Study of Improved Observation Modeling for Surveying Type Applications in Multipath Environment

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ABSTRACT

Besides ionospheric and tropospheric effects, multipath and diffraction are the factors which can most limit the accuracy of real-time applications. Phase observations contaminated by diffraction may have unwanted effects in kinematic applications and this would limit the suitability of monitoring systems based on GPS as well as pure GPS surveying real-time applications.

The concept of a self-calibrating weighting model is presented which can be used to weight down or completely eliminate poor signals from processing. The Signal-to-Noise ratio (SNR) is highly correlated with signals contaminated by diffraction. The problem with using the SNR for the weighting model is that the SNR is dependent on the setup, which means that different receiver/antenna combinations and cables with varying resistances show different elevation dependent SNR patterns. Even a different location would have an influence on this pattern.

For real-time applications it is therefore necessary to automatically calibrate a weighting model, which is based on the SNR. Our paper describes the advantages of such a self-calibrating weighting model compared to purely elevation dependent weighting models. The efficiency of the used model is demonstrated for a kinematic real-time application as well as for a typical static survey. The kinematic test was conducted on the world's largest suspension bridge in Hong Kong. Such monitoring applications, where the place of mounting a GPS-antenna is almost given, benefit strongly from this approach.

INTRODUCTION

GPS is becoming a standard measurement tool for both a large number of standard surveying applications and monitoring applications. Independence of visibility requirements and the ability of GPS to work under severe weather are often reasons to use GPS in preference to systems involving theodolites. GPS positioning accuracy is well understood in the user community and only in locations with limited sky view a degradation is expected. Some of the degradations might be the result of signal diffraction. Signal diffraction is an expression for an obstructed satellite where the signal is not completely masked and can still be tracked by the receiver.

Diffracted signals usually show higher residuals, because the signal's travel path is extended compared to the direct signal path. Therefore, a purely elevation dependent weighting model does not represent the stochastic model properly. Diffraction weakens the GPS signals, indicated by lower SNRs. This indicator can be used in an improved weighting model. SNRs represent the power of a satellite signal and are measured for L1&L2 independently. The higher this ratio, the better the receiver will perform in rapid static and kinematic applications, Nolan et al. (1992). The SNR translates directly into how long the receiver needs to integrate or average, e.g., the time it takes for the tracking loops to match the incoming signal. If the SNR of one receiver would be 10 times larger compared to another receiver, this would mean that the time for integration or averaging is reduced by 90 per cent.

Under ideal conditions the SNR plotted over elevation angles unveil the strong correlation between both. A pure elevation dependent weighting model might be interpreted as a different way of using a SNR dependent weighting model. In the case of a distorted SNR elevation correlation, simple elevation dependent models are no longer appropriate. The benefit of using mixed weighting models enhanced with an SNR dependency is already shown by Brunner et al (1999), where the so-called SIGMA-DELTA model has been presented. The basic information of the SIGMA-DELTA model is the SNR, but additionally the difference between a template and the actual SNR is taken into account. This means for a certain elevation angle, a certain SNR will be expected. The expected true SNRs are represented by a template, usually described by a polynomial of degree 2 or by the envelope of the values. However, if the actual value deviates from the expected value by Δ, the observation will be further down-weighted. Equation 1 describes how the variances of phase observations for the SIGMA-DELTA model are derived. The factor C_i consists of the carrier loop noise band-width and a conversion term from cycle^2 to mm^2. The factor alpha has been included to equation 1 to allow empirical scaling of the effect of Δ.

$$\sigma_{\Delta}^{2} = C_i \cdot 10^{-(SNR_{measured} - \alpha\cdot\Delta)/10} \qquad (1)$$

The above-mentioned relationship between the elevation angle and the SNR is illustrated in figure 1. The outlined actual measurement deviates from the expected value by Δ.

