Broadcast Network RTK – Transmission Standards and Results

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BIOGRAPHY

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Dr. Ulrich Vollath received a Ph.D. in Computer Science from the Munich University of Technology (TUM) in 1993. At Trimble Terrasat - where he has worked on GPS algorithms for almost ten years - he is responsible for the Department of Algorithm Development. His professional interest is focused on high-precision real-time kinematic positioning and reference station network processing.

ABSTRACT

Network Real-Time Kinematic (RTK) positioning is the latest innovation in high precision GPS positioning. Network RTK involves the use of three or more reference stations to collect GPS data and extract information about the atmospheric and ephemeris errors affecting signals within the network. A central processing facility uses the reference station data to generate corrections that are then relayed to RTK users operating within the coverage region of the network. Single-reference station RTK is widely used for many centimetre-level applications. However, users must operate within say a 10-20km radius of the reference station. Beyond this limit, atmospheric biases degrade results – network RTK helps to overcome this limitation.

Network RTK can be implemented in either a Virtual Reference Station (VRS) or broadcast mode. The former approach requires RTK rovers to send their location to the central processing facility in order to receive a corrected data-stream from the network. The broadcast mode places the onus on the rover to interpolate atmospheric and ephemeris corrections that are transmitted by the network. Data transmission bandwidth comes at a premium for the broadcast mode and careful consideration must be given to a data transmission standard used for network RTK. A standard must be efficient in terms of size, but flexible enough to allow different manufacturers to implement their own innovative approaches for using correction information. In particular manufacturers should be able to use their own correction interpolation schemes and not be bound to a single strategy.

The following paper presents a new Network RTK data transmission format that has been formulated within the RTCM-Version 3 framework. The new format encompasses both single-reference and network correction layers and is scaleable to city-, county- and nation-wide coverage. Furthermore, the standard is designed to support data archival which is important for legal traceability purposes. Performance results from Network RTK positioning are compared to single-reference station RTK using datasets collected from an operational network in Germany. The Network RTK approach was found to provide improvements in initialisation reliability and time-to-initialise metrics in cases where ionospheric biasing was significant.

INTRODUCTION

Traditionally RTK positioning has involved the use of a single reference station that occupies a known location. Dual-frequency code and carrier phase measurements taken at the reference station are formatted and then transmitted (typically) via radio-link to one or more rover receivers operating within a 10-20km radius. The rover receiver(s) combine the reference station data with locally collected measurements to estimate carrier-phase ambiguities, and in turn, three-dimensional position to centimetre-level precision. Many of the systematic atmospheric and satellite-related errors cancel when processing the reference and rover station data. However, as the spatial separation of reference and rover increases, the assumption of error cancellation degenerates and the performance of the system degrades. This explains why RTK equipment manufacturers specify upper limits on operating range of the system at 10-20km.

Network RTK incorporates the use of three or more reference stations to infer how satellite errors vary spatially over an area in which users wish to operate. A similar concept has been used for wide-area differential GPS for some time, where sub-meter level precision is required. In the case of Network RTK, the corrections supplied to the rover must have centimetre-level precision - commensurate with the positioning requirements.

There are essentially two types of Network RTK implementations. The first is termed a Virtual Reference Station (VRS) system where spatial corrections are evaluated and then applied to a synthesized data stream that mimics a reference station that is adjacent to each rover. The second scheme is Broadcast Network RTK, that involves a common one-way transmission of satellite corrections to all rovers. The spatial interpolation of the corrections is the responsibility of the rover equipment.

The Radio Technical Commission for Maritime Services, Special Committee 104 (RTCM-SC104) consists of U.S. government and industry representatives and is responsible for developing open data transmission standards to support differential satellite positioning techniques. The RTCM-SC104 is currently converging on Version 3.0 that includes major revisions to the format structure and will provide far more efficient data throughput.

The following paper presents some of the technical issues surrounding Network RTK and then includes a discussion on broadcast Network RTK data formats tabled at the RTCM-SC104 meetings. The performance of the broadcast Network RTK mode is assessed via some live trials recently conducted.

