Tersus GNSS
ExtremeRTK™ Technology
White Paper

Contents

Preface

With the increase of satellite constellations, the using scenarios of RTK have been greatly expanded. Meanwhile, working in extreme harsh environment has brought challenges to traditional RTK survey with the occurrence of false ambiguity resolution and RTK positioning outliers, which turns to be quality risks to surveying and mapping. The occurrence of false ambiguity resolution and occasional RTK positioning outliers is partially caused by the excessive pursuit of rapid RTK fix and high fix rate. It is difficult for surveyors to find errors on site easily and quickly. Therefore, a stable, reliable and accurate RTK product that is applicable in all scenarios shall be still the goal pursued by all surveying grade GNSS manufacturers. If we take a look at the latest RTK receivers from some leading manufacturers, the emphasis is still on the RTK stability and accuracy in various scenarios. As a professional RTK manufacturer, Tersus is customer-oriented and aims to provide customers with the most reliable products. Its industry-leading RTK products ensure accuracy as well as preventing false ambiguity resolution and occasional RTK positioning outliers. This white paper will focus on the excellent performance of Tersus's ExtremeRTK™ technology in all kinds of scenarios.

In the high-precision IOT (Internet of Things) field, there are also more and more devices with high-precision such as agricultural tractors, shared bikes and scooters, unmanned lawn mowers, precision-controlled drones and unmanned delivery trucks, which have all embedded GNSS module. The coordination of a high-precision RTK positioning and inertial navigation system has become an important topic. Tersus has the core algorithm of high-precision module and inertial navigation device and has made its first receiver with calibration-free tilt compensation through the coordination of RTK and IMU, which is popular among users all over the world. We will continue to develop more quality products for the integrated navigation of RTK and IMU. This white paper will also demonstrate the advantages and features of Tersus tilt compensation.

Being well aware of the complexities of a RTK product for surveying, we start from the very beginning. From signal capture and baseband tracking engine to PVT results and the overall algorithm of RTK, Tersus completes all the algorithm logic independently, which is also the core of Tersus to compete with the few fully independent manufacturers worldwide. ExtremeRTK™ emerged in this background and as a patented technology to start from, Tersus will continue to develop its markets for surveying and high-precision navigation so as to contribute and provide customers with more options.

1. Abstract

This white paper discusses Tersus's latest ExtremeRTK™ technology that integrates the receiver's hardware, high precision baseband IC, RTK engine, GNSS/INS coupling algorithm, etc. It enables an unprecedented stable performance in harsh environment and prevent the occurrence of occasional RTK positioning outliers fundamentally. It mainly includes:

- **Self-developed GNSS high-precision baseband IC tracking algorithm** with strong resistance to pseudorange and carrier phase multipath and strong mitigation of reflected multipath from buildings/ water/ ground and scattered multipath under trees.
- **The RTK algorithm performs a comprehensive check on the ambiguity search results in multiple dimensions**, including aperture, residual and global time domain, etc., to ensure that each group of accepted ambiguity has high credibility.

- **RTK does a comprehensive comparison of each accepted set of ambiguities, compared with a large number of other ambiguities (several hundred sets)**, to ensure that each accepted ambiguity set is optimal in a large enough space.
- **The test department has a database of thousands of test cases in various harsh scenarios and it is still expanding.** Before each version is updated and iterated, the case library test must be passed for release.
- **The innovative GNSS/INS coupling algorithm and accuracy control mechanism** ensure that the tilt measurement results meet expectations.
- **The GNSS boards are capable of recording raw observation data,** including raw RTCM data and baseband trace output results.

Tersus's latest ExtremeRTK™ technology provides a more reliable solution for a wide range of applications in surveying and mapping, precision agriculture, UAVs, autonomous driving, robotics, and so on.

The ExtremeRTK™ technology will be elaborated from the four most important factors of GNSS survey- signal tracking capability, fix speed, accuracy and operation efficiency. All data in this paper comes from the R&D team. The base station used in the test adopts Tersus and mainstream manufacturers' CORS service. Oscar Ultimate receiver is tested in different scenes of open sky, half-sky obstruction, dense forest and urban canyon, etc. Pictures are available in the subsequent test projects.

The main content is as follows:

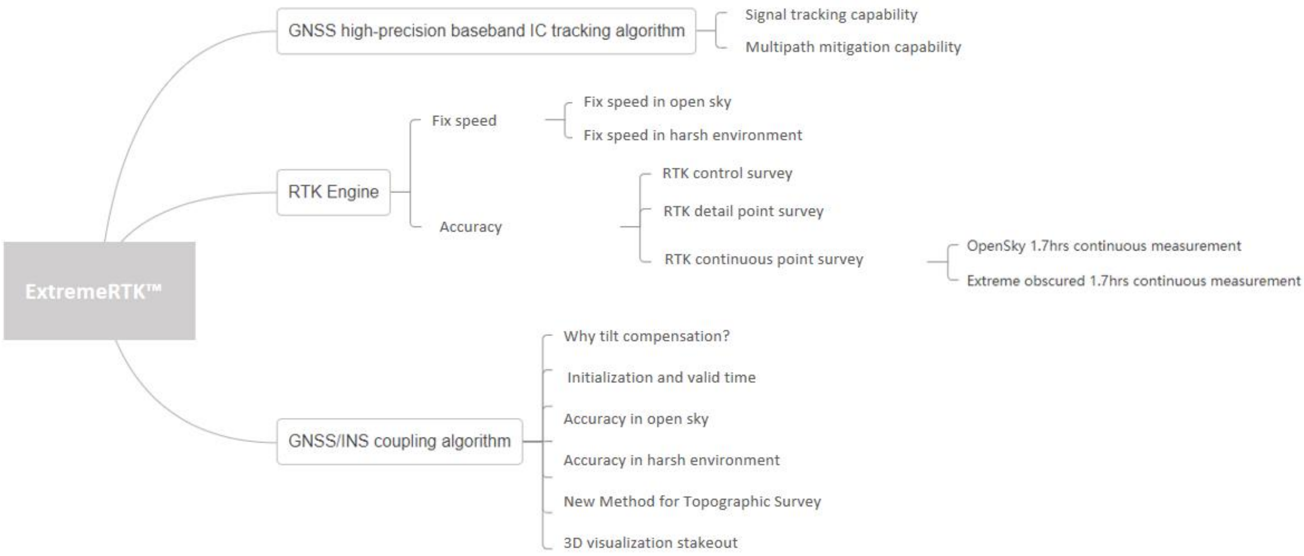


Figure 1.Main content of this paper

2. Signal tracking and multipath mitigation capabilities

2.1 Strong signal tracking capability

With ExtremeRTK^{TM} technology, Oscar GNSS receivers can **simultaneously track the satellite signals of 16 frequencies in the five constellations of BDS-2/BDS-3, GPS, GLONASS, Galileo, and QZSS, easily achieving 50+ satellite tracking on the ground.** The continuous optimization of GNSS high-precision baseband IC and RTK algorithm makes Oscar not only able to search more satellites, but also to effectively filter signals with serious multipath error and low signal-to-noise ratio. In urban canyons and dense forest areas where conventional receivers cannot measure due to insufficient searching or large noise, Oscar can still obtain high-precision. Being able to perform in all scenes and weather, Oscar has greatly broadened the application of RTK survey.

Table 2.1 Oscar’s satellite tracking capability

Constellation	Frequencies
BDS	B1I, B2I, B2a, B3I
GPS	L1 C/A, L2C, L2P, L5
GLONASS	L1 C/A, L2 C/A
Galileo	E1, E5a, E5b
QZSS	L1 C/A, L2C, L5

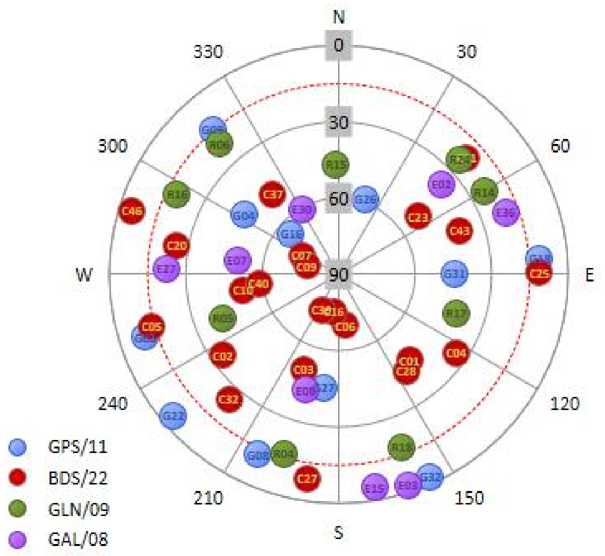


Figure 2.1 Sky map of satellite tracking

2.2 Multipath mitigation capability

According to the RTK double-difference model $\Delta\varphi_{AB}^{jk} = \frac{f}{c}\Delta\rho_{AB}^{jk} - \Delta N_{AB}^{jk} - \frac{f}{c}(V_{ion})_{AB}^{jk} - \frac{f}{c}(V_{trop})_{AB}^{jk}$, where $\Delta\varphi$ is the carrier phase observation, $\Delta\rho$ is the pseudorange observation, ΔN is the whole circumferential ambiguity, V_{ion} is the ionospheric delay, V_{trop} is the tropospheric delay. Through the double-difference solution, the error such as satellite clock error and receiver clock error are completely eliminated. Considering the proximity of two stations, the error caused by ionospheric and tropospheric delay will be eliminated according to the ionospheric and tropospheric spatial correlation. Thus, the source of RTK positioning error is basically multipath error.

