Does Beidou Enhance Positioning Performance within Corsnet-NSW?

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Key words: Beidou, GNSS, CORSnet-NSW, Height, APCV

SUMMARY

Beidou is China's independent Satellite Navigation System capable of providing positioning, navigation and timing (PNT) services regionally over China and ultimately globally. It comprises 14 operational satellites (plus 4 extra satellites in commission) as of October 2015.

CORSnet-NSW is a network of over 170 permanent satellite navigation tracking stations of which 63 receivers are now tracking Galileo, Beidou and the Japanese QZSS satellites. This project investigates if combining these new Beidou signals into GNSS solutions improves positioning performance in real–time.

This was tested by comparing GPS/Beidou vs GPS/GLONASS vs GPS/GLONASS/Beidou RTK combinations on six points in open and difficult environments using single base RTK. Each point was measured independently 15 times for each combination and parameters such as time to first fix (TTFF) as well as repeatability and accuracy in Easting, Northing and Height were compared.

This testing revealed that the addition of Beidou into the solution had little impact on TTFF and improved the robustness of the easting and northing solutions. However there was a distinct ~30mm bias in height when Beidou was combined in the solution.

This assertion was confirmed using a two-peg test and suggests that inappropriate Antenna Phase Centre Variation (APCV) modelling may be the cause of this bias. Some comments about APCV modelling with regard to Beidou signals conclude this paper.

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1. INTRODUCTION

Australia is uniquely located to benefit from the many new GNSS constellations developing over the Asia-Pacific region. This paper begins with an overview of the Beidou GNSS system with a focus on those aspects that differ from other GNSS constellations. The main objective of this paper is to consider the impact on accuracy (horizontal and vertical) and robustness of positioning when combining Beidou signals with the existing GPS/GLONASS position solutions. Single base RTK using GPS and Beidou in combination has been tested in Perth (Odolinski et al (2014), Odolinski et al (2015)). This paper provides testing results almost 5000km to the east in Sydney and provides single base RTK results using a different stand-alone receiver within the CORSnet-NSW infrastructure. Network RTK with Beidou is not available at the time of writing this paper.

Section 4 describes the single base RTK testing methodology using three different combinations of GPS, GLONASS and Beidou solutions over six known survey marks. Section 5 presents the results of this campaign and highlights an apparent height bias when the Beidou signals are included in the combined solution. A two peg test is performed to confirm this bias and some further investigation into the effects of APCV are presented.

2. BEIDOU

2.1 Beidou Architecture

2.1.1 Beidou Space Segment

The Beidou Navigation Satellite Systems (BDS) (as of October 2015) consists of 14 operational satellites: 5 geostationary (GEO) satellites, 5 satellites in inclined geosynchronous orbits (IGSO) and 4 medium earth orbit (MEO) satellites (Table 1). A further 3 satellites are in commission in 2015 (GPSworld, 2015, Spaceflight Now, 2015). Beidou achieved full operational capability (FOC) as a regional navigation satellite system (RNSS) in 2012 providing continuous positioning, navigation and timing (PNT) services across the Asia-Pacific region.

ORBIT	Number of Satellites	Number of Planes	Altitude	Inclination/Position
MEO	27	3	21,528 km	55^o inclination
IGSO	3	3	35,786 km	55^o inclination
GEO	5	5	35,786 km	Position: 58.75°E, 80°E, 110.5°E, 140°E and 160°E

Table 1: Planned Beidou orbital characteristics (CSNO, 2012).

The orbital characteristics of Beidou differ to those of GPS utilising three distinct orbits – Medium Earth Orbit (MEO), Inclined Geosynchronous Orbit (ISGO) and Geostationary Orbit (GEO) – with different orbital inclinations and altitudes in a common constellation (Table 1). The high elevation IGSO satellites are an important feature in mitigating the effects of ‘urban-canyoning’ experienced in high density urban environments – a common scenario in China. Similarities can be drawn between BDS and the Japanese Quasi Zenith Satellite System (QZSS) which also uses IGSO orbits to overcome masking in high density urban areas. However, Montenbruck et al (2013) argues that despite these common properties, the BDS system manages to achieve a more balanced coverage in both hemispheres.

