Improved high-precision RTK positioning through multipath reduction and interference mitigation

Miguel GONZÁLEZ-CALVO, Xiaoguang LUO, José Amado APONTE and Bernhard RICHTER, Switzerland

Key words: GNSS RTK, multipath, interference mitigation, HDR, digital filters

SUMMARY

The rapid development of multi-frequency and multi-constellation GNSS increases the usage of high-precision RTK under challenging conditions, where the GNSS measurements are severely affected by multipath errors. The characteristics of multipath effects are highly site-specific and cannot be generally modelled. Therefore, multipath remains a dominant error source in centimetre-level differential positioning. In addition, the increasing amount of ground wireless communication infrastructure results in radio-frequency interference, which could significantly degrade GNSS tracking and positioning capabilities. To provide high-quality GNSS observations and RTK performance in harsh environments, advanced multipath reduction and interference mitigation have been integrated in the latest Leica GNSS technology. This paper demonstrates the benefits of these techniques to GNSS signal tracking and RTK positioning. The measurement domain analysis shows a significant reduction in code multipath by up to 60%, whereas considerable RTK fix availability and accuracy improvements are observed in the position domain analysis.

Improved high-precision RTK positioning through multipath reduction and interference mitigation

Miguel GONZÁLEZ-CALVO, Xiaoguang LUO, José Amado APONTE and Bernhard RICHTER, Switzerland

1. INTRODUCTION

In recent years, high-precision real time kinematic (RTK) has been used in increasingly challenging surveying environments, enabled by technological innovations in global navigation satellite systems (GNSS), receivers, and antennas. The increased number of GNSS satellites and signals, the advanced signal structure and the extended RTK applicability through sensor fusion have made high-precision GNSS positioning possible in areas which were not suited for it before, such as heavy canopy and urban canyons. Under these harsh conditions, GNSS observables are severely affected by the multipath effects, which cannot be easily described and generally modelled. In addition to the multipath error, the radio-frequency spectrum is nowadays challenging the performance of GNSS positioning due to the growing number of interference sources (e.g., radio amateurs, navigation beacons, personal privacy devices). Positioning error due to interferences is also site-specific and cannot be simply modelled and removed by the GNSS receiver.

In high-precision RTK surveys, the ability of a GNSS receiver to use multiple frequencies from multiple GNSS constellations is essential to achieve optimal positioning performance. Utilising multi-frequency observations first enables more reliable cycle-slip detection by comparing the change in phase on one frequency to the change in phase on another from one epoch to the next. Second, more sophisticated ionospheric error modelling can be achieved with multiple frequencies. In fact, the larger the difference in frequency, the larger the difference in the ionospheric delay, making the estimation of the effect more accurate. Third, based on multi-frequency data, it is more flexible to form linear combinations of phase measurements with longer effective wavelengths, allowing for ambiguity resolution with shorter convergence times and over longer baselines. Fourth, multi-frequency receivers provide better immunity to interference, for example, if there is interference in the L2 frequency band, a multi-frequency receiver will still track L1 and L5 signals to ensure ongoing positioning (O'Keefe, 2016).

A multi-constellation receiver is able to receive GNSS signals from several systems such as GPS, GLONASS, Galileo and BeiDou. The inclusion of a larger number of satellites in the field of view results in the following advantages:

- Reduced signal acquisition time, accelerating the positioning procedure.
- Higher redundancy with a larger number of GNSS measurements, particularly under challenging conditions.

- Improved satellite geometry, providing better positioning quality.
- Resilience against a fault or glitch in any one GNSS constellation.

Focusing on the practical side of RTK applications, previous studies have demonstrated the benefits of BeiDou and Galileo integration in Leica GNSS positioning technologies with respect to satellite usage, RTK fix availability, accuracy, reliability, and time-to-fix (Fairhurst et al., 2013; Luo et al., 2017; Luo et al., 2021). These benefits encourage users to perform high-precision RTK in increasingly difficult environments such as urban canyon and dense canopy.

In addition to multi-frequency and multi-constellation GNSS positioning, dramatic advances in sensor fusion and computer vision in the last years continuously extend the applicability of cm-level RTK through IMU-based tilt compensation (e.g., Leica GS18 T; Luo et al., 2018a; Luo et al., 2018b) and visual positioning technology (e.g., Leica GS18 I; Schaufler et al., 2020). When taking RTK measurements with tilt compensation at building corners or near fences and walls, the reception of GNSS signals can be significantly degraded by multipath effects. In the case of image-based remote point measurements, multipath reflection appears increasingly while walking close to the object of interest to record the scene.

Apart from the multipath error, the radio-frequency (RF) environments for GNSS have become more challenging due to increasing interference sources such as radars, telecommunication infrastructure and microwave devices. Since GNSS signals are expected to travel more than 20,000 km and arrive relatively unscathed albeit with very low power, a weak interference source can cause the receiver to fail completely or to output an erroneous position. The resulting error magnitude is variable and depends on the interference characteristics such as frequency, modulation, power, and distance to the GNSS antenna. Nowadays, the RF interference is considered as one of the biggest, but often underestimated threats to GNSS-based applications and services (Hofmann-Wellenhof et al., 2008, p. 83; Rügamer and Kowalewski, 2015; INTERTANKO, 2019). To enable high-precision RTK positioning in complex observational and RF environments, advanced multipath reduction and interference mitigation techniques are required.

2. MULTIPATH REDUCTION AND INTERFERENCE MITIGATION

2.1 Multipath reduction

Being a major error source of cm-level positioning, multipath describes the effect that a GNSS signal is reflected by surrounding objects and arrives at the receiver by more than one path (Figure 1). There is no general model of the multipath effect due to its time- and location-dependent characteristics, which have a highly site-specific nature and vary with the satellite-receiver geometry (Fuhrmann et al., 2015). Note that code ranges are more affected by multipath than carrier phases. The impact of multipath on code measurements can be up to half a chip – about 150 m for the GPS C/A code (Groves, 2013). The phase multipath error can reach a quarter of a cycle – about 4.8 cm for the GPS L1 carrier (Hofmann-Wellenhof et al., 2008, p. 157). The multipath effects can be subdivided into a near-field and a far-field component. Far-field effects arise from distant reflecting surfaces and lead to short-periodic errors (up to half an hour; Seeber 2003, p. 317). In contrast, near-field effects result from the closest vicinity of the antenna, mostly described as the first 50 cm around the antenna, and lead to long-periodic errors (up to several hours; Wübbena et al., 2006). Purely from geometry, signals received at low (high) satellite elevation angles are more susceptible to the far-field (near-field) multipath.

