

IMU-Enhanced GNSS Receiver X1

COMPETITIVE ANALYSIS

TEST REPORT

ABSTRACT

This report summarizes the performances between Bynav GNSS/INS integrated system X1 (hereinafter referred to as X1) and other competitor receivers in 8 typical application scenarios. The results show that X1 can ensure real-time, continuous and reliable centimeter-level positioning results under harsh environments, providing geo-referencing for autonomous driving and unmanned systems.

INTRODUCTION

The Global Navigation Satellite System (GNSS) can provide centimeter-level high precision positioning in a long term, but with low output frequency, and the GNSS signal can be blocked or interfered easily.

The Inertial Navigation System (INS) can provide effective angular rate and acceleration, as well as accurate relative displacement in a short time, but the error will accumulate rapidly over time.

The GNSS/INS combines the advantages of both GNSS and INS system. On the one hand, it uses GNSS to suppress the long-term drift of INS, and on the other hand, it uses INS to smooth the short-term errors of GNSS, thereby providing real-time, continuous, and reliable centimeter-level high-precision positioning.

X1 is an industrial grade high precision GNSS/INS receiver with the following features:

- Deeply coupled algorithm
- Dual antenna RTK positioning and heading
- Built in tactical grade IMU
- Support full system including BDS-3, GALILEO
- Low latency

Tests conducted in the following typical scenarios :

- Open sky
- Urban canyon
- Foliage canopy
- Signal interference
- Underground parking
- Under elevated road
- Along elevated road
- Tunnel

Movement status:

As the GNSS/INS receiver performance is related to the movement status, special dynamic movement were randomly performed such as high speed, low speed, emergency stop, sharp turn, U-turn, uphill and downhill in each scenario.

Test results measured using the following criteria:

- RMS—Root mean square of horizontal position deviation (PRMS), velocity deviation (VRMS) or Azimuth deviation (ARMS)
- Availability—The percentage of horizontal position error $< 0.29\text{m}$, vertical position error $< 1.4\text{m}$, directional error $< 0.5^\circ$ [1]
- Integrity —The percentage of non-fixed solution when the positioning results are not available
- CEP95—95% of the positioning results are within the limit

Set-up and Methodology

The test set-up is shown in **Figure1** and ensured:

- All receivers used the same antenna;
- All the receivers received the same RTK correction data;
- All the receivers were disconnected with the satellite signals when interruption occurred;
- Power supply was within the range of each receiver, and was turned on and off at the same time;
- The values (lever arm/RBV) set into all receivers were obtained in the same way

X1 GNSS/INS Receiver

As shown in **Figure2**, X1 is a compact and highly integrated GNSS/INS receiver, whose specification is shown in **Table1**. X1-3 and X1-6 differ in IMU model as shown in **Table2**. (the system marked * was not enabled in this test in order to compare with the competitor receiver.)

GNSS Antenna

The BY300 high precision survey antenna shown in **Figure3** supports GPS(L1/L2/L5), BDS(B1/B2), GLONASS(G1/G2) and Galileo(E1/E5b), with typical gain 40±2 dB.

Base Station

The base station was built with NovAtel 718D as shown in **Figure4**.

Test Platform

The test platform, as shown in **Figure5**, was set up according to **Figure1**.

Benchmark

The post-processing results output by commercial software Inertial Explorer was considered as test benchmark.

Figure1 Set-up and Methodology

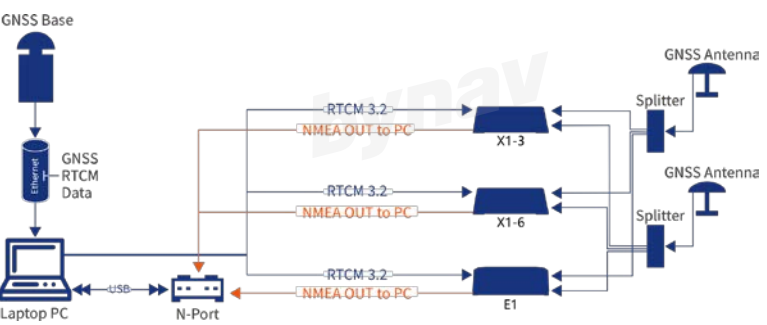


Figure2 X1



Table1 X1 Specification

Dimension	116*114.2*38.6 mm
Weight	432 g
Power Consumption	4.8 W
Temperature	-40~+85 °C
System	GPS, GLONASS, BDS, QZSS, Galileo*, BDS-3*, NavIC*

Figure3 GNSS antenna



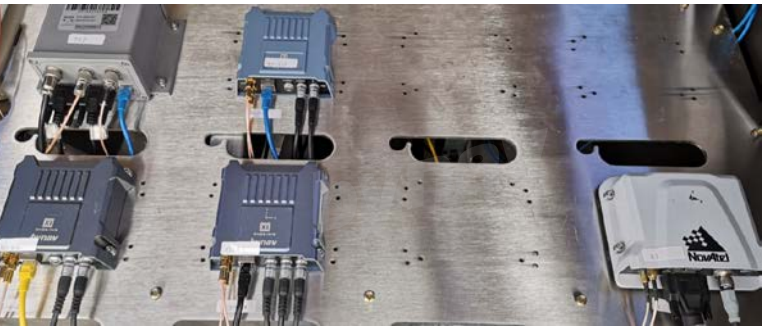
Figure4 Base Station



Table2 IMU Error Parameters

Parameter	Model	
	X1-3	X1-6
Gyro	Range(°/s)	500
	Repeatability (°/s)	0.14
	Stability (°/h)	2.7
	Angular Random Walk (°/√h)	0.15
Acceler	Range(g)	8
	Repeatability (mg)	2
	Stability(μg)	2.7
	Velocity Random Walk (m/s/√h)	0.009
IMU	Raw data output (Hz)	100

Figure5 Vehicle Test Platform



1. Open Sky

The vehicle drove under open sky without blockage or signal interference. To verify the accuracy and consistency of the positioning results, the test performed several round-trips along the same road and lasted 13m26s.

