How to Deal With Station Dependent Errors – New Developments of the Absolute Field Calibration of PCV and Phase-Multipath With a Precise Robot[1]

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BIOGRAPHY

Dr. Günter Seeber has been Professor at the Institut für Erdmessung, Universität Hannover since 1973, where he teaches satellite geodesy, geodetic astronomy and marine geodesy. He has specialized in satellite positioning techniques since 1969 and has published several scientific papers and books in the field of satellite and marine geodesy.

Volker Böder and Falko Menge received their Dipl.-Ing. in Geodesy from the Universität Hannover and are currently employed as research associates in satellite positioning at the Institut für Erdmessung. Their current project concerns the GPS antenna and multipath calibration.

Dr. Gerhard Wübbena received his degrees in Geodesy from the Universität Hannover. He has worked in the field of GPS since 1983 and developed the program system GEONAP. In 1990 he founded the company Geo++®, which develops satellite navigation and positioning software and systems. Dr. Martin Schmitz also received his degrees in Geodesy from the Universität Hannover. Present projects are i.e. active reference networks for highly precise RTK phase positioning (GNSMART) and the GPS station calibration project.

ABSTRACT

It has already been shown, that the absolute field calibration of GPS antenna phase center variations (PCV) with a precisely calibrated robot yields results with high accuracy and repeatability. Precise station independent absolute PCV are obtained. Many examples for different antenna types underline the high resolution in elevation and azimuth. It can be expected, that also IGS will switch to absolute PCV in a foreseeable period of time.

The precision of the PCV enables a separation from the multipath (MP) errors. For active reference station networks, also providing real-time corrections, carrier phase multipath is an urgent field of research, since its periodic character also influences the correct

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instantaneous ambiguity resolution and the real time kinematic (RTK) positioning. Different scenarios from reduction to estimation are conceivable how to deal with this error term using a robot. The most recent developments of this approach and options for further research will be presented.

INTRODUCTION

There have been considerable advances in the development of hard- and software, algorithms and methods for highly precise position determination at the (sub-)cm-level during the last years. Precise applications with cm-accuracy using carrier phase observations became an everyday work, even for larger networks. Current research is focused on the final frontier, the 1 mm level. Additionally, one strives for accurate and reliable results not only in local applications or by using long-term observations. This is also aimed for GPS measurements inside of larger networks and for very short observation times, e.g. for real time kinematic (RTK). Developments of algorithms for the modeling of distance dependent errors (atmosphere, orbit) in active reference networks already yielded much more accurate, reliable and faster ambiguity and consequently position solutions *(Wübbena* and *Willgalis 2001)*. Still, the knowledge of the systematic station dependent effects PCV and multipath is essential in order to separate all different error components. Only this procedure allows the precise estimation of each error and the decorrelation of effects as for example between troposphere, PCV and height.

The PCV as inherent antenna effects have to be estimated free of other effects like multipath. They should describe the undisturbed phase receiving behavior and therefore represent the best possible and independent antenna correction for any application and environment. The absolute field calibration of GPS antennas *(*e.g. *Wübbena et al. 2000)* marked a step forward towards station independent PCV with a higher resolution. Consequently, carrier phase multipath remains as the main station dependent error term. New techniques and models are required in order to reduce or remove this systematic error. A precise estimation at the aimed 1 mm level for the original L_1/L_2 GPS signals is only achievable, if one succeeds in the separation of all components within the whole error budget. A new development of this group - combining the use of a robot, absolute PCV results and a special measurement procedure on a short baseline - will show the recent improvements in estimating range corrections for carrier phase multipath of the original GPS signals in an absolute sense.

THE MULTIPATH PROBLEM

The multipath error on the received signal, as the composition of direct and reflected signals, affects both code and carrier phase measurements, as well as the signal's amplitude. The actual effects depend on the changing satellite-reflector-antenna geometry, the signal's strength, the reflector (e.g. material, size, surface) and the used hard- and software (antenna, receiver technology). It is a station dependent error, affecting each GPS station individually and therefore does not cancel out in observation differences. The effects on the code measurements are at the dm-m level, whereas the carrier phase error may vary at the mm-cm level. Multipath shows high-frequency and low-frequency features. In case of a static receiver, the changing reflector geometry due to the moving satellite produces multipath periods in the order of hours for a short distance between antenna and reflector (< 1 m). For longer reflector distances of several meter one yields periods in the order of minutes. In contrary to code multipath and the signal's amplitude (signal to noise SNR), carrier phase multipath is zero-mean.

The carrier phase multipath error is described in equation (1). Just as a brief background and since for highly precise applications we are especially interested in a distance correction for the carrier phase measurements. For a single reflector one yields the well known formula of the phase difference between the composite signal carrier and the direct signal with the carrier wavelength λ *(*e.g. *Georgiadou* and *Kleusberg 1988)*

$$\psi = \arctan \frac{\alpha \cdot \sin(\theta)}{1 + \alpha \cdot \cos(\theta)} . \tag{1}$$

The differential phase delay

$$\theta = \frac{2\pi}{\lambda} \cdot d ,$$

is a function of the actual reflector geometry, namely the differential path delay d of the reflected signal. The reflection coefficient α, defined by the ratio of direct signal amplitude to reflected signal amplitude, varies between 0 and 1. With a reflection coefficient of 1, representing a theoretical zero attenuation, the maximum carrier phase error due to multipath can reach 4.7 cm for L_1 and 6.1 cm for L_2.