The geostationary satellites act as a type of SBAS allowing for high precision ionosphere correction modelling of the Asia-Pacific region and China in particular. Within this region, Beidou is now the third GNSS constellation to offer independent PNT services with a growing number of permanently visible satellites (Montenbruck et al, 2012). Like GPS, the number of visible satellites will change at different times of the day (however in different patterns), and this number continues to grow with the scheduled deployment of Phase III satellites.

2.1.2 Beidou Control Segment

The Beidou control segment features a Master Control Station (MCS), two Upload/Time Synchronisation Stations (TS/US) and 30 monitoring stations (MS) that manage and control the operation of the Beidou constellation (CSNO, 2013a, Lu et al, 2012).

No official information exists regarding the exact position and distribution of the BDS monitoring network. Zhou et al (2012a) suggests the global coverage for MEO and GEO/IGSO satellites is mostly domestic with sparse global distribution concentrated in the Asia-Pacific region.

The lack of tracking coverage impacts the latency at which updated NAV messages can be generated and uploaded to satellites and subsequently the achievable standard positioning performance. Furthermore the weak global network distribution is symptomatic of the BDS challenge to generate precise satellite orbits – a problematic feature for precise positioning purposes. Zhou et al (2012a) reports that along with the above shortcomings, precise orbit determination is also affected by irregularities caused by strong statistical correlation between GEO orbit and clock estimates, as well as the unadjusted force models (e.g. solar radiation pressure model) used. With further evolution of the BDS constellation it is crucial that it is supported with a well-balanced, well-distributed monitoring network particularly for MEO satellites.

2.2. Beidou Signal Structure

The current Beidou system broadcasts signals on three frequencies comprising two civil navigation signals with full service (B1, B2), and a third authorised signal (B3). Both B1 and B2 bands consist of the carrier frequency, ranging code and NAV message – with the latter two components modulated using code division multiple access (CDMA) on the carrier (CSNO, 2013b). Nominal frequencies are at 1561.098 MHz and 1207.140 MHz for B1 and B2 respectively.

No official information from the Chinese Satellite Navigation Office (CSNO) has been released on the third authorised signal (B3), however basic signal properties and ranging codes have been determined through civilian research. Coinciding with the first launch of the first Compass M1 satellite in 2007, Gao et al (2007) and Grelier et al (2007) discovered that the B3 signal has a nominal frequency of 1268.52 MHz.

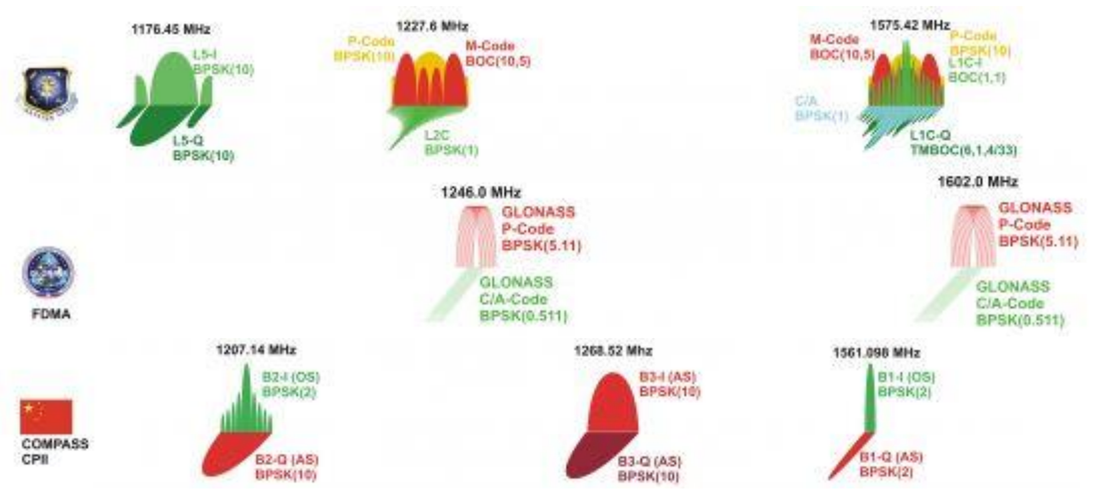

Figure 1: GNSS signals and the corresponding frequency spectrum (Navipedia, 2015).

