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INFLUENCE OF AN AIRPORT RADAR ON GPS-POSITIONING INCLUDING AMBIGUITY RESOLUTION ON-THE-FLY

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ABSTRACT: Differential GPS offers an ideal possibility for real-time avionics applications. However, two serious difficulties are faced in practical operation: interruptions in the data linking between reference station and airplane and malfunctions of the GPS-receiver due to interfering signals. The paper deals with the second problem, which becomes especially important in an airport environment, where many transmitters operate. A particular influence on GPS-receivers have the airport radars. In extreme cases the receiver is not able to operate at all. But even if the receiver seems to operate properly, the measurements can be seriously distorted.

The paper describes a test with modern geodetic receivers in the vicinity of an airport radar. The theoretical background concerning the receiver operation (C/A-code-ambiguities, measurement noise, gross errors) and the OTF algorithm is given. A detailed data analysis shows up to what extend the radar affects the receiver performance and the precision of the code-DGPS and how it causes the OTF algorithm to fail.

1. INTRODUCTION

Currently, several aviation authorities like FAA and ICAO are investigating the possibility of precision approach and landing up to CAT-III by means of DGPS. The integrity requirements of civil aviation for CAT II-III approaches are in the order of 10^{-9} (Hein, 1995) and cannot be fullfiled by GPS as a stand alone system. For that reason several techniques have been developed for enhancing the efficiency of GPS, like the FAA's Wide Area Augmentation System (WAAS) using pseudolites (Wullschleger et al., 1996).

The GPS-signals are very weak and thus quite vulnerable to radio frequency (RF) interferences. Although for commercial avionics receivers RF interference is expected to be originated from unintentional, out-of-band signals, lower power harmonics of powerful transmitters can cause in-band interferences (Ward, 1994). Interferences in their harmless form simply cause an increased measurement noise. In their most harmful form interferences cause a lot of cycle slips or even make the tracking of the GPS-signals impossible. An intermediate situation occurs when the receiver seems to operate normally but nevertheless the measurements are strongly distorted. This is a dangerous effect because these distortions lead to non-tolerable positioning errors. In addition, if the double difference (DD) system is not overdetermined (i.e. only four satellites are available) the errors cannot be detected.

The paper describes how an airport radar affects the performance of geodetic GPS-receivers and how it causes unacceptable errors in the position.

2. UNDERLYING THEORY

2.1. Positioning Algorithms

Talking about positioning algorithms in the context of this paper, all following approaches assume the use of differencing techniques applied to baselines not exceeding 10-15 kilometers.

2.1.1. Code Pseudoranges

The use of code pseudorange observations represents today's standard in differential positioning leading to accuracies between 1 and 10 meters. In principle, there are two different approaches: the use of differential corrections or raw obervation data. The great advantage of differential corrections - their compact data format and simple application - is at the same time its great disadvantage, because the small data amount of the differential corrections in comparison to raw observation data results in a lack of information for the processing algorithms. For this, the algorithms presented in the following use raw observation data. This allows the use of additional data, like signal-to-noise ratio (SNR), phase or doppler observations.

As the algorithms for position computation using code pseudoranges are developed for kinematic applications they must allow an epochwise independent solution. This will be achieved by the mathematical model of code (pseudorange) double differences (CDD). Neglecting remaining errors of the satellite and receiver clocks and the satellite orbit, the CDD reads:

$$\nabla\Delta PR = \nabla\Delta\rho + \nabla\Delta dion + \nabla\Delta dtrop + \nabla\Delta dmp + \nabla\Delta dn \qquad (1)$$

where $\nabla\Delta$ denotes the double difference between two satellites and two receivers, PR is the measured code pseudorange, ρ the distance satellite-receiver, *dion* the error due to ionospheric refraction, *dtrop* the error due to tropospheric refraction, *dmp* the error due to multipath, and *dn* the error due to measurement noise.

