Trimble RTX, an Innovative New Approach for Network RTK

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ABSTRACT

The concept of the Virtual Reference Station (VRS) for network RTK was introduced for real-time positioning in the late 90s. In this particular concept the atmospheric error sources and orbit errors are mitigated via the use of appropriate error models based on multiple base stations. The VRS technology requires bidirectional communication to allow the VRS server to generate data streams for specific rovers in a standardized data format such as RTCM or CMR. As an option for VRS, the RTCM SC104 committee has standardized a broadcast network RTK data format which is often referred as Master-Auxiliary Concept (MAC). This data format consists of the transmission of observational data from multiple stations to the rover, where the carrier phase ambiguities have been leveled between the different stations of the network. One of the limitations of the RTCM MAC format is that the number of stations that can be included in the data stream is limited. Thus, while this type of correction does not require a bidirectional communication link, it still suffers the effect of potential connectivity limitations. Similarly to the VRS concept, the MAC concept is not readily suitable for applications in areas with limited connectivity.

The paper introduces a new technology called RTX, which overcomes the limitations of the existing solutions and is now available as part of the Trimble CenterPoint RTX service. Trimble RTX is capable of providing cm-accurate positioning solutions in real-time with initialization times of less than a minute for unprecedented coverage areas.
The solution utilizes a broadcast transmission with extremely optimized bandwidth, supporting GPS and GLONASS, and supports large networks with 100 and more stations. The authors describe in detail the overall concept of the server software, the communication via L-band satellite link from a geostationary satellite or via NTRIP *(RTCM, 2011b)* and the RTX rover implementation.

Performance results from static and dynamic field testing demonstrate the overall Trimble CenterPoint RTX system performance.

INTRODUCTION

Network RTK schemes have been developed over the last 15 years, e.g. the Virtual Reference Station (VRS), best suited for bidirectional communication and the Master-Auxiliary Concept (MAC, *RTCM 2011a*), which was initially developed to provide a better broadcast solution but in practice it is today mainly used with cell phones using bidirectional communication. RTK networks today easily consist of 50 to 100 stations and the possibility to transmit the required data stream for a complete network of that size with the MAC RTCM format is just not possible given the data rate limits of communication media, and the fact that the number of stations in a MAC sub-network is limited to 32.

A new approach to Network RTK was developed and implemented in the Trimble CenterPoint RTX service to overcome some of the limitations of the classical VRS scheme and the RTCM MAC data format. Goals were:

- To provide a complete solution from server to rover
- Ability to transmit networks with 100 stations in one single broadcast stream via L-band link from a geostationary satellite and/or mobile phone
- Reduce the required bandwidth significantly to reduce transmission costs
- Longer inter-station distance to reduce network setup and maintenance cost
- Mitigation of code and carrier multipath
- Improved tropospheric and ionospheric error mitigation
- Ability to use precise real-time orbit and clock information
- Smooth concurrence of a global data stream with augmented data providing additional information for selected regions

- Ability to reach global positioning coverage with centimeter level accuracy
- Shorter convergence time with an enhanced rover RTX Engine

MODELLING THE ERRORS

The following simplified observation equations can be used to describe GNSS code/carrier phase data:

$$\lambda\,\phi_r^{\,s}(t_i) = \rho_r^{\,s}(t_i) + c\cdot(\tau_r(t_i) - \tau^s(t_i)) + \alpha_r^{\,s}(t_i) - I_r^{\,s}(t_i) + (\beta_r(t_i) - \beta^s(t_i)) + \lambda N_r^{\,s} + m^S{}_{\phi r}(t) + \varepsilon^S{}_{\phi r}(t_i)$$

$$P_r^{\,s}(t_i) = \rho_r^{\,s}(t_i) + c\cdot(\tau_r(t_i) - \tau^s(t_i)) + \alpha_r^{\,s}(t_i) + I_r^{\,s}(t_i) + (\gamma_r(t_i) - \gamma^s(t_i)) + m^S{}_{\mathrm{Pr}}(t_i) + \varepsilon^S{}_{\mathrm{Pr}}(t_i) \quad (1)$$

where

λ	nominal carrier phase wavelength, currently we are using L1 and L2 observables
ϕ_r^s	carrier phase observation for receiver r and satellite s,
P_r^s	pseudorange observation for receiver r and satellite s,
ρ_r^s	geometric range from receiver r to satellite s,
τ_r,τ^s	receiver and satellite clock bias terms respectively,
α_r^s	non-dispersive atmospheric delay,
I_r^s	dispersive atmospheric (ionospheric) delay,
β_r, β^s	receiver and satellite carrier bias terms respectively,
γ_r, γ^s	receiver and satellite code bias terms respectively,
N_r^s	integer ambiguity term, and
m_r^s	multipath on carrier and code, and
ε_r^s	noise on carrier and code, and
c	speed of light.