Beidou satellites transmit two different navigation (NAV) messages (D1 and D2) which are formatted depending on their rate and structure, as well as the orbits of the transmitting satellites. The D1 NAV message will be transmitted by MEO and IGSO satellites carrying fundamental navigation information including ephemeris and almanac data for all satellites in the constellation, as well as time offsets of other GNSSs. The D2 NAV message contains both basic navigation information as well as augmentation service data including Beidou integrity as well as differential and ionosphere grid information (CSNO 2013c).

NAV Message	Rate	Information
D1	50 bps	Almanac, time offsets
D2	500 bps	NAV and augmentation service info

Table 2: Beidou NAV message distinction and corresponding transmitting information.

The augmentation information broadcast in the D2 NAV message is part of a hybrid space based augmentation system (SBAS) enabled by the GEO and IGSO satellites within the Beidou constellation design. These same design features also enable Beidou to simultaneously offer both open and authorised services using the same control and monitoring segment (Zhou et al, 2012a). GPS and Galileo in contrast supplement their navigation system with a regional SBAS that contains a separate control and monitoring segment e.g. WAAS and EGNOS.

Ionosphere correction models provided by BDS differ in the open and closed services and consequently affect the standard positioning performance achievable with each service. Open service users derive ionosphere corrections using either an 8 or 14-parameter Klobuchar model provided in the D1 NAV message (Zhao et al, 2015). Authorised service users instead have access to higher accuracy ionospheric correction modelling through the D2 NAV message which uses the hybrid SBAS outlined above (Cao et al, 2012).

3. BEIDOU AND CORSNET-NSW

CORSnet-NSW is a state-wide network of GNSS continuously operating reference stations (CORS) run by NSW Land and Property Information (LPI) providing critical positioning infrastructure to a range of users across NSW.   It provides RINEX data for post processing, DGPS, RTK and Network RTK services to subscribers. CORSnet-NSW stations contribute data to the national AuSCOPE and regional Asia-Pacific Reference Frame (APREF) as part of a policy of improving positioning infrastructure and maintaining a modern datum linked to the ITRF (Janssen et al, 2011).

Figure 2: CORSnet-NSW stations capable of tracking Beidou satellites and providing user corrections (as of January 2015). Note that since June 2015, an expanded 61 CORS support Beidou positioning.

CORSnet-NSW currently tracks GPS and GLONASS constellations providing real time observations and corrections to the user. Approximately half the CORS hardware i.e. antenna/receivers, are already capable of tracking additional constellations such as Beidou and Galileo (Janssen, 2014). However integrating extra constellations depends on the operational capability, system robustness and reliability and indeed if there is sufficient user demand to warrant such inclusion (Janssen, 2014).

Since July 2015, CORSnet-NSW has endeavoured to expand their multi-GNSS capabilities with currently six Tier 2 CORS as well as 55 Tier 3 CORS, which support the Beidou system for research and evaluation purposes (Janssen et al, 2015). All sites contain Trimble NetR9 receivers with either choke ring antennas or Trimble Zephyr Geodetic II antennas which are all upgraded in the latest firmware to ensure Beidou compatibility. Currently GPS + GLONASS capabilities provided by CORSnet-NSW are sufficient. Lessons can also be learnt from the evolution of the former GPS only Sydnet network and the latter upgrade to GPS/GLONASS capability (Roberts et al, 2007, Grinter, 2008).

4. TESTING METHODOLOGY

The single base RTK testing was designed to determine whether the addition of Beidou observations enhances the robustness and accuracy of position in urban environments. Three GNSS combinations – GPS + GLONASS (GR), GPS + Beidou (GB), GPS + GLONASS + Beidou (GRB) – were tested in dual and triple combination solutions. Six points were identified in open and obstructed environments and 15 sets of RTK initialisations were performed at these points.

