Fugro-Marinestar G4+ GNSS PPP-RTK improvements for offshore applications

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Key words: GPS, GLONASS, BeiDou, Galileo, PPP-RTK, Marinestar

SUMMARY

Marinestar offers satellite-based GNSS correction services over the world. An overview of the minimum and maximum number of useable satellites in August 2016 is given: GPS (6-13 satellites), Glonass (4-10 satellites), Beidou (0-13 satellites) and Galileo (0-5 satellites).

Since 2006 Marinestar provides precise Orbit &Clock corrections for GPS. Glonass was added in 2009 and Beidou in 2014. Galileo will be added when "Early Services" is declared. Improvements in the height accuracy from 20 cm in 2011 to 10 cm in 2016 is shown. Here the G4+ service using all four GNSS constellations with fixed GPS ambiguities is introduced.

A description is given of the PPP-RTK algorithm. GPS satellite hardware delays(UPD's) are measured using an independent network of 110 reference stations. Using another network of 46 reference stations orbit and clock errors are estimated. Improvements are realized by applying the UPD's to GPS and adding GLONASS, Beidou and Galileo to the solution. A study on the age of corrections shows that the age can be extended to 10 minutes.

Investigating the minimum elevation mask shows that reducing the mask improves availability and accuracy during ionospheric scintillation and local blockage. For the hydrographic surveyor error sources of G4+ as radio interference, rain, local multipath and antenna type are discussed.

It is shown that G4+ gives standard deviations of 2-3 cm in east and north and 4-5 cm in height. Fixing the ambiguities improves the standard deviations between 10%-20%.

1. INTRODUCTION

Fugro Satellite Positioning operates a worldwide network of 110 GPS/Glonass reference stations. In addition, 46 reference stations track also BeiDou and Galileo. This network is used to calculate precise satellite orbit and clock corrections of all four constellations in real-time for hydrographic applications. The corrections are broadcast to the maritime users by eight geostationary L-band satellites providing worldwide coverage.

2. CURRENT STATUS OF GNSS

As the G4 service uses four satellite constellations an overview of the number of satellites visible with a minimum elevation of 5 degrees is given for each constellation. Showing that one constellation alone is not sufficient to deliver consistent positioning.

2.1. GPS

In September 2016 there are 31 healthy GPS satellites. Satellite SVN 34/PRN 04 is a spare satellite. Already 19 IIF satellites do have the extra L2C signal. L2C has 3 dB stronger signal power and therefore allows better tracking in marginal circumstances. Also L2C allows independent measurement of the L2 signal. With legacy L2 cross correlation is used to measure L2 and when the L1 signal is jammed also the L2 measurement is affected. 17 IIF satellites have more accurate rubidium clocks than the previous generation of satellites. See www.gps.gov.

According to Marinestar GNSS network data, on a worldwide daily basis between 6 and 13 GPS satellites are useable. Local blockage and interference can reduce this to less than 4 tracked satellites, which is not sufficient for a position calculation

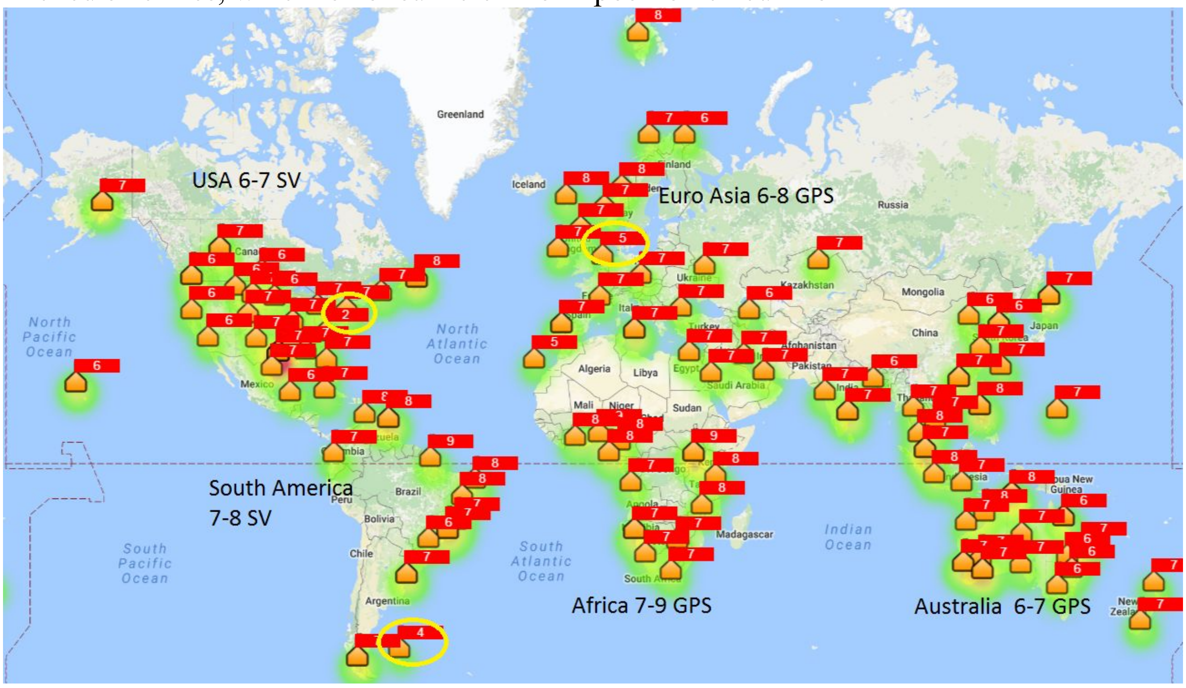

Figure 1 Minimum tracked GPS satellites in Marinestar network 21-August-2016

On a typical day, 3 sites were affected by short local GPS interference showing the need for more satellite constellations to offer continuous positioning. See Figure 1.

