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Real-Time Quality Control for CORS Networks and Mobile Users

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ABSTRACT

As real-time GNSS positioning becomes more affordable, accessible and reliable, the market for such services continues to grow as do the number and size of the CORS networks that underpin such positioning. This broadening of the GNSS user base that has occurred as a result of this expansion brings with it some interesting challenges for equipment manufacturers, software developers and the providers of CORS-based positioning services. In particular added responsibility - and in some cases legal liability - is being placed on CORS network operators to ensure that their positioning services consistently satisfy the requirements of users.

It is in light of this growing trend toward real-time positioning applied to an increasingly diverse range of non-traditional applications, that the need to supply users with dependable quality indicators has been identified. As a consequence, the CRC-SI is facilitating a project to develop a robust, independent real-time system that will inform users of the quality, dependability and fitness-for-purpose of their positioning results. This paper will describe the current state of development of this system, dealing with the design philosophy, system architecture and the fundamental principles being applied to assess and report on the quality of real-time GNNS data received simultaneously from a CORS network and a mobile user.

KEYWORDS: Real-Time, Quality Control, CORS networks, Network RTK.

1. INTRODUCTION

More and more users of GNSS-based positioning systems are demanding their results in real-time. This increasing requirement for instantaneous positioning is being made possible by the rapid growth of Continuously Operating Reference Station (CORS) networks around the world and the accompanying proliferation of commercial Network Real-Time Kinematic (NRTK) positioning services. As real-time GNSS positioning becomes more affordable, accessible and reliable, the market for such services continues to grow. Today, CORS-based GNSS positioning is being employed in a diverse range of applications, well beyond the traditional domain of the surveying and engineering disciplines.

This broadening of the GNSS user base brings with it some interesting challenges for equipment manufacturers, software developers and the providers of CORS-based positioning services. First, many of the new users are spatially illiterate – they do not have the technical background and knowledge to allow them to critically assess the quality or fitness-for-purpose of the positioning information they are receiving and depending on. A second, and somewhat related issue, is that the suppliers of NRTK positioning services are facing higher user expectations as critical operations become dependent on the provision of dependable and robust real-time positions. These challenges combine to place added responsibility – and in some cases legal liability – on the service provider to ultimately ensure that the NRTK service will consistently satisfy the requirements of the user.

It is in light of this growing trend toward real-time positioning applied to an increasingly diverse range of non-traditional applications, that the need to supply users with dependable quality indicators has been identified. As a consequence, the Cooperative Research Centre for Spatial Information (CRC-SI) is facilitating a project called Quality Control Issues for Real-Time Positioning. The fundamental objective of the project is to develop a robust, independent real-time system that will inform users of the quality, dependability and fitness-for-purpose of NRTK positioning results. The so called RT-QC quality system will be supplied as a valued added service to users to inform decision making, particularly in cases where such decisions are position-critical.

It is important to note that the essence of the RT-QC project is the assessment and reporting of quality information to users in real-time. While options exist for post-processing GNSS data to assess quality, presently no such option exists in the real-time domain. Furthermore, the software packages that allow quality assessment of GNSS data in a post processing mode, such as TEQC (Estey and Meertens, 1999) and Leica GNSS QC (Leica Geosystems, 2007), perform their analyses on individual data sets, they do not provide the capacity to look at the combined effect when multiple data sets are integrated to obtain a network solution for a user receiver. The RT-QC system addresses both of these shortcomings.

This paper will describe the current state of development of the RT-QC software, dealing with the design philosophy, system architecture and the fundamental principles being applied to assess and report on the quality of real-time GNNS data received simultaneously from a CORS network and a mobile user. The paper will conclude with some details on how this information is being delivered to users in real-time and some ideas for the future enhancement of the RT-QC system.

2. DEVELOPMENT DRIVERS

As described above, there is an increasing reliance on the part of GNSS users for access to real-time positioning services. The most convenient and cost effective way to provide such a service is through a CORS network. Today, there are literally hundreds of such networks around the world (BKG, 2007; Trimble, 2007). Australia is no exception to this trend, with at least six separate networks in various parts of the country offering some form of real-time positioning service. Increasingly, CORS network operators are offering a network solution to their users, whereby data from multiple CORS sites is combined to give an optimum solution for the user's position rather than relying solely on data from the nearest reference station. This network approach offers a measure of robustness and rigour that is lacking from a single reference station solution. When a network solution is required in real-time (i.e. NRTK positioning) there is a requirement on the part of the service provider to stream data from multiple CORS sites to a single processing hub, to carry out some data processing and then to provide that information in an appropriate form to the mobile user in a sufficiently short space of time (typically a few milliseconds) to qualify as a real-time positioning service. The volumes of data required to provide such a service are not trivial and the communications link and computing infrastructure must be robust and of high capacity.

In a sense, the growth of CORS networks and the provision of real-time network-based positioning services is at a relatively early stage of development. On-going improvements continue to be made to the associated hardware and software. One widely recognised shortcoming of the current commercially available systems is that they do not provide comprehensive and dependable quality indicators to the CORS network operator or to users of the NRTK service. It is this fundamental limitation that has given rise to the current RT-QC project with the CRC-SI.

Current approaches to GNSS quality control are not implemented in real-time. Typically, packages such as TEQC and Leica GNSS QC import previously collected data and assess and report on the quality of that data on a station-by-station basis. While some informative and helpful quality indicators can be provided using such a post-processing strategy, this approach offers no assistance to the real-time user and is of limited value to the CORS network operator in terms of detecting real-time failures of the positioning service. What is needed in a real-time environment is the capacity to quality check all real-time data streams (CORS network and mobile user) and to provide a full quality assessment of that data to the network operator and the mobile user. The RT-QC system to be described below aims to achieve this objective. Furthermore, as a result of the quality control calculations to be carried out, the RT-QC software will derive a stochastic model for the collected data that can be subsequently incorporated into the positioning solution, thereby providing a more realistic indication of the precision of user's position.