While in a classical RTK solution the positions are derived from a double difference approach, the Trimble RTX solution makes use of satellite position information influencing ρ_{rs}, satellite clock information τ_s. The satellite carrier and code bias information β^s and γ^s, all computed by the Trimble CenterPoint RTX control center. This information is derived from a global tracking network *(Leandro et al., 2011)*. A regional augmentation network provides local information on tropospheric and ionospheric errors in the region speeding up initialization times significantly. The rover RTX positioning solution makes use of all this information resulting in an optimum position solution.

The tropospheric and ionospheric information from the regional augmentation network in CenterPoint RTX is updated with a much lower frequency (e.g. ≥ 10 seconds) than the satellite clock information. The availability of the satellite clock information in the GNSS rover together with a high clock update rate can be used together with the rover observables to come up with precision position estimates at update rates of up to 50 Hz. Therefore Trimble RTX has the potential of serving various GNSS positioning solutions for different markets like Agriculture, Mapping, GIS, Survey, and Machine control.

THE SERVER SYSTEM

The Trimble CenterPoint server receives data from global reference stations equipped with Trimble NetR5/8/9 receivers. The latest Trimble NetR9 receiver has 440 parallel channels and is able to track all existing satellite navigation systems of GPS, GLONASS, QZSS, GALILEO and COMPASS. From these data streams we compute real-time orbit, clock information plus additional parameters allowing precise GNSS positioning in Trimble GNSS receivers. Depending on the communication links the information can be made available with update rates of up to 1Hz.

A second process on a separate server is using the real-time (orbits, clocks, etc.) information as input and uses additional reference station data from a regional network, e.g. a network covering the agriculturally most important parts of the mid-west states in the US. This particular network currently consists of 75 stations with an inter-station spacing of roughly 120 km (Fig. 2).

Data is forwarded to a NTRIP Caster for distribution to the satellite uplink station in the US and then uploaded to the SkyTerra satellite. The NTRIP Caster can also distribute the data stream into the Internet for possible use by all receivers connected to the Internet. While this is not a released Trimble service yet, the hardware and software is available distributing the data streams to large number of customers via cell phones etc. (Fig. 1).

It should be explicitly mentioned that the description and the figures in this paper are simplified in a descriptive way to allow easy interpretation for the reader. The real

Trimble CenterPoint system provides redundancy with backup hardware and software at each individual component to ensure the highest availability.

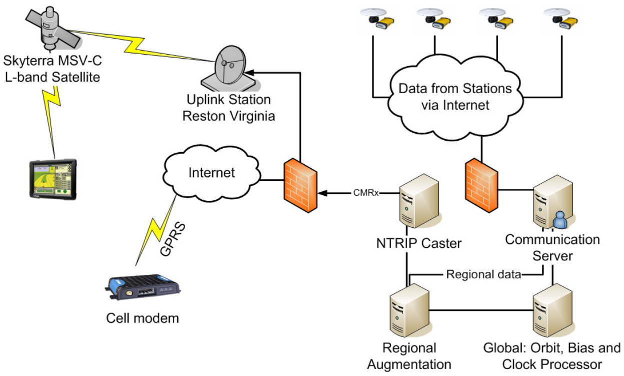

Figure 1: Data flow and processing in the Trimble CenterPoint system (descriptive simplified scheme)

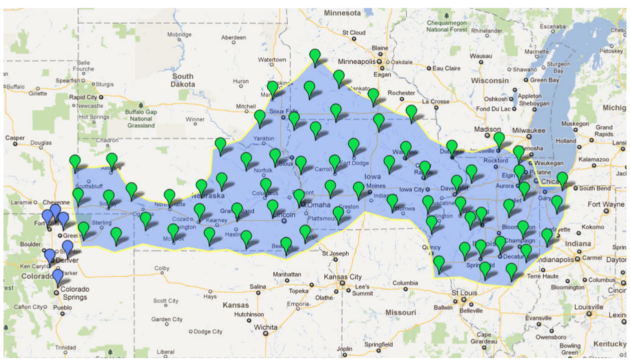

Figure 2: Trimble CenterPoint augmentation network in the mid-west (75 stations, 120 km station spacing, ~477400 km²)

The data stream distributed by the CenterPoint NTRIP Caster uses a special version of the Trimble proprietary data format CMRx, which was especially developed for Trimble CenterPoint RTX operation.

