Analysis of Multi-Constellation GNSS Signal Quality

T. Richardson, C. Hill, Terry Moore
University of Nottingham
P Toor
Veripos

1 BIOGRAPHY

Terri Richardson Ph.D., Nottingham Geospatial Institute, University of Nottingham, United Kingdom. Her research interests cover high-accuracy GPS/GNSS algorithms, multi-constellation positioning, and orthometric height determination using GPS/GNSS.

Chris Hill is an Associate Professor, Faculty of Engineering holding a PhD in satellite laser ranging. He is a Fellow of the Royal Institute of Navigation.

Terry Moore is the Director of the Nottingham Geospatial Institute (NGI) at the University of Nottingham and as such has overall responsibility for all the activities of this postgraduate research and teaching institute. His research interests and expertise are concerned with the development and applications of satellite navigation and positioning systems, such as GPS and Galileo. He has extensive research background in the navigation, engineering and environmental applications of these systems. These cover a variety of different domains such as air and marine navigation, road user charging, unoccupied aircraft, atmospheric monitoring, and indoor navigation. He is also actively involved in the developments of the underlying technology and algorithms. He has particular interest in the integration of satellite positioning sensors with other positioning to provide seamless and precise positioning for users of the systems. He is involved in the developments of the new European Galileo satellite system, both in terms of research and development programmes, but also through advice and consultancy services with industry and government agencies.

Pieter Toor is the GNSS Technology Manager at VERIPOS. His focus is on enabling accurate & reliable global high accuracy positioning services by integrating new GNSS technology within the VERIPOS global infrastructure and products & services. As GNSS Technology Manager he is responsible for the both development of GNSS augmentation services for VERIPOS and TerraStar and for the development of PPP and PPP-AR algorithm.

2 ABSTRACT

The code pseudo-ranges and phase pseudo-ranges are affected by the systematic errors or biases and random noises. These errors can be classified into three groups, satellite related errors, propagation-medium related errors and receiver related errors (Hofmann-Wellenhof, Lichtenegger and Collins 2001; Leick 2004). Effective GNSS positioning depends on an understanding of the measurement error budget and eliminating or reducing those errors. Some systematic errors can be modelled and gives rise to additional terms in the observation equation, while other systematic effects can also be eliminated (or greatly reduced) by appropriate combinations of observables. However in the case of stand-alone positioning the use of relative positioning to reduce or eliminate biases is not a possible option.

The GNSS signal observation quality and bias investigation involved a thorough review, analysis and quantification of the constellation error sources and mitigation processes, also, focusing on those effects which cannot be eliminated or modeled. Signal quality is usually represented as signal-to-noise ratio (SNR) or as carrier-to-noise ratio (C/No). Both of those parameters are essential to assess the performance of GNSS receiver and they are directly related to the precision of code-phase and carrier-phase pseudo-range observations (Langley, 1997). This paper presents the work done, to evaluate the relationship between the SNR value generated by the receiver and the pseudo-range residual and, to develop an observation weight function, including the scale parameters that are specific to the observation types and linear combinations that were assessed, this ultimately may be used as a relative weighting scheme for combining data from multiple signals & constellations.

The results obtained showed that the higher pseudo-range residual values were associated with lower SNR values irrespective of GNSS constellation or observation signals. As the SNR values increased 45-55 dBHz the pseudo-range residual values are generally reduced. The high residual values were observed mainly at the beginning and ends of the observation periods tested and maybe related to the ascension and descent of the satellite or multipath. The SNR weighing developed, produced comparably similar position solution results to that of elevation weighing, however this weighting method has the

advantage of allowing the use of a combination of different observations and signals.

3 INTRODUCTION

The code pseudo-ranges and phase pseudo-ranges are affected by the systematic errors or biases and random noises. These errors can be classified into three groups, satellite related errors, propagation-medium related errors and receiver related errors (Hofmann-Wellenhof, Lichtenegger and Wasle 2008; Leick 2004). Effective GNSS positioning depends on an understanding of the measurement error budget and eliminating or reducing those errors.

Some systematic errors can be modelled and gives rise to additional terms in the observation equation, while other systematic effects can also be eliminated (or greatly reduced) by appropriate combinations of observables. However in the case of stand-alone positioning the use of relative positioning to reduce or eliminate biases is not a possible option.

The GNSS signal observation quality and bias investigation involved a thorough review, analysis and quantification of the constellation error sources and mitigation processes, also, focusing on those effects which cannot be eliminated or modelled.