Figure 1 illustrates the fundamental design of the RT-QC system. The RT-QC Hub forms the heart of the system and is the point where all calculations are carried out. Typically, though not necessarily, the RT-QC Hub would be physically co-located with the CORS network processing centre. As can be seen from the figure, data is streamed from the CORS network stations and from the mobile user to the RT-QC Hub. Data streaming utilises the internet as the communications channel and is facilitated by the Radio Technical Commission on Maritime Services (RTCM) Version 3.x data format and the Network Transport of RTCM via Internet Protocol (NTRIP). Upon arriving at the RT-QC Hub the quality of the raw carrier phase data is assessed using two software modules known as RT-QC (CORS) and RT-QC (mobile) respectively. A distinction is made when assessing the quality of the CORS and mobile user's data on the basis that the CORS stations are stationary and significant volumes of historical data will exist to aid in the quality assessment process. The same will not generally be true of the mobile user, making the quality assessment process different and somewhat more demanding. The actual strategies used for the quality control process will be described in more detail later in the paper. One outcome of the RT-QC (CORS) and the RT-QC (mobile) computations will be refined stochastic models to be passed to the algorithm used for computing the final coordinates of the mobile receiver. A second output will be real-time quality information for the CORS network operator. The third output will be input data for the RT-QC (premium) module that will compute integrated quality indicators based on all data used for determining the user positions. It is this information that is ultimately provided back to the mobile user in the form of real-time quality control indicators.

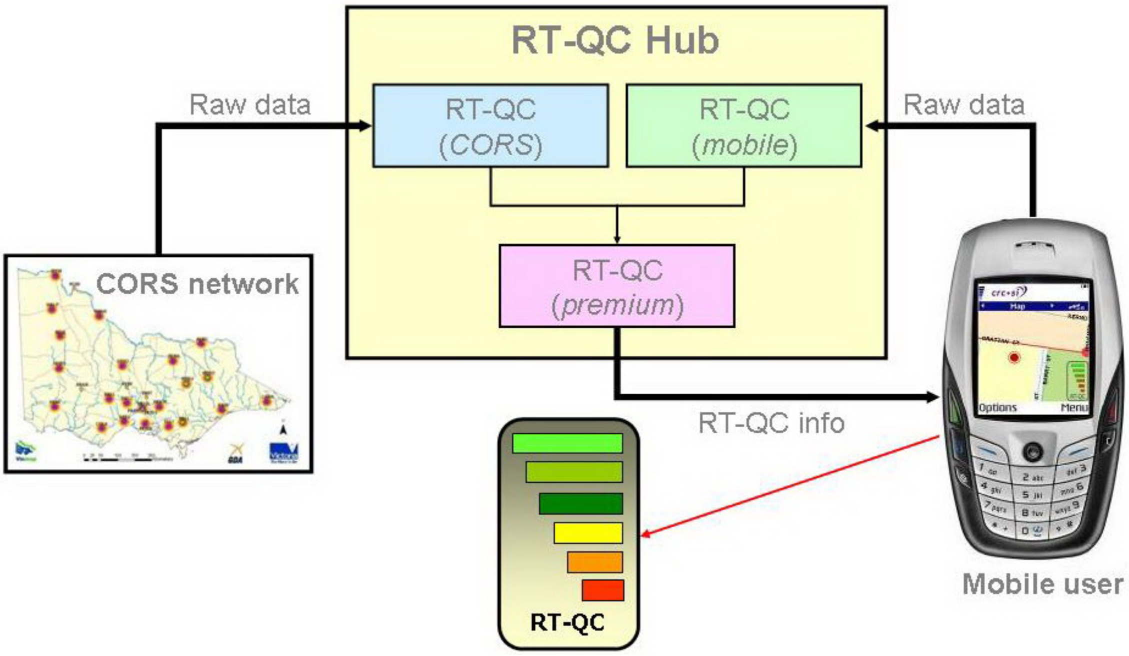

Figure 1. Design layout for the RT-QC system

3. DESIGN PHILOSOPHY

The design and development of the RT-QC software has been influenced by a number of key ideas relating to the assessment of GNSS data for quality purposes and the provision of quality information to system operators and users. Foremost has been the desire to deal with raw observation data, rather than products derived from positioning algorithms. This is closely linked to the idea of processing real time data streams autonomously – without the need for data from multiple receivers or satellites. Thirdly, a single quality indicator should be developed to replace the variety of quality indicators currently available. Finally, a more intelligent and adaptive alerting mechanism was required to streamline the barrage of existing quality warnings that are currently delivered to system operators.

3.1 Raw Observation Data

It was decided early in the development process that the RT-QC software should process raw observations (phase and code) wherever possible and make assessments of quality based on the observations, rather than on the derived products such as positions, variance/covariance matrices, residuals, tropospheric or ionospheric estimates and so forth. The reasoning behind this decision lies in the basic structure of positioning algorithms, where the calculation of position (and other products) from GNSS observations is almost entirely dependent upon the use of some form of "best-fit" algorithm. These algorithms, typically based on least squares estimation techniques, seek to produce an optimal solution for a set of defined parameters by minimising the size of the estimation error (residuals). The general flow of these algorithms is shown in Figure 2.