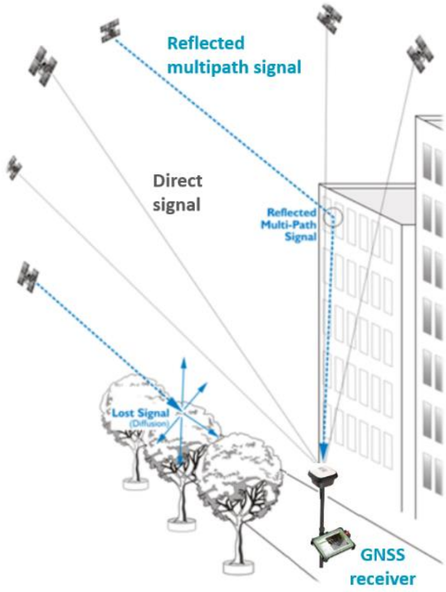

Figure 1 Multipath effect of GNSS signals.

In terms of multipath reduction, certain GNSS constellations have implemented signals with a more robust multipath behaviour at the cost of bandwidth, such as GPS L5 with a much shorter correlation time and therefore ten times more bandwidth compared to GPS L1, or at the cost of demodulation complexity, such as BOC or AltBOC (Betz, 2016, p. 565). On the receiver side, a variety of approaches have been applied in practice and they can be classified as follows: (1) antenna-based attenuation (e.g., using absorbent antenna ground planes, improving the antenna gain pattern by means of choke rings – especially on reference station antennas), (2) enhanced receiver acquisition and tracking loops with optimised correlation techniques (e.g., Narrow Correlator, PAC: Pulse Aperture Correlation, MEDLL: Multipath Estimating Delay Lock Loop), (3) advanced data processing (e.g., exploring signal-to-noise ratio measurements, wavelet decomposition, carrier smoothing). For more information about multipath reduction methods, the reader is referred to Irsigler (2008, Chap. 4).

The multipath reduction presented in this paper focuses on GNSS code ranges, where the multipath error is estimated for multi-frequency and multi-constellation observations in conjunction with an advanced narrow correlator. Since under challenging conditions the multipath estimates are noisy, the code measurements are smoothed after applying the multipath corrections. As the code data quality plays an important role in the preliminary stage of carrier phase ambiguity resolution, the proposed approach will enhance the RTK fixing performance in multipath environments. From Leica Captivate v6.50 onwards, the new multipath reduction option is available in both base and rover mode (Leica Geosystems, 2021, p. 10). In the single-baseline RTK use case, it is recommended to configure the multipath reduction option in a consistent manner between base and rover.

2.2 Interference mitigation

The specific characteristics of GNSS signals make them especially susceptible to RF interferences due to mainly two factors: (1) their low power caused by the low satellite transmit power (typically only tens of watts; Misra and Enge 2006, Tables 10.1–10.4) and by a significant path loss because of the long satellite-receiver distance when being received at the reception chain antenna; (2) extended bandwidth usage on the spectrum resulting from code division multiple access (CDMA).

Interferences may have a significant impact upon GNSS acquisition and tracking loops, affecting the observed measurements in terms of carrier-to-noise power density ratio (C/N_0), loss-of-lock, and number of observations as well as upon navigation message decoding processes. The effect of interferences on the positioning domain depends on several factors: relative position of the interference source with respect to the GNSS receiver, transmit power and signal characteristics of the interference (e.g., modulation). The interfering signals may reduce the availability of high-precision solutions (reduced number of observations leading to a lower number of fixed epochs) and degrade positioning accuracy due to the usage of lower-quality observations.

Based on the fact that interferences may have a known constant central frequency and bandwidth or a variable unpredictable behaviour, a GNSS receiver needs to offer different mitigation methods to be able to cope with different types of interfering signals. The mitigation approaches analysed in this paper are: high dynamic range (HDR) mode and programmable digital filters such as bandpass and notch filters. The HDR mode removes distortions from the spectrum by optimizing the automatic gain control to avoid losing GNSS-relevant signal content. It works efficiently against wide-band and out-of-band interference sources and is particularly effective when the central frequency of the interference is unknown.

On the other hand, programmable digital filters are effective against interferences with a known central frequency by attenuating a given frequency range of the spectrum. Bandpass filters are used when the interference central frequency lies outside of the analysed GNSS frequency band (i.e., out-of-band interferences), whereas notch filters are applied when the interference central frequency lies within that band (i.e., in-band interferences). When using notch filters, it is important to consider that relevant GNSS information might be lost if the filter is placed within the bandwidth of a GNSS signal; therefore, the bandwidth selected for the notch filter has a significant impact upon the tracking and positioning performance. This aspect does not affect bandpass filters since they do not cut off any GNSS bands.

3. MULTIPATH REDUCTION PERFORMANCE

To assess the performance of the multipath reduction, two Leica GS10 receivers were connected to a single AS11 antenna via an antenna splitter in the Heerbrugg testbed with strong multipath effects (Figure 2a). On one GS10 unit the multipath reduction was enabled, whereas on the other not. For the RTK base, a Leica GS18 T smart antenna was set up under open sky without multipath reduction due to the following two reasons: (1) low multipath effects under open sky (Figure 2b); (2) more realistic reflection of the current market use case since the multipath reduction feature is not available for the HxGN SmartNet GNSS correction services yet. Looking at the rover L1/E1/B1I code multipath sky plot in Figure 2c, the GNSS signals from north were largely obstructed at low elevation angles and those from south were strongly reflected by the surrounding buildings, showing significant multipath errors.

