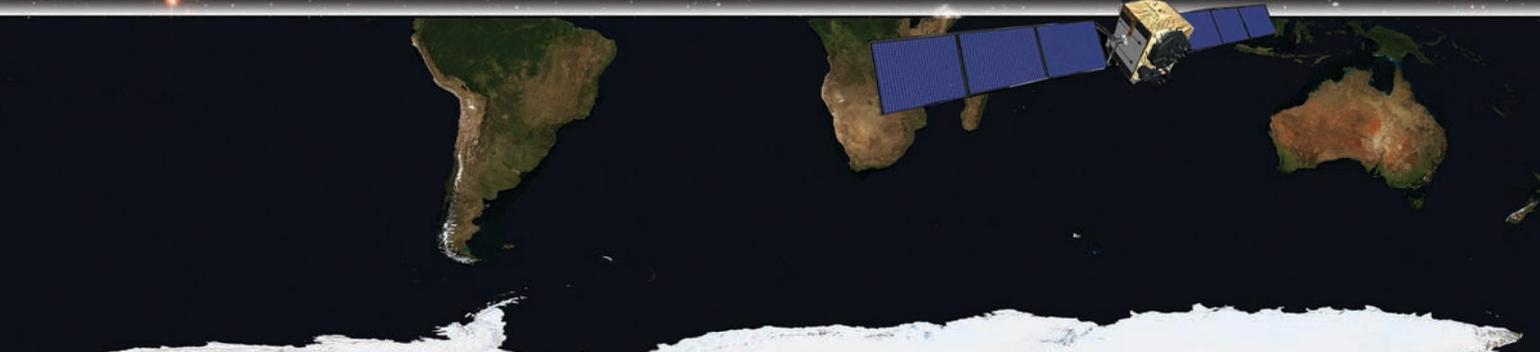


Integrated Navigation

GPS/BeiDou/INS Performance in Two Hemispheres



Rapid development of the BeiDou satellite navigation system over the past decade has made the new GNSS ready for evaluation of some of its capabilities. This article describes a series of road trials in China and Australia using a new multi-sensor integrated navigation system that fuses GPS, BeiDou and MEMS inertial sensors. Preliminary test results indicate that this integrated system can continuously provide navigation solutions in all the test environments, using inertial measurements to bridge GNSS outages. An analysis of various distributions of satellites in the constellations reveals the influence of the two GNSS systems' satellite geometry on real-time positioning.

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Due to the huge success of GPS in both military and civil applications, several other GNSSs have been developed, built, and operated in the last few decades. GNSS, regional, and augmentation systems are comprise a growing family that also includes GLONASS, Galileo, BeiDou, and Japan's Quasi-Zenith Satellite System (QZSS). New members, such as the Global Indian Navigation System (GINS), are preparing to join in next decade.

Multiple GNSSs not only provide users with multiple choices as to which system or systems to employ, but also improve accuracy and reliability of the GNSS receivers by using the compatible and interoperable receiving techniques.

The Chinese BeiDou system (BDS) began providing regional positioning services in December 2011. With 16 satellites launched into orbit by the end of the following year, BDS now can provide positioning, timing and short message communication services in China as well as adjacent Asian and Pacific areas. On December 27, 2012, China released the first version of a complete interface control document (ICD) for the BeiDou system's B1 Open Service signal-in-space.

As a new member of the GNSS community, BeiDou is experiencing rapid growth with strong support from both the Chinese government and numerous domestic BeiDou receiver manufacturers. The progress of BeiDou development

has also attracted a lot of attention from governmental, academic and industrial sectors outside of mainland China.

GNSSs are widely used for land vehicle position and navigation. But it is difficult for GNSS-only positioning systems to obtain a continuous solution when in GNSS signal-challenged environments. The most popular method is to use a self-contained system that is immune to signal jamming to assist the GNSS, such as an inertial navigation system (INS).