4 METHODOLOGY - SIGNAL QUALITY TESTING

To achieve the desired result, a sample datasets of GPS, GLONASS, Galileo and BeiDou signals from including both live sources and scenarios that were simulated. The quality assessment included processing pseudo-ranges in stand-alone and differential modes, as well as using the carrier phase measurements to phase-smooth the pseudo-ranges. The analysis outputs addressed the stochastic properties, as well as the impact of biases caused by unmitigated errors.

The datasets used were multi-constellation data extracted for a 24hr period from reference station within the Veripos control network. The stations selected are located in Aberdeen, Seoul and India and were selected as they provide optimum GNSS coverage to all of the existing constellations. These reference stations are equipped with multiple frequency GNSS receivers, Septentrio PolaRx4 (Aberdeen, Seoul) and NovAtel GNSSCard (India), Table 1, above list the details of the dataset used and the system and observation types captured. These stations are also fitted with choke ring antenna to mitigate the effect of multipath. It should be noted that the NovAtel receiver applied a smoothing time constant to the raw pseudo-range data received, while the Septentrio receiver raw data unaltered. This smoothing time constant feature in the NovAtel receiver could be reduced but not switched off. Applying a smoothing time constant, in advance eliminates the high measurement noise and the greater multipath disturbance of the raw pseudo-range data at the receiver level, this removes the need to apply any further smoothing of the data post processing.

The first series of test was carried out to determine the Signal Quality, using a series of simulated dataset and live data sets where applicable.

4.1 Test 1 – Signal to Noise Ratio

Signal-to-noise ratio (SNR) or as carrier-to-noise ratio (C/N_o), as recorded by the receiver, are used to model the pseudo-range observations noise variance.

Signal Quality is usually represented as signal-to-noise ratio (SNR) or as carrier-to-noise ratio (C/N_o). Both of those parameters are essential to assess the performance of GNSS receiver and they are directly related to the precision of code-phase and carrier-phase pseudo-range observations (Langley, 1997). SNR is obtained at the correlator output and is described as a ratio of the signal power S_{corr} to the noise power N_{corr} of the modulated signal. CNR is obtained at the receiving antenna and is described as a ratio of the signal power Cant to the noise power N_{ant} of the modulated signal. Due to the fact that signal and noise power are amplified (between antenna and correlator output) by approximately the same factor we can assume that ratio of those parameters is also almost the same (equation 1).

$$CNR = \frac{C_{ant}}{N_{ant}} \approx \frac{C_{corr}}{N_{corr}} = SNR \qquad (1)$$

Objective:

- To analyse, using simulated data the relationship between the GNSS signal quality and observation precision. The quality of the signals tracked would be analysed by examining the measured signal strength using the SNR value extracted from the receivers.

4.2 Test 2 – Pseudo-range residuals using Hatch Filter

One way of overcoming the two main problems associated with pseudo-range data, that is: (a) the high measurement noise, and (b) the greater multipath disturbance, in comparison to carrier phase data is to create a pseudo-range / carrier phase combination that, in effect, "smooths" the pseudo-range data. The basis of all data smoothing techniques is to derive the *rate of change of range from the carrier phase data* (the Doppler data can also be used for this purpose), and to combine this with the *absolute measurement of range provided by the pseudo-range data* (though it is a biased range). An example of a GNSS data smoothing technique was described by Hatch (1982) and make use of dual frequency phase and pseudo-range data.

The Hatch filter for estimation can be represented in recursive form:

$$\hat{\rho}(k) = \frac{1}{k}\sum_{j=1}^{k} \rho_j(k) = \frac{k-1}{k}\{\hat{\rho}\,(k-1) + \Delta\emptyset\,(k)\} + \frac{1}{k}\,\rho(k)\text{ ; for } k \le K \quad (2)$$

$$\hat{\rho}(k) = \frac{1}{K}\sum_{j=1}^{k} \rho_j(k) = \frac{K-1}{K}\{\hat{\rho}\,(k-1) + \Delta\emptyset\,(k)\} + \frac{1}{K}\,\rho(k)\text{ ; for } k > K \quad (3)$$

where:

$\rho(k)$ – raw pseudo-range measurement at the current epoch

$\Delta\emptyset\,(k)$ – change in carrier phase

$\hat{\rho}(k)$ – smoothed pseudo-range at current epoch

$\hat{\rho}\,(k-1)$ – smoothed pseudo-range at previous epoch

k – smoothing window width of Hatch filter

K – maximum value of (k)

The precision of the smoothed pseudo-range is a direct function of the number of epochs K