NETWORK RTK ARCHITECTURE

Figure 1 illustrates the general elements of a broadcast RTK network. At the heart of the system is the control server which performs the following functions:

- Focuses the real-time data received from the reference stations,
- Runs integrity checks on the reference station data,
- Computes atmospheric and ephemeris errors across the network,
- Formats a correction stream and communicates this to the data transmitter,

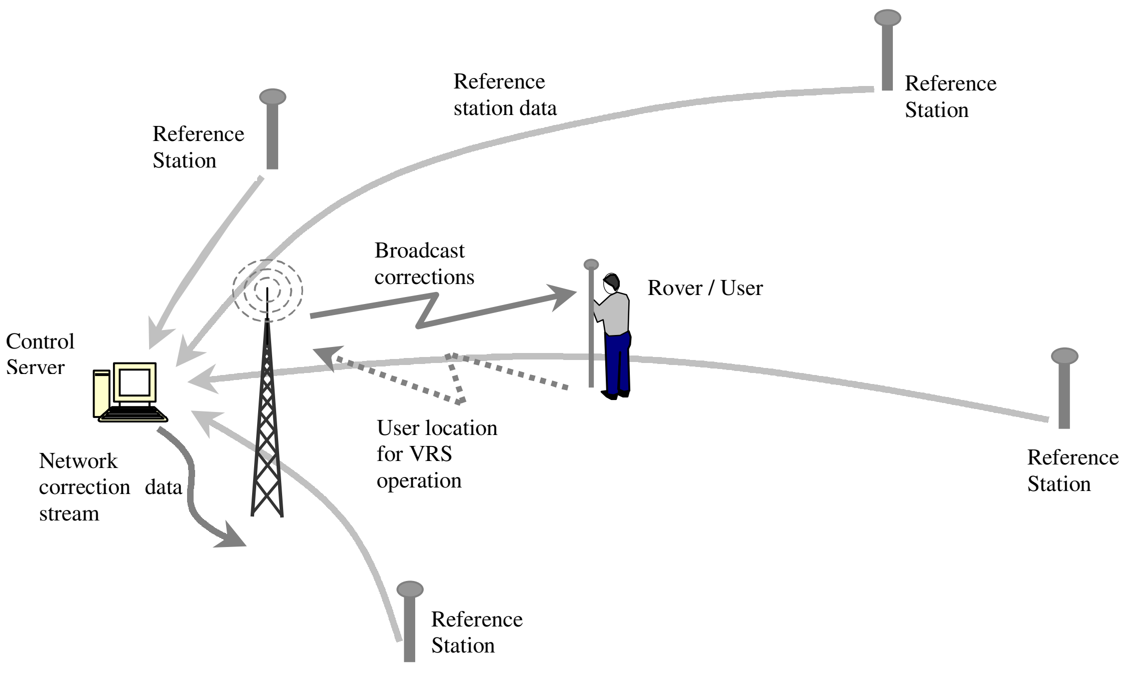


Figure 1. Network RTK system components and data flow.

The timely and reliable transmission of the reference station data to the control server is important to overall system performance. Typically data is relayed from reference stations to server using telephone lines with modems, or via the Internet. Where appropriate, microwave and other wireless technologies can be employed to reduce on-going costs.

The data transmission layer of the system relays the correct stream to one or more rovers operating within the network. The characteristics of the data transmission system have a large bearing on the perceived performance of network RTK. The transmission system should:

- support the transmission bandwidth requirements of the network RTK datastream,
- cover the region spanned by the reference stations,
- enable rovers to receive the data reliably and with equipment that is field-portable and accessible,
- be cost effective.

There are many options available today for supporting the data transmission component of the system, and include:

- VHF/UHF radio link,
- Cellular phone networks,
- Wireless Internet,
- Television and radio FM-subcarrier.

When the Network RTK is operated in a *broadcast mode*, data is transmitted one-way to the rovers. In contrast, a *Virtual Reference Station* system [Trimble, 2002] involves two-way interaction between each rover and the control server. It is worthwhile highlighting the differences between the two modes of Network RTK, which is the focus of the next section.

