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Integrity Monitoring of CORS Networks - TrigNet Case Study

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Abstract

This paper examines quality and integrity issues that need to be managed in order to successfully operate a real-time CORS network. Important concepts in quality control such as data availability, latency, multipath, atmospheric effects, and interference are discussed. These quality indicators are examined in the context of their capacity to indicate potential problems that can degrade the quality of real-time network positioning. The issue of intelligent alerting is raised and an alternative strategy, based on the use of relative thresholds, is proposed with the aim of reducing the number of unnecessary alerts provided to operators. South Africa's CORS network TrigNet is used as a case study to test some of these concepts.

1. Introduction

Continuously Operating Reference Station (CORS) networks are being established throughout the world to support Network Real-Time Kinematic (NRTK) positioning services. Africa is no exception to this global trend and several CORS networks have been (or are in the process of being) established (Hedling *et al.*, 2000; Jatau *et al.*, 2010; Al Arabi and Gledan, 2010).

Quality control and integrity monitoring are important aspects of operating a real-time CORS network. Due to the nature of NRTK positioning, the quality of the end user's position is intrinsically linked to the quality of the CORS data. As such CORS operators have a responsibility to ensure that the raw data from their reference stations is of high quality, and can consistently satisfy the requirements of users. Quality breaches need to be detected and dealt with in a timely fashion (including notifying users of the quality breach). In some cases detecting problems is trivial. For example if a CORS is offline due to a receiver hardware or communications malfunction, the operator and users receive immediate feedback and can take appropriate action. However in cases of increased data latency, localised multipath, or irregular ionospheric activity the consequences of the quality breach may not be so obvious. The data will be available but the quality will be degraded, resulting in users experiencing problems in the field. In the worst case scenario, the user's position could be in error whilst the user remains unaware of the problem.

This paper reviews some important concepts in quality control that need to be considered when operating a real-time CORS network. An alternative strategy to quality control using relative quality thresholds is introduced to support the concept of intelligent alerting. A case study is performed using the TrigNet CORS network in South Africa.

2. CORS Data Quality Issues

A CORS network comprises a number of permanent reference stations that collect raw Global Navigation Satellite Systems (GNSS) data on a continuous basis. The data is sent to a control centre where it is collected, analysed, processed, archived, and disseminated to field users in real-time to provide various levels of positioning service – differential GNSS (DGNSS), single-base RTK, or NRTK. The quality of the data received by the control centre needs to be continuously monitored to ensure that the data and information supplied to field users is reliable and fit-for-purpose. Issues that can have a negative effect on data quality include availability, cycle slips, latency, multipath, atmospheric effects and interference. These are examined in detail below.

2.1 Data Availability

The level of data availability at a CORS site provides a basic indication of data quality. Implementation of an indicator is simple, the data is either available or it is not. A single epoch of missing data is not cause for concern, but if several consecutive epochs are missing an alert should be issued. If the problem persists, the station may need to be removed from the network computation process, and the cause of the problem investigated. An alert should be sent to all users advising them that a particular station is offline. Common causes of missing data include receiver malfunction (hardware or antenna related) and problems with communication links. Alternatively, significant data gaps may be an indication of strong radio interference or significant atmospheric activity. Indicators of data availability provide immediate feedback on a critical aspect of a CORS network and the indicators need to be monitored in real-time (to inform users as problems occur) as well as on a daily basis (to detect patterns of behaviour).

2.2 Cycle Slips

Cycle slips are discontinuities in the integer number of carrier phase cycles between the receiver and a satellite. Cycle slips can be caused by physical obstructions to the satellite signal, a low Signal-to-Noise Ratio (SNR), ionospheric scintillation, multipath, radio interference, or a malfunction of the receiver tracking loops (Hofmann-Wellenhof *et al.*, 2008). High precision GNSS positioning requires that the integer number of carrier phase cycles must be known and this implies that cycle slips need to be detected and repaired. Numerous algorithms for the detection and repair of cycle slips have been proposed in literature (Blewitt, 1990; Kim and Langley, 2001; de Jong, 1998). The algorithm proposed by Blewitt (1990) uses the P code pseudoranges to automatically detect and correct for cycle slips in the wide-lane phase combination. Wide-lane combinations for carrier phase and pseudorange data are shown in equations [1] and [2]:

$$L_\delta = \rho + I\, f_1 f_2/(f_1^2 - f_2^2) + \lambda_\delta b_\delta \quad , \quad \lambda_\delta = c/(f_1 - f_2) \qquad [1]$$

