NetworkRTK – New Zealand

A summary of the concepts, methods, limitations and services in New Zealand

Contributors:

P. Denys[1], A. Liggett[2], R. Odolinski[1], C. Pearson[1], D Stewart[3], R. Winefield[4]

[1] School of Surveying, Otago University, Dunedin
[2] Fox and Associates, Christchurch
[3] Energy Surveys, Taupo
[4] Land Information New Zealand, Wellington

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1 Introduction

Network RTK (NRTK) is a common positioning technology that has become established in many regions of the world. This positioning infrastructure has been gradually developed in New Zealand on a commercial “as need basis”, largely centred on urban regions, but also in a few select non-urban regions. In this paper, we aim to describe the technical aspects of NRTK from a vendor neutral perspective.

It is hoped that the paper is a useful resource that covers the key components of NRTK. The topics covered include a brief outline of single-base RTK, NRTK concepts, methods and network design, the limitations and best practices as well as touching on alternative (satellite based) positioning systems. Although the status of NRTK in NZ will always be changing, the paper summaries the current status ((2017) as well as outlining developments in a few (selected) countries.

It is an opportunity to promote a greater discussion about what New Zealand survey industry aspires to in terms on a national NRTK infrastructure.

2 Single-base RTK and its drawbacks

Since the turn of the millennium, carrier wave GNSS technology and in particular Real Time Kinematic (RTK) GNSS, has been in widespread use in surveying, civil engineering and other positioning applications for which centimetre level precision is required. For many users, the introduction of multiple constellations, which became widespread in the mid-2000s, marked a turning point where RTK GNSS came into its own as a practical positioning solution for all but the most high-precision roles. The key limitations included the observing environment and the distance dependent errors.

2.1 Single-base RTK

The traditional, single-base RTK GNSS model involves the use of multiple receivers. A single receiver is deployed as a base station at a known position, and this transmits observational data to one or more roving receivers, conventionally via a UHF radio modem. It is then possible to compute the relative position between the base and rover receivers to around the one centimetre level or better, although the absolute position remains only as accurate as the coordinate of the base station. For a more detailed explanation of RTK GNSS refer to the European Space Agency Navipedia (www.navipedia.net/index.php/Real_Time_Kinematics).

While RTK GNSS may have been a "game changer" for positioning, the traditional operating model does have a number of drawbacks.

2.2 Drawbacks of single-base RTK

Any measurement device has measurement errors. For RTK GNSS this includes satellite, atmospheric and receiver errors, which can be reduced (but not eliminated) by using accurate algorithms and models. The errors that are not eliminated manifest as distance dependent errors. Other limitations include the data telemetry link, the observing environment, location of the base station and the purchase and set up costs.

2.2.1 Distance-dependent errors

The precision of single-base RTK GNSS measurements is highly dependent on the distance between the base and rover receivers. The main distance dependent errors are as follows:

- **Ionospheric Delay:** Variations in the time of travel for a GNSS satellite signal through the ionosphere. This delay is affected by solar activity, location, time of day and season.

- **Tropospheric Delay:** Variations in the time of travel for a GNSS satellite signal caused by changes in humidity, atmospheric pressure and temperature as the signal passes through the troposphere.
- **Satellite Orbit Errors:** SVs tend to deviate very slightly from their predicted orbits, and small deviations from the predicted orbit are magnified into significant positional error on earth.
- **Satellite Clock Errors:** The atomic clocks in the GNSS satellites are very accurate (10 µs or better), but they do drift over time. Small inaccuracies in the satellite clock results in a significant error in the position calculated by the receiver.

One of the fundamental premises of the algorithms used by RTK GNSS is that the magnitude of each of these errors for a given signal is assumed to be similar at the (known) base receiver and the mobile rover receiver and that the error can therefore be (mathematically) eliminated. For all these errors this assumption begins to break down as the distance between the roving receiver and the base station increases.

Typical published figures for high-end multi-constellation receivers[1] are 8 mm + 1 ppm horizontal and 15 mm +1 ppm vertical (1 sigma confidence level). These translate to relative accuracies of ±9 mm horizontal and ±16 mm vertical when the receivers are 1 km apart, but ±33 mm horizontal and ±40 mm vertical when they are separated by 25 km.

2.2.2 Data telemetry

For real time applications, a telemetry system is required to transmit the observation data from the base to the rover receiver for processing. Data telemetry may be through a cellular mobile network, radio modem or satellite modem link.

- **Cellular mobile network:** Using a data link from a commercial (subscription based) network operator. These networks are common in urban and populated (tourists) areas, but can have limited availability in rural and remote areas.
- **Radio modem:** A 0.5W on-board line-of-sight radio modem can yield a range of up to 5km in ideal conditions. However, this can be drastically reduced by topography or by RF interference sources such as overhead electricity wires. The practical range of a radio modem is typically no more than 1-2 km. One or more strategically placed

[1] Trimble R10 and Leica GS14: 8 mm + 1 ppm horizontal and 15 mm +1 ppm vertical; Topcon NET-G5: 10 mm + 1 ppm horizontal and 15 mm +1 ppm vertical

repeater radios can mitigate the problems of topography and increase the range significantly, however this comes at the cost of additional setup time and additional equipment such as batteries.

Further limitations of radio modems include being restricted to three free to air frequencies and the congestion caused by multi-users in urban areas. (Further details of the MBIE Radio Spectrum Management (RSM) website can be found at: www.rsm.govt.nz/consumers/frequencies-anyone-can-use)

- **Satellite modem link:** Can be used in isolated regions (e.g. central Australia) and in the hydrographic industry, but is an expensive option.

2.2.3 Post-processed kinematic

In the situation where a telemetry data link is not available or not possible, centimetre precision is achievable using post-processed kinematic (PPK) GNSS. In this case, simultaneous carrier phase data is logged at both the base station and rover receivers. Once the survey work has been completed, the data is downloaded and processed at a later time. As a result, there is no risk of data or carrier phase initialisation loss due to telemetry (e.g. radio) link outages.

PPK offers a good alternative to RTK for some applications. The main limitations include not being able to undertake survey set out or to find old survey marks (navigation) and that the coordinate results cannot be verified until after the fieldwork has been completed.

2.2.4 Base station site selection

Because single-base RTK relies entirely on the corrections transmitted by the base station, the position of this receiver must be carefully selected both with respect to the observing environment (to avoid terrain masking as well as multipath and RF interference sources and interference) and security/safety (from members of the public, traffic, livestock or wild animals). The effects of a poor base station site can vary from difficulty from establishing a radio link between base and rover through to an inability to achieve and maintain ambiguity initialisation due to insufficient satellites being tracked by both receivers. Furthermore, even a slight movement of the base station can jeopardise a measurement campaign, and in the worst case theft of valuable equipment can be a real threat.

2.2.5 Setup cost

A pair of multi-constellation RTK receivers including a proprietary survey controller, batteries and other peripheral equipment currently costs in the region of NZ$50,000 + GST. The cost can be reduced by purchasing equipment from a less well-established manufacturer, or by scaling back the capability of the equipment (number of channels, available constellations, tracked frequencies, application firmware). The bottom line remains, however, that two receivers are more expensive than one.

Figure 1: Care must be taken to select sites free from terrain masking and multipath sources.

3 NetworkRTK concepts

Operationally, a single-base RTK/PPK system requires a minimum of two GNSS receivers; a base and a rover. The base is typically (but not necessarily) located on a known mark. Both the base and rover receivers simultaneously track the carrier phase data, which is processed to determine the baseline between the base and the rover. Real time (RT) systems require a telemetry link to transmit the observational data to the rover (e.g. radio, cellular network, satellite) while for post-processing (PP) the two data sets will typically be processed in an office environment. The key limitation of a single-base system is that the GNSS distance dependent errors (e.g. atmosphere, orbit) become spatially decorrelated as the distance between the base and the rover becomes larger. Hence the precision of the baseline and therefore the precision of the rover's position is limited by distance.