For operations in such situations, most land and aerial vehicle navigation applications preferentially incorporate an inertial measurement unit (IMU) based on a microelectromechanical system (MEMS) form factor.

This article evaluates positioning performance in the northern and southern hemispheres using a new GPS/BeiDou/MEMS integrated navigation system. Road tests were conducted in real time in Nanjing, China, and Sydney, Australia, under various conditions: open sky view, urban downtown areas, tunnels and underground parking. We analyzed the results with BeiDou satellite visibility of the two cities respectively.

Integrated Navigation Hardware Platform

MEMS sensors usually have large drift errors that prevent them from being used in inertial-only mode. Therefore, the performance of the GNSS/MEMS-INS system degrades quickly during GNSS signal outages.

Some non-linear integration techniques — such as the extended Kal-

man filter, unscented Kalman filter, and particle filter — have been adopted to enhance the performance. Furthermore, auxiliary sensors such as odometers or magnetometers have been evaluated to possibly overcome performance limitations during GNSS outages.

Here we used a low-cost GPS/BeiDou/MEMS solution for real-time position, velocity, and attitude estimation. Integration with the BeiDou module was intended to enhance the overall navigation performance of the system compared with the use of GPS only. Technical details of the GPS/BeiDou/MEMS solution are included in the Manufacturer section near the end of this article.

Cars manufactured since 1996 are generally equipped with the On-Board Diagnostics (OBD)-II interface, which enables vehicle owner or a repair technician to access the state of health information for various vehicle sub-systems, including the vehicle speed and odometer readings. The OBD-II hardware interface is the female 16-pin (2x8) J1962 connector.

The OBD-II interface, which can usually be found underneath the dashboard on the driver's side of a vehicle, has four different protocols that manufacturers can use for their cars. The OBD-II protocol implemented in the device in our tests is currently compatible with the ISO 9141-2 standard widely used in European and Asian cars.

The GNSS/INS receiver implements the OBD-II protocol on the board to access the odometer speed of the vehicle, which improves the navigation performance during GNSS outages in GNSS

signal challenged environments such as urban canyons. By using the odometer data and an advanced data fusion algorithm, GNSS outages can be seamlessly bridged with inertial measurements and therefore provide continuous navigation.

In the field tests, the GPS/BeiDou/MEMS receiver kept valid solutions during GNSS outages spanning more than 300 seconds. These features make the integrated navigation system suitable for a wide range of applications, including: vehicle and personal navigation and tracking, vehicle orientation reference, autonomous machine guidance, aerial and land mobile mapping, unmanned aerial vehicles, and research on multi-sensor navigation.

Analysis of BeiDou Constellation's Global Coverage

BeiDou is one of the four main GNSSs in the world, which will provide positioning, navigation, and timing (PNT) service for global users by 2020. According to the development plan, BeiDou began providing PNT services for Asia-Pacific region this year.

As of December 2012, 14 usable BeiDou navigation satellites were on orbit, including 5 GEO (geosynchronous Earth orbit) satellites, 5 IGSO (inclined geosynchronous orbit) satellites and 4 MEO (medium Earth orbit) satellites.

Geographic coverage is an important indicator for assessing constellation design. **Figures 1** and **2**, respectively, show the average satellite visibility and position dilution of precision (PDOP) values over a 24-hour period for BDS.

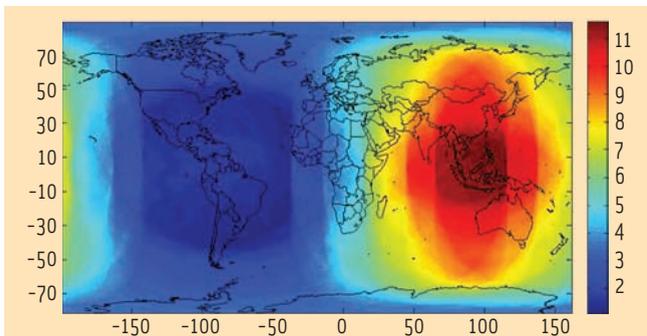


FIGURE 1 Average number of visible satellites of Beidou constellation over a 24 hour period (above a five degree elevation cutoff angle)