VIRTUAL REFERENCE STATION SYSTEMS VERSUS BROADCAST NETWORK RTK

Instead of broadcasting correction information to rovers and having them apply the network corrections, a Virtual Reference Station system takes an approximate location of a rover, interpolates corrections and generates a data stream for the specific rover location [Vollath, et.al, 2000, & Vollath, et.al, 2001]. The rover gets corrections that mimic those that would be generated from a nearby reference station. Apart from the necessity of two-way communication between control server and rover, there are other strengths and weaknesses of both broadcast-mode and VRS systems as summarised in Table 1.

The VRS mode is more suited to commercial applications where users are billed for access to the service [Vollath, et.al, 2000a]. It also provides backward compatibility with existing RTK equipment. The broadcast mode approach is good for free-to-air access over extended regions and for large numbers of users. The broadcast mode places the onus on the rover to interpolate corrections and therefore requires Network-RTK-enabled firmware.

Parameter	**VRS Mode**	**Broadcast Mode**
Data transmission model	Two-way	Primarily one-way
User-fee account management	Billing incorporated into system and readily managed	Need mechanism to stop unauthorized access to service and require billing process for commercial users
Number of users	Practical limits due to control server throughput	Unlimited – in principle
Communication media	Because of two-way communication requirement, best to use cell-phone, UHF/VHF, or wireless Internet link	Can use receive-only devices and therefore minimize size/weight/power at the rover
Computation burden	Control server performs interpolation of corrections and does not burden the rover.	Rover is responsible for applying corrections.
Backward compatibility	Existing RTK rover equipment should be able to utilise the data stream transparently.	Need rover equipment that is capable of decoding, and applying network corrections.

Table 1. Comparison of Network RTK operated in VRS- and Broadcast-Modes.

CHARACTERIZATION OF ERROR SOURCES

Careful consideration needs to be given to the characteristics of the biases affecting GPS observations in order to design a Network RTK system. Furthermore, the definition of a network RTK data format needs to provide sufficient range and precision to support the possible variation in the GPS biases [Talbot, et.al, 2002]. The transmission rate of corrections must be sufficient to represent the temporal changes of errors.

Ionosphere

The ionosphere encompasses the earth at an altitude of between 50 and 1000km. The ionosphere causes a dispersive effect on L-band microwave signals [Misra and Enge, 2001]. The effect is frequency-dependent and therefore can be essentially removed by combining L1 and L2 measurements.

The ionospheric bias is dependent on the following factors [Essex, 1997]:

- Elevation / azimuth angle of the satellite,
- Time of day (sun angle),
- Latitude,
- Solar storms.

Equatorial and polar regions experience extremes in ionospheric effects. The most serious effect is termed *scintillation* that causes rapid variation in the amplitude and phase of GPS signals [Aarons and Santimay, 1994; Klobuchar and Doherty, 1998]. Under turbulent conditions, the ionospheric biases spatially decorrelate rapidly [Skone and Cannon, 1997]. This means that reference stations spaced at 20km apart may be insufficient for inferring the intervening biases for rovers. During high ionospheric activity, the ionospheric biases at a point may vary by more than several centimetres per second, in which case ionospheric corrections quickly become outdated.

In mid-latitude regions, the ionospheric bias is more stable and generally only varies by up to a few millimetres per second, except for setting and rising satellites. Reference station spacings need only be every 50-100km for the purposes of sampling the ionosphere in mid-latitude networks.

The ionosphere is sometimes considered as a thin shell at an altitude of 350-450km. This is the altitude with the maximum electron density [Schaer, 1999].

Troposphere

The Troposphere is the lower part of the atmosphere and encompasses clouds (water vapour) and dry gases. It is generally accepted that the troposphere extends to an altitude of approximately 50km [Saastamoinen, 1972]. The troposphere is non dispersive and therefore its effect cannot be removed via observation on two frequencies. Fortunately the dry component of the troposphere accounts for the majority of the delay and can be derived via standard models [Goad and Goodman, 1974]. The wet component depends on prevailing weather conditions and is difficult to model.

