Leica GS18 T – World's Fastest GNSS RTK Rover (White Paper)

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Abstract

The rapid development of sensor fusion in GNSS and inertial measurement unit (IMU) is offering a great opportunity to improve the productivity and user experience of high-precision RTK positioning. In keeping pace with technological advances, the new Leica GS18 T GNSS RTK rover combines GNSS and IMU to automatically adjust pole tilt from plumb, which increases productivity, extends RTK applicability and reduces human errors. This IMU-based tilt compensation approach has the major advantages of being immune to magnetic disturbances, free from on-site calibrations and applicable at large tilt angles. These features enable high-precision RTK in more restrictive environments with enhanced efficiency and flexibility. This paper describes the technical backgrounds of the GS18 T and demonstrates the benefits of applying the IMU-based tilt compensation with respect to productivity, accuracy and reliability. With the GS18 T, Leica Geosystems takes a new path and sets new standards for precise GNSS positioning through easy-to-use sensor-fusion techniques.

Introduction

In RTK surveys, the GNSS receiver does not measure the position directly at the target point, but at the antenna phase centre. To optimise the reception of GNSS signals, the rover is usually mounted on a pole, and the pole tip is placed upon the point of interest. In conventional RTK surveying where the pole needs to be manually levelled with a circular bubble, the phase centre position is reduced to the pole tip by considering the antenna phase centre offset (PCO; Hofmann-Wellenhof et al., 2008, p. 148) and the length of the pole. This approach has the following disadvantages limiting the performance of high-precision RTK:

- In terms of productivity, levelling the pole takes time, particularly in stakeout where it needs to be repeated iteratively.
- With respect to accuracy, holding the pole vertically is influenced by human errors and instrumental imperfections, such as a misadjusted bubble.
- Regarding applicability, it is not always possible to hold the pole vertically on a target point, for example, when measuring building corners.

Therefore, it would be desirable to take precise RTK measurements of the target point without the need to level the pole.

Figure 1 - Leica GS18 T GNSS RTK rover with Leica CS20 field controller.

UNIQUE ADVANTAGES

To improve productivity and user experience of high-precision RTK positioning, the Leica GS18 T offers the following unique advantages:

- Free from on-site calibrations
- Immune to magnetic disturbances
- Applicable at large tilt angles
- Heading-aided 3D visualisation

The rapid development of GNSS, inertial and multi-sensor integrated navigation systems (Jekeli, 2001; Titterton and Weston, 2004; Groves, 2013) is offering a great opportunity to tilt compensation RTK that automatically adjusts pole tilt from plumb. Assuming the length of the pole is known, the position error due to tilt can be compensated if the attitude (or angular orientation) of the pole is precisely determined. Whilst measuring the angle of the pole from the vertical can be accurately achieved by means of accelerometers for instance, measuring the orientation of the pole with respect to geographic north is a far more challenging task (Hong et al., 2005). The conventional GNSS RTK rover products with tilt compensation use an electronic compass, which relies upon magnetometer measurements and provides the pole orientation with respect to magnetic north (Nichols and Talbot, 1996; Kurtovic and Pagan, 2009). Such a magnetometer-based approach has the following drawbacks:

- On-site calibrations are necessary, which are time-consuming and reduce productivity.
- A high-fidelity and computationally expensive magnetic model is needed. Otherwise, the local declination angle (the angle between geographic north and magnetic north) may be in error by up to three degrees, even without any local disturbing fields (Dusha, 2017).
- Magnetometer measurements are affected by magnetic disturbances caused by ferrous metals (e.g. cars, buildings with structural steel) and electric currents (e.g. power lines, electricity installations), which are usually present in RTK survey environments.
- The magnetic field measured at the magnetometer varies significantly with tilt angle (Pedley, 2012), limiting the tilt compensation range often to 15 degrees.

To avoid the drawbacks mentioned above, the tilt compensation solution of the Leica GS18 T utilises precise IMU measurements from industrial-grade micro-electro-mechanical sensors (MEMS), which are especially appropriate for surveying applications. Taking inspiration from technologies that have been successfully applied in aviation and marine navigation for years (Crassidis and Markley, 2003), a customised inertial navigation system (INS) is integrated with GNSS in a sophisticated manner to provide the world's fastest and easiest-to-use GNSS RTK rover.

Productivity and user experience

The GS18 T has been designed to improve the productivity and user experience of high-precision RTK positioning. Fig. 2 shows the key components that enable the GS18 T to be the world's fastest GNSS RTK rover. Due to tilt compensation, there is no need to level the pole, which increases productivity by an average of 20 per cent over conventional GNSS RTK surveying practices. In addition, the GS18 T utilises high-rate accelerations and angular velocities from MEMS IMU to determine the attitude of the pole in real time. Since these IMU measurements are not affected by magnetic fields, the GS18 T is immune to magnetic disturbances and does not require any time-consuming on-site calibrations. It works out of the box and is faster than magnetometer-based systems. Furthermore, the IMU-based tilt compensation technique in combination with instantaneous RTK enables the highest productivity, particularly in topographic surveys, and provides similar accuracy as measurements taken by levelling the pole manually.

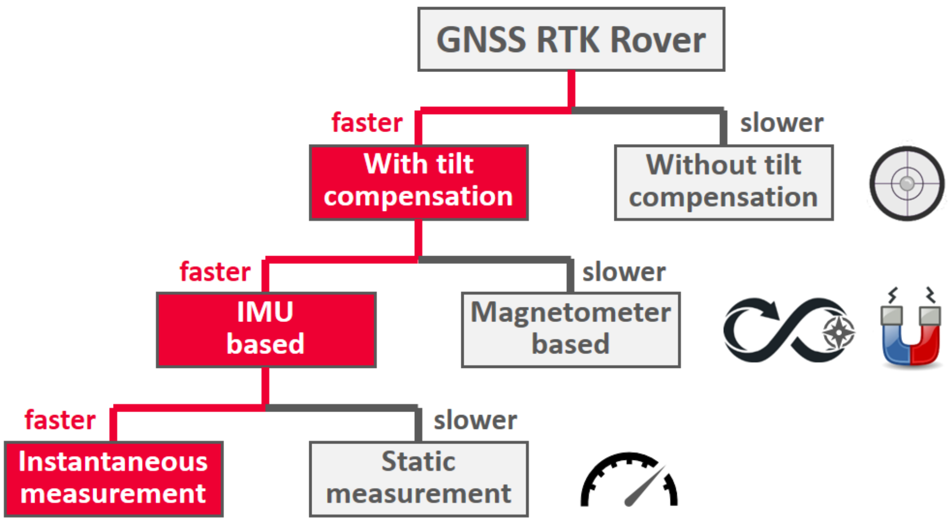

Figure 2 - Leica GS18 T as the fastest GNSS RTK rover with the IMU-based tilt compensation.

In terms of user experience, the GS18 T focuses on extending the applicability of high-precision RTK and enhancing user convenience in field surveys. By applying the IMU-based tilt compensation, the targets that were previously not accessible with GNSS, such as building corners and obstructed points (Fig. 3), can now be directly measured with RTK, even at large tilt angles of more than 30 degrees.

Without pole levelling, which does require a high level of concentration, the user can pay more attention to safety relevant events in the survey environment, such as passing vehicles and operating machines.

Furthermore, attitude information is used to help users orientate themselves in the field by automatically updating the 3D visualisation of the surroundings depending on the sensor orientation. This is particularly helpful when performing a stakeout. The attitude information of tilt-compensated measurements is fully traceable, enabling quality assurance for users themselves and their clients. The improvements in productivity and user experience achieved with the GS18 T rely upon a variety of innovations, particularly in GNSS signal tracking and sensor-fusion techniques.

