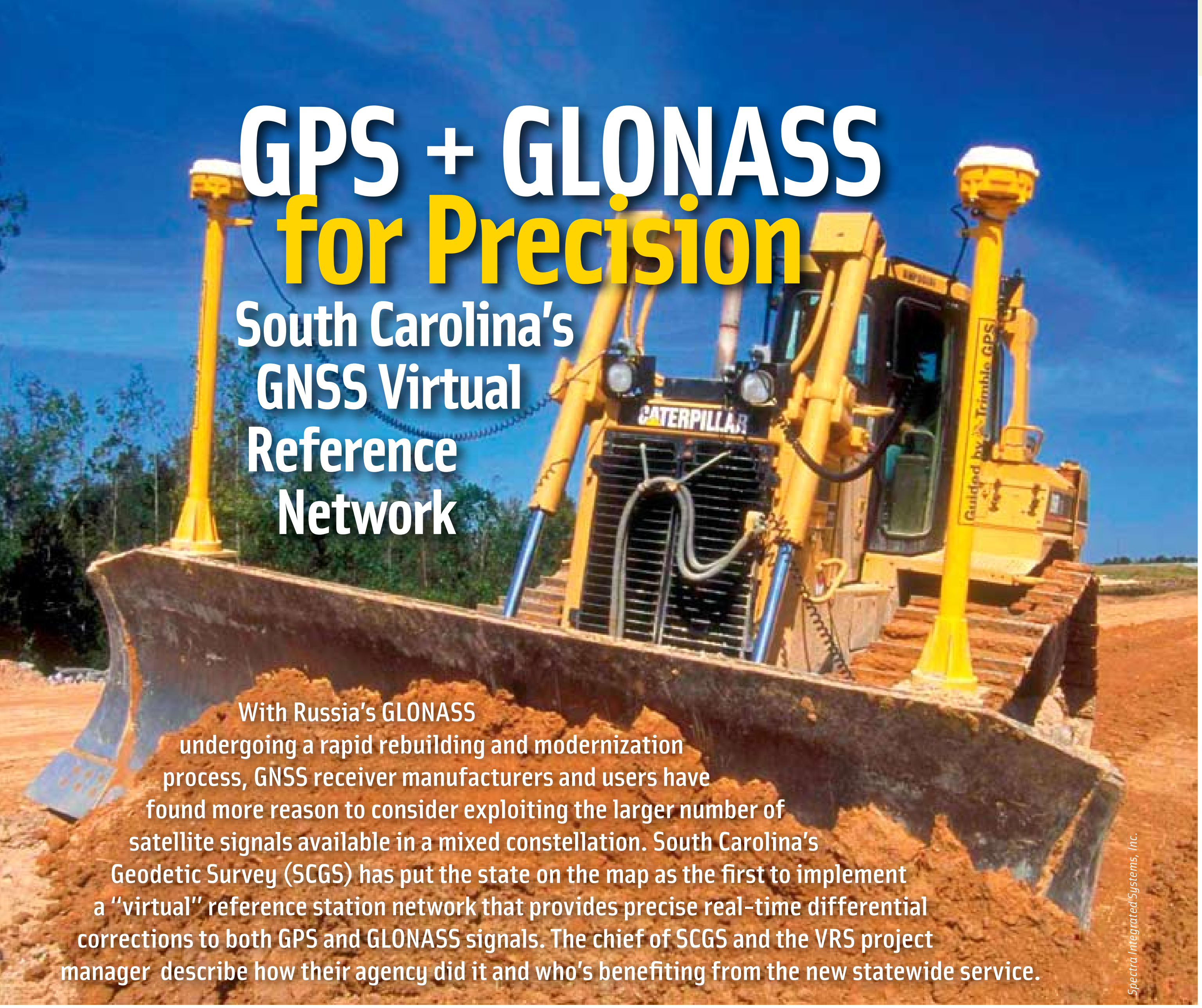


Spectra Integrated Systems, Inc.

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.

LEWIS A. LAPINE AND
MATTHEW J. WELLSLAGER
SOUTH CAROLINA GEODETIC SURVEY

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.

