Novel GNSS receiver test bench based on scenario database and signal playback technology

Ji Chen, Ying Rendong, Zhu Xiaoguang, Liu Peilin
Institute of Sensing and Navigation, Shanghai Jiao Tong University
Shanghai 200240, China
Email: *jc13546426690@sjtu.edu.cn*

***Abstract** –GNSS receiver testing technology plays a significant role in navigation algorithm research, receiver development and product selection. However, the distorted reflection of real environment and the non-repeatability respectively makes the mainstream satellite signal simulator and road drive test insatiable to receiver testing in specific application. In this paper, we propose a novel GNSS receiver test bench which based on real satellite signal record and playback technology. The scenario database is constructed to preserve recorded signal from real scenarios and provide rich cases for the test bench. The playback device is developed to enable high-fidelity signal playback and the front-end is developed to implement automatic testing. Experimental results show that the designed test bench is reasonable and effective to test receivers' performance in different scenarios, as well as identify their strengths and drawbacks.*

***Keywords** –scenario database, signal record and playback, test methodology, automatic test system, GNSS receiver test.*

I. INTRODUCTION

Currently there are two mainstream GNSS receiver testing approaches: one is relying on satellite signal simulator [1] and the other is based on road drive test [2]. The simulator can quantitatively assess receivers' performance through simulation of different signal power, motion status, boundary conditions [3]. However, it cannot so far accurately simulate environmental factors, such as multipath, ionosphere irregularities, power fading etc. These factors can lead to significant difference about the performance of receiver when using in real environments other that obtained in laboratory. On the other hand the road drive test compensates this drawback by using real satellite signals to evaluate receiver performance. However, it cannot be adopted in universal test bench because of the high cost and non-repeatability.

To solve these problems, the satellite signal record and playback technology has been proposed and developed in recent years [4]. The signal recorder can transform satellite radio-frequency (RF) analog signal to intermediate-frequency (IF) digital data and store them in hard disk, which can be transformed into RF signal later through the playback device. In this way, we can repeatedly play the IF data and evaluate the receiver performance as if in real scenarios.

However, there still exist several shortcomings for the current record and playback device [5]. A canonical test bench requires sufficient IF data at different scenarios as test cases and the corresponding high precision positioning information which is used to compare with the tested receiver's result for performance assessment. And the test bench is more demanded to provide a minimum set of scenario test cases and a standardized evaluation methodology which is suitable for reflecting the real performance of the tested receiver in applications. Unfortunately, none of the existing testing system can meet the above requirements.

In this paper a new GNSS receiver test bench based on real signal database of various scenarios is presented. The designed test bench consists of four parts developed by our group: the scenario database, playback device, test methodology and test front-end. First, the scenario database plays the role of providing rich data source for the test bench which includes IF data and high-precision positioning data at different scenarios. Second, the playback device replays IF data from the database with low distortion which ensures the reliability of playback test method. Third, the test methodology illustrates receiver performance specifications, test procedures and performance analysis method which helps reflect and assess receiver's performance in practical applications. At last, the test front-end completes the test set selection, the performance evaluation and the operation flow control which guarantees the test bench to work automatically and efficiently.

This paper is organized as follows. Section II introduces the scenario database composition and SJTU Navigation Data Service Platform construction briefly. Section III presents the test bench hardware foundation and architecture design. Section IV discusses the GNSS receiver test methodology in detail. In section V, a detailed comparison from experimental results is made among several receivers to validate the strength of the proposed test bench. Finally, some conclusions and future work are drawn.

II. REAL SIGNAL DATABASE

A. Scenario classification

The satellite navigation technology has got wide application in mapping, transportation, mass consumption, infrastructure construction, national defense construction, etc. The performance of GNSS receivers is closely related

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to the application environment which makes it necessary to test receivers at different scenarios. Several challenging factors may affect receivers' performance in practical environment, including multipath, signal block, signal attenuation and electromagnetic interference [6-7].

In urban canyon scenario, there exists severe multipath effect and satellite signal is much easier to be blocked by skyscrapers [8]. In shade way scenario, the satellite signal might be blocked or the direct path signal power might be attenuated by leaves. Under half-occlusion elevated bridge, part of satellite signal is blocked but the occlusion situation is extremely different with urban canyon and shade way. In some specific environment, there are man-made electromagnetic interference which demands receivers' anti-interference ability to detect the deception [9-10]. There are 8 kinds of scenarios listed based on geographical features, which is shown in Table I.

