Journal of Global Positioning Systems (2011)
Vol.10, No.2 :114-124
DOI: 10.5081/jgps.10.2.114

Journal of Global Positioning Systems
2011
© CPGPS

Impact of RNSSs on Positioning in the Asia-Oceania Region

Binghao Li[1], Shaocheng Zhang[2], Andrew G Dempster[1] and Chris Rizos[1]
[1]School of Surveying and Spatial Information Systems, University of New South Wales, Sydney, Australia
[2] SPACE Research Centre, RMIT University, Australia

Abstract

Regional Navigation Satellite Systems (RNSS) are being developed by Asian countries. The Asia-Oceania region becomes a hotspot that the maximum number of navigation satellites can be “seen”. There will be a great impact of the RNSSs on positioning in this region. This paper introduces the Asian RNSSs, discuses single point positioning and differential positioning using RNSSs and analyses the combination of GPS and RNSS for urban canyon positioning by simulation.

Keywords: RNSS, Regional Positioning, GNSS, Urban Canyon Positioning

1. Introduction

Since the late 1990s, several Asian countries have developed plans to launch their own navigation satellite systems (NSSs). As a Global Navigation Satellite System (GNSS) is very expensive and complex – only the US and Russia have fully developed GNSSs so far, with Europe and China promising systems – a Regional Navigation Satellite System (RNSS) is a more feasible option. China launched its first navigation satellite – Beidou 1A – in 2000 as part of its RNSS known as Beidou Twin-Star. With two more satellite launches, Beidou was fully operational in 2003 [1]. Beidou-2, also called Compass, is designed as a GNSS, but at the early stage, it will work as a RNSS covering China and neighbouring regions [2]. India and Japan also announced plans to deploy their own NSS. India is expected to launch the first satellite of its Indian Regional Navigation Satellite System (IRNSS) in 2010, and has stated the IRNSS constellation would be fully deployed by 2012 [3]. The Japan Aerospace Exploration Agency (JAXA) has launched the first satellite of the Quasi-Zenith Satellite System (QZSS), nicknamed Michibiki, on September 11, 2010 [4]. Apart from Beidou, there is a less well known Chinese RNSS known as the Chinese Area Positioning System (CAPS) under study [5], making a total of four potential RNSS.

The Global Positioning System (GPS) is the most widely used GNSS, however the requirement of tracking a minimum of four satellites simultaneously can not always be met in, for example, ‘urban canyon’ areas. In such cases, if more satellites at high elevation were visible, the satellite-availability problem could be, to some extent, addressed. Furthermore, more visible satellites will ensure that high accuracy carrier phase-based GNSS techniques, such as Real Time Kinematic (RTK) positioning, would be more available by help on reliable ambiguity resolutions. In addition, receiver autonomous integrity monitoring (RAIM) performance will also be improved. Obviously, the deployment of a number of Asian RNSSs will have a significant impact on navigation and positioning in Asia-Oceania region.

The rest of the paper is organized as follows: In section 2, the details of Asian RNSSs are introduced, and then using RNSSs for regional positioning are focused in section 3. Section 4 discusses the augmentation of GNSS(s) with RNSSs for regional urban canyon positioning. Finally, conclusion is given.

2. The Asian RNSSs

Beidou-1 is the only fully deployed RNSS in the Asian area. It consists of four geostationary (GEO) satellites. Two satellites are required for 2D positioning (two satellites are backups). However, unlike GPS, it is a two-way system, the user also sends messages to the Control Centre via the Beidou satellites [6]. Hence only authorised users can access the system. This limits the level of utilisation of the system, especially if it were to be used in combination with other RNSSs and GNSSs. As a result of this limitation the Beidou-1 was not included in this investigation. However, Compass phase II was included as it will be a RNSS with a 14-satellite constellation by 2012 [7].

Figure 1 shows the satellite ground tracks of four RNSSs: IRNSS (in blue), Compass phase II, QZSS (in green) and CAPS (in red). The four systems provide coverage over a large area of the Asia-Oceania region, and especially South-East Asia.

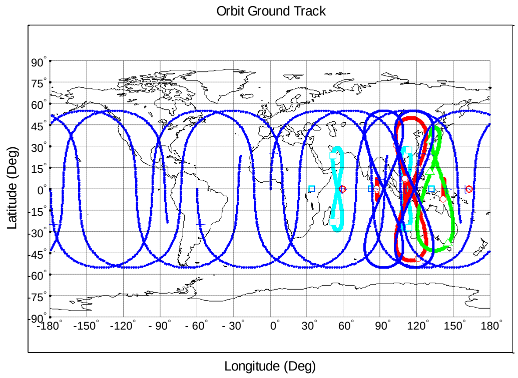

Figure 1: The satellite ground tracks of IRNSS (in cyan with squares), Compass phase II (in blue with crosses), QZSS (in green with triangles) and CAPS (in red with circles).

2.1 The Indian Regional Navigation Satellite System (IRNSS)

In 2006 the Indian government approved the deployment of the IRNSS over a period of 6-7 years as a constellation of seven satellites in order to provide navigation and timing services over the Indian subcontinent [3]. The constellation consists of three GEO satellites located at 34°E, 83°E and 132°E longitude, and four Inclined Geosynchronous Orbit (IGSO) satellites placed in orbits inclined at an angle of 29° with longitude crossings at 55°E and 111°E [7]. The four IGSO satellites have “figure-8” groundtracks in order to improve the satellite geometry and make 3D positioning possible. This approach will be used by other NSSs, including Compass (a under developed Chinese GNSS), for which three IGSO satellites are planned.

IRNSS will provide a ‘standard positioning service’ and a ‘precision service’. Both will be carried on L5 (1176.45MHz) and an S-band frequency (2492.08MHz). The standard positioning service signal will be modulated by a 1MHz BPSK signal while the precision service will use BOC(5,2) modulation. BOC (binary offset carrier) modulation which offers improved performance has been widely used for new GNSS signals, such as Galileo L1 signal, GPS L1C and M code signal [8] [9]. The system is intended to provide approximately 20 metre accuracy over the Indian Ocean area, and about 10 metres over the subcontinent. The service area is defined as being between 40°E to140°E longitude and in the latitude band ±40°.