Figure 3 - Using the Leica GS18 T to measure building corners and obstructed points that were previously not measurable in conventional RTK surveying with a vertical pole.

High-performance GNSS signal tracking

Challenges in tilt compensation RTK

In high-precision RTK positioning with tilt compensation, robust and high-sensitivity tracking of GNSS signals in all frequency bands is of immense importance, particularly at large tilt angles. As illustrated in Fig. 4, if the pole is tilted away from a satellite by t degrees, the elevation angle of the incoming GNSS signal with respect to the antenna horizon decreases by t as well, from α (vertical pole) to β (tilted pole).

For a given elevation angle of α, the larger the tilt t, the smaller the angle β. This indicates that a GNSS signal received at a high elevation angle in conventional RTK surveying with a vertical pole could become a low-elevation signal in the tilt compensation case, depending on the tilt angle and the direction of tilt. Moreover, when performing RTK measurements at building corners or near fences and walls, the reception of noise signals increases due to multipath or nearby interferences. To cope with these challenges, the GS18 T features advanced signal tracking technologies, providing maximum number of observations for tilt-compensated RTK solutions.

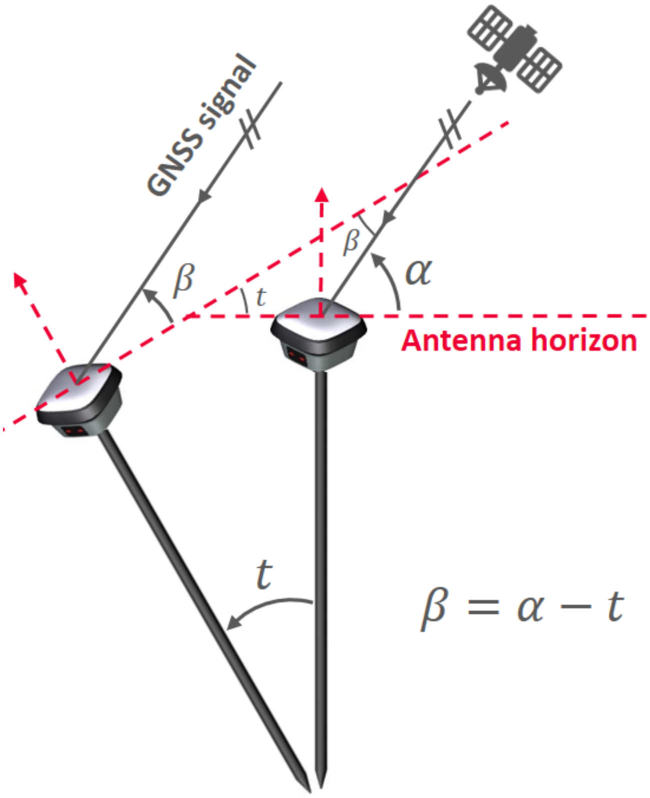

Figure 4 - Decrease in the elevation angle of the incoming GNSS signal when tilting a pole away from satellite (α αsatellite elevation angle for a vertical pole, β: satellite elevation angle for a tilted pole, t: tilt angle).

Advanced signal tracking technologies

The antenna element and the measurement engine (ME) of a GNSS RTK rover play a key role in tracking GNSS and L-band correction signals. The antenna of the GS18 T is a high-performance patch antenna, which keeps planar and low-profile structure for small size. Any planar antennas may unavoidably excite surface waves that propagate along the interface between the air and the metal ground plane. These waves diffract at the edge of the ground plane, causing radiations in all direction to the space. For GNSS applications, such unwanted radiations increase the reception of noise signals due to multipath or nearby interferences.

The parasitic circular array loading technology has been developed by Yang and Freestone (2017) to optimise the antenna radiation pattern through suppressing the surface waves from propagating. The concept of this technology is illustrated in Fig. 5. As can be seen, peripheral spiral shaped reactive/resistive-loaded monopoles are circularly arrayed around the main antenna element to manipulate the aroused surface waves. After interacting with the parasitic monopoles, the surface waves become scattered waves and re-radiate to the free-space. In this way, the antenna radiation pattern is reshaped to enhance the low elevation angle tracking capabilities. The ability to track low-elevation satellites while maintaining a high gain for higher elevation satellites is particularly important for RTK applications in difficult environments such as urban canyons and dense canopy.

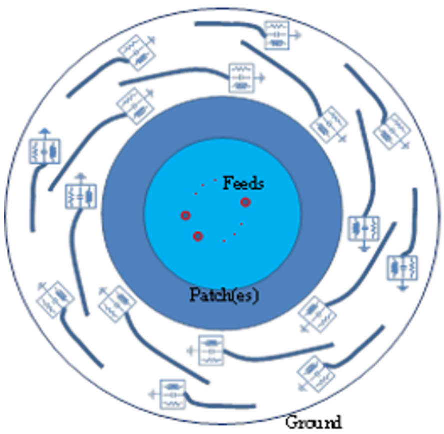

Figure 5 - Antenna concept with spiral shaped peripheral parasitic circular array loadings (Yang and Freestone, 2016).

Moreover, improved low-elevation tracking performance is also beneficial for receiving L-band correction signals from geostationary satellites at high latitudes (Yang and Freestone, 2016).

In addition to the parasitic circular array loading technology, the patented ultra-wideband antenna feeding technology (Yang and Gilbertson, 2016) has been used to achieve superior circular polarisation and symmetric radiation patterns over the entire GNSS bandwidth. Taking the L1 frequency as an example, the north and east PCO values from the Geo++ absolute field calibration (Schmitz et al., 2002) of the GS18 T antenna are −1 mm and −0.3 mm, respectively, exhibiting sub-millimetre phase centre stability. Furthermore, the use of multiple feeding points, where the GNSS signals are fed into the antenna, leads to uniform radiation pattern and low cross-polarisation (Caizzone et al., 2018). According to antenna theory, cross-polarisation is one of the main causes of strong multipath noise and low radiation efficiency.

Apart from the high-performance patch antenna, the GS18 T incorporates the latest generation of measurement engine ME7. It has a 555-channel architecture and is capable of tracking all current and upcoming satellite constellations at multiple frequencies, including GPS, GLONASS, Galileo, BeiDou, QZSS and NavIC. At the time of writing this paper, the Galileo constellation consists of 18 operational satellites, which already benefit multi-GNSS RTK positioning, as demonstrated in Luo et al. (2017). A total of 19 BeiDou-3 satellites (18 MEO and one GEO) will be launched by the end of 2018, bringing the constellation to the initial operational capability (Yang, 2017). The QZSS system has reached a four-satellite configuration that provides continuous visibility of three satellites in the service area (Steigenberger et al., 2018). In the tilt compensation case, the use of these new systems in addition to GPS and GLONASS helps maintain high-precision RTK solutions when moving close to objects such as building corners and house walls. Besides navigation satellite signals, the ME7 tracks multi-channel L-band correction signals from the TerraStar augmentation satellites, enabling the real-time cm-level SmartLink service. Leica SmartLink utilises the precise point positioning (PPP) technique to produce high-precision GNSS solutions without RTK data. Due to faster signal acquisition, higher tracking sensitivity and better multipath rejection, the ME7 provides superior signal tracking performance for tilt compensation RTK.

Benefits of advanced signal tracking

To demonstrate the benefits of advanced signal tracking under open sky, the signal-to-noise ratio (SNR; Luo, 2013, Sect. 5.1) measurements from a GS18 T are compared to another commercial survey-grade GNSS smart antenna denoted as Rover A. By analysing 24 hours of 1-Hz data, Fig. 6 shows the median SNR for the GPS signals with 5-degree elevation angle bins. In comparison to Rover A, the GS18 T exhibits higher SNR levels over the whole elevation range, where more significant improvements are visible for the lower frequency bands L2 and L5 (Fig. 6b, c). On average, the median SNR increases by 2 dBHz (decibel Hertz), 4 dBHz and 8 dBHz for the GPS L1, L2 and L5 signals, respectively. Under normal conditions, the larger the SNR, the better the signal quality, and the smaller the observation noise.