To mitigate the distance dependent precision of a single system, GNSS data from a regional network of reference stations is used to model the biases in (near) real time. The reference station would typically be part of a permanent continuous GNSS (cGNSS) network. The GNSS carrier phase data from multiple reference stations is streamed to a Network Processing Server (NPS) and this data is used to model and correct for biases such as atmosphere, orbit and carrier phase ambiguity terms. This enables access to data from multiple cGNSS, more powerful computer(s) to be used for the processing and more sophisticated models to be applied.

RTK that is operated in conjunction with multiple reference stations and bias modelling is called network RTK (networkRTK or NRTK). It should not to be confused with single-base GNSS that connects to a single reference station (typically through a cellular or mobile network) and therefore does not benefit from spatially modelled GNSS error sources.

3.1 NetworkRTK components

There are four key components that are required or make up a NRTK system. These include the reference stations (network), the method of modelling the bias terms which in turn generate correction terms, the interpolation of the corrections for a required user's (or rover's) position and the method of transmission of both the observation data and correction data to the user/rover.

3.1.1 Reference stations

The physical NRTK component involves groups or networks of reference stations that stream 1 Hz carrier phase and pseudorange observation data to a NPS. The method of data streaming is typically through the internet, although radio or satellite links can be used. Data latency (and data outages) are critical and if too great will relegate a reference station unreliable or unusable.

The density and geometry of the reference stations affects the performance of NRTK. Best practice suggests that the inter-site distance be less than 70km (placing a user a maximum of approximately 35km from a reference station). However, NRTK needs to operate satisfactorily if a reference station fails, hence reference station redundancy is a consideration. As for most modelling and interpolation algorithms, uniform spacing of reference stations (a regular grid) is the ideal configuration.

When selecting a reference site, in addition to the site's stability and sky visibility, the following need to be taken into consideration: site security, access for maintenance, power reliability (including UPS), a reliable, low latency internet connection and site observing conditions including the level of multipath.

3.1.2 Generation of bias corrections

NRTK improves positioning accuracy through the modelling of distance dependent errors. These include the orbit, ionospheric and troposphere errors. Other GNSS biases that must also be accounted for include the antenna phase centre and the carrier phase ambiguity terms.

The first step in this process is to resolve the carrier phase ambiguity between the reference stations in order to achieve optimum position accuracy. This is known as a carrier phase fixed solution. The ambiguities are resolved to a common level when all ambiguity terms are determined to a single reference satellite. This requires all satellites in the solution to be visible (or tracked) by all the reference stations, which in turn implies that the reference stations must be sufficiently close together to enable this to occur. Groups of reference station are often called clusters.

The second step deals with the bias terms. The simplest approach is to group all the distance dependent errors together as a single bias at each reference station. Using the carrier phase fixed solution, the observation residuals at each reference station are monitored. Hence each reference station will exhibit a bias that is a function of position and time. A second approach, is to model each error separately as a linear combination that typically divides the biases into dispersive and non-dispersive error terms. This approach requires more computing power and will generally be done at a central computing facility.

3.1.3 Correction interpolation

Once the carrier phases ambiguities are reduced to a common level and the reference station error determined, the error must be determined for the user's position. The error is modelled using an interpolation method. Standard interpolation methods include bi/linear interpolation, low order polynomial, least squares collocation and grid based parameters.

The interpolation method used is dependent upon the software manufacturer, but will also depend upon the computing facilities available and whether the interpolation is carried out at the computing facilities or by the roving receiver at the user's end.

3.1.4 Correction transmission

The NRTK method used is largely defined by the observation and correction data transmission method to the user (rover) together with the data format used. The data transmission is either 1- or 2-way communication.

- **1-way**: All required observation and correction data is transmitted from the NPS to the user or rover receiver. The user must have sufficient bandwidth to receive the data in a timely manner and have sufficient processing power to perform the required calculations. Data transmission formats may be optimised to help achieve this.
- **2-way**: Enables bi-direction communication between the user and NPS. This allows for information, such as the rover's (approximate) position, to be sent to the NPS. The main advantage is that more sophisticated and complex modelling can be carried out using the additional processing power available at the NPS. Hence, the GNSS positioning is not restricted by the processing power of the rover.

3.1.5 Data formats

Efficient data transmission is critical to NRTK, for either 1-way and 2-way communication. Depending upon the data being transmitted, specific formats are used (e.g. NEMA for position information) or have been developed (e.g. RTCM 3 for multi-constellation carrier phase data). It is equally important to choose an appropriate broadcast protocols to maximize data throughput i.e. number of satellites.

Data formats are briefly described in Appendix A.

4 NetworkRTK methods

Brief descriptions of common NRTK methods are given for the Flächen-Korrecktur-Parameter (FKP), Virtual Reference Station[2] (VRS) (developed by Trimble) and the Master Auxilliary Concept (MAC, MAC-MAX, MAC-iMAX) (developed by Leica). Although the FKP method is conceptually the most straight forward approach, it is not extensively used. The VRS and MAC methods are the most common methods used today. In addition to the conceptual algorithms and data transmission, the data formats used between the network processing server (NPS) and rover is critical for the efficient operation of NRTK systems.

4.1 FKP

Single-base RTK works well over short distances. GNSS errors (orbit, clock and atmosphere) are mathematically removed from the baseline. This assumes that the error at both the base station and rover are similar, an assumption that holds true in normal observing conditions. Hence, the modelling of the GNSS errors is based on two receivers, the rover and base. By using additional error estimates from several (nearby) reference stations it is possible to model and thus interpolate the error at the user's position.

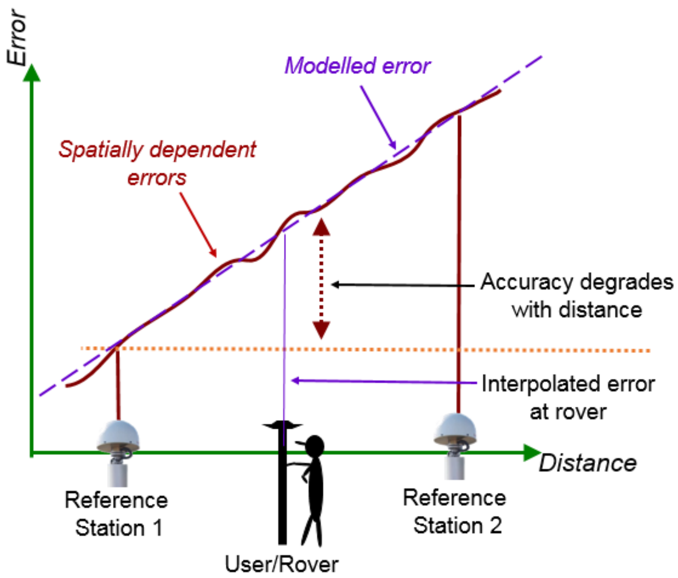

Figure 4: Flächen-Korrecktur-Parameter (FKP) models the error as a flat plane or tilt correction.

[2] Topcon's NRTK product, Modelled RTK, is equivalent in logic to VRS.

The Flächen-Korrecktur-Parameter (FKP) or Flat Plane/Area Correction Parameters method attempts to model the error over multiple reference stations using a flat plan or tilt correction. Figure 2 shows the error varying with distance between two reference stations (brown line). This error is modelled using an inclined plane (blue dashed line) and interpolated at the user's position to determine the correction term to apply at the rover. This computation is carried out in two dimensions, thus there are two correction or tilt terms, one each in the north-south and east-west directions.

The FKP correction method requires the flat plane model to be generated by the NPS and transmitted using 1-way telemetry. The rover interpolates the flat plane model using the user's current position.

4.2 VRS

The Virtual Reference Station (VRS) approach requires the GNSS data to be streamed to the NPS. The data rate is 1 Hz and the data link is typically the internet, but can be LAN, satellite or radio links. In addition, a NMEA string with the user's (approximate) position is sent to the NPS (Figure 3).