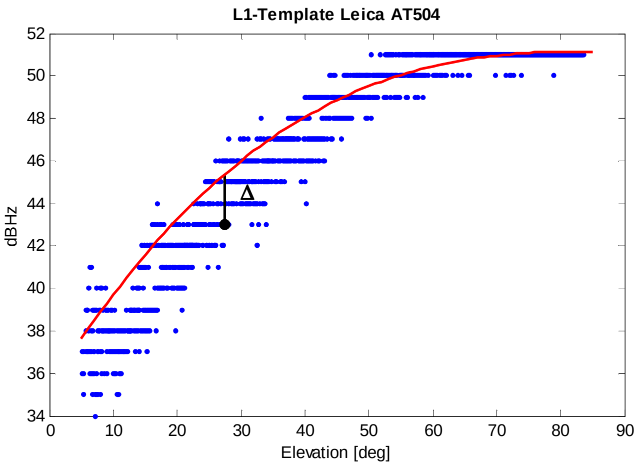

Fig. 1. SNR characteristics of the Leica AT504 choke ring antenna.

To make use of the advantages of the SIGMA-DELTA weighting model for real-time applications as well as for post-processing applications, templates would be necessary for each antenna/receiver combination. But there are more aggravating factors, which make it difficult to provide standard templates for different antenna/receiver combinations. It is not only the antenna and the combination of antenna/receiver which influences the SNR characteristics, but even the attenuation of the coaxial cable between the antenna and receiver effects the SNR patterns. The relationship between antenna, cable and sensor is described in the next section. Apart from hardware specific parameters the location where the antenna is mounted can also influence the SNR patterns. Similar to antenna phase center (PCV) correction files, which are needed to model the phase center variations, the template information of the SNR characteristics would have to be available on the sensor for all used antennas. This would result in an additional logistic effort on the manufacturer's side as well as a deep technical understanding on the customer's side.

The handling of the whole equipment would become quite complicated, if all these factors had to be observed. In order to keep the use of real-time GPS for surveying type applications as simple as they are today, but nevertheless profit from an advanced weighting model, a study of an improved observation modeling was carried out. Two self-calibrating models will be described, which automatically adjust the SNR templates according to the antenna-receiver setup and according to the predominant conditions on the chosen location.

ATTENUATION EFFECTS

NOISE FIGURE OF THE ENTIRE SYSTEM

Apart from multipath, the total noise figure of the whole system determines the amount of noise being added to the incoming signal. If the signal strength is expressed in dB there is a simple relationship between the signal strength of the incoming signal and the total noise figure of the system, which is obtained by simply subtracting those figures. Figure 2 illustrates how the noise figure can be used to calculate the SNR at the output port from the noise figure and the SNR at the input port.

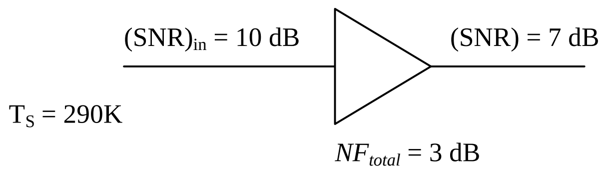

Fig. 2. Noise figure example

The total noise figure of the system NF_{total} itself comprises of the noise figure of the antenna NF_{Ant} and the noise figure of the sensor NF_{SR} divided by the antenna gain G_{Ant}. Figure 3 and equation 2 illustrate this relationship.