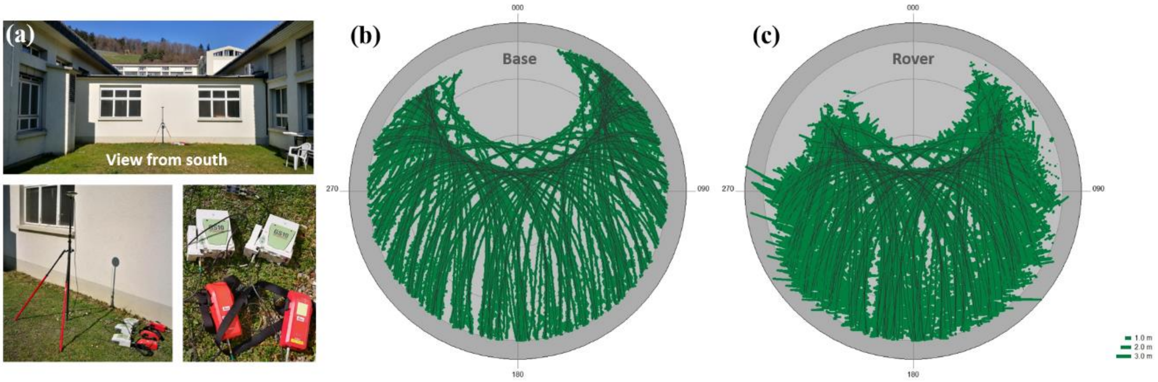

Figure 2 (a) Test setup in a strong multipath environment (base: GS18 T under open sky, rover: two GS10s, antenna: AS11, antenna height: 1.800 m), (b) and (c) L1/E1/B1I code multipath sky plot for base and rover (without multipath reduction).

The default elevation cut-off angle of 10° was applied. The rover received four-system and multi-frequency corrections in the RTCM v3 MSM format, where the baseline length was approximately 100 m. A total of 54.25 hours of 1-Hz GNSS data were analysed in the measurement and position domains to demonstrate the benefits of the multipath reduction to signal tracking and RTK positioning.

3.1 Code multipath performance

The measurement domain analysis was performed with the Leica SpiderQC software v7.7.0 and focused on the code multipath performance. For each frequency group, the average value of code multipath was estimated based on all satellites above the cut-off angle and is summarised in Table 1 with respect to multipath reduction. It can be seen that by applying the multipath reduction, the average code multipath performance is significantly improved by almost 40% for the upper frequency band L1/E1/B1I. Regarding the lower frequency bands such as E6/B3I and L5/E5a/B2a, an even higher degree of enhancement by more than 60% is observed. During the course of GNSS modernisation and evolution, the new signals in the lower frequency bands will play an increasingly important role in multi-frequency and multi-constellation RTK positioning. Therefore, the significant reduction of code multipath in the lower GNSS bands will enhance the high-precision RTK performance in a sustainable way.

Table 1 Average value of code multipath for different frequency groups (cut-off angle: 10°).

Multipath reduction	L1/E1/B1I	L2/B1C	L5/E5a/B2a	E5b/B2I/B2b	E6/B3I
Without	0.712 m	0.744 m	0.887 m	0.855 m	1.000 m
With	0.431 m	0.489 m	0.343 m	0.565 m	0.400 m
Improvement	39.5%	34.3%	61.3%	33.9%	60.0%

In addition to the overall performance evaluation, the effectiveness of the multipath reduction was investigated depending on the satellite elevation angle. Figure 3 shows the average value of code multipath with 5-degree elevation angle bins. As can be seen for all frequency groups, the code multipath first increases with decreasing elevation angle and reaches its maximum at 20°–25°, and then starts decreasing. Such a variation pattern demonstrates the site-specific characteristics of multipath effects, which are exemplarily visualised in Figure 2c. With multipath reduction, the code multipath error is considerably reduced over the whole elevation range, particularly at low elevation angles. In comparison to Figure 3a, a more significant improvement in the lower frequency bands is visible in Figure 3c and d.

Taking the GPS L5 signal as an example, Figure 4 compares the code multipath sky plot with and without multipath reduction. Depending on the azimuth and elevation angle of each satellite, the multipath sky plot illustrates the code multipath estimates (in green) along the satellite track (in black). By utilising the multipath reduction, the GPS L5 code multipath errors are significantly mitigated for all azimuthal directions, which is particularly visible at low elevation angles. Moreover, the proposed approach primarily attenuates the amplitude of the multipath oscillation, and the remaining multipath effects in Figure 4b need to be handled in the RTK algorithms. In the measurement domain analysis, other tracking performance aspects such as observation count, data completeness, carrier-to-noise density ratio and number of cycle slips were considered as well, where no significant impact was found due to the use of multipath reduction.

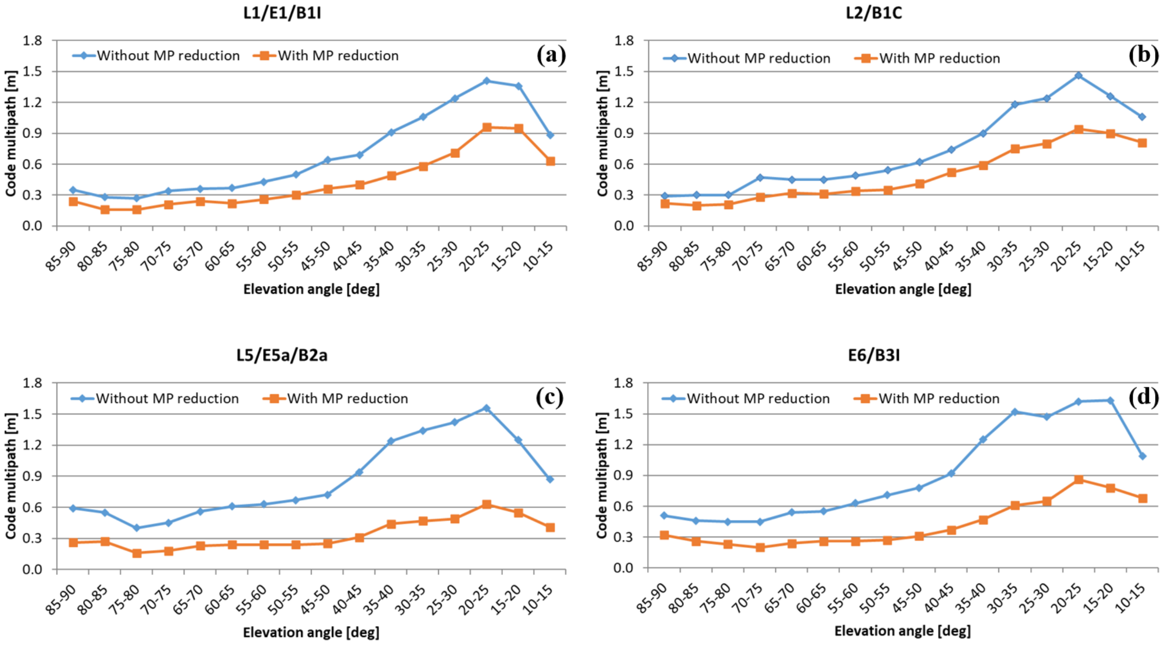

Figure 3 Comparison of the code multipath (MP) over the satellite elevation angle for different frequency groups (cut-off angle: 10°).