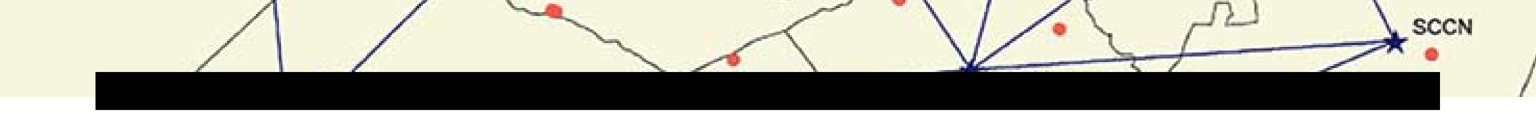
Named the SC Virtual Reference Station (VRS*) Network, the system is composed of 45 global navigation satellite system (GNSS) receivers installed statewide and connected by high-speed Internet to servers in the state capital, Columbia. Users connect in the field via cellular digital data communications 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 conversions.

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.*



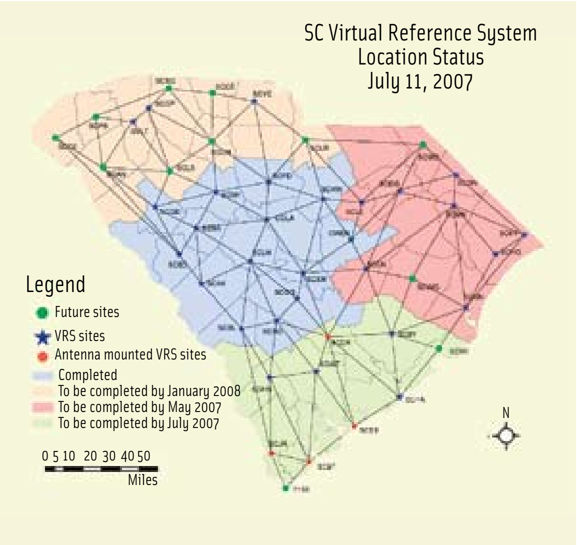


FIGURE 1 South Carolina Virtual Reference Station Network

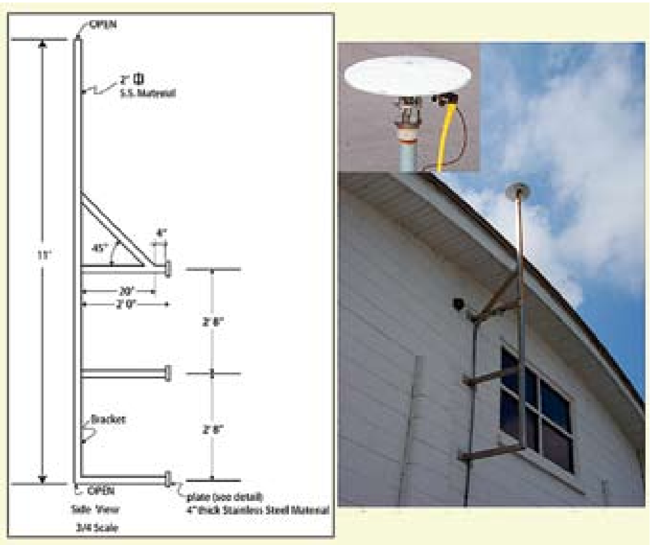


FIGURE 2 Typical building antenna mount and tamper-proof leveling head

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) of the distance from 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 cycle carrier in addition to GLONASS L1 C/A-code, L1 P-code, L2 P-code, and L1/L2 full cycle 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 geodetic 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.


Self-supporting tower

Trimble Navigation Ltd

As a result of these criteria, many of the sites were located at South Carolina Department of Transportation (SCDoT) facilities. SCGS and SCDoT servers are located on the state Internet backbone and connected to each other by a virtual private network (VPN). At those sites where a suitable structure was not available, specially designed steel towers were erected as seen in the accompanying photograph.

Ambiguity Resolution

Cycle ambiguity and station coordinates for all-in-view satellite/receiver combinations is computed once a second between selected adjacent pairs of network receivers. The roving receiver is always surrounded by three network vector pairs with known cycle ambiguities; therefore, the solution for the vector pairs between the rover and the three network points is optimized (**Figure 3**).