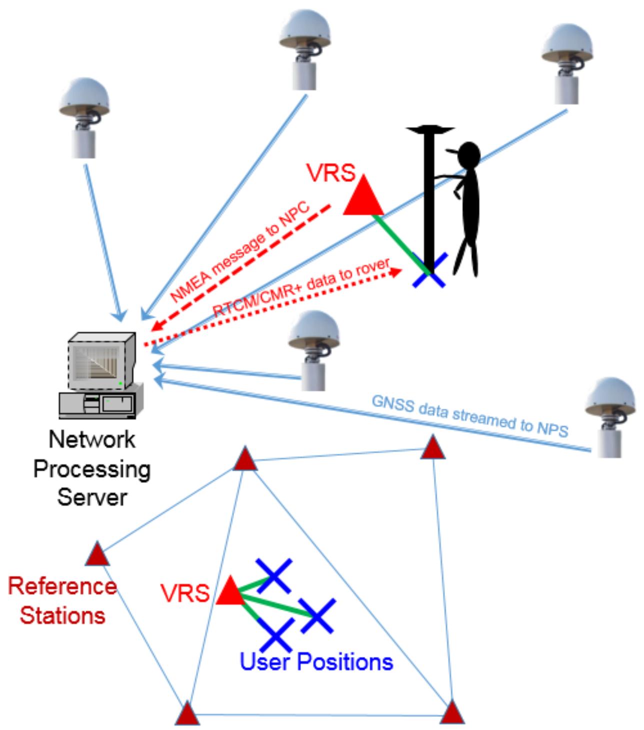

Figure 7: The Virtual Reference Station (VRS) approach computes the baseline (green) between the VRS and rover position.

The NPS collects the GNSS data and performs quality assurance checks on the data. The network server will resolve (and maintain) the carrier phase ambiguities and models the common mode errors. The server generates GNSS data for a location close to the rover's position that is corrected for the common mode errors (CME). This position is known as the Virtual Reference Station or VRS. The (virtual) observation data is transmitted to the rover using a RTCM or CMR format (see Appendix A), which allows the rover to compute the (short) baseline between the VRS and rover position.

4.3 MAC

The Master Auxiliary Concept (MAC) can be applied in two forms: Master Auxiliary Corrections (MAX) and individualised-MAX (iMAX). This approach has been developed based on the RTCM 3 format that optimises data transmission by reducing the quantity of data transmitted to the user's receiver.

Similar to the VRS concept, GNSS data is transmitted to the NPS from all reference stations. At this level, the ambiguities are resolved on a common level (i.e. all reference stations observing the same satellites). A master reference station is designated and the other stations in the network become auxiliary reference stations (Figure 4).

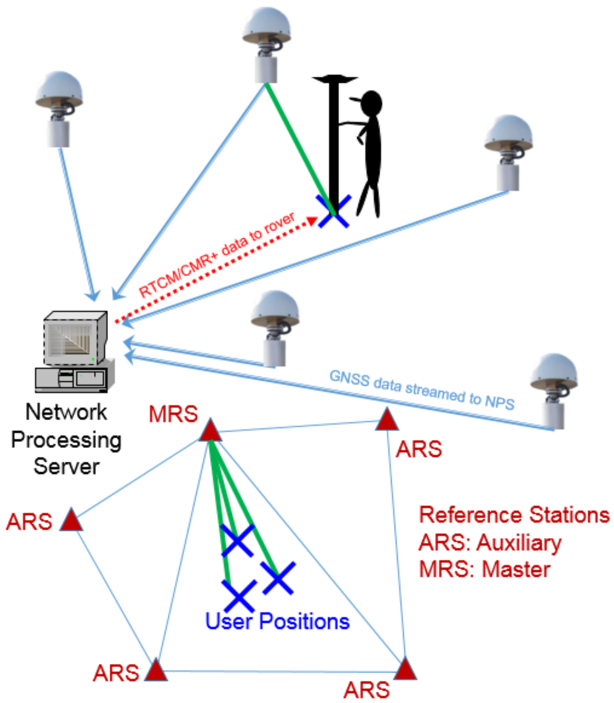

Figure 10: The Master Auxiliary Concept (MAC) approach computes the baseline between the master reference station and rover position

Using the ambiguity resolved GNSS data, the single difference GNSS observable is computed i.e. the difference between the carrier phase data for two reference stations and a common satellite. Using the single difference observable, correction differences are computed between the master and auxiliary reference stations. Effectively correction differences are network error offsets at each auxiliary reference station relative to the master reference station.

The network errors are further reduced to dispersive (mainly ionosphere) and non-dispersive (mainly orbit and troposphere) errors. The advantage of grouping the GNSS biases is that non-dispersive errors tend to vary less rapidly over time compared to the dispersive errors. Hence data transmission rates can be different for each correction term and bandwidth use can be optimised.

4.3.1 MAC – MAX

For the Master Auxiliary Correction (MAX) approach, the NPS processes the reference station network, resolves the carrier phase ambiguities (common level), and using the RTCM 3 format, transmits the GNSS observation data for the master site and the correction differences for each of the auxiliary stations.

The rover receiver computes the master-rover baseline and interpolates the correction differences for the user's location. The MAC–MAX approach only requires 1-way data transmission.

4.3.2 MAC – iMAX

The individual Master Auxiliary Correction (iMAX) approach requires bi-directional data transmission. The user's position (e.g. NMEA message, see Appendix A.1) is transmitted from the user to the NPS. The same computations steps are carried out at the NPS i.e. MAC, except that the error correction for the user's location is computed at the NPS. This approach allows for support of earlier receiver types that do not support the RTCM 3.x format.

5 Network Design

5.1 LINZ PositioNZ-RT Service (PositioNZ-RT)

LINZ currently provides 1 Hz GNSS data at selected PositioNZ sites through its PositioNZ RT service. In addition, the data from a number of GeoNet GNSS sites are also made available for NRTK services. The real time data service is operated by GeoNet, who provide data using the RTCM format (RTCM 3.1) and the NTRIP protocol (Appendix A briefly describes each of these data formats). The expected data latency is less than 2 seconds (95% confidence interval).

Users can connect to a single PositioNZ base station as a single-base RTK application using a suitable GNSS data format (see Appendix A). However, the PositioNZ reference station data is also used by NRTK service providers (Section 5.2) to strengthen their networks through greater spatial coverage and density of reference stations.

For more details see:

- www.linz.govt.nz/positionz-rt

5.2 Service providers

Commercial GNSS data and correction services first became available in New Zealand in the mid-2000s, and initially provided single-base corrections from a single reference station located in each of the major cities. Services were expanded with investment in additional reference stations, greater processing power, and more robust computing and data communication systems.

Public CORS sites were incorporated into the commercial service providers' networks as they were made available by LINZ, and a limited amount of joint development of further reference stations occurred.

By the end of the decade the local distribution partners of Trimble, Leica and Topcon all had networks in operation that were subscribed to primarily by surveyors, earthworks contractors, and precision agriculturists. Also at that time network corrections services were available in the major urban centres, with most of the remaining population centres able to utilise single-base corrections from at least one of the three services.

In recent years, the original reference stations have been gradually upgraded to multi-constellation GNSS, with system upgrades to support the new RTCM-3 MSM signal format, and further densification of networks.

The status of GNSS correction services in operation in NZ in 2017 is summarised in Table 1.

Service:	iBase	SmartFix	SkyNet	ESCORS
Provider:	AllTerra	Global Survey	Synergy Positioning Systems	Eliot Sinclair
Technology platform:	Trimble VRS	Leica Spider MAX/iMAX	Topcon TopNET	Trimble
Geographic coverage:	Network solutions in selected areas. Single base solutions nationwide.	Network solutions in selected areas. Single base solutions nationwide.	Network solutions in selected areas. Single base solutions covering 80% of NZ population.	Single base solutions covering Christchurch & Canterbury.
Reference stations:	67 stations – 26 iBase – 4 shared – 37 public	Approx. 84 stations – 27 SmartFix – 7 shared – all available LINZ/GNS sites	35 stations – 20 SkyNet – 25 public	10 stations – up to 5 ESCORS – 3 shared – 2-4 public
Availability:	By subscription	By subscription	By subscription	Private service
General information:	www.allterra.co.nz/geospatial-solutions/positioning-services/	globalsurvey.co.nz/shop/solutions/agriculture/reference-station-data/smartfix/	synergypositioning.co.nz/skynet-rtk	eliotsinclair.com/escors-network/
Coverage map:	y16.ibase.co.nz/Map/SensorMap.aspx	www.smartfix.co.nz/SBC	synergypositioning.co.nz/skynet-rtk	eliotsinclair.com/wp-content/uploads/2014/10/ESCORS_Thumb_1-Custom.jpg

Table 1: Network RTK service providers available in New Zealand (May 2016)

6 NetworkRTK limitations

6.1 Communications services

Data telemetry or communications is critical for NRTK systems. There are two telemetry components (to and from the NPS) for which the telemetry method can be different:

1. **Data to the NPS**: This includes telemetry methods to transmit raw GNSS data, and for some NRTK systems, data from the rover to the NPS.
2. **Data from the NPS**: Telemetry methods for data dissemination (raw, processed, corrections) from the NPS to the user or rover receiver.