ExtremeRTK™ creatively adopts a new solution that significantly mitigates multipath effect through hardware design such as anti-multipath antenna and GNSS high-precision baseband IC algorithm. Based on zero baseline test method, this test introduces the same observation signal to receiver brand A, Tersus BX40C, receiver brand B and receiver brand C. (later referred as REC1, REC2 (BX40C), REC3, and REC4). Figure 2.2 and 2.3 provides their respective pseudorange multipath statistics. The abscissa represents GNSS satellite frequencies and the ordinate represents multipath error. The smaller the error, the better the performance. Figure 2.4 to 2.6 shows the comparison of carrier multipath mitigation effects, in which the sky map corresponds to different satellite elevation of GPS, GLONASS, Galileo and BDS constellations. The lighter the color (green), the better the performance. It can be seen **that BX40C has stronger capability of mitigating multipath error at each frequency, especially for BeiDou constellation and low-elevation satellites.**

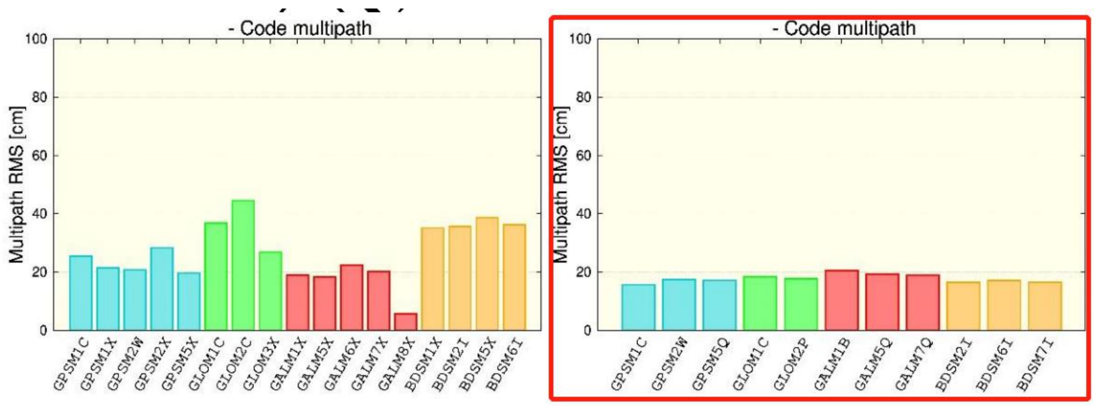


Figure 2.2 Pseudorange multipath statistics of REC1 and REC2 (BX40C)