Objective

- ❖ To evaluate the precision of the smoothed pseudo-range (utilising the Hatch filter) at different smoothing window width (k) of the Hatch filter. In principle the more epochs of data used in the smoothing process the more precise the smoothed pseudo-range should become, and should approach the precision of the carrier range. Testing different values of k, will allow for the analysis of the precision of the smoothed pseudo-range as it relates to the filter smoothing window. Also, to determine the: (1) optimum k for our purpose of assessing observation precision and (2) ”safe” k for avoiding ionospheric divergence
- ❖ To analyse, using GNSS data the relationship between the GNSS signal quality and observation precision. This is done by evaluating the relationship between the SNR value generated by the receiver and the pseudo-range residual extracted from the Hatch filter. To be tested
    - o Multiple constellation (based on availability)
        - ▪ GPS, GLONASS; BeiDou; Galileo
    - o Multiple observation type of the available frequency band (based on availability)
        - ▪ GPS: C1C, C2C, C5Q
        - ▪ GLO: C1C, C2C
        - ▪ GAL: C1C, C5Q, (C7Q; AltBOC: C8Q)
        - ▪ BDS: C1I, C7I (optionally, if available: C6I)
- ❖ To develop an observation weight function, including the scale parameters that are specific to the observation types and linear combinations that were assessed, this ultimately will be the relative weighting scheme for combining data from multiple signals for initial testing the GPS constellation will be used.

5 RESULTS

5.1 SNR and Pseudo-range Relationship

The results presented below shows the time series based on the Hatch filter residual and the satellite SNR, for 3 selected GPS reference station within the Veripos network; India, Seoul and Aberdeen. From the selected reference stations, high elevation satellites were selected for analysis. The figures 1 to 3 below, shows the time series for satellites in the GPS constellation for Aberdeen station. The Hatch filter residuals were derived using a smoothing window width (k) of 100 epochs.

Here it can be seen that there is a relationship between the pseudo-range residuals and SNR and elevation (as the SNR increases the Residuals decrease, likewise the SNR increase as the elevation increases for the GPS constellation. A similar relationship was exhibited for the remaining constellation Glonass, Galileo and BeiDou for example the GPS results are show here.

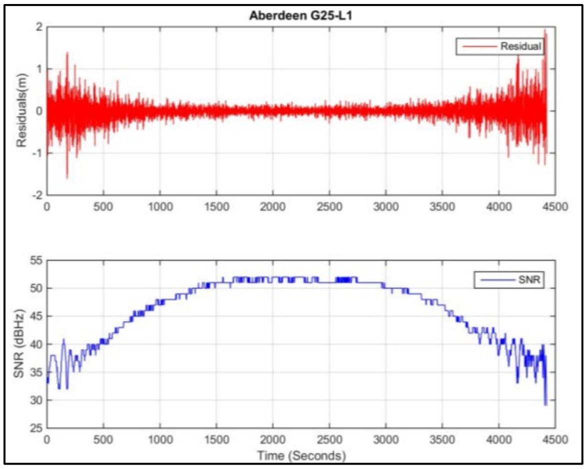

Figure 1 - Aberdeen Reference Station: Time series of the Pseudo-Range of Residual and SNR of GPS satellite 25-L1 frequency

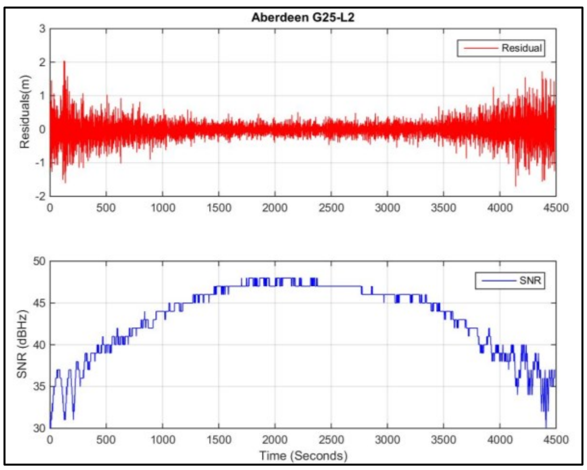

Figure 2 - Aberdeen Reference Station: Time series of the Pseudo-Range of Residual and SNR of GPS satellite 25-L2 frequency