Several techniques can be used for the reduction or mitigation of multipath effects. Before the receiver's signal processing, antenna-based mitigation - beside a careful site selection and antenna location - is feasible. This first group comprises different antenna constructions and features as for example special ground planes (shape, material, surface), choke rings, axial ratio design concerning the rejection of left-handed circular polarized (LHCP) signals, low gain or even a gain cut-off at low elevation angles, the use of antenna arrays etc. Carrier phase multipath occuring from ground reflections and coming from directions in low elevations can be reduced quite effectively with these methods. Still, antenna construction is always a compromise between an ideal signal reception over the whole hemisphere and the actual characteristics and performance in order to encounter multipath and other signal disturbances.

Developments for improved receiver technology and signal processing mainly concentrate on the mitigation of code multipath with enhanced correlator techniques, e.g. Narrow Correlator *(Van Dierendonck et al. 1992)*, MEDLL-technique *(Townsend et al. 1995)*, Strobe Correlator *(Garin and Rousseau 1997)* etc. A separation of direct and reflected signals with these on-receiver techniques is only possible for quite long differential path delays (e.g. 10 m and more). Problems arise to reduce multipath with short path delays. But especially carrier phase multipath may have its maxima in this situation. The carrier phase smoothing of code observations is also a sort of multipath reduction, which can be done outside the receiver as well. Combined procedures using special antenna arrays together with digital signal processing help to reduce - code and carrier phase - multipath signals (e.g. *Brown 2001)*. A few examples of course cannot nearly give a complete overview about existing procedures. The mentioned examples should underline that a large part of the methods concern the avoiding and reduction of code multipath.

Nevertheless, having the observations at hand after the signal processing in the receiver, post-reception data processing of code, phase and amplitude (SNR) measurements can help to mitigate multipath effects, also carrier phase multipath. Here, one can find attempts not only for reduction but as well for the calibration of remaining carrier phase multipath. Multipath is a dominant error source for highly precise geodetic applications, e.g. RTK using network corrections, and it characterizes the actual situation within active reference networks. Of course, it is intended to use up-to-date equipment and the most sophisticated geodetic receiver units. Great attention is paid to the location of the antenna. Still, very often one has to use sites on roofs with its unfavorable multipath environments. Even with sophisticated antenna and receiver technology, carrier phase multipath cannot be avoided. Long term observations in order to average the periodic multipath effects or even the very effective use of daytime differences for highly precise geodynamic or deformation monitoring *(Seeber et al. 1998, Wübbena et al. 2001)* are not suitable tools for active reference stations providing carrier phase corrections. The same statement is of course applicable for post-processing observations, especially for short time measurements. The direction dependent geometrical error on the distance measurements has to be calibrated.

Already encouraging carrier phase multipath calibration procedures have been examined and developed by other groups. *Comp* and *Axelrad (1996)* use spectral parameters of the multipath in the SNR in order to derive carrier phase corrections. The correlation of multipath errors between multiple closely-spaced antennas is the basis for carrier phase corrections estimated in a filter algorithm by *Ray (2000)*. Short baseline tests by *Ge et al. (2000)* showed the possibilities of a real-time adaptive filter model for differential carrier phase corrections. Also data from regional networks themselves have been used for the estimation of carrier phase multipath *(Wanninger* and *May 2000)*. An antenna multipath calibration system (AMCS) using a parabolic reflector radio antenna with high directivity is currently tested at UNAVCO *(Davis et al. 1999)*. These examples confirm that there exist already several approaches or ideas for carrier phase multipath calibration. Still, some restrictions in the before mentioned approaches limit their use as universal and operational instruments for highly precise applications. Some of these restricting factors within different approaches are e.g. assumptions about gain and PCV pattern of antennas, about the reference site multipath situation (reflectors, multipath-free satellites or elevation masks), the limitation on corrections for linear combinations (i.e. ionospheric corrected signal L_0) due to other station and distance dependent errors, problems with high frequency multipath, the limitation on relative or differential corrections. As already mentioned, a desirable solution would be an operational approach, which can reliably estimate absolute carrier phase multipath of the original GPS signals at the 1 mm-level wherever it is needed. We want to come closer to this goal with a new absolute approach using a moving robot.

ABSOLUTE PCV CALIBRATION

A prerequisite for the new approach is the separation of PCV and multipath. During the last years, the absolute field calibration of GPS antenna's PCV has been developed into an operational and highly precise real-time procedure using a calibrated robot (*Wübbena et al. 1997*, *Menge et al. 1998*, *Wübbena et al. 2000)*.

Fig. 1: Absolute field calibration of PCV with a robot.