Figure1.1 Environment



Figure1.2 Trajectories

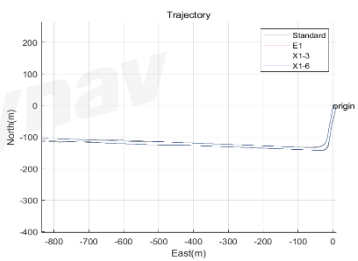


Table1.1 Positioning Results

Model	Availability (%)	Integrity (%)	CEP95 (m)	PRMS (m)	VRMS (m/s)	ARMS(deg)
E1	100	100	0.064	0.037	0.028	0.687
X1-3	100	100	0.047	0.027	0.025	0.753
X1-6	100	100	0.036	0.021	0.019	0.143

Figure1.3 Partial Trajectories

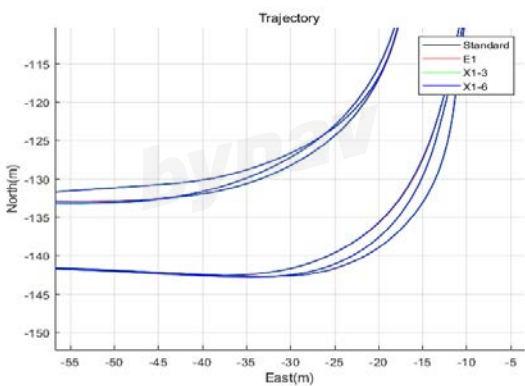


Figure1.4 Horizontal Position Deviation

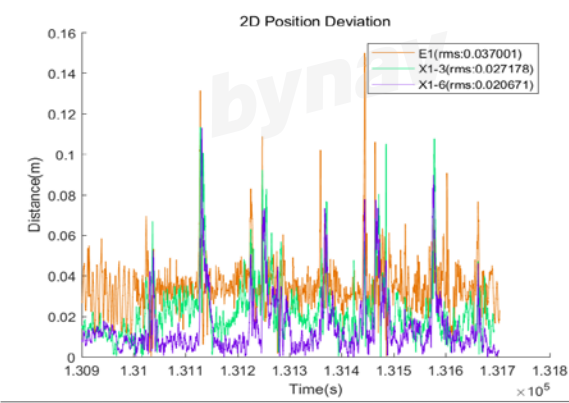


Figure1.5 Velocity Deviation

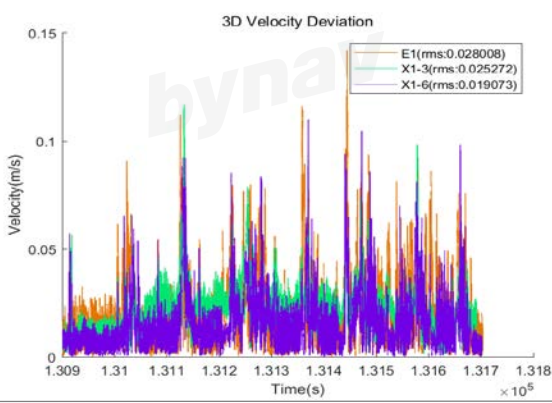


Figure1.6 Azimuth Deviation

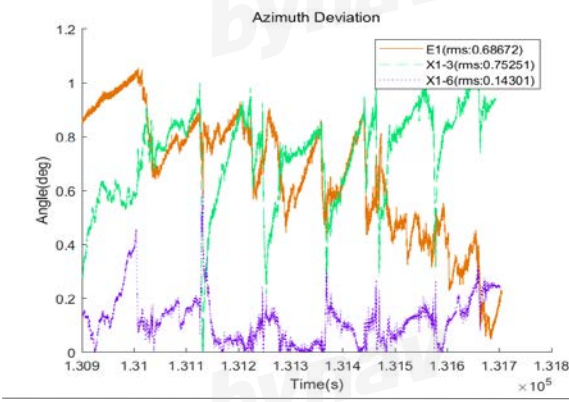
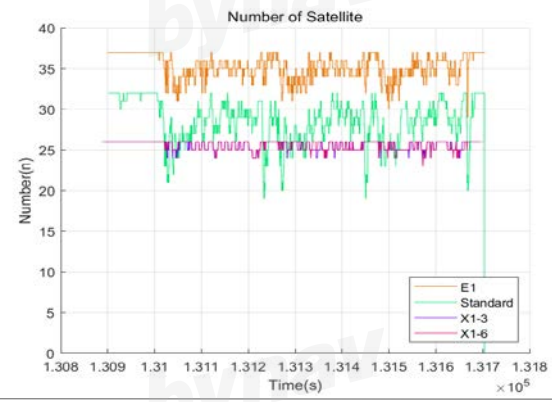


Figure1.7 Number of Satellites



Summary

Under open sky, X1-6 had the best performance in position and orientation accuracy with 3.6cm of CEP95 and 2cm of horizontal position accuracy. The X1-3 performance was close to or slightly better than that of competitor receiver. Since X1 did not enable GALILEO and BDS-3 during the test, the Number of Satellites was a bit low.

2. Urban Canyon

Under this scenario the vehicle drove through the high-rise buildings with a limited sky view, where all receivers were powered on and finished alignment. The test lasted 11m32s, of which the building blockage occupied about 50%.

Table2.1 Environment



Figure2.2 Trajectories

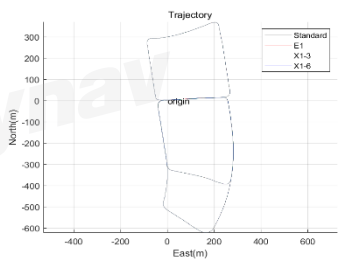


Table2.1 Positioning Results

Model	Availability (%)	Integrity (%)	CEP95 (m)	PRMS (m)	VRMS (m/s)	ARMS (deg)
E1	97.1	0	0.223	0.134	0.042	0.657
X1-3	99.2	83.3	0.196	0.113	0.035	0.687
X1-6	100	100	0.105	0.061	0.019	0.261