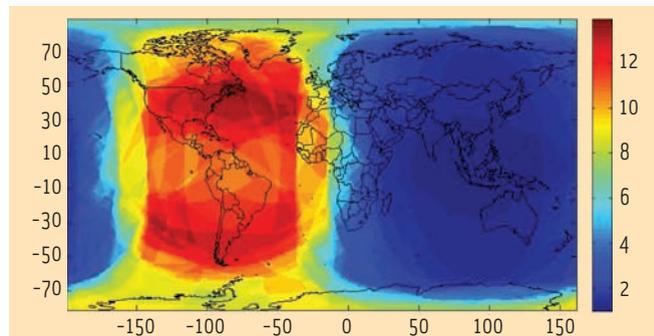


FIGURE 2 Average PDOP value of BeiDou constellation over a 24 hour period (above a five degree elevation cutoff angle)

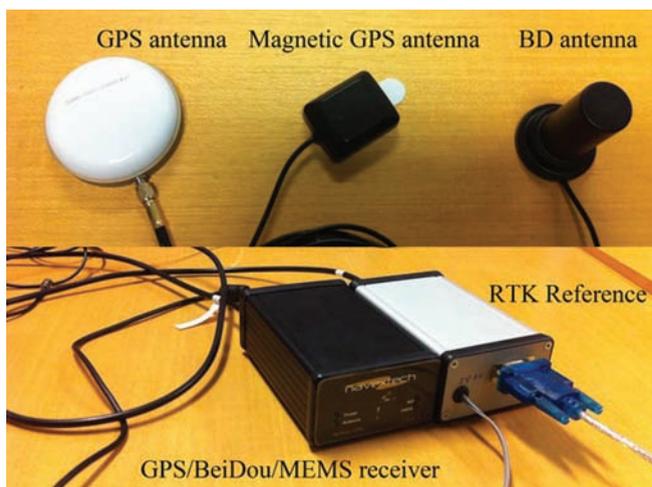


FIGURE 3 Three different antennas and GPS/BeiDou/MEMS receiver for the antenna evaluation

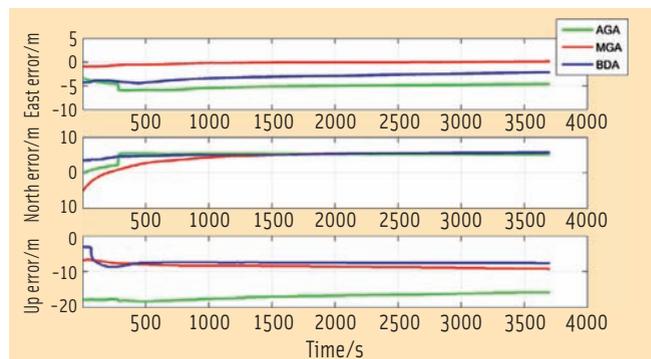


FIGURE 4 Static positioning error of three antennas on ENU direction: AGA, GPS antenna; MGA, magnetic GPS antenna; BDA, BeiDou antenna

Reflecting BDS's current phase of development, which concentrates the satellites over China and adjacent countries, more than eight satellites can be seen at many locations in the Asia-Oceania region, where the BDS PDOP is as small as 2 (with the elevation cut-off angle set as five degrees), providing assured PNT services in this area. Some effects on the PNT services from the constellation configuration will be presented and analyzed later during our description and evaluation of the road tests.

Comparison of Antennas

The GPS L1 signal frequency is 1575.42MHz, while the BeiDou B1 signal is 1561.098MHz. Frequency is one of the differences between GPS and BeiDou antenna. Most antenna manufactures have designed the BeiDou antennas that support both B1 and L1 frequencies.