6.1.1 Wired connections

It is preferable for GNSS reference stations to have hard-wired connections to an intranet or the internet. The raw reference station GNSS data is transmitted back to the NPS using fibre, ADSL or ethernet routes. This is the most reliable means of communications and preferable if available, practical and economic.

6.1.2 Mobile networks

Cellular or mobile networks are the most common communication channels by which users connect to NRTK services. These networks can also be utilised to transmit raw GNSS data from individual reference stations to the NPS.

Most common problems encountered are to do with mobile network coverage, capacity and latency.

- **Coverage:** Large swathes of rural/wilderness NZ have little or no mobile network coverage. Imprecise quantification of areas with/without mobile network coverage results in conservative approach when considering utilisation of NRTK services in areas with possibly marginal mobile network coverage. Multiple mobile network providers do not have duplicate extents of coverage, necessitating the subscription of multiple mobile networks by users wishing to ensure maximum mobile network coverage. There is little commercial incentive for telecommunication companies to expand their mobile network coverage beyond population centres (i.e. extents of existing coverage).
- **Contention Ratio:** Mobile networks have a limit to number of customer’s to the available bandwidth within each “cell”, which may result in demand periodically

exceeding capacity. A commercial reseller reported that to their knowledge no communications provider is able to offer priority of service to data packets. This aligns with anecdotal reports that voice calls always take priority over data packets when cell network traffic reaches capacity limit. When demand exceeds capacity, data connections already in use may be interrupted and new data connections may be refused until sufficient mobile network capacity is restored.

- **Latency:** Accuracy decreases with an increasing latency of the reference station data. Centimetre-accurate positioning requires data transmission latencies of one second or shorter. Latency can be defined by three main components: the call set-up delay (the time elapsed between call initiation and receiving a response from the NPS), network delay (the time needed to transmit the signal) and the processing delay (the time needed by the rover to measure and calculate its position).
  In general, the data from the LINZ and GeoNet reference stations have a higher data latency than other sites. This is largely because many of the sites use satellite or radio based telemetry systems. The communication methods utilised by other public sites appear to have significant variations in latency performance.

6.1.3 Radio telemetry and WiFi

Hard-wired and mobile data telemetry systems are the communications methods most commonly utilised by NRTK services. However, terrestrial radio telemetry, satellite telemetry and WiFi could potentially provide alternative communications options. These vary considerably in their suitability, depending on the environment and circumstances in which they are deployed. Radio telemetry (terrestrial or satellite) is generally unsuitable or impractical as a means for connecting rovers with an NPS. It may be suitable for connecting reference stations with an NPS when hard-wired or mobile connectivity is not possible, but achieving acceptable latencies through to an NRTK rover user is likely to be challenging. With terrestrial radio telemetry, directional antennas and radio repeaters provide options for long range connectivity. Satellite telemetry is more suitable for connecting reference stations in remote locations to an NPS. Urban WiFi networks may become more suitable for rover connections to an NPS, particularly as the number of sub-metre positioning applications proliferate.

Additional information on radio telemetry is given in Section 2.2.2 and the MBIE Radio Spectrum Management (RSM) website www.rsm.govt.nz/consumers/frequencies-anyone-can-use.

6.2 RTK Network services

6.2.1 Network coverage and site density

International best practice appears to be a network of reference stations of semi-uniform density spaced at not more than 50-70km. Greater density provides greater redundancy for planned and unplanned outages of individual reference stations.

6.2.2 Data outages and reliability

To obtain a useful NRTK solution, a rover user requires: connectivity between reference stations and an NPS; connectivity between the NPS and the rover; processing at the NPS; processing at the rover. Total or partial failure of any of these can result in an outage or degraded performance. Automated software routines at the NPS are effective at managing the quality of the solution delivered to users upon exiting the NPS. Survey grade GNSS rovers are effective at managing quality control when communications connectivity is optimal, and also when it is significantly degraded. However problems can be encountered when the communications connectivity is marginal (e.g. alternating between optimal and sub-optimal states). It appears that rover quality control processes are not totally reliable when certain marginal communications connectivity states occur. This can result in positioning errors which are not reflected in the rover quality statistics.

6.3 Reference station coordinate accuracy

A prerequisite for accurate user (rover) positioning is that the reference station coordinates are of sufficient accuracy. Clearly, if the reference station coordinates are inaccurate, then various parts of the NRTK algorithm will not be optimum (e.g. ambiguity realisation), and such errors will propagate to the rover position solution. Ideally, the reference station coordinates should be an order of magnitude more precise than required by the rover. This would imply that if the user requires a coordinate accuracy of ±10 mm, then the reference station coordinates should be approaching a few millimetres.

To do this, the reference station coordinates must be in terms of the current coordinate frame of the satellite ephemeris (e.g. ITRF2014) and they must be current day coordinates, i.e. where the reference station is today (and not NZGD2000, epoch 2000.0). The reason for this is to account for any relative motion between region wide reference sites in the network. This is particularly important for New Zealand as it is actively deforming. Consequently, the rover position will also be in terms of the same coordinate frame and observation epoch position.

In New Zealand determining accurate reference station coordinates can be a challenging task as the country crosses an active plate boundary. Large earthquake events are relatively easy to deal with as a new position for one or more reference station can be determined after the event and the site coordinates updated. What is more difficult to predict are the non-linear motions associated with slow slip events (North Island east coast and Kapiti coast, top of the South Island) and post seismic deformation following earthquake events (e.g. Christchurch 2010-11 and Kaikoura 2016 events). Both are slow moving but will change reference station coordinates cumulatively by centimetres to decimetres, depending upon the size of the event. For example the 2013 Kapiti Coast slow slip event changed coordinates by 50 mm over the period of one year (Denys and Pearson, 2016) and the post-seismic motion following the Kaikoura 2016 earthquake has changed the PositioNZ sites by up to 200 mm over the first 4 months, and will continue for years to come.

There are two problems associated with reference station coordinates:

1. **Accurate Coordinates:** The ability to compute and maintain accurate reference station coordinates in a consistent manor. How the network reference stations are positioned with respect to the ITRF using stable cGNSS sites (e.g. IGS sites).
2. **Linear Velocity Model:** All commercial software assumes a linear velocity model. That is the reference site has a known coordinate (e.g. E, N, H) at a given epoch and a velocity. The coordinate is computed for the current epoch and cannot allow for any non-linear motion e.g. SSEs or post-seismic motion.