Applying (1) to short baselines, the influences of the ionosphere are widely cancelling out and can be neglected. Due to different station heights, the tropospheric refraction must be applied to the observations. Based on this modelling of the CDD, the baseline vector will be calculated according to (Sauermann, 1993) by means of a regular Gauss-Markoff model. Within this model, corrections due to signal travelling time, clock errors, and earth rotation will be applied to the observation equations; errors due to multipath and measurement noise are treated like system noise. A minimum number of 4 satellites is required to solve for a three-dimensional position. The error computation within the Gauss-Markoff model will become possible with a minimum number of 5 satellites.

An accuracy improvement up to 30% of the CDD-positions can be achieved by using low satellites between 7-15 degrees and by introducing a different weighting of the code pseudoranges, e.g. by means of SNR values (Gianniou and Groten, 1996).

2.1.2. Ambiguity Resolution 'On-the-Fly'

Besides the code pseudoranges with a noise level of about 0.3-3 meters, carrier phase pseudoranges can be used for position computation. The carrier phases have a noise level of some millimeters. Due to the fact that at the beginning of each carrier phase observation only the current phase of the incomming signal could be measured, the number of whole cycles during signal propagation from the satellite to the receiver remains unknown (ambiguities). If the ambiguities for each satellite are known and as long as no signal interruption occurs, a position computation with accuracies of several centimeters by means of carrier phases is possible. The mathematical model used is the phase (pseudorange) double difference (PDD). Under the same assumptions as (1) and neglecting the influences of the atmosphere the PDD reads:

$$\nabla\Delta\Phi = \nabla\Delta\rho + \lambda \cdot \nabla\Delta N + \nabla\Delta dmp + \nabla\Delta dn \qquad (2)$$

where Φ is the measured carrier phase, λ the wavelength of the carrier, and N the ambiguity value. If the ambiguities are known, the computation of the baseline vectors is done with the same Gauss-Markoff model as mentioned above. The crucial point in every PDD-position computation is the correct resolution of the unknown ambiguities, even if the mobile antenna is in motion like it is in the kinematic case (OTF).

For every OTF algorithm two aspects are of special interest: the reliability and the availability of the ambiguities. Here, reliability means the ratio of correct ambiguity resolutions to incorrect ones, and availability means the percentage of observation time where an accurate position computation with correctly resolved ambiguities is available. So, the OTF-availability goes hand in hand with the number of observation epochs needed for ambiguity resolution. The presented OTF algorithm shows a very high reliability and availability, due to the exploitation of two-frequency data, the high accuracy of the code solution, the rejection of most of the possible candidates, and an extremly fast computation.

More detailed, our ambiguity resolution algorithm 'On-The-Fly' performs following steps:

1. Based on the algorithms of chapter 2.1.1, a CDD solution is computed for the mobile antenna. With this position real values for the DD-ambiguities (float ambiguities) on L1 and L2 are determined. The float ambiguities are first estimations of the unknown integer DD-ambiguities.
2. Under the assumption that the correct integer ambiguities are in the vicinity of the float ambiguities, a searching space on L1 around the float ambiguities is defined. The definition of the searching space in units of cycles around each float DD-ambiguity is realized via the accuracy estimation of the CDD solution (Mathes and Gianniou, 1994).
3. Starting with the L1 float ambiguities, only those integer ambiguities within the searching space are determined, that fullfil the 'Two-Frequency-Criterion' (TFC) (Mathes and Gianniou, 1994). The TFC takes full advantage of two frequency data, where possible L1 integer ambiguities are transformed into L2 ambiguities and rejected if they do not fullfil the following condition:

$$\Delta N_{L2} - \frac{\lambda_{L1}}{\lambda_{L2}} \Delta N_{L1} \leq barrier \qquad (3)$$

where N_{L1} and N_{L2} are the corresponding DD-ambiguities, λ are the wavelengths of the carrier, Δ denotes the difference between the float ambiguities and the integer values, and *barrier* represents an uncertainty value for the integer requirement depending on the elevation of the satellites. All possible candidates within the searching space are determined using the TFC. The immense reduction by the TFC of ambiguities to be tested is - besides the high reliability of the solution - the main reason for using L1 and L2 observations.