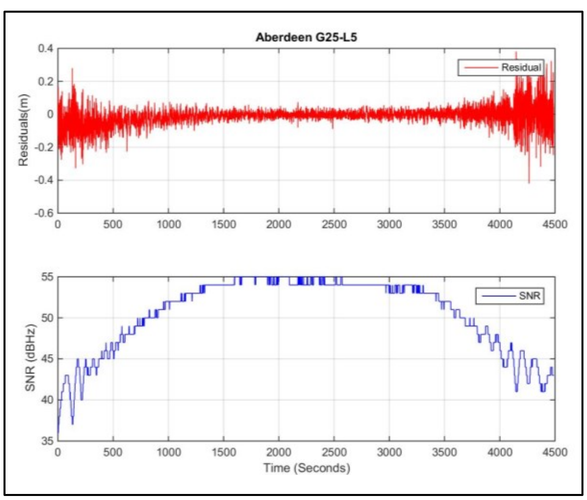

Figure 3 - Aberdeen Reference Station: Time series of the Pseudo-Range of Residual and SNR of GPS satellite 25-L5 frequency

Figures 1 to 3, above shows this relationship in time series between Pseudo-Range of Residual and SNR of GPS satellite 25-L1, L2 and L5 frequencies. It can be seen that within the first and last 500 seconds for the time series there are large residuals ranging between 05- 2 m of the L1 and L2 frequencies seen in Figure 1 and 2 and between 0.2 - 0.3 m of the L5 frequency seen in Figure 3. The higher residual values were associated with lower SNR values. As the SNR values increased 45-55 dBHz the pseudo-range values generally reduced. These high residual values maybe related to the ascension of the satellite and multipath.

5.2 Observation Quality measure

Taking the RMS of the pseudo-range residuals assisted in determining the quality of the GNSS signals observed for the selected stations. Using the relationship between RMS of the Pseudo-range residual and SNR for the related frequency an exponential curve was fitted to an average of the satellites pseudo-range residuals.

Figure 4, shows a complied graph of the Galileo and BeiDou signals in relation to the GPS signals, from this graph, it can be seen that the; Galileo signals provides a great improvement in terms of code measurements noise compared to the other signals of GPS and BeiDou which means the Galileo signal exhibits the smallest RMS values as the SNR increases. Additionally, both BeiDou signals L2 and L7 showed the smallest disparities between each other in the RMS/SNR relationship. Conversely, both GPS and Galileo signals behave similarly, showing large disparities in RMS amongst each signal at lower SNR values, while slowly converging to a lower RMS as the SNR value increases.

Figure 5, shows a complied graph of the Galileo and BeiDou signals in relation to the GPS signals, from this graph, it can be seen similar to that in Figure 4, that the; Galileo signals provides a great improvement in terms of code measurements noise compared to the other signals of GPS and BeiDou which means the Galileo signal exhibits the smallest RMS values as the SNR increases.