Unfortunately there is very little information available about IRNSS; however India’s purchase of rubidium space clocks has been confirmed by the manufacturer [10]. It is claimed that the system will be fully deployed by 2012.

2.2 Compass phase II

There are three development phases of the Compass system. A demonstration system was completed in phase I (3 GEO satellites). Before a global system (phase III) is created by 2020, a regional system which covers Asia-Pacific area will be deployed around 2012 in phase II. Fourteen satellites would comprise the regional constellation: five GEOs, four MEOs, and five inclined geosynchronous orbit (IGSO) satellites [2][11]. Up to the present (August 2011), nine Compass space vehicles has been launched (four GEOs, four IGSOs and one MEO). Three GEOs located at 84°E, 144.5°E and 160°E longitude, one GEO (G2) is drifting; IGSOs placed in orbits inclined at an angle of 55° with longitude crossings at 118°E (IGSO1-3) and 93°E (IGSO4). The MEO satellites is an experimental one which is not expected to be used in the future RNSS. According to reports, Compass (which means Compass phase II in the rest of this paper) signals will be transmitting on three frequencies (1561.098 MHz, 1207.14 MHz and 1268.52 MHz) using quadrature phase shift keying (QPSK).

2.3 The Quasi-Zenith Satellite System (QZSS)

The concept of QZSS for Japan was first mooted about four decades ago [12]. However only in 1997 did serious discussions begin as more people have become aware of the importance of positioning satellites as a form of national infrastructure. The QZSS project commenced in 2003 when the government approved the first budget tranche.

Strictly speaking QZSS is not a RNSS, but rather an augmentation of GPS and the EU’s GALILEO as it cannot provide navigation solution when it is used alone. The QZSS consists of three satellites that have the same orbital period as GEO satellites but in orbits that are elliptical – sometimes referred to as Highly-inclined Elliptical Orbits (HEO). The QZSS’s HEO groundtrack will move further from the Earth in the northern hemisphere than in the southern hemisphere so that the satellite will be at a high elevation angle over Japan for a longer period of time than when over the southern hemisphere. The QZSS coverage area is East Asia and Oceania, and the design of the constellation guarantees that users in the coverage area can receive satellite signals from a high elevation angle at all times (from one of the three QZSS satellites). In fact, one satellite always appears near the zenith above the region of Japan [13] – hence its name “quasi-zenith”.

QZSS will be a rich signal source. It will transmit signals on L1 (1575.42MHz), L2 (1227.6MHz), and the L5 (1176.45MHz) frequencies which will be compatible and interoperable with GPS. An interesting fact is that the new modernized GPS L1C signal will be transmitted by QZSS before GPS! The Japanese authorities expect that this in itself will inspire new applications in the service area. QZSS will also transmit a new experimental signal (LEX) in the same band as GALILEO's E6 (1278.75MHz) signal and a new GPS augmentation signal L1-SAIF (submeter-class augmentation with integrity function) [13]. The utility of QZSS to augment GPS and GALILEO has been investigated by several researchers [14] [15].

2.4 Chinese Area Positioning System (CAPS)

CAPS is a less well-known Chinese RNSS. Similar to most navigation satellite systems, CAPS is a ‘passive’ one-way system – satellites broadcast the navigation messages and user receivers are only ‘listeners’. However, there is a significant difference between CAPS and all the other NSSs – the navigation messages are generated on the ground and uploaded to the communication satellites, with the satellites acting only as transponders [5][16]; see Figure 2.

The CAPS project was initiated in 2002 and the constellation design requires several communication satellites – GEO and IGSO. These spacecraft are not standard navigation satellites – all the navigation-related facilities are all located on the ground. The advantages of this type of system are:

- Low cost - bandwidth can be rented on commercial communications satellites.
- Comparatively simple - the navigation-related facilities, including the atomic clocks, are located at a ground station.
- Communication ability - innovative applications can be developed.

CAPS uses C-band frequencies for transmitting the navigation signals. The two carrier frequencies (downlink) are C_1=4143.15MHz and C_2=3826.02MHz. Nevertheless CAPS has a very similar signal structure to GPS. Since the navigation messages are generated on the ground and transmitted to the satellites, the range that is measured by the receiver is that from the ground station. To obtain the pseudoranges between the satellite and the user, a Virtual Atomic Clock (VAC), which could be considered to be operating on the satellite, is introduced. VAC time can be calculated based on the signal transmission time from the ground station, and the signal travel time from the ground station to the satellite, including the atmospheric delays, satellite receiving and broadcasting delays, etc.

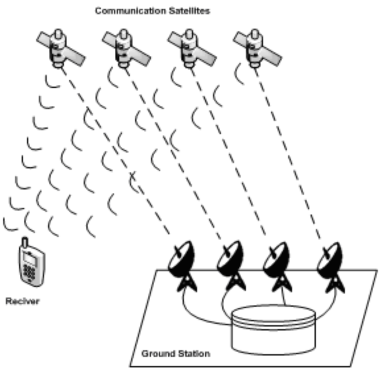

Figure 2: The principle of CAPS

In 2005 a validation system was developed, consisting of four commercial GEO communication satellites. Since the satellites are all located in orbit over the equator, 3D positioning can not be provided. CAPS equipment designers incorporated a barometer into receivers to provide a height estimate. At least three satellite-receiver ranges are needed for a position fix, while a fourth range can increase the coverage and provide redundant measurements. To avoid the need to use a barometer it is proposed to launch several IGSO satellites or to utilize retired GEO communication satellites by manoeuvring them into so-called Slightly Inclined Geostationary Satellite Orbits (SIGSO). In this paper, the simulated CAPS constellation is based on the following configuration: two GEO satellites located at 59°E and 163°E longitude; three SIGSO satellites and three IGSO satellites.