4. The criterion which ambiguity set should be further tested in the next step, is realized by the sum of squared residuals. This combination with the minimum impact on the sum of squared residuals of the CDD solution will be selected. In this step, the computational effort is reduced by time optimized algorithms, e.g. a cholesky decomposition.

5. The final criterion to accept the ambiguity set of 4. is the a-posteriori variance of the PDD position computed with these ambiguities. The variance must be within the limit of a standard PDD computation, in our case 27 centimeters.
6. If the ambiguities are accepted under 5. a verification test similar to 5. follows in the next two observation epochs. Within these two epochs the ambiguities will be finally accepted or rejected. If they are rejected or do not pass the test in 5., a L1 CDD solution will be computed for this epoch(s).

Due to the fact, that the rejection criteria of 4. and 5. are based on the error computation of the adjustment model, a minimum number of 5 satellites must be tracked on both frequencies at the reference and the mobile site if the ambiguity resolution is in progress. For the position computation after a successful ambiguity resolution 4 satellites are sufficient.

Normally, the correct ambiguities are solved instantaneously in about 95-97% of all cases. Instantaneously means in this context within 3 observation epochs (see 6.). For the remaining cases the resolution lasts up to 30 epochs or will not be possible, e.g. under the influence of strong interferences.

2.2 Impact of Interferences

2.2.1 Interferences and C/A-code-ambiguities

The C/A-code has a dual importance in GPS-positioning. First, it is the only code available to civil users after AS was permanent turned-on. Second, the C/A-code is being used in order to acquire the other GPS-measurements, i.e. the P(Y)-code and the carrier phase measurements.

The C/A-code consists of 1023 bits and has a chipping rate of 1.023 Mbps. Thus, it has a period of 1 msec (Spilker, 1980). In other words every millisecond the same 1023 bits will be found in the satellite signal. Due to its very short duration (and low chipping rate) the C/A-code can easily be tracked. The receiver however has to resolve this one-millisecond ambiguity.

Under certain circumstances the receiver is not able to resolve correctly the C/A-code ambiguities. This can be caused for example by an interfering signal having similar properties like the GPS-signal (Gianniou, 1996).

2.2.2. Interferences and signal-to-noise ratio

Roughly speaking, the signal-to-noise ratio (SNR) gives the power of the desired signal relative to that of the noise. Under RF interferences the so-called equivalent SNR expressed as a ratio (not in dB) is (Ward, 1994):

$$[c/n_0]_{eq} = \frac{1}{\frac{1}{c/n_0} + \frac{j/s}{Q f_c}} \tag{4}$$

where c/n_0 is the unjammed signal to noise power in 1 Hz bandwidth expressed as a ratio, j/s the jammer to signal power expressed as a ratio, f_c the code chipping rate and Q is 1 for narrowband und 2 for wideband jammer.

According to (4), interferences reduce the SNR, a fact that one would expect. However, the distinction between signal and noise is sometimes a difficult task, because the two components may have common characteristics. In general, in such a situation the SNR fluctuates. This behaviour is well known from the multipath effect (Axelrad et al., 1994). Fluctuations in SNR can however be caused also by RF interferences (Gianniou, 1996).

2.2.3 Impact on the measurement quality

The reduction of SNR means an increased observation noise. This is a quite logical consequence, because low SNR corresponds to high noise level in the incoming signal. The standard deviation (in meters) of the code-measurement in the delay-lock loop (DLL) as a function of SNR is (Ward, 1994):

$$\sigma_{DLL} = \sqrt{\frac{FB_C}{c/n_0}\left[1+\frac{2}{T\,c/n_0}\right]}\;\lambda_C \tag{5}$$

where F is the DLL discriminator correlator factor, B_C is the code loop noise bandwidth in Hz, c/n_0 the signal to noise power expressed as a ratio (not in dB), T is the predetection integration time and λ_c is the code wavelength. With the same notation the standard deviation (in meters) of the phase measurement in the phase-lock loop (PLL) is (Ward, 1994):

$$\sigma_{PLL} = \sqrt{\frac{B_P}{c/n_0}\left[1+\frac{1}{2T\,c/n_0}\right]}\;\frac{\lambda_L}{2\pi} \tag{6}$$

with λ_L the carrier wavelength.