$$P_\delta = \rho + I\, f_1 f_2/(f_1^2 - f_2^2) \qquad [2]$$

where L_δ is the wide-lane carrier phase expressed in metres $L_\delta = (L_1 - L_2)$; ρ is the geometric delay which includes the effects of the clocks, troposphere, and any other biases that affect all data types in the same way; I is the ionospheric delay; f_1 and f_2 are the carrier frequencies; c is the speed of light; λ_δ is the wide-lane wavelength; and b_δ is the wide-lane bias which includes the cycle slips. The bias is isolated by subtracting [2] from [1]:

$$b_\delta = \frac{1}{\lambda_\delta}(L_\delta - P_\delta) \qquad [3]$$

The value of b_δ is computed independently every epoch. In post-processed analysis the current value is compared to the data both sides of the epoch to detect differences. In real-time analysis only past data can be used. Cycle slips at CORS sites need to be monitored as they are an early and robust indicator of data quality issues such as multipath, interference, or abnormal ionospheric conditions.

2.3 Multipath

Multipath occurs when GNSS signals arrive at an antenna via an indirect path as a result of reflection from a nearby surface (Hofmann-Wellenhof *et al.*, 2008). Multipath is an important quality issue for CORS sites. Multipath mitigation is normally done through careful site selection. Ideally CORS sites should be located in a “clean” environment with clear sky view and away from obstructions. While this is generally achievable, occasionally restrictions limit site selection, for example due to the need to have access to power and communications. In many cases, CORS antennas are placed on or near the roof of a building where the roof itself can be a significant source of multipath. To mitigate multipath from the antenna installation, the antenna needs to be elevated above the roof as much as possible, and receiver with multipath mitigation technology coupled with a choke ring antenna should also be used. In any case, it is important to monitor the multipath levels at the CORS sites. The most common multipath indicators are the *mp1* and *mp2* linear combinations that define the pseudorange multipath on the L1 and L2 frequency (Estey and Meertens, 1999). These are defined by equations [4] and [5]:

$$mp1 = P_1 - \left(1 + \frac{2}{\alpha - 1}\right)L_1 + \left(\frac{2}{\alpha - 1}\right)L_2 \quad , \quad \alpha = \frac{f_1^2}{f_2^2} \qquad [4]$$

$$mp2 = P_2 - \left(\frac{2\alpha}{\alpha - 1}\right)L_1 + \left(\frac{2\alpha}{\alpha - 1} - 1\right)L_2 \qquad [5]$$

where P_i and L_i are pseudorange and carrier-phase observations on the f_i frequency, for i = 1, 2. These indicators are measured in metres and have a standard threshold of 0.5m. Values higher than 0.5m observed for high elevation satellites can have a negative impact on data quality.

2.4 Data Latency

Latency is a measure of data transmission time. Data is transmitted from CORS sites to the control centre and consequently disseminated to users. Data transmission from CORS sites to the control centre is usually achieved via dedicated connections that ensure high speed data transfer. CORS sites need to have a robust internet connection and enough bandwidth to handle data transfer during periods of peak load. In an NRTK solution normally 3-6 reference stations are used to compute the correction for the rover. If just one of the stations is experiencing unacceptable levels of latency it will have a negative effect on the whole NRTK computation. Ideally data latency needs to be under 1 second with a maximum of 2 seconds. Yan *et al*. (2009) showed that if the latency exceeds 2 seconds, it begins to have a detrimental effect on the quality of the positioning solution.

2.5 Atmospheric Biases

Atmospheric biases affecting GNSS signal propagation include the ionosphere and the troposphere. The troposphere is a non-dispersive medium at radio frequencies and as such affects all GNSS signals equally. In NRTK positioning algorithms, tropospheric biases are often lumped together with residual orbit biases to form a *geometric* bias term (Seeber, 2003). On the other hand, the ionosphere is a dispersive medium and as such its influence depends on the frequency of the signal. The number of free electrons directly impacts on how much the signals are affected. The electron density in the ionosphere is measured by the Total Electron Content (TEC), which is the number of electrons per square metre measured either vertically (VTEC) or along the signal path. Total Electron Content is measured in TEC Units (TECU) with 1 TECU being equal to 10^{16} electrons per m^2 (Hofmann-Wellenhof *et al.*, 2008). The TEC is a direct function of the Sun's solar radiation and as such has diurnal, seasonal, and solar cycle variations. During periods of high solar activity, there is an increased level of TEC variability which can disturb the GNSS signals causing ionospheric scintillation. Figure 1 depicts the global VTEC map centred on Africa taken on 11th April 2001 (solar maximum), and the same date in 2009 (solar minimum).