Table 1: Compass phase II, IRNSS, QZSS and CAPS orbit information

RNSSs	Constellation	Orbit information
Compass phase II	5 GEO	Longitude: 58.75° E, 84 ° E, 110.5° E, 144.5 ° E, 160 ° E
	5 IGSO	Central longitude of ground trace: 93°E (x2), 118°E(x3) Inclination: 55°
	4 MEO	Semi-major axis: 27840km Inclination: 55° Mean anomaly: 0°,180° Ascending node longitude: 0°, 120°
IRNSS	3 GEO	Longitude: 34° E, 83° E, 132° E
	4 IGSO (2X2)	Central longitude of ground trace: 55°E, 111°E Inclination: 29°
QZSS	3 HEO	Semi-major axis: 42164 km Eccentricity: 0.075 Inclination: 43° Mean anomaly:0º, 240º, 120° Ascending node longitude: 225º, 345º, 105° Argument of perigee: 270°
CAPS	2 GEO	Longitude: 59°E, 163°E
	3 IGSO	Central longitude of ground trace: 115°E Inclination: 50°
	3 SIGSO	Central longitude of ground trace: 87.5°E, 110.5°E, 142°E Inclination: 7°

Details of the orbits of the four NSS constellations are listed in Table 1.

3. Using RNSSs for Regional Positioning

3.1 Single point positioning using each RNSS alone

IRNSS, Compass phase II or CAPS can be used alone for positioning purposes (they also provide velocity and time). Similar to GPS single point positioning (SPP), the observation equations of the code measurement of the RNSSs can be expressed as

$$r = \rho + Trop + I + ct^{s} - cT_{r} + o^{s} + e \qquad (1)$$

where R is range measurement, ρ is the geometric range, t^{S} and T_r are the satellite clock bias and receiver clock bias respectively, c is the speed of light, $Trop$ and I are the tropospheric refraction bias and ionospheric refraction bias respectively, o^{s} is orbit error and e is observation noise and multipath. For simplicity, the code measurements alone are assumed to be used in SPP.

Figures 3 and 4 show the average satellite visibility and PDOP values over a 24 hour period for IRNSS and CAPS respectively. At many locations in the Asia-Oceania region more than four IRNSS satellites and more than five CAPS satellites can be seen. The PDOP of IRNSS can be as small as 3 while that of CAPS can be 2.2. The coverage of CAPS is slightly better than that of IRNSS. There is, however, a considerable overlap of these two systems. It should be noted that the relatively good coverage and low PDOP assumes a small elevation cutoff angle (5 degrees – effectively an 'open sky'). If the mask angle is set to 15 degrees or higher, the situation changes dramatically. Compass is more complicated than IRNSS and CAPS and it can achieve better coverage, visibility and PDOP. Figure 5 gives the details. QZSS cannot be used alone as it is designed as an augmentation system of GPS or GALILEO. Figure 5 shows the number of QZSS satellites that can be seen (elevation cutoff angle is also 5 degrees). Obviously, it can also be used as an augmentation of other NSSs.

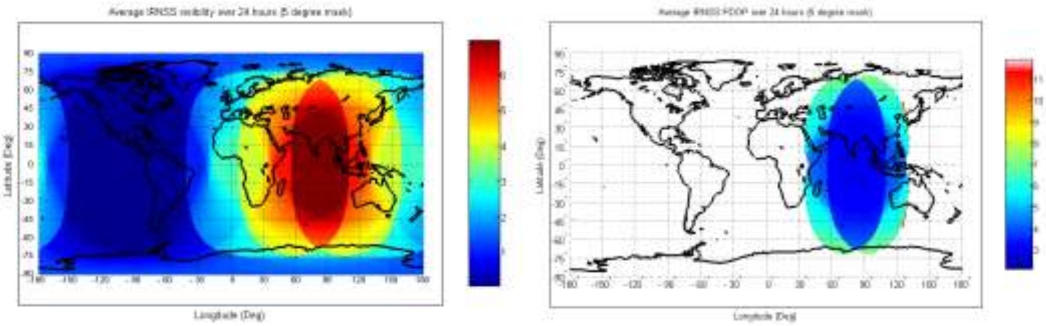

Figure 3: Average number of visible satellites (left) and average PDOP value (right) of the IRNSS constellation over a 24 hour period (above a five degree elevation cutoff angle) – white area indicates that the PDOP value is higher than 12

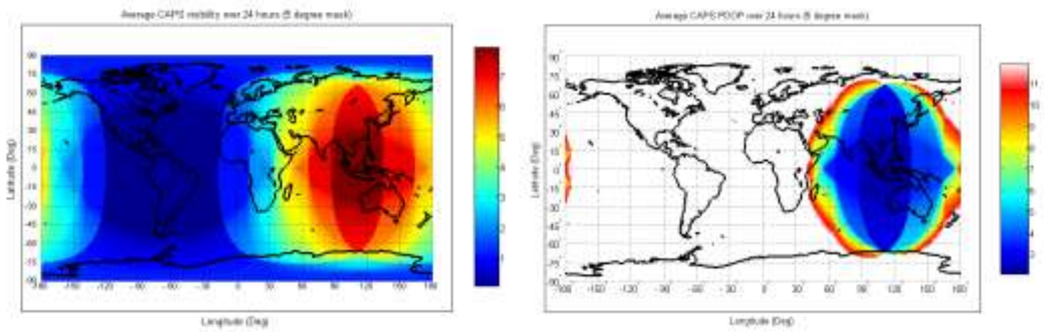

Figure 4: Average number of visible satellites (left) and average PDOP value (right) of the CAPS constellation over a 24 hour period (above a five degree elevation cutoff angle) – white area indicates that the PDOP value is higher than 12