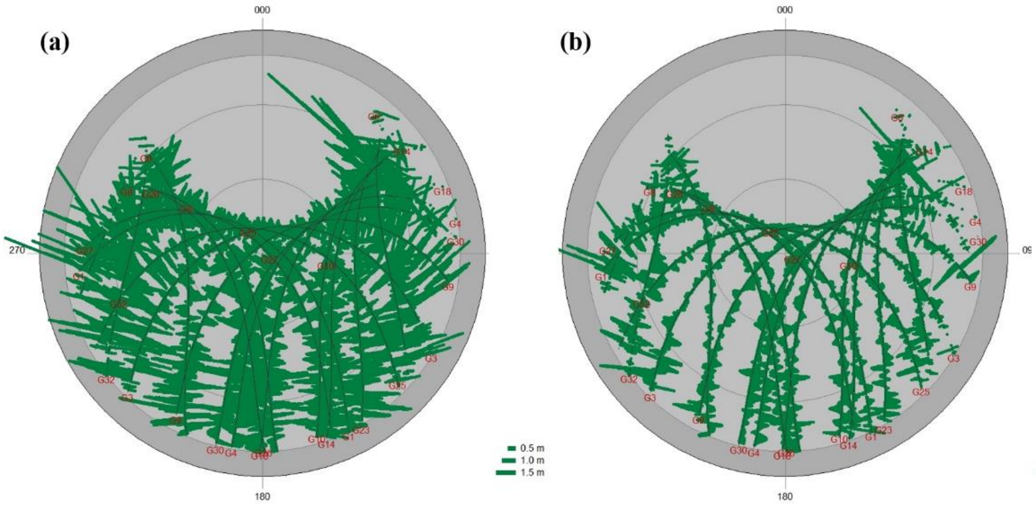

Figure 4 Comparison of the GPS L5 code multipath sky plot with respect to multipath reduction (cut-off angle: 10°) (a) Without multipath reduction, (b) With multipath reduction.

3.2 RTK positioning performance

GNSS RTK based on multi-constellation and multi-frequency data is a complex real-time process, which aims to provide cm-level positioning accuracy with as few as possible observation epochs for variable rover dynamics, particularly in challenging environments. To evaluate the system-level performance and to address users' concerns in GNSS applications, the following key parameters are used in this paper to assess the benefits of the multipath reduction to high-precision RTK positioning (Feng and Wang, 2008; Luo et al., 2017; Luo et al., 2021):

- **Availability.** Absolute number of RTK fixed solutions during a certain period.
- **Accuracy.** Deviation of RTK fixed positions from ground truth with a higher degree of accuracy, where the ground truth can be determined by means of a total station or by post-processing long-term GNSS data.
- **Reliability.** Percentage that the position error (with respect to ground truth) is less than three times the corresponding estimate of the coordinate quality (CQ).

In the Leica RTK algorithms, the CQ value is estimated together with the position and represents a statistical metric for the position quality. It is itself subject to uncertainty and is derived based on the mathematical models of GNSS observations and environmental conditions, along with empirical assumptions. Under normal measuring conditions there is at least a two third probability that the position error (with respect to ground truth) is less than the corresponding CQ value.

To analyse the RTK positioning performance, the GNSS data were processed in the kinematic mode with epoch-wise coordinate solution, where the RTK fix was reinitialised after each successful ambiguity resolution. Figure 5 illustrates the impact of multipath reduction on the availability and accuracy of RTK fixed solutions under strong multipath. As can be seen in Figure 4a, the use of multipath reduction results in a relative availability improvement by 23.7%, from 11724 to 14508. This can be explained by the enhanced precision of the code measurements with multipath reduction, which helps reduce the convergence time of the ambiguity resolution and thus increases the availability of RTK fixes. Considering the whole data period of 54.25 hours (i.e., 195300 s), the average values of time-to-fix amount to 13.5 s and 16.7 s for the test scenarios with and without multipath reduction, respectively. Moreover, with multipath reduction, large position errors at the meter level are considerably reduced (Figure 5b), whereas the cm-level 3D errors remain comparable (Figure 5c). This indicates that the availability improvement by applying the multipath reduction does not lead to a systematic degradation of accuracy in this experiment.

Table 2 provides statistics on the RTK performance parameters with respect to multipath reduction. First, additional 2419 RTK fixes are produced with a 3D error below 10 cm, which leads to a 22.9% relative increase in the availability of high-precision solutions. In addition, the occurrence of incorrect ambiguity fix causing m-level 3D errors is effectively reduced by 36.9% (cf. Figure 5b). Since the majority of the additional RTK fixes are accurate, there is no significant degradation in the 3D root mean square error. The reliability value remains the same, indicating that in this test the multipath reduction causes no change in the consistency between the actual position error and the CQ indicator.

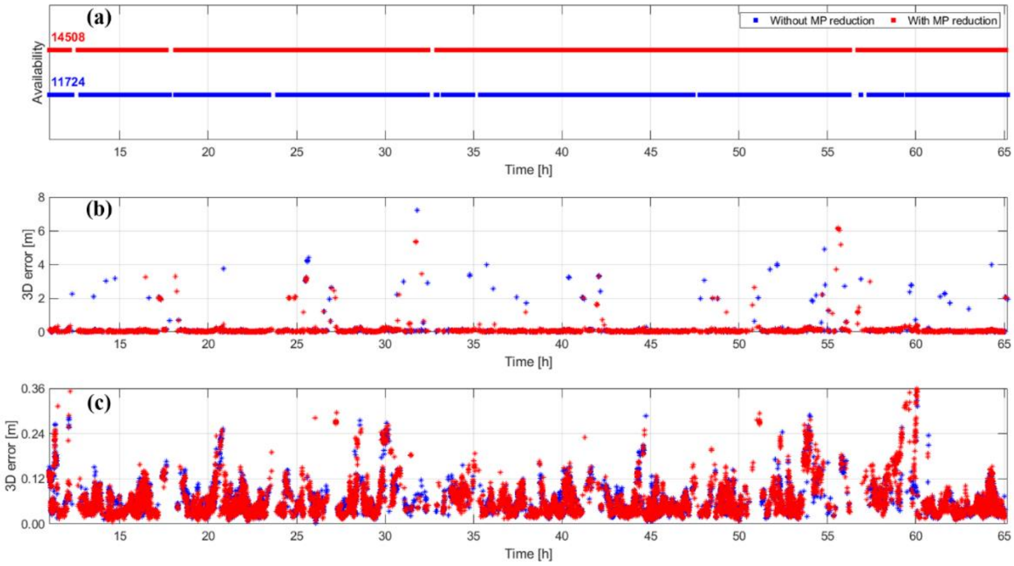

Figure 5 Impact of multipath (MP) reduction on the RTK performance under strong multipath (a) Availability of RTK fixed solutions, (b) and (c) 3D errors of RTK fixed positions with different y-axis limits.