It should be mentioned, that in the presence of effects causing fluctuations of the SNR (see also 2.2.2) the formulas (5)-(6) do not realistically describe the measurement precision.

A way to assess the degradation of the precision of the code or phase measurement is to build the second order time differences of these measurements (Gianniou, 1996). In order to consider for small instabilities of the sampling rate, the first order time differences $\delta_n m(t)$ of the measurements $m(t)$ are normalized by the time interval between the consecutive epochs:

$$\delta_n m(t_{k+1}) = \frac{m(t_{k+1}) - m(t_k)}{t_{k+1} - t_k}. \tag{7}$$

The normalized second order time differences are:

$$\delta_n^2 m(t_{k+2}) = \delta m(t_{k+2}) - \delta m(t_{k+1}) \quad = \quad \frac{m(t_{k+2}) - m(t_{k+1})}{t_{k+2} - t_{k+1}} - \frac{m(t_{k+1}) - m(t_k)}{t_{k+1} - t_k}. \tag{8}$$

If the data is sampled at a high rate (higher than 0.5 Hz), the time second differences describe quite well the noise in the measurement. Obviously, coloured noise with a long correlation length will vanish in the time differences of data sampled at a high rate. To search for long-period effects one can plot the code- or phase-DD versus the time. The distortion of the phase-DD is usually much more smaller compared to that of code-DD and probably can not be seen in the diagram time-DD. However, if the effect has a dispersive character the relation between the L1 and L2 phase measurements will be distorted. This can be tested by computing the difference (Gianniou, 1996):

$$\frac{\lambda_1}{\lambda_2}\cdot\left[\phi_1(t_k)-\phi_1(t_{k-1})\right]-\left[\phi_2(t_k)-\phi_2(t_{k-1})\right]. \tag{9}$$

2.2.4. Impact on the positioning

As long as the interfering signal has other characteristics than the GPS-signal, the interference simply results in a lower positioning precision. The standard deviation of the coordinates can so be increased by a factor 2 or 3.

On the contrary, if the receiver cannot distinguish between the GPS and the interfering signal, the measurement can be affected by big errors. This will lead to big errors in the CDD-position. In addition, the signal distortions have a dramatical impact on the ambiguity resolution and usually cause an OTF algorithm to fail. For the OTF algorithm described in 2.1.2 this can be easily understood due to the big errors in the CDD-coordinates and the distortion of the relation between the L1 and L2 phase measurements.

3. DATA ANALYSIS

The data analysed here are collected in the vicinity of a powerful ground radar at the Rhein/Main airport, Frankfurt. Two Trimble 4000 geodetic receivers have been used: a 4000SSE and a 4000SSi. The main purpose of the test was to compare the resistance capability of the two receivers against interferences. The geodetic Trimble compact antennas (with groundplanes) were mounted on the roof of a van. The distance between their phase centers was 1.234 meters. The measurments are conducted at a sampling rate of 1 sec.

3.1 C/A-Code-Ambiguities

The figure 1 shows the C/A-code pseudorange for the SSE and the SSi receiver. The distance between the ticks on the vertical axis is equal to the pseudorange error that corresponds to one C/A-code period, i.e. approximately 300000 meters. Every jump in the pseudorange of the SSE is a multiple of this quantity. This proves that the receiver could not correctly resolve the C/A-code-ambiguities (Gianniou, 1996). In contrast, the SSi was not affected by this problem. It should be mentioned that the SSE did not give a clock offset, which is an indicator of malfunction.