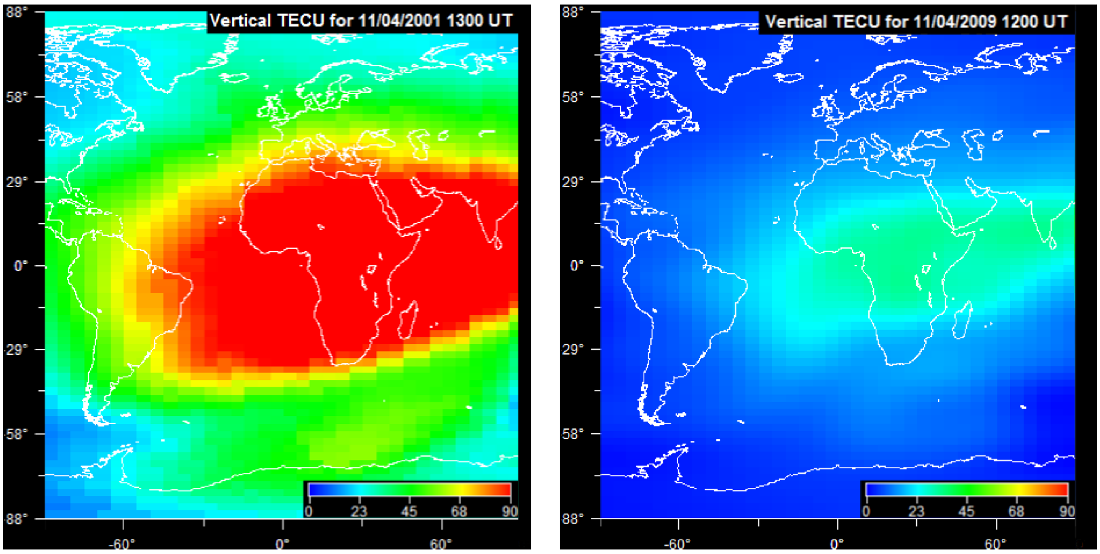

Figure 1. Global VTEC map during solar maximum (left) and solar minimum (right).

It can be seen that around midday during the solar maximum the TEC is at extreme levels. Whilst high level of TEC does not automatically warrant ionospheric scintillation, precise positioning would most likely be adversely affected at that time. Significant ionospheric events such as geo-magnetic storms can be predicted at least 24 hours in advance (SWPC, 2011), and for CORS operators it is important to be aware of these events. In South Africa the agency in charge of space weather alerting is the South African National Space Agency (SANSA, 2011).

It must be noted that NRTK has been in wide commercial use for only the last five years, which was a period of solar minimum. During that time ionospheric activity has been low, resulting in minimal ionospheric impact and reliable positioning performance. However, the next solar maximum (Solar Cycle 24) is underway and is expected to peak around May 2013 (SWPC, 2011). Hence it is critical to monitor NRTK performance over the next 2-3 years leading up to and during the period of expected high ionospheric activity.

One measure of ionospheric activity is the I_{95} index developed by Wanninger (1999). The I_{95} index is a statistical figure describing the amount of differential ionospheric biases as experienced by GNSS users. Wanninger (2004) extended this indicator (I_{95L}) for use with network RTK. Positioning algorithms applied to NRTK use sophisticated ionospheric models to account for the linear component of the ionosphere, however non-linear biases still remain. The I_{95L} index attempts to describe the non-linear biases that remain between the network reference stations.

2.6 Interference

Interference can either be intentional or unintentional. Unintentional interference comes from radio signals transmitted at frequencies within or near the GNSS signal spectrum and can come from any radio frequency (RF) transmitter. Unintentional interference, much like multipath, can usually be avoided through careful site selection. Intentional interference (or jamming) is a deliberate act of transmitting in the GNSS band. Jamming poses a serious threat to any GNSS receiver. Commercial jammers, although illegal in many countries, can be purchased cheaply over the internet. The problem with interference is that it is hard to detect. If the source of the interference is strong enough, it can overpower the GNSS signals completely. One interference detection method was proposed by Weston *et al*. (2010). The procedure involves processing hourly RINEX files from the CORS sites and comparing the results against the published coordinates to see whether a significant change in position is observed. Whilst effective, the method does not take into account that there are other factors that can influence the coordinates.

2.7 Antenna Stability

Daily coordinate solutions of all the reference stations should be processed and analysed for excessive movement. The preferred method is an automated process using specialist geodetic software such as BERNESE (Dach *et al.*, 2007), GAMIT (Herring *et al.*, 2006) or GIPSY (Lichten *et al.*, 1995). One example of CORS network coordinate analysis is presented in Haasdyk *et al.* (2010). This type of analysis is important as it can reveal the stability of the network, station velocities due to tectonic movement, and any datum inconsistencies due to local distortions.