Table 2 RTK performance parameters with respect to multipath reduction (with ambiguity reset after each RTK fix, RMS: root mean square).

Multipath reduction	Availability Total	Availability 3D err ≤ 10 cm	Availability 3D err > 1 m	3D RMS error	Reliability
Without	11724	10550	241	0.055 m	83.5%
With	14508	12969	152	0.056 m	83.5%
Diff (abs)	2784	2419	–89	0.001 m	0.0%
Diff (rel)	23.7%	22.9%	–36.9%	1.8%	0.0%

4. INTERFERENCE MITIGATION PERFORMANCE

A total of three test scenarios were designed to demonstrate the performance of the interference mitigation. Scenarios 1 and 2 show the benefits of applying digital filters in the measurement and position domains, where scenario 3 exhibits the advantages of the HDR mode in RTK positioning under difficult conditions. Figure 6 illustrates the test setup used in scenarios 1 and 2. A Leica AR10 antenna is connected to a RF combiner, which outputs the GNSS signals received from the antenna and the interference resulting from a signal generator, attenuated with a 40 dB attenuator. Such an attenuation is necessary to avoid saturating the receiver front-end. The RF combiner is then connected to a Leica GR50 GNSS receiver, which also receives RTK correction data from a site over a baseline of 20 km to produce the positioning results.

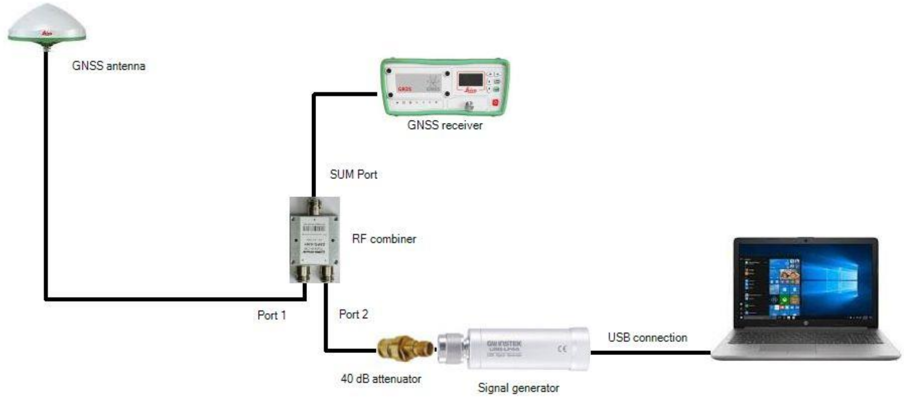

Figure 6 Test setup to assess the performance of the digital filters used in interference mitigation (receiver: GR50, antenna: AR10, RTK baseline length: 20 km).

In scenario 3 the same setup as shown in Figure 2a was used under multipath and canopy conditions, where the HDR mode was enabled on one GS10 receiver while on the other not. On both GS10 units the multipath reduction was disabled to focus on the impact of the HDR mode upon the RTK positioning performance.

4.1 Scenario 1: Frequency hopping

To verify the effectiveness of applying digital filters against interferences with a known central frequency affecting several GNSS bands, the signal generator was configured to output a sine wave whose central frequency hops between 1232 MHz and 1579 MHz. These frequencies are close to the central frequencies of GNSS signals (L1: 1575.42 MHz, L2: 1227.60 MHz). The interference signal power is set to –30 dBm. The mitigation solution in this scenario consists of two notch filters with a central frequency of 1232 MHz and 1579 MHz, respectively, and a cut-off frequency of 0.15 MHz, which corresponds to the attenuated bandwidth (Figure 7).

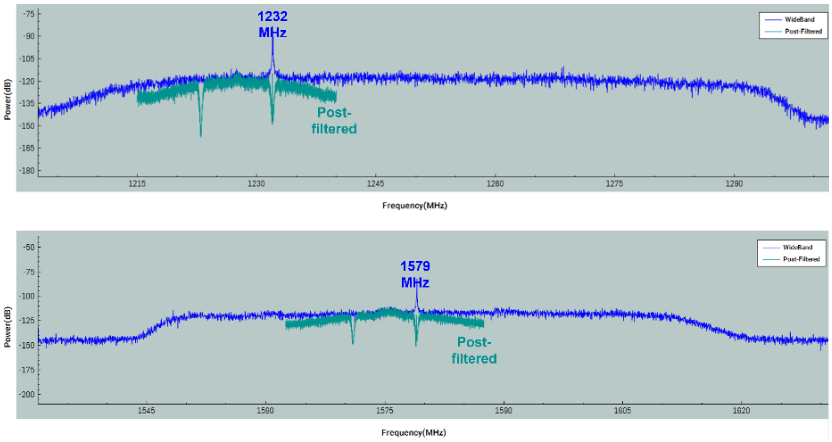

Figure 7 Notch filters applied to mitigate interferences due to frequency hopping.

Figure 8 shows the impact of the interference mitigation upon the carrier-to-noise density ratio (C/N_0) for different GNSS signals in the L1 and L2 bands. The C/N_0 estimate drops significantly by up to 8.5 dB-Hz when activating the interference signal. However, when enabling the digital notch filters on the receiver, the C/N_0 reaches a similar level to the one without interference. For GPS L1, GPS L2, Galileo E1 and BeiDou B1C, the average improvements in the C/N_0 values are 7.2 dB-Hz, 6.4 dB-Hz, 6.3 dB-Hz and 8.4 dB-Hz, respectively.