CORRECTION STREAM PROPERTIES

The CMRx correction stream comprises the following information:

- Precise satellite position
- Precise satellite clock
- Additional biases
- Quality indicators
- Additional flags and indicators
- Tropospheric data
- Ionospheric data

While the server system is totally configurable to allow easy adaptation for different communication media, the update intervals we currently use for the SkyTerra spot beam link in Central North America are

- Satellite position: 20 sec
- Satellite Clocks. 2 sec
- Biases and other parameters: 60 seconds
- Iono-, troposphere: 12 seconds

The overall coverage of the spot beam is described in *Leandro et al (2011)*. The L-band bandwidth available for the service is 2400 bps. This gives us enough space to transmit all required data for all visible GPS and GLONASS satellites.

RTX POSITIONING TECHNOLOGY

Most of the traditional Network RTK techniques like VRS and RTCM 3 MAC rely on a physical base station (PBS) or Master station. The advantage is that the network processing software is relatively simple – there is no need to estimate all error sources precisely. The drawback is that the data quality of this station strongly influences the rover performance, i.e. the multipath effect of this station is 100% transferred to the rover positioning.

The new approach presented in this paper gets rid of the dependency on a physical station (PBS). Instead, this approach models all error sources precisely with either mathematic models, e.g. antenna phase center variation, solid earth tides, or computes error estimates with regional network data (i.e. tropospheric and ionospheric effects). Orbit error is not modeled in the regional network as the orbit can be modeled much better with a global network (with Trimble Real-time precise orbit or IGS ultra-rapid orbit). The satellite clock error is modeled in the regional network to absorb residual orbit error seen in the region. Additional biases are estimated to preserve the integer nature of carrier phase observation.

Trimble RTX server processing averages multipath m_r^s and noise states ε_r^s of code and carrier observations from the reference stations involved and thus results in superior positioning solutions when compared with the classical network RTK concepts.

RTX rover positioning is an enhanced extension to a long tradition of RTK technology developed and optimized by Trimble over the last decade for both benign and challenging tracking environments. That alone makes our RTX positioning solution reasonably different from other positioning engines developed elsewhere in both design and performance. Furthermore, the RTX rover comprises state-of-art ambiguity estimation, taking advantage of the integer nature of RTX corrections received by the rover. Last but not least, we have developed and optimized a number of innovative features that help to increase the productivity in practical applications in the field.

SUPPORTING EXISTING COMMUNICATION FORMAT STANDARDS

As mentioned above, the CenterPoint RTX system transmits and applies state space parameters at the rover receiver resulting in optimum precise position estimates. In order to support existing standards like the RTCM 3 format we can also transform the state space information to observation space and transmit it in RTCM or CMR format as described by equation (2).

$$\lambda \tilde{\phi}_v^s(t_i) = \bar{\rho}_v^s(t_i) - c \cdot \bar{\tau}^s(t_i) + \tilde{\alpha}_v^s(t_i) - \tilde{I}_v^s(t_i) - \tilde{\beta}^s(t_i)$$

$$\tilde{P}_v^s(t_i) = \bar{\rho}_v^s(t_i) - c \cdot \bar{\tau}^s(t_i) + \tilde{\alpha}_v^s(t_i) + \tilde{I}_v^s(t_i) - \tilde{\gamma}^s(t_i) \tag{2}$$

where:

$\tilde{\phi}_v^s$	reconstructed carrier phase observation at approximate rover location v from the state space parameters,
$\tilde{P}_v^s$	reconstructed pseudorange observation at approximate rover location v from the state space parameters,
$\bar{\rho}_v^s$	geometric range from location v to satellites computed from the estimated precise orbit
$\bar{\tau}^s$	estimated precise satellite clock error
$\tilde{\alpha}_v^s$	non-dispersive atmospheric delay at location v estimated (interpolated) from regional network
$\tilde{I}_v^s$	dispersive atmospheric delay at location v estimated (interpolated) from regional network
$\tilde{\beta}^s$	satellite carrier phase bias estimated from regional network
$\tilde{\gamma}^s$	satellite code bias estimated from global network

As the reconstructed carrier phase and pseudorange observations are built from the state space parameters that are computed with large number of global and regional reference station data, the code and carrier phase multipath are greatly reduced. This leads to a better position performance than a classical Network RTK solution.