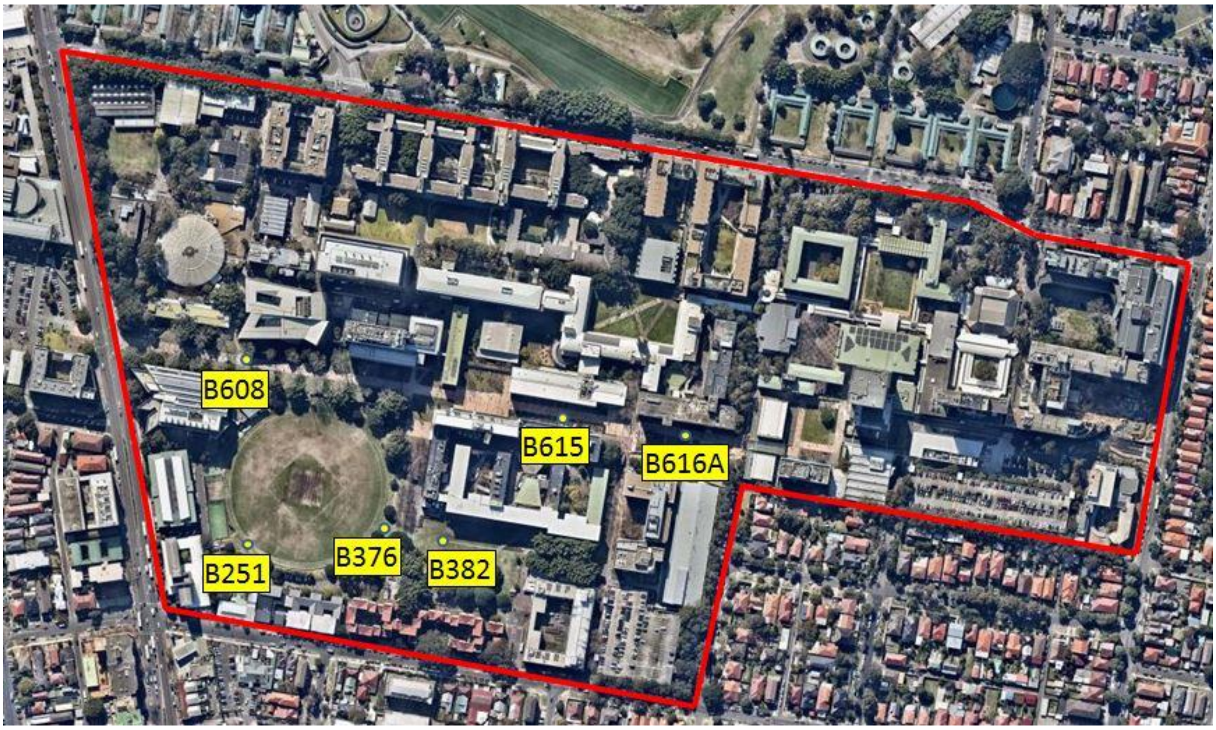

Figure 3: The location of observations points are shown on the UNSW campus grounds (outlined in red) (Nearmap, 2015). B616A, B615 and B608 are in urban canyons. B251, B376 and B382 are in open/ moderate environments.

4.1. Site & Equipment

The single base RTK campaign was performed on campus at the University of New South Wales (UNSW) on a range of marks with known coordinates. Due to the limited Beidou enabled CORS sites available at the time of testing, Villawood CORS (TS 12050) was selected. The baseline distance is approximately 25km.

A total of 6 marks (3 with open to moderate coverage and 3 in difficult environments) were chosen on campus for testing, simulating different environments in terms of satellite visibility, elevation cut off angles and practicality. Coordinates are given in GDA94(1997) relating to the SCIMS network surrounding the UNSW campus.

Fieldwork was carried out using a Leica Viva GS15 that enabled single base RTK using multi-GNSS observations – GPS, GLONASS, Beidou. GNSS observations necessary for single base RTK were sourced from CORSnet-NSW through a special stream provided by LPI for the purposes of this paper.

4.2. Single base RTK Fieldwork Procedure & Processing

Tripods were set up at each mark and single base RTK combinations of GR, GB, GRB were observed 15 times at each mark, leading to 90 measurements for each combination and an overall total of 270 measurements. Observations were taken at 1 second epochs, so for each point measurement, a total of 120 epochs were collected. Measurements were abandoned when the instrument would fail to initialise after a period of 5+ minutes (Table 3). This was a common occurrence in urban canyons with limited satellite coverage. The inclusion of Beidou signals did not noticeably reduce the time to first fix TTFF for any points.