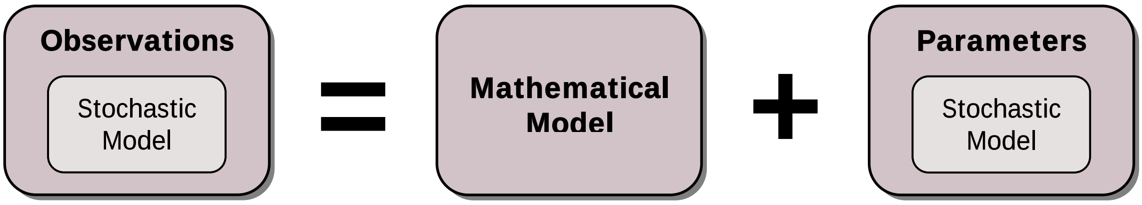

Figure 2. General structure of positioning algorithms

Depending on the user's application the number, type, and nature of the parameters required will change, as will the mathematical model used to derive them. Furthermore, it is often the case that the mathematical model used to determine the same set of parameters (e.g. position) may vary from manufacturer to manufacturer or software package to software package and the intricacies of the model are most likely a closely guarded secret.

However, the one constant in all applications and algorithms is the observations themselves. Irrespective of the desired parameters or mathematical model all algorithms rely on the same set of phase and code observations. Thus in determining how the RT-QC software would assess quality it was decided that the analysis of raw observation data (phase and code) would be the most flexible and powerful solution. Analysing raw observations before processing removes the need to understand how each individual algorithm works, thereby allowing the RT-QC software to provide quality information to all algorithms in an independent fashion.

3.2 Autonomy

The analysis of raw observations, rather than products derived from positioning algorithms (outlined in the previous section) allows a data stream to be analysed for quality without reference to observations collected by other receivers. Thus it is possible to avoid the analysis of single or double difference quantities between receivers and/or satellites. These quantities, whilst useful in certain algorithms, are abstracted from the raw observations and lack a strong physical correlation with the original data, which makes it difficult to extract information on the performance of an individual receiver or satellite.

However, observation differencing offers significant benefits when assessing the quality of raw observations and its use cannot be totally disregarded. The general approach adopted within the RT-QC software therefore is to limit the use of differencing to individual receiver/satellite combinations. Limiting the use of differencing in this way maintains a strong physical link between the original observations and the differenced quantities, thereby enabling simpler interpretation for quality purposes. Furthermore, quality control can be carried out at the most basic level, observations to a specific satellite from a particular receiver.

3.3 Single Quality Indicator

During the initial design stages of the RT-QC software it quickly became apparent that there are a range of indicators used to assess the quality of GNSS observations and derived products. In the case of derived products (e.g. positions) there is a different quality indicator for each algorithm in use. To a lesser extent this also applies to post-processing methods, which utilise quality indicators that are somewhat standardised. However, there are a plethora of indicators available and it is a question of where to look for the pertinent information.

Thus a key driver behind the RT-QC software has been an attempt to develop a quality indicator to replace or encompass the range of indicators currently available. The indicator would be derived from raw observation data and be capable of autonomous operation, for the reasons outlined in the previous sections. Furthermore, it should be possible to derive stochastic information from the indicator in order to enhance the performance of positioning algorithms, rather than to simply inform them of potentially troublesome data.

3.4 Intelligent Alerting

At present, system operators are alerted (via email or SMS) of potential quality issues when a set of quality thresholds are breached. However, there are a range of indicators that can be monitored and the thresholds are often arbitrarily set, are constant for each receiver, and are rarely updated. This often results in “over-alerting” of system operators and as a result this approach is not conducive to alerting mobile users.

Given the large number of observations analysed and the plethora of quality indicators available it was determined that a more sophisticated alerting system should be incorporated into the RT-QC software. The approach adopted was to archive observation and quality information over a period of time and to compare (in real time) the current quality information to historical information. This would enable a satellite observed at a particular receiver to be assessed for quality based upon its recent performance (is it better or worse than yesterday, two days ago, a week ago) rather than against a set of arbitrary thresholds. Figure 3 demonstrates this principle for the RT-QC indicator developed by Project 1.2, historical data (for 5 days, each day offset by 0.03m) is shown in red, with the “current” epoch shown in green. In this way quality alerting is tailored for each individual satellite at each individual receiver, providing a more adaptive and intelligent set of quality thresholds that evolve over time. This approach is only applicable to CORS network sites (as they are permanently installed) and different techniques are required for the mobile user’s data, and as such there are two different modules, RT-QC (CORS) and RT-QC (mobile), in the software to handle these different scenarios.