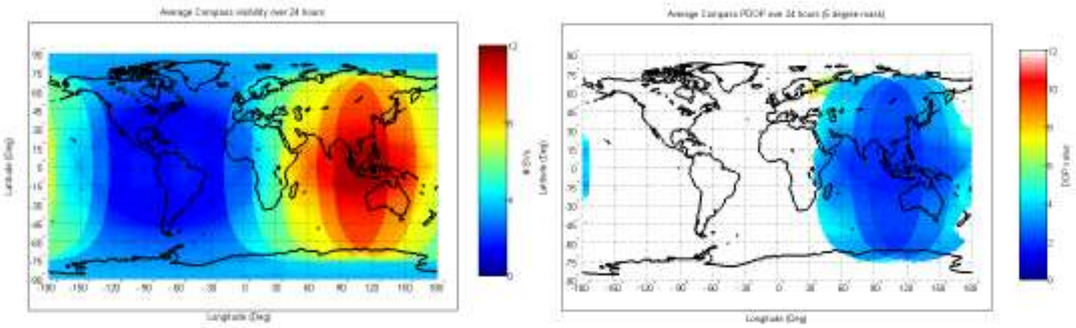

Figure 5: Average number of visible satellites (left) and average PDOP value (right) of the Compass phase II constellation over a 24 hour period (above a five degree elevation cutoff angle)

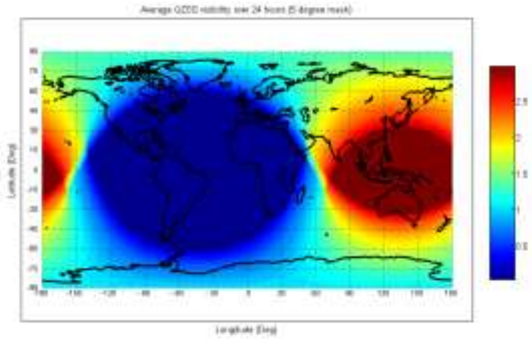

Figure 6: Average number of visible satellites of the QZSS constellation over a 24 hour period (above a five degree elevation cutoff angle)

3.2 Single point positioning using the combined RNSSs

When the four constellations are combined, better results can be expected. There are two issues should be noticed, one is the datum used by different systems which can be ignored as the differences are very small for navigation solutions; the other is the different time standards which should be considered when the combination is conducted. Equation (1) can be simplified then applied to all four systems as following

$$\begin{aligned} R_{irn(i)} &= \rho_{irn} - cT_{irn} + e_{irn(i)} \\ R_{com(j)} &= \rho_{com} - cT_{com} + e_{com(j)} \\ R_{cap(k)} &= \rho_{cap} - cT_{cap} + e_{cap(k)} \\ R_{qzs(l)} &= \rho_{qzs} - cT_{qzs} + e_{qzs(l)} \end{aligned} \tag{2}$$

where R is the corrected code measurement by applying correction of atmosphere bias, satellite clock error and ignore the orbit error. $i=1,\ldots,m;$ $j=1,\ldots,n;$ $k=1,\ldots,o;$ $l=1,\ldots,p.$ The linearized observation equations can be expressed as

$$\begin{bmatrix} dR_{irn} \\ dR_{com} \\ dR_{cap} \\ dR_{qzs} \end{bmatrix} = \begin{bmatrix} A_{irn} & -J_m & 0 & 0 & 0 \\ A_{com} & 0 & -J_n & 0 & 0 \\ A_{cap} & 0 & 0 & -J_o & 0 \\ A_{qzs} & 0 & 0 & 0 & -J_p \end{bmatrix} \begin{bmatrix} dX \\ cdT_{irn} \\ cdT_{com} \\ cdT_{cap} \\ cdT_{qzs} \end{bmatrix} + \begin{bmatrix} \varepsilon_{irn} \\ \varepsilon_{com} \\ \varepsilon_{cap} \\ \varepsilon_{qzs} \end{bmatrix} \tag{3}$$

where $dR=R-f(X_0)$, X_0 is the approximate user location; A is the design matrix for a single system; J is a vector with n by 1 vector of ones; X is 3 by 1 user coordinate vector.

Figure 7 shows the average satellite visibility and PDOP when IRNSS, Compass phase II, QZSS and CAPS are considered together. Comparing to Compass phase II only, there is no significant change in the area of coverage, however the number of visible satellites in the Asia-Oceania region increases up to 29. In a large area more than 20 satellites are visible. The change in the values of PDOP is not significant; however the area where a reasonable PDOP can be achieved is expended. The area with average PDOP less than 5 increase 8.4%, if PDOP less than 8 is considered, the increase is 25.7%. The PDOP value also decreases slightly (about 3.5%). Again, the results were calculated based on the assumption of a 5 degrees elevation mask angle. In many real applications, however, the cutoff angle can be much higher, especially when the user is in an 'urban canyon' – the cutoff angle could be more than 30 degrees, even as high as 45 degrees [14][17].

Positioning and navigation in urban canyon areas is problematic – due to blockage of the signals, severe multipath, poor PDOP, etc. Although other technologies for positioning in urban canyon areas have been proposed – such as mobile network [18], WiFi [19], multi-sensor integration [20] – there is no clear 'winner'. One approach is simply to use more satellites which are at a high elevation angle, and accept the reduction in accuracy due to poor geometry. For example, QZSS is designed to ensure one satellite always is visible near the zenith above the region of Japan. The full deployment of the RNSSs in Asia will increase the number of satellites visible at high elevation angles. Figure 8 shows the satellite visibility and PDOP values for the combined Asian RNSSs when the elevation mask angle was set to 30 degrees. It is impressive that, on average, more than ten satellites, in latitude band ±50° are visible. But only a relative small area in South-East Asia can enjoy a good PDOP value. Nevertheless, it is possible to obtain a user's position in an urban canyon most of the day when the four RNSS constellations are combined.