The tropospheric delay varies with:

- Satellite elevation angle,
- Height above sea level,
- Temperature,
- Pressure,
- Relative Humidity.

Compared to the ionosphere, the tropospheric delay is slowly varying and rarely changes by more than a centimetre per second for satellites above 30 degrees elevation. Geographic areas can experience localized weather patterns and tropospheric delays, hence when establishing an RTK Network, it is important to locate the reference stations within the same climatic region (e.g. same valley).

Ephemeris

The GPS broadcast satellite ephemerides are updated every few hours. The accuracy of the broadcast ephemeris is normally 1-3m, but under eclipse conditions, errors in excess of 20m occur. A 10m ephemeris error translates into a differential error of 0.5 parts per million of the baseline length. Therefore, in the context of a 100km x 100km network, the ephemeris bias should contribute less than a decimetre to the error budget.

Each ephemeris update carries with it an issue number (Issue Of Data Ephemeris – IODE). It is essential for the reference station network and rover equipment to keep track of the current ephemeris issue number and match this to the appropriate corrections. This is particularly important during receiver start-up and during ephemeris rollovers.

ESTIMATING NETWORK CORRECTIONS

The control server software makes use of the dual-frequency code and carrier phase observations from the network to extract the prevailing errors affecting rover equipment. The theoretical foundation for this process starts with the following L1 and L2 phase equations (expressed in metres):

$$_{L1}\Phi^{j}(t) = \rho^{j}(t) + e^{j}(t) - \frac{I^{j}(t)}{_{L1}f^{2}} + \tau^{j}(t) + {}_{L1}N^{j} \qquad (1)$$

$$_{L2}\Phi^{j}(t) = \rho^{j}(t) + e^{j}(t) - \frac{I^{j}(t)}{_{L2}f^{2}} + \tau^{j}(t) + {}_{L2}N^{j} \qquad (2)$$

Equations 1 and 2 are presented in single difference form – where a common satellite (superscript – j) is differenced between a Master Reference Station (M) and Auxiliary Reference Station (A). The following definitions apply:

$_{L1}\Phi^{j}(t)$, single-difference L1 phase measurements observed to satellite j between stations M-A, at epoch t;

$_{L2}\Phi^{j}(t)$, single-difference L2 phase measurements observed to satellite j between stations M-A, at epoch t;

$\rho^{j}(t)$ geometric range term for satellite j, and reference stations M-A, taken at epoch t. This term is calculated by the Network RTK processing software using knowledge of the satellite location and station coordinates;

$e^j(t)$ — ephemeris error term for satellite j, stations M-A, at epoch t;

$\frac{I^j(t)}{{}_{L1}f^2}$ — ionospheric error term for the L1 frequency band for satellite j and stations M-A, at epoch t. In equation 2, the denominator of the ionospheric term contains the L2 frequency;

$\tau^j(t)$ — tropospheric error term for satellite j, stations M-A, at epoch t.

${}_{L1}N^j, {}_{L2}N^j$ — L1, L2 carrier phase ambiguity terms converted into meters.

Receiver clock error terms can be estimated by the control station software and have been ignored in equations 1 and 2. Similarly, antenna phase offsets are not explicitly shown, since they can be removed from the geometric range terms via standard models [Mader, 2002]. Although random errors and multipath affect (1) and (2) they have been ignored since they are not directly relevant for the discussions below.

The control server software estimates and resolves the integer carrier phase ambiguity terms contained in ${}_{L1}N$ and ${}_{L2}N$ with the aid of pseudorange observations and with a-priori knowledge of the reference station locations [Han and Rizos, 1996]. Once the L1 and L2 ambiguity terms are known, they can be used to form unbiased carrier phase observations – these are distinguished with a superscript bar in (3) and (4) below.