Combination	B616A	B615	B608	B251	B376	B382
GR	15	2	14	15	15	15
GB	15	6	10	15	15	15
GRB	15	5	12	15	15	15

Table 3: Initialisation success rate.

Field practice followed the recommendations set out by Janssen & Haasdyk (2011). This includes 2 min observation times, minimum 30min waiting times between each observation on a mark, multiple mark occupations, as well as using a tripod for stability. Each mark was observed in succession for the one combination for a day's fieldwork e.g. all GB on one day in a loop. The loop was repeated to ensure at least 30 mins between measurements.

All observations were processed using Leica Geo Office and using the AusGeoid09 model to produce AHD heights. Accuracy is investigated by comparing each combination solution to the 'true' campus coordinates which are based on GDA94(1997) and compatible with the external SCIMS network. CORSnet-NSW derived coordinates are based on GDA94(2010), so a simple block shift was applied on all measured coordinates for consistency. The block shift was derived from the difference in GDA94(1997) and GDA94(2010) coordinates for the VLWD and FTDN CORSnet-NSW stations corresponding to the relevant single base RTK measurement (Vanderstappen, 2015).

5. BEIDOU SINGLE BASE RTK RESULTS

The results of the single base RTK campaign are summarised below in terms of positioning accuracy and performance in open and obstructed environments.

5.1. Horizontal Accuracy

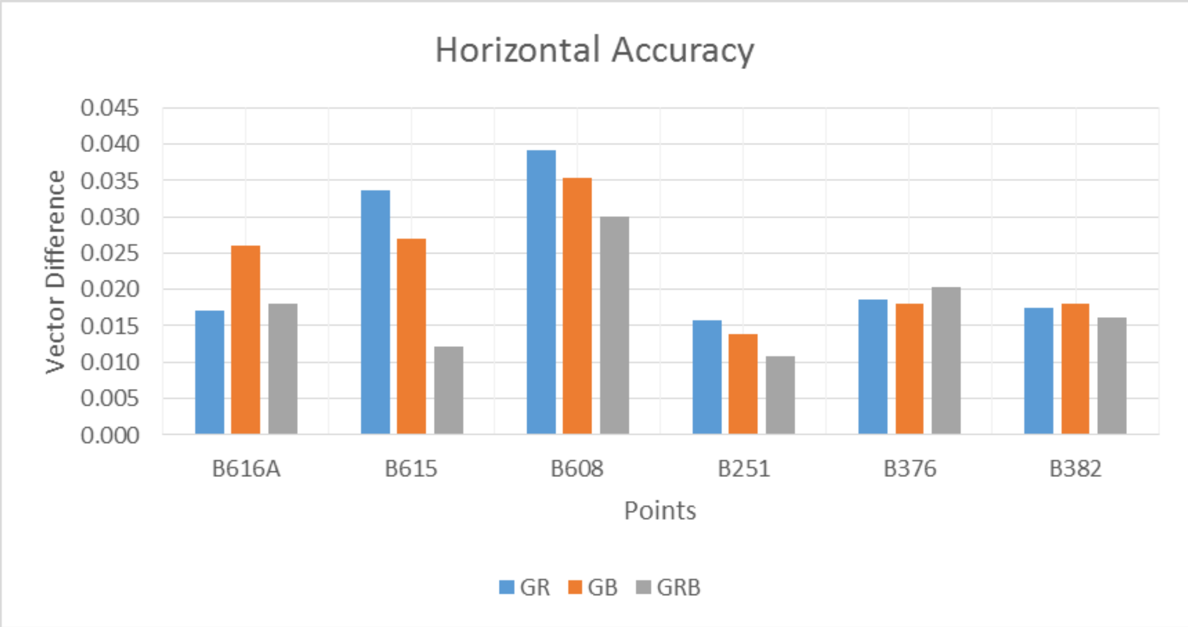

Figure 4: Graphical representation of single-base RTK accuracy in terms of vector difference (in metres) between 'known' coordinates and measured coordinates.