3. Intelligent Alerting Strategy – Relative Thresholds

The quality indicators described thus far need to be monitored in order to detect potential problems at the CORS sites. All of these indicators can be tested against absolute thresholds (*e.g. mp1* value of 0.5m, data availability of 99%, latency of 2 seconds etc.) that if breached will generate an alert to the network operator. However not all quality breaches are equally critical, and if every breach is reported it can result in over-alerting (a problem that is compounded as the network grows). This could lead to operator complacency and reduced attention to warnings. At the same time genuine quality breaches can go unnoticed. Both of these outcomes are undesirable. It follows that an effective quality control system needs to be able to detect all the quality breaches in a timely manner, but at the same time it needs to be flexible enough to report only genuine problems.

Fuller *et al*. (2008) proposed an alternative strategy to CORS quality control which involves the use of relative, rather than absolute, thresholds. This approach is based on the concept of examining quality indicators for individual satellites at the current epoch relative to the historical quality indicators at the "same epoch" on previous days. In this context the "same epoch" means the recurrence of matching satellite geometry. This approach is implemented in the Real-Time Quality Control (RTQC) software (Fuller *et al*., 2007), which keeps a 7-day archive of historical data for each satellite at each site, and compares quality indicators at the current epoch against historical performance. This method can help identify patterns in satellite behaviour. For example, at a particular CORS site, one satellite might experience an increased level of multipath at the "same epoch" each day, causing the absolute threshold to be breached and an alert to be issued each time. In the case of relative thresholds, because the breach is repeated on a daily basis, no alerts would be issued unless an increased level of multipath was detected. Fuller *et al.* (2008) showed that by using relative thresholds the number of unnecessary alerts can be reduced by 30-60%.

4. TrigNet Network and Services

TrigNet is a network of continuously operating GNSS base stations covering South Africa at an inter-station spacing of between 40km and 300km. The first four stations were installed in 1999 with assistance from the Swede Survey and with the guidance of the National Land Survey of Sweden. In the early stages of development, only post-processing products were available to users. Since 1999 the network has expanded, and at present (September 2011) consists of 58 stations providing a range of real-time and post-processing services (Figure 2). Stations have been selected so as to maximise satellite availability and minimise multipath. To further reduce multipath, 48 of the 58 stations are equipped with choke ring antennas. Stations are built on bedrock or on buildings giving high levels of security for the safety of the equipment, easy access to a stable power supply and dedicated telephone line connections.

TrigNet provides a range of real-time and post-processing services such as an RTK solution from each base station, a country-wide Virtual Reference Station (VRS) DGPS solution, and VRS NRTK in the three areas circled in Figure 2. The use of TrigNet data is not confined to positioning. Other applications include weather forecasting, climate monitoring, ionosphere mapping, and geophysical research. Recent research on the stability of the South African portion of the Nubian plate using 42

TrigNet stations showed that the plate is tectonically stable, with residual motion of less than 0.5mm/year (Malservisi *et al*., 2011).

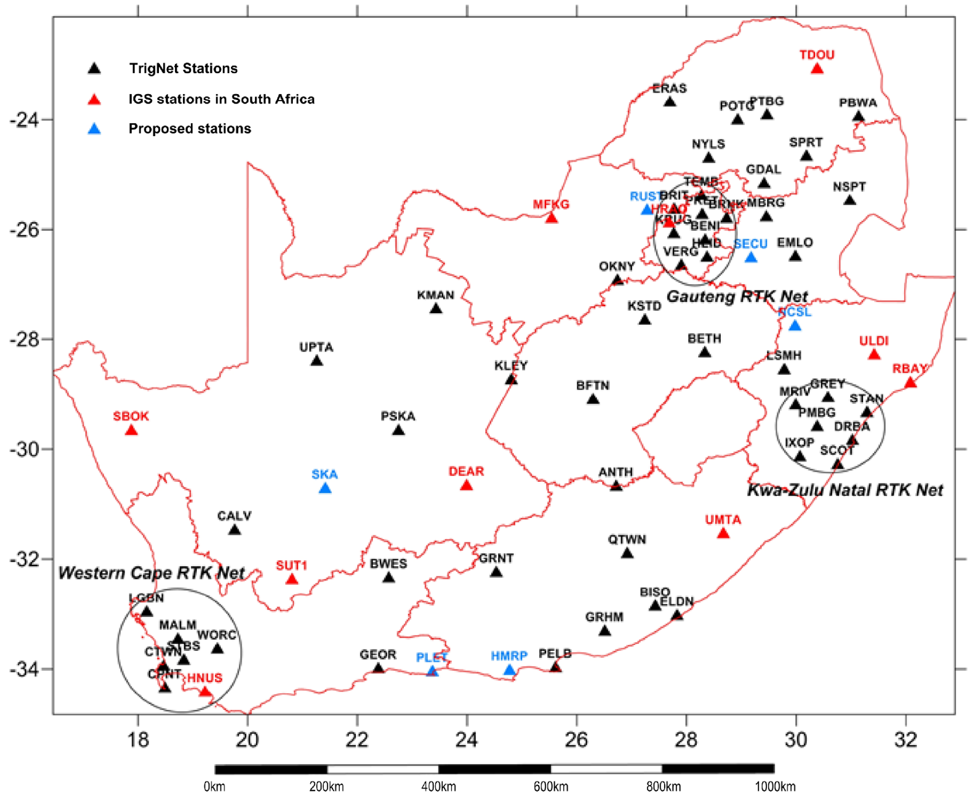

Figure 2. Status of TrigNet with NRTK clusters (September 2011).