By forming ionosphere-free and geometry-free linear combinations of (1) and (2), we arrive at expressions that have observed and known quantities on the right-side and the required parameters on the left-side [Talbot, et.al, 2002]:

$$e^j(t)+\tau^j(t)=\frac{{}_{L1}f^2\times{}_{L1}\overline{\Phi}^j(t)-{}_{L2}f^2\times{}_{L2}\overline{\Phi}^j(t)}{{}_{L1}f^2-{}_{L2}f^2}-\rho^j(j) \quad (3)$$

$$\frac{I^j(t)}{{}_{L1}f^2}=\left[\frac{{}_{L2}f^2}{{}_{L2}f^2-{}_{L1}f^2}\right]\times\left[{}_{L1}\overline{\Phi}^j(t)-{}_{L2}\overline{\Phi}^j(t)\right] \quad (4)$$

Equation (3) contains the geometric bias that combines the ephemeris and tropospheric terms. The ionospheric bias (in meters) on the L1 signal is directly available from equation (4). The geometric and ionospheric bias terms are derived by the control server between each reference station in the network and at each epoch time (t).

INTERPOLATION OF BIASES

Once the ionospheric and geometric bias terms have been estimated between the reference stations in the network, both time-wise and spatial interpolation algorithms are needed to derive corrections for the rover receivers. The interpolation technique should have a theoretical foundation that matches the physical characteristics of the problem. Figure 2 depicts a cross-section of a network. Although the separation of the reference stations is exaggerated in relation to the earth's radius and satellite altitude, it endeavours to highlight the spatial decorrelation that tends to occur in the atmospheric biases as baseline lengths increase.

The onus for interpolating the spatial- and time-wise biases can be placed completely on the control server software, as is the case with a VRS. Alternatively, if corrections are sent in a raw form, the rover must perform the interpolation. A compromise is to split the responsibilities between the control server software and rover. The decision on where the interpolation should take place is intrinsically linked to the broadcast network RTK data format and must consider data bandwidth and computational throughput issues.

Two of the network RTK data formats before the RTCM suggest sending geometric and ionospheric correction parameters for each satellite and each reference station in the network [Zebhauser, et.al, 2002; Talbot, et.al, 2002]. This approach provides the greatest flexibility for processing the data at the rover, however it is not the most bandwidth efficient. An alternative scheme is to produce an error model that describes the ionospheric and geometric corrections for each satellite over the entire network region. The advantage of the network-wide approach is that the bandwidth requirement does not increase with increasing numbers of reference stations. The disadvantage is that the correction models must be sufficiently detailed to accurately represent errors across potentially large regions.

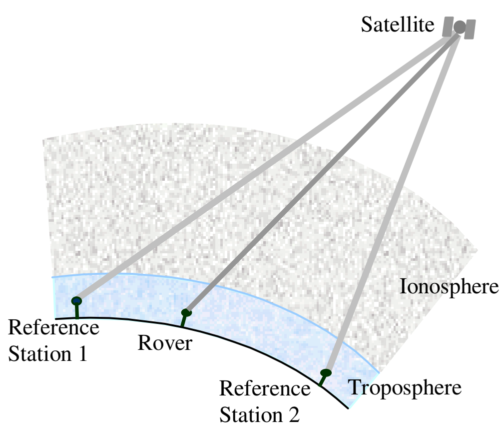


Figure 2. Cross-section representation of network correction interpolation.

A variety of techniques have been proposed for encapsulating the ionospheric and geometric corrections across an RTK network. Wübbena and Bagge [2002] suggest the use of a linear area polynomial (bi-linear interpolator). The interpolator uses a reference surface defined parallel to the WGS84 ellipsoid and at the height of one of the reference stations. East and north part-per-million gradients are then used to complete the model.

Higher-order interpolators have also been considered for the ionospheric and geometric biases such as bi-quadratic surfaces. Tomography is yet another mechanism being studied for use in describing the ionospheric bias over large regions. Colombo et.al. [1999], divide the ionosphere into two-layers and then use satellite ray pierce points to derive ionospheric bias values for three-dimensional cells overhead.

Raquet [1998] proposes the use of collocation techniques to model the spatial variation of the geometric and ionospheric biases across a network. Collocation is already an established tool for estimating physical phenomenon such as the earth's gravity field [Bomford, 1980]. The collocation method separates errors into signal and random components. The signals are estimated at the reference stations and hence provide an interpolator for the rover stations. An important aspect of collocation is the derivation of covariance matrices that are parameterised in terms of distance and time.