Table I. Scenario classification result

Scenario Classification	Scenario geographical features
Urban Canyon	There are tall buildings on both sides of the road.
Urban Block	There are medium high buildings on both sides of the road.
Urban Square	There are low buildings on one side or both sides of the road.
Full-occlusion Area	The shelter completely blocks the road below.
Half-occlusion Area	The shelter partially blocks the road below, and on the other side is open ground.
Open Sky	Without occlusion or approximately without occlusion.
Water Surface	On the surface of river or lake
Shade Way	There are dense trees on the road.

B. Hardware foundation: data collection system

The navigation data collection system, consisting of high-fidelity satellite signal sampler and high-precision calibration system, can provide IF digital signal and corresponding benchmark data for scenario database. The developed signal sampler transforms RF signal to IF digital signal through down-conversion and IF sampling technology. The IF data preserves most of the energy from GPS-L1 and BDS-B1 frequency point for the wide bandwidth (25MHz), high sampling rate (124MHz) and high quantization bits (8bit) so that it can be stored with low distortion. Through the optimum design of sampler parameters, including filter bandwidth, sampling rate, quantization bits, intermediate frequency, etc., the SNR loss caused by collection process can be controlled in the minimum range.

The calibration system aims to get accurate position, velocity, and time information of motion carrier which would be used in playback test reference and error analysis. The Novatel-SPAN-FSAS system with the aid of the CORS and high grade inertial sensor is adopted in our collection system which has precision prior to 0.5 meter [11]. During data collection, the sampler and calibration system are connected to the fixed antennas on the designed van and several labels are recorded for data warehousing, such as scenario classification, carrier motion state, weather condition, collection location, etc.

C. Navigation Data Serve Platform (NDSP)

The scenario database plays the role of providing rich data source for the test bench. In the test bench more than 100TB data which covers different scenarios, different motion states and different weather conditions have been collected. So far there are 16 kinds of scenarios which include open sky, suburb, urban canyon, shade way, mountains, water surface, highway, under half-occlusion elevated bridge, etc.

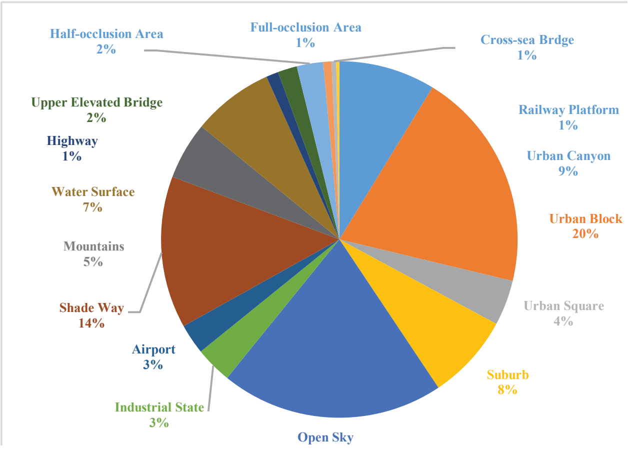

Fig. 1 Data distribution on Navigation Data Service Platform

These data are stored on NDSP which can be used for navigation data sharing, GNSS receiver development and testing, scenario classification algorithm research based on big data, etc. In addition to retrieval, download and upload functions about navigation data, the platform displays data trajectory, carrier velocity and electrical parameters for each item, including visible satellite number, DOP value, signal power distribution and multipath description through receiver raw observations and software analysis receiver developed by our group. In this way, users can intuitively browse statistical characteristics of data and give deeper insight into algorithm research.

III. TEST BENCH ARCHITECTURE

A. Hardware foundation: IF data playback system

The playback system converts IF digital signal to RF signal so that IF data can be replayed in the laboratory. High-fidelity is the most essential demand for the playback system which ensures the availability of the proposed test bench. Besides, it is better for the playback to flexibly suit to IF data with different formats.

The playback device is developed based on NI PXIe-5673, a universal software radio board which support high rate playback of IF data with different formats through programming. The playback process can be controlled after configuring IF data path, up-conversion frequency, sampling rate of IF data, etc. on user console. Moreover, the playback program provides socket server interface which can be used for remote test control.