The GS18 T is especially suitable for RTK applications where the sky is partially visible, for example, operating close to tree lines, under foliage or in urban canyons. To show the benefits of advanced signal tracking in difficult environments, Fig. 7 compares the number of cycles slips between GS18 T and Rover A under heavy tree canopy. In such an environment, GNSS signals are blocked, attenuated and reflected, leading to a large amount of cycle slips. As can be seen, over a four-hour period, the GS18 T produces considerably fewer cycle slips than Rover A, particularly for elevation angles 75°–80° (by 50 per cent), 55°–60° (by 64 per cent) and 30°–35° (by 43 per cent). This demonstrates the advantages of the GS18 T in robust and high-sensitivity signal tracking over a wide elevation coverage, providing maximum number of continuous GNSS observations for an enhanced positioning solution.

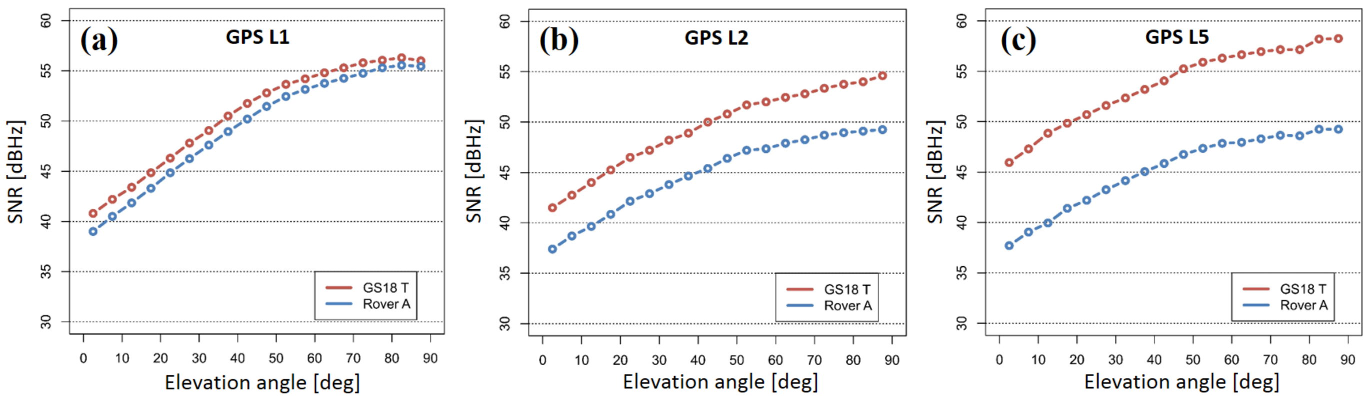

Figure 6 - Comparison of the GPS signal-to-noise ratio (SNR) measurements between GS18 T and Rover A under open sky (24 hours of 1-Hz data, elevation cut-off: 0 degrees).

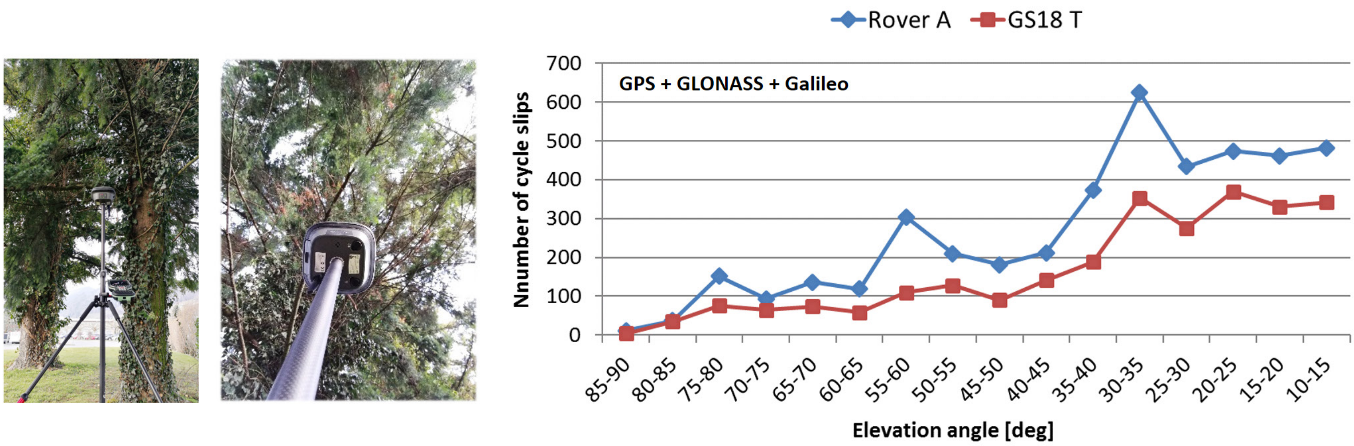

Figure 7 - Comparison of the number of cycle slips between GS18 T and Rover A under heavy tree canopy (four hours of 1-Hz data, elevation cut-off: 10 degrees).

IMU-based tilt compensation RTK

Interpretation of pole attitude

Assuming the length of the pole is known, the position error due to pole tilt can be compensated by precisely determining the pole attitude (Luo et al., 2018). Fig. 8 shows the interpretation of pole attitude in the GS18 T, consisting of tilt, direction of tilt and sensor heading. The tilt t is the angle between the local zenith and the pole. The direction of tilt λ describes the angular orientation of the orthogonal projection of the pole on a horizontal plane with respect to geographic north. The heading γ shows the direction that the sensor is pointing to and is also expressed regarding geographic north. Note that if the pole is vertical the heading γ is still well defined, whereas the direction of tilt λ does not exist because the orthogonal projection of the pole on a horizontal plane is a single point in this case. Apart from the attitude components themselves, the Leica Captivate field software also provides the corresponding quality estimates, along with the overall uncertainty of 3D attitude determination.

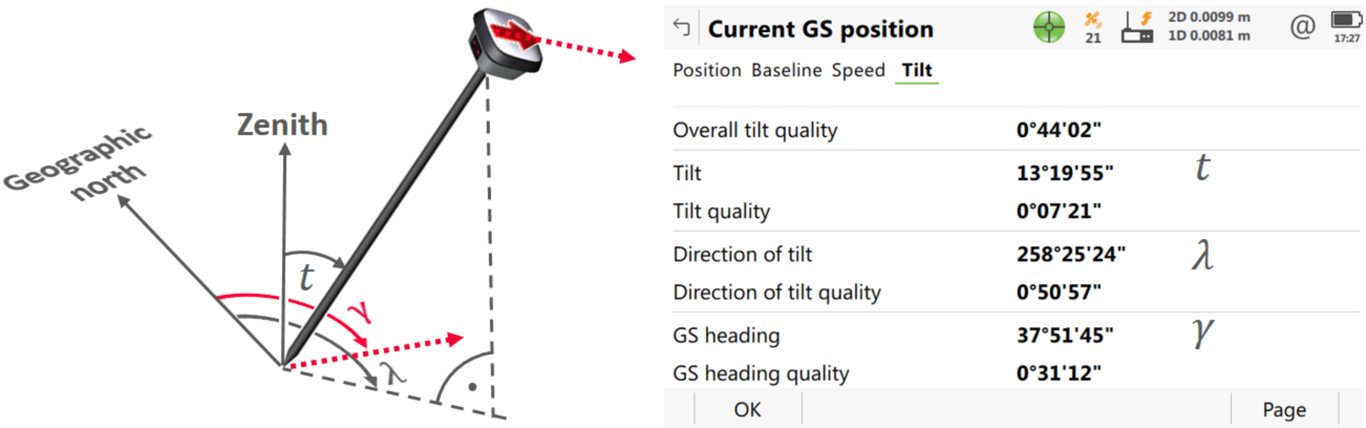

Figure 8 - Interpretation of pole attitude in the Leica GS18 T using tilt t, direction of tilt λ and sensor heading γ. α