Spherical harmonic expansions are used in the derivation of the IONEX format for worldwide ionospheric modelling [Schaer, 1999]. Unfortunately the IONEX models are very generalised and are not suitable for the representation of ionospheric bias over small regions.

Error sources affecting the rover equipment are significantly reduced as a result of using proper interpolation techniques. In addition, the characteristics of the errors are changed in a manner that supports convergence of navigation and ambiguity resolution filters. In particular, the bias magnitude and temporal correlation are reduced. (Vollath, et.al., 2002).

As Network RTK technology matures, it seems likely that standardized interpolation/extrapolation algorithms will be developed and finally adopted by the RTCM. Until then, a data transmission scheme that does not enforce a particular interpolation scheme on the rover, is most suitable for the Network RTK messages.

TRANSMISSION FORMAT

There are some basic assumptions upon which a Network RTK data transmission standard should be built [Talbot, et.al, 2002]:

- General - the format should be sufficiently general to allow open interoperability between control server software systems and rover equipment from different manufacturers,
- Robust – the integrity of the rover position is paramount and must not be compromised by ambiguity or uncertainty in the transmission format,
- Scaleable – the format should be scaleable from three stations operating in a city, right through to hundreds of stations across a country,
- Efficient – the format must fit within the practical limitations of wireless data link bandwidth.

A data transmission format has been developed using a balanced view of the aforementioned requirements [Talbot, et.al., 2002]. The format extends the work of Zebhauser, et.al., [2002], and Townsend, et.al., [2000]. The network format starts with the concept of a cell.

Cells

Network cells are used to divide the computation of network corrections into manageable segments (< 32 stations) and to link this to the data delivery mechanism, somewhat along similar lines to cellular phone networks.

A layered approach has been taken for the Network RTK corrections. Standard RTK (carrier phase and pseudorange data) is transmitted from a Master Reference Station within the network. Existing single-baseline RTK users can therefore operate without knowledge of network corrections. Where possible the Master Reference Station should be located at the activity focus of the cell (figure 3). In the context of regional coverage, the Master Reference Station might be located at the centre of a large city.

If the Master Reference Station ever fails, the control server must switch the master to another station in the cell.

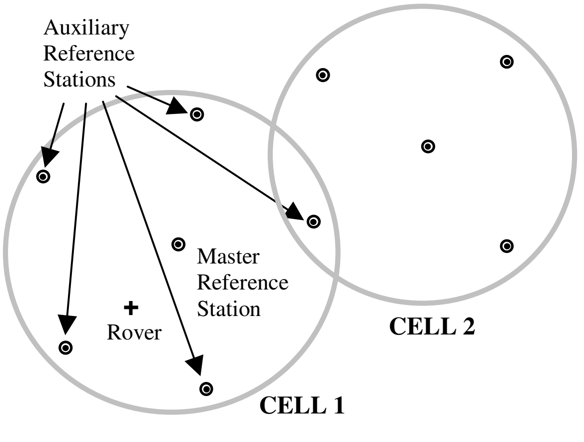


Figure 3. Plan view of an RTK Network.

Rover receivers require reference station locations for network correction interpolation. Instead of sending the full geographric coordinates of the auxiliary reference station, their location is encoded relative to the Master Reference Station in a *cell definition* message. The size of the cell definition message can therefore be minimised while still providing metre-level precision for horizontal coordinates and centimetre-level precision for height. The tropospheric bias is sensitive to height and therefore more precision is devoted to height, than horizontal coordinates. The precise WGS84 coordinates of the Master Reference Station are available directly from the standard RTK data layer.

Network Corrections

Separate ionospheric and geometric correction messages have been devised. A block of ionospheric, or geometric corrections is sent for satellites tracked at each auxiliary reference station. The absolute ionospheric and tropospheric biases are generally not accurately known for each satellite, however the relative (differential) biases between the Master and Auxiliary stations is precisely known and this is the information that is sent (refer to equations (3) and (4) above). The format makes provision for absolute corrections to be transmitted albeit with lesser precision.

