GPS + GLONASS for Precision

South Carolina’s GNSS Virtual Reference Network

With Russia’s GLONASS undergoing a rapid rebuilding and modernization process, GNSS receiver manufacturers and users have found more reason to consider exploiting the larger number of satellite signals available in a mixed constellation. South Carolina’s Geodetic Survey (SCGS) has put the state on the map as the first to implement a “virtual” reference station network that provides precise real-time differential corrections to both GPS and GLONASS signals. The chief of SCGS and the VRS project manager describe how their agency did it and who’s benefiting from the new statewide service.

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The SC Geodetic Survey (SCGS) has combined the technologies of the GPS, GLONASS, cellular communications and high-speed server networks to provide centimeter-level accuracy in real-time for surveying, mapping, and engineering applications.

Named the SC Virtual Reference Station (VRS) Network, the system is composed of 45 global navigation satellite system (GNSS) receivers installed statewide and connected by high-speed Internet to servers in the state capital, Columbia. Users connect in the field via cellular digital data communications to access the servers and obtain near real-time custom corrections to position objects or automate vehicle operations.

The South Carolina Department of Transportation has partnered with the SCGS with the intention of using the VRS for machine control to automate highway construction. South Carolina is the only state in the nation to use this technology to include the Russian GLONASS satellites as well as GPS satellites for a more robust solution.

Important to the implementation of the VRS is the provision of a common and consistent connection to the North American Datum NAD83 (2007) via the South Carolina State Plane Coordinate System. All coordinates produced through the use of VRS can be directly tied to NAD83 (2007). Surveyors and engineers will no longer need to be concerned about datum issues and coordinate conversion.

This article will describe how SCGS, which operates within the state Budget & Control Board’s Office of Research and Statistics, designed, implemented, tested, and operates the GNSS VRS network today.

*The term “VRS” is widely used to describe real-time correction networks. The term “VRS” and the technology originated with and are trademarked by Trimble.*

VRS Network Design

The VRS concept involves collecting raw carrier phase and code information from GNSS satellites once a second (1Hz) at each of the 45 GNSS receivers that are uniformly distributed across the state at an average spacing of 70 kilometers. A remote user in the field (rover) connects their GNSS (or GPS) only receiver to the server in Columbia using cellular communications.

Most cell phones used for voice communications will work as an Internet Provider (IP). The server creates a custom set of corrections based on the location of the rover. Applied to incoming raw satellite data at the rover location, these corrections can improve the positional accuracy from the Standard Positioning Service average of 10 meters to centimeters.

A “virtual” base station is mathematically simulated in the proximity of the rover’s location; therefore, the VRS positional accuracy is not degraded by an additional part per million (ppm) from the distance to a base station as in the typical real-time kinematic (RTK) technology.

This dramatic increase of accuracy results from a combination of equipment, network design, real-time knowledge of the cycle ambiguities between the network stations and all in-view satellites, application of sophisticated atmospheric modeling, the ability to model the multipath effects at the network stations, and server hardware and software design. We will discuss each of these aspects in more detail.

Network Hardware Design

The VRS network consists entirely of advanced commercial GNSS receivers capable of tracking up to 72 channels of data from both GPS and GLONASS satellites. The receiver technology includes high precision multiple correlators for pseudorange measurements and employs unfiltered, unsmoothed pseudorange measurement data for low noise, low multipath error, a low time-domain correlation, and as a result has a high dynamic response.

These receivers can track GPS L1 C/A-code, L2C, and L1/L2 full carrier in addition to GLONASS L1 C/A-code, L1 P-code, L2 P-code, and L1/L2 full carrier. A typical kinematic horizontal precision of ± 10 millimeters + 1ppm RMS is specified by the manufacturer.

The SCGS also procured GPS/ GLONASS-capable GNSS receivers with built-in geometric quality antennas for field operations. The rovers are controlled by a data collector that has a Bluetooth wireless connectivity to the receivers and cell phones used by SCGS.

The number and spacing of the VRS network receivers was designed to provide centimeter-level positioning performance on a 24/7 basis. A station spacing of 70 kilometers (see Figure 1) between adjacent network receivers was considered dense enough to provide this accuracy even if several of the receivers were out of service at the same time (assuming that the out-of-service receivers were not in the immediate vicinity of one another).

The loss of several stations throughout the network can be tolerated because the solution for any given rover receiver is based on correctors generated for the network as a whole with a heavier weight to the nearest stations. The largest distance, 93 kilometers, between network receivers is in northeastern South Carolina, in the vicinity of the Sumter National Forest.