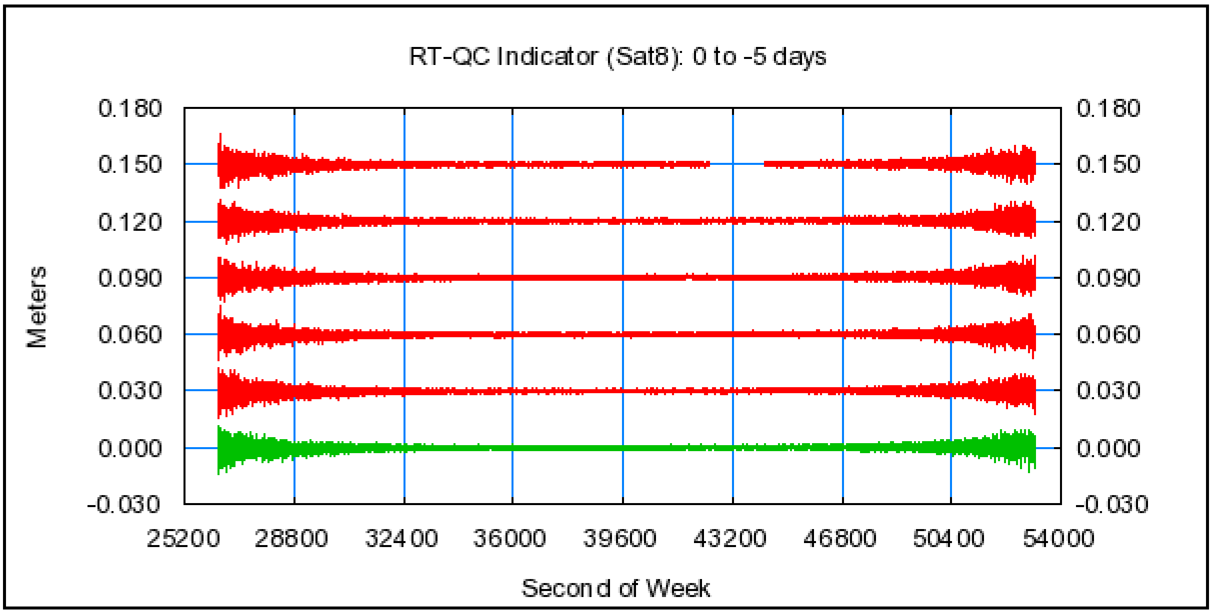

Figure 3. Quality indicator performance over time

4. SOFTWARE ARCHITECTURE

The RT-QC software architecture has been designed to allow the maximum flexibility with respect to the data streams monitored, the quality algorithms utilised, and the quality reporting and alerting provided. As such the software architecture can be broadly divided into the three main components shown in Figure 4 and described below.

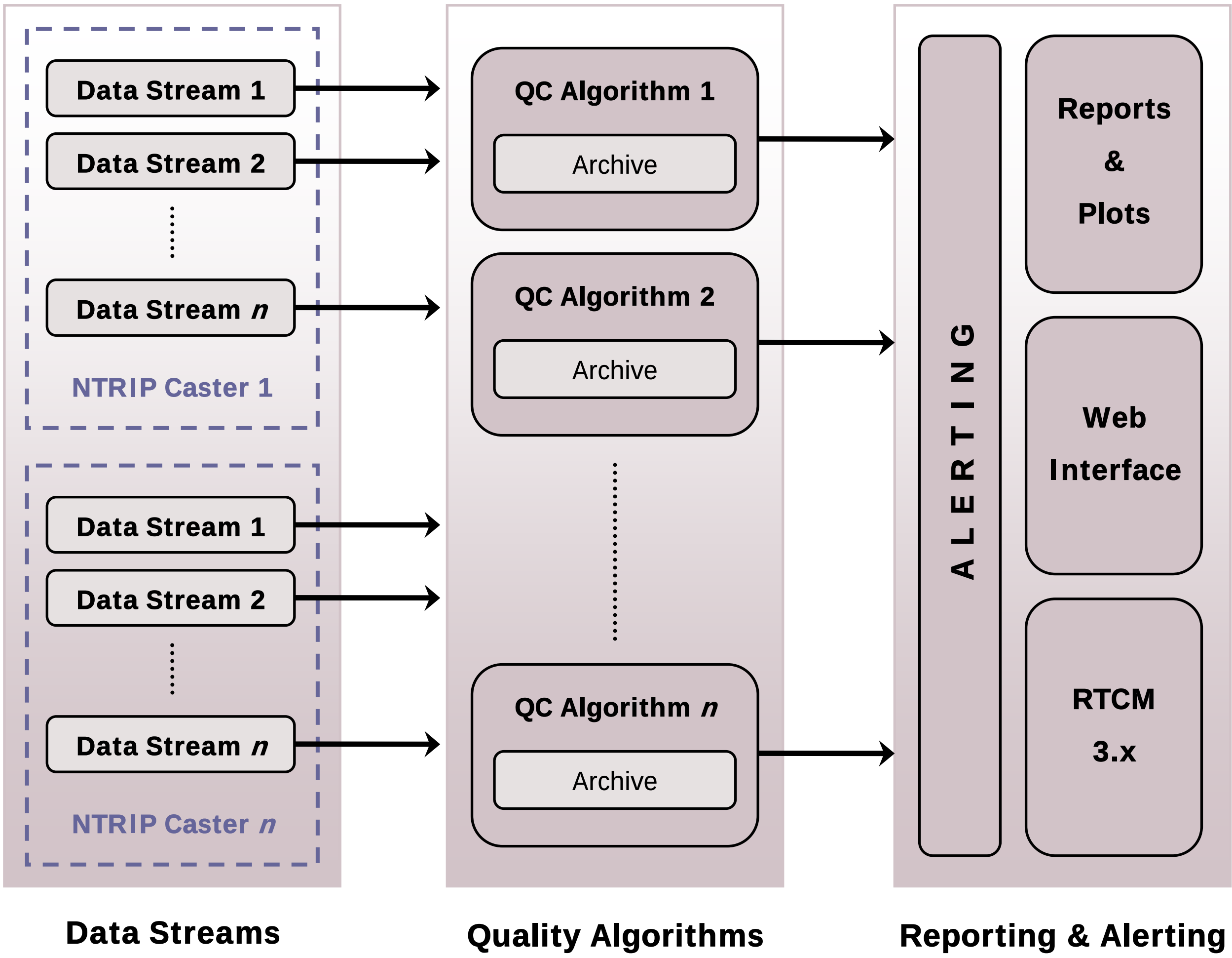

Figure 4. The RT-QC software architecture

4.1 Data Streams

The RT-QC software is capable of analysing GNSS data received from real time data streams delivered via the internet, or from previously recorded files for post-processing. Currently RTCM 3.x and RINEX are the supported data formats, although there are plans to incorporate the RT-IGS format in the near future.

4.1.1 Real-Time Data Streams

Streaming of real time GNSS data via the internet to the RT-QC software is facilitated through the use of NTRIP. An NTRIP enabled system (Figure 5) generally consists of an NTRIP Caster, NTRIP Client and various NTRIP Servers (Weber *et al*, 2005). The NTRIP Caster provides information on the data streams (NTRIP Servers) that are available and handles requests for connection to a particular data stream. The NTRIP Client may request a list of the available data streams from the NTRIP Caster and may subsequently connect to one or more of the available streams. The RT-QC software essentially acts as an NTRIP Client within this scenario (Figure 5), whilst the CORS Network operator provides the NTRIP Caster, usually through proprietary software such as Leica SpiderNET or Trimble GPSNet. Each individual CORS Network has its own NTRIP Caster, generally identified by an IP address and a port number.