Message Scheduling

Except for ephemeris updates, differential ephemeris errors change slowly over time. Likewise, the tropospheric biases for satellites above 30 degrees, vary by less than 1cm / minute. Where possible the data transmission throughput should be spread-out so that it doesn't contain peaks and troughs. Therefore an important aspect of the data transmission standard is the flexibility to divide satellite corrections into *slow* and *fast* rate categories. Geometric correction parameters need only be sent every 10-15 seconds, while fast-rate ionospheric corrections should be sent every 1-2 seconds.

All information that is required to commence operation in the field should be sent in a timely fashion. Therefore both correction messages for all satellites/stations and the cell definition message should be sent within a 30 second window.

Message Summary

Table 2 contains a summary of message sizes for the network correction layer [Talbot, et.al, 2002]. Standard RTK transmissions for the Master Reference Station must be included in a calculation of the total throughput. Assuming that there are 10 satellites in view, 6 reference stations (master plus 5 auxiliary), the throughput will be:

- ~180 bytes for the standard RTK layer,
- 59 bytes for the cell definition,
- 225 bytes for the ionospheric corrections, and
- 275 bytes for the geometric corrections.

Therefore even if all messages are scheduled at the same 1Hz rate, the total throughput is ~739 bytes which would be supported on a 9600 baud link. Normally message scheduling would be used as alluded to above, in which case the peak throughput could be kept below 4800 baud.

Message Type	Size [bytes]	Description
Cell Definition	14 + (9 * N)	Contains the location of auxiliary reference stations in a cell.
Ionospheric Correction	[15 + (3*S)]*N	Ionospheric corrections for satellites between master/auxiliary stations
Geometric Correction	[15+(4*S)]*N	Combined ephemeris and tropospheric corrections for satellites between master/auxiliary stations

Table 2. Throughput requirements for Network RTK correction layer. (N=number of auxiliary stations; S= number of satellites).

TESTING BROADCAST NETWORK RTK

As a test network, a part around Munich, Germany of the BLVA network of the land surveying authorities in Bavaria has been used. This test-bed is continuously operated for GPSnet software testing and development. The network consists of 7 stations, each station has a dual-frequency GPS receiver and is permanently connected to the Trimble Terrasat office via leased data lines. The network configuration is shown in figure 4 including the inter-station baseline lengths.

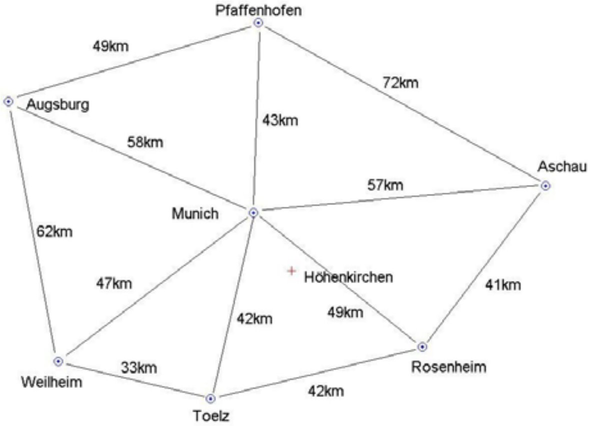


Figure 4. Munich test network used for RTK evaluation in single-baseline and broadcast network modes.

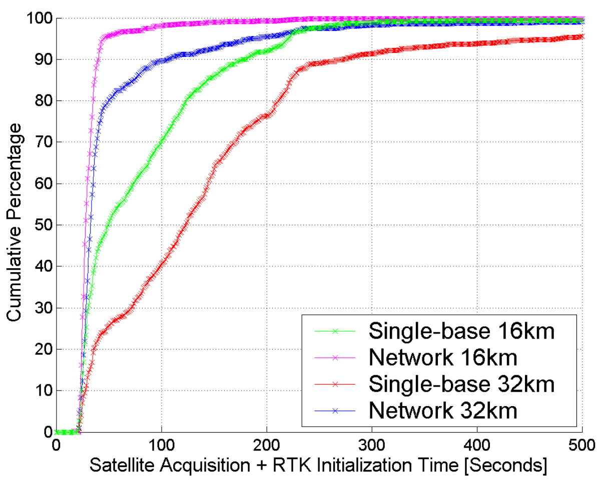
The Trimble Network RTK software [Trimble, 2002] can be operated in either a VRS or Broadcast mode. The broadcast mode was used for the tests described below.