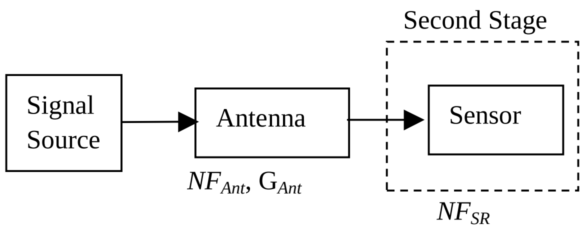

Fig. 3. Second stage noise figure

$$NF_{total} = NF_{Ant} + \frac{NF_{SR} - 1}{G_{Ant}} \qquad (2)$$

Influence of the Antenna Cable

As mentioned in the introduction even the cable length may influence the SNR measured by the sensor. The general understanding that the resistance of the antenna cable attenuates the actual GPS-signal and the noise by the same amount and therefore does not influence the derived SNR is only true to a certain extent. The impedance of the antenna cable directly influences the gain at the sensor input. A small overall gain value results in a higher influence of the noise figure of the sensor and consequently the total noise figure of the system is increased. Figure 4 illustrates the attenuation in dependence on frequency of a commonly used RG223 antenna cable. The unit of the attenuation in this figure is dB/100m. To derive the attenuation e.g. for a 10m cable, the value of the table has simply to be divided by 10, because of the linear relationship between attenuation and cable length.

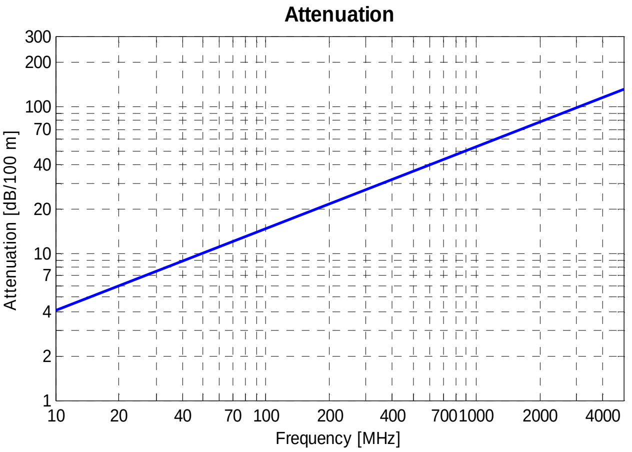

Fig. 4. Attenuation values of a double screened antenna cable (RG 223) at 20°C.

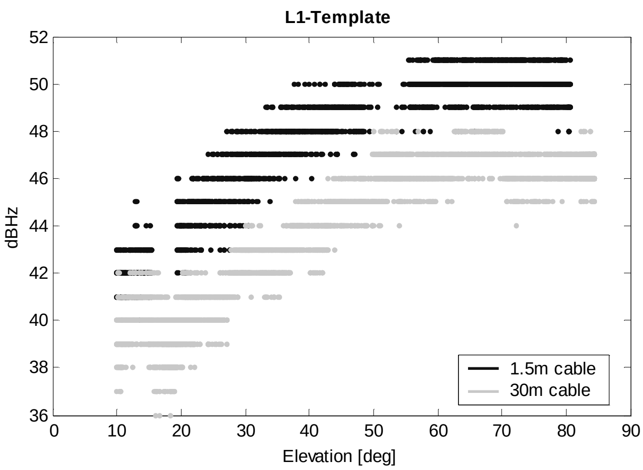

Fig. 5. SNR scatter diagram with a 1.5m antenna cable and with a 30m antenna cable.

The derived SNR in the sensor does not exactly follow the linear behavior of equation 1. Providing the gain at the sensor input is above a certain value (dependent on the receiver), there will be little difference seen in the SNRs when using different antenna cables with different attenuation characteristics. But if the gain at the receiver input is low, long antenna cables will influence the derived SNR by almost 1:1. This means that at a certain gain level a further attenuation of 1dB from the cable will additionally influence the SNR by 1dB. Such behavior is illustrated by figure 5, where the SNR scatter diagram of a 30m long antenna cable with high attenuation is plotted versus a 1.5m long antenna cable. As clearly seen in figure 5, one rigid SNR template used for all setups cannot cover all combinations.

Improved Stochastic Modeling

The Weighting Model

Observations at low elevations are much more corrupted by tropospheric and ionospheric refraction and multipath effects than those at high elevations. The systematic errors which cannot be modeled increase the root mean square value of the GPS-processing. In order to optimize the usage of low-elevation observations, elevation dependent weighting of the observations has become a standard in all real-time and post-processing software packages.