5. TrigNet Case Study

Quality analysis was performed on a subset of CORS sites from the TrigNet network using the RTQC software. Normally quality control is performed in near real-time (hourly analysis) or in a post-processed mode (daily analysis) using absolute thresholds. A different approach is used by RTQC whereby all quality control computations are performed in real-time using relative thresholds described in Section 3. This means that some quality algorithms need to be modified for real-time use. One such example is the cycle slip detection algorithm developed by Blewitt (1990). The advantage of real-time analysis is that alerting is also possible in real-time which is more beneficial for real-time users. In the analysis presented below it will be shown that the RTQC approach has significant advantages when compared to the more conventional approach. In this case study, six TrigNet stations were monitored for a period of one week during 10-16 September 2011. Two stations were chosen from each of the three NRTK clusters (CTWN and MALM from the Western Cape cluster, PRET and VERG from the Gauteng cluster, DRBA and SCOT from the Kwa-Zulu Natal cluster).

5.1 TrigNet Availability

The availability statistics for the six stations are shown in Figure 3. It can be seen that all the sites had a near perfect availability throughout the testing period with average numbers of 99.9%.

This shows that the TrigNet sites are of high quality and do not suffer problems from receiver hardware, communication links or interference problems.

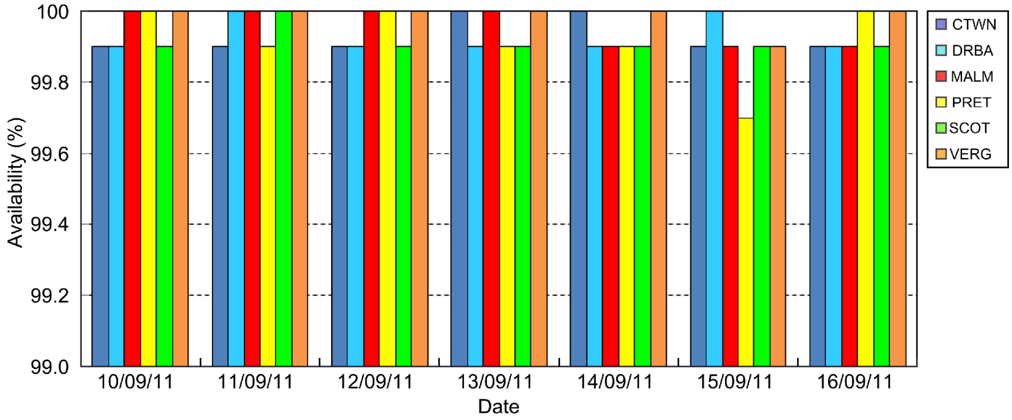

Figure 3. TrigNet availability results.

5.2 TrigNet Cycle Slip Analysis

Cycle slip analysis was performed on the six stations throughout the testing period and is shown in Figure 4. It can be seen that SCOT has a considerably higher number of cycle slips compared to the rest of the sites. Further analysis revealed that (apart from several exceptions) all of the cycle slips occurred on three satellites only (SV2, SV12, SV20) at elevations of 15-20° and azimuths of 250-280°, which clearly indicates a local obstruction. If absolute thresholds are used, each of the three satellites will generate an alert every day at around the same time at SCOT site due to the increased number of cycle slips. With relative thresholds, because the same pattern is repeated every day, this behaviour is considered normal for these three satellites and as a result no alerts would be issued.