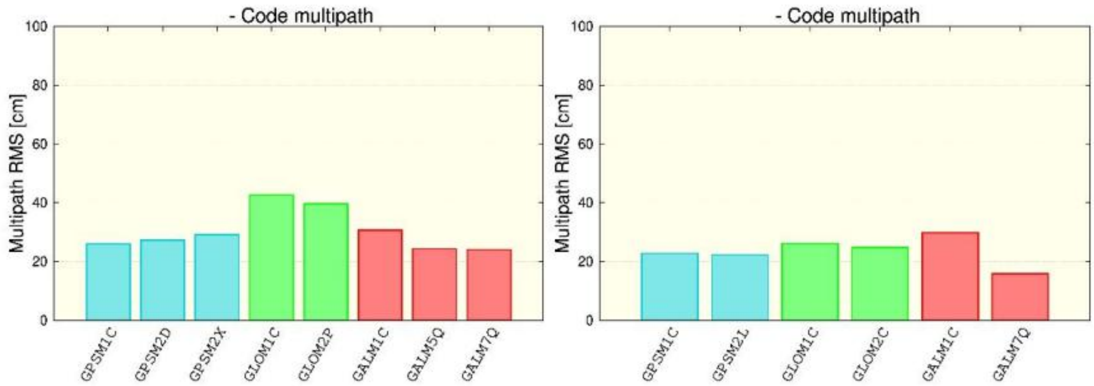


Figure 2.3 Pseudorange multipath statistics of REC3 and REC4

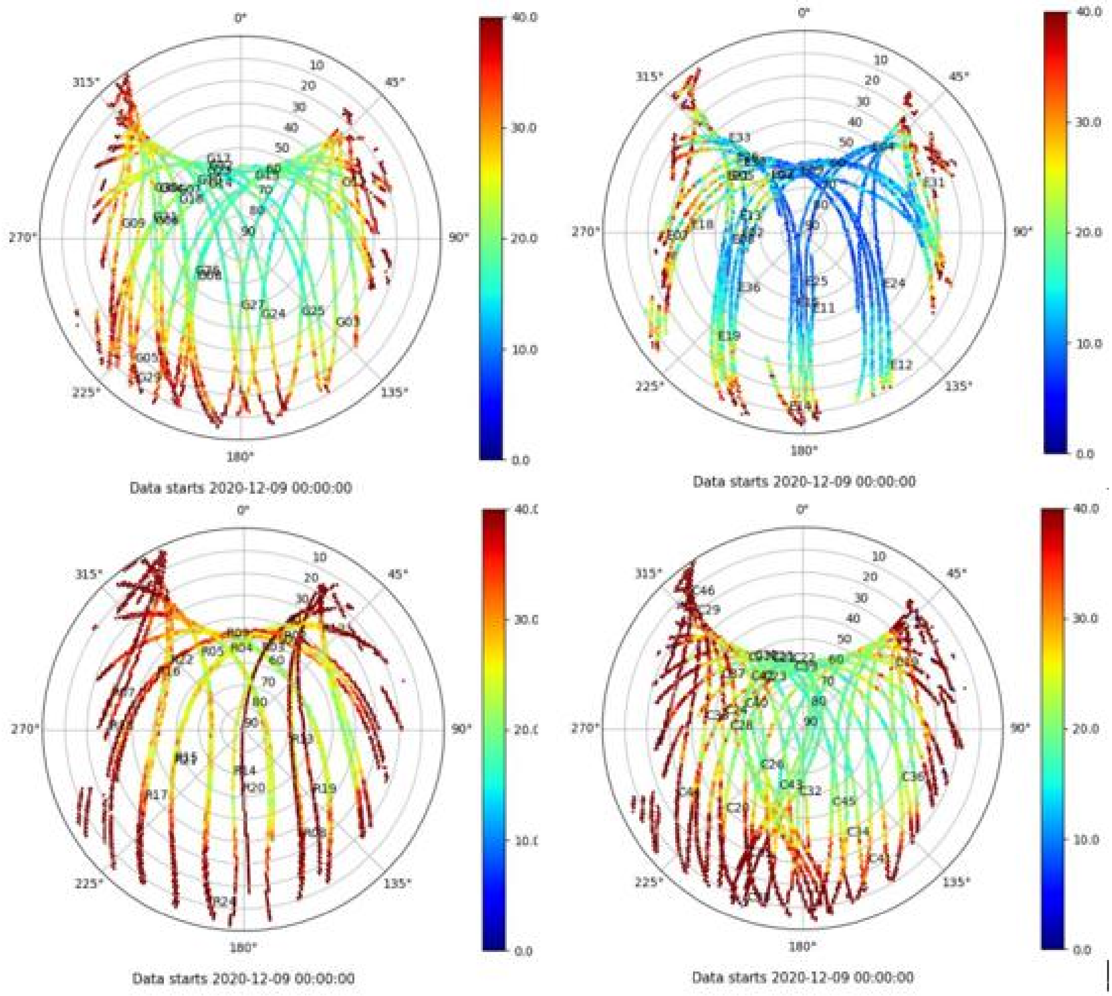


Figure 2.4 Sky map- carrier multipath error of REC1

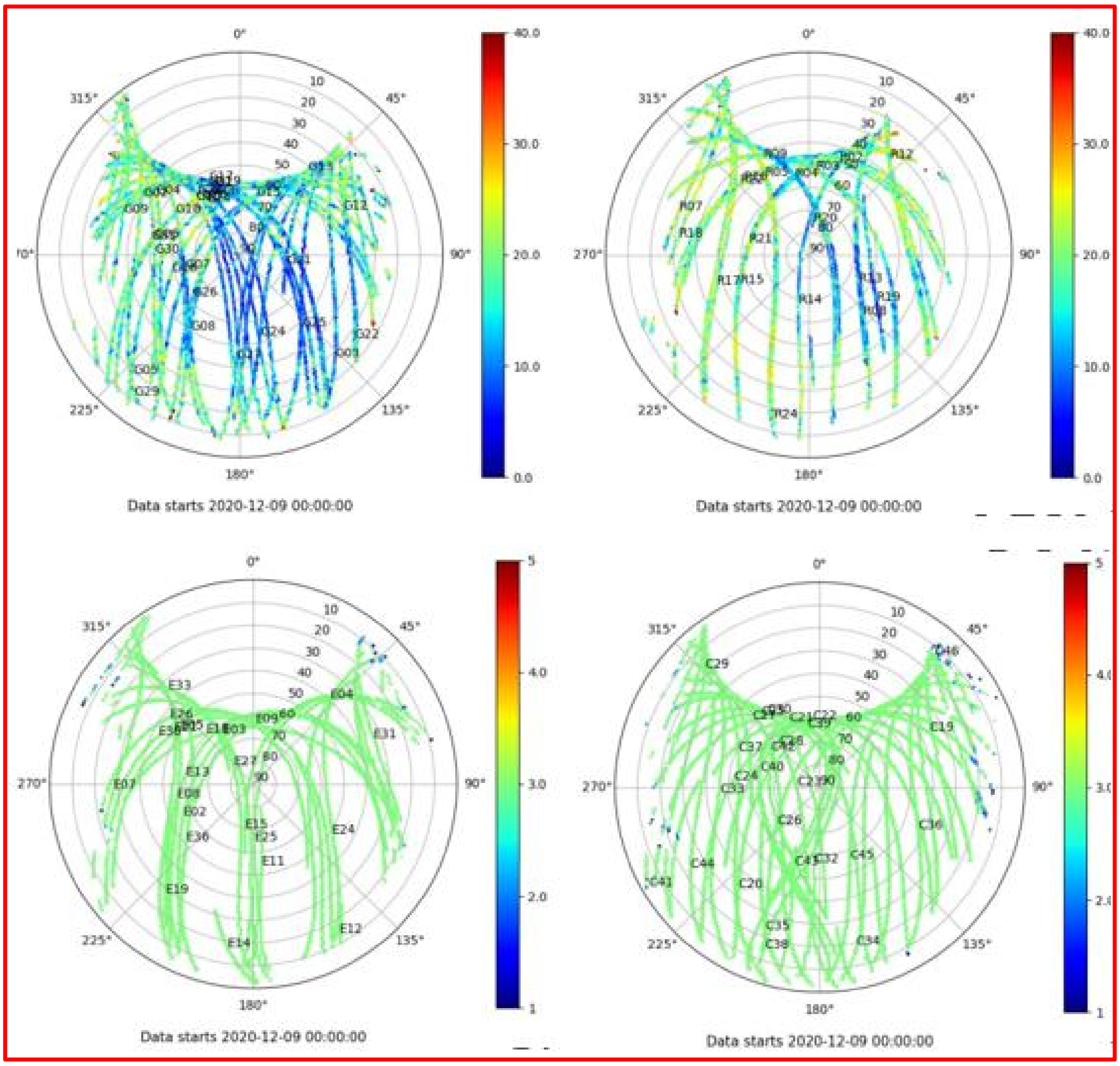


Figure 2.5 Sky map- carrier multipath error of REC2 (BX40C)

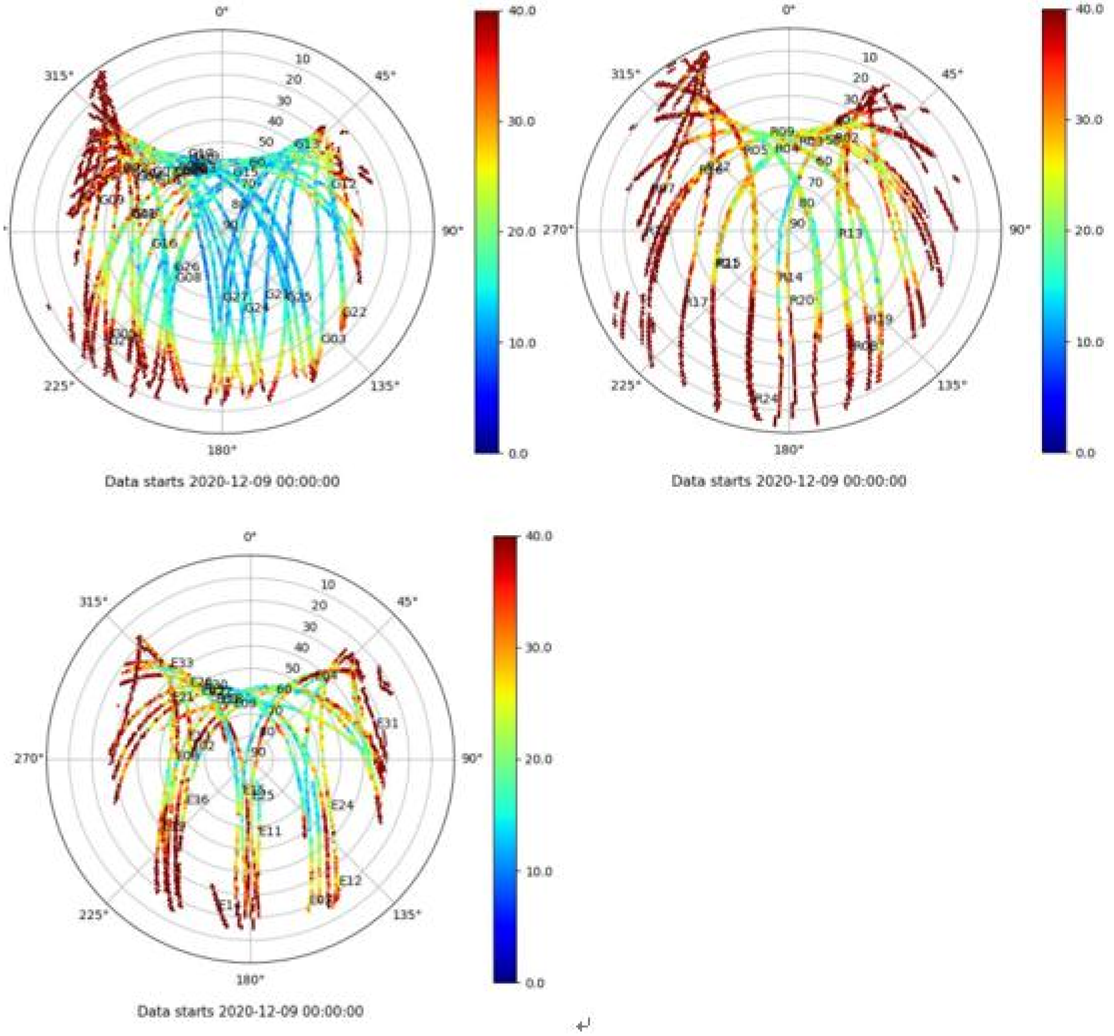


Figure 2.6 sky map- carrier multipath error of REC3

3. ExtremeRTK™ fix speed

3.1 ExtremeRTK™ fix speed in open sky

To present ExtremeRTK™ fix speed accurately, our test adopts Tersus base station, baseline distance of 15km and open sky environment. We use the state identifier in the GPGGA data stream and count the duration from receiving the first packet of correction data to RTK fix state, as TTFF (time to first fix). A total of 59 times of RTK reset were done, in which RTK reset is to redo RTK initialization (ambiguity resolution). The BX40C TTFF is shown in figure 3.1. It can be seen that **in open sky, the shortest TTFF is about 2s, the longest is about 3s, and the average time is 2.29s, which truly reflects the excellent performance of getting fixed in seconds through ExtremeRTK™ technology.**