2.2. GLONASS

Currently there are nominal 24 Russian Glonass satellites available. Satellite R11 does not have L2 and is therefore unusable. Other satellites can have higher clock noise and are then removed from the Marinestar service. Between 4 and 10 Glonass satellites are visible in the Marinestar network. There are two new satellites in test mode. See https://www.glonass-iac.ru/en/glonass/

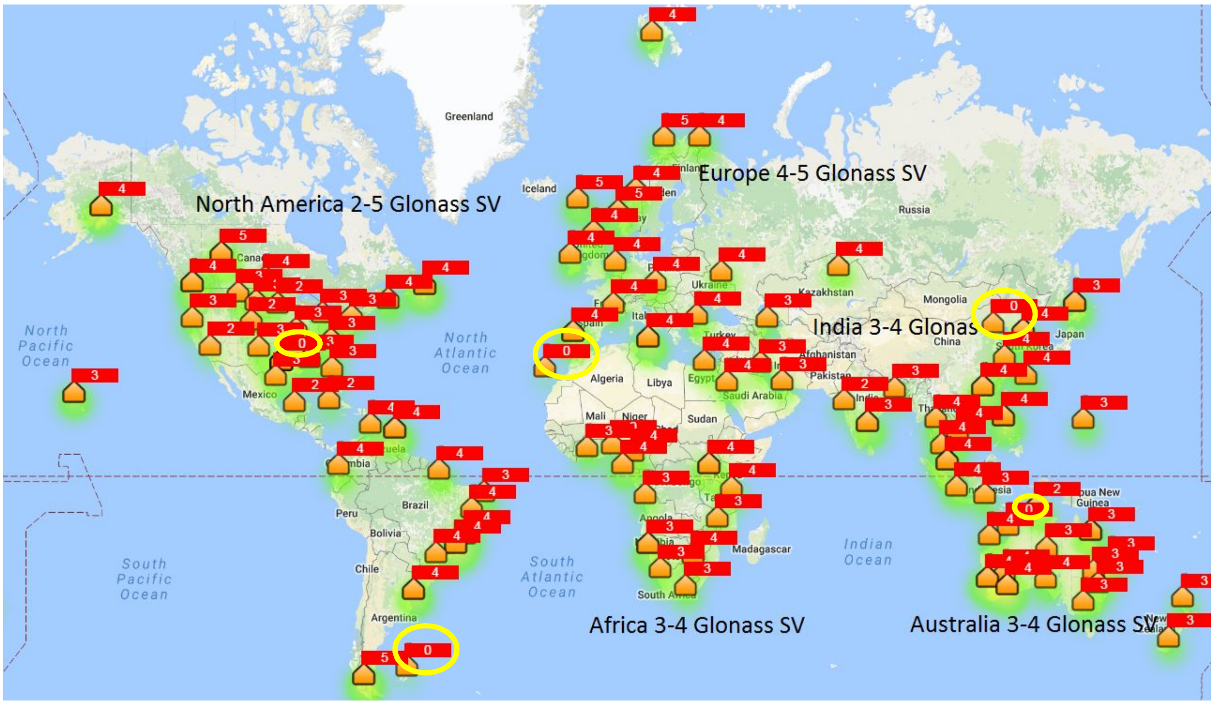

Figure 2 Typical minimum tracked Glonass satellites 21-Aug-2016

Figure 2 shows that five sites do have Glonass interference reducing tracked Glonass satellites to two or zero on an arbitrary day. This is due to short local Globalstar Iridium Interference, Glonass L2 Amateur radio interference or cellular interference. This again shows the need for more constellations.

2.3. BeiDou

The Chinese BeiDou navigation system has currently 14 satellites operational. 5 Geosynchronous satellites on the equator covering China, 5 Inclined Geostationary Satellites (IGSO) and there are 4 Medium Earth Orbit (MEO) satellites, which rotate the earth 13 times in one week. See http://en.beidou.gov.cn/ . Within the Chinese Beidou Conus there are always between 6 and 14 satellites visible. The three MEO's limit availability in the America's between 0 and 3. In Patagonia Beidou IGSO satellites are visible over the South Pole increasing the number to 4. SeeFigure 3 and Figure 4.

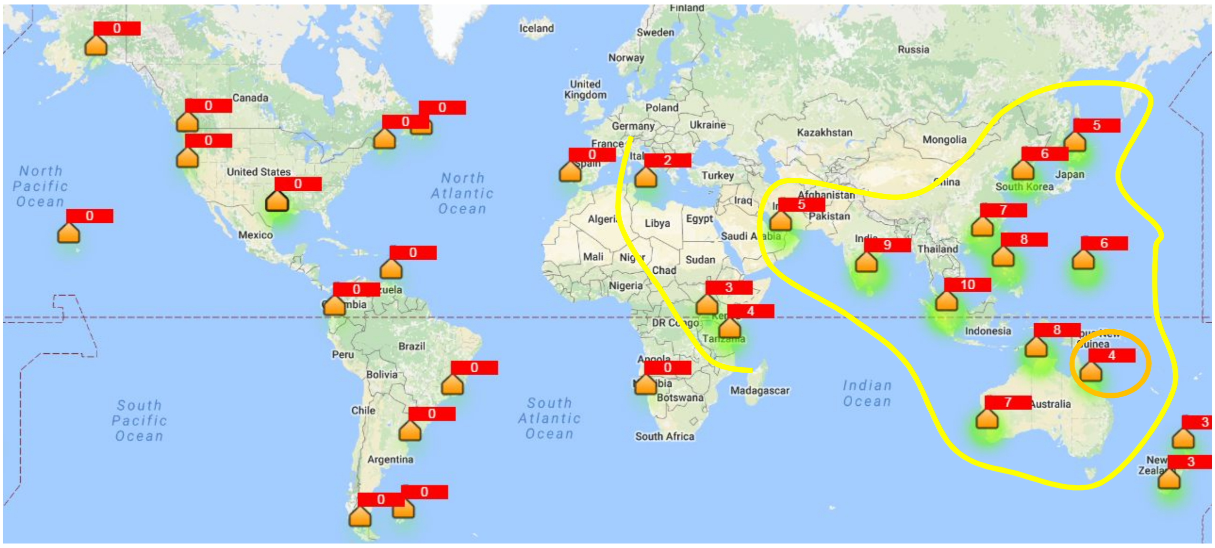

Figure 3 Typical minimum tracked Beidou Satellites 21-August-2016
Note the short reduced tracking in North East Australia, due to local BeiDou interference (Orange)