Test results show that it can achieve approximately lower than 0.5dB carrier to noise ratio loss and higher than $\pm 5\times10^{-10}$ frequency stability. Furthermore, the playback SNR remains high even for IF data collected in harsh environment.

B. Test bench architecture

The test bench composes of Navigation Data Service Platform, IF data playback system, the receiver to be tested and the front-end, which is shown in Fig.2. First, the playback system replay the qualified IF data transferred from the server. Second, the terminal receives playback signal through RF cable and feeds NMEA-0183 frames back to the front-end through RS-232 bus. At last, the front-end generates evaluation report by comparing retrieve frames with high-precision calibration data according to test methodology.

An efficient and user-friendly front-end is developed to simplify the operation of test and evaluation as much as possible, which is shown in Fig.3. After selecting test cases from scenario database, the front-end automatically start testing procedure and provide performance analysis report in the end. In order to realize test automation, receiver and playback control, data query and high speed transmission functions are developed on the front-end. Beside, task scheduling module, user interaction module and test analysis module are also developed to guarantee the test bench work automatically and smoothly.

The receiver control module implements the communication between GNSS receiver and the front-end based on RS-232. The receiver to be tested can been seen as an object with a universal communication interface and its unique control instruction set, including RS-232 baud rate configuration, reset mode (cold, warm, hot) and demanded output of NMEA-0183 frames, etc.

Fig. 2 Hardware framework of GNSS receiver test bench

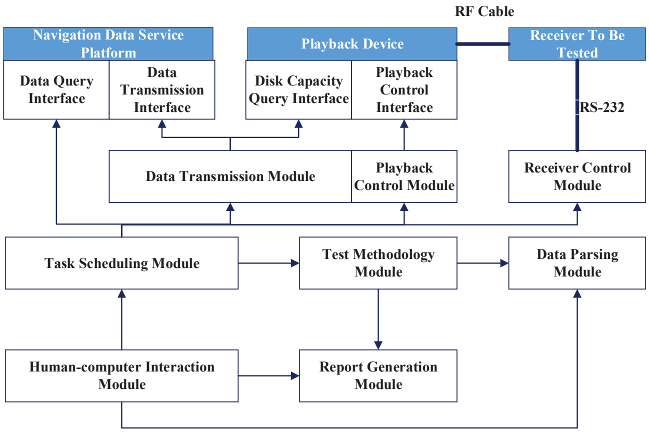

Fig. 3 Software framework of GNSS receiver test bench

The test bench is applicable to vast majority of commercial receivers owe to NMEA-0183, which is the standard protocol for GNSS receivers. Of all the frames, $GPGGA, $GPVTG, $GPGSA, and $GPGSV are necessary in virtue of position, velocity, DOP and visible satellites information. If the receiver to be tested is already in our database, the operator can select the specific type to load the previous configuration intelligently. Otherwise, the operator should configure requisite parameters and instructions first according to the guide of the front-end to make sure the test procedure works robustly, and the configuration of this new receiver type would be added into the database afterwards so that it can be invoked directly the next time.

The playback control module implements the communication between the playback device and the front-end based on TCP/IP protocol. We have added the socket interface to the playback system so that the playback program can be controlled by front-end through socket communication. The control instruction set composes of start, stop, set data path, query progress and corresponding response. A query thread is arranged to update playback progress continuously after the start-up of playback procedure. Once the progress rate reaches 100%, it means the current playback is complete and the front-end could prepare for the test of the next data.

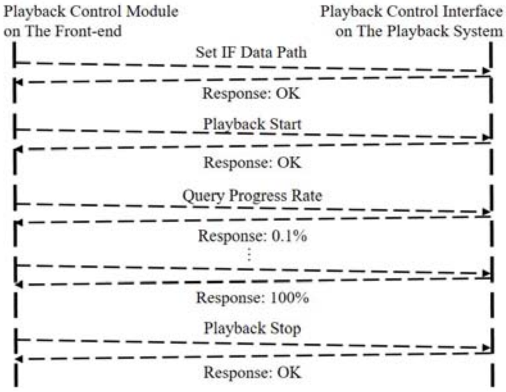

Fig. 4 Remote control communication between front-end and playback device

The data transmission module implements the high speed transmission between the server and the playback system in LAN. As the 124MB/s rate of IF data, it is unrealistic for the playback system to store all the data under test in board which makes the real-time download of demanded IF data from the server the alternative solution. Since the transmission rate is co subject to read rate of server dick, network bandwidth and write rate of playback disk, the front-end allocates extra memory for several buffer blocks to maximize transmission efficiency. The results show that the stable transmission between the server and playback can achieve a rate of 85MB/s which has attained the optimal performance.