6.4 Local datum user positions

As mentioned in Section 6.3, user coordinates are with respect to the NRTK reference coordinate frame at the epoch of the observations. Often users require local datum coordinates and therefore need to be able to transform the observed position to the local datum and epoch. This can be a technically advanced process. In New Zealand this is a two stage process that involves a time-dependent 14 parameter Helmert transformation plus the application of the National Deformation Model (NDM) (see Figure 8). The 14 parameter Helmert transformation includes the normal Helmert 7 parameters (3 translations, 3 rotations, 1 scale change) except that the parameters are time dependent. Although the

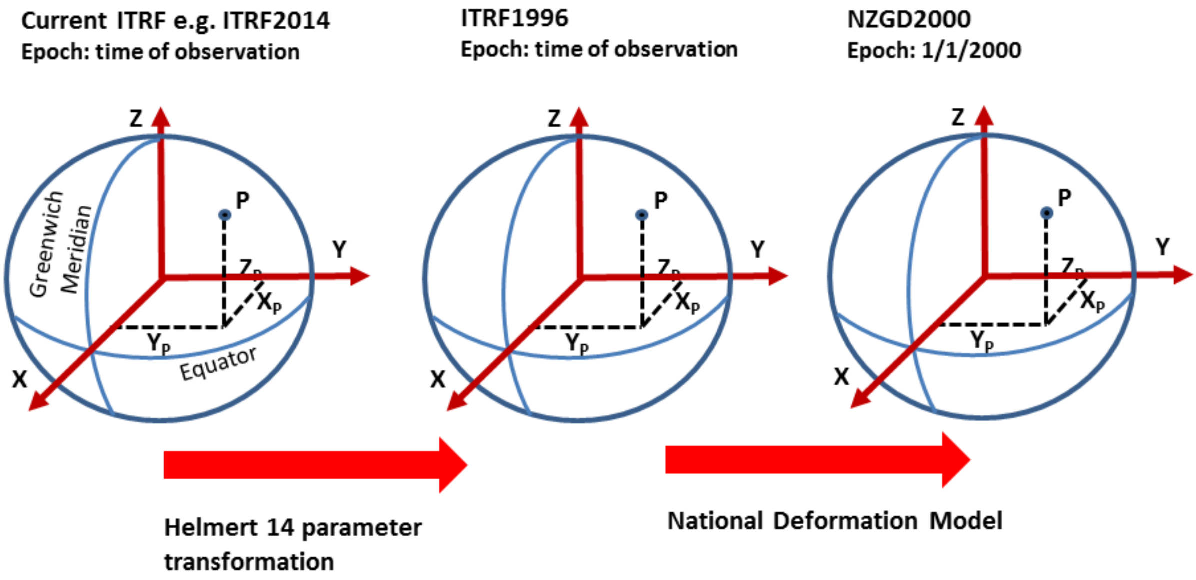

Figure 18: ITRF to NZGD2000 coordinate transformation

magnitude of the Helmert parameters are small (typically the translations are up to a few centimetres), the parameters change overtime.

- **ITRF2014, Epoch: time of observation**
  - Observed position
  - Compute Helmert parameters for observation epoch
  - Apply Helmert 7 parameter model
- **ITRF1996, Epoch: time of observation**
  - Corresponds to the definition of NZGD2000
- **NZGD2000, Epoch 1st January 2000**
  - Compute NDM motion for the difference between time of observation and 1st January 2000.
  - Apply NDM motion

Even though this process is applicable throughout the country using a current version of the NDM, it is not a convenient approach. Other common and simpler approaches to account for reference frame and deformation include:

1. **Local Transformation:** Tie to reliable local control marks and compute a horizontal or 2D transformation. The number of control marks to tie to depends on the application and survey reliability required. The most common method is to do a single point (3D) transformation with an additional check measurement to another reliable survey mark. For more reliability, additional survey marks need to be tied to and an inspection on the coordinate residuals to identify survey sites that are not reliable (outliers). Accounts for the difference between coordinate frames and deformation.
2. **Helmert transformation:** Tie to reliable local control marks and compute a Helmert transformation (7 or a combination of parameters). Not generally used for local surveys but applicable for regional surveys. Assumes that there is no significant deformation over the region surveyed. Accounts only for the difference between coordinate frames.
3. **Baseline vectors:** For some applications, the vectors between marks are required. By taking the join (distance, bearing, and/or height), the difference between coordinate frames i.e. ITRF and ITRF1996/NZGD2000 will be accounted for. Provided the control and observed marks are sufficiently close, any deformation will also be accounted for. Regions that do not have significant ongoing deformation (e.g. Northland, Southland) are unlikely to be affected by deformation.

Typical methods are listed in Table 2. The methods all account for the difference between coordinate frames (ITRF and ITRF1996/NZXGD2000), but only the 14p Helmert plus NDM will include motion due to deformation. The other methods either assume that the survey will be sufficiently small that deformation is not significant or that the deformation is not significant on a regional scale.

Table 5: Methods of remove coordinate frame and deformation biases.

Method	Scale	Application	Biases Removed	
			Coordinate Frame	Deformation
14p Helmert + NDM	National	Any coordinate based survey	✓	✓
7p Helmert	Region	Any coordinate based survey	✓	×
3p Helmert	Local	Topographical	✓	×
Local 2D transformation	Local	Any coordinate based survey	✓	×
Baseline vectors	Local	Cadastral	✓	×

7 NetworkRTK best practice

The NRTK method of operation is simple to use. However, serious positioning errors can be introduced if the user has no or only modest knowledge of the factors affecting the NRTK observations. Hence the need for best practice user guidelines is essential. The following outlines the necessary preparations, settings and quality indicators and check measurement procedures.

7.1 Preparation

Satellite prediction tools are valuable to use when the receiver-satellite geometry and number of satellites are of critical importance for the application at hand. In some software it is possible to change the elevation mask and draw obstacles so that an estimation of the quality indicators for a particular time of the day will be available. Other important preparations can be to calibrate the optical plumb of the antenna pole. It might also be necessary to mount the antenna on a tripod or use supporting legs (bi-pole), depending on the application at hand.

7.2 Settings and quality indicators

Making use of a higher than customary elevation cut-off angles is crucial in environments with low-elevation multipath. Elevation cut-off angle settings up to 15° can be suitable when GPS only is being used. However, it is then also important to carefully watch the Position Dilution of Precision (PDOPs) as a measure of the receiver-satellite geometry strength. Large PDOPs can cause positional excursions of several decimetres to metres even if the carrier phase ambiguities are correctly fixed (Teunissen et al., 2014).

The instrument-reported coordinate quality measures provided by most manufacturers are given at the one-sigma level, thus the user needs to multiply this value by 2.5 to be confident that at least 95% of the measurements are within the reported values. Note, however, that multipath, residual atmospheric errors and incorrectly fixed solutions are normally not included in the instrument-derived uncertainty values. Consequently, this can give the user a misleading impression of the expected positioning precision. Hence, additional check procedures on NRTK positions are always advisable.

7.3 Measurement check (control) procedures

Since the surveyor normally collects RTK measurements for at the most a few seconds or minutes at each point, check procedures are necessary. It is essential that check measurements are conducted with a fixed time separation since the measurements are highly correlated in time. This is mainly due to multipath effects, residual atmospheric delays and the slowly changing receiver-satellite geometry.

As an example, consider revisiting a previously measured point after an appropriate time separation, preferably 30-45 minutes or more (Odolinski, 2012), between the measurements. If this time separation is ignored the measurements are likely to be highly correlated in time, and any systematic biases can remain undetected as both measurements are contaminated by the same bias. This gives an inherent overly optimistic indication of accurate positioning (see Figure 9).

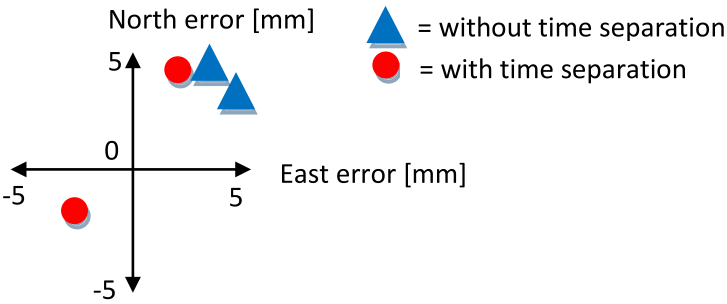

Figure 16: Example of two networkRTK positions in blue measured directly after each other, where strong time correlation between the positions exists. Positions in red are collected with a time separation between the measurements so that any time correlation can be reduced and thus any systematic biases can be detected.