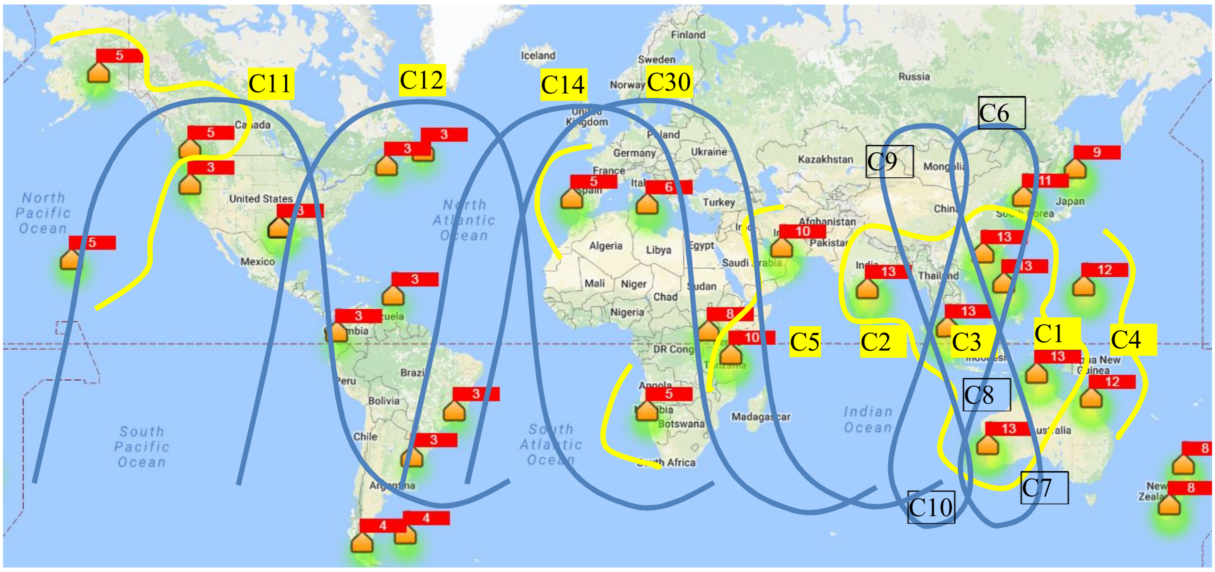

Figure 4 Typical maximum tracked Beidou Satellites 21-August-2016

2.4. Galileo.

On 21-August 2016, there are 11 Galileo Satellites available, E14 and E18 are in an elliptic orbit. Technically it will be possible to use these elliptic satellites. See [1] Tegedor, ENC2016. There are between 0 and 5 Galileo Satellites in view. 17 November 2016 four extra satellites are planned for launch. The maximum period with 4 Galileo satellites in view is 4 hours. However already with 2 Galileo satellites, Galileo adds value, because of the accurate clocks and increased availability of signals.

2.5. Multiple constellations.

Currently Marinestar broadcasts the orbit and clock corrections for GPS, Glonass and Beidou. Broadcast of Galileo orbit and clock corrections is possible, but is waiting on the declaration of the Galileo early service by the EU. The total number of nominal available satellites is 70 (32 GPS, 24 Glonass, 14 BeiDou). When all constellations will be established by 2020, there will be 116 satellites (32 GPS +24 Glonass +30 Beidou+30 Galileo). G4+ uses measurements from all four constellations (hence G4) and fix ambiguities on GPS (hence +). See [2] Tegedor