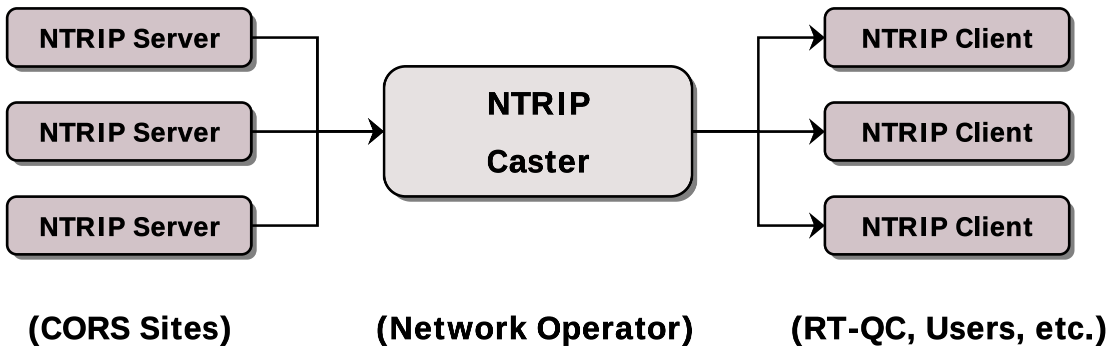

Figure 5. Basic NTRIP system architecture

The RT-QC software allows connections to multiple data streams from several NTRIP Casters simultaneously. Thus data from one or more CORS Networks can be monitored from a single installation of RT-QC (although this may not necessarily be the wisest option). Data streams may either be "single base" or "network" streams. Figure 6 shows RT-QC monitoring three single base data streams from the Victorian GPSnet Network, the mp1 time series for one of the streams is also visible. The maximum number of data streams (be it from one or multiple networks) is limited only by the processing capacity and network connection of the computer on which the RT-QC software is installed. Current test installations are monitoring between 20-30 data streams (from a single network) simultaneously.

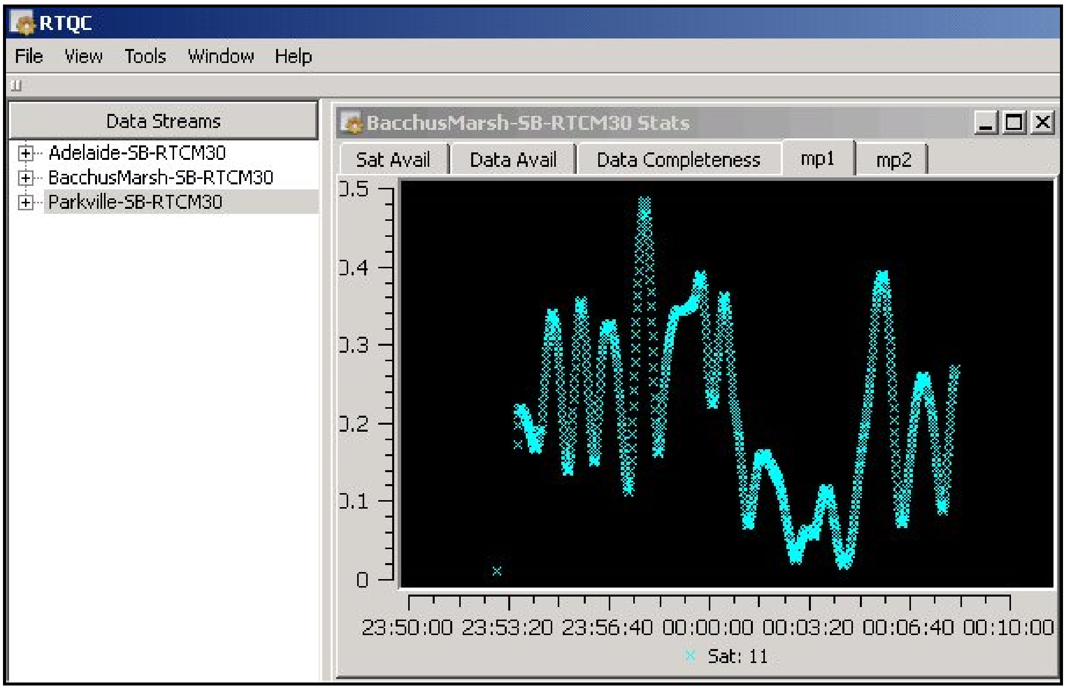

Figure 6. Example of monitoring multiple data streams from a single network

4.1.2 File Based Data Streams (Post-Processing)

The RT-QC software also supports the analysis of GNSS data from RINEX or RTCM 3.x files in post-processing mode. However, this functionality is designed as a means to simulate a real time data stream, rather than as a replacement for current post-processing software such as TEQC or Leica GNSS QC.

4.2 Data Analysis & Quality Assessment

The heart of the RT-QC software consists of various quality algorithms (Figure 4) which process and analyse the raw observation data epoch by epoch for each data stream. The algorithms currently in place calculate data statistics, monitor the observations for multipath and cycle slips, carry out gross error checking on the receiver coordinates, and perform the calculations required for a new quality indicator being developed as a part of Project 1.2 (hereafter referred to as the "RT-QC indicator"). In addition to carrying out the necessary calculations for each algorithm, the RT-QC software also archives the algorithm results for up to one week in order to gather information on the behaviour and performance of individual satellites and receivers. This information is used in the reporting and alerting stages of the software to customise the alerting process for each data stream.