The real-time calibration approach separates multipath effects from the PCV. Additionally, thousands of rotations and tilts of the robot lead to a complete and redundant covering of the antenna's hemisphere with observations. This enables the estimation of elevation and azimuth dependent and high resolution PCV corrections, even down to the antenna horizon. Independent comparisons of the results by other groups with relative (e.g. *Mader 2001)* as well as with absolute PCV from chamber measurements *(e.g. Rothacher 2001)* confirm the quality of the procedure. The utilizability of these PCV as an absolute reference is accepted by the International GPS Service (IGS), although there arises - compared to processing with relative PCV - a scale factor of about 0.015 ppm while using absolute PCV. That is why global network solutions still do not take the absolute corrections into account. Since there are no more doubts about the correctness of absolute PCV, confirmed in several tests and comparisons, the more or less unknown phase center behavior of the satellites remains as an explanation. Currently, the satellite antenna's PCV are investigated in field calibrations *(Mader* and *Czopek 2001).*

Applying individual absolute PCV corrections allows us to separate antenna and multipath errors. Thus, it is possible to study the absolute multipath effect of one station without summing up station dependent errors.

MULTIPATH DECORRELATION WITH A MOVING ROBOT

The general idea for the development of a calibration procedure is the use of a moving robot with precisely known positions in order to remove the systematic multipath effects on that particular station. A quite reasonable explanation would be that the moving robot's purpose is to randomize or noisify multipath.

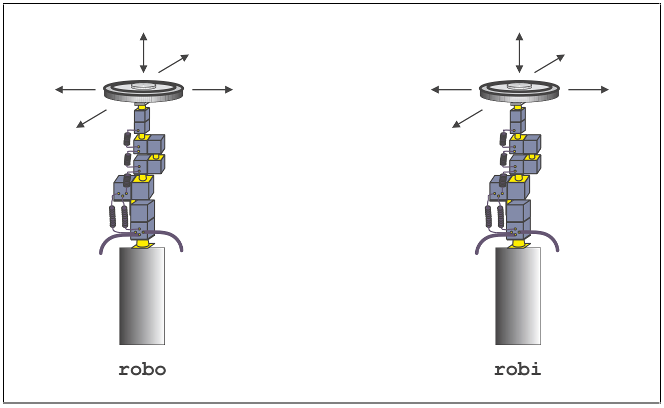

Fig. 2: Principle for the reduction of multipath effects with two moving robots.

The robot is in a continuous but (pseudo-)random motion with a range of up to +/- 2 wavelengths in all directions from a center position (zero- or starting point). Absolute PCV are always applied individually. For the first tests the antenna always remained horizontal and directed to north during short static periods in order to take measurements. The exact coordinates of the antenna are always known. The known position components are used to reduce (centering) the observations back to the reference marker. The centered observations then are comparable to the observations of a static antenna but are free of systematic multipath effects due to the kinematic robot. With the moving antenna these effects turn nearly into a random error. The phase measurements for each antenna position comprise different multipath effects because of the permanently changing geometry between antenna, reflector and satellite. Antenna position changes of more than one wavelength between the measurements can even alter the sign of the multipath error. Thus, the periodic character of a particular multipath geometry cannot affect the observations. It only remains a higher noise level. One has to emphasize again that of course there is still multipath. But the systematic characteristics disappear with the fast position and therefore geometry changes. The multipath errors between all epochs are decorrelated (see equation (2), next paragraph). The resulting high frequent signals are almost noise. Still, the amplitude level is higher and dependent on the original multipath signal's amplitudes.

Fig. 3: GPS measurements with two moving robots.

Simulated carrier phase multipath errors based on equation (1) confirm the above stated changes of the original signal due to the motion of an antenna (figure 4). The top graph shows a simulated carrier phase multipath signal for the L_1-signal, using a distance of 20 m between antenna and a single reflector. A particular satellite motion is taken into account. The reflection coefficient was set to a value of 0.75. The original phase noise is neglected. In case of a linear motion of the antenna towards the reflector, the original periodic signal becomes - in dependence on the velocity - very high frequent. With a circular motion (third graph), one can see remaining systematic effects, because of only small changes in the differential path delay for subsequent geometry situations. The graph at the bottom shows the altered signal due to an original robot motion, with (pseudo-)random position changes in a 3D-space of +/- 2 wavelengths for each epoch. This is almost the real measurement situation and underlines the principle of multipath decorrelation.

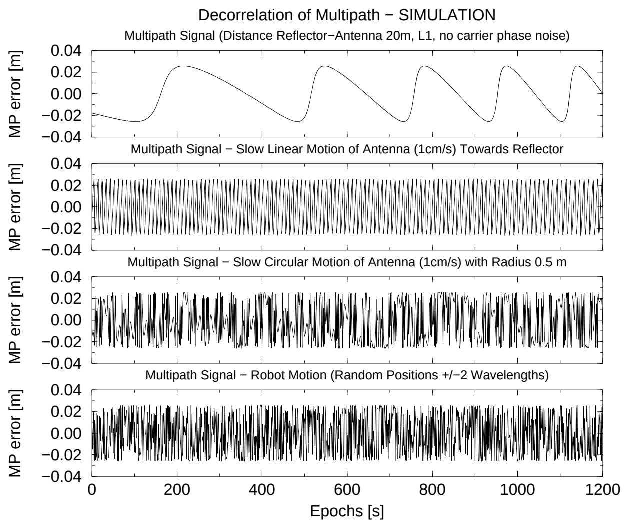

Fig. 4: Simulation for decorrelation of multipath due to an antenna in motion (original carrier phase noise neglected).