Figure2.3 Partial Trajectories

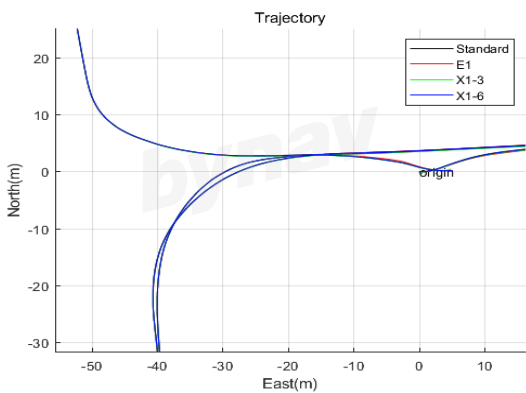


Figure2.4 Horizontal Position Deviation

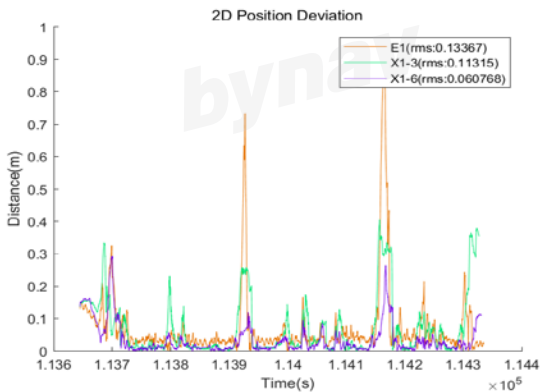


Figure2.5 Velocity Deviation

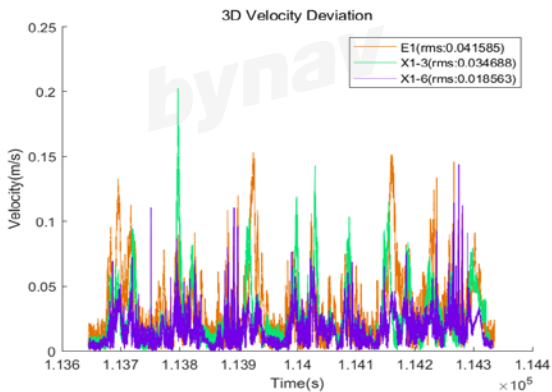


Figure2.6 Azimuth Deviation

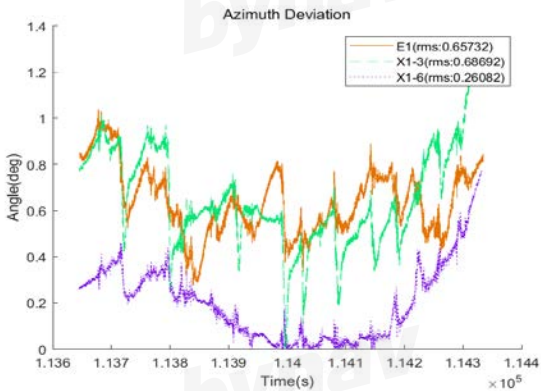
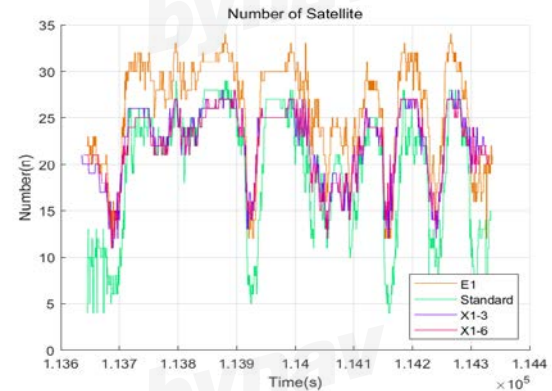


Figure2.7 Number of Satellites



Summary

X1-6 achieved 100% availability in urban canyons with a high accuracy on position and orientation. Its CEP95 was much better than that of the competitor receiver. X1-3's performance in urban canyons was close to competitor receiver.

3. Foliage Canopy

Under this scenario the vehicle drove through foliage canopy. To verify the positioning accuracy, the test was performed several round-trips. The test lasted 11m12s, of which the severe occlusion occupied about 80%.

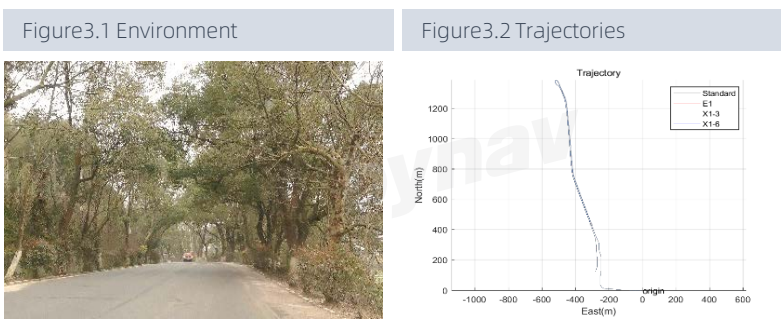
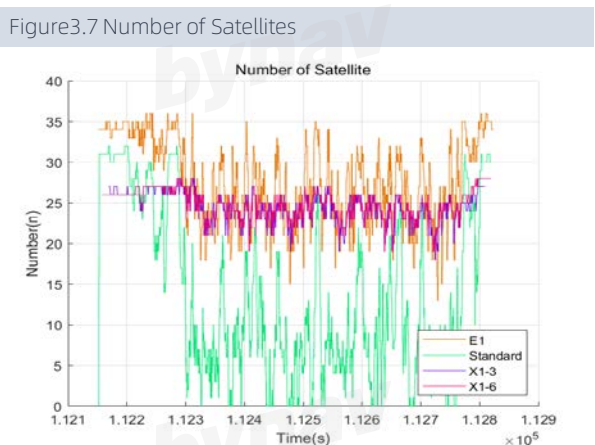
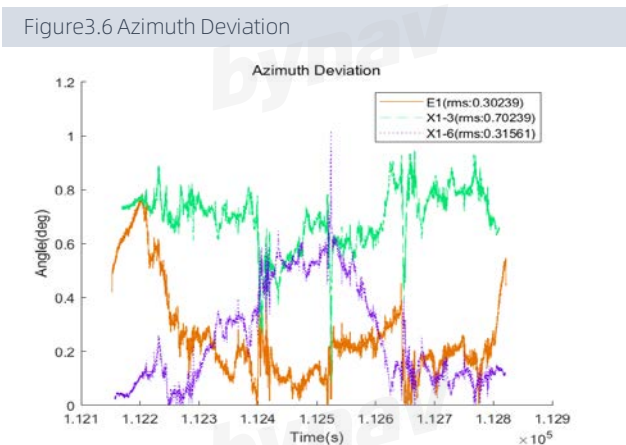
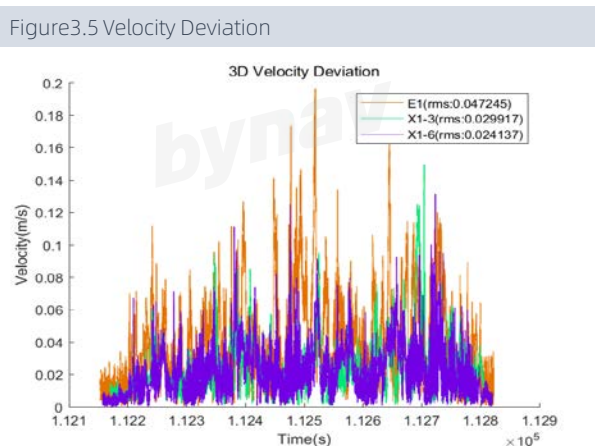
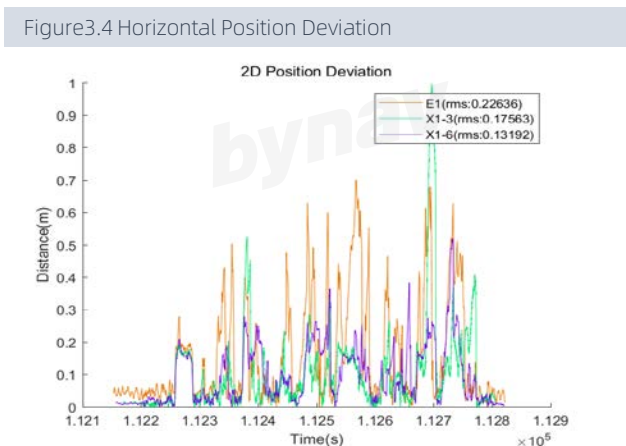
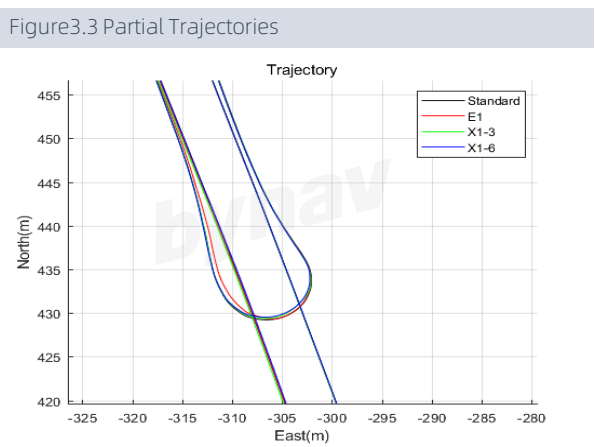