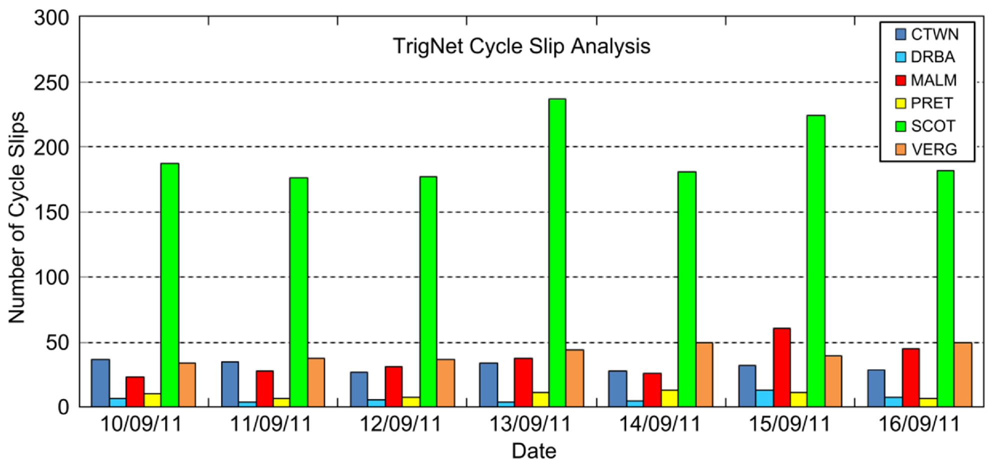

Figure 4. TrigNet cycle slip analysis.

5.3 TrigNet Latency Analysis

Latency for the six stations was recorded at the RTQC server in Melbourne, Australia. The results for one day (12 September 2011) are shown, as the results were similar for the other days. Latency was recorded every epoch and the average hourly latency is shown in Figure 5. Average latency figures are under 1 second for most of the day, an excellent result considering the additional latency introduced by the server location (Australia). It can be seen that the latency varies throughout the day as a result of changing internet traffic and the amount of bandwidth available. CTWN CORS (located in Cape Town) is co-located with the network processing centre, and feeds directly into the control system, which explains lower latency values for this site. As mentioned, the latency was recorded in Australia, so for users in South Africa these figures would be expected to be even less as the data will have less distance to travel.

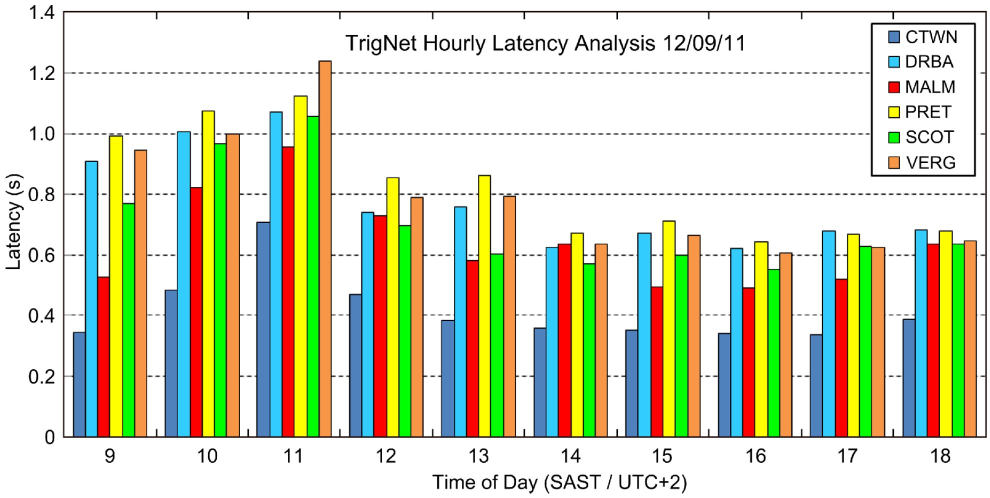

Figure 5. TrigNet hourly latency analysis.

Hourly latency analysis is adequate to distinguish latency variations throughout the day, but it fails to isolate short-term latency variations that are absorbed by the averaging process. Figure 6 shows the real-time, epoch-by-epoch, latency for the SCOT site during the same time period as used in the hourly analysis. The red dashed line indicates the two second absolute latency threshold.

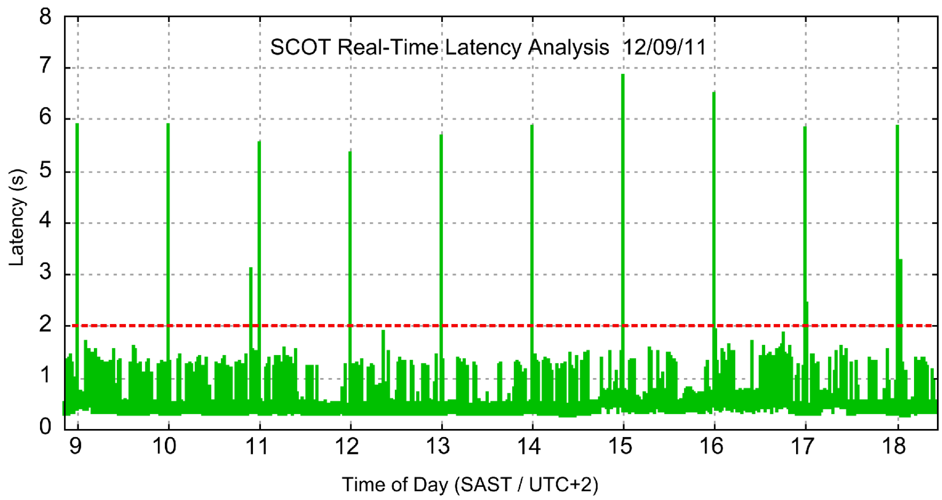

Figure 6. TrigNet real-time latency analysis (SCOT site).