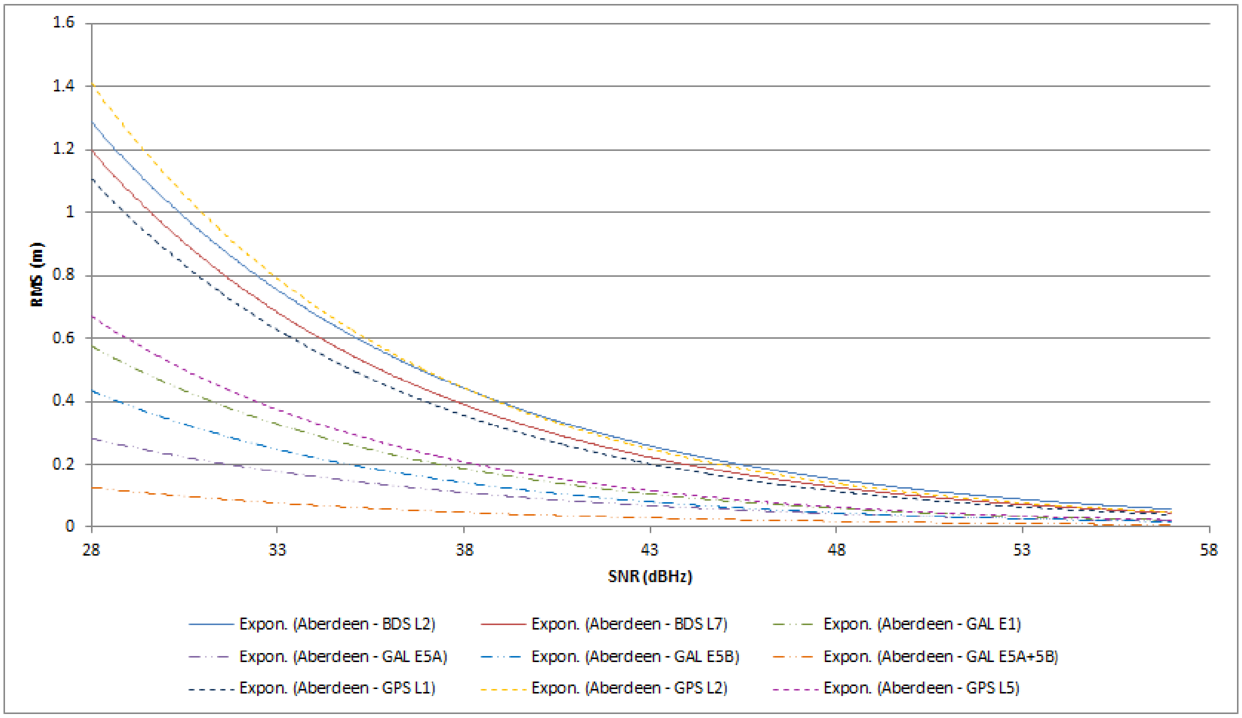

Figure 4 - Aberdeen Reference Station – Exponential Model for Galileo and BeiDou observables in relation to GPS observables

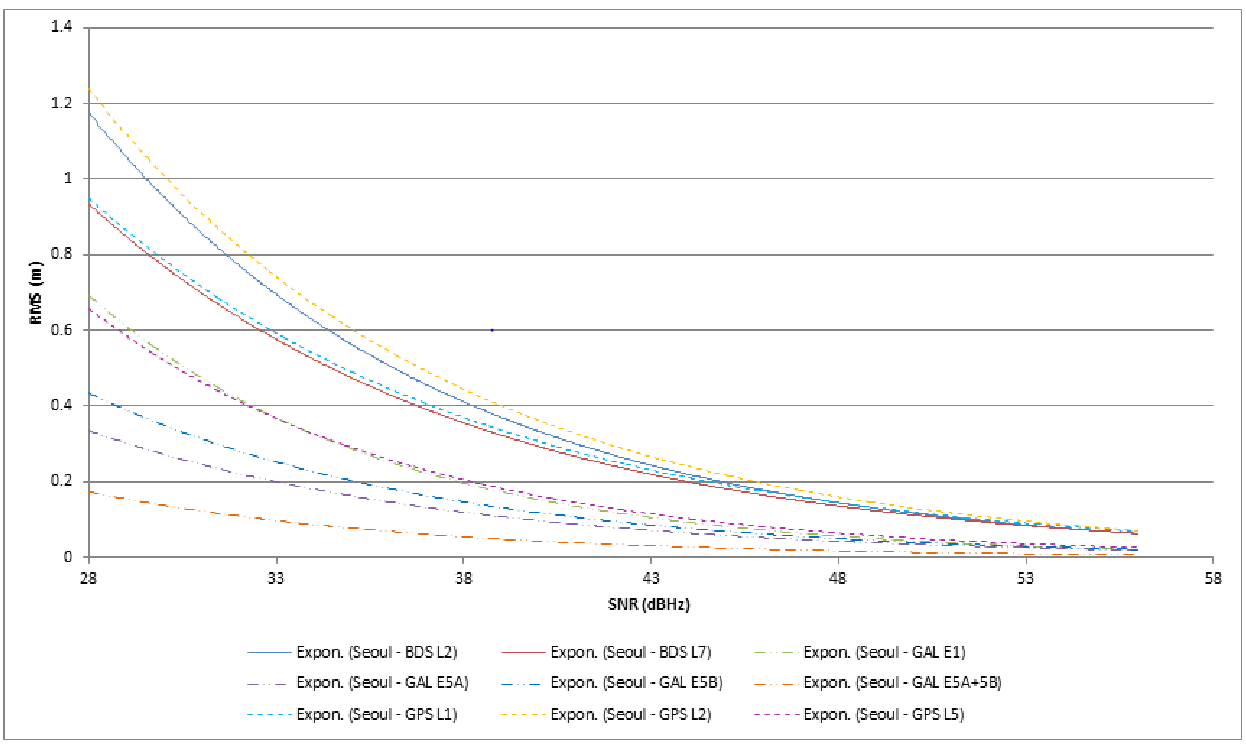

Figure 5 - Seoul Reference Station – Exponential Model for Galileo and BeiDou observables in relation to GPS observables

5.3 SNR Weight Determination Unsmooth Receiver data

Using the relationship between RMS of the Pseudo-range Residual and SNR for L1/L2 frequency an exponential curve was fitted to an average of the satellites pseudo-range residuals. Figure 6 below shows the exponential curve derived for the Aberdeen station using the GPS constellation (data logged using Septentrio receiver).