Another difference in the two types of antennas is the communication mode between satellites and receiver they supported. GPS is a passive, one-way communication system. The GPS receiver only receives the signals from the satellites. It does not transmit any signals to the satellites.

In contrast, BDS has two generation of satellites operating in the orbits. The first generation is based on the active positioning technology, which means the receiver not only receives the signals from satellites but also transmits self-information to the satellites (e.g. the short message service).

Upgrading from the first-generation, the second-generation BDS designs in the passive positioning technology, which is same as the GPS. Without doubt, it also supports all services including a short message service (SMS). Therefore, all antennas for BDS must be compatible with these two generations of satellites.

The GPS/BeiDou/MEMS receiver used in this article integrates GPS/BeiDou module but with only one RF input. It is important to evaluate its positioning performance with different antennas, including the specially designed BeiDou antenna. A comparison of solutions using different types of antennas is presented.

This antenna evaluation was carried out in the University of New South Wales Satellite Navigation and Positioning (SNAP) Lab, in Sydney, Australia. As shown in **Figure 3**, three different antennas were evaluated by one-hour static positioning test using the GPS/BeiDou/MEMS receiver. From left to the right, they are a GPS antenna (AGA), general magnetic GPS antenna (MGA), and the BeiDou antenna (BDA). (Only the BDA antenna can track both BeiDou and GPS signals. The Beidou L1 frequency falls into the AGA antenna's frequency band, but we have not yet confirmed that it can track the Beidou signals.) The reference receiver provided a high-precision RTK solution.

Figure 4 provides the positioning errors of each antenna for the east/north/up (ENU) direction. The bias

between MGA and BDA positioning results are 0.05 meter in north-south, 2.3 meter in east-west, and 1.6 meter in up-down direction.

It's interesting to note that the AGA has the largest error on east and up directions, but less error on north direction. Even so, the positioning performance of the AGA is more numerically stable and its convergence speed, faster than the others.

The results in **Figure 4** indicate that the GPS/BeiDou/MEMS receiver is able to provide positioning service with both the GPS antennas and the BeiDou antenna. However, solutions from the three antennas revealed some differences. Because the comparison tests of the three antennas were not conducted at the same time, and the GPS/BeiDou/MEMS receiver is based on satellite pseudorange processing, the differences between three antennas (less than three meters in horizontal directions and less than seven meters in vertical direction) are within an acceptable error range.

The differences between the MGA and BDA antennas in all three directions were small (less than two meters after convergence on a position solution). Therefore, using a BeiDou antenna or GPS antenna would not significantly affect the positioning performance.

Performance in Field Trials

Several field trials were conducted to evaluate the performance of the integrated navigation system in different scenes and different hemispheres. In these tri-



GPS/BeiDou/MEMS configuration (left) and GPS/MEMS configuration (right)

als, a GPS/BeiDou/MEMS receiver and a GPS/MEMS receiver were mounted on the central armrest beside the driver as seen in the accompanying photo.

The solutions from these two systems were compared to reveal whether adding BeiDou capability to the integrated navigation system improved positioning performance. Two antennas were placed on the top of the car, a MAZDA 6 which uses the ISO 9141-2 OBDII protocol: these were the general magnetic GPS antenna for the GPS/MEMS receiver and the BeiDou antenna for the GPS/BeiDou/MEMS receiver.

Test One: Round Trip in Nanjing

We designed the road test route to ensure a variety of road conditions and environments, as shown in Figure 5. Section 1 is the airport highway with an open sky view. Section 2 is the city road crossing Nanjing from south to north with two short tunnels and two longer tunnels, including the longest tunnel (about 2.3 kilometers) in Nanjing under Xuanwu Lake. Section 3 is the return path crossing the urban downtown areas with tall buildings on both sides.

We expected that the GNSS-only solution would be of poor quality or unavailable due to these multipath and outage scenarios. The distance of the entire test trajectory was approximately 53 kilometers (≈33 miles).