COMPARING VRS AND RTX RESULTS

The main difference between VRS and RTX is the way the corrections are applied. For VRS, the differential corrections (geometric and ionospheric correction) between the Physical Base Station (PBS) and the VRS location are added to the PBS observation and then a geometric displacement from the PBS to the VRS location is optionally applied (*Vollath et al., 2000*). This means the VRS data will inherit 100% of the multipath effects from the PBS. On the other hand, RTX applies directly the corrections computed from the global and regional networks (or uses the corrections to generate synthetic reference station data from equation 2), thus multipath errors are greatly mitigated. Fig. 3 shows the comparison of rover 2D positioning performance during a time period where the nearest reference station to rover has quite strong multipath. The green and red lines in the plot shows 50, 68, 90 and 95 percentile of 2D positioning error of RTX and VRS respectively. The light blue bars shows improvement of 2D positioning error as a percentage. Generally, 2D positioning of RTX is about 25% better than VRS at 68 percentile and 24% better at 95 percentile.

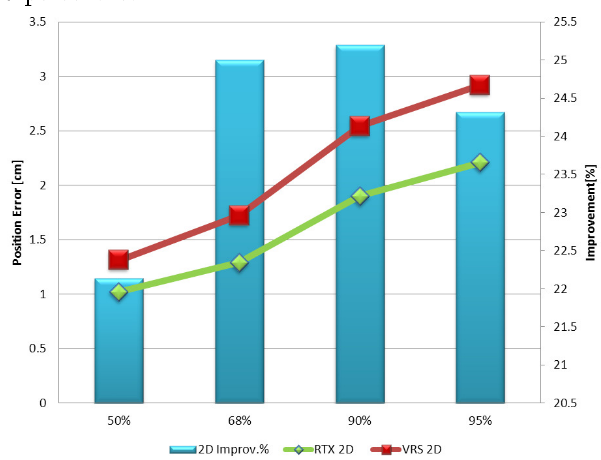

Figure 3 VRS and RTX positioning performance comparison at time period that the closest reference station has strong multipath

USING CENTERPOINT RTX IN THE MID-WEST OF THE US

Figure 2 shows the coverage area of the CenterPoint service in the mid-west. A typical kinematic positioning performance plot showing the horizontal position error of a CenterPoint RTX rover receiving the correction stream via the SkyTerra satellite over a full day is shown in Figure 4. The horizontal RMS is typically around 1.5 cm while the 95 percentile is 2.7 cm or 1.1 inch. This accuracy is reached on a daily basis by a large number of monitor stations in the coverage area and has been verified in real dynamic agricultural scenarios with tractor mounted equipment.

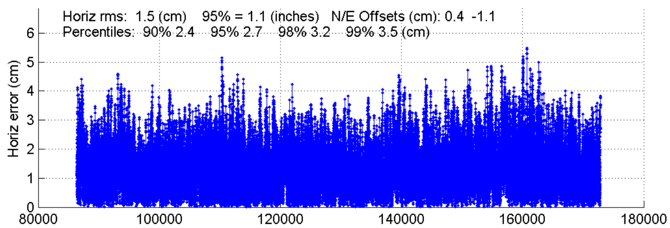

Figure 4: Typical horizontal rover positioning result for a rover in Illinois using Trimble CenterPoint RTX

Successful RTX rover ambiguity resolution is typically achieved within one minute of rover receiver operation. Re-initialization test runs are performed continuously by monitoring stations. A typical example of such re-initialization run results is shown in Figure 5. The initialization times were allocated to 5 second bins for a suitable bar chart. Initialization times start at 20 seconds due to the 12 second update interval of the regional augmentation data and the latency of the communication link. The majority of initialization runs provide successful ambiguity resolution between 20 and 45 seconds. The mean initialization time is 32 seconds.