The inclusion of Beidou signals into the RTK positioning indicated the following points:

- As expected, points B251, B376 and B382 in open environments exhibit a smaller vector difference between the 'known' marks and those measured.
- The GRB solution only offers a marginal increase in accuracy across all marks despite the increased number of satellites.
- Initialisation success rates did not substantially improve in any environment.
- The Beidou geometry (GDOP) was often quite weak in comparison to GPS and GLONASS.

The addition of Beidou satellites appears to add little to the geometrical strength and therefore initialisation success rates which may be attributable to the current lack of available MEO satellites within the constellation and the difficulty in tracking the GEO/IGSO satellites in Sydney which is on the outer extremity of the Beidou satellite footprint.

5.2. Vertical Accuracy

The height results for the single base RTK campaign are outlined below.

Figure 5: The height accuracy shown for all three GNSS combination solutions on all 6 measured marks as compared to “known” heights. It can be clearly seen that the introduction of the Beidou system causes a greater height difference especially for the open sky points B251, B376, B382.

Figure 5 shows the height difference between the known height and the three GNSS combination results. A distinct height bias can be seen for the open sites at B251, B376 and B382 when combining Beidou observations into the RTK solution. Even for the obstructed sites B616A, B615 and B608, the height results still show a 50–60 mm trend. The GPS/GLONASS results are within 20mm which is to be expected for RTK heighting. This result suggests an unaccounted systematic error present in the fieldwork methodology and subsequent processing.

It was hypothesised that the height issue could be due to either an ionosphere/troposphere bias given the long distance between the UNSW test site and Villawood CORS site (~25km), or the antenna phase centre variation (APCV) model of the Leica GS15 did not sufficiently account for Beidou signals. The configuration of the antenna settings remained unchanged between the different combinations. In order to further investigate this apparent height bias, a GNSS two-peg test was performed in an attempt to isolate any potential errors.

6. TWO-PEG TEST

The two peg test involved setting up two tripods with GNSS receivers next to each other at the same height and ensuring they are perfectly level and centred (Figure 6). Measurements are then taken at the same time but in different combinations, to determine the effect different GNSS systems have on positioning performance i.e. receiver 1 measures GR whilst simultaneously receiver 2 measures GB. Once the first measurements are taken, the receivers are swapped and then another set of measurements are taken, meaning that tripod 1 and 2 both have measurements in the GR and GB combination at the same time.

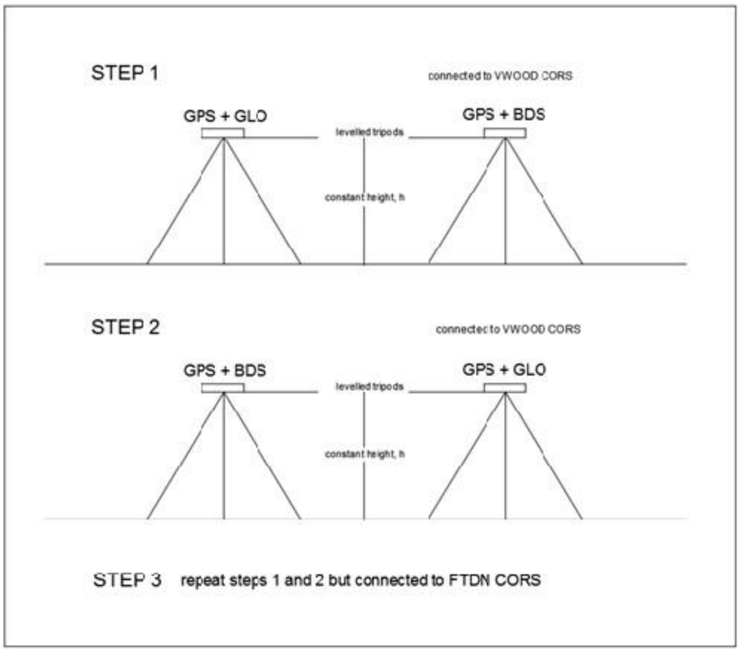

Figure 6: A schematic detailing the methodology required to perform a GNSS two peg test.