Test results show that the GPS/BeiDou solution (yellow) keeps working in both areas of open sky view and urban canyons. When driving through the tunnels, the INS-only mode was activated to update the current position. In the short tunnels (Tunnel 1 and Tunnel 2), the GPS/BeiDou module continued

outputting its position solution (the yellow dots diverging from the route), which is obviously poor and jumps far away from the road.

In the long tunnels (Tunnel 3 and Tunnel 4) under the lake, the GPS/BeiDou module totally stopped outputting a solution. There is a short sky view when passing by the junction of two-direction tunnels and a way out. However, the integrated navigation system continued to output a solution (red) in all tunnels, which reasonably bridged the GPS/BeiDou outages.

Let's look at the performance of the system in greater detail.

Comparison of Visible Satellites between GPS and BDS. Figure 6 depicts the numbers of visible GPS/BDS space vehicles (SVs) when the car was stationary. At the same time, a zero-velocity update (ZUPT) function was working to eliminate the inertial sensor errors. Ten GPS SVs and eight or nine BDS SVs were available. That is a good result in light of the BeiDou constellation coverage seen in Figure 1.

Results of GPS-Only vs. GPS/BeiDou with Open Sky. The section of the road-

test route depicted in Figure 7 had a clear sky view from the highway during which the receiver could track enough satellites to provide position fixes. The positioning results from GPS/BeiDou and GPS-only are slightly different from each other. By overlaying the solutions on a Google Earth image, we found that the GPS-only solution (red) fits the traffic lanes very well, but GPS/BeiDou solution (yellow) has a bias within two meters. These errors were mostly toward the south.

As we have analyzed the BeiDou antenna and GPS antennas and excluded the antenna contribution as the reason for the bias, it seems that this bias can somehow be explained by the satellite geometry. Figure 8(a) shows the skyplot of the BeiDou constellation in Nanjing at the time of the experiment (around 14:00 UTC), and Figure 8(b) shows the skyplot of GPS constellation at the same time. Quite obviously the distribution of the BeiDou SVs in the current regional phase of BDS is rather unsymmetrical in the North-South direction and more weighted on the south, while the skyplot of GPS constellation is more symmetrical than the BDS.

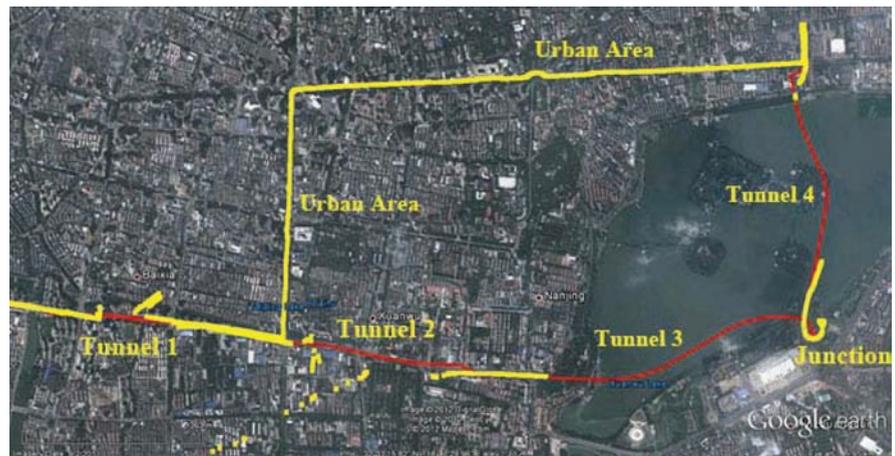


FIGURE 5 Two-way road test in Nanjing: yellow, GPS/BeiDou positioning; red, GPS/BeiDou/MEMS positioning