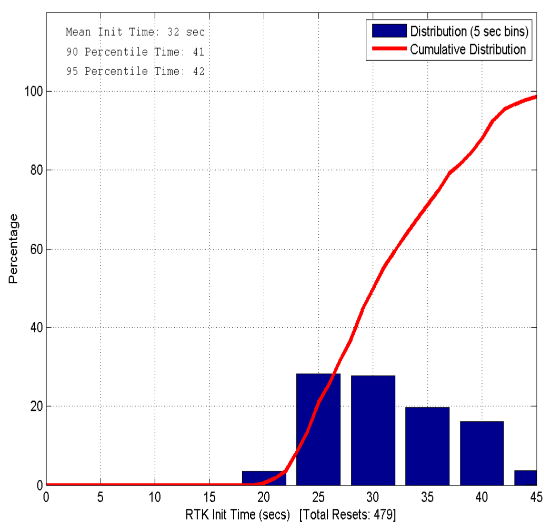

Figure 5: Typical initialization times with the Rapid Initialization feature of Trimble CenterPoint RTX (example taken from a rover in the central US spot beam of the MSV-C satellite, the vertical shows the percentage of init runs for each 5 second bin and the red curve represents the cumulative percentage of inits)

RECEIVER HARDWARE SUPPORTED

The initial release of CenterPoint RTX targets the agricultural market. Two different receiver types (Fig. 6 and Fig. 7) used in precision farming applications are currently supporting RTX technology. Both are able to track the L-band CenterPoint correction stream from the SkyTerra satellite using their GNSS antenna

The Ag FMX receiver supports GPS+GLONASS tracking and has 72 parallel channels.

Figure 6: Trimble Ag FMX receiver display

The Ag CFX receiver supports GPS+GLONASS tracking with 220 parallel channels. It was released in September 2010.

Figure 7: Trimble Ag CFX receiver display

Both receiver boards are integrated in a display unit for easy installation in the tractor cab.

USING TRIMBLE CENTERPOINT RTX ON THE TRACTOR IN THE MID-WEST OF THE US

Before releasing Trimble CenterPoint RTX the system underwent immense testing over the last 18 months. This included testing on a large selection of monitoring stations together with field trials using the products displayed above in their typical agricultural environments. The following shows an example of such a test, which was performed in Illinois in May 2011. Fig. 10 shows the tractor path during that test, which was done over a time period of 69 minutes.

Figure 10: Google Earth view of a 69 minute dynamic Field testing on a tractor in Illinois, May 2011 (Green < 1 inch, Yellow < 2 inch, Orange < 3 inch)

The tractor was equipped with two receivers, one was providing the CenterPoint RTX solution while receiving the data via the SkyTerra satellite, while the other was computing a single base RTK solution using the radio link from a nearby reference station. The latter one was considered to be truth for the test although the single base solution obviously also has an inherent position noise itself. Therefore, the comparison of positions from the two solutions will result in contributions from the single base as well as from the Trimble CenterPoint RTX solution.

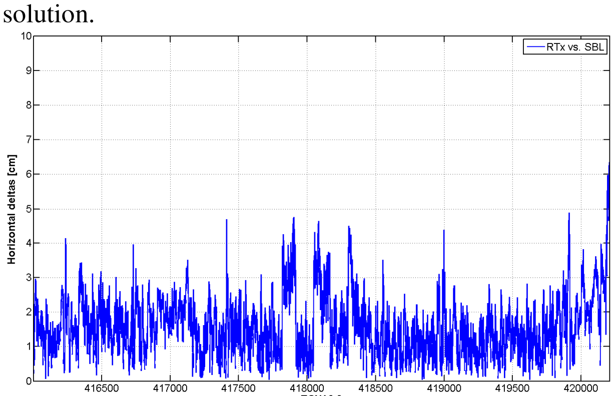

Figure 3: Dynamic Field testing on a tractor (69 minutes): Horizontal position difference between the CenterPoint RTX and a single base RTK solution using a local base station (2DRMS=1.7 cm, 95% 2DRMS=3.1 cm).

The overall accuracy analysis by differencing the two position solutions result in horizontal errors of 1.7 cm RMS and a 95% value of 3.1 cm or 1.2 inches as shown in Fig. 11.

CONCLUSIONS

Trimble RTX technology and the newly launched Trimble CenterPoint RTX service deliver a complete system solution from server to rover.

The general RTX network modeling approach is superior to classical VRS and MAC concepts with respect to final accuracy.

Positioning accuracy with RTX is dependent on the update rate of the different parameters involved. In the specific implementation of the CenterPoint RTX in the US we achieve 1.5 inch horizontal accuracy (95%) in kinematic and static environments while using a 2400 bps satellite link transferring data from 75 stations. The convergence time is typically less than one minute when using the CenterPoint RTX system in the US.

The new technology can be applied in various applications requiring high precision positioning including agriculture, mapping and GIS, machine control, survey and construction.

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