The GNSS antenna mounts conform where possible to the National Geodetic Survey (NGS) Continuously Operating Reference Station (CORS) guidelines. NGS specifies the use of stainless steel brackets mounted to masonry structures with the antenna supported by a tamper-proof leveling head as shown in Figure 2. Antenna mounts for sites near the coast were designed to withstand up to a Category 3 hurricane. Site selection was based heavily on the reliability of Internet connectivity, building design (masonry construction required in all cases where the antenna was to be mounted to the structure), and emergency backup power on site.
coordinates to ensure the values held fixed from the OPUS solutions do not vary more than a few centimeters.

The network software issues a warning if larger positional changes are detected. In the future, SCGS will perform a local survey tie to each network station in order to ensure that the network station coordinates are consistent with the monumented National Spatial Reference System (NSRS) using NAD83/2007 and NAVD88 (North American Vertical Datum of 1988). NGS height modernization specifications will be used for these local surveys, and the data will be submitted to NGS for approval.

Once the network coordinates have stabilized, approximately 15 of the 45 stations will be submitted to NGS to become part of the agency’s national CORS network. These 15 CORS will then become the fiducial network for the SC VRS.

### Atmospheric Refraction

Atmospheric refraction is dealt with as a network solution. Three parameters for ionospheric refraction are solved each second. The network design and station spacing permits the derivation of a constant ionospheric correction (I) from the dual frequency information as well as two time-dependent gradient estimates (a and b) that result from the change in the zenith distances between satellite and network stations (i.e., signal path change) for the entire network.

In other words, changes in satellite position lead to changes in the mapping function of ionospheric refraction. A change in the satellite position results in a change to the piercing coordinates through the ionosphere, at the same time dynamic changes occur in the ionosphere. Both of these changes lead to the time-dependent terms of ionospheric refraction. I(a, b) represents the total ionospheric refraction and can be represented by:

\( I(a, b) = 1 + a \lambda + b \phi \)

where the partial derivatives \( a_{\lambda} \) and \( a_{\phi} \) are defined as \( a_{\lambda} = \frac{\partial I}{\partial \lambda} \) and \( a_{\phi} = \frac{\partial I}{\partial \phi} \).

Therefore, every second, the ionospheric refraction for the entire network is modeled along with an estimate of how it is changing with time (Figure 4). In addition to a more robust solution for ionospheric refraction, this time-dependent portion of the model is used to minimize the effect of latency between the reception of satellite data and rover corrections.

### Modeling Signal Multipath

One pervasive concern regarding GNSS accuracy is the ability to detect and mitigate multipath effects. Multipath is the result of the satellite signal reflecting off objects before it reaches the GNSS antenna. The receiver must be able to differentiate a signal received directly from the satellite versus a reflected signal.

The design of the antenna ground plane stops most signals that are reflected up to the antenna element. Receiver design uses various electronic filtering and correlation techniques to detect and eliminate multipath effects. Multipath effects can be minimized by the proper selection of sites for the network stations; however, regardless of design and placement of antenna, a certain level of multipath remains.

Because the network stations receive the same satellite signals repeatedly over consecutive 12-hour periods, a history of multipath can be established for each satellite/receiver combination. The multipath effect can then be modeled in the network software state-vector solution to minimize multipath effects at the network stations (Figure 5). Roving GNSS users must still be careful to select sites that are resistant to multipath effects when performing their work.

### Server Network Design

The conceptual design of the SC VRS server network is summarized in Figure 6. The data collected from the 45 network stations stream to one of three virtual servers. South Carolina has taken an innovative approach by using two to house the three virtual servers created with virtualization software and used for the SC VRS.

The virtual servers have a 3.0 GHz CPU and 2 GB of RAM. The virtual server infrastructure resources are re-allocated as needed with VMware. Two of the three virtual servers host the RTK network kernel of the receiver manufacturer’s GPS network software and provide the user community with virtual network station corrections. If one of the virtual servers were to fail, the second, redundant virtual server would automatically take the load and the network would continue to operate seamlessly. The third virtual server operates as the repository of the carrier phase data collected from the network stations and hosts several additional applications in the GNSSNet suite of software.

Data from the reference stations enter the virtual infrastructure through a firewall. The data then streams to each of the three servers: ORSV005, ORSV006, and ORSV007. ORSV005 collects the VRS data and distributes the real-time corrections, determined by the RTK network software, to the user via one of three formats: CMR+, RTCM 3.0, and RTCM 3.1. ORSV006 and ORSV007 are clones of ORSV005 and are used to re-distribute the workload of ORSV005 if VRS software detects the need. A possible cause for this would be a large number of users accessing the VRS network simultaneously.

### RTCM 3.1 and CMR+ Details

The virtual server operates as the FTP client site for the NGS and hosts the Network Transport of RTCM via Internet (NTRIP) Caster. The NGS server network design

FIGURE 5

FIGURE 6

FIGURE 4

FIGURE 3

FIGURE 2

FIGURE 1
accesses the server hourly to download files for the national CORS located in South Carolina. Finally, the ORSV/MON server is used for the WebServer.