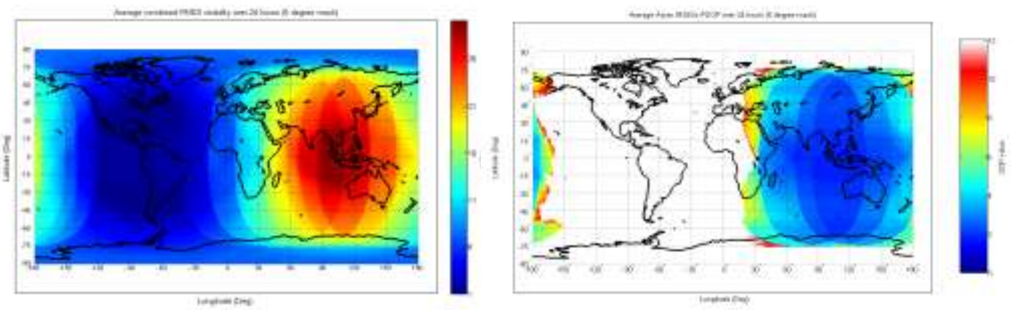

Figure 7: Average number of visible satellites (left) and average PDOP value (right) of combined RNSSs over a 24 hour period (above a five degree elevation cutoff angle)

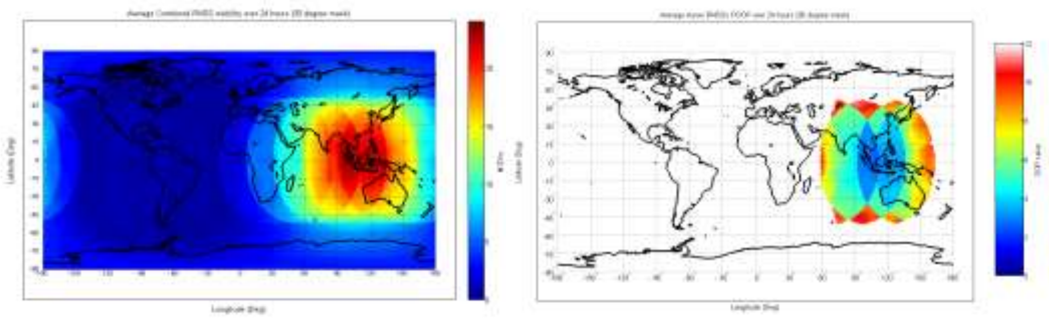

Figure 8: Average number of visible satellites (left) and average PDOP value (right) of combined RNSSs over a 24 hour period (above a 30 degree elevation cutoff angle)

When satellite positioning in urban areas is discussed, it is necessary also to consider the temporal variation of satellite visibility and PDOP at some specific locations – the big cities where urban canyon conditions exist in the Asia-Oceania region. A set of cities were selected (see Table 2) and Table 3 gives some results. When the elevation mask angle was set to 30 degrees, the average number of visible satellite at these 10 cities was between 14 and 23. In general, for those cities which are close to the equator and the center of the four constellations more satellites can be observed, which leads to a lower PDOP. For example, at Bangkok, Singapore and Shanghai, the PDOP values are always less than 5. However, at Mumbai, despite being relatively close to the equator, the results are not as good because it is located too far from the center of the four constellations. At other cities the PDOP values are more likely greater than 5 and less than 8. If the elevation mask angle increases to 40 degrees, a much worse results can be achieved. Even in Singapore, only about 8 hours during a day, the PDOP value is less than 5. It is clear that using RNSSs alone is possible to provide 3D position. However, the PDOP values are generally poor. To obtain a better PDOP, which implies more precise positioning results, augmentation of the RNSSs (or using RNSSs to augment GNSS) has to be considered.

Table 2: Selected cities in the Asia-Oceania region

Cities	Coordinates		
	Longitude (deg)	Latitude (deg)	Ellipsoidal height (m)
Beijing	116.4E	39.9N	80
Seoul	127.0E	37.5N	50
Tokyo	139.7E	35.7N	20
Shanghai	121.5E	31.2N	20
New Delhi	77.2E	28.6N	200
Mumbai	72.9E	19.0N	50
Bangkok	100.5E	13.7N	20
Singapore	103.8E	1.4N	20
Perth	115.9E	31.9S	50
Sydney	151.2E	33.9S	50

Table 3: Average number of visible satellites and the percentage of PDOP less than a specific value (5 and 8) over a 24 hour period at selected cities with different cutoff angles (40 degree and 30 degree)

Cities	Avg Visible sat		PDOP≤5 (%)		PDOP≤8 (%)	
	40°	30°	40°	30°	40°	30°
Beijing	10.6	16.5	2	38	5	100
Seoul	11.7	16.2	8	36	37	83
Tokyo	12.3	15.2	3	27	17	68
Shanghai	13.5	19.4	7	100	40	100
New Delhi	12.6	17.3	6	37	49	97
Mumbai	13.3	16.7	4	27	35	77
Bangkok	17.4	22.3	8	100	48	100
Singapore	16.7	23.0	34	100	87	100
Perth	13.1	18.3	11	100	38	100
Sydney	10.8	14.0	0	18	15	55

3.3 Differential positioning

For code-based differential positioning, the combination of the RNSSs is simple; the previous discussed model can be used. However, for carrier-phase-based differential positioning, things are more complicated. The double differenced phase (to simplify the discussion, only single frequency is considered) and code observation equations within one RNSS can be formed as:

$$L_{mn}^{sk} = \rho_{mn}^{sk} + Trop_{mn}^{sk} - I_{mn}^{sk} + (\lambda^s N_{mn}^s - \lambda^k N_{mn}^k) + \varepsilon_{mn}^{sk} \quad (4)$$

$$r_{mn}^{sk} = \rho_{mn}^{sk} + Trop_{mn}^{sk} + I_{mn}^{sk} + e_{mn}^{sk} \quad (5)$$

where L and r are phase and code measurements respectively; m and n are the indices of the stations, s and k are the indices of the satellites, λ is the wave length of the carrier. N is the carrier phase ambiguity, ε and e are the random noises of phase and code measurements respectively. Within each RNSS, the wave length of carrier is the same; hence the terms of single differenced ambiguities can be merged to form a double differenced ambiguity term

$$\lambda^s N_{mn}^s - \lambda^k N_{mn}^k = \lambda N_{mn}^{sk} \quad (6)$$

When the intersystem combination is considered, λ^s and λ^k are different; the corresponding double differenced ambiguity term is expressed as

$$\lambda^s N_{mn}^s - \lambda^k N_{mn}^k = \lambda^s N_{mn}^{sk} + (\lambda^s - \lambda^k) N_{mn}^k \quad (7)$$