Four concurrent tests were run over a 40-hour period to evaluate the performance of RTK in single-baseline and network modes. Four Trimble 5700 receivers were connected to the same antenna at the Trimble Terrasat office at Höhenkirchen. Standard single-baseline data was fed from Munich and Toelz into two 5700 receivers, thus giving rise to 16km and 32km baselines, respectively. Network corrections were input to the other two 5700 receivers at Höhenkirchen. One set of corrections was derived from the entire network, while the second correction stream was created without the nearest network station - Munich.

Each 5700 receiver was configured to output position information via serial cable to the same personal computer. A proprietary PC test application monitored the initialisation status of each receiver. Position, satellite and ambiguity resolution status information was logged continuously. Once all receivers gained initialisation, power to the common antenna was cycled, thus forcing all receivers to reacquire satellites and repeat the initialisation process. This test system is described by Riley, et.al, [2000] and has been very useful in benchmarking and improving RTK products over the past decade.

RESULTS

Figure 5 illustrates the cumulative time-to-initialise for the 4 different 5700 receivers. The importance of removing the ionospheric bias from data for ambiguity resolution purposes is well documented in theory [Teunissen, 1997], and the results of network corrected data provide very noticeable benefits for the time-to-initialise statistics. The 16km baseline with network corrections exhibits the sharpest elbow in figure 5. In other words, the majority of initialisations occur within a short period of time. The network-corrected 16km baseline results are comparable to those regularly achieved with single-baseline RTK on lines less than 10km where ionospheric biases are typically small. The 32km baseline with network corrections has the next-best performance. The single-base RTK results for the 16 and 32km lines exhibit the worst



initialisation times.

Figure 5. Cumulative probability of ambiguity resolution for single-base and network modes over 16km and 32km baselines.

The single-32km baseline has the worst performance of the four scenarios, which is to be expected. Note that the initialisation times include satellite acquisition, convergence of the float ambiguities and finally the search and validation phases of the initialisation. This means that all traces start along the x-axis and not from zero.

The accuracy of the initialized solutions is an important metric used to evaluate RTK Systems. Table 3 contains a summary of the mean and standard deviation of the network and single-baseline initialized solutions, for east, north and up components. Once again, the benefits of the network corrections are immediately evident. The standard deviations of the network results are smaller than the single-baseline solution. This is partly due to a reduction in the spatial ionospheric and geometric errors in the network solution; plus the reference station phase multipath is reduced. The network corrections do not totally remove the spatial errors affecting the rover receiver, particularly as the length to the nearest reference station is increased.

Mode	Length	Mean [mm]			Sigma [mm]		
		E	N	U	E	N	U
Single	16 km	7	-6	7	14	11	25
Network	16 km	-3	2	8	11	7	22
Single	32 km	-20	-7	-1	21	14	42
Network	32 km	-4	-4	0	17	10	38

Table 3. Positioning results for single-baseline and network RTK tests.

CONCLUSION

Broadcast network RTK techniques are gaining momentum and provide potential for delivering centimetre-level accuracy to an unlimited number of users operating in cities, states and even across countries.

Network RTK techniques reduce the impact of ionospheric and geometric errors over the spatial bounds of a set of reference stations.

Live testing of broadcast network RTK data have shown that both the initialisation time and baseline accuracy is improved compared with single-baseline techniques. The 90 percentile initialisation times were more than halved with network corrections applied to 16km and 32 km baselines.

The proposed network RTK data format currently before the RTCM-SC104 can readily support open operability between control server software packages and rover equipment from different manufacturers. The data format can operate within the bandwidth limitations of common wireless delivery systems and has been designed so that it can be scaled from city-wide, to national coverage.

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