GNSS/INS integration

Taking advantage of the complementary characteristics of the two navigation sources, integrated GNSS/INS navigation systems which have long existed in the aerospace industry are now available in surveying applications (Scherzinger, 2009; Dusha, 2017). In Fig. 9, the GNSS/INS integration of the Leica GS18 T is schematically illustrated. The MEMS IMU utilises a three-axis accelerometer and a three-axis gyroscope. Each IMU is individually factory calibrated by Leica Geosystems over the whole operating temperature range. Precise acceleration and angular velocity measurements from IMU are provided to INS, along with high-rate position and velocity estimates from GNSS. The INS algorithm mathematically rotates and integrates the IMU measurements to determine the attitude of the pole and the associated quality measure. In addition, the sensor fusion of GNSS and IMU enables a real-time estimation of accelerometer and gyroscope biases to minimise the time-dependent drift in the attitude solution. Based on the GNSS position, the INS attitude and the pole length, the field software Leica Captivate computes the tilt-compensated pole tip position and the coordinate quality (CQ) including both GNSS and INS uncertainties. Furthermore, the heading information is used to automatically update the 3D visualisation of the surroundings to help the user easily orientate himself in the survey environment.

The GS18 T is self-initialising and does not require any calibration procedure in the field. The internal quality control mechanisms allow an automatic start/stop of tilt compensation if the estimated 3D attitude uncertainty (see "Overall tilt quality" in Fig. 8) is below/above 2 degrees. Under normal conditions with sufficient movements, the 2-degree attitude uncertainty can be initially achieved within seconds through metre-level movements. Consistency checks between GNSS and INS are carried out constantly to enable a robust system that can cope with extreme pole dynamics, such as hard shocks. Since no magnetometer measurements are involved in the computation of tilt-compensated positions, the GS18 T is immune to magnetic disturbances.

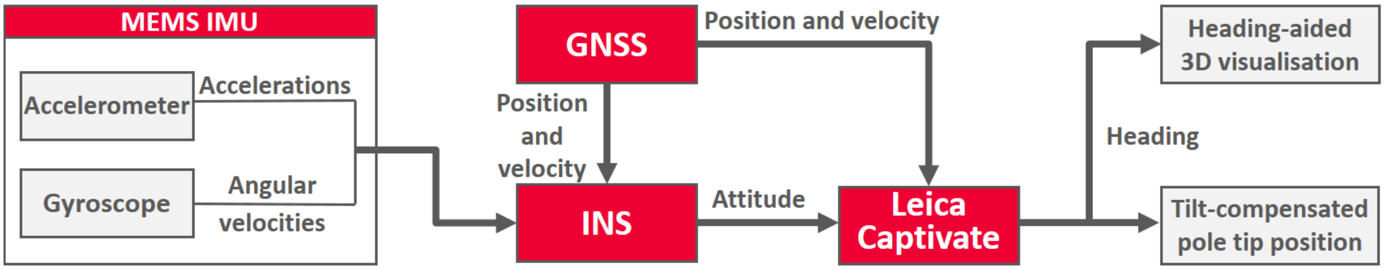

Figure 9 - Schematic and simplified illustration of the GNSS/INS integration implemented in the Leica GS18 T.

Accuracy aspects

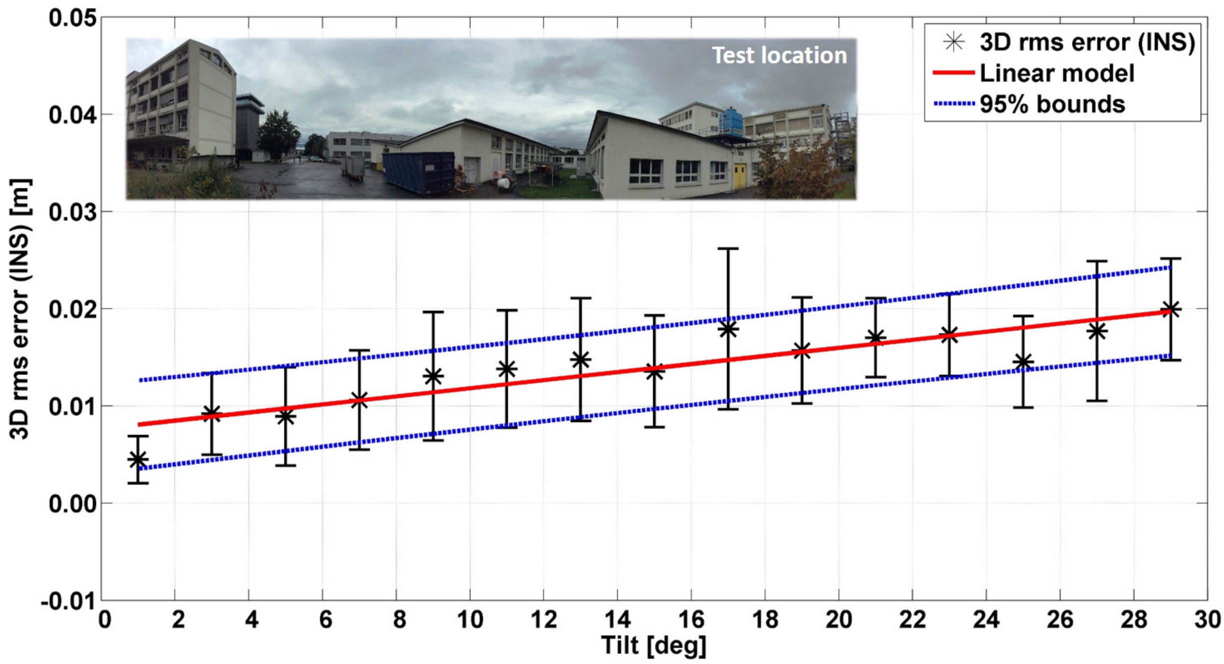

Figure 10 - 3D root mean square (rms) error of the pole tip position due to the INS attitude error by using a laser-based measurement system as a reference (pole length: 1.800 m, tilt bin width: 2 degrees).

Assuming the pole is a rigid body, the error in the tilt-compensated pole tip position is mainly attributed to the GNSS position error and to the INS attitude error. Using a laser-based measurement system as a reference, the contributions of the individual error sources of the GS18 T to the overall pole tip position error can be analysed. Based on representative data sets including various pole dynamics such as static, kinematic and stop-and-go, Fig. 10

shows the 3D root mean square (rms) error of the pole tip position, which is purely caused by the INS attitude error over a pole length of 1.800 m. A bin width of 2 degrees is used for the tilt angle, where the vertical bars show the dispersion of the 3D error samples in the bins. Using a linear regression model, the 3D rms position error due to the attitude error grows from 8 mm to 2 cm as the tilt increases from 1 to 30 degrees.