The improved weighting model, worked out for this study, is a combination between Leica's standard elevation dependent weighting model and the use of the difference Δ between the expected true SNR and the actual SNR. The question arises how to combine the elevation dependent weighting model with the information Δ. Empirical tests resulted in an exponential relationship between phase variance and SNR. This exponential relationship between SNRs and the residuals of a diffracted satellite can be seen in figure 6. The exponential relationship is described in detail by e.g. Ward (1996).

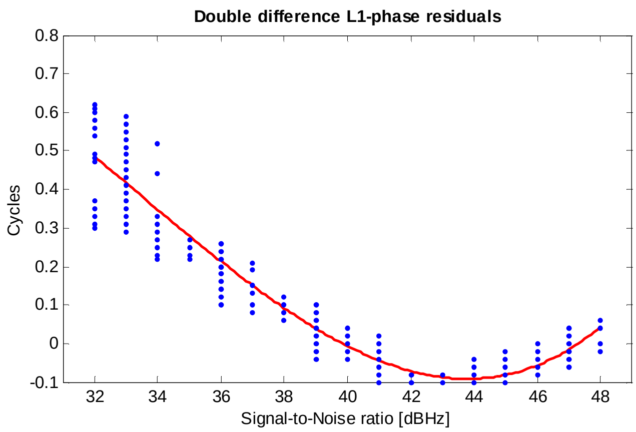

Fig. 6. Example of the relationship between L1-phase residuals of a diffracted satellite and the SNR.

$$\sigma_i^{\ 2} = \sigma_o^{\ 2} \cdot \left[\mathrm{F}(z) \cdot \alpha^{\Delta} \right]^2 \tag{3}$$

Equation 3 describes how the a priori standard deviations are derived in our studies. The term F(z) stands for Leica's standard elevation dependent weighting model, where z is the zenith angle. The factor α is a scale factor less or equal to one and Δ is the difference between the measured SNR and the template value at the appropriate satellite elevation. In addition to the weighting function, a limit of the maximum allowed difference Δ between the actual SNR and the template value can be set. If the computed value Δ of a certain observation exceeds this limit, this observation will not be used for processing.

Automatic Calibration of Templates

Returning to the problem that the correct template for the corresponding antenna-receiver combination has to be available to make use of the benefits of our modified weighting model. As mentioned in the introduction, this problem would be similar to the problem of providing the correct PCV calibration files for the antennas. Although the matching of all standard antennas is done automatically in Leica's post processing software SKI-Pro and PCV-files can be downloaded from the internet and directly imported into SKI-Pro, Leica has found many errors are still made by the user. The automated generation or adjustment of an SNR template during processing is the only way to avoid complication on the user's side, who would otherwise have to ensure that the correct template is provided. As may be imagined the additional logistic effort of providing templates for a weighting model for all possible antenna/receiver combinations would be huge and is the main reason that similar weighting models have not yet been implemented in commercial GPS processing software packages.

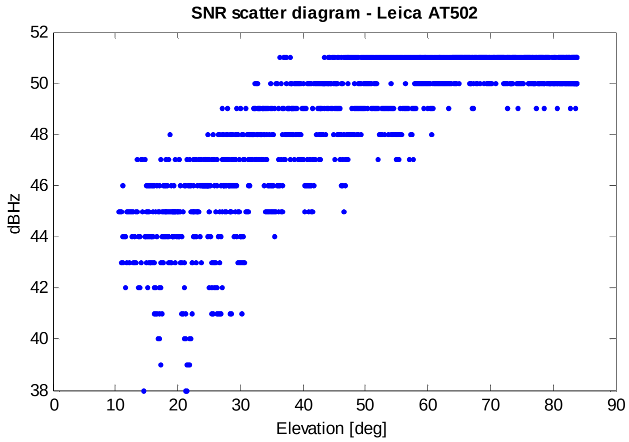

Fig. 7. SNR characteristics of the Leica AT502 antenna.