It can be seen that exactly on the hour, the latency spikes briefly for a period of 5-10 seconds. This behaviour was observed at other sites in the case study and across different days. This interesting pattern can potentially be explained by the fact that an automated process (or several processes) takes place at the control centre every hour (*e.g.* creating an hourly RINEX file and pushing it onto the FTP server). This process would absorb bandwidth for a short time, resulting in slower communications. Due to the fact that the time for which latency is degraded is brief (5-10 seconds), it is doubtful that it will affect the users in the field, however for the operator it is important to be aware of such events, which are hidden by the averaging process in the hourly analysis. If absolute thresholds are used to monitor the latency, each site in the testing (potentially each site in the network) would issue 24 alerts every day which would result in hundreds of unnecessary alerts. With relative thresholds, because this behaviour is repeatable from day to day, no alerts would be issued.

5.4 TrigNet Multipath Analysis

Multipath analysis was performed on the same subnet of CORS sites throughout the testing period. Figure 7 shows average daily *mp1* and *mp2* values for all the sites. It can be seen that all the sites are performing well under the accepted 0.5m absolute threshold. Stations MALM and VERG have slightly higher multipath than the other sites and are the only sites in the testing that do not have choke ring antennas, which could explain higher multipath values. However whilst the results from Figure 7 imply low multipath results overall, they do not provide a detailed multipath assessment on how well each satellite performs at each site. The *mp1* and *mp2* values for individual satellites are aggregated to derive a single figure for each of the sites. This value is then averaged further on an hourly or daily basis.

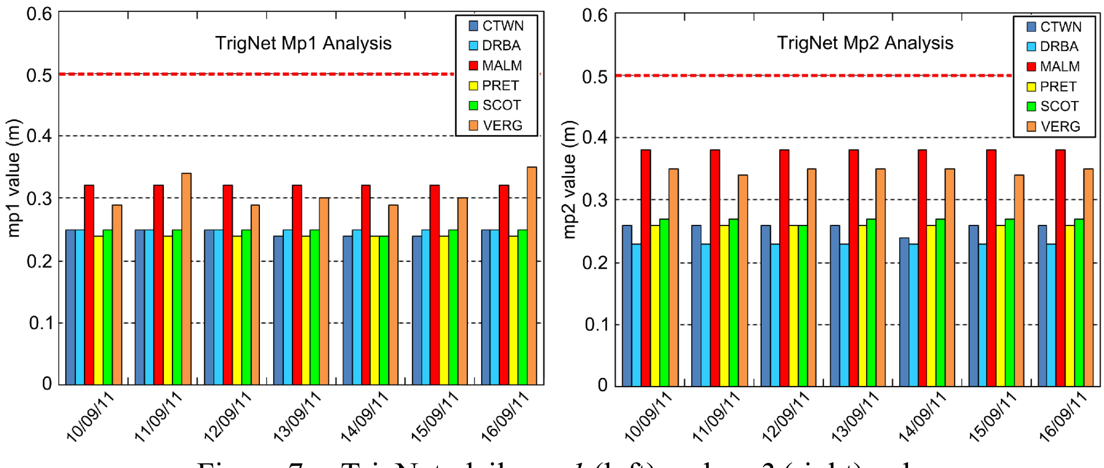

Figure 7. TrigNet daily *mp1* (left) and *mp2* (right) values.

RTQC software monitors individual multipath indicators for each satellite at every epoch. Figure 8 displays skyplots of *mp1* and *mp2* values at the MALM site for a period of four hours on the 10th September 2011. This real-time analysis allows the detection of trends in satellite behaviour at each of the sites. If any satellite exceeds the threshold (dashed box in Figure 8) the operator can be alerted in real-time. The real-time analysis of individual satellites will inevitably result in additional quality breaches as no averaging is performed (either between satellites or between epochs). For example on 10th September 2011 MALM recorded 67 *mp1* and 51 *mp2* individual satellite breaches. If each of those was reported, 118 multipath alerts would have been issued on that day.