Table3.1 Positioning Results

Model	Availability (%)	Integrity (%)	CEP95 (m)	PRMS (m)	VRMS (m/s)	ARMS (deg)
E1	85.0	0	0.393	0.226	0.047	0.302
X1-3	95.7	81.9	0.298	0.176	0.030	0.702
X1-6	98.5	84.6	0.225	0.132	0.024	0.316



Summary

As the vehicle drove repeatedly between semi-occlusion and occlusion, all receivers had obvious fluctuations in the position and velocity deviations, however, as X1 was not affected much in terms of number of satellites, it showed more stable performance than competitor receiver. The number of satellites of the test benchmark is the number used in post-processing, which is relatively few.

4. Signal Interference

To ensure reliable positioning results under extreme complex electromagnetic environment, the signal interference was performed using a signal jammer in the 1.5G-1.6GHz range with the B1/L1/G1 signal. This test lasted 5mins.

Figure4.1 Signal Jammer



Figure4.2 Environment

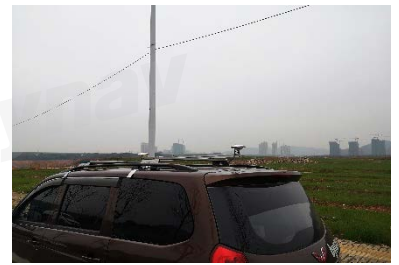


Table4.1 Positioning Results

Model	Availability (%)	Integrity (%)	CEP95 (m)	PRMS (m)	VRMS (m/s)	ARMS (deg)
E1	69.4	0.7	5.707	3.417	0.115	0.788
X1-3	71.5	90.5	6.517	3.829	0.085	1.072
X1-6	69.4	90.6	6.274	3.782	0.083	0.266

Figure4.3 Partial Trajectories

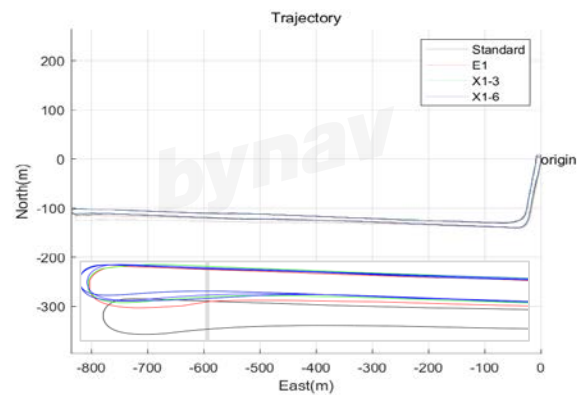


Figure4.4 Horizontal Position Deviation

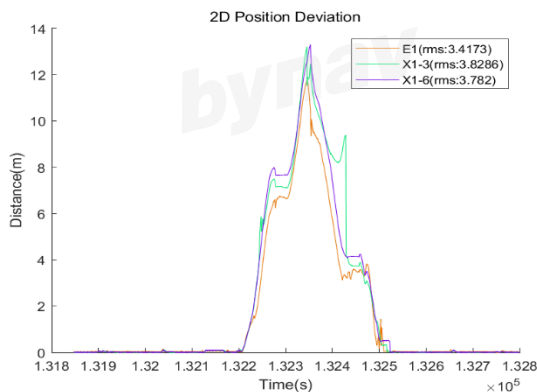


Figure4.5 Velocity Deviation

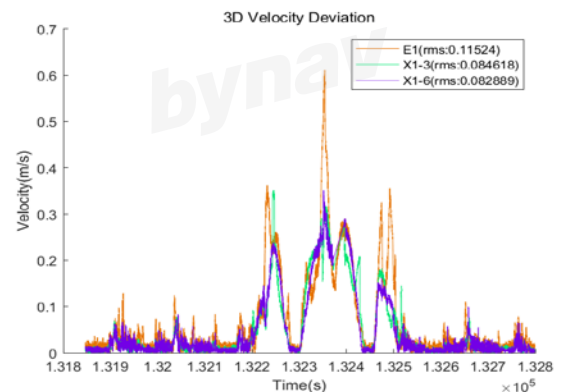


Figure4.6 Azimuth Deviation

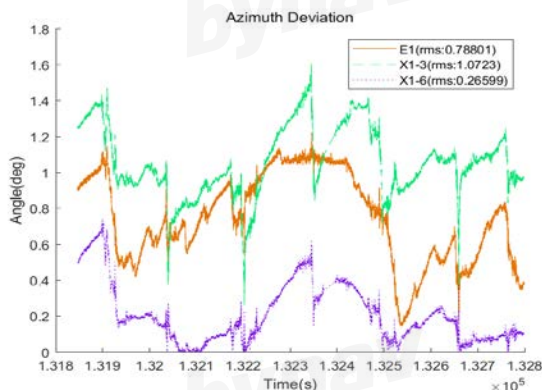
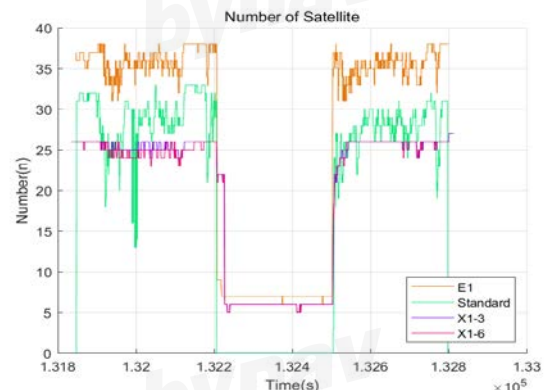


Figure4.7 Number of Satellites



Summary

During satellite signal interference, the orientation accuracy of X1-6 is obviously better than that of competitor receiver, and the position accuracy of all three receivers were very close. The number of satellites received by X1 can still remain about 5 during satellite signal interference, which is also the same as that of competitor receiver.

5. Underground Parking

In this scenario the vehicle entered the underground parking lot after the initial alignment was finished outside, and then performed parking, turns, reverse and then finally drove out of it. The test lasted 5m8s.