To point out the differences of templates of various antenna models we compare the scatter diagram of figure 1 with the scatter diagram of figure 7. A distinct difference can be recognized in the slope of the template, but also the points at which the signal strengths become almost constant vary. Looking at only these two examples we experience, again, that only one standard template would not fulfill the needs for the self-calibrating SNR weighting model. In the next two sections two different approaches are described which show how templates are generated.

Template generation – Method I

Assuming that a sufficient amount of data has been collected, a purely statistical method can be implemented. The generation of the template is done in discrete steps, by counting the number of SNR measurements falling into a certain signal strength interval. This is done for each elevation interval at an interval width of a few degrees. The interval width can be adjusted. Figure 8 illustrates the counted SNR measurements for elevation angles between 30° and 35°. As to be expected, the majority of counts are concentrating on some classes where the most, presumably good, observations were collected. Observations with SNR values further away from this cluster, one would want to down-weight or even exclude in the data processing, since these observations will probably show higher deviation from the truth. To derive the representative SNR, used as the template value during the calculations later, for such an interval, the median count value of all SNRs within the defined interval plus an additional correction is computed (see figure 9).

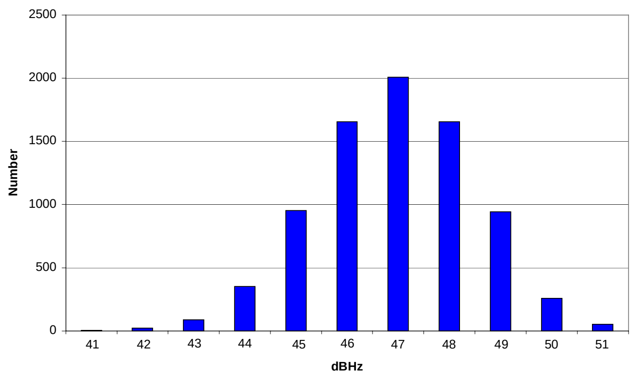

Fig. 8. Example of a statistic of all measured SNRs of satellites between 30 and 35 degrees.

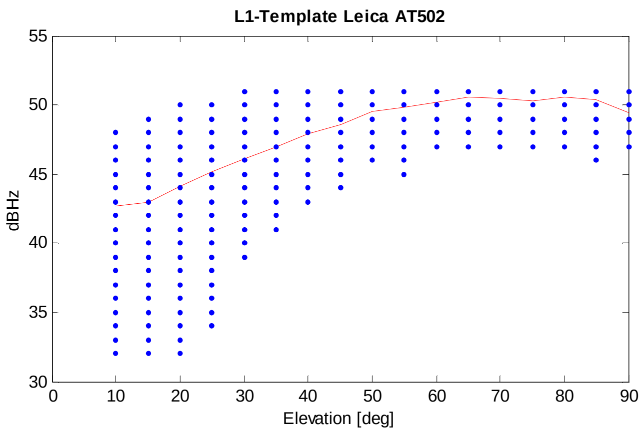

Fig. 9. Example of a template derived with method I.

During the actual calculations when an enhanced SNR weighting model is used, an observed SNR value would be compared with the derived template value in a particular elevation range. The difference between both is used then in the weighting model described in equation 3.

The method works perfectly as long as the majority of SNR values in all elevation classes are those for uncorrupted observations. This can be ensured when long observation intervals are being analyzed in post-processing or when the system was running already several hours for real-time. If not enough data is available, one problem of method I will become obvious. As long as information has only been collected for a certain elevation angle class from a diffracted satellite, the template value will reflect this diffraction. A weighting model based on that information would not down-weight the diffracted observations during processing. In some situations it may even amplify the influences of diffracted observations by down-weighting undisturbed observations.

For method I it is crucial to provide sufficient data over a long period, so that the template values would no longer change. This is clearly a disadvantage of method I and, therefore, it is more practicable for post-processing and only if a sufficient coverage of the sky is provided during the survey.