3. GPS L1 VBS

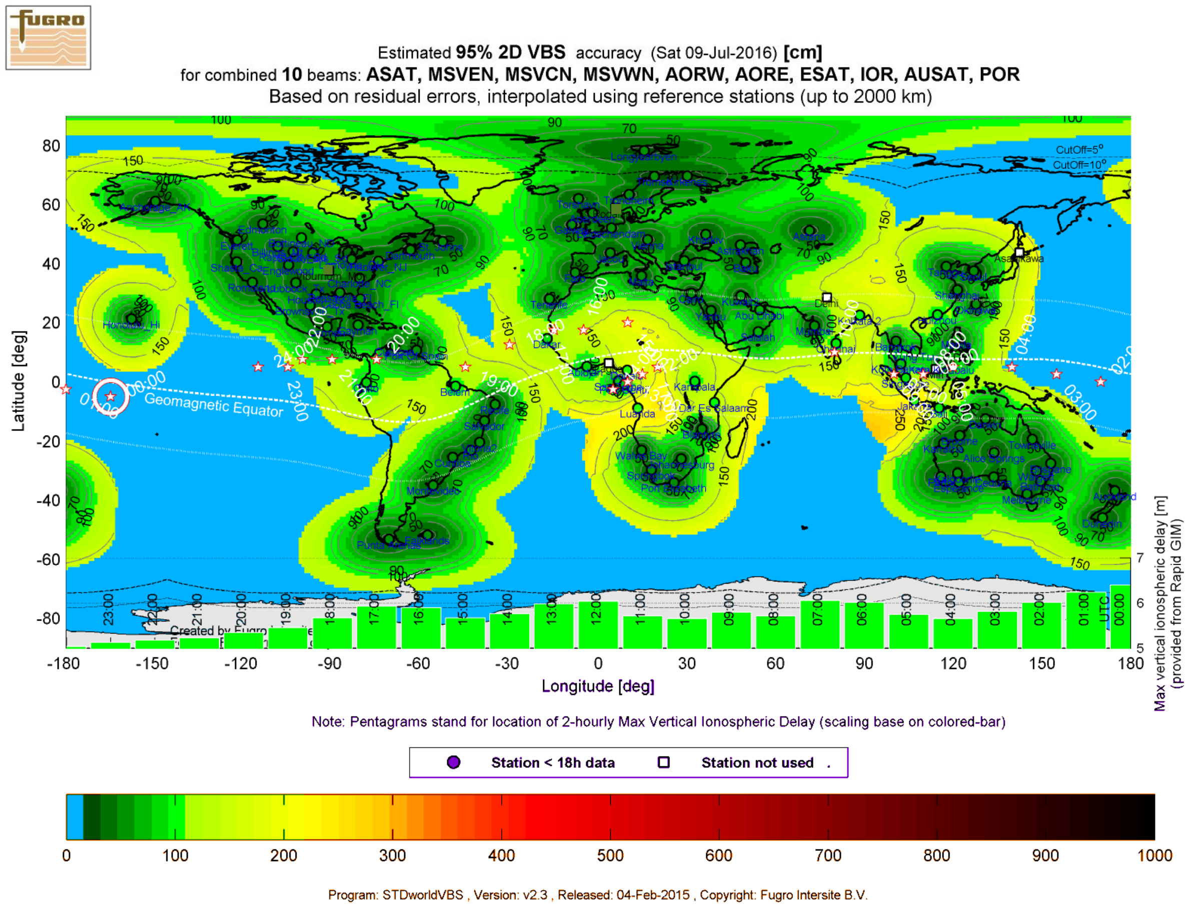

Figure 5 Marinestar L1 VBS typical code accuracy 09-July-2016

Virtual Base Station (VBS) is a DGPS positioning service that uses L1 Code/Phase GPS observations from multiple local reference stations and has been available since 1999 providing sub-meter accuracy in the non-equatorial regions. With the reduction of the solar activity as we move to the solar minimum, ionospheric disturbances in the equatorial region are considerably decreasing giving also sub meter positioning in that part of the world. From 2013 till 2016 that was not possible, because of the high daily ionospheric Total Electric Content (TEC) disturbances in the equatorial region. There will be days with some ionosphere disturbances, but in general till ~2023 when the next solar maximum activity starts, the TEC is expected to remain relative low. Within Marinestar's dense VBS network with inter distances of 1000 km the horizontal 95% accuracy is 50-60 cm. At the edge of the coverage at 2000 km from reference stations the accuracy degrades to the 2-meter level (See Figure 5).

4. Precise Orbit and Clock determination

Using GNSS data of a network of around 46 GNSS reference stations (distributed globally) the precise orbit of the GNSS satellites are determined and the Clock corrections are measured in real-time. The orbit corrections are transmitted every minute by the L-band satellites. Typically, errors of GPS precise orbit are 3-4 cm rms, Glonass 8-9 cm, Galileo 6-18 cm, Beidou, MEO 10-13 cm, IGSO 12-13 cm, and GEO 48-60 cm [1] Tegedor J (2016).

The satellite clock error is also measured using a network of all reference stations in view of the satellite. Every ten seconds the clock corrections are broadcasted to the user. The precision of clock corrections for GPS is 2 cm, Galileo 1.5-4 cm, Glonass 3-8 cm, Beidou MEO 1-2 cm, IGSO 2 cm GEO 3-7 cm.

5. Improvements of the Marinestar solution over the years.

To see how the prime G2 GPS/Glonass Orbit and Clock solution has improved over the years for every continent the typical one week 95% height is determined. The average of all continents is shown in Figure 6. The horizontal 95% error improves from 10 cm to 6 cm. The height improves from 18 to 10 cm. This is due to better orbit and clock estimation and better algorithms. The 2014 slight increase is due to scintillations during the solar maximum in 2014, which has been improved by better scintillation handling algorithms in 2015.

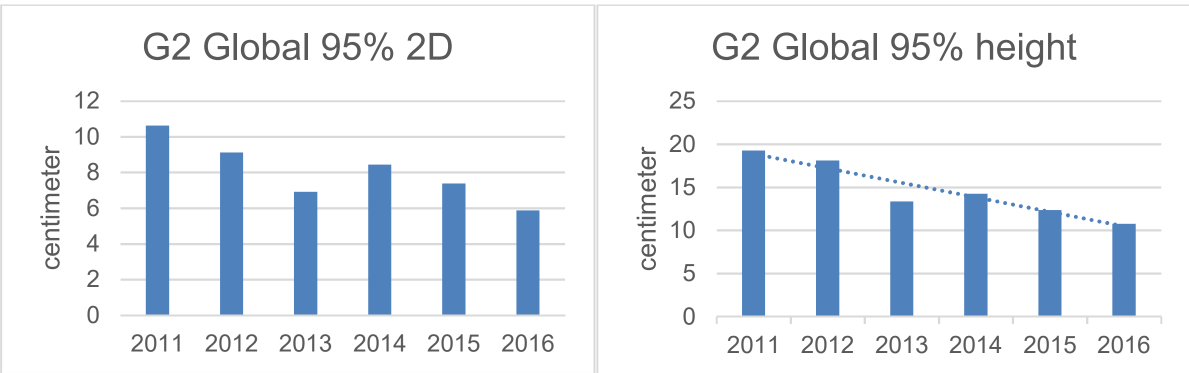

Figure 6 Improvements of the Marinestar solution height over the years

5.1. Minimum elevation

Lower minimum elevation results in larger error in the GNSS observations due to the troposphere, multipath fading and blockage of objects. However, the larger number of GNSS measurements available. Having more measurements is crucial during heavy scintillation in the equatorial region as seen in Africa and Brazil in 2013-2015. For GPS alone positioning, more measurements are crucial because of unhealthy satellites there are not always sufficient GPS Satellites available (See [6] NANU's). Adding GLONASS measurements using G2 service resolves that problem. Nowadays, having new satellites with more signal power, better antenna gain designs and better receiver tracking allows reducing the minimum elevation.