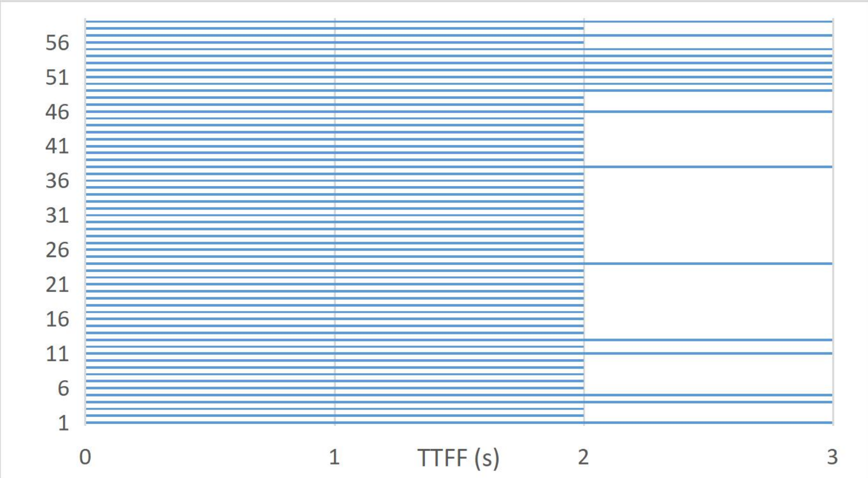


Figure 3.1 TTFF at 15km baseline

3.2 ExtremeRTK™ fix speed in harsh environment

To further demonstrate the excellent performance of ExtremeRTK™, the harsh scenario of Figure 3.2 was selected to test the fix speed. This scenario has multipath reflection error caused by glass and hard wall as well as scattering multipath error caused by dense forest. Similar to the open sky scenario, we conduct the RTK reset 23 times to count the RTK fix speed. After each reset, one measurement is conducted at the point. In this test, **the shortest RTK fixed time is 11 seconds, the longest is 29 seconds, and the average is 17.9 seconds. The measured value is 3.5cm of maximum error and 0.8cm of minimum error from the true value (3D Error), which fully meets the measurement specification**.

Figure 3.2 Outlook of harsh environment

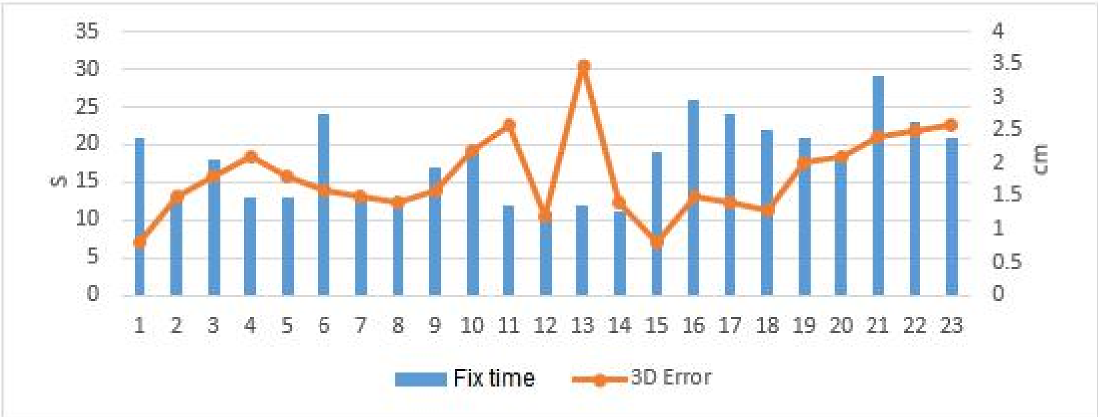


Figure 3.3 RTK fix time

4. ExtremeRTK™ accuracy

4.1 RTK control survey

With the maturity of RTK, many countries/cities have now allowed the use of it for control survey. Taking DG/TJ08-2121-2013 "Shanghai Engineering Construction Specification- Technical Specification for Satellite Positioning Measurement" as an example, the specification stipulates that RTK horizontal control survey should be carried out after RTK fix and for measuring each point, RTK should be independently initialized twice. Two sets of data should be collected for each initialization, the horizontal difference of four sets of data should be less than 2cm. Repeated sampling check should be carried out on the next day or near the time of collection finishing, and the difference between repeated sampling check and initial collection should be less than 3cm. It is also stipulated that RTK geodetic height control survey should be carried out after RTK fix, and for measuring each point, RTK should be initialized four times independently. Two sets of data should be collected for each initialization, and the vertical difference between the eight sets of data of one point should be less than 3cm. Repeated sampling check should be carried out on the next day or near the time of collection finishing, and the point elevation difference between the repeated sampling collection and the initial collection should be less than 5cm.

With reference to Shanghai GNSS Control Survey Specification, we adopt Tersus 5km baseline and design a test of four periods in a total of three days-2021-02-23 12:57:13- 2021-02-23 13:04:34 (period 1), 2021-02-24 09:24:43-2021-02-24 09:32:17 (period 2), 2021-02-24 14:18:50- 2021-02-24 14:26:13 (period 3), 2021-02-25 09:37:10- 2021-02-25 09:44:16 (period 4). In each period, the receiver is initiated eight times and two sets of data are collected after each initialization. Thus, 16 sets of data are collected in a single period and 66 sets of data are collected in total. From the table below, we can see that **under more stringent surveying environment than required, the difference during the single period and the error RMS in each period both meet the requirements of the Shanghai specification.**

Table 4.1 Statistics of RTK control survey

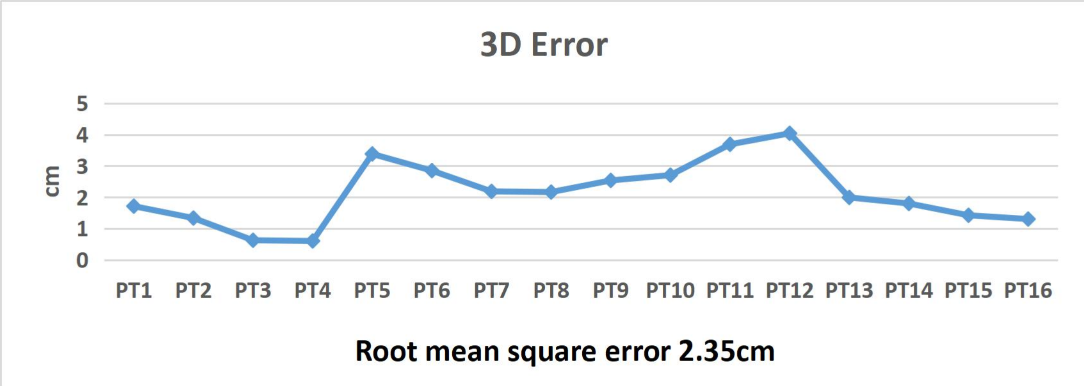
Period	Points	Horizontal error (RMS)	Vertical error (RMS)	Maximum difference (Horizontal)	Maximum difference (Vertical)	Spec requires (Horizontal)	Spec requires (Vertical)	Meet the spec.
1	16	0.32cm	0.42cm	0.83cm	1.32cm	≤2	≤3	Yes

2	16	0.25cm	0.39cm	0.79cm	1.32cm	≤2	≤3	Yes
3	18	0.35cm	0.78cm	1.24cm	2.68cm	≤2	≤3	Yes
4	16	0.29cm	0.96cm	0.85cm	2.66cm	≤2	≤3	Yes
Difference	66	0.66cm	0.74cm	2.66cm	3.66cm	≤3	≤5	Yes

4.2 RTK detail point survey

To test the accuracy, we set the control points in a severe scene and determine the true value accurately by conducting the traverse survey by the total station. In each of the four periods of 2021-03-22 12:25, 2021-03-22 13:42, 2021-03-22 14:52, and 2021-03-22 16:08, the receiver is switched on and off independently. One group of data is collected respectively in east/west/south/north. Thus, four groups are collected in each period and 16 groups are collected in total. **According to statistical analysis, the maximum value of 3D error was 4.0cm and the minimum value was 0.6cm. The percentage of points with 3D error less than 3cm was more than 81%. The 3D error RMS was 2.35cm, which met the requirement of detail point survey.**

Figure 4.1 RTK detail point survey in harsh environment



4.3 RTK continuous point survey

To intuitively show the stability of continuous survey accuracy of ExtremeRTK™, two testing environments of open sky and severe obstruction are selected. 1200 points are observed continuously for around 1.7 hours. Then we calculate the horizontal and vertical error RMS value. **As shown in Figure 4.2, in open sky, the horizontal error of 1200 points in 1.7 hours is only 0.64cm and the vertical error is only 1.44cm. As shown in Figure 4.3, in the severe scene with 10-story building and dense forest, the horizontal error of 1200 points in 1.7 hours is only 2.40cm and the vertical error is only 3.08cm**. Thus it is a verification that ExtremeRTK™ is fully qualified for all scenarios.