The VRS receiver coordinates are initially computed from several four-hour NGS On-Line Positioning Users Service (OPUS) solutions. The network software continually re-computes the station coordinates to ensure the values held fixed from the OPUS solutions do not vary by 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_0) from the dual frequency information as well as two time dependent gradient estimates (a_λ and a_φ) 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. $I(\lambda,\varphi)$ represents the total ionospheric refraction and can be represented by:

$$I(\lambda,\varphi) = I_0 + a_\lambda \Delta\lambda + a_\varphi \Delta\varphi$$

where the partial derivatives a_λ and a_φ are defined as: $a_\lambda = \delta I / \delta \lambda$ and $a_\varphi = \delta I / \delta \varphi$

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

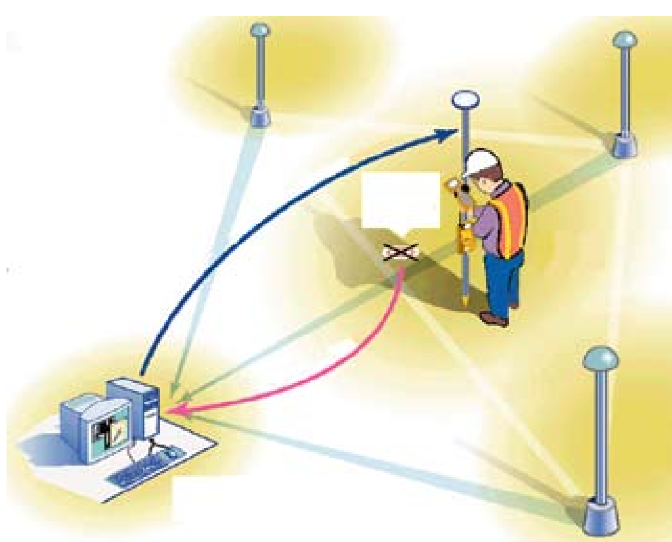

Trimble Navigation Ltd

FIGURE 3 VRS and rover

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.

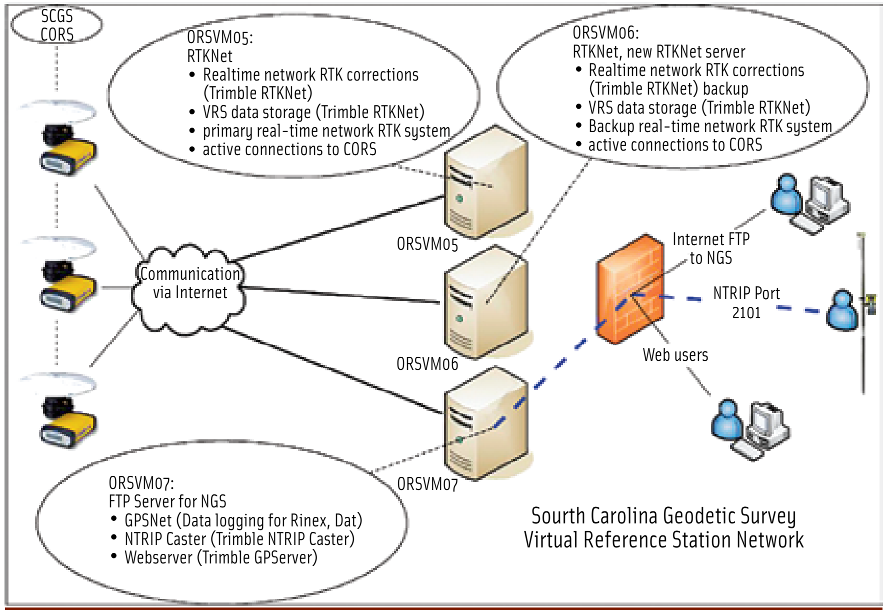


FIGURE 6 **Server network design**

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.