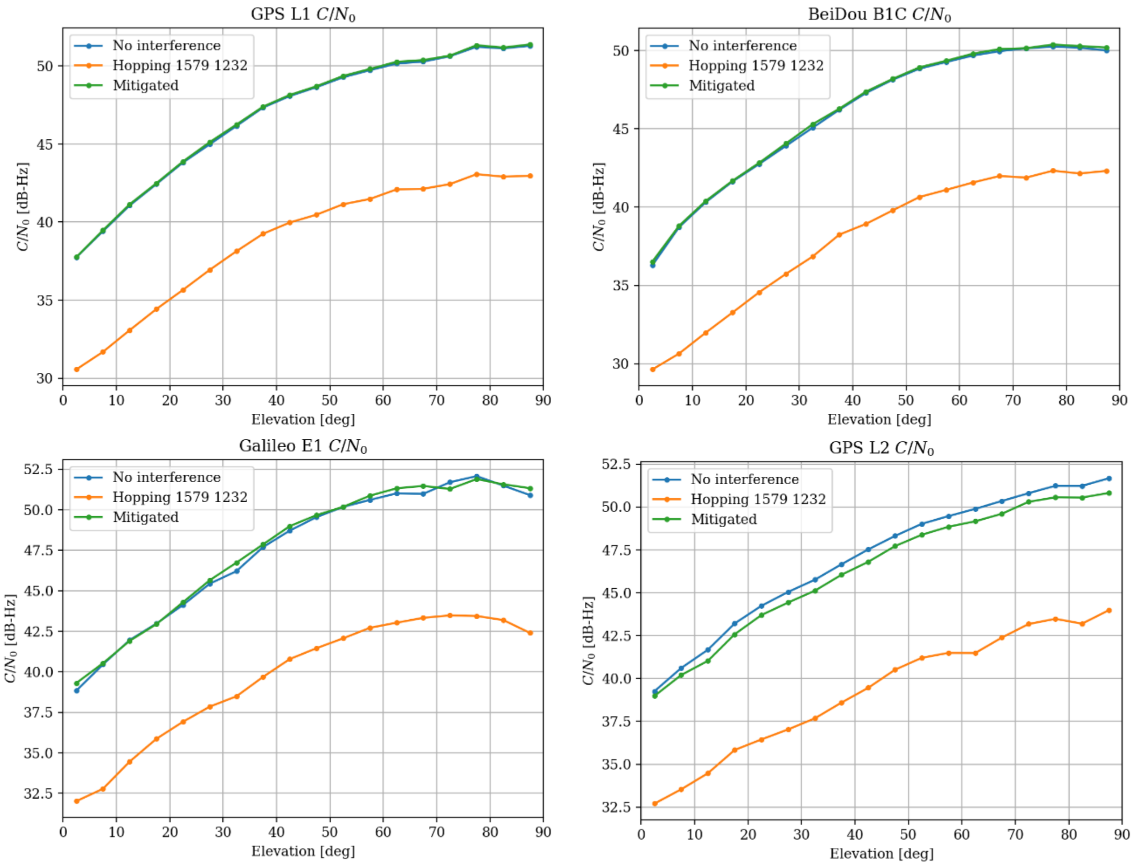

Figure 8 Carrier-to-noise density ratio (*C/N_0*) measured with no interference, frequency hopping and interference mitigation.

Table 3 summarises the impact of interference mitigation upon the RTK performance with respect to accuracy and availability. When enabling interference mitigation on the same receiver, a significant improvement is observed in both the positioning accuracy (up to 67% in the height component) and the 3D CQ value (by 40%). In addition, the percentage of RTK fix increases by 8%.

Table 3 Comparison of the RTK performance with no interference, frequency hopping and interference mitigation (CQ: coordinate quality).

Interference situation	Easting (1σ)	Northing (1σ)	Height (1σ)	3D CQ	Percentage of RTK fix
No interference	0.004 m	0.006 m	0.008 m	0.011 m	100%
Interference	0.007 m	0.006 m	0.024 m	0.020 m	92%
Interference mitigation	0.003 m	0.007 m	0.008 m	0.012 m	100%

4.2 Scenario 2: Single interference

This test scenario has the goal of analysing the effectiveness of the mitigation techniques when dealing with a constant interference on a single frequency as close as 1.42 MHz to the GPS L1 central frequency (1575.42 MHz). The signal generator was configured to output a continuous sine-wave interference with a central frequency of 1574 MHz and a power of –30 dBm. As the mitigation solution, a notch filter with a central frequency of 1575 MHz and a cut-off frequency of 0.15 MHz was applied on the receiver (Figure 9).

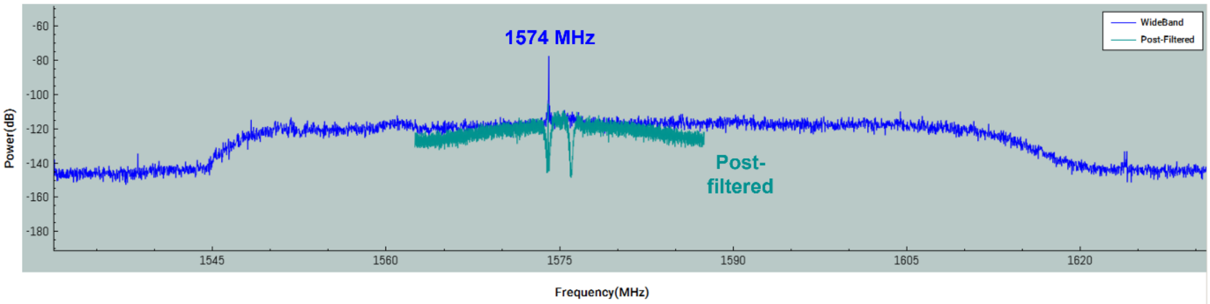

Figure 9 Notch filter applied to mitigate the single interference in the near of the GPS L1 central frequency.

Figure 10 shows the impact of the single interference on GNSS raw observations with a drop on carrier-to-noise density ratio up to 13 dB-Hz. When mitigation steps are performed, the receiver is able to provide observations with a slightly lower C/N$_0$ than the case without interference. By applying the notch filter, significant improvements in C/N$_0$ are observed for all the affected signals, on average, 10 dB-Hz for GPS L1, 6.9 dB-Hz for Galileo E1 and 9.7 dB-Hz for BeiDou B1C.