The task scheduling module manages the whole operation flow by calling the functional modules mentioned above. As is shown in Fig.5, the tester should sequentially complete the receiver connection, playback connection and test cases selection in guide pages to afford reliable communication between the front-end and other three parts. Then for each item in test cases set, first, the front-end transfers the IF data from server to the playback by calling the data transmission module. Second, the receiver would be reset in cold mode to clear all information in board by calling the receiver control module. Third, the playback data path would be updated to have the new playback carried out by calling the playback control module. Then the reconstructed signal is transmitted into the RF input interface of receiver through cable. Meanwhile, the front-end records the requisite NMEA-0183 frames to file in real-time which is generated by the receiver. When all cases are tested, the front-end would provide assessment report automatically by calling the test methodology module.

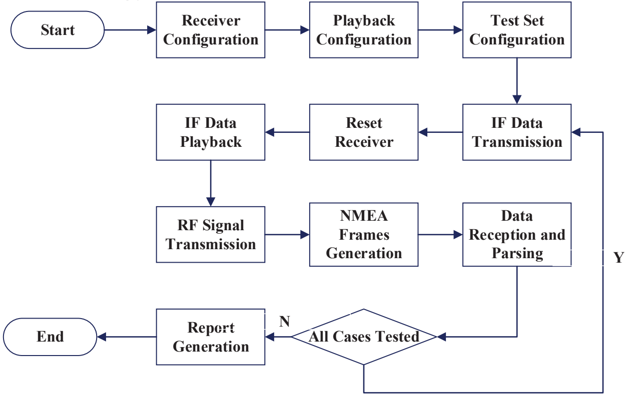

Fig. 5 Front-end flowchart of GNSS receiver test bench

IV. RECEIVER TEST METHODOLOGY

A. Positioning accuracy

Positioning accuracy, the most significant performance indicator of one receiver, refers to the coincidence degree between the real-time position the receiver provided and the actual position when HDOP ≤4 or PDOP ≤ 6 [12]. The actual position can be replaced by the calibration data in database. The static accuracy and dynamic accuracy can be measured separately by the playback of IF data in static motion or dynamic motion.

Positioning bias and relative circular error probable (RCEP) are introduced to evaluate the positioning performance of GNSS receiver [10]. Positioning bias represents the mean error in the east and north direction relative to the actual coordinates, while the RCEP (95%) demonstrates the minimum radius of the circle which covers 95% of sample points around the 2D coordinates of the bias. First, the East-North-Up (ENU) error of each observation epoch would be calculated by coordination transformation of positions the receiver provided and corresponding reference positions. Second, the bias coordinate and the RCEP (95%) would be extracted from the error sequence at certain times based on 3-σ criterion. The data processing method above applies to both static and dynamic situations because of the relative ENU coordinate system. The ENU error sequence is shown in Fig.6.