One intersystem double difference observation will introduce two ambiguities, one is the double differenced ambiguity N_{mn}^{sk}, and the other is the single differenced ambiguity of the reference satellite N_{mn}^k. If the same reference satellite is used for the combination, the single differenced ambiguity is the same for different intersystem double differenced observation. When the carrier frequency of the two systems are significantly different, N_{mn}^k has to be estimated to its correct integer value, otherwise the big error will disturb the double difference ambiguity resolution. However, when the carrier frequencies of the two systems are close enough, a simple rounding of the float ambiguity for N_{mn}^k will not affect much about fixing the double difference ambiguities. For instance, there is a common frequency of Compass and QZSS (L1) although the centre frequencies of the carriers are not exactly the same (1561.098 MHz and 1575.42MHz) - the difference is not significant (14.322MHz corresponding to 3 mm wave length difference). A wrongly estimated ambiguity for N_{mn}^k within a few circles is acceptable. As CAPS uses C band and IRNSS uses L5 and S band, it is more reasonable to apply double differences within each system (the same frequency). Generally, carrier phase measurement is more difficult to obtain than code measurement. If only code measurements for a RNSS such as CAPS are available (so far, no carrier phase measurement has been done for CAPS), it is still helpful to fix the carrier phase ambiguities for another system such as Compass.

4. Augmentation GNSS(s) with RNSSs for Urban Canyon Positioning

Using the RNSSs discussed in the previous section to augment GPS is an obvious choice since CDMA signal modulation is used in all these systems. As GPS is the most popular GNSS, in this section, using the four

RNSSs (one RNSS or several RNSSs) to augment GPS is investigated.

4.1 GPS+QZSS

Using QZSS to augment GPS has been well investigated [14] [15] [17] [21]. To ensure interoperability and compatibility with modernized GPS civil signals, QZSS satellites transmit the L1C/A, L1C, L2C and L5 signals almost exactly the same as GPS signals [13]. Hence after upgrading the firmware, a GPS receiver should be fine to obtain the QZSS measurements. Generally, only dual frequency (L1 and L2) are considered at this stage as the third frequency (L5) will not be broadcasted by all GPS satellites in the near future. Combining QZSS and GPS is easy by simply treating QZSS satellites as extra GPS satellites. In [15], the performance of using QZSS to augment GPS in the Asian-Pacific and Australian area was studied. It shows that comparing to GPS only the augmented system can achieve better performance: the area where positioning is available will be extended for about 10%, the average number of visible satellites will be increased from 5.2 to 6.4, the average GDOP will be decreased from 14.2 to 7.1 and the average ambiguity success rate will go up from 64.5% to 84.3%. In [14], analyses of the positioning performance (such as the number of visible satellites and the associated DOPs, the accuracy of standalone positioning) of the combined GPS-QZSS system in several large Asian and Oceanian cities were given. QZSS will clearly benefit the urban canyon users in these big cities.

4.2 GPS+QZSS+Compass phase II

Obviously, the combination of GPS, QZSS and Compass will increase the number of visible satellites and improve the PDOP value. Carrier phase based positioning is investigated in this subsection. The double-differenced observation can be expressed as

$$\begin{aligned}
\nabla\Delta R_{gps} &= \nabla\Delta\rho_{gps} + \nabla\Delta e_{gps} \\
\nabla\Delta\varphi_{gps} &= \nabla\Delta\rho_{gps} + \nabla\Delta N_{gps} + \nabla\Delta\varepsilon_{\varphi} \\
\nabla\Delta R_{com} &= \nabla\Delta\rho_{com} + \nabla\Delta e_{com} \\
\nabla\Delta\varphi_{com} &= \nabla\Delta\rho_{com} + \nabla\Delta N_{com} + \nabla\Delta\varepsilon_{\varphi}
\end{aligned} \tag{8}$$

Double differencing is applied within each system (L1 only). After linearization, the mathematic model can be simplified as a mix integer least square model as following:

$$Y = AX + BN, \qquad Q_Y \tag{9}$$

Where Y is the measurements, including both the carrier phase and pseudo-range observations, X and N are the unknown coordinates and carrier phase integer ambiguities, A and B are the coefficient matrixes, and Q_Y is the variance-covariance matrix of the measurements.

The variance-covariance matrix of the least squares solution is:

$$Q = \begin{bmatrix} Q_{\hat{X}\hat{X}} & Q_{\hat{X}\hat{N}} \\ Q_{\hat{N}\hat{X}} & Q_{\hat{N}\hat{N}} \end{bmatrix} = \begin{bmatrix} A^T Q_Y A & A^T Q_Y B \\ B^T Q_Y A & B^T Q_Y B \end{bmatrix}^{-1} \tag{10}$$

The elements of the variance-covariance matrix can be calculated:

$$Q_{\hat{X}\hat{X}} = \left(A^T Q_Y A - A^T Q_Y B \left(B^T Q_Y B \right)^{-1} B^T Q_Y A \right)^{-1} \tag{11}$$

$$Q_{\hat{N}\hat{N}} = \left(B^T Q_Y B - B^T Q_Y A \left(A^T Q_Y A \right)^{-1} A^T Q_Y B \right)^{-1} \tag{12}$$

$$Q_{\hat{X}\hat{N}} = Q_{\hat{N}\hat{X}}^T = -\left(A^T Q_Y A \right)^{-1} A^T Q_Y B Q_{\hat{N}\hat{N}} \tag{13}$$

Once the carrier phase integer ambiguities are fixed, the precision of the ambiguity-fixed solution (coordinates) is much better than that of the ambiguity-float solution, and the variance matrix is:

$$Q_{\tilde{X}\tilde{X}} = Q_{\hat{X}\hat{X}} - Q_{\hat{X}\hat{N}} Q_{\hat{N}\hat{N}}^{-1} Q_{\hat{N}\hat{X}} \tag{14}$$

The performance is evaluated by accessing the expected ambiguity success rate and the precision of the fixed solution.