Template generation – Method II

The approach of using the median values for defined elevation intervals turned out to be not applicable for real-time surveying applications. Because GPS post-processing seems to be a dying breed for pure surveying applications, post-processing will often only be used if the real-time radio link fails. One requirement for these studies was to develop a model which is also appropriate for real-time applications.

Independent of the antenna/receiver combination, all SNR patterns show the same characteristic. Up to a certain point - the point of inflection - the SNR follows a linear curve with a positive gradient. Elevation angles larger than the point of inflection show ideally constant values. Method II is based on the observation that all analyzed SNR/elevation patterns show similar shapes for template values within the same antenna type models. Under the assumption that the principle shape of the SNR/elevation pattern does not change, a different approach can be used for the generation of a template. We describe a characteristic master template for every antenna type model by two straight lines. One line has a positive gradient and the other line is horizontal. The master template needs to be adjusted for representing the actual SNR data by finding suitable coefficients of these two straight lines. One way would be, for instance, to use a least-squares adjustment in conjunction with the statistical table generated as in method I. However, to avoid outliers having too much influence on the derived template this approach is not recommended, especially when a considerable amount of data is corrupted. The median of the residuals between the master template and the statistical table as produced for method I is calculated and the master template is shifted by this amount to reflect the actual conditions.

With this approach the amount of data being necessary to derive a template is significantly reduced and already after a few epochs of data, a representative template can be generated. Predefining the slope and the elevation angle of the point of inflection for different antenna types is advantageous for short observations, especially when diffracted signals would influence the gradient of the template.

For static surveys all SNRs of all satellites are retained and used to generate the template. Over time the values would approximately converge to template values as being derived with method I. For kinematic applications a so called ring buffer is advantageous. Such a ring buffer stores the relevant SNR information only for a certain period of time and permanently updates the template.

TEST RESULTS

KINEMATIC TESTS ON TSING MA BRIDGE

Hong Kong's Tsing Ma Bridge (see figure 10) is the world's largest span suspension bridge with 1,377 meters across the Ma Wan shipping channel. A real-time kinematic GPS monitoring system was installed to provide the centimeter-level accuracy to detect bridge movements beyond normal ranges, Wong (2001).

Fig. 10. Tsing Ma Bridge (Hong Kong)

The trigger for the studies to integrate the SNR dependency in Leica's weighting model function was the analysis of problematic data of this monitoring application. Always at the same time of the day peaks in the height components were noticed. These peaks are highly correlated with an abnormal decrease (figure 11) of the signal strength of one satellite in each case. One example of these unexpected drops in the SNR is given by figure 11.

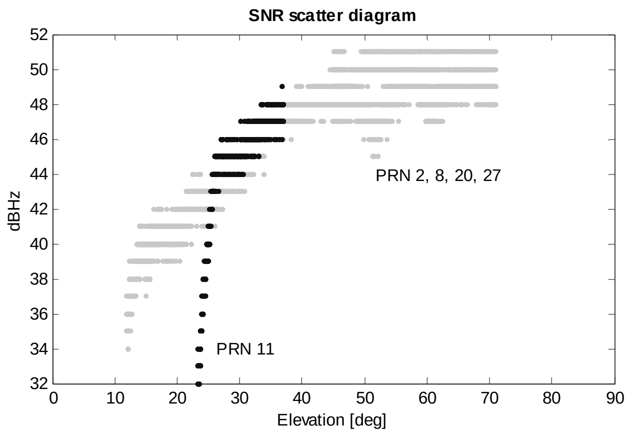

Fig. 11. Example of an abnormal decrease of the signal strength of satellite 11.

The correlation between double difference L1-phase residuals and the measured SNRs is illustrated by figure 12. The double difference L1-phase residuals are computed with reference to satellite 2, a satellite with a large elevation angle. The extremely high and unexpected drop in the signal strength of satellite 11 coincides with an increase of the residuals of satellite 11. Satellite 11 has still a relatively moderate elevation angle of more than 20 degrees when the satellite signal is distorted and the SNR immediately goes down. According to the template the signal strength should be about 46dBHz at an elevation angle of 20° in an undisturbed environment.