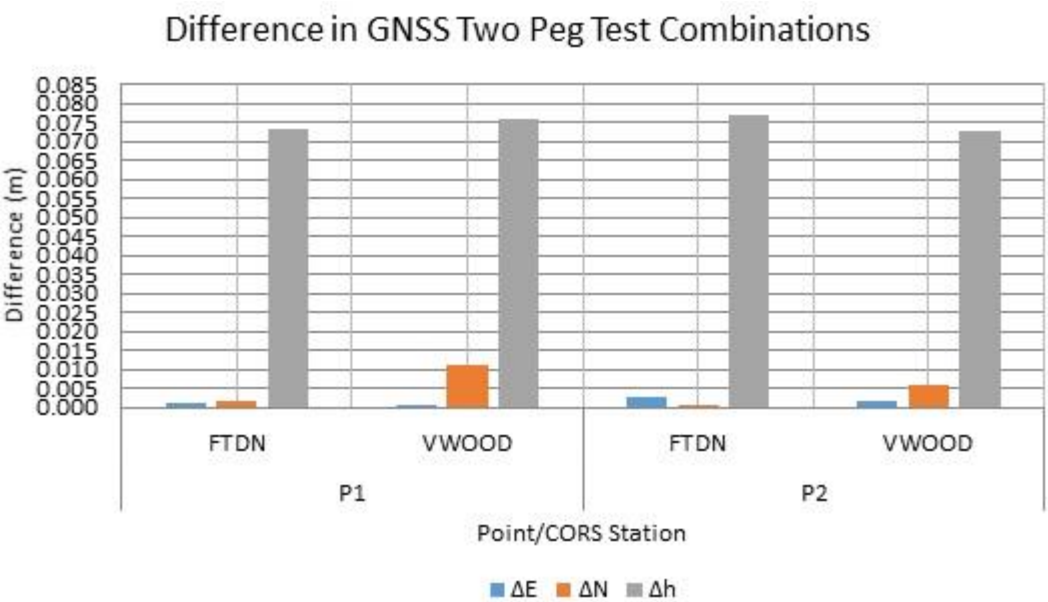

Figure 7: The relative difference between the GPS+GLONASS and GPS+ Beidou solutions for both VLWD and FTDN CORS sites. The difference shown is calculated by taking the absolute difference between the GR and GB combination i.e. diff = ABS(GR-GB). Results are shown in metres.

By the time the two-peg test was performed, a new CORSnet-NSW station at Fort Denison (FTDN) began streaming Beidou data. As this site was only 5km from the UNSW test site, it was decided to perform the two-peg test twice using VLWD and then again using FTDN. This would isolate a height bias due to unmodelled atmospheric errors mapping into the height component. A period of 30min waiting time is taken between each set of observations. A total of four measurements on each mark for each GNSS combination and CORS station are taken.
Figure 7 demonstrates the relative difference between the two GNSS combinations using both FTDN and VLWD base stations. Whilst there is only a minor variation in horizontal components, there is a significant relative difference in height between the two combinations of over 70mm and the same magnitude for both VLWD and FTDN connections, eliminating the possibility of atmospheric biases being the source problem. It can be seen that there is more noise when using the VLWD base station which is consistent with atmospheric biases over longer baseline lengths. Therefore it is hypothesised that the height difference introduced using the Beidou system is perhaps due to unaccounted antenna phase centre variation or difficulties with the configuration of the receiver or CORSnet-NSW when switching to combine Beidou signals/streams in the solution. However it is unknown why the magnitude of the bias using the two-peg test is double that as seen in the previous single-base RTK test.

7. ANTENNA PHASE CENTRE VARIATION

The electrical phase centre is the point to which all phase measurements received from GNSS signals refer. It is not possible to measure directly to this physical point. The antenna reference point (ARP) is therefore a physical reference point to which the two components of the electrical phase measurements refer namely, the phase centre offset (PCO) and the phase centre variation component (dependent on the zenith and azimuth of the incoming signal).