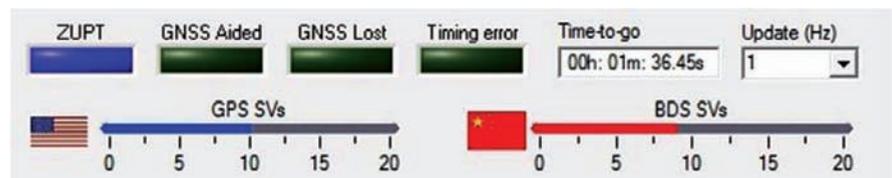


FIGURE 6 Visible SVs number of GPS and BDS



FIGURE 7 Solutions from GPS-only (red) and GPS/BeiDou (yellow) on airport highway

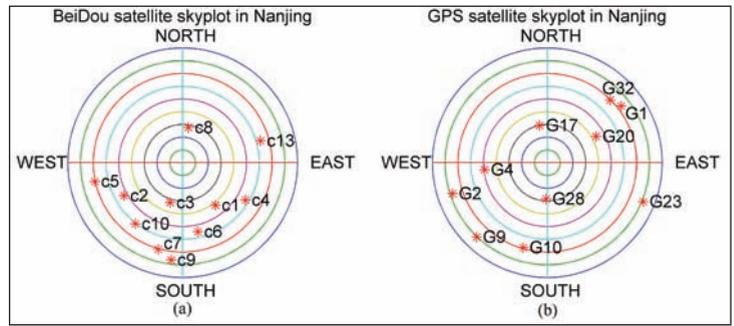


FIGURE 8 BDS (a) and GPS (b) skyplot of the test in Nanjing



FIGURE 9 Performance of GPS/BeiDou/MEMS receiver in underground parking site

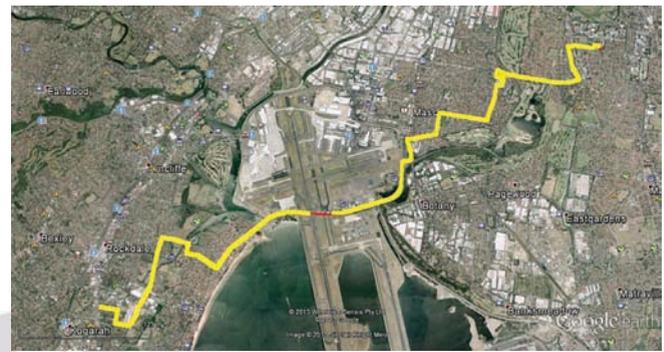


FIGURE 10 Trajectory of Sydney road trial

GPS/BeiDou vs. GPS/BeiDou/MEMS.

Referring again to Figure 5, on the way back to the starting point, no GNSS positioning blockage appeared in the urban area. This shows that GPS/BeiDou has the potential to provide more reliable and continuous solutions than GNSS standalone.

Test Two: Underground Parking

The GNSS/INS unit can continuously operate in INS-only mode, useful in such places as the underground parking lots where drivers could lose their way. When returning from the road test, the car was driven back to the underground parking lot (under the white roof building shown in Figure 9). Beginning at the entrance to the parking lot, the GPS/BeiDou solutions (yellow) quite obviously began to jump far away from the actual direction of the vehicle's path because of the extremely poor or blocked GNSS signals underground. Meanwhile, the integrated solution (red) gave continuously accurate positions, from the entrance to where the car eventually was parked.

Test Three: Vehicle Field Test in Sydney

As Nanjing is located in the northern hemisphere, a corresponding vehicle trial was conducted in one of the big cities of the southern hemisphere, Sydney, Australia. Similar to the road test in Nanjing, this trip was also designed to include both open sky view and urban view with dense trees, as well as a section with a short tunnel.

The trajectory is shown in Figure 10 with the GPS/BeiDou solution plotted in yellow and the GPS/BeiDou/MEMS solution plotted in red. We can see that the integrated navigation system is able to provide continuous solution during

the entire trial, including when in the tunnel.