4.2.1 Data Statistics

Standard data statistics such as data availability (the number of epochs received versus the number expected), data completeness (the number of received epochs which have a full set of observations, eg. C/A code, P-code, L1 phase, L2 phase, etc.), average number of satellites, observations per elevation bin, and so forth. In addition, a set of statistics applicable only to real-time data streams are provided. These statistics include, the latency of the network connection, the number and duration of dropouts, and the level of data corruption as a result of dropped network packets or other network problems. An example of the latency for a single base data stream (via a dial-up internet connection) is shown in Figure 7.

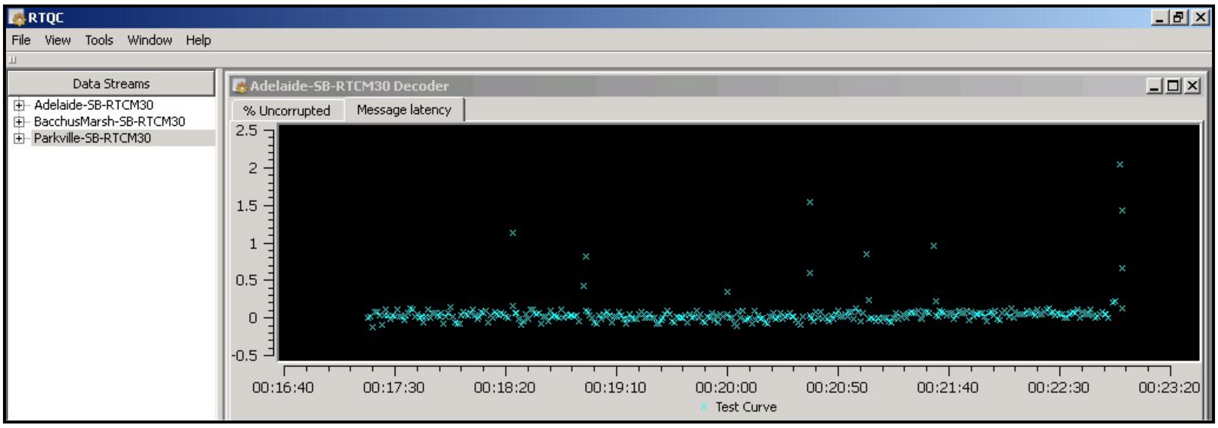

Figure 7. Data latency (Adelaide Single Base RTCM 3.0)

4.2.2 Multipath

The RT-QC software calculates the well known *mp1* and *mp2* multipath values (Estey and Meertens, 1999) which provide an indication of the relative level of multipath on the L1 and L2 pseudoranges. The multipath can be viewed as a time series (on a satellite by satellite basis) or as a sky plot, colour coded to represent different levels of multipath. As with all processing undertaken by the RT-QC software the multipath calculations are performed in real time for each data stream.

4.2.3 Outlier and Cycle Slip Detection

Outliers and cycle slips are identified by the RT-QC software using two independent methods. The first method is an adaptation of the cycle slip algorithm developed by Blewitt (1990), which utilises the widelane and geometry free linear combinations (phase and code). This algorithm was originally developed for post-processing purposes and was adapted for real time use within the RT-QC software. The second method utilises the new RT-QC indicator and will be the subject of a future paper.

4.2.4 New RT-QC Indicator

One of the key goals of the RT-QC software has been development of a quality indicator that would encompass the various quality indicators currently in use and would provide some measure of the stochastic properties of the observations. Whilst the inner workings of the indicator cannot be discussed in this paper, some of the initial results are shown in Figure 8. The graph clearly demonstrates a strong degree of elevation dependence in the indicator. Superimposed over this long-term trend are spikes and other irregularities that hint at other phenomena affecting the quality of the observations. The highlighted spikes correlate with quality breaches (e.g. cycle slips, outliers) detected by other methods. The behaviour of the RT-QC indicator over extended time periods (Figure 3) exhibits strong day to day correlations which are expected to prove useful in the intelligent alerting system (see below). Based on these early signs, the research team is optimistic about the performance and usefulness of the new quality indicator.