Users of the SC VRS gain access to the VRS network via a database that contains all of the user’s key and password information. Before gaining access to the network each user must have a username and password assigned by SCGS. Usernames and passwords must be maintained in the database and verified by NTRIP before the user is allowed access to network corrections.

The SC VRS is operating with 30 network stations installed in the initial operating condition, (IOC). The VRS is operational across two-thirds of the state where the spacing of network stations meets the minimum standards required for accurate RTK corrections. The IOC designation is beneficial for the SCGS. It allows the staff of the Office of Research and SCGS personnel to troubleshoot IT and infrastructure problems as they arise.

When the final operating condition is implemented, RTK corrections will be available 99.9% of the time. The NTRIP and IP services have been enabled and users of the network interested in a VRS solution, log on to the network using a Windows mobile device accessing an IP address and port.

Beginning on October 1, 2007, RTCM 3.0, RTCM 2.3, CMRs, and single baseline solutions will be available using NTRIP. The SC VRS currently has 64 users and will be capable of supplying RTK solutions to 200 users simultaneously.

Examples of SCGS projects using the VRS network are described in the sidebar, “A Sampler of VRS Projects.” Users include professional land surveyors, construction and other types of companies with machine control applications; environmental, agricultural, and forestry engineers; engineering companies, and several federal, state, county, and municipal technicians.

Among the range of user applications for the SC VRS network are: machine control, engineering, and forestry applications; data layers within a geographic information system, precision agriculture, site preparation for general construction, and layout, designing, and staking of land to make it suitable for the construction of a road. All of these applications are tied to a common coordinate system, the SC State Plane Coordinate System and the NAD 83(2007) adjustment.

Testing Network Performance

All sites are expected to meet NGS standards for Continuously Operating References Stations (CORS). The design specification for the SC VRS calls for real-time accuracy at the rover location of 1.2-centimeter horizontal root mean square error (2-D RMSE) with a 95 percent confidence interval, as shown in Figure 7, and 2.4-cm vertical (1-D RMSE) accuracy with a 95 percent confidence interval. Both specifications are based on a position dilution of precision (PDOP) of 5 or less with five or more satellites. The network spacing design of about 70 kilometers with 45 GNSS stations should accomplish these specifications.

To use the network’s accuracy, three rovers were used to measure 50 NGS Height Modernization Program geodetic control points. The 50 points span an 11-county area (Figure 8). All sample points meet the National Geodetic Survey accuracy standard of 2-centimeter orthometric heights for the National Height Modernization Standard. As a side note, the horizontal component of GPS derived orthometric heights are generally considered twice as accurate as their vertical component for directly connected control points. The 50 sample points chosen not only meet the Height Modernization Standard but are also directly tied to the High Accuracy Reference Network and CORS managed by NGS.

The network design calls for rovers to always be operated inside the bounds of the network. The control point sample includes the NTRIP control points outside the perimeter of the test network to ascertain if the determination of the coordinates would be degraded.

The test procedure consisted of visiting each site twice on two different days with a time separation of 27 hours. This is similar to the National Height Modernization Standard procedure. Each rover was attached to the top of a fixed two-meter high pole and supported by a bi-pod. The leveling bubble on each pole was checked for proper collimation before and after the test period.

Site Measurements. At each visit, the rover was turned on and allowed one minute to connect to the network. Upon initialization and cycle ambiguity resolution, a five-minute data set at a 1Hz rate was collected. The PDOP and number of satellites during data collection had to meet the design specification throughout the five-minute session. Each configuration was repeated, down, reset over the mark, and powered up again; this time a one-minute data set at 1Hz was collected. The process was repeated a third time collecting a five-second data set at 1Hz. The data were recorded as a single-point value for the orthometric height using the South Carolina State Plane Coordinate System on NAD83/2007 and NAVD 88 for the orthometric heights.

Accuracy Metrics. The design specification accuracy is just one component of the total system accuracy. The system accuracy was then powered down. The orthometric network accuracy and potential eccentricity of the rover over the survey mark.
The allowable Vertical RMSEv (95%) is:  

\[
1.96 \times \text{RMSEv} = (2.0^2 \times 2.0^2 + 0.3^2 \times 0.3^2 + 2.25 \times 2.25 + 2.39 \times 2.39 + 2.40 \times 2.40)^{1/2}
\]

Thus, the 95% confidence interval is approximately 2.4 centimeters.

The number one user of the VRS network is predicted to be engineering and construction companies engaged in highway construction.