Assume that our NRTK receiver can give us a nominal horizontal standard error (σ_{hz}) of ±10 mm, and a standard error in ellipsoidal height (σ_{vt}) of ±20 mm. Assuming no centring errors, we can expect a revisit or reoccupation of a point to achieve the following positioning precision levels at the 95% confidence level, computed using the law of error propagation (Odolinski, 2010),

$$\begin{aligned} \Delta^{\text{revist}}_{\text{horizontal}} &= 2.5\sqrt{2\sigma^2{}_{hz}} &\approx \pm 35\text{ mm} \\ \Delta^{\text{revist}}_{\text{vertical}} &= 2\sqrt{2\sigma^2{}_{hgt}} &\approx \pm 55\text{ mm} \end{aligned} \qquad (1)$$

If the values in (1) are exceeded when comparing two (or more) positions, further investigations into systematic errors should be conducted. Note that the geoid error is assumed to be equal between the two measurements in (1) under the assumption that the same geoid model has been used. These recommendations can be updated in future best practice guidelines when the positioning performance of the NRTK services is improved through multi-constellations. Other control procedures can be found in Odolinski (2010).

8 Alternative positioning methods

There are now a number of GNSS processing engines available online. In general, GNSS data in a RINEX format is uploaded to an online site, the data is processed, and the results (position, precision) is either downloaded from a web site or emailed to the user. The input requirements are different for each GNSS engine, but typical user input can require antenna height(s), antenna type(s) and to select an ITRF or local datum coordinate frame.

8.1 Online GNSS processing engines

Most online engines process the GNSS data in one of two methods, namely; in a baseline mode or as a precise point positioning mode. Currently both methods require a minimum of 1-2 hours of GNSS data for the position to converge, but do allow for longer baselines to be included, enabling better modelling of the troposphere to be undertaken. However, this requirement is changing quickly especially in regions where there is a dense cGNSS network and advanced troposphere modelling (e.g. Trimble's RTX).

In New Zealand, the biggest issue with online GNSS engines is the ongoing deformation. With the exception of the PositioNZ PP GNSS engine, online GNSS engines only provide coordinates in the current coordinate reference frame at the epoch of observation. Some engines provide transformation options, but this is generally only a coordinate frame transformation to an existing well defined local datum.

While online engines cannot afford the user real time positioning, they can be used to establish control coordinates in remote areas. One implementation of this is to provide an absolute coordinate for the base station in an RTK survey. An example workflow is for the base station to be logging (static) data at the same time that a RTK survey is being undertaken, provided that absolute coordinates are not required in real time.

8.1.1 Precise Point Positioning

Precise Point Positioning is a positioning methodology in which GNSS data from a single receiver (i.e. no nearby base station) to compute positions. The data from the receiver is processed using precise satellite orbits and clock data, to provide an absolute coordinate for the station to an accuracy of a few centimetres to decimetre level, in terms of the current ITRF coordinate frame.

Typically the technique requires 15-20 minutes of data for the position to converge to a solution at the sub-decimetre level, although recent advances show that the convergence time can be reduced to a few minutes. For more details of PPP refer to the European Space Agency Navipedia (www.navipedia.net/index.php/Precise_Point_Positioning).

8.1.2 Baseline positioning

A baseline processing solution takes the logged GNSS data at the site of interest and processes the baselines to selected cGNSS sites as a network solution. The coordinates of the cGNSS sites are assumed fixed at the epoch of observation. Typically three cGNSS sites are used and generally will be the three cGNSS closest to the new site.

8.1.3 Selected GNSS processing engines

Several online processing engines are currently available. Some examples are given in Table

Table 7: Selected GNSS Processing Engines

Software	Organisation	URL
GAPS	University New Brunswick	gaps.gge.unb.ca
APPS	Jet Propulsion Laboratory	apps.gdGNSS.net
magicGNSS	GMV Innovating Solutions	magicgnss.gmv.com
RTX	Trimble Centerpoint RTX PP	www.trimblertx.com
AUSPOS	Geosciences Australia	www.ga.gov.au
CRS-PPP	Natural Resources Canada	www.geod.nrcan.gc.ca
OPUS	NOAA's National Geodetic Survey	www.ngs.noaa.gov
PositioNZ-PP	Land Information New Zealand	www.linz.govt.nz

3

8.1.4 LINZ PositioNZ Post Processing Service (PositioNZ-PP)

In New Zealand, LINZ offered the PositioNZ PP service (www.linz.govt.nz/positionzpp). It uses the baseline mode by selecting three PositioNZ cGNSS sites. The reporting from this service includes coordinates in terms of ITRF2008, NZGD2000 geodetic coordinates and Meridional Circuit projection coordinates. Heights are in terms of NZVD2016.

The big advantage of PositioNZ PP is that the coordinates are transformed to NZGD2000 using the Helmert 14 parameter coordinate transformation and National Deformation Model. The process is describe in Pearson et al., (2015) and the method to compute the reference station coordinates given in Pearson and Denys (2015).

For more details see:

- www.linz.govt.nz/positionz-pp

8.2 Multi-GNSS

The American Global Positioning System (GPS), consisting currently (2016) of 32 satellites, has been used for decades for centimetre-level precise positioning surveying applications using the single-baseline/network RTK techniques. The Russian GLONASS system has also been a common complement to GPS in many GNSS receivers in recent times, as to increase the satellite availability and receiver-satellite geometry strength. The drawback with the GLONASS system is that the satellite signals are based on the Frequency Division Multiple Access (FDMA) technique, which is not compatible with the Code Division Multiple Access (CDMA) used by GPS. This can cause issues for the integer ambiguity resolution (Banville et al., 2013). Fortunately, Russia plans to launch new GLONASS satellites with CDMA signals to increase its interoperability with GPS (Kosenko and Revnivykh, 2015).

8.2.1 The emerging GNSSs

In the past few years new satellite systems have also been developed, such as the regional Chinese BeiDou Navigation Satellite System (BDS, currently 14 regional satellites), regional Japanese Quasi-Zenith Satellite System (QZSS, currently 1 satellite), Indian Regional Navigation Satellite System (IRNSS, currently 6 satellites), and the global European Galileo satellite system (currently more than 10 satellites). By 2020 BDS will become a global system and consist of 35 satellites in total, QZSS by around 7 satellites and Galileo will consist of 27 satellites. What is common for all these systems is that they are based on the CDMA technique similar to GPS. The surveyor will thus by 2020 have access to more than 100 different satellites that can be used in a combined RTK model. Regular updates of the current status of all GNSS constellations are published at: gpsworld.com/the-almanac.

8.2.2 Positioning availability and performance

The number of satellites for four satellite systems is depicted in Figure 9 over a 24 hour period in Dunedin, New Zealand (February, 2015). It can be seen that when all four satellite systems are combined the total of number of satellites (black lines) is often double the number of GPS satellites (blue lines). This leads to the conclusion that when using a combined system one is allowed to increase the elevation cut-off angle as to avoid low-elevation multipath signals, which will be of particular benefit in urban canyon environments.

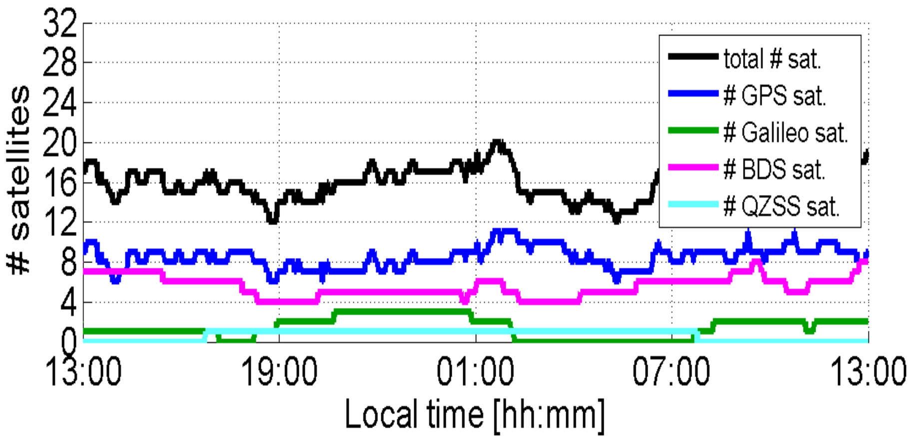

Figure 19: Satellite visibility in Dunedin, New Zealand (February 6, 2015) for an elevation cut-off angle of 10°. (Source: Odolinski and Denys (2015)).