The first multipath decorrelation or reduction tests comprised the observations of two Ashtech choke ring antennas (ASH700936) on two moving robots with different motions. The distance between the pillars was about 8 m. In order to prove the multipath reduction, we used two robots. Therefore, no assumption about multipath on a second station is necessary. During the kinematic mode of the two robots, multipath on both stations will be decorrelated. The systematic behavior of multipath should be eliminated.

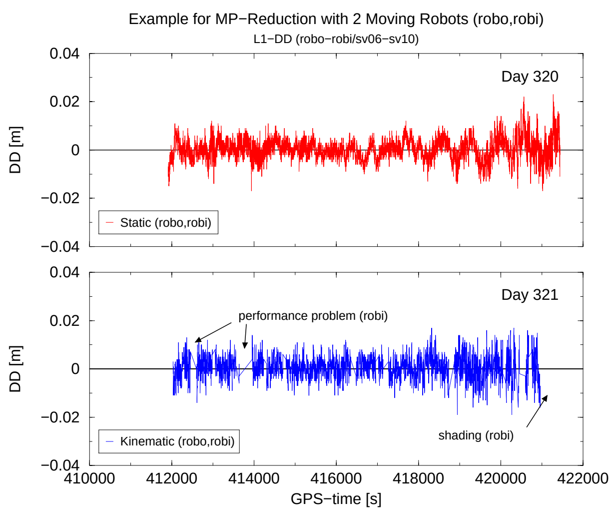

Fig. 5: Multipath decorrelation with two moving robots. Example for Double Differences DD of static and moving antennas, L_1-signal.

As already indicated above, the procedure has to be improved with a synchronization between the position determination of the robot and the GPS measurements. The current hard- and software does not allow permanent precise robot position determinations for each epoch during dynamics. Short static periods with one or two measurement epochs had to be used. Nevertheless, the double difference (DD) time series in figure 5 as one example clearly confirms the assumptions and the simulations for the decorrelation of multipath in a real experiment with a fast moving robot. The DD residuals on two static robots show - especially at the end of the time series - periodic behavior due to multipath. All other GPS errors can be excluded as explanation. Having both robots in motion, the residuals - after centering to the static zero-position - are nearly free of any systematics, only the noise level is increased. A further confirmation is given with the statistics in table 1. The standard deviation for DD does not change significantly between the static and the kinematic data, since the increased noise of the two kinematic stations is summed up. But it is obvious from the numbers that the systematic effects are highly reduced. The improvement is visible after the calculation of a moving average for the DD.

Tab. 1: Examples for noise reduction after multipath elimination with moving robots. The DD standard deviations *s* for L_1 are calculated from differences to mean values. Comparisons of static and moving stations robo and robi.

		sv02-11	sv03-19	sv06-10	sv19-31
s [mm] $robo_{static} - robi_{static}$	(1)	5.2	5.4	4.3	6.3
s [mm] $robo_{kin} - robi_{kin}$	(2)	4.9	5.0	4.9	6.1
s [mm] $robo_{kin} - robi_{kin}$ (*)	(3)	2.8	2.5	2.0	2.8
MP/noise reduction [%] (1/3)	(4)	46.2	53.7	53.5	55.6

(*) moving average (60 s) of DD ($robo_{kin} - robi_{kin}$)

Time series of signal to noise SNR (better carrier to noise C/No) underline the obtained results. For the moving robot, the multipath effects are clearly reduced while a slightly increased noise level appears (figure 6).

The daytime difference between the observations - for the same two satellites used in figure 6 - with static and moving robot shows the expected result (figure 7). Due to the day-to-day repeatability of multipath, the SNR difference for the static case is only noise. The daytime difference between static and moving modes represents the multipath of the static day and the added noise. In addition, it proves that even small spatial variations of an antenna do have an effect on the SNR observable.

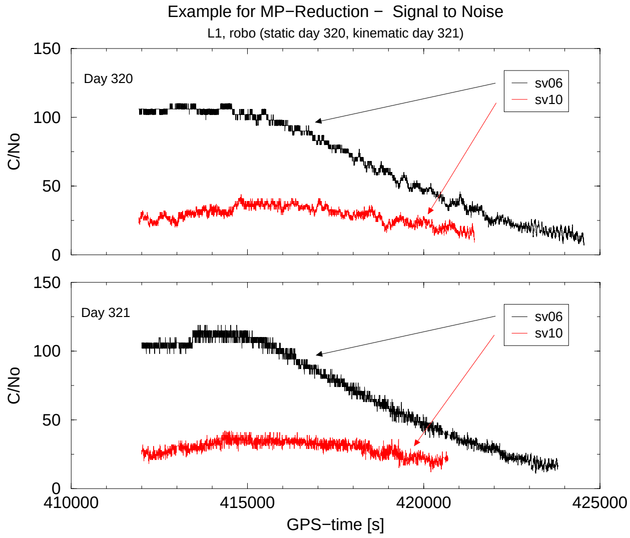

Fig. 6: Multipath decorrelation with two moving robots. Example for SNR of static and moving antennas, L_1-signal.