Although the control points selected for the test are directly connected, many are not. SCGS decided to take the most conservative approach and use the 2-cm accuracy. SCGS generally uses 3 millimeters as an estimate of allowable eccentricity for collimating the GNSS antenna over a control point value when using a properly adjusted 2-meter pole. Therefore, the combined allowable accuracy for the test is: 

Allowable 2-D RMSE, 95% = (Local Accuracy + Eccentricity + System Design)\(^{1/2}\) 

A 2-D 95% Confidence Interval is equivalent to 1.7308\(r\)

Therefore the Allowable 2-D RMSE, 95% (cm) = 

1.7308 \times \text{RMSE} = (2.0^2 \times 2.0^2 + 0.3^2 \times 0.3^2 + 2.25 \times 2.25 + 2.39 \times 2.39 + 2.40 \times 2.40)^{1/2}

Therefore, the 2-D RMSE, 95 percent computed from the observed values must be less than or equal to 2.4 centimeters. The RMSE, (2-D 95%) computed from the five-minute, one-minute and five-second tests were:

\[
\begin{align*}
&2.19, 2.40, \text{ and } 2.41, \text{ respectively.} \\
&\text{The computed RMSE accuracies are all less than the estimate for allowable accuracy for both horizontal and vertical, which suggests that the design error limit was not exceeded even for the five-second collection period. No degradation was noticed for the control points located outside the network.} \\
&\text{Conclusions: Who Benefits?} \\
&\text{At this point, 30 VRS network stations are running in South Carolina. The network covers two-thirds of the state, and 64 users enjoy single-receiver, centimeter-level accuracy. Why was the system built? Who are the ultimate users? What will it cost?} \\
&\text{The number one user is predicted to be engineering and construction companies engaged in highway construction.} \\
&\text{Although the RMSE values all suggest that the design criteria were met, the standard deviations for the sample group taken inversely proportional to the sample period. SCGS recommends no less than three-minute sample periods in order to obtain accurate and reliable elevations.} \\
&\text{The third largest user will be the surveying and mapping community. Already numerous surveying firms rely on the VRS for property surveys, stakeout, and wetlands boundary surveys. The ability to determine accurate elevations is a compelling reason for using the VRS over other traditional techniques. As the demand for positional accuracy grows, the South Carolina VRS Network will most likely be the only local base stations. VRS will also eliminate the need for local base stations. The present practice is also limited to the distance that RTK messages can be transmitted to the earth-moving machines. The earth-moving machines’ progress often outpaces a crew’s ability to reposition RTK base stations eliminating the possibility of accuracy caused by the distance (1-2 ppm) between local base station and earth-moving machines.} \\
&\text{Three-dimensional guidance systems work by first creating a digital terrain model for the project site. The model is loaded into a computer display in the cab of the earth-moving machines. The GNSS receivers at each tip of the blade provide actual position of the blade. The computer calculates the difference between the three-dimensional surface and the actual blade position. It then sends the proper correction — adjustments to the blade.} \\
&\text{GPS control is accurate enough for sub-centimeter tolerances of approximately 2 centimeters. Using additional sensors such as lasers or robotic total stations, earth-moving machines are capable of finer grade leveling.} \\
&\text{The second-largest users of the SCGS VRS network will most likely be the agricultural industry. Although present systems can provide sub-meter positional accuracy, certain crops require higher positional accuracy. For example, sub-centimeter positional accuracy for peanut farmers would reportedly enable an increased harvested harvest of 50 pounds per acre from existing fields. Certain vegetable growers must rely on hand harvesting at the present time due to limited capability to position automated harvesting equipment.} \\
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Thus, the 95% confidence interval is approximately 2.4 centimeters.

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Although some of the control points located outside the network can be recouped. Assuming 150 users, the entire hardware installation. This estimate includes sufficient spare hardware infrastructure (minus antenna mounts) can be replaced on the sixth year with a planned replacement cycle every five years thereafter.

Manufacturers

The South Carolina VRS Network base station receivers are Trimble NetR5 and use Zephyr Geodetic Model 2 antennas from Trimble Navigation Ltd., Sunnyvale, California USA. Trimble R8 GNSS receivers with built-in Zephyr-style antennas are used for field operations. The rovers are controlled by a Trimble Ranger (TSG2) data collector, which has a Bluetooth wireless connectivity to the R8 and cell phones.

The VRS network being used in California are PowerEdge 1955 Blade Servers from Dell Computer Corporation, Austin, Texas USA. Each virtual server was created using virtualization software from VMware Inc., Palo Alto, California USA, a wholly-owned subsidiary of EMC Corporation, and operates with the Microsoft Server 2003 SP2 operating system from Microsoft Corporation, Redmond, Washington USA. Two of the three virtual servers host the Trimble RTKNet software. Data from the reference stations enters the virtual infrastructure through a firewall using Cisco PIX Device Manager 3.0 from Cisco Systems, Inc., San Jose, California USA. SCGS VRS users gain access to the VRS network via a Microsoft Access database.

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