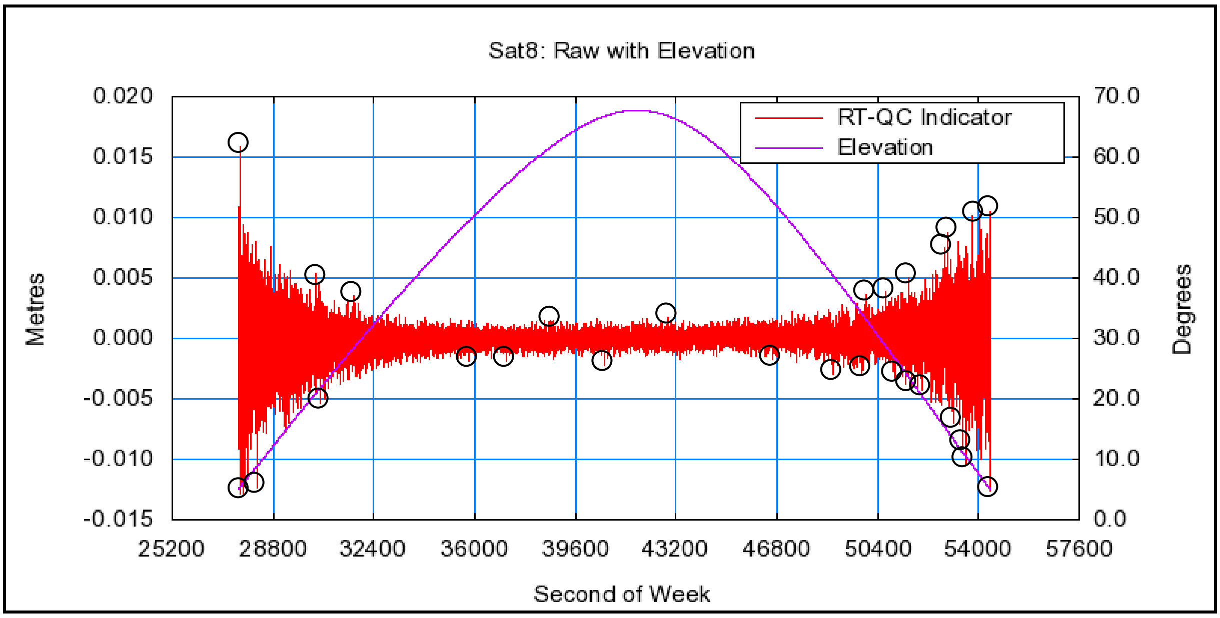

Figure 8. New RT-QC indicator

4.3 Reporting and Alerting

4.3.1 Reporting

The results of the RT-QC software's quality algorithms are made available to users through a series of real time plots and reports. These plots and reports are of most use to CORS operators as they are the likely dominant users of the software. However, communicating quality information to mobile users is also a key goal of the project, thus two parallel mechanisms for delivering quality information to mobile users have been developed. Firstly, quality information is made available on the internet through a dynamic web interface. Secondly, key quality information can be delivered to mobile users using RTCM 3.x, utilising the proprietary messages (4001-4095) and the Unicode message (1029). The various reporting options are discussed below.

4.3.1.1 Software Reporting

The plots and reports generated by the RT-QC software are of most use to the individuals or organisations running the software and that can access the computer where the software is installed. Plots are updated in real time for the current window of observation data and are available for all quality algorithms (multipath, data statistics, latency, data corruption etc.) and the raw observation data. (C/A code, P-code, L1 phase, L2 phase, etc.)

An extensive quality report (Figure 9) is produced which details the properties of the current observation window (start and end times, number of epochs, observation rate, etc.), displays data stream information (receiver make and model, amount of data read, outages, messages received, etc.), and provides extensive information on the quality algorithm results (data statistics, multipath, cycle slips, etc.). The report can be updated in real time or at a user specified time interval.

Session/Window Summary:

Start Epoch: Fri 6. Jul 15:05:54 2007
End Epoch: Fri 6. Jul 16:05:54 2007
Number Epochs: 3600
Maximum Epochs: 3600
Observation Interval: 1 seconds
Maximum Window Size (Secs): 3600
Number SVs with Obs: 12
SVs with Obs: G 3, G 6, G 7, G 10, G 16, G 18, G 21, G 22, G 24, G 26, G 29, G 30

Decoder Summary:

Marker ID: ADEL
Marker Name: Adelaide-SB-RTCM30
Receiver Type:
Antenna Type:
Data Stream: Adelaide-SB-RTCM30
Decoding Started: Fri 6. Jul 14:53:27 2007
Decoder Uptime (secs): 5128
Mb Read: 1.39143
Total Messages: 14202
Uncorrupted Messages: 14202
Uncorrupted Messages (%): 100
RT Data outages: 2
RT Data outages average length (secs): 72, average reconnect retries: 11
RT Data outages maximum length (secs): 139, maximum reconnect tries: 21

Figure 9. RTQC quality report

4.3.1.2 Web Interface

Communicating quality information to mobile users in real time is a key goal of the RT-QC software. One of the major difficulties in attempting to do so is the potentially limitless number of hardware and software configurations employed by mobile users. Rather than developing specific software for each individual hardware/software combination, the research team decided to take advantage of a piece of software available on practically all mobile devices - the web browser.

A number of issues arose when attempting to provide quality information to mobile users via the internet. Firstly, the content needs to be tailored to the user's device, secondly the content needs to be standards compliant and free of client based scripting or applets which may not be supported on all devices. Finally, the amount of content had to be minimized wherever possible, to facilitate rapid download and display on bandwidth limited devices.

To satisfy these criteria, the web interface was developed using a combination of a Structured Query Language (SQL) database, Hypertext Pre-processor (PHP) scripting, and Cascading Style Sheets (CSS), to deliver dynamic web pages that are customized to the user's hardware platform. The basic architecture of the web interface is shown in Figure 10.

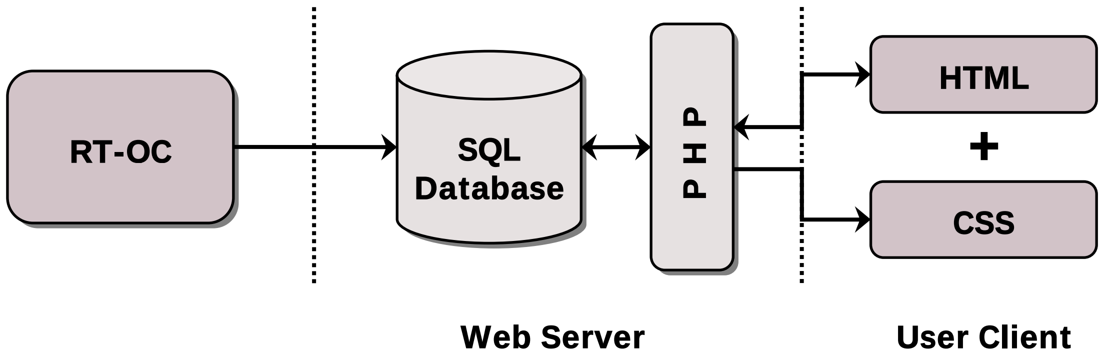

Figure 10. Web interface architecture

The quality information displayed through the web interface is practically identical to that displayed within the RT-QC software with minor modification to streamline the content.