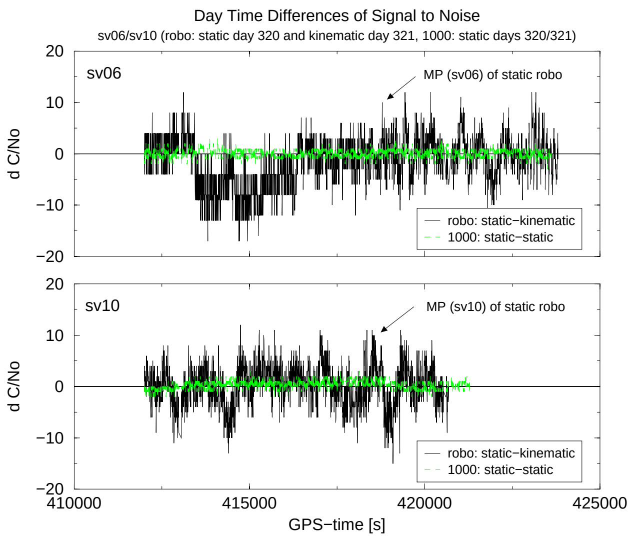

Fig. 7: Multipath decorrelation with two moving robots. Example for SNR daytime differences of static and moving antennas, L_1-signal. Small spatial variations of the antenna do have an effect on the SNR.

The above described procedure for the decorrelation of multipath from epoch to epoch, and therefore for the reduction of the systematic multipath effects with a moving antenna, serves as the basic idea for the calibration approach.

ABSOLUTE MULTIPATH CALIBRATION

As described in the previous paragraph, the systematic multipath effect is greatly reduced using a robot in motion. Thus, a robot can be in the vicinity of any reference station site on which multipath effects have to be calibrated. It then serves in a short baseline measurement as a reference, which is free of systematic multipath effects. The fixed station can be calibrated concerning multipath with the normally used antenna and equipment in its original environment (figure 8). The absolute PCV of the antennas must be known beforehand and applied during the calibration.

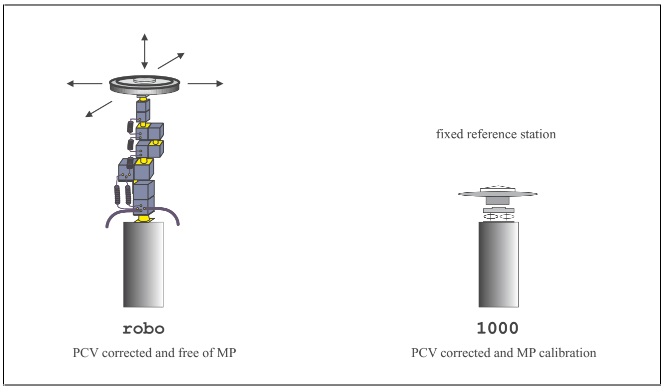

Fig. 8: Principle of multipath calibration with one moving robot.

In order to explain the changes of multipath by the described procedure, a single difference (SD) illustrates the effects clearly. The SD of the linearized observation equation (receiver *i*, *k* and satellite *j*) yields:

$$\Delta l^{\ j}_{\varphi_{i,k}} = \mathbf{a}^j_{i,k} \cdot \Delta \mathbf{x}_{i,k} + c_0 \cdot \Delta dt_{i,k} - \lambda \cdot \Delta N^j_{i,k} + (d_{MP_i}^{\ j} - d_{MP_k}^{\ j}) + \Delta\varepsilon_\Phi . \qquad (2)$$

Due to the identical conditions on a short baseline, atmospheric and orbit errors cancel out. They are not shown in the above formula. The same holds true for the removed satellite clock error and the antenna's PCV. Precise absolute PCV corrections are introduced. The coordinate difference $\triangle \mathbf{x}$, the receiver clock error difference $\triangle dt$ and the single difference ambiguities $\triangle N$ are estimated. It only remains the difference of the multipath errors $\triangle d_{MP}$. The systematic multipath error of the reference station to calibrate

$$d_{MP_i}^{\ j} = f(\sigma^2_{MP}, \tau)$$

can be described as stochastic parameter with a variance σ^2 and correlation length τ (e.g. minutes). This error will be calibrated with a suitable mathematical model. The multipath of the continuously and randomly moving robot

$$d_{MP_k}^{\ j} = f(\sigma^2_{MP(kin)}, \tau = 0)$$

does not contain systematics anymore. The correlation length is therefore zero. The multipath error of each measurement epoch is uncorrelated with the multipath error of previous and following measurement epochs. It remains noise with an increased amplitude. Staying with the SD in (2), the single difference noise $\triangle\varepsilon$ alters with

$$\sigma^2_{\Delta l_\Phi} + \sigma^2_{MP(kin)} \Rightarrow \Delta\varepsilon_{\Phi(new)}$$

due to the added "multipath noise" of the kinematic robot station. It has to be mentioned that the current procedure and a future more sophisticated mathematical model are currently implemented within the GEONAP/GNNET software package using undifferenced GPS observables.

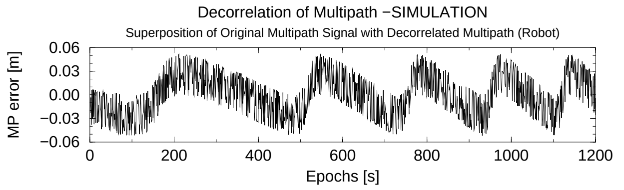

Fig. 9: Simulation for decorrelation of multipath due to a moving antenna (see figure 4). The superposition of the multipath (static) and the decorrelated multipath (robot) signals represents the signal to use for the calibration.