This has been tested using data from Macae, Brazil during scintillation in december-2015 See Figure 7.

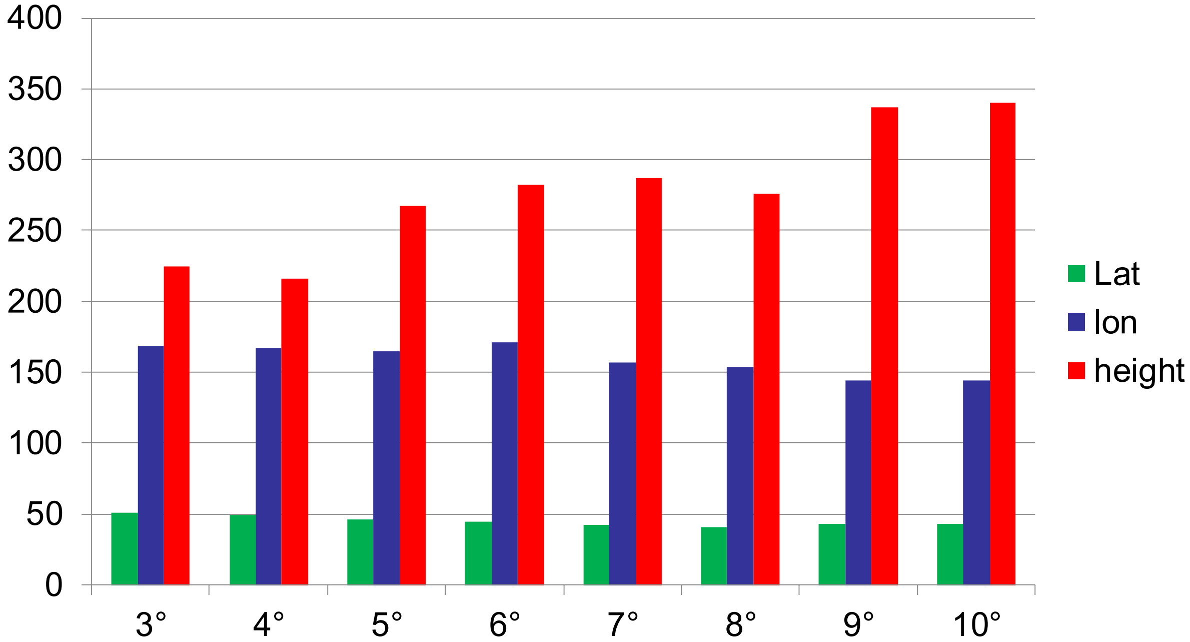

Figure 7 Macae, Brazil standard deviation in mm versus minimum elevation mask December-2013

During a period of active scintillation, low elevation satellites can resolve blockage of large parts of the sky due to scintillation.

5.2. Extending the age of corrections

Due to improved GPS IIF Satellite rubidium clocks it is now possible to extend the age of clock corrections from 5 to 10 minutes. The position error does degrade slowly as the age increases. Here is a balance between availability and accuracy. Automatic quality control is used to remove satellites with fast clock drift from the position solution.

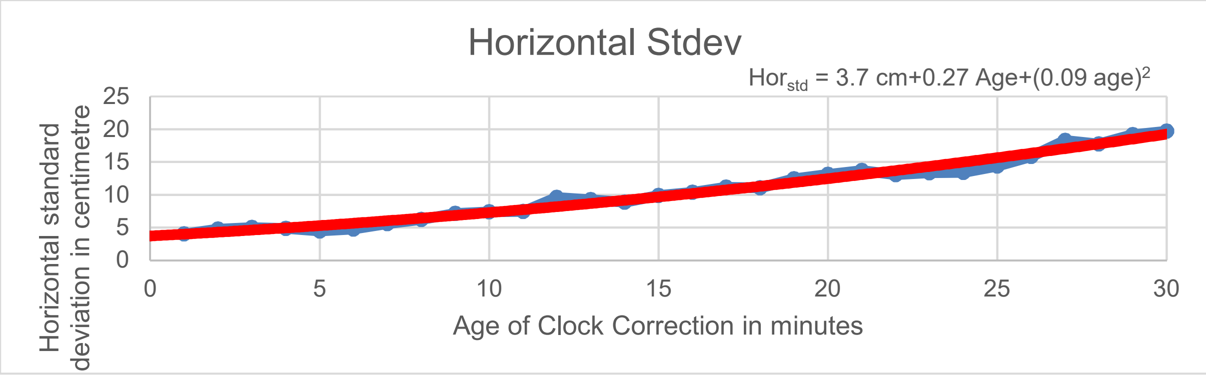

Figure 8 Horizontal standard deviation in meter versus age of correction in minutes

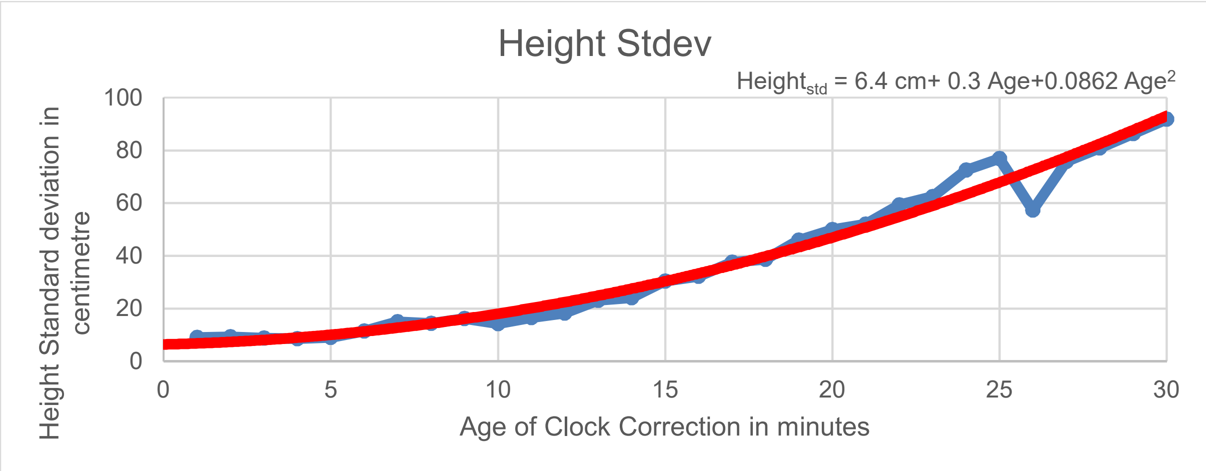

Figure 9 Horizontal standard deviation in meter versus age of correction in minutes