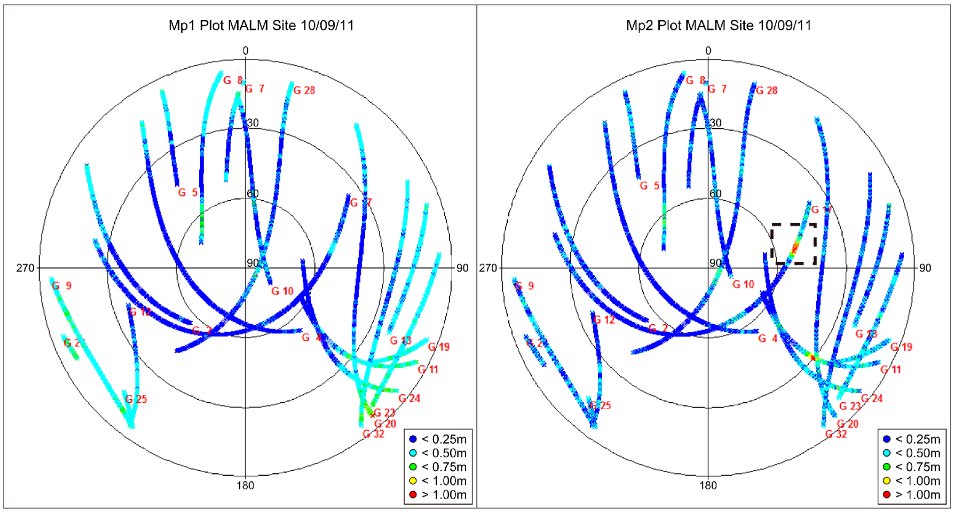

Figure 8. Real-time *mp1* (left) and *mp2* (right) plots at MALM site.

To avoid this RTQC uses the relative thresholds strategy described in Section 3. The application of relative thresholds is illustrated in Figure 9, where two instances of the *mp2* indicator for SV10 at the MALM site are displayed. The current *mp2* value (red line) is shown along with the values for the previous four days. The average (yellow line) and 3-sigma (blue line) threshold computed from the historic data are also shown. In the first instance the *mp2* value at the current epoch (dashed box) is 1.65m which exceeds the absolute threshold of 0.5m by a factor of 3, however it can be seen that during the past four days the satellite behaved at similar levels at this time. Thus the behaviour is considered normal and no alert is generated. In the second instance the *mp2* value is 0.37m, which is below the 0.5m threshold, but the current behaviour (dashed box) is significantly different from the past four days, so in this case the value is considered an outlier and will generate an alert.

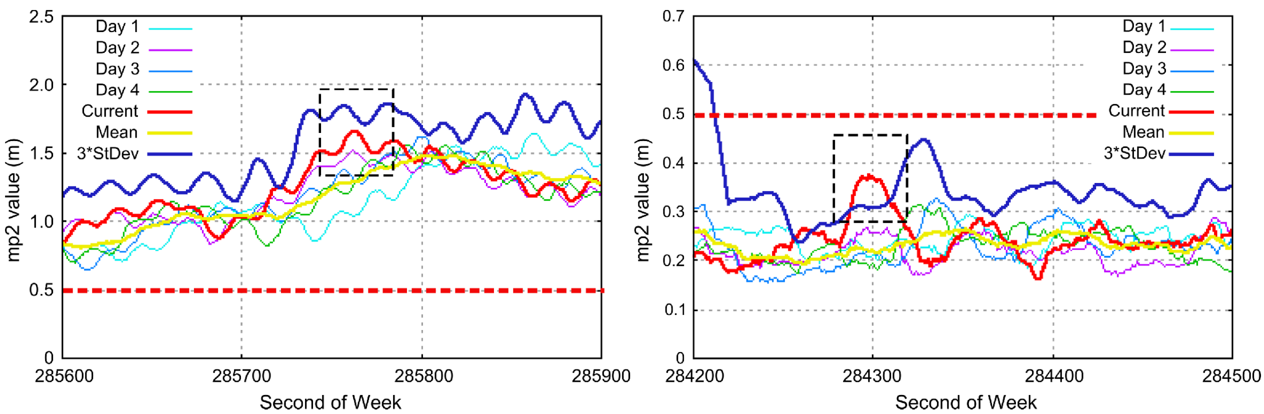

Figure 9. Relative thresholds applied to the *mp2* indicator.

6. Conclusion

This paper presented important aspects of quality control and integrity monitoring of CORS networks. Two factors were highlighted – detecting the problems in real-time and intelligent alerting. An alternative alerting strategy based on relative thresholds was presented which is aimed at reducing the number of unnecessary alerts and only reporting on genuine quality breaches. A case study of some of the concepts described in the paper has been carried out on the TrigNet network in South Africa. The analysis showed that TrigNet sites (based on the six stations analysed) are of high quality and perform well above the standard quality thresholds. It was also shown that the use of intelligent alerting can detect patterns in satellite behaviour and improve the reliability and integrity of alerting procedures.

7. Acknowledgements

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