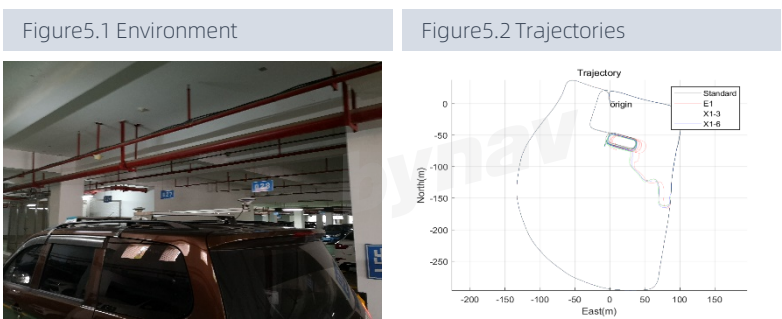
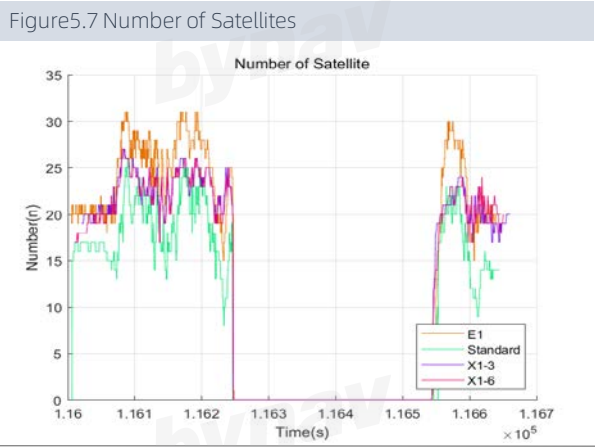
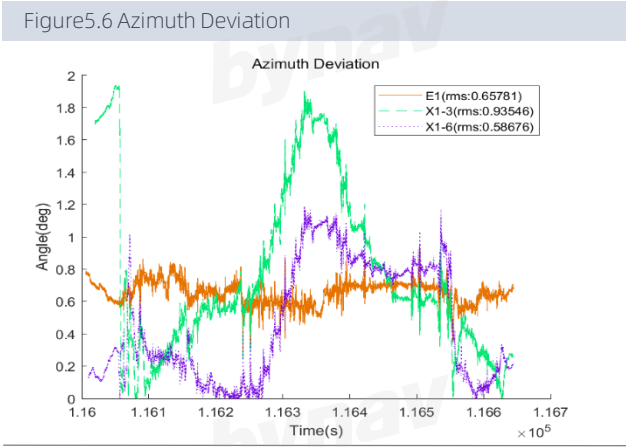
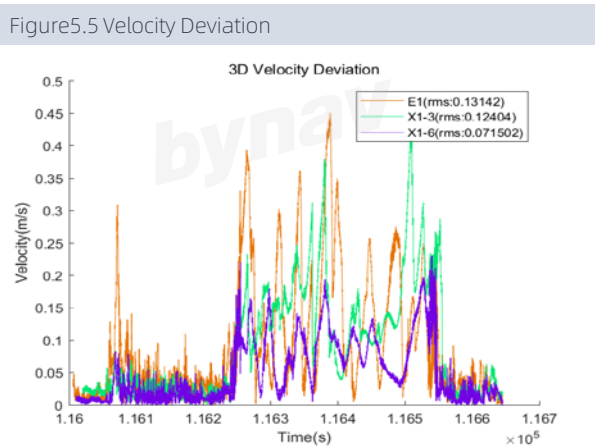
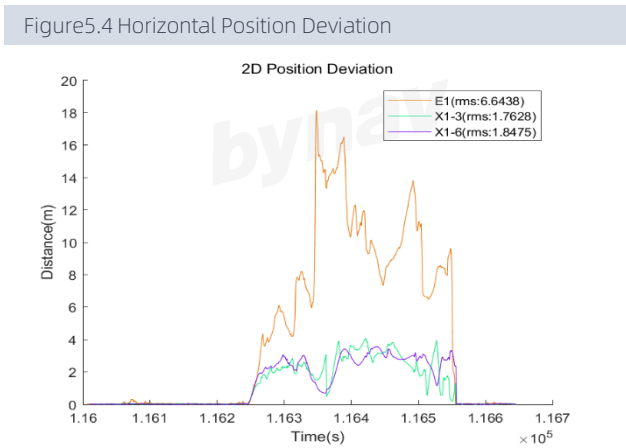
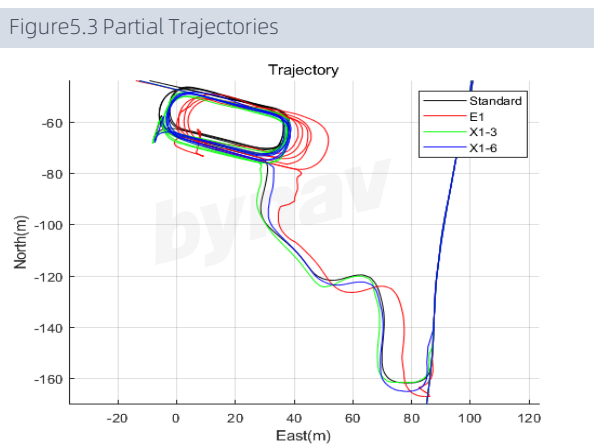


Table5.1 Positioning Results

Mo del	Availa bility (%)	Integri ty (%)	CEP95 (m)	PRMS (m)	VRMS (m/s)	ARMS (deg)
E1	62.8	83.2	10.78	6.644	0.131	0.658
X1-3	62.9	99.3	2.898	1.763	0.124	0.935
X1-6	57.7	98.4	3.198	1.847	0.072	0.587



Summary

While driving in the underground parking lot, the satellite signal was completely lost. Under this condition, X1-3 and X1-6 performed significantly better than competitor receiver.

6. Tunnel

Under this scenario the vehicle drove through a tunnel at a high speed after finished the initial alignment, and then turned around and went back from the same one. The driving speed was 80-100 km/h, and the total length of the tunnel is about 4.33km.

Figure6.1 Environment



Figure6.2 Trajectories

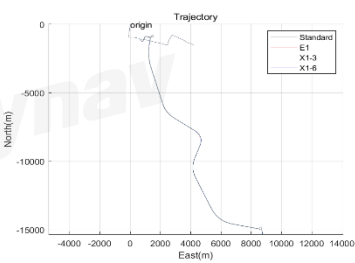


Table6.1 Positioning Results

Model	Availability (%)	Integrity (%)	CEP95 (m)	PRMS (m)	VRMS (m/s)	ARMS (deg)
E1	86.8	76.6	24.21	14.145	0.275	0.467
X1-3	85.5	88.5	24.09	13.991	0.398	0.571
X1-6	84.3	83.9	10.70	6.239	0.123	0.465