In Figure 8 and 9 data of Karratha in northwest Australia for 10-Jan-2015 has been replayed in G2 mode. Restarting the calculation every minute from minute 0 till minute 1440. the standard deviation of 1440 samples over the whole day is shown. After 10 minutes the horizontal standard deviation is 7 cm and the height 14 cm.

5.3. Reduction of clock jitter

Over time older GNSS satellite clocks can become noisier. Examples of these are e.g. SVN43/PRN13 See [5] Benton&Mitchel, SVN 45/PRN21 or retired Glonass 746(R17). Typically, these satellites are within the specifications for general use, but for high end PPP-RTK they are a challenge as the variations between correction epochs can be up to 10 cm. The effect of clock jitter has been reduced in the position solution. See Figure 10 where any horizontal error is removed and the maximum height error is improved from 40 cm to 20 cm.

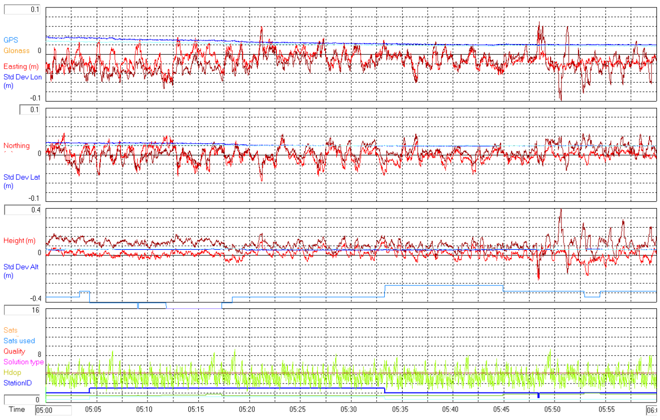

Figure 10 Improved handling of G13 clock jitter (Red) in Montevideo 30-July-2016

6. Adding of Beidou

Adding Beidou to the PPP solution improves availability. Especially in cases of GPS L1 jammer interference where the GPS L1 frequency of 1572 MHz is blocked, but the BeiDou B1 frequency of 1561 MHz survives. In case of Iridium/Globalstar interference from >1612 MHz, the Beidou B1 frequency is still tracked while Glonass and to a lesser extend GPS L1 signals are disturbed.

6.1. Resolving data outages with BeiDou

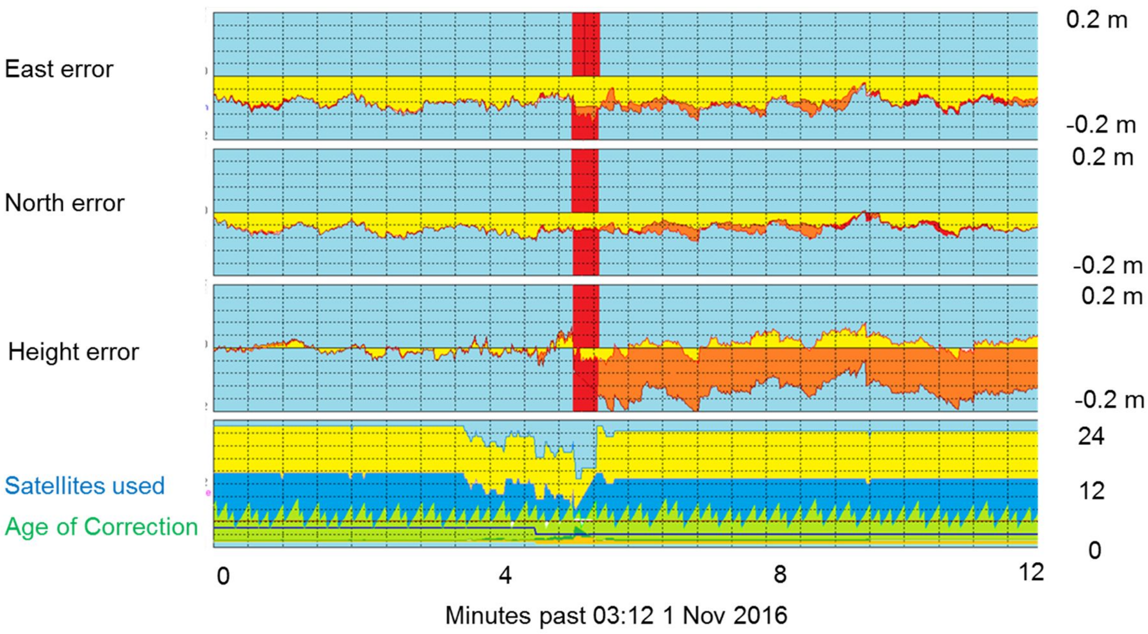

Figure 11 BeiDou fixing a GPS L1 Jamming position gap in Perth on 01-Nov-2016

The Beidou Geo and IGSO orbit accuracy is limited due to the larger distance to the earth. However, the satellites are very helpful in fixing short one-minute data gaps due to e.g. local interference. See for example Figure 10 where in Perth, Australia, during local GPS and Glonass L1 interference (Orange) the 11 BeiDou satellites are able to maintain a good position (Yellow).

7. GPS AMBIQUITY FIXING

The accuracy of PPP can be further improved if the e complete carrier-phase wavelengths can be resolved as done by standard RTK.