The benefit of using the enhanced SNR weighting model, which reflects the stochastic of the observations much better, can be clearly seen in figure 13. The top row of figure 13 was created by using a standard processing scheme without an additional phase check. By using the enhanced SNR weighting model the observations of the diffracted satellite PRN 11 are down-weighted and the improved result is illustrated by the middle row of figure 13. To generate the SNR template method II was used, which has been explained in the previous section. If method I were applied, exactly the same results would be produced provided there is enough information to generate an appropriate template. In this case about one hour of data would be necessary to have a sufficient coverage of the sky. For processing, the scale factor α in equation 3 was set to 1.1 and the maximum deviation from the template value to eliminate single satellites was 5dBHz. The diffraction effect on the height component is completely removed and additionally the a posteriori rms is reduced from 3.1mm to 2.9mm. The diffraction effect on horizontal components is in most cases not as severe. In addition to the improvement of the positioning accuracy, the ambiguity fixing process is considerably supported, if the stochastic model fits the truth more realistically.

The bottom row of figure 13 shows the height component over a period of nine hours. The light-gray curve is computed by using the standard elevation dependent weighting model and the black curve is derived by using the enhanced SNR weighting model. Every time a satellite comes close to an area between 23 and 25 degrees of elevation and between 38 and 40 degrees of azimuth, peaks repeatedly appear in the height component in the light-gray curve, whereas the black curve is not influenced by these diffraction effects. It is important here to distinguish between multipath and diffraction, where the effects analyzed here are diffraction effects and not caused by multipath.

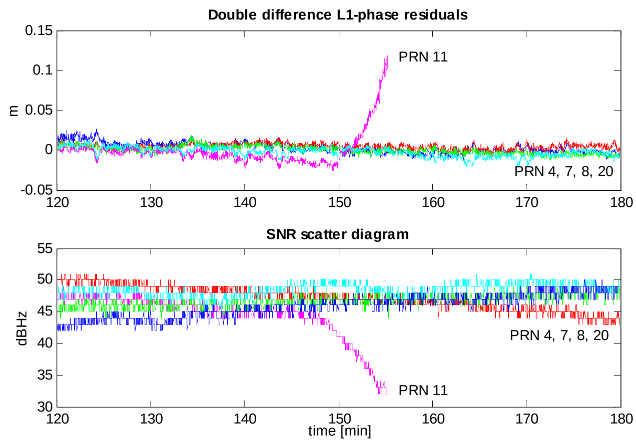

Fig. 12. Correlation between double difference L1-phase residuals of a diffracted satellite and the SNRs of the same satellite.

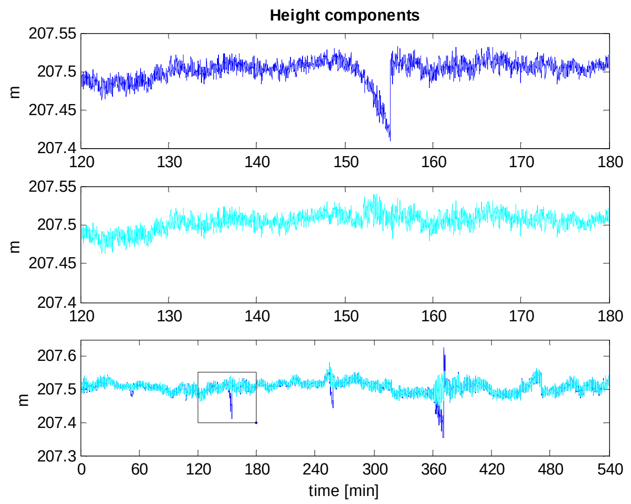

Fig. 13. *Top row* Standard elevation dependent weighting. *Middle row* Improved weighting model. *Bottom row* Elevation dependent weighting model versus improved weighting model over a period of nine hours.