The simulated signal in figure 9 is equivalent to the signal, which will be used in the calibration. It depicts the superposition of the robot station's noise (decorrelated multipath, see bottom figure 4) and the multipath signal of the station to be calibrated (see top figure 4). The same signal characteristic can be seen in the results of real data in figure 10 (examples for L_1-DD). The same measurements as described before in the multipath decorrelation test with two robots were used for a calibration experiment in a quite realistic reference station environment (pillars, roof). Beside the Ashtech choke ring antenna on the robot, a Javad REGANT dual depth choke ring antenna (JPSREGANT_DD_E) worked on the station to be calibrated. This geodetic equipment should already mitigate phase multipath up to a certain amount. Elevation masks were set to zero degree. Only 14 h of observation were available due to the failure of one robot.

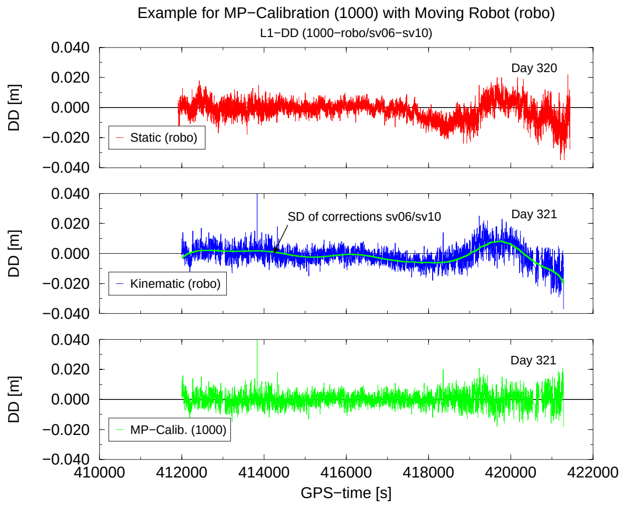

Fig. 10: Carrier phase multipath calibration of a reference station with one moving robot. Example for DD of original and multipath corrected phase data, L_1-signal.

The top graph in figure 10 shows the original DD with static observations on robot and reference station. The second graph describes the signal to use for the multipath calibration. The only difference to the graph before is the mitigation of the systematic multipath effect of the robot station due to its motion. This is a situation comparable to the simulation in figure 9. A spherical harmonic function of degree and order 20 served for the estimation of absolute carrier phase multipath corrections. The difference of the absolute corrections of the two satellites is printed over the DD time series. It fits very well to the systematic multipath behavior. The bottom graph represents the situation after the correction. The remaining DD residuals are free of the periodic variation of the station to be calibrated. The noise level remains slightly higher than normal, because of the decorrelated multipath of the robot. It should be emphasized again that absolute corrections are estimated, which are shown in figure 11. Absolute corrections (L_1) for all satellite tracks of the 14 h calibration are depicted in figure 12, which gives a good overview about amplitudes, frequencies and location of carrier phase multipath effects. For longer measurement periods, the noise of the corrections will be significantly reduced.

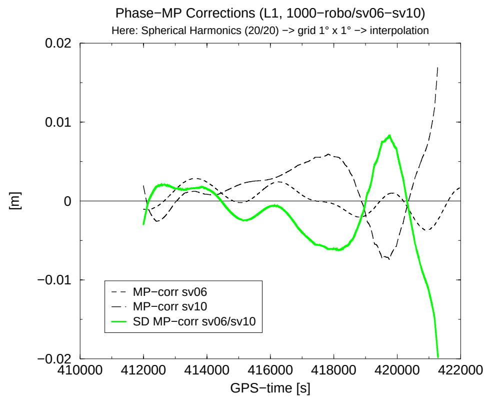

Fig. 11: Example for absolute multipath corrections.

Tab. 2: Examples for DD standard deviations *s* for L_1, calculated from differences to mean values. Reference station on robot in motion. Comparisons for station 1000 without and with MP corrections.

	sv02-11	sv03-19	sv06-10	sv19-31
s [mm] $robo_{kin}$ – 1000_{no_corr} (1)	6.9	6.9	6.7	8.2
s [mm] $robo_{kin}$ – 1000_{corr} (2)	5.2	5.6	5.2	7.2
MP-reduction [%] (1/2) (3)	24.6	18.8	22.4	12.2
s [mm] $robo_{kin}$ – $1000_{corr}^{(*)}$ (4)	2.1	2.5	1.9	3.2
MP-reduction [%] (1/4) (5)	69.6	63.8	71.6	61.0

(*) moving average (60 s) of DD ($robo_{kin}$ - 1000_{corr})