In PPP-RTK, this can be done using Uncalibrated Phase Delays (UPDs). Marinestar offers the G4+ service based on PPP-RTK with fixed GPS integer ambiguities using UPD's generated within the Marinestar network.

GPS L1 has a wavelength of ~19 cm and L2 ~24 cm Subtracting L1 frequency from L2 a narrow lane of ~11 cm can be formed. Differencing L1 and L2 phase observations results in a wide-lane observation with a wavelength of ~86 cm. Fixing the widelane ambiguities to the correct integer values is easier because of the large wavelength.

Subtracting L1/L2 Geometry-free code and the wide-lane phase linear combinations makes it possible to measure and fix the wide-lane ambiguities by applying the UPDs corrections at the user receiver. Differencing between L1 and L2 phase observations (L1-L2) gives ionosphere-free observation,. which correspond to a narrow-lane signal of 10.7 cm wavelength. Its ambiguity term is a linear function of GPS L1 and wide-lane ambiguities. Ones the wide-lane ambiguity is fixed it can be used with the narrow-lane ambiguity to measure and fix the L1 GPS ambiguity

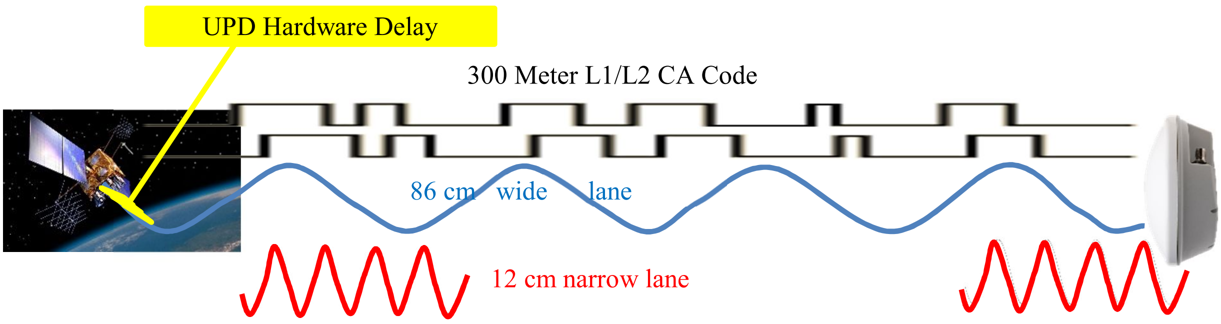

Figure 12 Schematic graph of CA Code (300 meter), wide lane (L1-L2) frequency (86 cm) and narrow Lane(L1+L2) 10.7 cm.

Applying precise O&C corrections in the network of reference stations with inter distances of 1000-2000 km, it is possible to estimate the UPDs precisely for the GPS L1 observations and the wide-lane observations for every satellite in real-time.

An additional advantage of using UPD corrections is that any remaining small gradual satellite orbit error is absorbed by the hardware delay and thus any residual orbit error can be further reduced.

7.1. Applying the UPD's

The UPD corrections are broadcast over the satellite links to the G4+ users. In the user's receiver, the integer numbers of GPS ambiguities (complete wavelengths of L1 and L2 signals) are estimated using the Lambda Method See [3] Teunissen. The fixed GPS ambiguities are used in the solution model to re-calculate more precisely the final position (G4+) solution using GPS, GLO, BeiDou, Galileo observations.

8. G4+ accuracy

Fixing ambiguities requires better measurements than traditional PPP. For a detailed description see [4] Liu. Items effecting the final accuracy are:

8.1. Radio interference

Far away radio interference, which is normally not noticeable, does have effect on positioning. For instance, in the Netherlands an L2 radio amateur transmitting on 1247 MHz at 2 km distance did degrade the standard deviations by 3 mm due to interference with Glonass L2 and GPS L2.

8.2. Antenna type

A choke ring or high end geodetic antenna that is resistant against signal multipath gives better accuracy than normal marine type antennas. However due to shape, size, design and interference characteristics such antenna type can be preferred for practical operations.

8.3. Tropospheric error

Heavy tropical rain showers can result in a large tropospheric range errors due to the unpredictably delay of GNSS signals. Therefore rain can degrade the G4+ solution.

8.4. phase multipath

With traditional code multipath in the range of 1-5 meters effects performance of VBS. Phase-multipath due to reflections less than 20-30 cm distance of the antenna play an important role. Placement of the antenna on a horizontal pole and with other metal obstructions close by can lead to significant phase error and consequently problem for fixing the ambiguities.

Taking all limitations into account Figure 13 shows the G2+ standard deviations of seven sites around the globe during two weeks. The typical overall standard deviation of G4+ solution is better than 2-3 cm in horizontal and 4-5 cm in height.