Figure6.3 Partial Trajectories

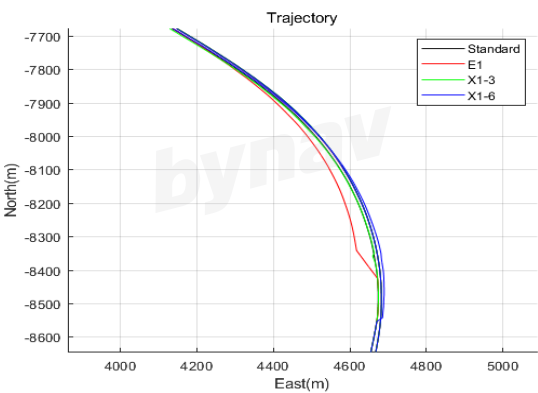


Figure6.4 Horizontal Position Deviation

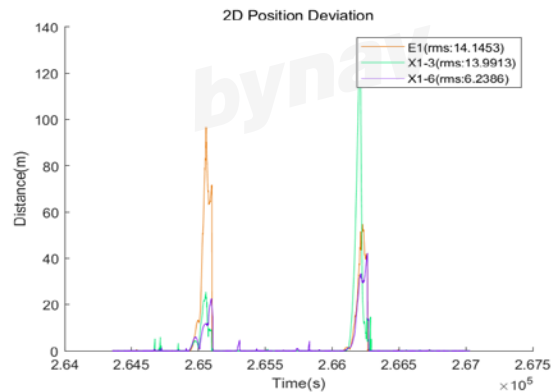


Figure6.5 Velocity Deviation

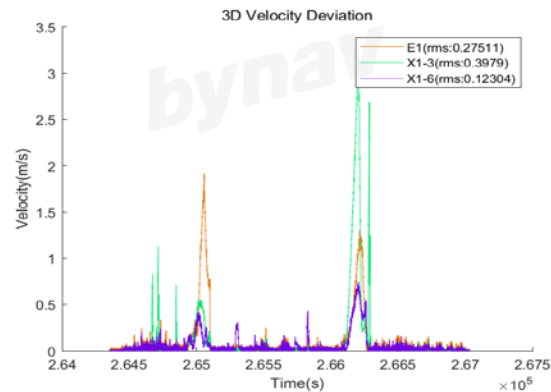


Figure6.6 Azimuth Deviation

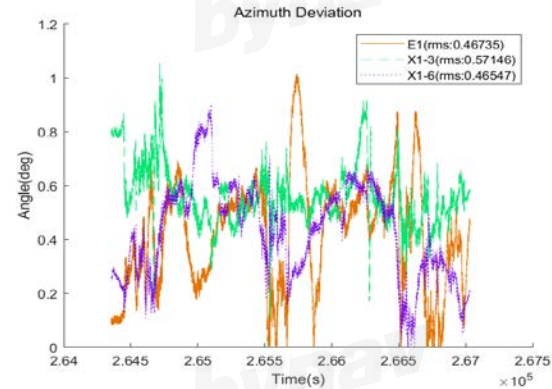
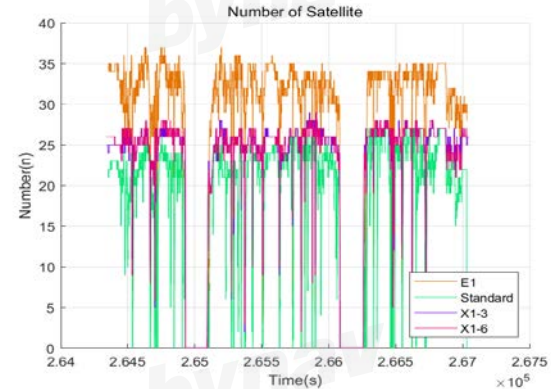


Figure6.7 Number of Satellites



Summary

When passing through the tunnel, the number of satellites was reduced to 0, and each receiver had some position, velocity and orientation deviation in different level. The position deviation of X1-6 was significantly lower than other receivers, and the performance of X1-3 was close to that of competitor receiver.

7. Under Elevated Road

The vehicle was driven round-trips under the elevated road after finished initial alignment, in which the satellite signals were repeatedly blocked. The whole test lasted about 7m30s.

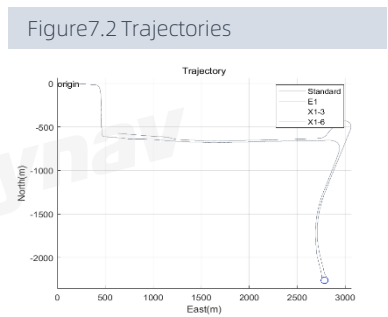
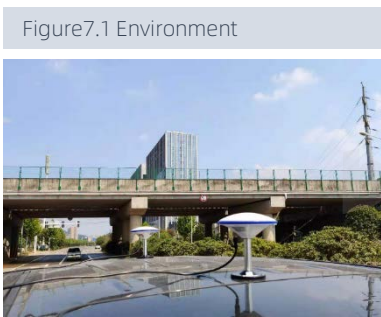
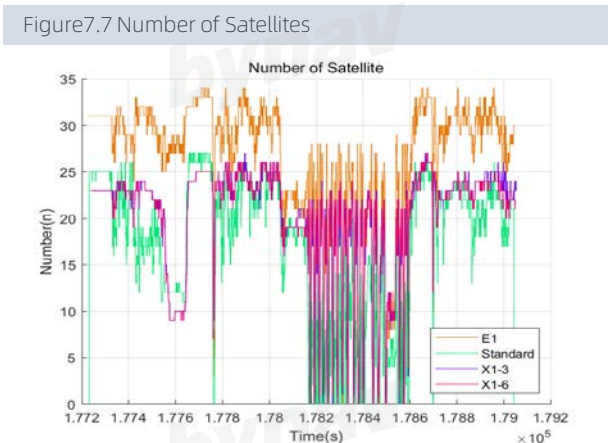
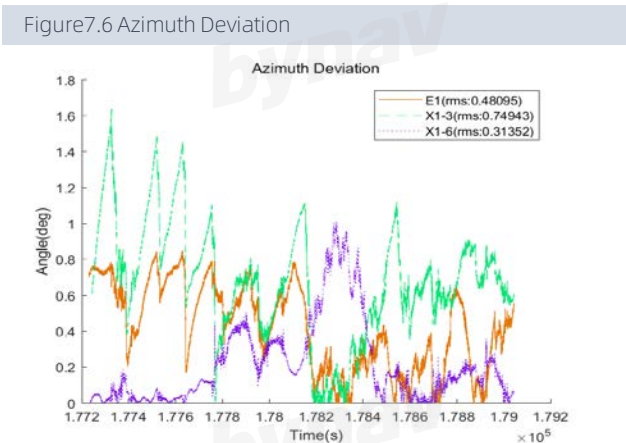
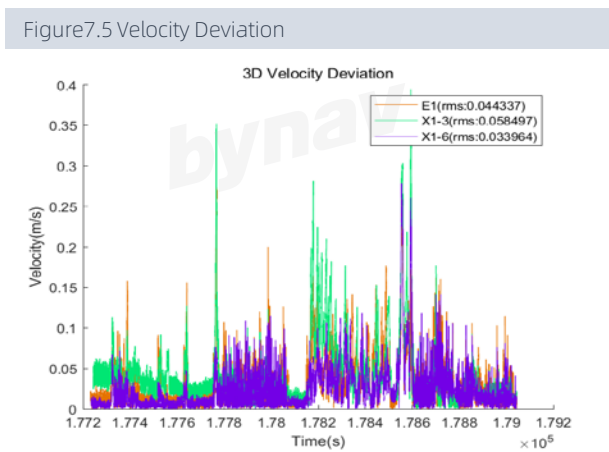
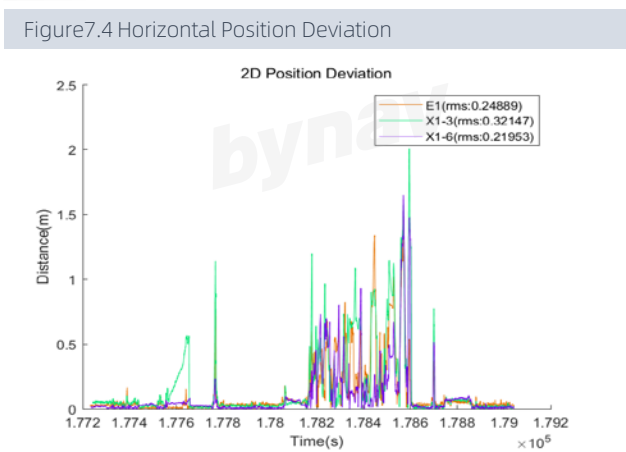
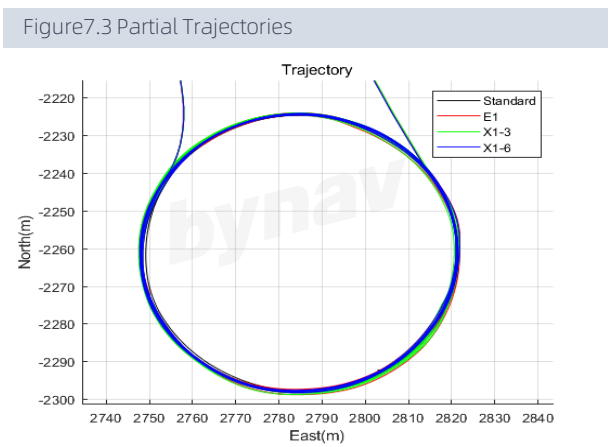