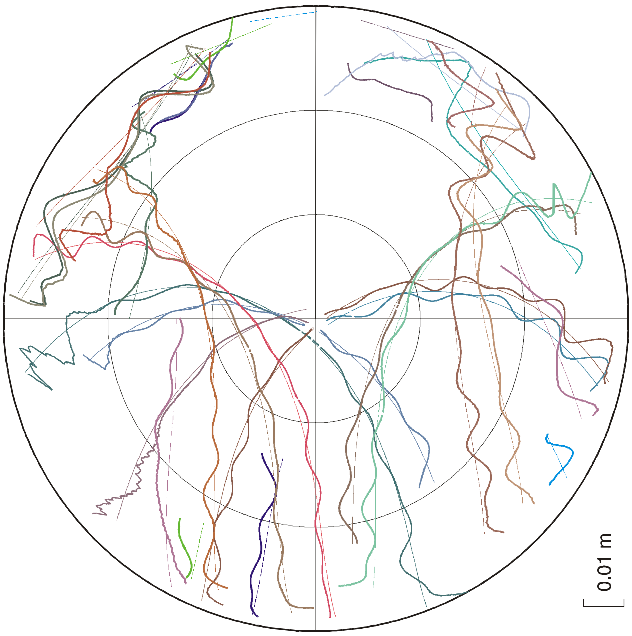

Fig. 12: Skyplot with satellite tracks and absolute carrier phase multipath corrections (L_1-signal, 14 h calibration, using spherical harmonic function).

The statistics of several DD, always with the kinematic robot station as reference, in table 2 underline the significant multipath reduction for the original GPS signals. Because of the robot station's increased noise, the reduction of the DD standard deviation is not better than 30 %. The improvement is even more obvious for a moving average of the DD time series. This is an appropriate method, because the periodical variations have already been removed. One yields enhancements in the DD of up to 70 %. The most rigorous and independent test is still a comparison of two calibrated stations without the increased noise of a moving station.

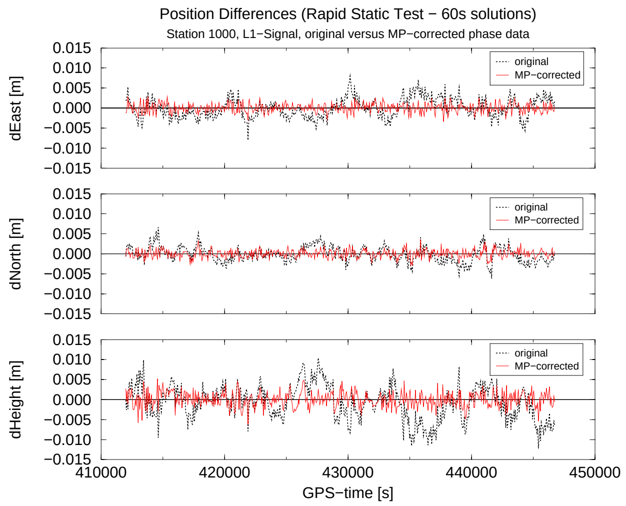

Fig. 13: Example for carrier phase multipath calibration of a reference station with one moving robot. Position differences of original versus multipath corrected phase data, rapid static solutions 60 s, L_1-signal.

Tab. 3: Standard deviations *s* (n,e,h) for L_1 (rapid static solutions 60 s for station 1000 without and with MP corrections), calculated from differences to mean values. Reference station on robot in motion.

L_1	*s* (no corr) [mm]	*s* (corr) [mm]	Improvement [%]
North	2.44	1.10	54.9
East	1.93	0.99	48.7
Height	4.29	1.87	56.4

Another criterion for the improvement is the behavior of positioning results for short time observations due to the eliminated multipath. Rapid static solutions (60 s) for L_1 and L_0 were calculated using data with and without multipath corrections in order to assess the influence on this kind of application (figure 13, figure 14). Smaller variations of the position solutions after the correction are clearly visible, especially for the height component. The statistics in table 3 and table 4 do confirm this interpretation with improvements of up to nearly 60 %. Again, it has to be mentioned that the reference station is on a moving robot. The pure effect of the calibration of one station can only be shown with this procedure. In addition, it verifies the multipath decorrelation, too.

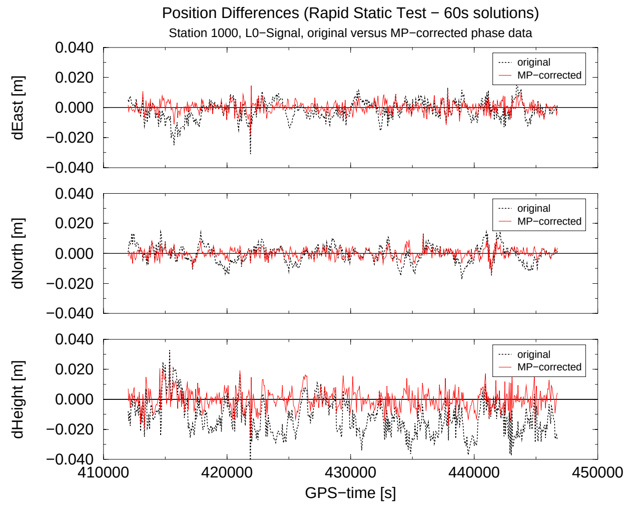

Fig. 14: Example for carrier phase multipath calibration of a reference station with one moving robot. Position differences of original versus multipath corrected phase data, rapid static solutions 60 s, L_0-signal.

Tab. 4: Standard deviations *s* (n,e,h) for L_0 (rapid static solutions 60 s for station 1000 without and with MP corrections), calculated from differences to mean values. Reference station on robot in motion.