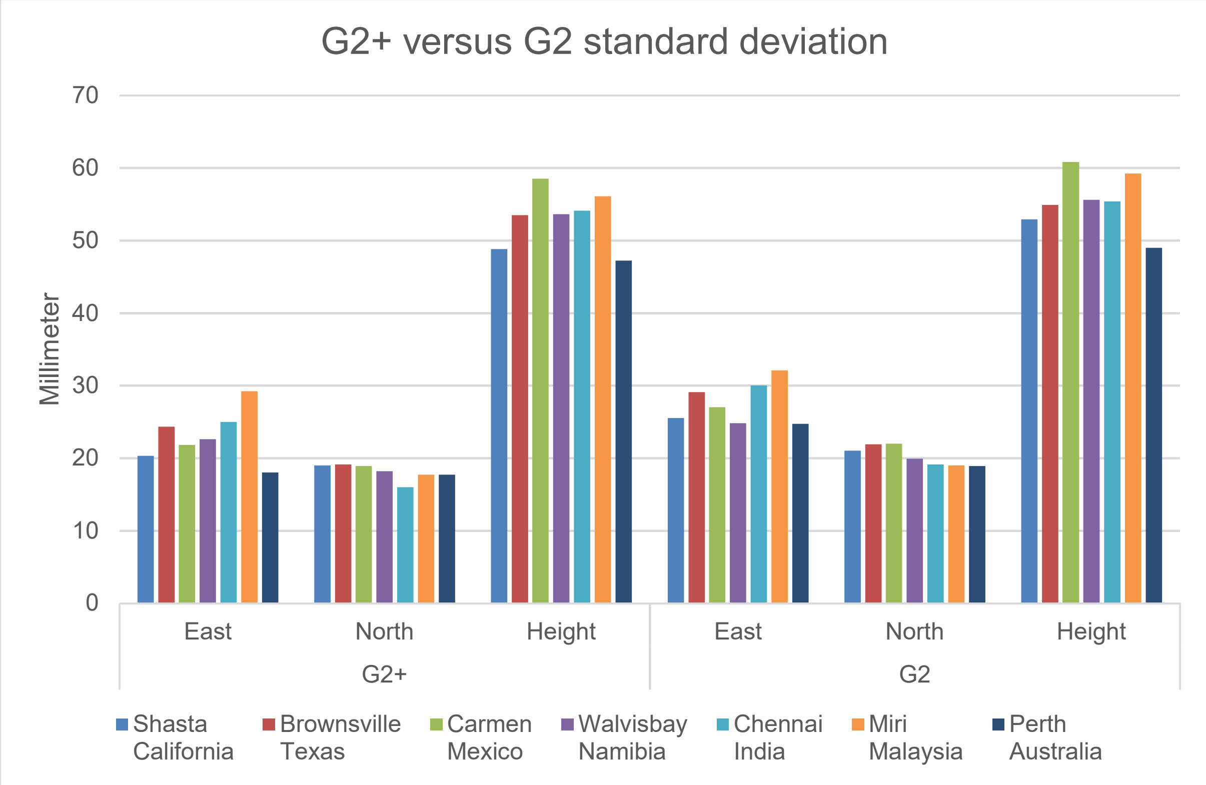

Figure 13 G2+ Standard deviation for several sites compared with G2

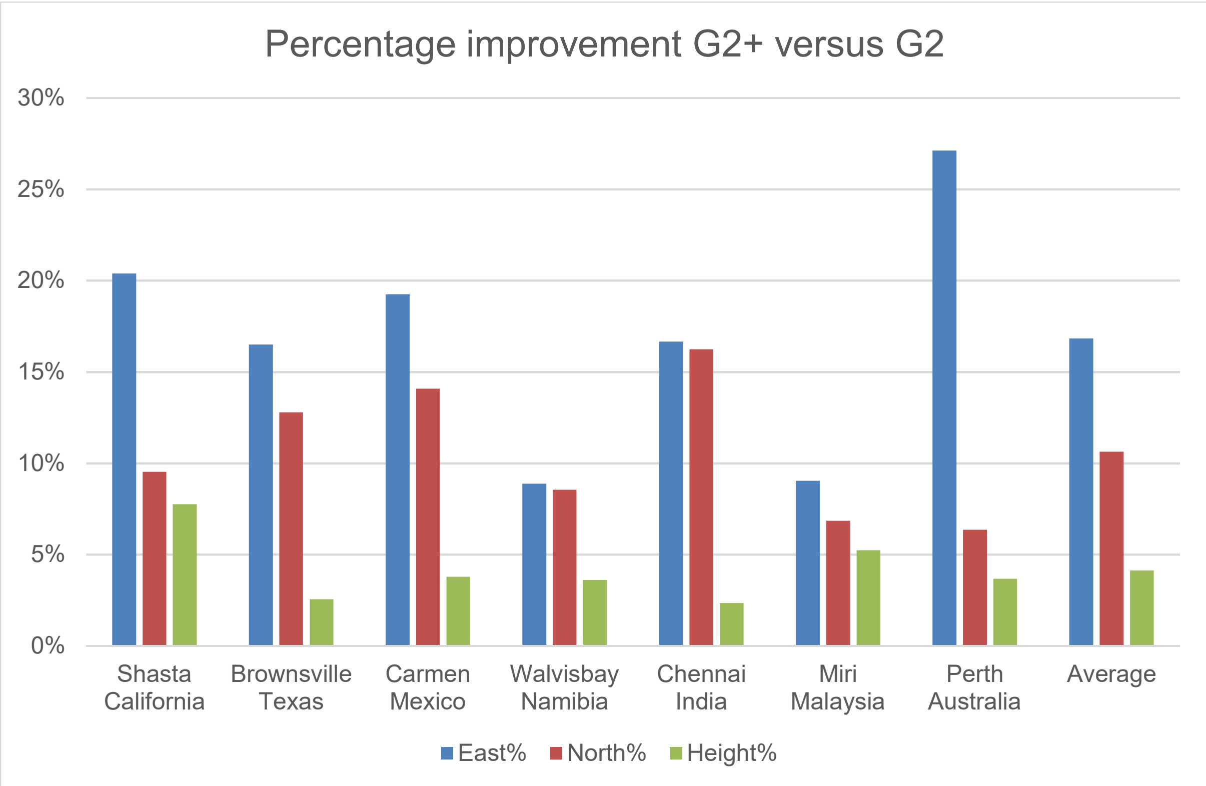

Figure 14 G2+ Versus G2 relative improvement

The horizontal improvements is between 6% and 27%. For height is the improvement between 2%-8%. The improvement in height is limited by tropospheric effects lumping in the height component.

9. Conclusions

The quality of the Marinestar position services is continuously improving. Taking advantage of GNSS observations of multiple constellations using up to 72 GNSS satellites improves accuracy, availability and robustness of the position solutions. The horizontal standard deviation is now 2-3 cm and the height is between 4-5 cm . Due to the reduced ionospheric disturbances after the solar maximum, GNSS positioning results will be better till the rise of the next solar maximum in 2023. Positioning by PPP-RTK techniques requires more attention to the receiver-antenna setup and environment of the surveyor.

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BIOGRAPHICAL NOTES

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