Neglecting the correlations between the GNSS position error and the INS attitude error, the relationship between the pole tip position error and the individual GNSS/INS error components can be expressed according to the error propagation law as

$$\sigma_{PT} = \sqrt{\sigma_{GNSS}^2 + \sigma_{INS}^2}\,, \tag{1}$$

where σ_{PT} denotes the pole tip position error, σ_{GNSS} is the GNSS position error, and σ_{INS} refers to the position error induced by the INS attitude error over the pole length. As the tilt angle increases, σ_{GNSS} becomes larger due to degradation in signal tracking (Fig. 4). Also, σ_{INS} grows, as illustrated in Fig. 10. Therefore, the pole tip position error, σ_{PT}, increases with increasing tilt.

Table 1 provides the GNSS and INS error components of the GS18 T from two independent accuracy tests. It can be seen that the tilt is accurately determined with a mean error of 0.2 degrees. The overall 3D attitude error is below 1.5 degrees, and its contribution to the pole tip position error, σ_{INS}, is smaller than 2 cm over a pole length of 1.800 m. Furthermore, the pole tip position error calculated using Eq. (1) is highly consistent with the reference value at the millimetre level, confirming the negligible correlations between the GNSS and INS error components. Note that the current tilt compensation algorithm of the GS18 T does not account for the pole bending effects, which degrade the positioning accuracy more significantly as the pole length increases. Thus, a stable 2-metre carbon fibre pole is recommended to achieve the specified accuracy.

	No. of positions	Tilt error [deg]	3D attitude error [deg]	σ_{GNSS} [m]	σ_{INS} [m]	σ_{PT} [m]	σ_{PT} (Eq. (1)) [m]
Test 1	18986	0.15	1.014	0.018	0.011	0.022	0.021
Test 2	20499	0.21	1.498	0.024	0.017	0.026	0.029

Table 1 - Attitude and position errors of the Leica GS18 T by using a laser-based measurement system as a reference (pole length: 1.800 m, see Fig. 10 for the test location).

Performance analysis

STATIC MEASUREMENT VS. INSTANTANEOUS MEASUREMENT

In static RTK measurement, a target point is usually occupied for a short period, for example 5 s, where multiple positions are collected to provide a weighted mean solution. In conventional RTK surveying where the pole needs to be levelled, this approach has the advantage of reducing the human error appearing when trying to centre the bubble. In the tilt compensation case, levelling the pole is not needed, and thus this advantage does not exist anymore. In addition, a static occupation over such short time does not benefit from decorrelation of satellite geometry, atmospheric conditions and multipath effects. According to Hofmann-Wellenhof et al. (2008, p. 158), an antenna height of 2 m leads to an approximate period of 16 minutes for the multipath error. To take RTK measurements as fast as possible, particularly in topographic surveys, the instantaneous method is more suitable, where the coordinate for the measurement time tag is interpolated between the positions at the neighbouring two epochs to filter out effects of slight movement.

Table 2 compares the rms errors from the tilt-compensated static and instantaneous measurements of a known point using the GS18 T under open sky. Different occupation times such as 5 s, 15 s and 30 s were considered, which are commonly used in GNSS RTK surveying practices. In all three tests, the rms errors from the static and instantaneous measurements are comparable. The additional time spent in the static occupation does not lead to improved positioning accuracy, indicating in turn higher productivity of the instantaneous method. Taking Test 3 in Table 2 as an example, Fig. 11 compares the 2D (horizontal) position errors, showing similar accuracy performance between the 30-s static and instantaneous measurements.

	Test 1: Static occupation 5 s			Test 2: Static occupation 15 s			Test 3: Static occupation 30 s		
	3D	2D	1D	3D	2D	1D	3D	2D	1D
Static	0.013	0.011	0.005	0.014	0.013	0.007	0.014	0.013	0.005
Instantaneous	0.010	0.009	0.005	0.014	0.012	0.008	0.014	0.012	0.006

Table 2 - Comparison of the rms errors [m] from the tilt-compensated static and instantaneous measurements using the Leica GS18 T (pole length: 1.800 m, open sky, 100 measurements for each test).

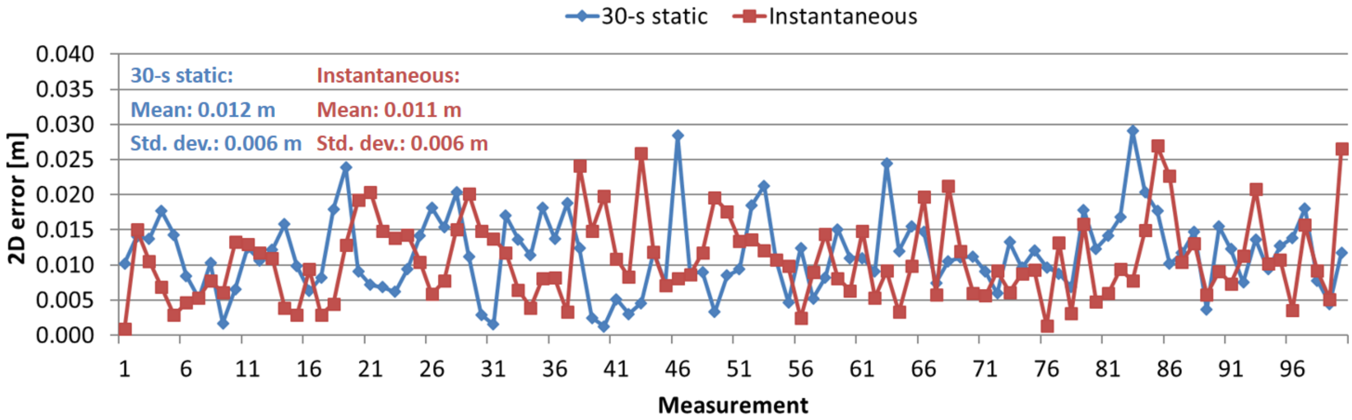

Figure 11 - Comparison of the 2D position errors from the tilt-compensated 30-s static and instantaneous measurements using the Leica GS18 T (pole length: 1.800 m, open sky; see Test 3 in Table 2).

CONVENTIONAL RTK VS. TILT COMPENSATION RTK

To demonstrate the advantages of using tilt compensation, the GS18 T was benchmarked against Rover A under open sky and strong multipath conditions. In the open-sky test (Fig. 12), two known points P1 and P2 that are separated by 8 m were measured alternately in the instantaneous mode for 10 minutes. Using Rover A, the pole needs to be levelled precisely before taking an instantaneous measurement, which is not necessary for the GS18 T due to tilt compensation. The number of measured points within 10 minutes represents a simple indicator for productivity. Table 3 summarises the results from the open-sky test with respect to productivity and accuracy. Without the need to level the pole, the GS18 T significantly reduces the time spent on a measurement, and thus increases the number of measured points by 33 per cent from 57 to 76 within a 10-minute period. In the tilt compensation case, despite the additional error from attitude determination, the 3D rms error is only 3 mm larger when compared to Rover A and amounts to 2.4 cm, which is acceptable for most topographic surveys.

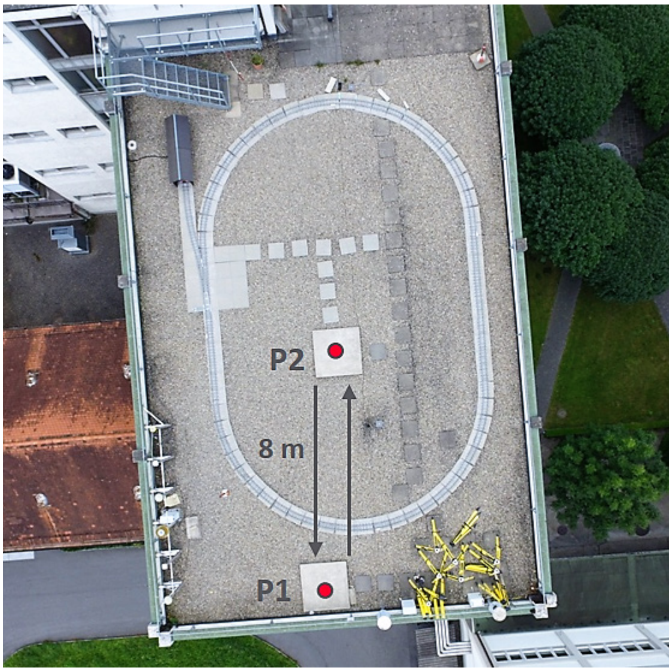

Figure 12 - RTK performance benchmarking under open sky by measuring two points alternately in the instantaneous mode for 10 minutes (Rover A vs. GS18 T, pole length: 1.800 m).