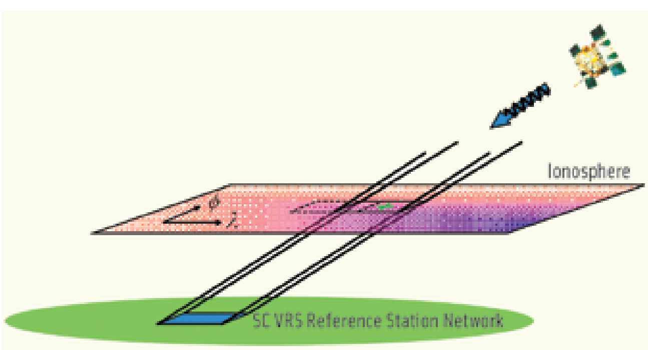


FIGURE 4 **Change in ionospheric mapping function**

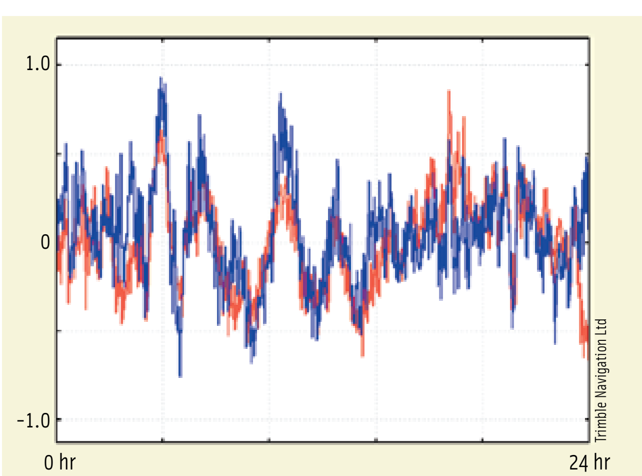


FIGURE 5 **Multipath Modeling over a 24-hour period**

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 GPSNet suite of software.

Data from the reference stations enters the virtual infrastructure through a firewall. The data then streams to each of the three servers: ORSVM05, ORSVM06 and ORSVM07. ORSVM05 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 2.3.

ORSVM06 is a clone of ORSVM05 and is used to re-distribute the workload of ORSVM05 if VMWare detects the needs. A possible cause for this would be a large number of users accessing the VRS network simultaneously.

ORSVM07 is used for Storage Integrity and data storage. Storage Integrity is a mechanism used to identify gaps in the data files as they are downloaded from the reference stations. If a break is detected, the GPS network software uses the FTP protocol to download a replacement data file. Stored data formats include the native .DAT format and Receiver Independent Exchange Format (RINEX), version 2.1.

The ORSVM07 server also is the FTP client site for the NGS and hosts the Network Transport of RTCM via Internet Protocol (NTRIP) Caster. The NGS

accesses the server hourly to download files for the national CORS located in South Carolina. Finally, the ORSVM07 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 login and password information. Before gaining access to the network each user must have a username and password assigned by SCGS. Username and passwords are 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 RTCM corrections. The IOC designation is beneficial for the SCGS. It allows the staff of the Office of Research and SCGS personnel to trouble shoot 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 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, CMR+, 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 VRS network are management 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.

A Sampler of VRS Projects

SCGS has used the VRS for some interesting projects, the first being an elevation check survey for a dam deformation project. This project area includes 14 traditional benchmarks and 10 self-centering pillars, the position of which was determined using NGS Height Modernization Standards with the elevations confirmed by First-Order Class II leveling.

The 24 orthometric heights were checked using a single five-minute VRS solution. The average difference between leveling and VRS-determined elevation was 12 millimeters with a standard deviation of 13 millimeters. The leveling was conducted over a five-day period while the VRS observations and processing was completed in four hours.

SCGS has also used the VRS at airports for locating runway end points and Automated Weather Observing Systems (AWOS). Runway endpoint locations are submitted to the Federal Aviation Administration to be used as navigation aids, for runway alignment, and to determine maximum landing and take-off capacities.

Runway end point positions are time-consuming to determine by traditional methods: safety reasons require that the runway be shut down to traffic during the survey. SCGS can obtain a centimeter-level position in 60 seconds with the VRS, thereby avoiding delays in aircraft schedules.

AWOS sites require a precise location of the wind sensor and a North marker located approximately 150 feet away from the sensor. Using the VRS the sensor can be positioned in three minutes and a North mark established by using the real-time navigation capability of VRS to stay on a constant longitude heading. The North marker can then be set and positioned in three minutes. An accuracy of one arc-minute (4 centimeter displacement) can be obtained.

Another SCGS project involved a water-level transfer from a known historic tidal station to a second location on the same creek separated by about 2 miles. The objective was to measure a close approximation of mean high water at the second location site to determine if it was the same mean high water elevation as at the tidal station.