Also interesting to note from Figure 10 is that the number of BDS satellites (magenta lines) is sufficient to provide for continuous standalone positioning over the day (at least four satellites are required). The current BDS constellation's geometry is, however, not always sufficiently strong to provide for reliable precise positioning when viewed from receivers in New Zealand. Nevertheless when BDS is combined with GPS (and the other systems) there are significant improvements that can be achieved. This will have significant benefits for NRTK users in terms of increased satellite availability, better and faster availability of correctly fixed positions, and better receiver-satellite geometries (PDOPs) that results in more precise positions and better performance especially in challenging locations (see also Odolinski and Khodabandeh, 2016).

9 Operations in other countries

9.1 Germany

The German SAPOS network is centrally operated as a joint project between multiple state governmental agencies, and is the official spatial reference system for all of Germany. It has been in operation for more than twenty years with on-going development. The SAPOS network consists of more than 270 SAPOS owned reference stations, plus another 30 stations owned and operated by other network operators in nine adjacent countries. The layout of reference stations was designed with reference stations spaced over the whole country at approximately 20-60 km separation. It supports GPS, GLONASS, Galileo, and regional augmentation systems (e.g. EGNOS), and uses international, open and standardised formats. SAPOS provides multiple service products to cater for a range of user types. Subscriptions are not free, and are comparable to commercial rates.

SAPOS is a benchmark for the NRTK system many countries would aspire to have. However it is perhaps an unrealistic model for an all-of-NZ network because of the quite different population densities and coverage of mobile data networks.

Further information can be found at:

- www.sapos.de/files/SAPOS-Broschuere-2015-eng.pdf.

9.2 North America

9.2.1 Providers

NRTK providers in North America are a mixture of State Governments and private enterprise. As of 2014, a total of 28 states offered state-wide NRTK service of some sort. These were offered by state government entities (generally the Department of Transport or State Geodetic Surveys for states that have them). There are a few cases where these are offered by University based entities, which are funded by federal grants. There are also two states that provide services covering certain urban areas that are operated by county governments. The state government networks are almost always available to the public (with the exception of Texas where the service is restricted to Department of Transport employees and contractors). Charging policies are variable. In many cases the service is provided free, in other cases there is a charge to partly defray costs of providing the service. The only significant public provider of RTK corrections is UNAVCO. They provide streaming services from many of their PBO stations but these are only single-base.

There are also several private providers, although none providing anything like nationwide coverage. The two main private providers are both associated with the manufacturers. Trimble VRS Now covers Florida, Georgia, Mississippi, Alabama, the eastern half of Texas and a broad zone across the Midwest (www.trimble.com/positioning-services/VRS-Now). Leica operates the SmartNet site (smartnet.leica-geosystems.us/coverage_network). This provides access to a series of networks operated by Leica. These nominally cover about half of the contiguous US and nearly all of Canada but in practice the networks are generally restricted to the more populous areas.

9.2.2 Best practice

The National Geodetic Survey has an extensive document covering best practice including designs for building and pillar mounts, and many of the issues covered in this white paper (www.ngs.noaa.gov/PUBS_LIB/NGS.RTN.Public.v2.0.pdf). Probably the sections of greatest interest to New Zealand is contained in Section V Obtaining Station Coordinates Consistent with NAD 83 and ITRS. Three key recommendations are:

- “Some RTN reference stations should also be contained in the CORS network” This recommendation is much easier to accomplish in the US than New Zealand because the US has depended almost exclusively on stations that are volunteered rather than being owned by NGS. As a result NGS has well established procedures to take in stations from a variety of owners and has developed the capacity to process a very large network.
- “For each reference station contained in the RTN, adopt values for its 3-dimensional positional coordinates (at a selected reference date) and a velocity that are consistent, with corresponding values adopted by NGS for reference stations in the CORS network, to within 2 cm in each horizontal dimension (north-south and east-west) and 4 cm in ellipsoid height.” This procedure will provide a constraint as coordinates and velocities are determined for other stations by the software. The major problem is the long lead time required to get reliable coordinates from continuous stations which means that, to provide constraints on the network during the early phase, which is when the coordinates and velocities are most uncertain, the CORS must be an existing station. In practice this is not too much of a problem for the most part given the very wide spread distribution of NGS CORS and PBO stations over the US.
- “For each reference station in the RTN, use the Online Positioning User Service (OPUS) at www.ngs.noaa.gov/OPUS or some similar utility, on a daily basis, to test

for the continued consistency of the station's positional coordinates and velocity, as adopted by the RTN administrator, with the coordinates computed by the utility; and revise the station's adopted coordinates and/or velocity if coordinate differences in excess of 2 cm in either horizontal dimension and/or 4 cm in ellipsoid height persist over a period of several days." A very sensible recommendation which would have avoided some of the problems observed in New Zealand RTN networks. The only concern is that if using some other online processing utility it should be capable of generating authoritative coordinates.

9.3 Australia

Similar to New Zealand, the big three surveying equipment manufacturers are all represented in Australia with RTK networks operated by their local distribution partners: CR Kennedy & Leica JV's "SmartNet Aus"; Positioning Partner's "AllDayRTK" (Topcon) service; Ultimate Positioning Group's "Trimble VRS Now" service. However, as might be expected in a country as large as Australia, network coverage and density of reference stations differs considerably between providers. The largest network consists of more than 500 reference stations, and all networks are focused on centres of population and industry (with no coverage of large swathes of the outback). Some of the networks encourage other organisations to add their own reference stations to their networks for commercial gain. Interestingly, Perth and other population centres in Western Australia are covered by "RTKnetwest" - a commercial service operated by four practising surveyors.

The situation in Australia is further complicated by public CORS sites being developed and managed by a variety of state and national agencies, most notably: CORSnet NSW (operated by NSW's Land & Property Information); Vicmap Position-GPS Net (run by the Victoria state government); AuScope Geospatial (a collaboration between Geoscience Australia and the Australian National University). As in New Zealand many of these public CORS sites are available to other users and are also incorporated into the commercial providers' networks.

CORSnet NSW is operated to a model which aims to balance public-good and commercial mandates. Users are charged to subscribe to its service, but the public agency responsible for the network recognises the wider economic benefits NRTK can provide to a range of sectors. In 2016 the network consisted of 180 reference stations, with further expansion planned. For more detail refer to "CORSnet-NSW: A Success Story" (Janssen *et al*. 2016).

10 Summary

NRTK involves the combination of multiple reference stations to improve the positional accuracy and reliability compared to single-base RTK. This is achieved through advanced spatial modelling of the atmospheric (troposphere, ionosphere) biases, satellite orbits and the resolution of the reference station carrier phase ambiguity terms. The improved level of positioning uncertainty at the rover is achieved by reducing the distance dependant errors that can dominate single-base RTK.

For rover users, NRTK improves productivity as a (local) base station is not required. There are savings in time since there is no requirement for setting up (or removing) a base station, reduced capital cost and elimination of base station equipment security issues.

NRTK requires efficient data communications and data processing. This is a three stage process: (1) near real time communication of the GNSS data from the reference stations to the NPS, (2) biases modelling and (3) GNSS data and spatial data models/corrections dissemination from the NPS to the rover user(s). Data latency is a limitation of this process, which is dependent upon robust and reliable data communication.

A key factor in the success of NRTK is the ability of the network to accurately model the atmospheric conditions, which in turn requires a reference network that is well distributed and with sufficient density in order to sample the atmospheric conditions.

Reference station coordinates need to be generated in terms of the current ITRF (currently ITRF2014). The relative position between reference stations must take into account regional deformation that has occurred over time. Similarly, care must be taken to accurately transform the rover coordinates to the local datum (i.e. NZGD2000). Depending on the application, this can be through a Helmert 14 parameter transformation, local transformation or baseline vectors.