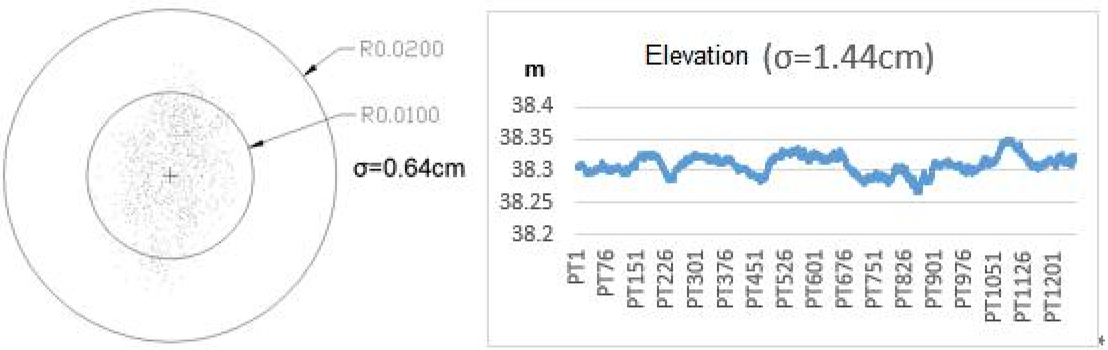


Figure 4.2 Continuous RMS in open sky

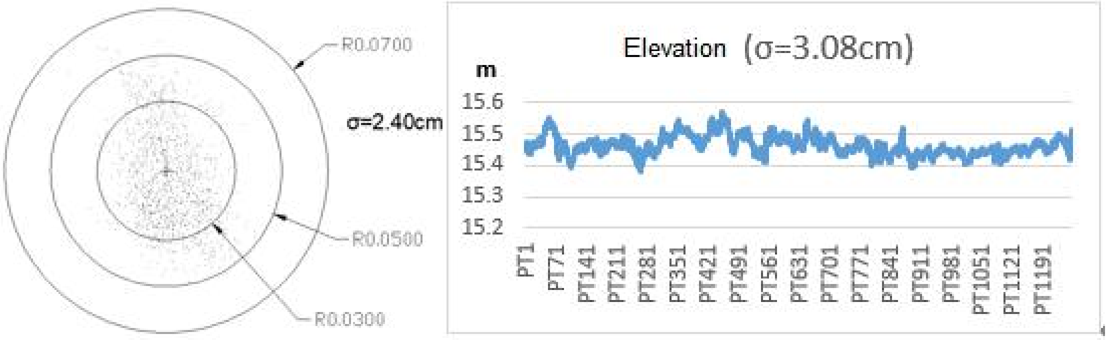


Figure 4.3 Continuous RMS in severe obstruction

5. GNSS/INS tilt compensation

5.1 Why tilt compensation?

With GNSS technology, the coordinates obtained directly are not that of the target point of the pole tip but of the phase center of the receiver antenna. Therefore, with traditional RTK receiver, the phase center coordinates can be calculated to the pole tip only when the pole is strictly upright and the pole height is known. The pole shall be ensured to be completely vertical throughout the measurement with the help of the bubble indicator, which could cause below problems:

a. Certain hidden points cannot be measured in the traditional way (such as points under the car);
b. It can be dangerous to measure in certain places;
c. It is inefficient and accuracy can be greatly affected by surveyors. For the inexperienced ones, it is difficult and physically demanding to ensure the bubble to be centered in the whole process.

With GNSS and IMU based tilt compensation technology, although the coordinates directly from GNSS are still of the receiver antenna phase center, through the six-axis IMU output and the GNSS/INS fusion algorithm, the Oscar GNSS Receiver can output the attitude information of the receiver and pole. With pole height as an input, a quick realization of a series of transformation of the Body coordinate system- NED coordinate system- ECEF coordinate system, and real time calculation of the receiver phase center coordinates to the pole tip, i.e., the target position can be achieved. The user only needs to turn on the receiver and set the pole height correct, then the subsequent measurement can be carried out at any tilt angle.

The advantages of Tersus's tilt compensated survey solution can be summarized as:

1) For the signals at low elevation angle, with the advantage of BX40C baseband IC algorithm, it can effectively mitigate the observation error such as multipath;

2) Equipped with the cutting edge IMU hardware, abandoning the traditional solution based on the magnetometer for heading, it is not affected by geomagnetism or surrounding magnetic objects;

3) Support larger tilting angle. It can help to keep the antenna away from the obstructions, which widens the satellite searching field and weakens the influence of multipath effect in the real surveying practice;

4) Reliable GNSS and IMU fusion algorithm, providing an efficient accuracy control mechanism to ensure that the output meets expectations.

Figure 5.1 Tilt survey– on the high way

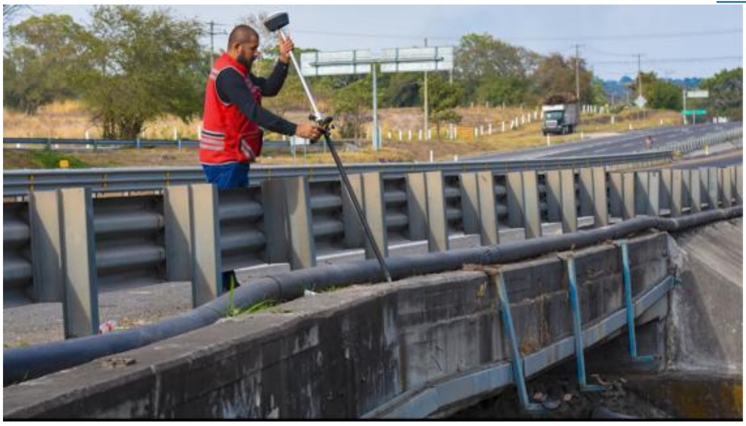


Figure 5.2 Tilt survey– on the bridge

5.2 Initialization and valid time

As found in the market research, the initialization time is one of the most important user concerns. Looking back at the development of tilt compensation solution, the first generation solutions have been gradually abandoned because the design is based on magnetometers for heading, which will be seriously affected by the surrounding geomagnetic environment. The ExtremeRTK™ receiver, benefited from the latest high-performance, high-precision and six-axis IMU, is completely immune to magnetic interference. It is ready to survey once the surveyor turns on the receiver and walks to the interested point. According to the actual test, compared with 40s' initialization time of the flagship receiver of the mainstream brand A, Tersus Oscar Receiver with ExtremeRTK™ technology needs only 5-15s random movement for initialization, which is obviously faster and easier. For details, please refer to the test video : https://youtu.be/Pr5eFV8WNtc .

Meanwhile, in order to solve the problem of easy loss of tilt compensation state, the ExtremeRTK™ tilt compensated survey solution comes up with a brand-new design of innovative GNSS/IMU coupling mechanism. It enables the user to initialize the tilt compensation even when the receiver is in the status of single point positioning. It is different from some other brands' tilt compensation solution which needs to ensure the receiver's status to be RTK fix. During the measurement, the IMU does not need to be reinitialized even after Tersus Oscar Receiver loses its RTK fix solution. To intuitively present the ExtremeRTK™ receiver's tilt performance, the test was conducted in an open sky environment with a 5km baseline and tilt angles of 10°, 30°, 45°, and 60°. The holding time of the tilt compensation available state was counted for each angle when Tersus Oscar Receiver was still. As shown in table below, even at 60°, the tilt available time can still last 216s (about 4 minutes). Compared with the performance of the other manufacturers, of which the tilt available time lasts only 30s, ExtremeRTK™ receiver has significantly improved the tilt compensation availability.