Figures 11 and 12 show two magnified portions of the trajectory, which are road segments aligned east-west and north-south, respectively. Note that the trajectory in Figure 11 shows an obvious bias from the main road in the north direction, while Figure 12 shows an error away from the road in the west.

Figure 13(a) shows a skyplot of the BDS constellation over Sydney at the time of the test (22:0 UTC), and a corresponding skyplot of the GPS constellation at the same time depicted in Figure 13(b). Again, the distribution of BeiDou SVs is unsymmetrical in both the north-



FIGURE 11 Part trajectory of Sydney road test (E-W direction)



FIGURE 12 Part trajectory Sydney road test (N-S direction)

south and east-west directions. Most satellites distribute in the north-west, which cause the error to accumulate in the north and west directions.

The distribution of GPS satellites is much better than the BDS, a situation that is very similar with the Nanjing test. All these phenomena are consistent with the road test results.

Nanjing and Sydney are at similar distances from the equator, with both located in mid-latitude area. From the Figure 8(b) and Figure 13(b), it can be seen more BDS satellites are distributed on the parts towards the equator. This is the probable reason for the apparent

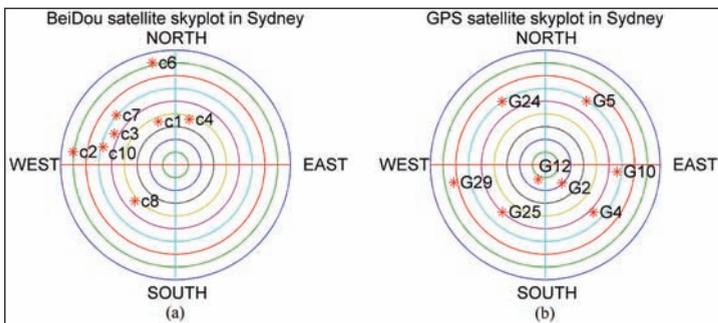


FIGURE 13 BDS (a) and GPS (b) skyplot of the test in Sydney



Front view (left) and back view (right) of nAX5.2

constant offset positioning errors. However, as a GNSS under development, BDS currently has only 14 operational satellites. After it has reached full deployment with more working satellites providing global coverage, we expect to see better performance from BDS.

Concluding Remarks

This article presented the navigation performance of a new GPS/BeiDou/MEMS integrated navigation system. We compared and evaluated the system's performance in different scenarios in field trials in the northern and southern hemispheres.

Analysis of results show that the BDS has the ability to provide accurate and reliable positioning solution to support navigation applications. But the overall performance of BeiDou in these tests is still not as good as GPS. One probable reason is that the GPS/BeiDou module in GPS/BeiDou/MEMS receiver only uses B1 signals, which degrades the positioning accuracy. Therefore, performance may improve by accessing B2 and B3 signals with a more advanced receiver.

In urban canyon and tunnels, GPS/BeiDou/MEMS receiver can provide accurate and robust navigation solutions even during GNSS outages by integrating GNSS and inertial measurements.

Further investigation of constant error trends found in

both tests in terms of satellite visibility and geometry revealed that the direction of a position bias is consistent with the satellites' unsymmetrical distribution. This is understandable as BeiDou is not a fully deployed system, but we can expect better performance over time with more satellites.

Acknowledgment

The authors appreciate the generosity of Nanjing TXZ Technology Ltd. in allowing them to borrow the GNSS/INS devices for these tests. TXZ Technology specializes in GNSS and INS integration and its applications.

Manufacturers

The integrated GPS/MEMS receiver and GPS/BeiDou/MEMS receiver used for the research described in this article were the Navextech nAX5.1 and nAX5.2 from **TXZ Technology, Ltd.**, Nanjing, China. The antennas tested during the research were the G5 antenna from Antcom Corporation, Torrance, California USA, the TUV magnetic mount GPS antenna, and TXZ's BeiDou antenna. The real-time RTK solution was obtained with the NAX-RTK system manufactured by TXZ Technology.