The ambiguity success rate describes the reliability of the ambiguities which are fixed based on the integer least square theory. This conception was proposed by Teunissen in 2000 [22], and defined as following [23]:

$$P(\tilde{N}_{LS} = N_{true}) \approx \left| 2\Phi\left(\frac{1}{2ADOP}\right) - 1 \right|^n \tag{15}$$

Where $\tilde{N}_{LS}$ is the estimated ambiguities base on integer least square, N_{true} is the true value of ambiguities, n is the number of ambiguities, and ADOP stands for Ambiguity Dilution of Precision [24]. ADOP was defined as:

$$ADOP = | Q_{\hat{N}\hat{N}} |^{1/(2n)} \ (cyc) \tag{16}$$

Also, a so-called “Nines” characteristic [25] was utilised to indicate the ambiguity success rate. The “Nines” are computed using the relation:

$$Nines(p) = -\log_{10}(1-p) \tag{17}$$

where p is the ambiguity success rate, the value of one Nine means a probability of 90%, and three Nines give a probability of 99.9%.

Figure 9 shows 24 hours “Nines” of the single-frequency (L1 or B1) ambiguity success rate at selected cities (listed in Table 2). Different combinations, i.e. GPS only, GPS+QZSS, and GPS+QZSS+Compass phase II, were analysed for each city. The accuracy of carrier phase and code measurements is assumed to be 3 millimetres and 0.3 metres respectively, and the cutoff angle was set to 30 degrees. The simulation results show clearly that the combination of GPS, QZSS and Compass phase II can increase the single-frequency ambiguity resolution success rate significantly.

4.3 GPS+RNSSs

As discussed in section 3.3, it is more reasonable to only discuss single point positioning using the combined GPS and all RNSSs. The development of a multi-constellation receiver is certainly possible (to receive S band and C band signals will require a complex frontend). Equation (3) can be applied without substantial modification (a QZS can be treated as a GPS satellite, so it only needs a change of the subscripts from *qzs* to *gps*). Figure 10 shows the results. Comparing to GPS only, the improvement of the average number of visible satellites and average PDOP value is significant.

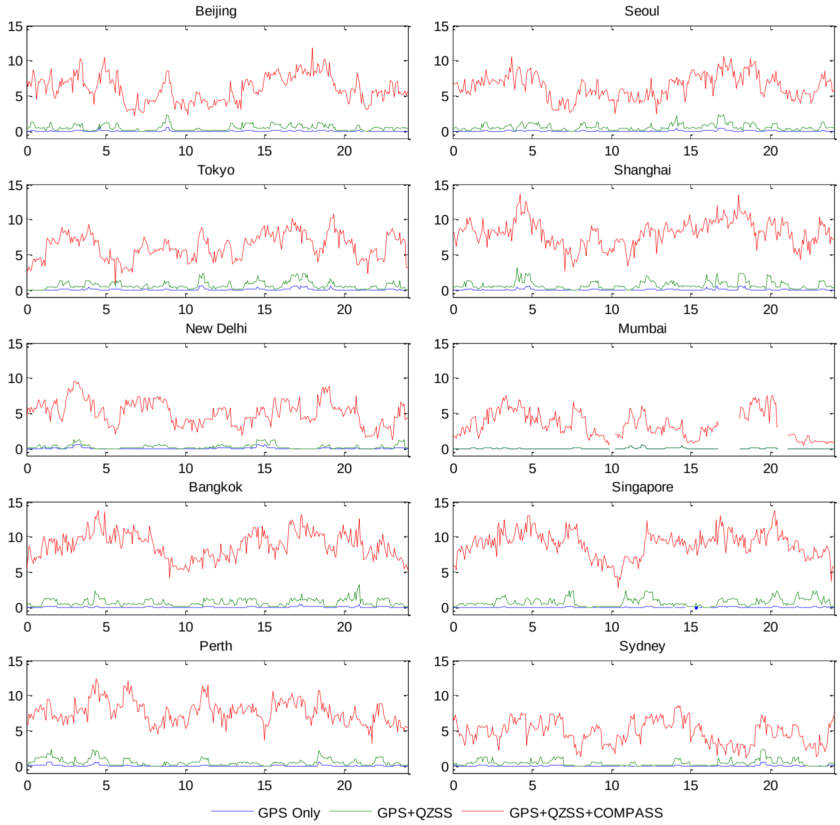

Figure 9: "Nines" of the single-frequency ambiguity resolution success rate for different combination at selected cities (above a 30 degree cutoff angle).

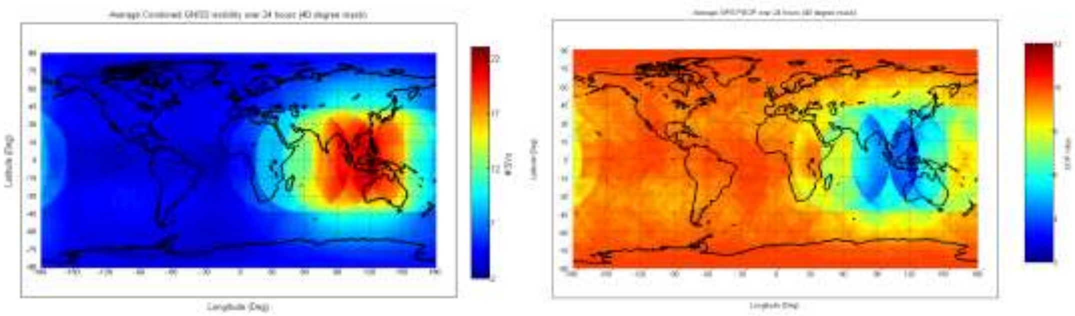

Figure 10: Average number of visible satellites (left) and average PDOP value (right) of combined GPS/RNSSs over a 24 hour period (above a 40 degree elevation cutoff angle)

5. Concluding Remarks

As the Asian countries are keen to develop and deploy their own RNSSs, the number of navigation satellites above the Asia-Oceania region over the next decade will increase significantly. It is possible to use these RNSSs to ensure a better coverage and a more accurate positioning result. Using the RNSS alone can cover a relative small area of interest and provide a reasonable positioning result. The combination of these RNSS can provide a better coverage and accuracy. If the RNSSs are used to argument the current GNSS (using GPS as an example) a reliable single point positioning can be achieved in urban canyon. The RTK performance also can be improved significantly. Compared to deploying a GNSS, RNSS is less expensive and faster to deploy. The four constellations are likely to be fully operational in the coming decade – perhaps earlier than that of the full deployment of GALILEO.