Table 5.1 Tilt available time for different angle

Tilt angle (°) / Hold time (s)	10°	30°	45°	60°
Time	＞600	510	442	216

5.3 Accuracy in open sky

To demonstrate the tilt compensation accuracy, measurement was conducted at tilt angles of 30°, 45° and 60° on the control point on the roof of Tersus's building and the accuracy at each angle was counted. The steps are as below:

(1) Firstly, turn off the tilt compensation function, level the pole, face the Tersus Oscar Receiver to 8 directions and measure 8 times. Take the average value as the true value for this control point. Then turn on the tilt compensation function, the tilt direction starts from the north, tilt the pole 30° and measure this control point once and set the measurement epoch for 5s.

(2) Adjust the tilt direction of the pole clockwise at 45° intervals, tilt the pole 30° to measure this control point, and set the measurement epoch for 5s.

(3) Repeat step (2) until all 8 tilt directions of data is collected. 12 cycles means about 96 sets of data are collected in total.

(4) After the data collection of 30° tilt angle, repeat steps (1)- (3) to collect data of 45° and 60° tilt angle.

The 3D error analysis of the statistics shows that even at the large tilt angle of 60°, the error RMS of the 94 sets of data is only 1.99cm.

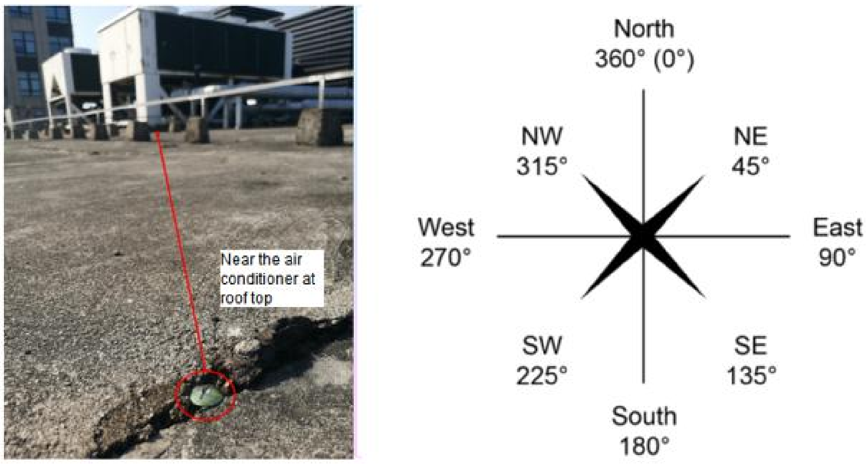


Figure 5.3 Test location and eight directions

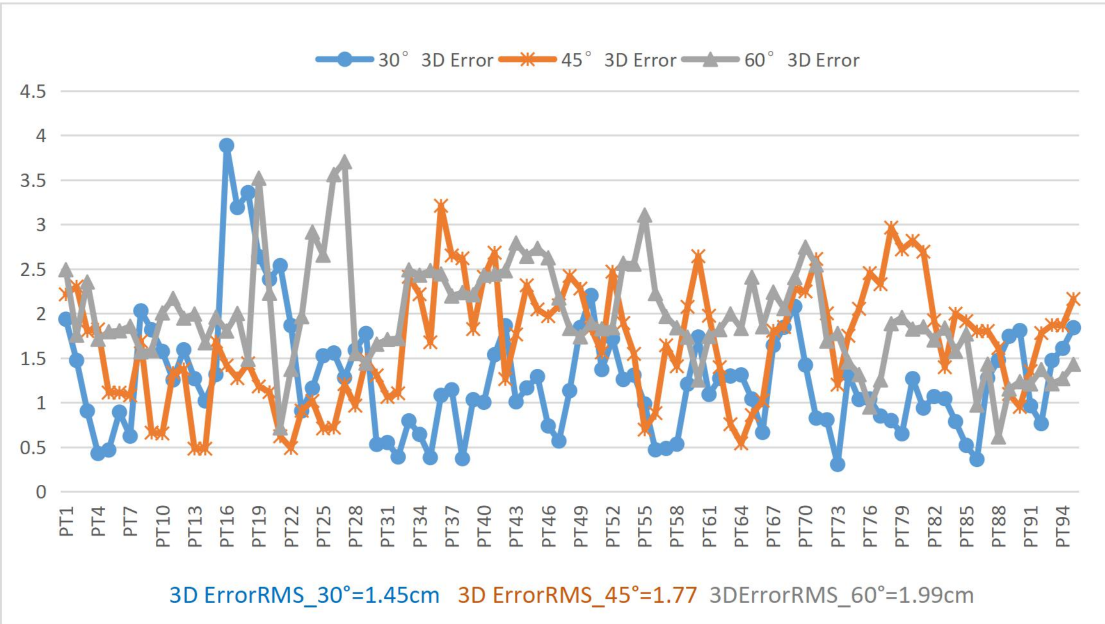


Figure 5.4 3D error analysis at three tilt angles in open sky

Given the excellent performance of Tersus Oscar GNSS Receiver with ExtremeRTK^{TM} tilt compensation, surveying is no longer affected by the magnetic disturbance and tilt angle. Even in the large angle of 60°, it can still provide high accuracy RTK solution with the empowerment of robust capabilities in tracking satellite signal. Therefore, ExtremeRTK™ is more suitable for measurement of concealed points, house corner and the point dangerous to access. The figure below shows the points at manholes and obscured by car parking, **even with a tilt angle of 50~60°, the RMS (due to the limitation of measuring methods, the average value of each angle is taken as the most reliable value, and assume it as true value) can still be stable within 2cm.**