The AX5.2 is hosted in a small box (L127×W78×H43 millimeters) with a simple user interface. The front panel of the box (photo on left) has two LEDs on the left-hand side to indicate status of power supply and the antenna connection. Two LEDs on the right side indicate the operational status of the GNSS and the INS. On the back panel (photo on right) a multi-function interface implements two UARTs, the OBD-II communication, and power supply from either the OBD-II or the vehicle 12-volt sup-

Supply voltage	7 to 12 VDC	Output rate	10Hz (default)
Power dissipation	2.6W	Odometer	OBD-II interface
Operating temp.	-40 to +85°C	Orientation range	360° about all axes
Weight	250g	Pitch and roll accuracy	<0.2°
Size	127×78×43mm	Yaw accuracy	<0.1°
Output type	R5232 and USB	Position accuracy	<2m RMS (with GNSS)
COM settings	115,200 bps, 8 bits data, no-parity, 1-bit stop	Velocity accuracy	<0.1m/s (with GNSS)
Output data format	GPS info, inertial sensor raw data, PVA solution	GNSS outage span	>300s

TABLE 1. nAX5.2 specifications

GNSS specifications			
Channel	50 channels, L1	Signal strength	-144dBm(Acquire), -159dBm (Tracking)
Position accuracy	<5m(Horizontal), <10m(Vertical)	Power dissipation	75mA@3.3v(Average)
Cold start	35s	Speed accuracy	<1m/s
Hot start	2s	Operating temp.	-30 to +70°C
Accelerometer specifications			
Range	±18g	Temp. sensitivity	±120ppm/°C
Initial bias	±50mg (1G)	Nonlinearity	0.1%
Bias stability	±0.2mg (1σ)		
Gyroscope specifications			
Range	±350°/s	Temp. sensitivity	±250ppm/°C
Initial bias	±2°/s (1σ)	Nonlinearity	0.1%
Bias stability	±0.007°/s (1σ)		

TABLE 2. Sensor specifications

ply. A micro-USB virtual COM on the panel facilitates communication with a computer via a standard USB port. An SMA connector on the panel is used to connect an external GPS antenna. **Table 1** and **2** provide the detailed specifications of nAX5.2 and the sensors.

Reference

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- [2] Wikipedia. http://en.wikipedia.org/wiki/On-board_diagnostics#OBD-II. Accessed June 2013.

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Locata /GNSS/INS multi-sensor integration, particularly the implementation of new navigation and data fusion algorithms. 

Solutions continued from page 42

tributors to the GNSS position error in urban environments. The error characteristics are quite different from those of multipath interference and different techniques are needed to mitigate them. Therefore, NLOS reception should be treated as a separate error source by the GNSS community.

Additional Resources

Further discussion of NLOS and multipath mitigation techniques, together with a list of references, may be found in a paper by P. D. Groves *et alia*, “A Portfolio Approach to NLOS and Multipath Mitigation in Dense Urban Areas,” *Proceedings of ION GNSS+ 2013*, which is also available from UCL Discovery.



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University College London, where he leads research into robust positioning and navigation within the Space Geodesy and Navigation Laboratory. With colleague Dr. Ziyi Jiang, he recently completed an investigation of new GNSS NLOS and multipath mitigation techniques. Groves recently published the greatly expanded second edition of his book, *Principles of GNSS, Inertial, and Multisensor Integrated Navigation Systems* (Artech House). The first edition was reviewed by Demoz Gebre-Egziabher in the September/October 2008 issue of *Inside GNSS*. His most recent article for *Inside GNSS* was *The PNT Boom: Future Trends in Integrated Navigation* in the March-April 2013 issue. Previously, he authored an article on deep integration of GNSS/inertial systems in the January/February 2008 issue. 



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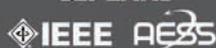


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