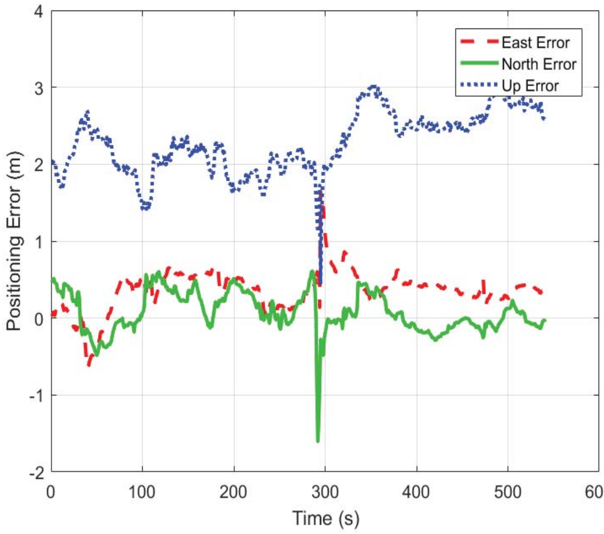

Fig.6 ENU error sequence diagram in open sky

B. Velocity accuracy

Velocity accuracy refers to the coincidence degree between the real-time velocity the receiver provided and the actual velocity when HDOP≤4 or PDOP≤6 [12]. As with the statistical theory of positioning accuracy, velocity accuracy would be drawn by calculating the bias and RCEP (95%) of the velocity error sequence. Fig.7 illustrates a comparison of the velocity sequence the receiver estimated with the actual velocity. The overall trend of estimated velocity curve is well consistent with reality, while the smoothness is inferior since the smooth filtering arithmetic is adopted in post processing to make the reference result closer to reality.

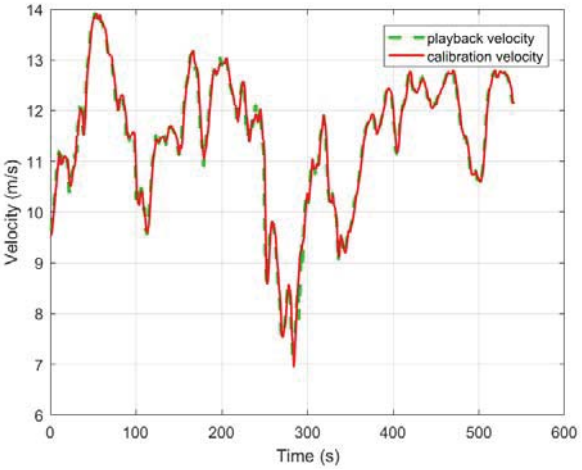

Fig. 7 Velocity comparison of playback test and calibration

C. Positioning integrity & reliability

All of the sample points can be divided into three parts according to the distribution of observations: lack of position or velocity, the error of 3D position within 50m and the error exceeding 50m. Positioning integrity refers to the proportion of the latter two parts which represents the receiver's capability of working in positioning state or estimating state, while positioning reliability refers to the proportion of the former two parts which demonstrates the capability of providing reliable observations in general situation and not exporting uncertain information in poor situation [13].

The requirements for positioning integrity and reliability vary with applications. For example, some commercial receivers demand high positioning integrity for user experience [14]. In such conditions, it is expected to export predicted trajectory even in poor environment and there is no particular requirement for accuracy. However, receivers based on multi-source fusion framework requires higher reliability than those merely work on satellite since the probability of each sample point would be used in fusion algorithm. In such conditions, it is essential to intelligently identify the poor environment and it is worse to provide estimated position of large error than no output [15-16].

D. Scenario adaptability

The performance of receivers is closely related to the application environment and the scenario adaptability assesses the receivers' comprehensive performance at different scenarios. Receivers always perform better in open sky than other challenging environment with lower number of visible satellite, poor distribution of GNSS constellation and worse carrier-to-noise ratio. IF data recorded at different scenarios should be selected as test cases to judge whether the receiver performs well at scenarios with wide disparity of electrical parameters. The 2D positioning errors in three scenarios are shown in Fig.8, in which we can find that the 2D positioning accuracy of the tested receiver decreases with the deterioration of signal propagation environment.

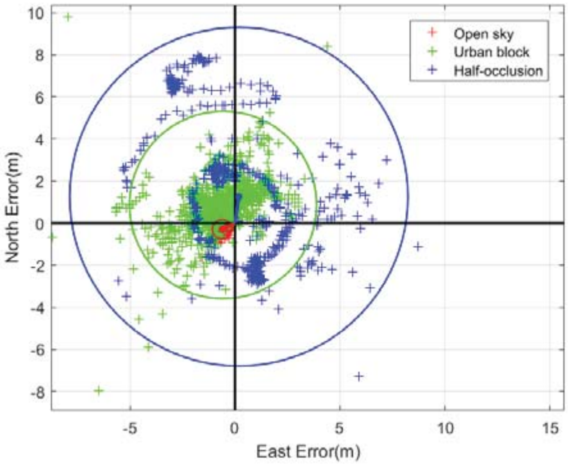

Fig. 8 Positioning error comparison in different scenarios

V. EXPERIMENTAL RESULTS

In order to verify the validity of the designed test bench, the performances of three representative receivers in the market are compared in scenarios with varying signal quality, including open sky, urban block and half-occlusion area for the wide disparity of electrical parameters. Among participant receivers, NovAtel-Propak6 from Canada is famous for its high-precision and reliability while Ublox-M8T from Switzerland and Unicorecomm-UM220 from China are commercial receivers which excel in integrity, continuity and low cost.

