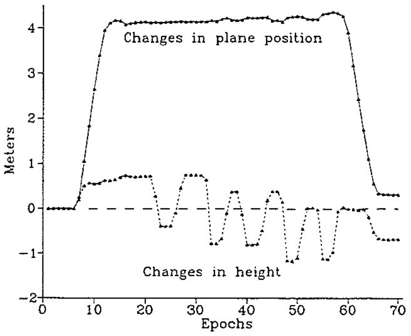

Figure 2: Uncorrected result of free-fall tests

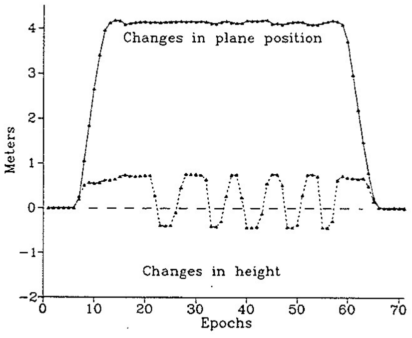

Figure 3: Corrected result of free-fall tests

of the test results does not depend on the data sampling rate. Also, there is no strong correlation of the cycle slips amounting to one cycle with the elevations of the satellites. The conclusion from all these tests is that particularly vertical accelerations can cause cycle slips of one cycle which lead to unacceptable errors in rail-track survey. One strategy to overcome the problem is to check the ambiguities on an epoch by epoch basis by introducing predicted coordinates of the antenna as known values. Predictions may be obtained by taking into account the smoothness of the track geometry.

4. MINIATURE RAILWAY MODEL

A miniature railway track was installed on the roof of the university building, cf. Fig. 4, to test our software for cycle slip detection.

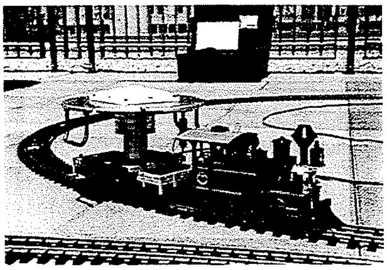

Figure 4: Miniature railway model

Various layouts of the miniature track by combining curved and straight elements enable proofs of the robustness of the software with respect to different track geometry. Also, the miniature model can be used as ground truth since the track geometry can be accurately determined with millimeter accuracy. Thus, the model may also be applied to investigate the effect of multipath. Another goal of the model is to test the algorithm for several corrections, e.g., due to longitudinal inclination or track-superelevations.

To illustrate the achievable accuracy of this model, Fig. 5 is given. This figure shows the result of a stop and go survey in a circular track. Starting from the initialization point, the antenna was mounted on the miniature railway freight car. Then, the antenna was moved along the circle and was stopped on 16 regularly distributed points. For an assessment of the positioning accuracy, the diameter of the circle was calculated from symmetrical points, cf. Table 2. Concluding from the results in this table, the precision of GPS in kinematic mode amounts to about 5 mm. However, the average of the calculated diameters differs from the true diameter by 12 mm. These numbers agree with the results of previous tests, cf. Lichtenegger et al. (1993).

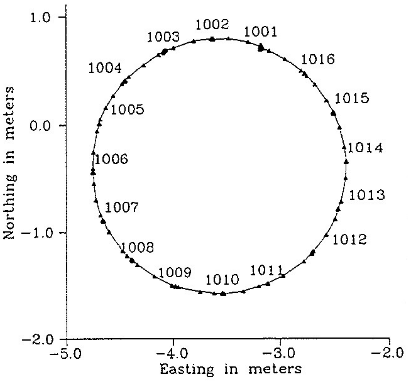

Figure 5: Survey of a cirular track

From–To	Diameter [m]
1001–1009	2.367
1002–1010	2.373
1003–1011	2.372
1004–1012	2.376
1005–1013	2.369
1006–1014	2.368
1007–1015	2.378
1008–1016	2.375

Table 2: Calculated diameters in a circular track

5. CONCLUSIONS

From extensive measurments it can be concluded that in kinematic mode a precision (i.e., relative accuracy) of about 0.5–1.0 cm for baselines up to 1 km can be achieved with GPS. The absolute accuracy estimated from reoccupations varied in the range from 1 to 2 cm. Already well-known is that the precison and the accuracy of heights and horizontal positions differ by a factor of 2 to 3.

The results of test measurements revealed high sensitivity of Ashtech antennas against strong accelerations or shocks, particularly in vertical direction. In most cases, these shocks did not cause loss of lock of the satellite signals in the usual sense leading to "regular cycle slips" with an arbitrary change of the ambiguity. However, they sometimes resulted in one-cycle changes of the phase ambiguities. There is only a weak correlation between these jumps and satellite elevations. These cycle slips are not recovered by the commercial Ashtech software and lead to position errors in the range of several decimeters! As usual, the effect on the heights is again larger than the effect on positions. In cases when more than four satellites are tracked, the cycle slips of one cycle become evident in form of large residuals in the level of decimeters while they are usually in the centimeter level.

The reason for the one-cycle cycle slips is not yet fully evident. Additional tests are necessary. Among them, the antennas will be mounted on a shaking-platform which can be operated in vertical and horizontal direction and with different velocities. Also, it is not known whether the effect is specific to Ashtech antennas. Therefore, other antennas must be tested and the data must be processed with different software.

One method to detect and correct the cycle slips of one cycle is to implement better hardware and software filters. Another method can be applied in railway engineering. Because of the smooth geometry of the rail-track, the antenna position can be predicted at each epoch with an accuracy of say some centimeters when a sufficient high data sampling rate is chosen. This accuracy allows to recompute at each epoch the ambiguities by means of the predicted position. Thus, on-the-fly ambiguity resolution as well as detection of very small cycle slips is possible.

REFERENCES

Hofmann-Wellenhof B, Lichtenegger H, Collins J (1994): GPS – Theory and practice, 3rd edition. Springer, Wien New York.

Lichtenegger H, Klostius W, Hofmann-Wellenhof B, Lichtberger B (1993): Real time GPS – An application for railway engineering. General Meeting of IAG, Beijing, P.R.China, August 6–13.