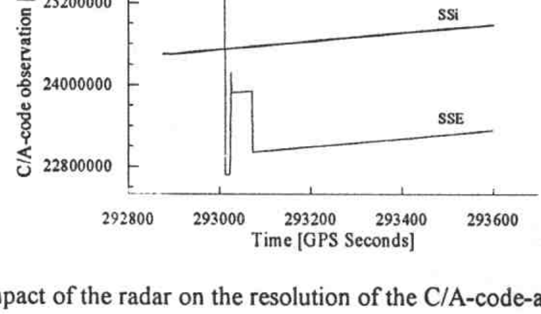

Fig. 1: Impact of the radar on the resolution of the C/A-code-ambiguities.

3.2 Signal-to-Noise Ratio

During a second test on the airport the van was standing for about 10 minutes behind a building hiding the radar. Thereafter, the van moved to a place with free line of sight to the radar. The figure 2a shows the L1- and L2-SNR (in Trimble units) for the SSE. The very strong oszillations of the SNR indicate that the receiver could not completely distinguish between the GPS and the interfering signal. In addition, the SNR becomes smaller (clearly by the L2-SNR), which indicates degradation of the measurement precision.

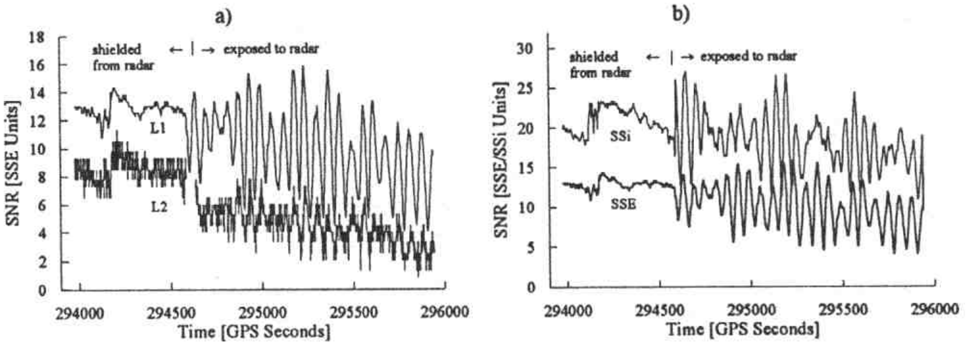

Fig. 2: (a) L1- and L2-SNR for the Trimble SSE receiver,
(b) L1-SNR for the SSE and the SSi receiver.

The figure 2b gives the L1-SNR for the SSE and the SSi receiver. The SNR of the SSi is significantly higher than that of the SSE, which indicates the enhanced resistance of the SSi to interferences. The better quality of the measurements of the SSi will also be demonstrated in figure 4b.

3.3. Impact on the measurement quality

As explained in 2.2.2-3, the degradation of the measurement quality cannot be assessed by means of the formulas (5)-(6), because of the fluctuations of the SNR. For estimating the (uncorrelated in time) noise of the observations, the formula (8) can be used. Figure 3 shows the normalized second order time differences of the code measurement on L2 for the SSE receiver. The influence of the radar can easily be seen.

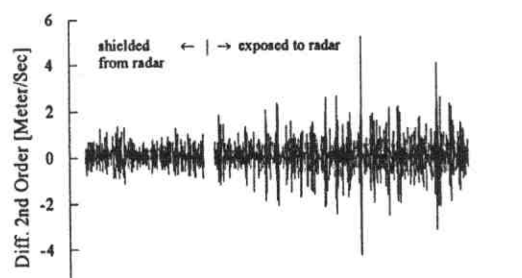

Fig. 3: Influence of the radar on the precision of the L2 code measurement.

The coloured noise in the code measurements is shown in figure 4a, which gives the CDD between the SSE and the SSi receiver. Figure 4b shows the distortion of the relation between the L1- and L2-phase measurements. The vertical axis corresponds to the difference in formula (9).