In the test under strong multipath conditions (Fig. 13a), a known point was chosen that is located very close to a building and can still be measured with Rover A by holding the pole vertically. In addition, a building with metal facades was selected to show the immunity of the GS18 T to magnetic disturbances. A total of 200 instantaneous measurements were taken under different satellite geometries and Table 4 summarises the results regarding availability, accuracy and reliability. Using the GS18 T with tilt compensation, the availability of RTK fixed solutions increases by 15 per cent when compared to conventional RTK using Rover A. The positioning accuracy is significantly improved, on average by 50 per cent. The reliability gives the percentage that the position error is less than three times the CQ, which is slightly enhanced by up to 6 per cent for the horizontal components. These improvements with the GS18 T are attributed to 1) robust and high-sensitivity GNSS signal tracking in difficult environments, 2) a larger distance of the antenna to the building as a result of a tilted surveying pole (Fig. 13b), encountering weaker multipath effects, and 3) sophisticated GNSS/INS integration allowing accurate tilt compensation. Note that such a strong multipath environment is considered as an extreme case and is far beyond the standard conditions relevant for accuracy and reliability specifications. In addition, points closer than 10 cm to a building cannot be measured with Rover A at all since in this case it is not possible to level the pole at the target point.

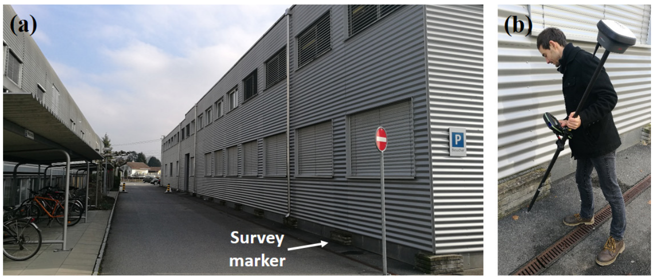

Figure 13 - RTK positioning test in a strong multipath environment (pole length: 1.800 m) (a) Survey marker near a building with metal facades, (b) Tilt compensation RTK measurement with the Leica GS18 T.

	Pole attitude	No. of points	3D [m]	2D [m]	1D [m]
Rover A	Vertical	57	0.021	0.014	0.016
GS18 T	Tilted	76	0.024	0.021	0.012

Table 3 - Comparison of the number of measured points within a 10-minute period and the resulting rms errors between GS18 T and Rover A (open sky, pole length: 1.800 m, instantaneous measurement).

	Pole attitude	RTK fixed/Total	Availability [%]	Accuracy (rms) [m]			Reliability [%]		
				3D	2D	1D	3D	2D	1D
Rover A	Vertical	141/200	70.5	0.101	0.084	0.057	96.5	92.9	95.7
GS18 T	Tilted	171/200	85.5	0.051	0.039	0.032	99.4	98.8	99.4

Table 4 - Comparison of the availability, accuracy and reliability of RTK fixed positions between GS18 T and Rover A in a strong multipath environment (pole length: 1.800 m, instantaneous measurement).

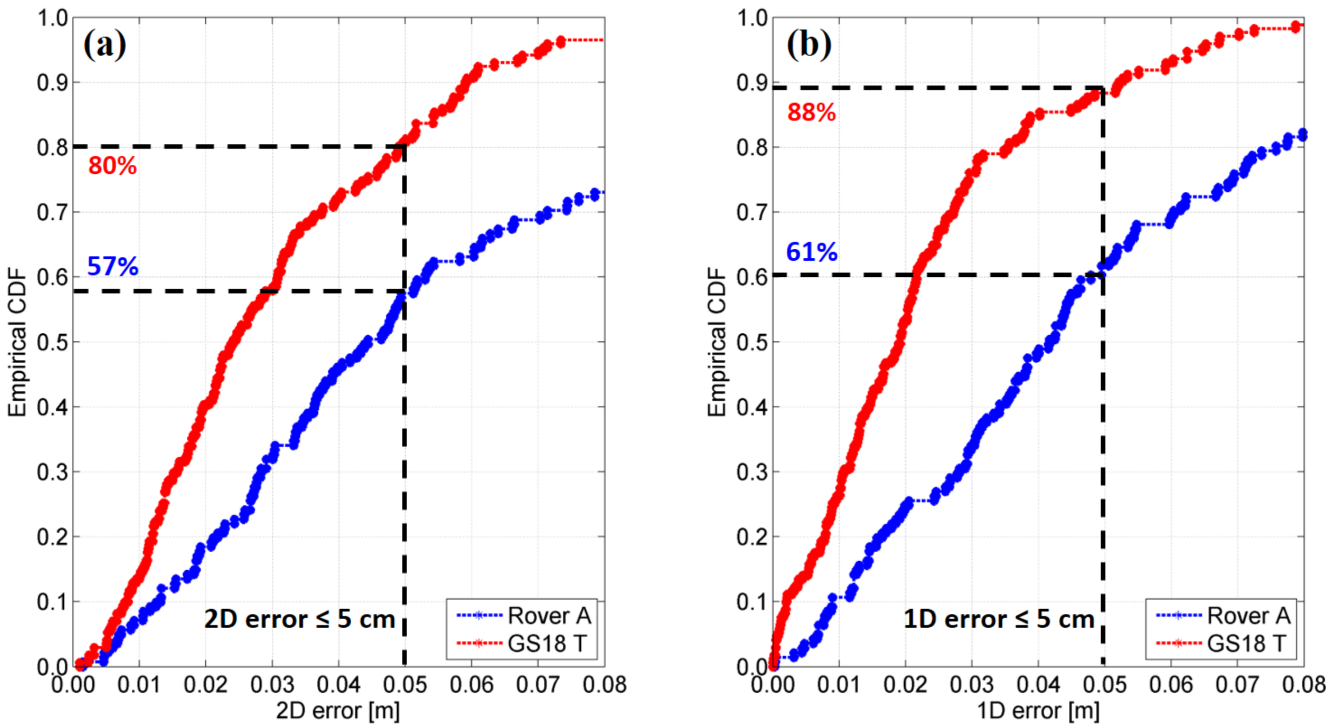

Figure 14 - Comparison of the error distributions between GS18 T and Rover A in a strong multipath environment (pole length: 1.800 m, instantaneous measurement) (a) 2D error CDF, (b) 1D error CDF.

In terms of accuracy, Fig. 14 shows the empirical cumulative distribution functions (CDF) of the 2D and 1D errors of RTK fixed positions, where the sample sizes are 141 and 171 for Rover A and GS18 T, respectively (Table 4). In comparison to conventional RTK using Rover A, the probability that the 2D (1D) error is within 5 cm increases by 23 per cent (27 per cent) when applying tilt compensation RTK with the GS18 T. In addition, the improvements in the height seem to be more significant when compared to the horizontal components.