Table7.1 Positioning Results

Model	Availability (%)	Integrity (%)	CEP95 (m)	PRMS (m)	VRMS (m/s)	ARMS (deg)
E1	87.3	0	0.431	0.249	0.044	0.481
X1-3	85.4	76.1	0.543	0.321	0.058	0.749
X1-6	92.4	74.2	0.358	0.220	0.034	0.314



Summary

During the circles under the elevated road, the signal was periodically blocked, resulting in regular fluctuations in position, velocity and the number of satellites. X1-6 performed better than other receivers in all respects.

8. Along Elevated Road

Under this scenario the vehicle drove along an elevated road where satellite signals were mostly blocked. After finished the initial alignment, the vehicle drove into the test road section with several round-trips for 17m45s.

Figure8.1 Environment



Figure8.2 Trajectories

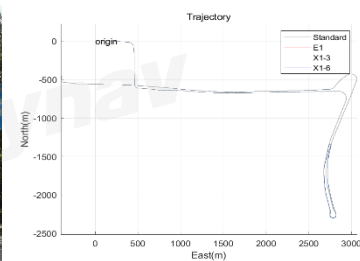


Table8.1 Positioning Results

Model	Availability (%)	Integrity (%)	CEP95 (m)	PRMS (m)	VRMS (m/s)	ARMS (deg)
E1	90.5	0	0.442	0.259	0.047	0.527
X1-3	89.0	45.8	0.824	0.475	0.053	0.613
X1-6	92.3	39.2	0.326	0.189	0.024	0.270

Figure8.3 Partial Trajectories

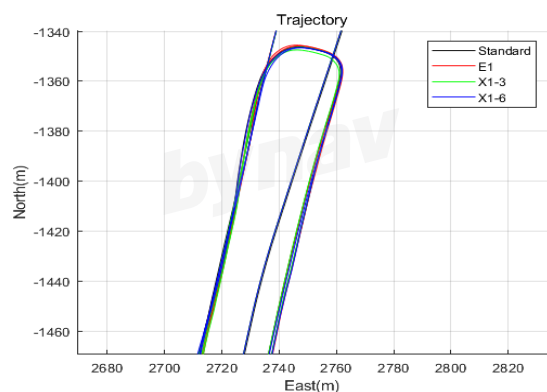


Figure8.4 Horizontal Position Deviation

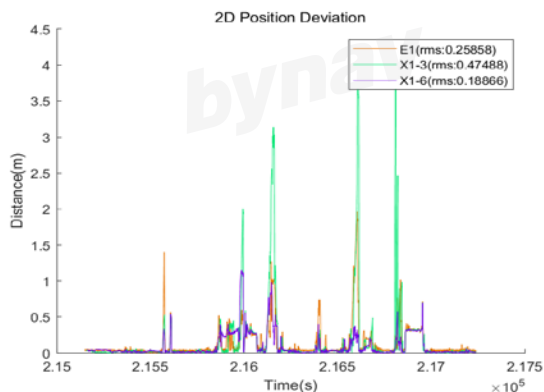


Figure8.5 Velocity Deviation

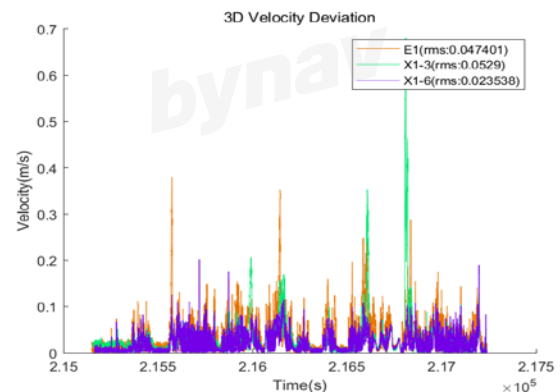


Figure8.6 Azimuth Deviation

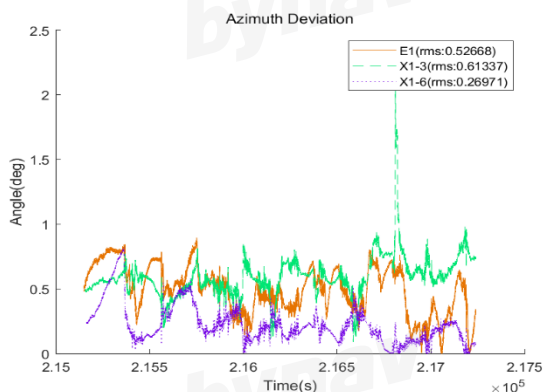
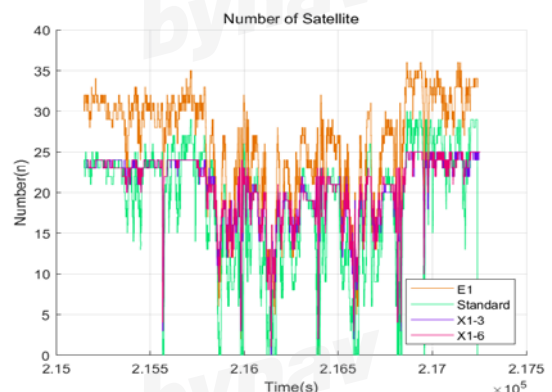


Figure8.7 Number of Satellites



Summary

While driving along the elevated road, the signals were continuously blocked, resulting in a reduction of 5-10 satellites in general. During the test, X1-3 experienced several large positioning deviations, but X1-6 always showed better performance with higher position and orientation accuracy than competitor receiver.