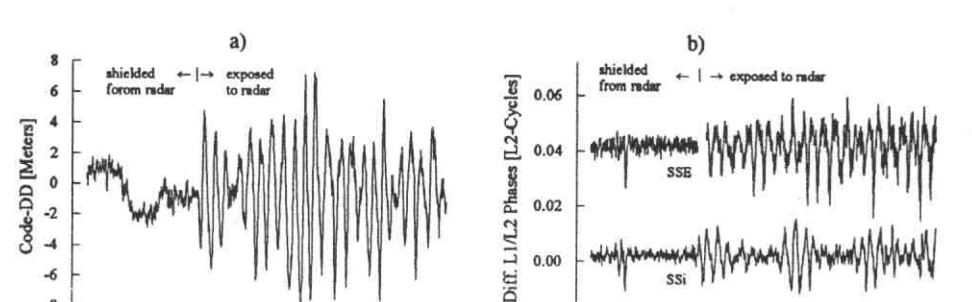

Fig. 4: Distortion of (a) the CDD and (b) the relation between the L1- and L2-phase measurements caused by the radar (The SSE-curve in the right figure is shifted by 0.04 cycles).

3.4. Impact on the positioning

From figure 4a it can easily be understood that the distortion of the CDD will lead to bad results when computing a CDD-solution. While under good conditions the errors of the computed CDD baseline are not exceeding 1.5 meters, the errors increase dramatically under strong interferences (for the case in figure 5a up to 70 meters).

Also the OTF algorithm is not able to solve for the correct set of ambiguities while the antenna is exposed to the radar as can be seen in figure 5b. Often no ambiguities will be tested in steps 5. and 6. of chapter 2.1.2. In those cases the CDD-position will be computed. But sometimes (short horizontal lines while exposed to radar) wrong ambiguities are selected and rejected after a couple of seconds. The reasons for this are the bad CDD-positions and the distorted relation between the L1 and L2 phase observations.

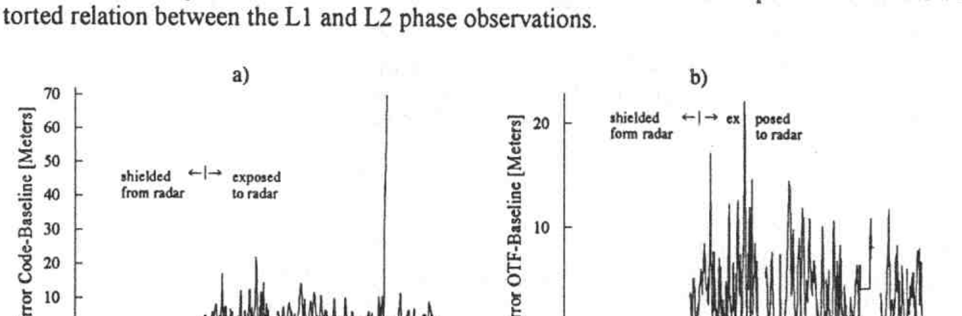

Fig. 5: Error of the computed baselines (a) CDD-solution with L1 data and (b) OTF-solution with L1/L2 data (to the known length of 1.234 meters).

4. CONCLUSIONS

The test measurements with high quality geodetic dual frequency GPS-receivers from Trimble at an international airport has shown, that radars, have a strong influence on the observations. Besides effects like slightly decreased SNR or frequent losses of lock, the more dangerous case of strong distortions of the signals occur. The distortion could influence the tracking performance of a receiver in different ways: First, the receiver can fail to resolve the C/A-code ambiguities and second, the measurement noise of code and phase observation will be dramatically increased leading to big errors. For the positioning this results in wrong CDD-coordinates and the inability to resolve the correct ambiguities (figure 5).

The comparison of the both Trimble receivers SSE and SSi has shown, that the SSi has a better tracking performance under strong interferences. This becomes clear when looking at the resolution of the the C/A-code ambiguitiies (figure 1), the signal-to-noise ratio (figure 2b), and the relation between the L1 and L2 carrier phase measurements (figure 4b).

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