It has been mentioned previously that a key goal of the RT-QC software is to provide a single quality indicator, based on raw observation data, to encompass the range of quality indicators currently available. As such the web interface provides, as a first port of call, an indication of each data streams' quality based on the RT-QC quality indicator. This gives the mobile user (particularly those who are less adept at interpreting quality information) a simple and familiar indication of the network quality. In addition to information on the network quality (provided by the RT-QC (CORS) module) the mobile user may also be able to access an indication of their own data quality through the RT-QC (premium) service (Figure 1), which attempts to incorporate the mobile user's data into the quality control process. The default method for viewing both sets of quality information is in the form of a "signal strength" indicator, akin to those seen on mobile phones.

4.3.2 Alerting

A key component of any quality control software, in particular real time software, is the ability to alert system operators and users of any quality breaches. The RT-QC software utilizes an innovative "performance over time" method to determine if quality thresholds have been breached, rather than arbitrary performance thresholds. Alerts are delivered to system operators and users via email or SMS.

The alerting system in the RT-QC software is based on the historical performance of an individual satellite for each data stream. Quality information for each satellite, on a stream by stream basis, is archived for up to one week. As new data becomes available in real time the current set of quality information is compared to the archived information. This approach is only applicable to data streams received from CORS networks, where the GNSS receiver and antenna are permanently installed.

There are two components to the comparison process, identifying the archived epochs which match the current epoch, and determining whether the current epoch's quality information is significantly different from the archived quality information and therefore merits the issuing of an alert.

4.3.2.1 Epoch Matching

When attempting to match archived epochs to the current epoch, the RT-QC software takes advantage of the repeatability of the GPS orbits. GPS satellites orbit the Earth with a period of approximately 11 hours and 58 minutes, and as such they repeat their ground track roughly 4 minutes earlier each day. The RT-QC software makes the assumption that, for practical purposes, a GPS satellite will be in the same position each day, four minutes earlier. However, to provide additional rigour to the epoch matching algorithm, a search of the best matching constellation is conducted, rather than simply assuming a 4 minute time difference. This technique ensures optimum comparison of quality indicators based on identical satellite geometry, with results indicating that the calculated time difference (for the best matching geometry) is within a few seconds of the approximate value of 4 minutes (Figure 11). The applicability of this technique to other GNSS constellations has not yet been investigated. It may be necessary to modify the algorithms to deal with data from constellations such as GLONASS and/or Galileo.

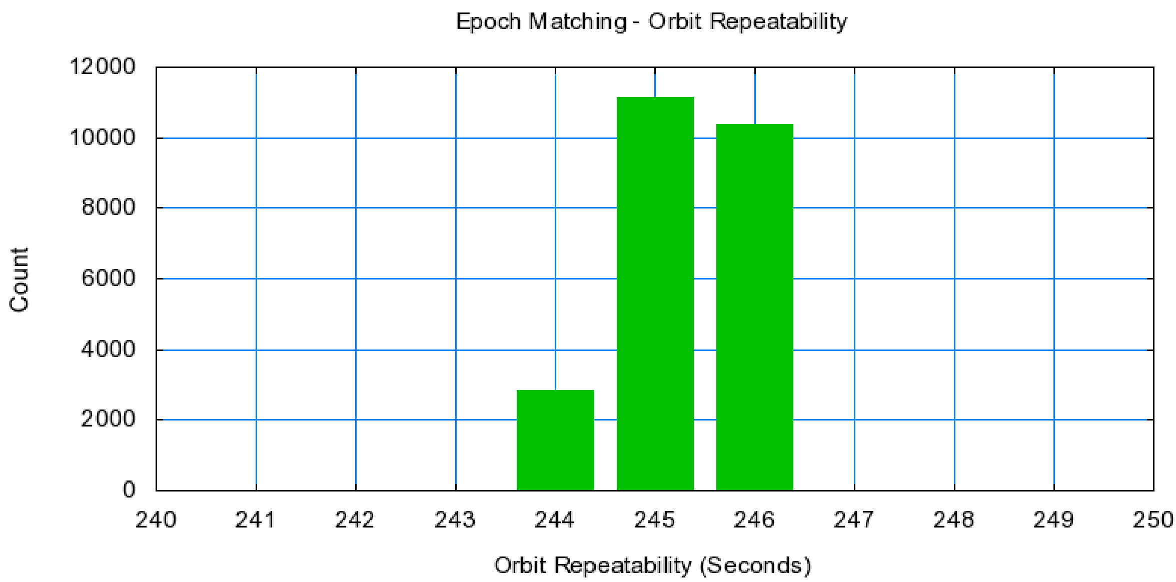

Figure 11. Calculated orbit repeatability

4.3.2.2 Quality Comparison

Having identified the archived epochs that match the current epoch a comparison of the quality information available is carried out. The aim of this comparison is to determine if there is a statistically significant difference between the past performance of a satellite and its current performance. This technique can be utilised for virtually any quality parameter (currently used with multipath, cycle slips, and the new quality indicator developed by Project 1.2) without the need to set arbitrary thresholds. The only requirement is that the system operator selects an appropriate significance level for the statistical testing.

5. FUTURE WORK & TESTING

At the time of writing (June 2007) the RT-QC software was being configured to monitor the quality of a major CORS Network in Australia, with a second network expected to be online by mid July 2007. These installations will enable the research team to monitor the performance of the software in a real world environment and will provide valuable feedback on the performance and usability of the new quality indicator.

Development work is currently focussed on the integration of mobile user data, with a proof-of-concept test scheduled for early July. Support for the Real Time – International GNSS Service format (RT-IGS) is also under consideration, particularly with the expected expansion of Australia's GNSS infrastructure through the AUSCOPE project. Finally, research into the RT-QC indicator is ongoing, with the current emphasis being on the stochastic properties of the indicator and its potential use for the generation of real time stochastic models.

ACKNOWLEDGEMENTS

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