Summary

Table3 Positioning Results

Model	Availability (%)	Integrity (%)	CEP95 (m)	PRMS (m)	VRMS (m/s)	ARMS (deg)
E1	86.1	33.3	13.25	7.738	0.157	0.557
X1-3	86.2	81.3	13.06	7.576	0.219	0.726
X1-6	87.5	81	6.16	3.567	0.075	0.360

Figure6 Integrity

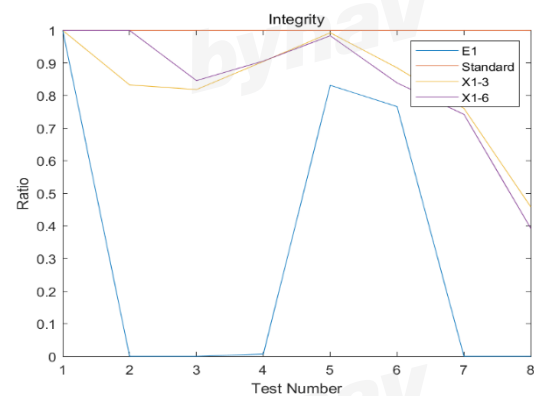


Figure7 Horizontal Position Deviation RMS

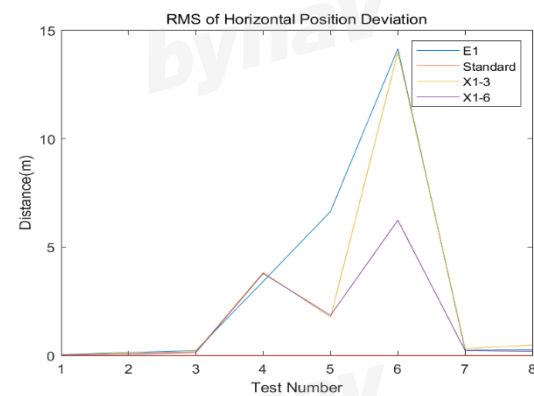


Figure8 Velocity Deviation RMS

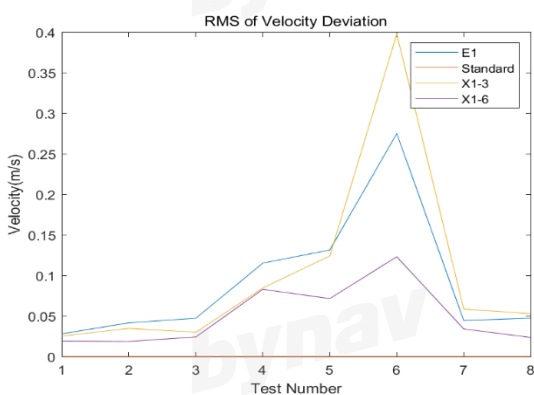


Figure9 Azimuth Deviation RMS

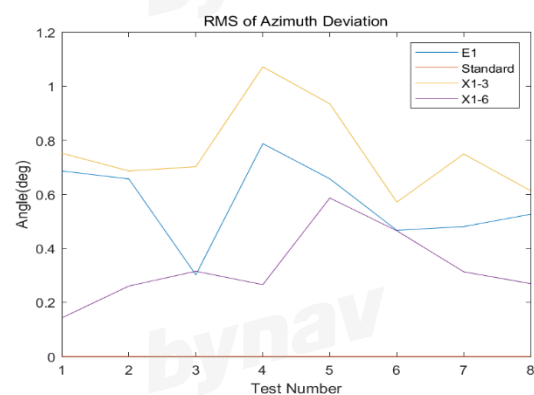


Figure10 Availability

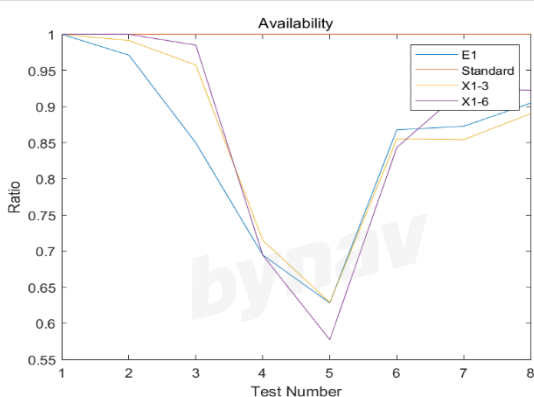
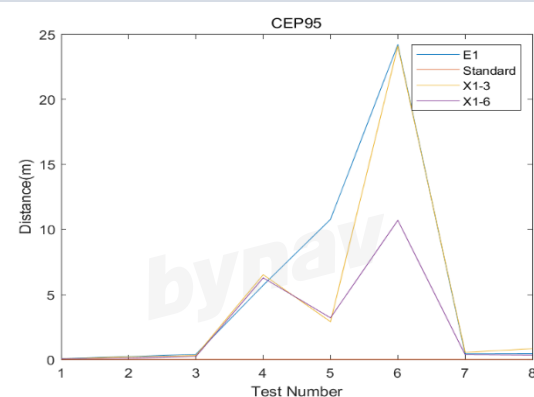


Figure11 CEP95



This report summarizes the performances of various GNSS/INS receivers, using availability, CEP95, and RMS as indicators, in the following scenarios:

- Open sky
- Urban canyon
- Foliage canopy
- Signal interference
- Underground parking
- Under elevated road
- Along elevated road
- Tunnel

The test results showed:

X1-3 and X1-6 have a better performance in integrity than E1.

X1-6 achieved 100% availability in the open sky and urban canyon environments, and can also provide real-time, continuous and reliable positioning results in other harsh environments, with its overall performance better than competitor receiver.

X1-3 and E1 were easier to be affected by external environments. When encountered long-term signal blockage (such as elevated road or tunnel), both diverged quickly in position, velocity and orientation errors. To sum up, the performance of X1-3 and E1 are quite close.

To download test raw data :

<http://www.bynav.com/cn/resource/bywork/geek-observation/rawdata.html>

Or contact us via en@bynav.com.

Reference:

[1] T. G. Reid, S. E. Houts, R. Cammarata, G. Mills, S. Agarwal, A. Vora, and G. Pandey, "Localization requirements for autonomous vehicles," SAE International Journal of Connected and Automated Vehicles, vol. 2, Sep 2019.



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