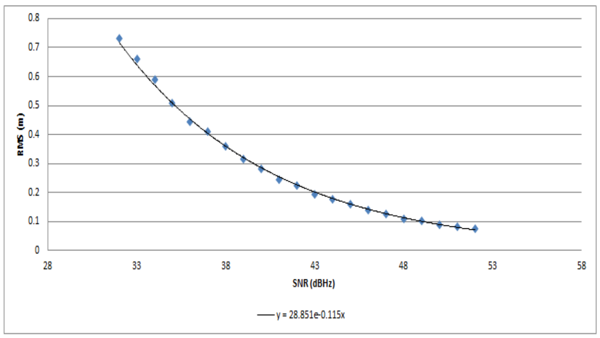

Figure 6 - Aberdeen Reference Station: Exponential Trend defining the SNR weighting using GPS L1 and L2 frequencies.

The exponential curve equation was used in the ionospheric-free positioning algorithm, where the position solution was compared to the position solution derived using Elevation based weighting. Table 2 and figures 7, illustrates the results.

Table 1 - Aberdeen Reference Station: SNR weighting analysis comparison with Elevation weighting (unsmoothed data from Septentrio receiver)

Solution statistics - Elevation Weighing

Parameter	*Units*	*Min*	*Max*	*Mean*	*2 SD*
Horizontal error	metres	0.05	3.50	1.11	1.23
Vertical error	metres	-3.86	4.15	0.25	2.82
Longitude error	metres	-2.09	1.34	-0.12	1.33
Latitude error	metres	-3.40	2.07	-0.46	1.94
HDOP		0.00	0.00	0.00	0.00
Mean correction age	seconds	0.00	0.00	0.00	0.00
Satellites in fix		9.00	14.00	11.20	2.86

Solution statistics - SNR Weighing

Parameter	*Units*	*Min*	*Max*	*Mean*	*2 SD*
Horizontal error	metres	0.01	3.61	1.11	1.28
Vertical error	metres	-3.81	4.24	0.56	2.67
Longitude error	metres	-1.95	1.44	-0.13	1.32
Latitude error	metres	-3.47	2.05	-0.50	1.94
HDOP		0.00	0.00	0.00	0.00
Mean correction age	seconds	0.00	0.00	0.00	0.00
Satellites in fix		9.00	14.00	11.20	2.86

Table 1, summaries the results of position solution using the elevation based weighting versus the SNR based weighting for the unsmoothed data. From these statistics it can be seen that very little to no improvement in using the elevation weighing over the SNR weighting in a position solution. However the errors derived for the vertical component produced a smaller distribution from the mean for the SNR weighting over the Elevation weighting. Figures 7, shows the times series of accuracies produced in terms of horizontal and vertical components.

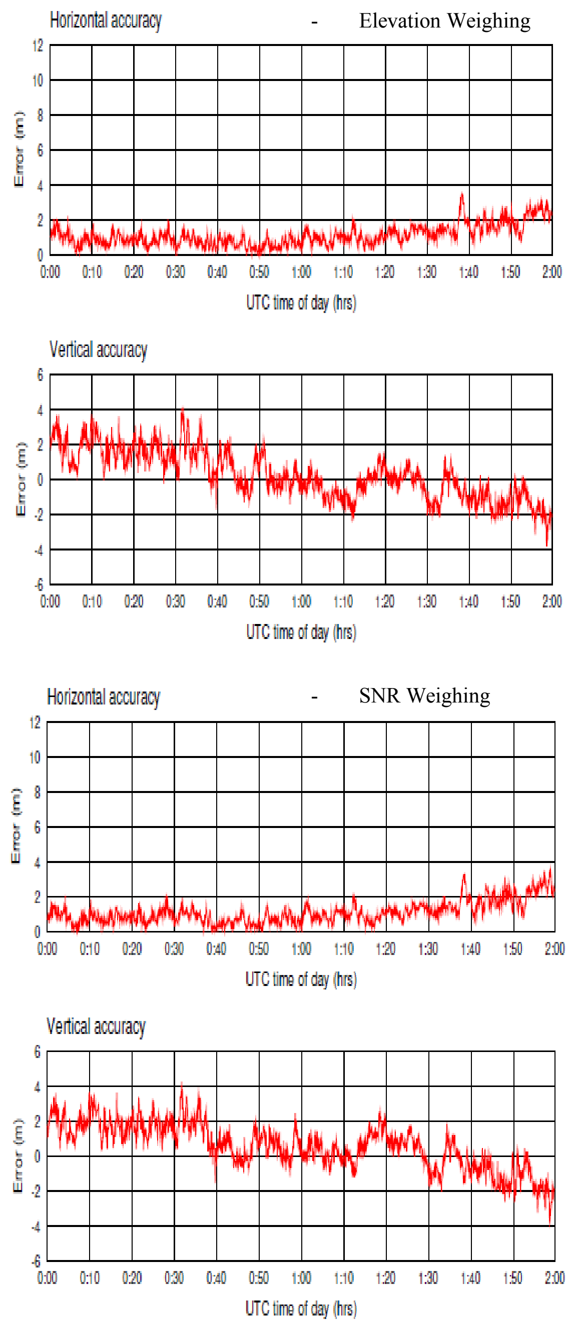

Figure 7 - Aberdeen Reference Station: SNR weighting analysis comparison with Elevation weighting (unsmoothed data from Septentrio receiver) – Horizontal and vertical derived accuracy