Figure 5.5 Tilt survey for a manhole

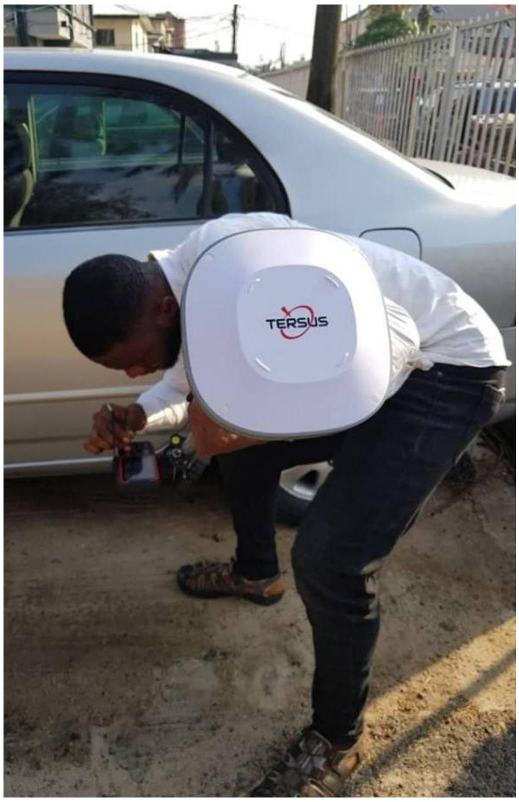


Figure 5.6 Tilt survey under a car

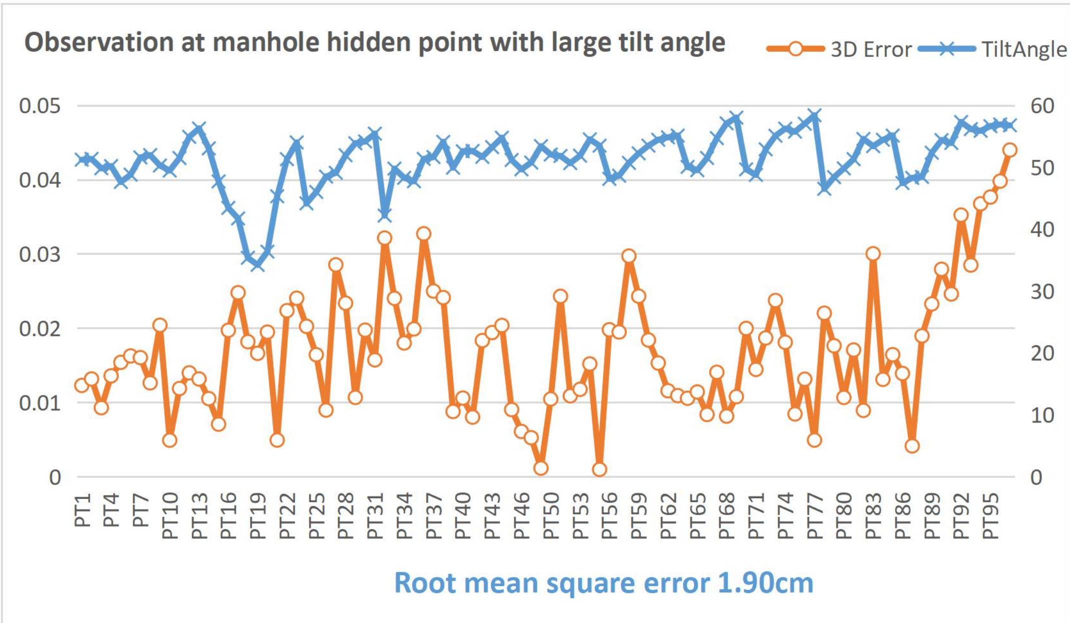


Figure 5.7 3D error at manhole hidden point with large tilt angle

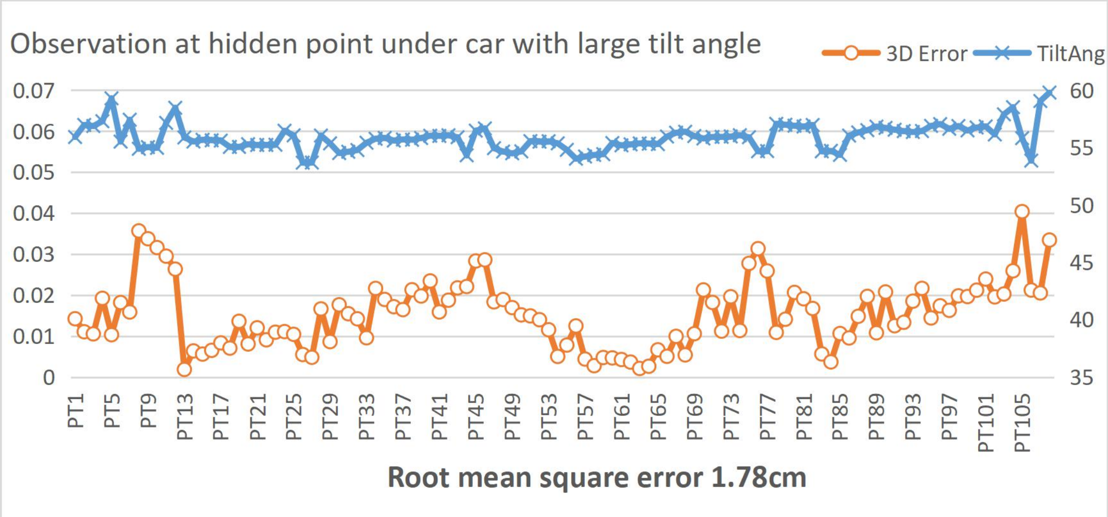


Figure 5.8 3D error at hidden point under car with large tilt angle

5.4 Accuracy in harsh environment

To demonstrate the excellent performance of tilt compensation, half-sky occlusion and urban canyon were selected. 600 points are collected continuously in each scene at a 1s acquisition interval. The horizontal and vertical error is calculated, using the average of all the measurement as the most probable value for true value. Figure 5.11 shows that for 604 points in the half-sky, there is a root mean square error of 1.35cm horizontally and 1.59cm vertically. Figure 5.14 shows that for 611 points in the urban canyon, it has a root mean square error of 1.31cm horizontally and 1.51cmvertically. It can be seen that the tilt compensation can still maintain high accuracy even in harsh environment.

Figure 5.9 Half-sky environment

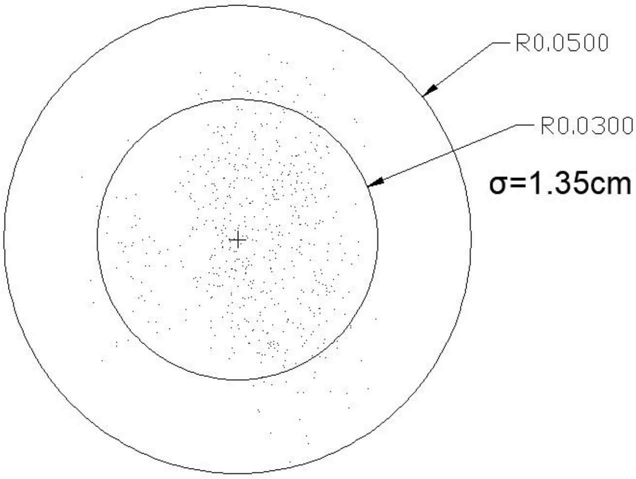


Figure 5.10 horizontal error in half-sky environment

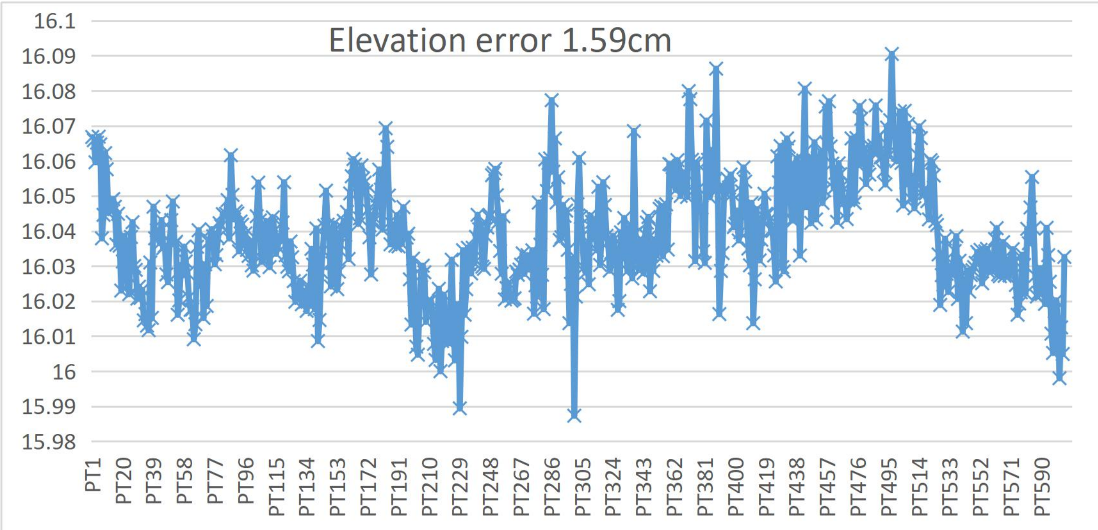


Figure 5.11 Vertical error in half-sky environment

Figure 5.12 Urban canyon environment

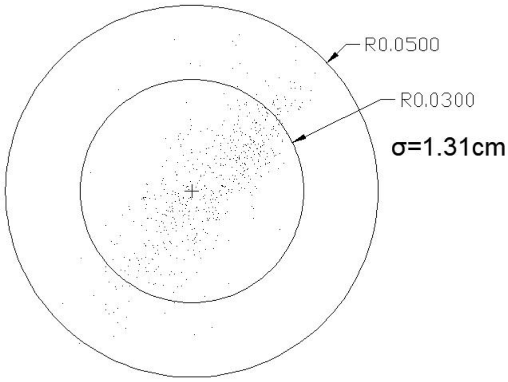


Figure 5.13 horizontal error in urban canyon

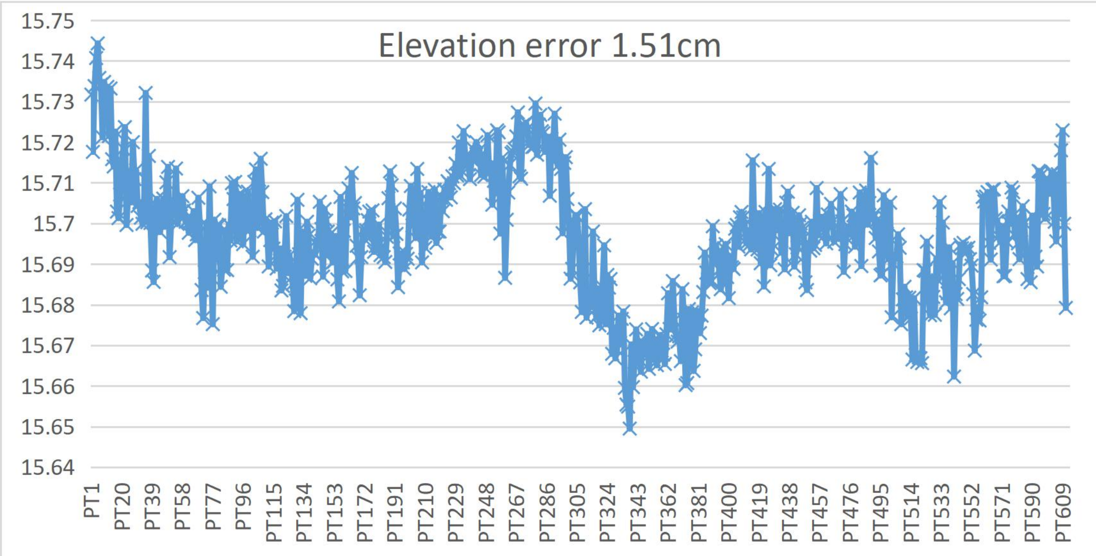


Figure 5.14 Vertical error in urban canyon environment

5.5 New Method for Topographic Survey

ExtremeRTK™-powered tilt compensation solution has excellent performance in initialization speed, available rate and accuracy, thus enables an unprecedented method for topographic survey. Taking earthwork volume survey as an example, it