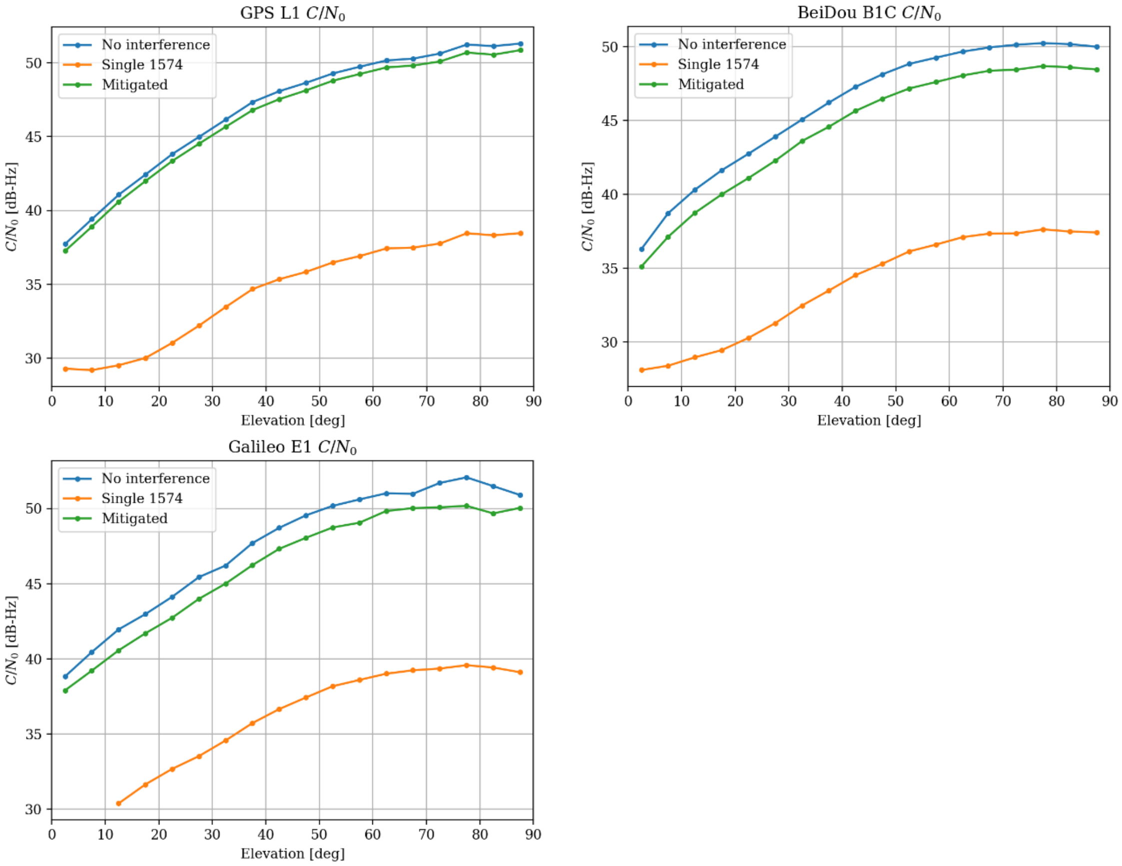

Figure 10 Carrier-to-noise density ratio (C/N_0) measured with no interference, single interference and interference mitigation.

4.3 Scenario 3: RTK positioning with HDR

Based on the knowledge that the HDR mode increases tracking sensitivity, this experiment analyses its effects on the RTK performance under difficult conditions including multipath and tree canopy. To focus on the impact of HDR, the multipath reduction was disabled in this test scenario. As can be seen in Figure 11, with the HDR mode large position errors at the decimetre to meter level are considerably reduced in both test setups. This indicates that, even in the absence of interferences, the HDR mode helps reduce incorrect ambiguity fixes by providing cleaner GNSS signals, particularly in challenging environments.

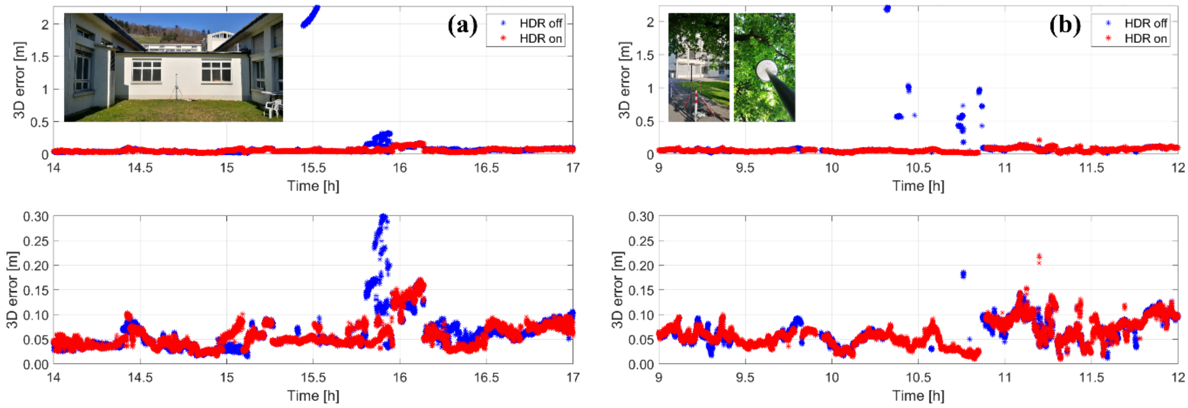

Figure 11 Impact of the HDR mode on the RTK performance under difficult conditions (rover: two GS10s with multipath reduction disabled, antenna: AS11, antenna height: 1.800 m) (a) Multipath (b) Tree canopy.

5. CONCLUSIONS

Both multipath and interference-related errors have a site-specific nature and cannot be generally modelled and easily corrected. In this paper, advanced techniques for multipath reduction and interference mitigation have been presented and their benefits to high-precision GNSS positioning were demonstrated in representative test scenarios.

The proposed multipath reduction significantly reduces the code multipath error by up to 60%, particularly in the lower frequency bands such as E6/B3I and L5/E5a/B2a. In addition, it improves the RTK fix availability under difficult conditions and reduces decimetre-to-meter level position errors, with no degradation in accuracy and reliability of cm-level positioning.

The enhanced interference mitigation consists of programmable digital filters and the HDR mode. These techniques work most effectively against specific interference types: the digital filters are applicable to interferences with a known central frequency (both in-band and out-of-band), while the HDR mode is suitable when the central frequency is unknown or varies with time. Furthermore, under difficult conditions the HDR mode improves the RTK performance by reducing large position errors at the decimetre to meter level.