5.4 SNR Weight Determination - Receiver Smooth data

Using the relationship between RMS of the Pseudo-range Residual and SNR for L1/L2 frequency an exponential curve was fitted to an average of the satellites pseudo-range residuals. Figure 16 below shows the exponential curve derived for the India station using the GPS constellation, the data was logged using NovAtel receiver with a present smoothing time constant of 100 seconds.

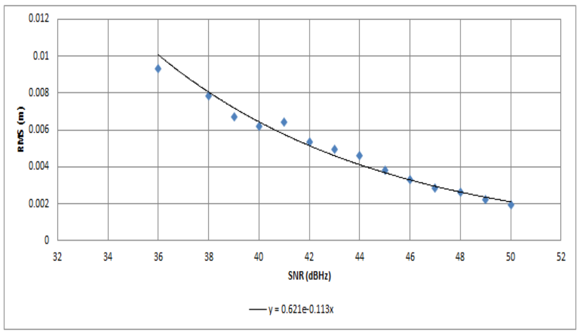

Figure 8 - India Reference Station: Exponential Trend defining the SNR weighting using GPS L1 and L2 frequencies

The exponential curve equation was used in the ionospheric-free positioning algorithm, where the position solution was compared to the position solution derived using Elevation based weighting. Table 3 and figures 9, illustrates the results.

Table 2 - India Reference Station: SNR weighting analysis comparison with Elevation weighting (smoothed data from NovAtel receiver)

Solution statistics - Elevation Weighing

Parameter	Units	Min	Max	Mean	2 SD
Horizontal error	metres	0.21	3.02	1.53	1.10
Vertical error	metres	-4.77	3.92	0.34	4.06
Longitude error	metres	-2.47	0.97	-0.63	1.53
Latitude error	metres	-2.24	-0.04	-1.23	0.77
HDOP		0.00	0.00	0.00	0.00
Mean correction age	seconds	0.00	0.00	0.00	0.00
Satellites in fix		8.00	12.00	10.19	2.59

Solution statistics - SNR Weighing

Parameter	Units	Min	Max	Mean	2 SD
Horizontal error	metres	0.14	2.83	1.32	0.86
Vertical error	metres	-3.96	4.41	0.32	3.83
Longitude error	metres	-1.95	1.02	-0.37	1.33
Latitude error	metres	-2.14	-0.05	-1.09	0.77
HDOP		0.00	0.00	0.00	0.00
Mean correction age	seconds	0.00	0.00	0.00	0.00
Satellites in fix		8.00	12.00	10.19	2.59

Table 3, summaries the results of position solution using the elevation based weighting versus the SNR based weighting for the smoothed data. From these statistics it can be seen that very little improvement in using the SNR weighing over the Elevation weighting in a position solution. The errors derived for the components measurement produced a smaller distribution from the mean for the SNR weighting over the Elevation weighting. Figures 15 and 16, shows the times series of accuracies produced in terms of latitude, longitude, horizontal and vertical components.

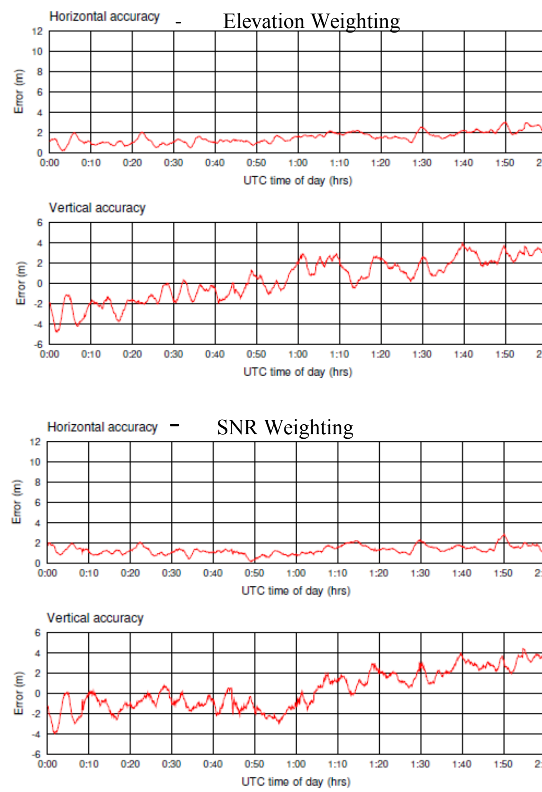

Figure 9 – India Reference Station: SNR weighting analysis comparison with Elevation weighting (smoothed data from NovAtel receiver) – Horizontal and vertical derived accuracy