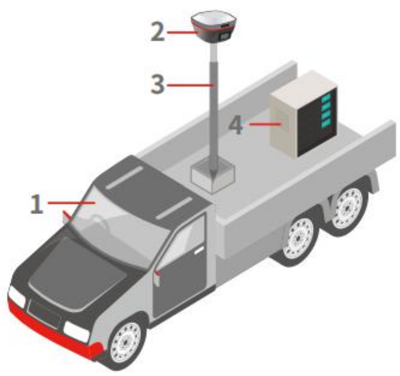
1) allows surveyors to drag the poles or use vehicle for continuous measurement without leveling;

2) accuracy is not affected by the capabilities of the surveyor; meanwhile, higher accuracy is achieved while efficiency greatly improved

3) in the same period, more dense points can be obtained to build a more

accurate TIN model;

To demonstrate the advantages of the new method for topographic surveying efficiency and accuracy, an area of 5.7m*38.7m was selected for testing. The results show that **compared with the traditional RTK measurement method (stop and level the pole), the efficiency of new method utilizing tilt compensation is improved by 85%, and the difference between two methods is only 2.3%.**



1. Mechanized carrier
2. Oscar Ultimate receiver
3. High-precision measuring pole
4. Processing module

Figure 5.15 Topology survey setting

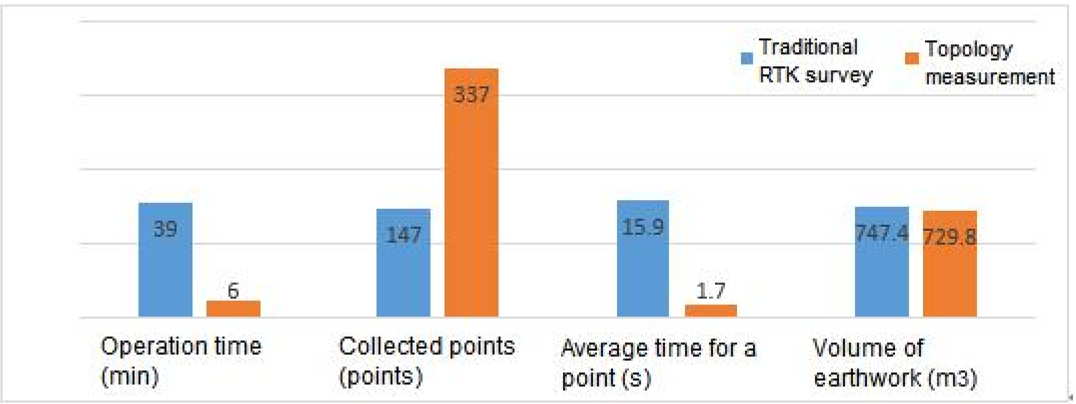


Figure 5.16 Comparison between traditional RTK survey and topology survey

5.6 3D visualization stakeout

Stakeout is one of the most important tasks in engineering survey. Without tilt compensation function, measuring a interested point needs leveling once. But to stakeout a point, the surveyor needs to level the pole until he finds the exact point in the field, which is very time consuming. When tilt compensation is used, looking at the level bubble is no longer needed, and the surveyor only needs to focus on finding the point on the ground by moving the pole tip. Beside, for the tilt compensated stakeout solution based on ExtremeRTK^{TM}, the 3D visualization stakeout function can be enabled by checking 'Rotate map during stakeout' in Nuwa display configuration.

The arrow A in the figure below indicates the receiver's direction and B indicates the moving direction of the pole tip. When starting to stakeout a point, make sure that the receiver display panel is facing you and select a stakeout point, then rotate arrow A (rotate the pole) to the staking point, and then work forward. When surveyor is closed to the staking point, the pole tip can be adjusted according to the arrow B indication. It is easy to achieve

1) intuitive 3D stakeout instructions, the pole's status can be displayed in real time with the 10Hz refresh rate and the user can quickly determine the orientation and the approximate distance of the current position to the point to be staked.
2) near the stakeout point, the position can be quickly determined by sliding the pole tip against the ground, without leveling point by point.
3) no need to find north point by point during stakeout, which improves the accuracy and efficiency as well as reduces the workload.

The application scenario of road centerline stakeout is selected and the straight line length of the road is 27.5m. The centerline are staked out at 1m intervals. Two methods of traditional RTK and tilt compensated stakeout are selected. It is required that when the horizontal deviation between the stakeout and design point should be <1cm, the location can be collected.The stakeout time and accuracy will be counted afterwards (Take the value of traditional RTK stakeout as the true value). **The results shows that compared with the**

traditional RTK method, the efficiency of tilt stakeout is improved by about 50%, and the deviation in root mean square error is only 1.48cm.

Table 5.2 Comparison between tilt takeout and traditional RTK stakeout

Comparison item	Tilt stakeout	Traditional RTK stakeout
Operation time (min)	16	32
Staking points (points)	29	29
Average time for a point (s)	33	66

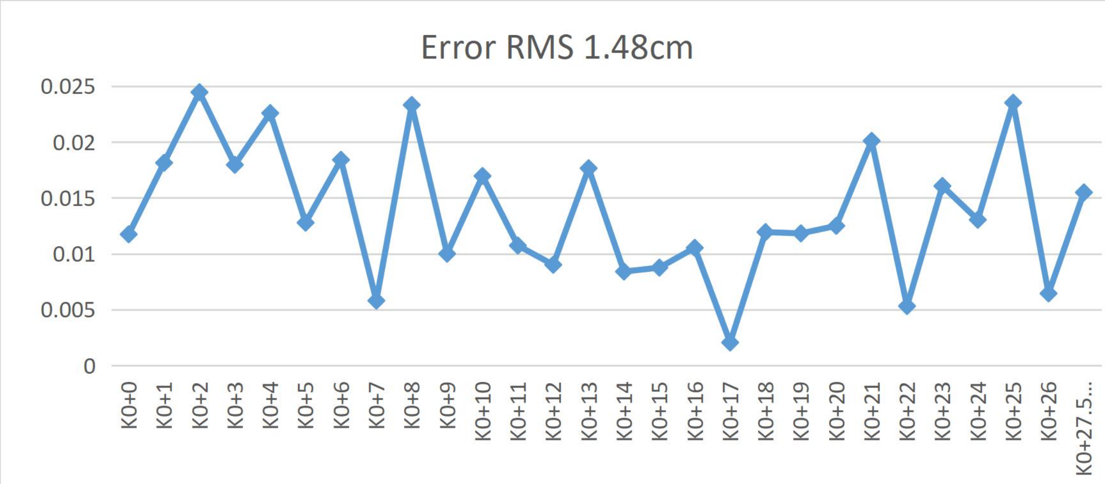


Figure 5.17 Root mean square error of tilt stakeout

6. Conclusion

As indicated from the test results presented in this white paper, ExtremeRTK^{TM} has remarkable performance in **RTK initialization, accuracy, tilt compensation**, etc., and possesses the strength as international mainstream brands do. Based on ExtremeRTK^{TM}, we will continue to invest in RTK Receiver with photogrammetry and laser scanning function. Meanwhile, we will focus on the R&D of professional industry software and integration of resources in data management and big data applications so as to provide users with professional services such as global CORS raw data download, Network RTK service, precision ephemeris download, high-precision ionospheric/ tropospheric models and fast PPP. Thus, a new Tersus ecological platform will be created to bring more possibilities and convenience for user applications.

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