It has to be noted, pseudorange multipath and carrier phase multipath behave very much the same, except that the variation of the pseudorange multipath is in phase with the variation of the SNR variations whereas for the carrier phase multipath there is a phase shift of $\pi/2$, Braasch (1996). A phase shift of $\pi/2$ cannot be recognized in the example data and is an indication that multipath is not the reason for the peaks in height. Furthermore, the enhanced SNR weighting model may have a counterproductive effect in the existence of true, pure phase multipath.

STATIC TESTS

Further static testing was performed on the roof of a Leica building in Heerbrugg. The rover station was set up very close to a lift shaft, which can be seen in figure 14. The reference was placed only 20 m away, but not masked below an elevation angle of 15° and the observation duration was 4 hours. Exactly the same effects will be observed as before if the data are processed in a kinematic mode. Every time when a satellite signal is partially obstructed by the lift shaft, this signal influences the kinematic position to such an extent that a peak of up to 4cm in the height component can be seen (see figure 15).

Fig. 14. Rover station in multipath environment.

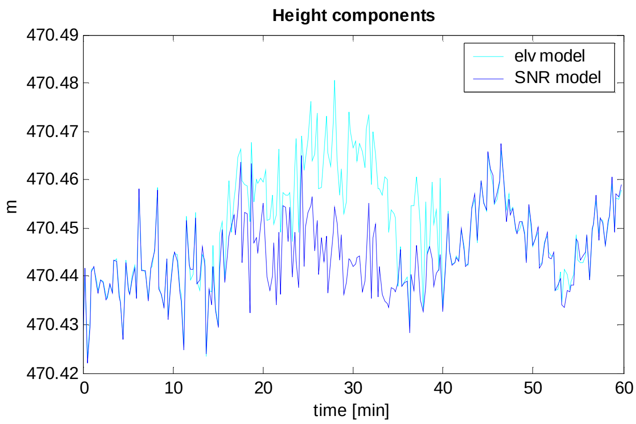

Fig. 15. Elevation dependent weighting model versus improved weighting model over a period of 1 hour.

It is obvious that also static applications would benefit from a more suitable stochastic model. The rms a posteriori is an precision indicator of how good the stochastic model reflects the reality. In our example the rms is reduced considerably from 3.2mm to 1.2mm, when applying the improved weighting model. Again both methods of generating templates were used and delivered the same results (see table 1).

Weighting model	Rms [mm]
Standard	3.2
Improved weighting model (method I)	1.2
Improved weighting model (method II)	1.2

Table 1. Rms values of different weighting models

CONCLUSION

Signal diffraction is a dominant technical problem in the widespread use of GPS in real-time operations for general surveying and monitoring applications. Diffraction is difficult to avoid when using GPS in a real world environment. The efficiency of using weighting models which make use of the measured SNR has been proved several times, e.g. Hartinger (1998). Errors caused by diffraction can be reduced by more than 50% with this method. Instead of manually excluding satellites from the processing run, the weighting model automatically detects diffracted satellites by analyzing the SNR.

This study showed the conceptual realization of integrating an enhanced SNR weighting model into commercial processing software. The described weighting model is similar to the SIGMA-DELTA model. The phase noise is computed by using the elevation angle, but additionally diffracted signals will be further down weighted if the measured SNR deviates significantly from the expected SNR. The expected SNRs as used for calculations are defined by templates. The main reason that similar models have not yet been implemented in commercial GPS processing software packages is that the logistic effort of providing templates for all possible antenna/receiver combinations would be enormous. This problem would be similar to the problem of providing the correct PCV-files for the antennas, where Leica has found many errors are still made by the user. The solution to overcome this problem is a self-calibrating weighting model which updates the used templates according to the predominant conditions.

The test results proved the effectiveness of such a weighting model to reduce signal diffraction effects. Independent of the antenna/receiver setup the model is self-calibrating. This means no user input would be required, but the user would still benefit from a weighting model that fits the truth more realistically in cases when satellite signals are diffracted.

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