6 CONCLUSION

This study investigated the Signal Quality, using a series of simulated dataset and lives data sets where applicable. Signal Quality is usually represented as signal-to-noise ratio (SNR) or as carrier-to-noise ratio (C/N_o).

One way of overcoming the two main problems associated with pseudo-range data, that is: (a) the high measurement noise, and (b) the greater multipath disturbance, in comparison to carrier phase data is to create a pseudo-range / carrier phase combination that, in effect, "smooths" the pseudo-range data. The basis of all data smoothing techniques is to derive the *rate of change of range from the carrier phase data* (the Doppler data can also be used for this purpose), and to combine this with the *absolute measurement of range provided by the pseudo-range data* (though it is a biased range). An example of a GNSS data smoothing technique was described by Hatch (1982) and make use of dual frequency phase and pseudo-range data.

The main issue encounter in this work was analysing data collected from two different receiver manufacturers. Thought the Septentrio and NovAtel receivers capture GNSS data there are proprietary feature embedded in these receiver that handles the received GNSS signals differently. In this case it was discovered that the NovAtel receiver applied a smoothing time constant to the raw pseudo-range data received, while the Septentrio receiver left the raw data unaltered. This smoothing time constant feature in the NovAtel receiver could be reduced but not switched off. Applying a smoothing time constant is ultimately not bad, as it eliminates the high measurement noise and the greater multipath disturbance of the raw pseudo-range data. However for this work which aims to analyse GNSS signal quality, the preferred data set, would have been to have data that was unsmoothed, so that a standard smoothing time constant could be used to analyse the effect of the signal quality to different time constants. However this issue gave me the ability to compare receiver applied smoothed data vs unsmoothed data as it relates the signal quality.

The Hatch filter was utilised to analyse the relationship between the pseudo-range residuals and SNR with the intended goal of developing a SNR-based weighting scheme that will improve on Elevation based weighting. Figures 1 – 3, above shows this relationship in time series between Pseudo-Range of Residual and SNR of GPS satellite 25-L1, L2 and L5 frequencies. It can be seen that within the first and last 500 seconds for the time series there are large residuals ranging between 0.2-0.3 m in the of the L5 frequency seen in Figure 3. The higher residual values were associated with lower SNR values. As the SNR values increased 45-55 dBHz the pseudo-range values generally reduced. These high residual values maybe related to the ascension of the satellite and multipath.

Using the relationship between RMS of the Pseudo-range Residual and SNR for L1/L2 frequency an exponential curve was fitted to an average of the satellites pseudo-range residuals. This exponential model was used as the SNR weighing scheme and implemented in the position solution algorithm as an alternation solution weighing to Elevation weighting. The results generated were based on analysis of: unsmoothed data, receiver applied smoothed data and logged data with a smoothing filter applied during data processing. From the results it can be seen that there is little improvement in the position solution with regards to smooth or unsmooth data in terms of which weighing scheme was used. However, overall the smoothed data did produce a better result using the SNR weighting generally. The errors derived for the vertical component produced a smaller distribution from the mean for the SNR weighting over the Elevation weighting. Therefore to conclude from this study, the SNR weighing created produced comparably similar results to elevation weighing, however this weighting method has the advantage of allowing the use of observations down to the horizon and also eliminates the need to use an elevation mask.

7 REFERENCES

Hatch , R. (1982). The Synergism of GPS Code and Carrier measurements. Proceedings of the Third International Geodetic Symposium on Satellite Doppler Positioning, 2, pp. 1213-1231. New Mexico.

Hofmann-Wellenhof, B., Lichtenegger, H., & Wasle, E. (2008). GNSS-Global Navigation Satellite System, GPS GLONASS, Galileo and more. New York: Springer Vienna.

Langley , R. B. (1997). GPS receiver system noise. GPS World.

8 ACKNOWLEDGEMENTS

The authors would like to acknowledge the support for this work provided by the University of Nottingham and Veripos.