L_0	*s* (no corr) [mm]	*s* (corr) [mm]	Improvement [%]
North	6.25	3.61	42.2
East	5.70	3.03	46.8
Height	11.44	6.73	41.2

These first tests are very promising. It is possible to separate and make the carrier phase multipath visible with the approach. No prerequisite assumptions are necessary. We are aware that the currently used mathematical model is not the best suitable for multipath corrections, especially for non-continuous multipath behavior. The spherical harmonic function served for a verification of the correct working of the procedure.

Modifications of the robot, the measurement procedure and the modeling are currently investigated. The actual implementation shows the principle functioning and already yields good results. 1-D wavelet analyses of DD (figure 15) confirm the elimination of multipath. The remaining high frequencies in the order of only some minutes are due to the not yet optimized robot motion and multipath modeling. One has to notice the changing color scale between top and bottom graph in figure 15. The amplitudes of the remaining high frequencies are certainly not increased. In contrary, the results in table 2 underline an overall reduction.

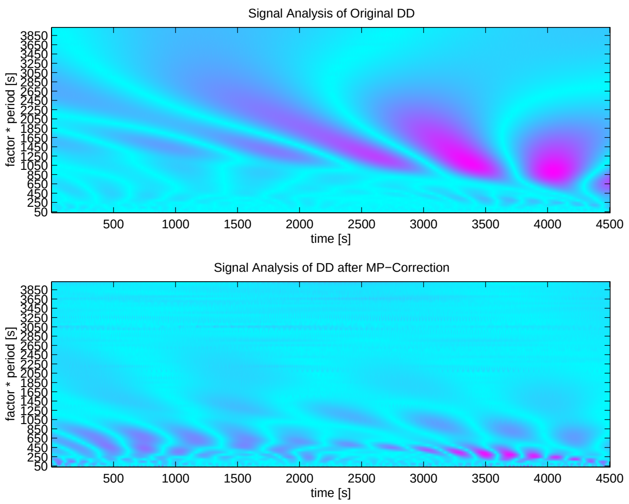

Fig. 15: 1D-wavelet analysis on DD shows remaining high frequencies after multipath corrections. The DD of figure 10 were used for the above graph.

UPCOMING DEVELOPMENTS

There are several aspects, which degrade the accuracy and resolution of the multipath corrections. We strive for an improved performance with several alteration of the procedure. Two main areas for improvements are obviously.

The first concerns the motion of the robot and the GPS measurements on the robot. This connection has to be fine-tuned. A constant motion without static periods while permanently logging GPS data should be used. Currently, several changes in hard- and software are implemented. The timing signal of the GPS receiver (pulse per second PPS) will be employed for a precise synchronized position determination of the robot. It will be used for permanent GPS observations in every measurement epoch. Each epoch then can be assigned to a precise antenna position, even though the robot is in a continuous motion. Additionally, a sophistication of the program for a pseudo-random motion will improve the procedure.

In spite of the already very promising results, a spherical harmonic function for modeling multipath is not satisfactory. First of all, it is not a very suitable model for a possibly non-continuous multipath behavior. Furthermore, the covering of the antenna’s hemisphere with multipath observations is rather poor because of the constant satellite geometry. There exist only the repeating satellite tracks and only observations down to zero degree or even higher. As already described, additional data gaps may occur. This situation is not optimal for the estimation of a spherical harmonic function. Estimated “corrections” outside the available satellite signal tracks do not represent any real multipath situation but generate large gradients. Normally, we do not need such corrections. But slightly changes in satellite constellation yield small changes in the signal’s directions, which then can cause extra- or interpolation errors. In a future modification of the approach, data gaps have to be avoided by a careful site selection and will be specially treated during the modeling. Thus, a modified mathematical multipath calibration model will improve the whole procedure.

Finally, verifications on repeatability of multipath corrections concerning small changes in satellite constellation and weather dependencies (e.g. snow) have to be examined. The results and experiences will give more information on how long and how often a station has to be calibrated.

SUMMARY AND CONCLUSIONS

Carrier phase multipath is a very important station dependent systematic error term. Its periodic behavior degrades speed, accuracy and reliability of ambiguity and position determination. This is especially valid for short time observations and RTK. The calibration problem of remaining carrier phase multipath on reference stations has not been satisfactory solved so far.

The procedure of the automated absolute field calibration of GPS antennas in real-time is currently extended into a complete absolute station calibration. Our group has presented a new method for multipath calibration. The basis for the method is a moving robot, which enables a multipath decorrelation and thus reduction on one station. While introducing absolute PCV, there are no other station dependent errors. Thus, an estimation of the multipath for a static reference station nearby is possible without changing its set-up. The only requirements for this flexible approach are the high technical constraints for the robot and the necessity for a stable robot set-up (e.g. pillar) at a local site.

The basis for the presented approach is the separation of PCV and multipath. It is possible to estimate carrier phase multipath corrections for the original L_1-, L_2-signals using local measurements (PCV and multipath as dominant errors) at the reference station site with two regular GPS receivers and antennas. Very promising first results have been shown. The procedure enables the separation of absolute carrier phase multipath without further assumptions. For an operational calibration approach, a sophisticated mathematical model will be developed.

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