References

[1] SinoDefence.com, BeiDou 1 Experimental Satellite Navigation System, 24 September 2008, http://www.sinodefence.com/space/spacecraft/beidou1.asp. Retrieved 20 July 2010.

[2] GPS World, "China Begins Broadcasts on Latest Compass GNSS GEO Satellite", July/August, 2010, http://www.insidegnss.com/node/2134

[3] Indian Space Research Organization, Indian Space Programme - Major Events During 2006, http://www.isro.org/pressrelease/scripts/pressreleasein.aspx?Dec27_2006. Retrieved 20 July 2010.

[4] Japan Aerospace Exploration Agency, Launch Result of the First Quasi-Zenith Satellite 'MICHIBIKI' by H-IIA Launch Vehicle No. 18 http://www.jaxa.jp/press/2010/09/20100911_h2af18_e.html

[5] B. Li and A.G. Dempster, China's Regional Navigation Satellite System – CAPS, *Inside GNSS*, 5(4), 59-63, June 2010.

[6] J. Wei, D. Xu, J. Deng and P. Huang, Synchronization for "Beidou" Satellite Terrestrial Improvement Radio Navigation System, International Conference on Intelligent Mechatronics and Automation, Chengdu, China, 26-31 August 2004.

[7] A. Singh and S.K. Saraswati, India Heads for a Regional Navigation Satellite System, *Coordinates*, a Magazine on Positioning and Navigation, November 2006.

[8] J.W. Betz, Binary offset carrier modulations for radio navigation, *Navigation, Journal of the Institute of Navigation*, 48, (4), pp. 227–286, 2001

[9] G.W. Hein, J.-A. Avila-Rodriguez, S. Wallner, A.R. Pratt, J.I.R.Owen, J.-L. Issler, J.W. Betz, C.J. Hegarty, L.S. Lenahan, J.J. Rushanan, A.L. Kraay, T.A. Stansell, MBOC: The New Optimized Spreading Modulation Recommended for GALILEO L1 OS and GPS L1C" , Proceedings of IEEE/ION PLANS 2006, 24-27 April 2006, San Diego, California, USA.

[10] SpectraTime to Supply Atomic Clocks to IRNSS, *Inside GNSS,* September/October 2008, http://www.insidegnss.com/node/789.

[11] GPS World, "Another Beidou/Compass Satellite Launched", July, 2011, http://www.gpsworld.com/gnss-system/compass/news/another-beidoucompass-satellite-launched-11913

[12] T. Tsujino, Effectiveness of the Quasi-Zenith Satellite System in Ubiquitous Positioning, *Science & Technology Trends*, Quarterly Review, 16, 2005, 88-101.

[13] Japan Aerospace Exploration Agency, Interface Specification for QZSS, Draft V1.2, March 19, 2010.

[14] N. Kubo, How QZSS contributes to positioning performance in large Asian cities? *ICCAS-SICE2009*, Fukuoka, Japan, 18-21 August 2009.

[15] F. Wu, N. Kubo and A. Yasuda, Performance evaluation of GPS augmentation using quasi-zenith satellite system, *IEEE Trans Aerospace & Electronic Systems*, 40(4), 1249–1261.

[16] G. Ai, H. Shi, H. Wu, Y. Yan, Y. Bian, Y. Hu, Z. Li, J. Guo and X. Cai, A positioning system based satellite communication and Chinese Area Positioning System (CAPS), *Chinese Journal of Astronomy and Astrophysics*, 8(6), 611-635, 2008.

[17] S. Kogure and I. Kawano, GPS augmentation and complement using Quasi-Zenith Satellite System (QZSS), *21st AIAA International Communications Satellite Systems*, Yokohama, Japan, 2003.

[18] Y. Zhao, Mobile phone location determination and its impact on intelligent transport systems, *IEEE Trans. Intell. Transport. Syst.*, 1, 55–64, 2000.

[19] B. Li, Y.K. Tan and A.G. Dempster, Using two GPS satellites to improve WiFi positioning accuracy in urban canyons, *IET Com*, accepted, June 2010.

[20] Y. Li, A.G. Dempster, B. Li, J. Wang and C. Rizos, A low-cost attitude heading reference system by combination of GPS and magnetometers and MEMS inertial sensors for mobile applications, *Journal of Global Positioning Systems*, 5(1-2), 88-95.

[21] S. Kogure, M. Kishimoto, M. Sawabe, K. Terada, Performance Analysis of the QZSS SIS-URE and user Positioning Accuracy with GPS and QZSS, *Proceedings of the 2008 National Technical Meeting of The Institute of Navigation*, San Diego, CA, January 2008, pp. 452-457.

[22] P.J.G. Teunissen, The success rate and precision of GPS ambiguities, *Journal of Geodesy*, 74(3-4), 321-326. doi:10.1007/s001900050289

[23] D. Odijk and P.J.G. Teunissen, ADOP in closed form for a hierarchy of multi-frequency single-baseline GNSS models, *Journal of Geodesy*, 82(8), 473-492. doi:10.1007/s00190-007-0197-2

[24] P.J.G. Teunissen and D. Odijk, Ambiguity Dilution of Precision: Definition, Properties and Application, *ION GPS-1997*, September 16–19, Kansas City, US, pp. 891-899.

[25] U. Vollath, K. Sauer, F. Amarillo, J. Pereira, Three or Four Carriers - How many are enough? ION GPS/GNSS 2003, Portland, Oregan, September 9-12, 2003, 1470-1477.

Biography

Dr. Binghao Li is a VC's Post-Doctoral Research Fellow in the School of Surveying and Spatial Information Systems, The University of New South Wales, Sydney, Australia. Binghao obtained B.Sc. in Electrical & Mechanical Eng. from Northern Jiaotong University, P.R. China in 1994 and M.Sc. in Civil Eng., Tsinghua University, P.R. China in 2001. He received his Ph.D. from the University of New South Wales, Sydney, Australia in 2006. His research area is pedestrian navigation, new positioning technologies and network-RTK