Largely due to vendors efforts, New Zealand’s NRTK now extends to tens of reference stations, in the main clustered around the urban centres. While the vendor’s software is well established globally, there is evidence that suggests that current operations can be sub-optimal (although this is not always the fault of the service provider). The following are potential issues that are likely to affect operations:

- Density and configuration of reference stations,
- Mobile coverage across regional New Zealand,

- Data latency, and
- Reference station and user position coordination methodology.

NRTK is likely to become increasingly important across a range of sectors (not just surveying), and it may eventually come to be regarded as critical infrastructure. In order to achieve greater collaboration and more cohesive planning, it would be desirable to develop a national NRTK strategy between the stack holders: government, vendors, industry and other user groups.

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Appendix A : Data formats

Non-proprietary GNSS data formats enable the transfer of position, observation and correction data. Most data formats have been designed for particular purpose(s), which therefore limits the application of the format for specific applications. As technology has developed, a format may not be able to cater for new data types and therefore no longer be "fit for purpose". To overcome such limitations an existing format must be modified, extended or a new format developed.

Open GNSS formats were originally developed for real time applications, e.g. Differential GPS. For example, NMEA messages were developed for real time positioning applications to communicate position, velocity, time (PVT) and auxiliary information. The RTCM 2 format that followed was developed to cater for DGPS correction data i.e. Pseudorange Corrections (PRC). With the development of RTK and NRTK applications, a new format was required to include transmission of observational data that the RTCM 2 format could not contain. RTCM 3 was developed and then extended to cater for these applications.

The early data formats failed due to the lack of bandwidth when transmission of larger quantities of data was required (e.g. multi-constellation observational data) in real time (e.g. 1 Hz). To overcome these limitations, more effective methods have been developed such as efficient data compression techniques and the use of binary formats.

A.1 NMEA

An ASCII format developed by the National Marine Electronics Association (NMEA) to define data formats between (originally) marine instruments. For example; echo sounders, sonars, anemometer, gyrocompass, autopilot, GNSS receivers. Each message starts with a dollar ($) symbol and the data fields are separated by commas (see Figure 5).

Following the dollar symbol, there is a five character code that identifies the talker (or sending instrument), for example GP defines GPS, GL GLONASS; followed by three characters identifying the message type. Common message types include (but are not limited to) GGA: fix information, GLL: latitude, longitude data, GSA: satellite data, GSV: detailed satellite data

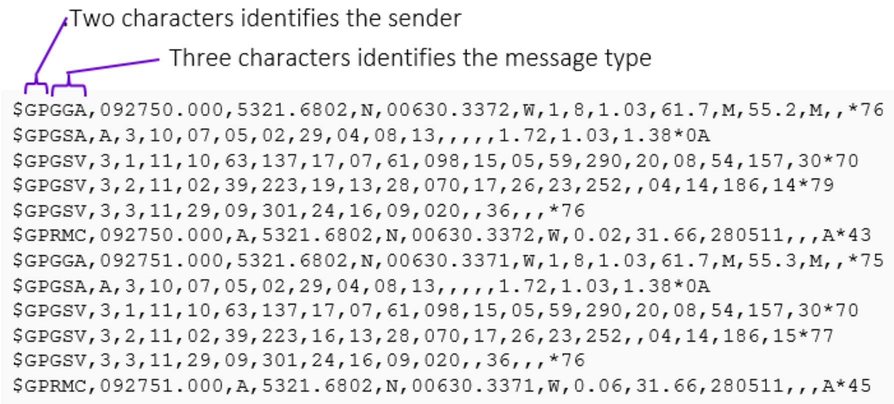

Figure 22: NEMA data records.

Details of the NMEA format can be found at:

- en.wikipedia.org/wiki/National_Marine_Electronics_Association

A.2 RTCM

To allow for the real time transmission of Differential Global Navigation Satellite Systems (DGPS/DGNSS) data, the Radio Technical Commission for Maritime Services (RTCM) Special Committee 104 developed the RTCM 2 format.

While initially supporting only DGPS (RTCM2.0), subsequent versions added capabilities such as the transmission of carrier phase data which allowed for RTK applications, GLONASS data and antenna types definition and reference point. Figure 6 gives an example of the message types available in RTCM 2.

RTCM2.X (X=1, 2, 3)

Message type	Content
3	(X,Y,Z) coordinates of antenna phase center, cm-precision
18	Code data
19	Carrier phase data
22	(dX, dY, dZ) corrections to message 3 coordinates to achieve mm-precision for L1 and L2 antenna phase center + height of antenna phase center above marker
23	Antenna and radome type definition
24	(X,Y,Z) coordinates of the antenna reference point

Figure 25: A selection of RTCM 2 message types

RTCM 3 was designed to be more efficient, initially consisting of message types to support RTK applications (GPS and GLONASS) (Figure 7). It was a completely new standard with new message types and a new structure. The format was enhanced (RTCM 3.1) with the addition of a NRTK correction message types.

RTCM 3.X (X=0,1)

Message type	Content
1003	GPS code and carrier phase observations
1004	GPS code and carrier phase observations + code noise ratio
1005	(X,Y,Z) coordinates of the antenna reference point
1006	(X,Y,Z) coordinates of the antenna reference point + height of antenna reference point above marker
1007	Antenna and radome type definition
1008	Antenna and radome type definition + Antenna serial number
1011	GLONASS code and carrier phase observations
1012	GLONASS code and carrier phase observations + code noise ratio

Figure 28: A selection of RTCM 3 message types

More recently, the standard has been modernised with the Multiple Signals Messages (MSM) record type that allows for the generic inclusion of new constellations and signals. MSM currently supports GPS, GLONASS, Galileo, BDS and SBAS.

Additional information on the RTCM standards can be found at:

- en.wikipedia.org/wiki/RTCM
- www.navipedia.net/index.php/RTK_Standards

A.3 CMR/CMR+/CMRx

The Compact Measurement Record (CMR) format was developed by Trimble in 1992. It was developed to provide a bandwidth-efficient alternative to RTCM 2 for RTK (GPS only) users. CMR+ is an improved version of the original CMR. With the advent of multi-constellations, a third frequency and possible carrier phase data from Satellite Based Augmentation Systems (SBAS), Trimble have developed CMRx. Although the CMR/CMR+ formats have been made public, the CMRx format is proprietary to Trimble.

Additional information on the standards can be found at:

- trl.trimble.com/docushare/dsweb/Get/Document-469944/WhitePaper_HeavyHighway_CMRxrev1

A.4 NTRIP

The Networked Transport of RTCM via Internet Protocol (NTRIP) was developed by the German Federal Agency for Cartography and Geodesy (BKG) and Dortmund University Department of Computer Science. The protocol was specifically designed to stream GNSS data over the internet based on the RTCM format.

Software to do this is freely available from BKG and includes three components: NTRIP Clients, NTRIP Servers and NTRIP Casters.

Additional information on the protocol can be found at:

- en.wikipedia.org/wiki/Networked_Transport_of_RTCM_via_Internet_Protocol
- igs.bkg.bund.de/NTRIP/about

A.5 RINEX and SINEX

While the RINEX and SINEX formats are not explicitly required for NRTK applications, the standards are widely used for GNSS data and solutions.

The Receiver Independent Exchange (RINEX) format has been used since 1993 for the dissemination and archiving of GPS/GNSS data. The key motivation for this format was to have a common standard for GNSS data that was independent of GNSS manufacturer's proprietary formats.

The RINEX format has been developed to include both GPS and GLONASS observation data, meteorological data and the satellite navigation data. The last RINEX 2 format (2.11) was extended to include Galileo data (observations, navigation), as well as the L2C, L5 codes. With new GNSS constellations, a new data structure was introduced with RINEX 3. The format includes BDS, QZSS, SBAS, detailed standards for the new carrier phase and code observables generated, GLONASS frequency slots and code-phase bias terms.

The Solution Independent Exchange (SINEX) is the standard for the exchange of GNSS solutions included station position, velocities, their precisions (covariance matrices) and receiver/antenna metadata.

Additional information on the standards can be found at:

- igscb.jpl.nasa.gov/components/formats.html