A. Receivers' performance in different scenarios

The motion trajectory on a wide road in Xujiahui, shown in yellow line in Fig.9, is selected to test receivers' performance in open sky scenario. The red points represent the playback positioning result of NovAtel-Propak6 with 1 Hz update frequency, green points represent the result of Ublox-M8T and blue points correspond to Unicorecomm-UM220.

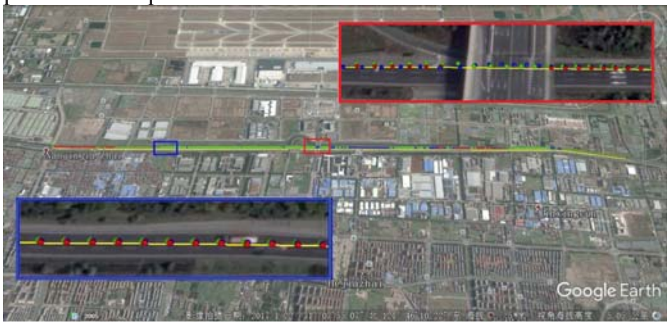

Fig. 9 Data trajectory and receivers' performance in open sky scenario

The blame square illustrates the partial enlarged view of the wide road and the three receivers all perform well by being consistent with the actual trajectory. The red flame shows the condition with temporary occlusion in which Novatel stops the location output while the other two receivers predict continuously.

Fig.10 shows the trajectory in urban block with buildings on both sides of the road. As can be seen in the partial enlarged squares, the three receivers deviate from the calibration trajectory and the deviation degree is much larger than in open sky.

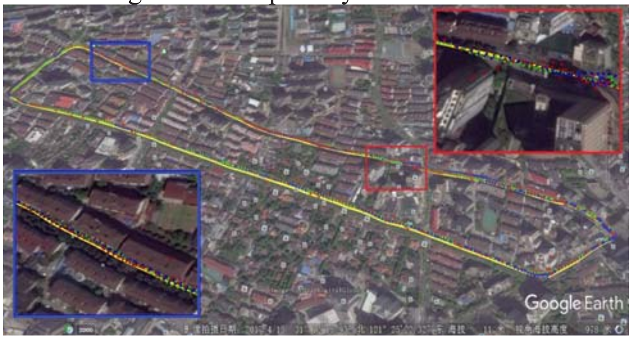

Fig. 10 Data trajectory and receivers' performance in urban block scenario

Fig.11 shows the trajectory in Pudong Airport with complicated environment, including a large part of half-occlusion area and a small part of full-occlusion area. As can be seen in the blue squares, when signal is blocked by the terminal roof, Ublox-M8T give locations continuously with higher precision than Unicorecomm-UM220, while Novatel exports discontinuously when signal is seriously blocked. The three receivers all stops exporting locations in the tunnel, and when receiver moves into the tunnel from open space, the scenario change is first identified by Novatel, Ublox-M8T follows behind, while Unicorecomm-UM220 exports biased locations in short duration.

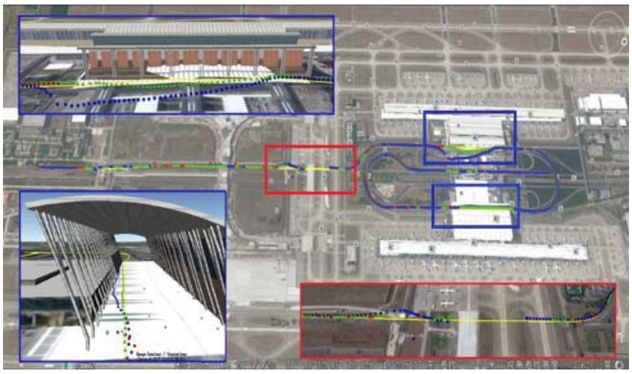

Fig. 11 Data trajectory and receivers' performance in half-occlusion scenario

B. Comparison and discussion

To comprehensively evaluate the receivers' performance at different scenarios, we calculate four indicators of each receiver at scenarios mentioned above, which are shown in Table II, III and IV.