MAGNETOMETER-BASED APPROACH VS. IMU-BASED APPROACH

Apart from no need of on-site calibrations, one major advantage of the IMU-based tilt compensation over the magnetometer-based approach is the immunity to magnetic field disturbances. Local magnetic disturbances can be caused by cars, power lines and buildings with structural steel, which usually exist in RTK surveying environments. To show the robustness of the GS18 T against magnetic disturbances, 1-s static measurements of a known point on a parking lot were carried out. Another survey-grade GNSS smart antenna denoted as Rover B was also used, which allows magnetometer-based tilt compensation up to 15 degrees.

Fig. 15 illustrates the 2D errors and CQ of 100 static RTK measurements with the GS18 T and Rover B. By comparing the 2D errors in Fig. 15a, the GS18 T provides higher accuracy and consistency than Rover B. Moreover, the 2D CQ estimates agree with the 2D errors, reflecting the positioning accuracy in a realistic manner. Regarding the results from Rover B in Fig. 15b, the 2D CQ values are significantly larger than the 2D errors if magnetic disturbances are detected, indicating unreliable tilt-compensated solutions. In this case, the user needs to repeat the measurement or to switch to the conventional RTK mode, which decreases productivity. Under certain circumstances, for example, when measuring points at larger tilt angles, the user would not be notified by a magnetometer-based system that the displayed accuracy cannot be achieved. Looking at the rms errors summarised in Table 5, the 2D accuracy of GS18 T is approximately 2 cm better than that of Rover B, whereas the 1D accuracy is at a similar level.

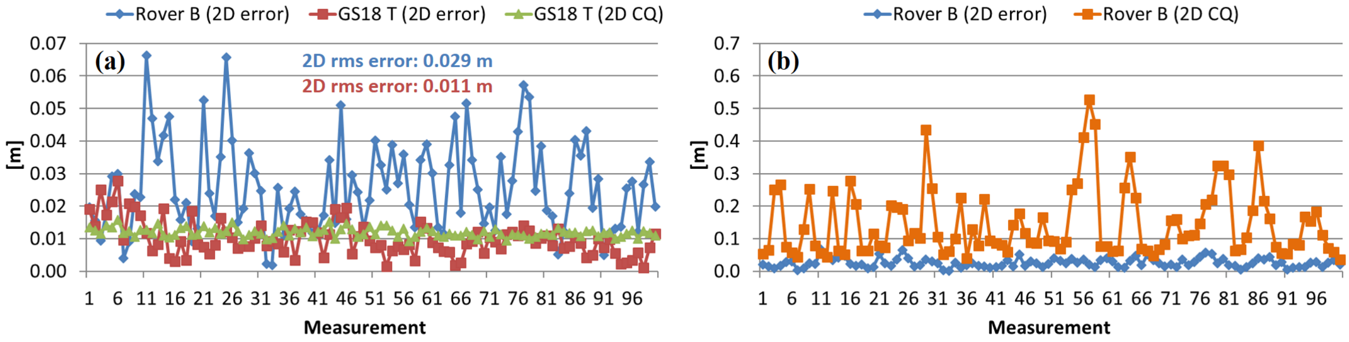

Figure 15 - Comparison of the 2D position errors and CQ between GS18 T and Rover B under magnetic disturbances (parking lot, pole length: 1.800 m, 1-s static measurement).

	Tilt compensation	No. of measurements	3D [m]	2D [m]	1D [m]
Rover B	Magnetometer-based	100	0.039	0.029	0.026
GS18 T	IMU-based	100	0.025	0.011	0.023

Table 5 - Comparison of the rms errors between GS18 T and Rover B under magnetic disturbances (parking lot, pole length: 1.800 m, 1-s static measurement).

PERFORMANCE WITH LARGE TILT ANGLES

Applying the IMU-based tilt compensation of the GS18 T, there is no limit to the maximum tilt angle as long as a sufficient number of GNSS satellites are tracked to be able to provide high-precision RTK solutions. Therefore, the GS18 T is applicable to hidden point measurements, for instance, hidden corners or points partly blocked by parked cars. Fig. 16a shows an example, where the survey marker is obstructed by a car and the pole needs to be largely tilted to be able to measure the point. In Fig. 16b, the 3D errors and CQ from 100 instantaneous measurements are illustrated, along with the tilt angles ranging between 36 and 56 degrees. The 3D rms error is 1.6 cm, and for 87 per cent of the measurements, the 3D error is below the 3D CQ, implying high reliability even when the pole is strongly tilted. The 2D and 1D rms errors are 1.3 cm and 9 mm, respectively. The high performance of the GS18 T in large-tilt use case is due to 1) enhanced low elevation angle tracking capabilities, 2) use of precise IMU measurements instead of a magnetometer, and 3) robust quality control mechanisms in the GNSS/INS integration.

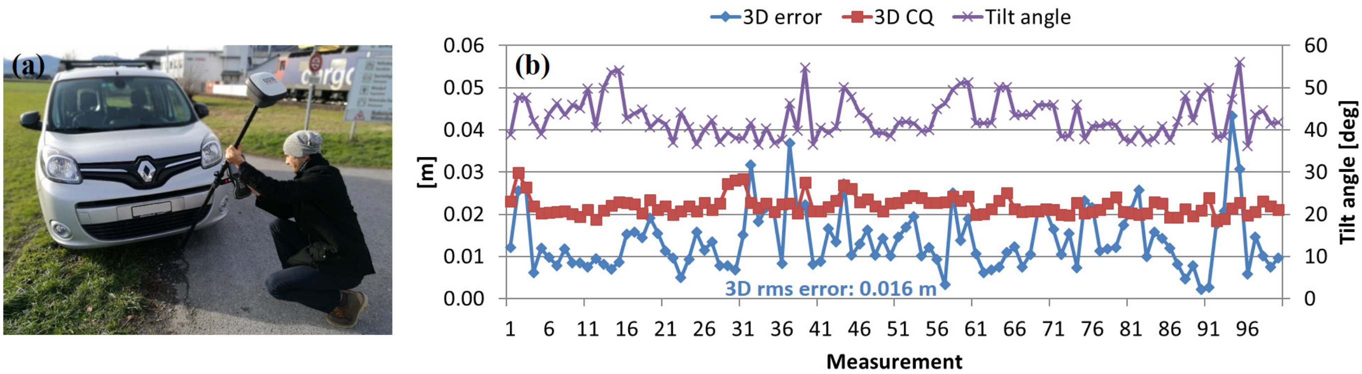

Figure 16 - 3D position errors and CQ from instantaneous measurements with large tilt angles between 36 and 56 degrees (Leica GS18 T, pole length: 1.800 m, open sky).

Heading-aided 3D visualisation

In addition to tilt and direction of tilt, the attitude estimate from the INS also includes sensor heading (Fig. 8). This information is used to support the user in the field by automatically updating the 3D visualisation of the surroundings depending on the sensor orientation. Taking RTK stakeout surveys as an example, if the sensor heading changes, the stake view and stake instructions in the Leica Captivate field software will update accordingly. Fig. 17 illustrates how the heading information helps when staking points with the GS18 T in the navigation view. If the stakeout point is more than 0.5 m away, the view shows the surroundings in the heading direction and follows the sensor from above and behind (Fig. 17a). The 3D view and stake instructions update automatically according to the current position and sensor heading, which changes from westward over southward to eastward in this example (Fig. 17b–d). By incorporating the sensor heading into 3D visualisation, the user can easily orientate himself in the survey environment and quickly move toward the target points, improving user experience and productivity.