Organisations such as the IGS, NGS and Geo++ produce antenna phase centre variation (APCV) models for various antennas (see Figure 8). The IGS ANTEX product shows that the APCV model was produced using a robot by GEO++ in 2011 for GPS L1/ L2 signals.

```
LEIGS15         NONE Internal geodetic antenna, SmartTrack+,  IGS (  5) 11/03/25
     -0.8     -0.5     202.1
  0.0   0.0   0.1   0.1   0.1  -0.2  -0.5  -0.8  -1.0  -1.1
 -1.1  -1.0  -1.0  -0.9  -0.7  -0.3   0.5   1.5   2.4
      0.8      2.1     200.7
  0.0   0.1   0.2   0.3   0.3  -0.1  -0.5  -0.8  -1.0  -0.9
 -0.6  -0.4  -0.4  -0.5  -0.5  -0.2   0.5   1.4   1.8
```

Figure 8: Antenna Phase Centre Variation model for Leica GS15 antenna (NGS, 2016). The offset numbers refer to the ARP for this antenna (-0.8mm, -0.5mm, 202.1mm: N/ E/ UP) for GPS L1. The numbers below refer to the variable zenith dependant component. There is a corresponding set of model numbers for GPS L2.

Figure 8 shows the APCV model for GPS L1, L2, however this APCV model does not take account of the combined observations for GPS, GLONASS and indeed Beidou as was used in this study. Investigation of the IGS ANTEX file reveals that the LEIGS15 APCV model only considers the GPS L1/L2 signals.

Wübbena et al, (2006) detail methods to account for multi-GNSS antennas and estimate APCV models for GPS and GLONASS combined measurements. This is further complicated by the fact that current GLONASS signals are FDMA so different satellites emit slightly different frequencies. To accommodate this into the GPS/GLONASS modelling, Wübbena et al, (2006) have developed a delta PCV modelling technique under the assumption of linear PCV changes between the GPS and GLONASS frequencies. In the IGS ANTEX file, such modelling is denoted by a ”delta PCV” in the header section.

For the purposes of this study, an APCV model which also considers the Beidou signals would be ideal. However as the current Beidou constellation is incomplete, a field calibration cannot be optimised across the antenna hemisphere. At present no APCV model for combined GPS/ GLONASS/ Beidou exists for the Leica GS15 antenna used in this study.

8. CONCLUSIONS

As the Beidou constellation expands, especially over Australia, CORS operators such as NSW LPI are considering the impact of providing additional signal measurements for users. This project attempted to test the impact of including Beidou signals into existing GPS and GPS/GLONASS single base RTK combination solutions. Six points in open and urban canyon environments were measured 15 times.

Some conclusions drawn from this limited testing indicate that the horizontal position accuracy had a negligible improvement with the addition of Beidou signals. The Beidou constellation of GEO/IGSO satellites is concentrated on longitudes to the west of the UNSW test site and also the current MEO constellation is incomplete. Never-the-less, even with Beidou FOC only marginal improvements to horizontal positioning accuracy is anticipated. Improvements to the control segment may improve this further. Similarly, time to first fix and initialisation success rate enjoyed only negligible gains with the addition of Beidou signals.

However a major conclusion from this paper was revealed in the vertical accuracy with a height bias of over 30mm. A two-peg test was performed and confirmed a significant bias and simultaneously eliminated the potential of tropospheric/ionospheric bias mapping into the vertical component. It is postulated that the APCV models, which do not consider the addition of the Beidou signals, could be the cause of this height bias. Alternatively, the way the receiver device is configured or the method that Beidou data is streamed from CORSnet-NSW may affect how the APCV models are utilised in the solution.

In any case and important conclusion for CORS network operators and users alike is to ensure that this height bias can be identified and remedied if Beidou signals are to be offered to users in the future.

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BIOGRAPHICAL NOTES

Craig Roberts is a Senior Lecturer majoring in Surveying/ GPS/ Geodesy in the Surveying and Geospatial Engineering group at the School of Civil and Environmental Engineering, University of New South Wales, Sydney, Australia. He graduated from the South Australian Institute of Technology with a Bachelor of Surveying in 1988. He began his career as a private surveyor in Adelaide and has since worked as a Geodetic Engineer at UNAVCO, USA involved with GPS for geodynamic studies in Nepal, Ethiopia, Argentina and Indonesia. He worked as a scientific assistant at the GeoForschungsZentrum, Germany where his main focus was orbit determination and prediction for a number of geodetic research satellites. He completed his PhD thesis on volcano monitoring using low-cost GPS networks in March 2002. He has lectured at RMIT University in Melbourne for two years. His current research interests involve implications of datum modernisation and leveraging CORS infrastructure for practical application to surveying and geospatial information as well as a growing interest in the use of UAVs.

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