REFERENCES

Betz, John W. (2016) *Engineering Satellite-Based Navigation and Timing*: *Global Navigation Satellite Systems, Signals, and Receivers*. Wiley, IEEE Press, Hoboken, New Jersey, 672 pp.

Fairhurst, P., Luo, X., Aponte, J. (2013) New systems, new signals, new positions − Providing BeiDou integration. In: Proceedings of ION GNSS+ 2013, Nashville, TN, September 16–20, 2013, pp. 3214–3220.

Feng, Y., Wang, J. (2008) GPS RTK performance characteristics and analysis. *Journal of Global Positioning Systems*, 7(1):1−8.

Fuhrmann, T., Luo, X., Knöpfler, A., Mayer, M. (2015) Generating statistically robust multipath stacking maps using congruent cells. *GPS Solutions*, 19(1):83–92. https://doi.org/10.1007/s10291-014-0367-7.

Groves, P. (2013) GNSS solutions: Multipath vs. NLOS signals. How does non-line-of-sight reception differ from multipath interference? *Inside GNSS*, 8(6):40–44.

Hofmann-Wellenhof, B., Lichtenegger, H., Wasle, E., (2008) *GNSS − Global Navigation Satellite Systems: GPS, GLONASS, Galileo & more*. Springer-Verlag, Wien, 516 pp.

INTERTANKO (2019) Jamming and Spoofing of Global Navigation Satellite Systems (GNSS). White Paper, INTERTANKO, 2019.

Irsigler, M. (2008) Multipath propagation, mitigation and monitoring in the light of Galileo and the modernized GPS. PhD thesis, Bundeswehr University, Munich.

Leica Geosystems (2021) Leica Captivate v6.50 – Software Release Notes. Leica Geosystems AG, Heerbrugg, Switzerland, May 18, 2021, 18 pp.

Luo, X., Chen, J., Richter, B. (2017) How Galileo benefits high-precision RTK − What to expect with the current constellation. *GPS World*, 28(8):22–28.

Luo, X., Schaufler, S., Branzanti, M., Chen, J. (2021) Assessing the benefits of Galileo to high-precision GNSS positioning – RTK, PPP and post-processing. *Advances in Space Research*, 68(12):4916–4931. https://doi.org/10.1016/j.asr.2020.08.022.

Luo, X., Schaufler, S., Carrera, M., Celebi, I. (2018a) High-precision RTK positioning with calibration-free tilt compensation. In: Proceedings of FIG Congress 2018, Istanbul, Turkey, May 6–11, 2018, 17 pp.

Luo, X., Schaufler, S., Richter, B. (2018b) Leica GS18 T − World's fastest GNSS RTK rover. White Paper, Leica Geosystems AG, Heerbrugg, Switzerland.

Misra, P., Enge, P. (2006) *Global Positioning System: Signals, measurements and performance* (2nd ed.). Ganga-Jamuna Press, Lincoln, 569 pp.

O'Keefe, K. (2016) Single versus multiple: How frequencies make a difference in GNSS receivers. *Inside GNSS*, 11(5):32–33.

Schaufler, S., Fischell, M., Boffi, G., Luo, X., Török, Z. (2020) An innovative image-based surveying approach for globally referenced remote point measurements. In: Proceedings of FIG Congress 2020, Amsterdam, Netherlands, May 10–14, 2020, 13 pp.

Seeber, G. (2003) *Satellite geodesy* (2nd ed.). Walter de Gruyter, Berlin, 612 pp.

Rügamer, A., Kowalewski, D. (2015) Jamming and spoofing of GNSS signals – An underestimated risk?! In: Proceedings of FIG Working Week 2015, Sofia, Bulgaria, May 17–21, 2015, 21 pp.

Wübbena, G., Schmitz, M., Boettcher, G. (2006) Near-field effects on GNSS sites: Analysis using absolute robot calibrations and procedures to determine corrections. In: Proceedings of the IGS Workshop – Perspectives and Visions for 2010 and beyond, ESOC, Darmstadt, Germany, May 8–12, 2006, 7 pp.

BIOGRAPHICAL NOTES

Miguel GONZÁLEZ-CALVO is a GNSS Product Engineer in the GNSS Product Management group at Leica Geosystems. He received his M.Sc. degree in signal processing and communications from Universidad Politécnica de Madrid, Spain.

Dr. Xiaoguang LUO is a Senior Product Engineer in the GNSS Product Management group at Leica Geosystems. He received his Ph.D. in geodesy and geoinformatics from the Karlsruhe Institute of Technology, Germany.

José Amado APONTE is a Senior Product Manager and Team Leader of the GNSS Product Management group at Leica Geosystems. He received a MSc. in Satellite Positioning Technology from the University of Nottingham, England and, more recently, an MBA from the University of Strathclyde, Scotland.

Bernhard RICHTER received a M.Sc. in Geodesy from the Technical University of Vienna in 1999. He was a research assistant at the Technical University of Graz. In 2005, he received a Master of Business Administration from the University of Gloucestershire, England. Since 2000 he is working for Leica Geosystems in Switzerland. He had several leading positions in the field of GNSS, focused on professional receivers. Since more than three years he is Vice President of Geomatics at Leica Geosystems.

CONTACTS

Mr. Miguel González Calvo
Leica Geosystems AG
Heinrich-Wild-Strasse 201
Heerbrugg
SWITZERLAND
Tel. +41 71 727 3551
Email: miguel.gonzalez@leica-geosystems.com
Web site: www.leica-geosystems.com

Dr. Xiaoguang Luo
Leica Geosystems AG
Heinrich-Wild-Strasse 201
Heerbrugg
SWITZERLAND
Tel. +41 71 727 3801
Email: xiaoguang.luo@leica-geosystems.com
Web site: www.leica-geosystems.com

Mr. José Amado Aponte
Leica Geosystems AG
Heinrich-Wild-Strasse 201
Heerbrugg
SWITZERLAND
Tel. +41 71 727 4132
Email: jose.aponte@leica-geosystems.com
Web site: www.leica-geosystems.com

Mr. Bernhard Richter
Leica Geosystems AG
Heinrich-Wild-Strasse 201
Heerbrugg
SWITZERLAND
Tel. +41 71 727 3626
Email: bernhard.richter@leica-geosystems.com
Web site: www.leica-geosystems.com