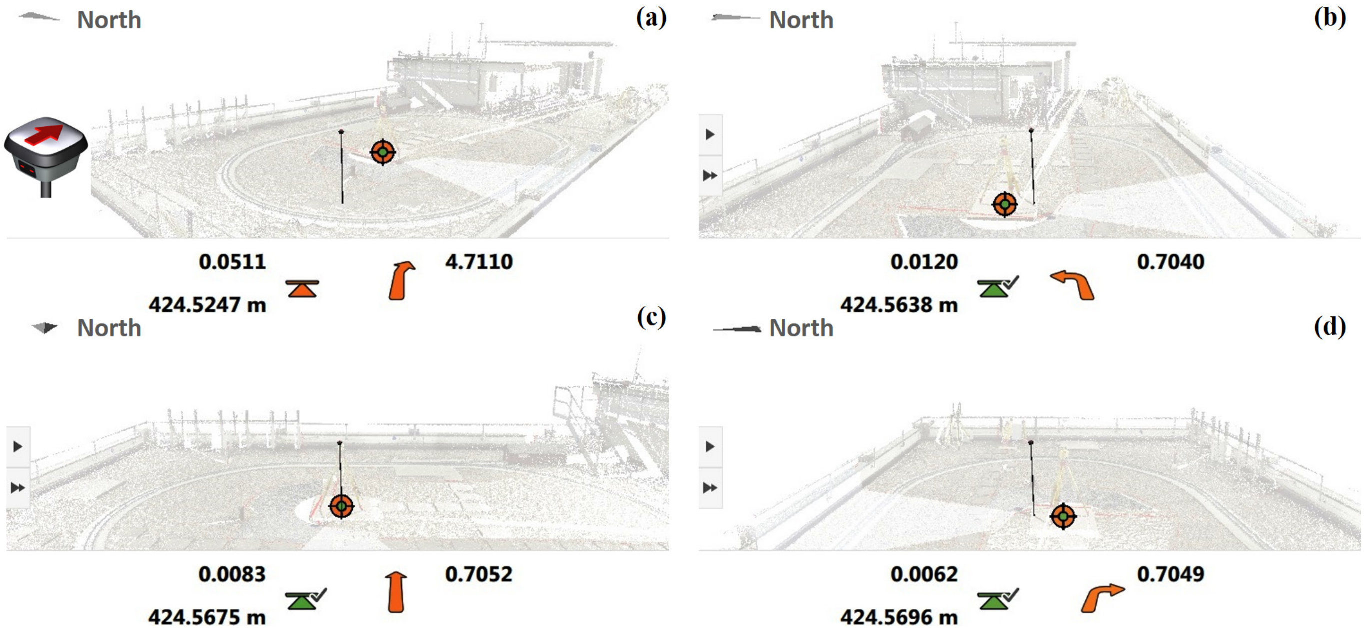

Figure 17 - Example of heading-aided 3D visualisation when staking points with the Leica GS18 T (open sky, pole length: 1.800 m)
(a) Navigation view, (b) View towards west, (c) View towards south, (d) View towards east.

Traceability of tilt-compensated measurements

Using the GS18 T to take tilt-compensated RTK measurements, the pole attitude and the associated uncertainty are stored in the point record, allowing full traceability and complete quality reporting. The attitude information can be exported directly from Leica Captivate by means of a stylesheet for instance. When importing GS18 T field jobs into the Leica Infinity office software 2.4 (Hanson, 2017, p. 5), the points measured with tilt compensation show the attitude components including tilt, max. tilt, tilt direction and sensor heading (Fig. 18).

For static measurements, the “tilt” is the last-measured tilt before storing the point, whereas the “max. tilt” is the maximum tilt reached during the occupation. For instantaneous measurements, the tilt and max. tilt values are identical. Within Infinity, it is possible to edit the pole length in the case of an incorrect input from the field, where the last-measured attitude is used to recalculate the pole tip position. In this way, correct coordinates are still obtainable, with full traceability of the components impacting upon the quality of tilt-compensated RTK solutions.

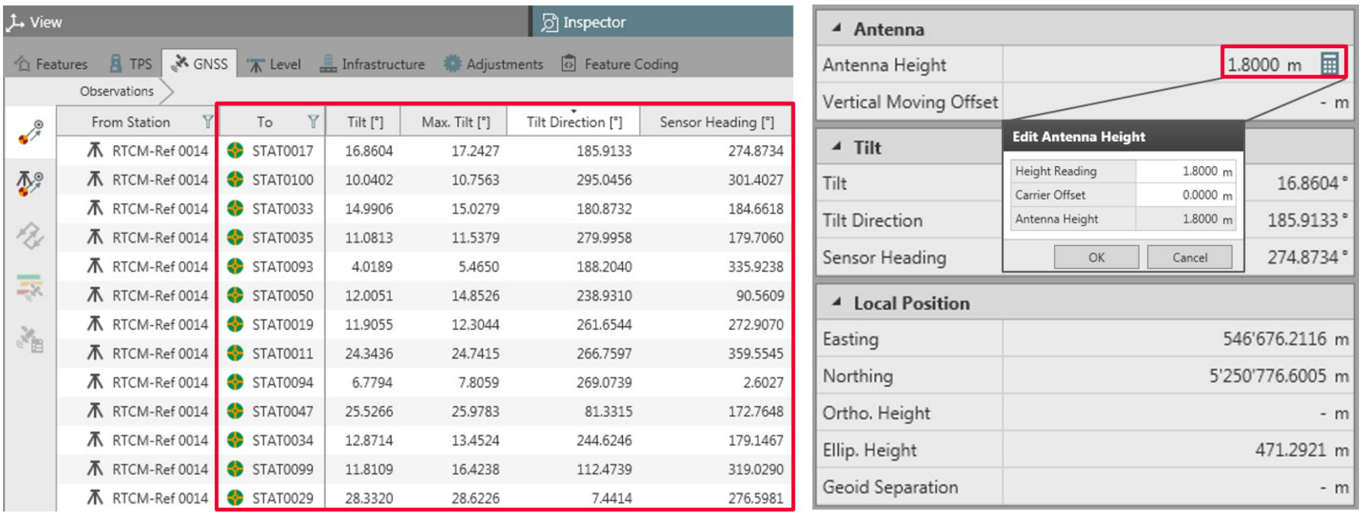

Figure 18 - Presentation of the attitude information from the Leica GS18 T in the Leica Infinity office software 2.4 with the possibility of editing the pole length.

Conclusions

This paper presented the new Leica GS18 T smart antenna, which makes use of an IMU-based tilt compensation approach to improve the productivity and user experience of high-precision RTK positioning. In comparison to magnetometer-based tilt-compensating systems, the GS18 T has the major advantages of being free from on-site calibrations, immune to magnetic disturbances and applicable at large tilt angles. Representative test results and benchmarking studies showed that using tilt compensation of the GS18 T significantly increases productivity and enhances the RTK positioning performance in difficult environments. These benefits are achieved by applying innovative technologies in satellite signal tracking and GNSS/INS integration. The main characteristics and benefits of the GS18 T are summarised as follows:

- Using tilt compensation, instantaneous measurement provides a similar accuracy level as static RTK measurement, along with a favourable time-saving effect.
- In comparison to conventional RTK with a vertical pole, tilt-compensating RTK significantly increases productivity by up to 33 per cent and considerably improves the near-building positioning performance regarding availability and accuracy.
- On a parking lot with magnetic disturbances, the IMU-based tilt compensation produces more accurate positions and more realistic CQ than the magnetometer-based approach.
- The IMU-based tilt-compensating RTK is applicable at large tilt angles of more than 30 degrees, where a 3D positioning accuracy of 2 cm is still achievable.
- By incorporating sensor heading into 3D visualisation of the surroundings, the user can easily orientate himself in the surveying environment, which improves productivity and user experience.
- The attitude information of tilt-compensated RTK measurements is fully traceable, enabling quality assurance for users themselves and their clients.

With the Leica GS18 T, the world's fastest GNSS RTK rover, Leica Geosystems sets new standards for precise positioning through easy-to-use sensor-fusion techniques.

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