Table II. Playback test results of NovAtel-Propak6

NovAtel-Propak6	Open Sky	Urban Block	Half Occlusi
Positioning Accuracy (m)	1.1449	5.4854	9.3212
Velocity Accuracy (m/s)	0.3092	0.3885	0.3547
Data Integrity	96.86%	93.01%	71.39%
Data Reliability	100.00%	100.00%	99.88%

Table III. Playback test results of Ublox-M8T

Ublox-M8T	Open Sky	Urban Block	Half Occlusi
Positioning Accuracy	1.1125	6.5816	15.6287
Velocity Accuracy	0.2755	0.7406	1.3652
Data Integrity	100.00%	100.00%	94.20%
Data Reliability	100.00%	100.00%	95.81%

Table IV. Playback test results of Unicorecomm-UM220

Unicorecomm-UM220	Open Sky	Urban Block	Half Occlusi
Positioning Accuracy	2.5640	7.2574	35.8543
Velocity Accuracy	0.4458	0.5397	1.0730
Data Integrity	100.00%	100.00%	100.00%
Data Reliability	100.00%	100.00%	94.20%

By analyzing the indicators in above tables, we can see that:

1) NovAtel-Propak6 performs well at all scenarios with high positioning accuracy, velocity accuracy and nearly 100% data reliability, and excel in identifying environment changes. In complicated scenario, the reliability strength is much obvious but data integrity is worse without the help of sensors.

2) Ubox-M8T performs well at open sky and urban block where signal propagation environment is friendly without much occlusion. It performs moderately in complicated environment, all the indicators are inferior to NovAtel-Propak6 except for data integrity. The strength in the tradeoff between accuracy and data integrity makes it the wide scope of application.

3) Unicorecomm-UM220 performs well at friendly scenarios just slightly inferior to Ublox-M8T. In complicated environment, the performance is not entirely satisfactory, through still better than most commercial receivers in the market. The strength is that data integrity is always 100% while there is still room

for improvement in accuracy and reliability which implies the ability of identifying harsh signal environment.

VI. CONCLUSION AND FUTURE WORK

This article has presented a novel GNSS receiver test bench which based on the real scenario database and signal playback system. The contributions can be concluded as below. (1) The scenario database provides abundant IF data from various scenarios for researchers and companies, which accelerates the navigation data sharing. (2) The high-fidelity signal record and playback technology ensures reliability for performance evaluation of different receivers. (3) The user-friendly front-end helps automatically execute substantive tests for receivers from home and abroad and upload the test results to database which provides statistics for the continuous improvement of test methodology.

In future, more research work should be focus on the test methodology for high-precision receivers which demands for multi-frequency record and playback technology, as well as the synchronous playback of NRTK data. The development of multi-frequency record and playback device is been promoted in our lab to satisfy the test requirement of multi-mode multi-frequency receivers. Furthermore, the traditional test approaches based on signal simulator should also been combined to our test bench to compensate the limitations of playback method on the assessment of sensitivity indexes.

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AUTHOR BIOGRAPHY

Ji Chen was born in Taiyuan, China, in 1992. She received B.S. from Shanghai Jiao Tong University (SJTU), China, in 2014. Now she is a postgraduate student majoring in Electronic Engineering, SJTU, China. Her research interests include scenario database construction, automatic test system development and GNSS receiver test methodology.

Ying Rendong received the Ph.D. degree in Shanghai Jiao Tong University (SJTU), Shanghai, China, in 2007. He is a vice Professor in the department of Electronic Engineering, SJTU and researches in digital signal processing. He has been engaged in chip architecture design and embedded system technology at the same time.

Zhu Xiaoguang receiverd the M.S. degree in Shanghai Jiao Tong University (SJTU), Shanghai, China, in 2017. Now he is a Ph.D. student in Electronic Engineering, SJTU. He researches in scenario classification algorithm based on real scenario database.

Liu Peilin received the Ph.D. degree in Tokyo University, Japan, in 1999. She is a Professor in the department of Electronic Engineering, SJTU and researches in signal processing and SOC architecture design in navigation. She has participated in teaching digital circuit, signal and information system for long time.