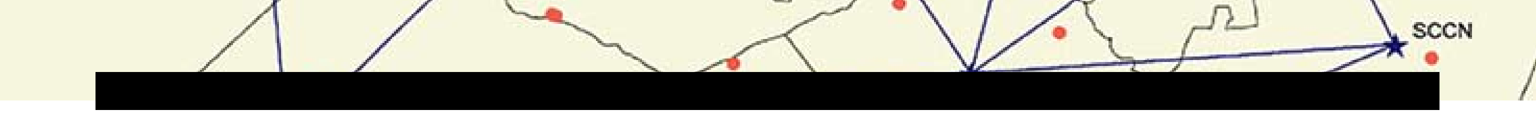
SCGS accomplished this task using a combination of local tidal observations combined with VRS at both stations. Because we could meet the accuracy of this project more efficiently, we chose VRS over more time-consuming, traditional water-level transfer methods, which require observations over three tide cycles. The orthometric height of mean high water at the tidal station was determined from information obtained from the National Geodetic Survey.

Two tidal benchmarks at the tidal station that had NAVD 88 elevations were observed with the VRS. The VRS-derived elevations checked out within 1.5 centimeters of NGS published data; so, we assumed that the orthometric heights determined at both sites by VRS could be used as a measure of high water as well.

A temporary tide staff was installed at each location. The top of the tide staffs were occupied with the VRS rover to determine position and orthometric height. A day was chosen when the high tide for the day as predicted by National Ocean Service (NOS) would be the same as the mean high water at the gauge location. Water-level observations were then made at both locations. The orthometric height of the highest water level measured was determined from the orthometric height observed at the top of the staff.

The high water at the gauge site was 1.5 centimeter above the orthometric height of mean high water predicted by the NOS. The orthometric height of the highest water at the second site was 3.3 centimeters higher than the orthometric height at the tidal station. Therefore, the mean high water at the second station was almost 2 centimeters higher than the tidal station, thus providing us with the information needed for the project.

Although this method does not conform to the exacting standards of the National Ocean Service, it represents an efficient manner for transferring water-level datum.



Both specifications are based on a position dilution of precision (PDOP) of 5.0 or less with five or more satellites. The network spacing design of about 70 kilometers with 45 GNSS stations should accomplish these specifications.

To test 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 survey control 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 some 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 procedures. 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.

The rover was then powered 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 each observation period using the South Carolina State Plane Coordinate System on NAD83/2007 and NAVD 88 for the orthometric heights.

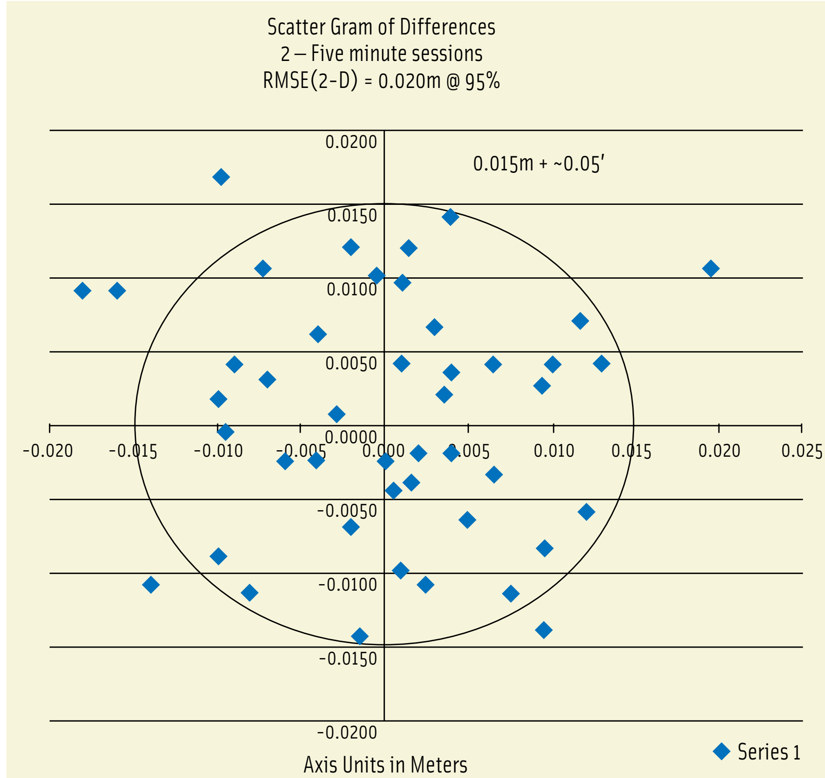


FIGURE 7 VRS real-time accuracy at the rover location of 1.2-centimeter (2-D RMSE)

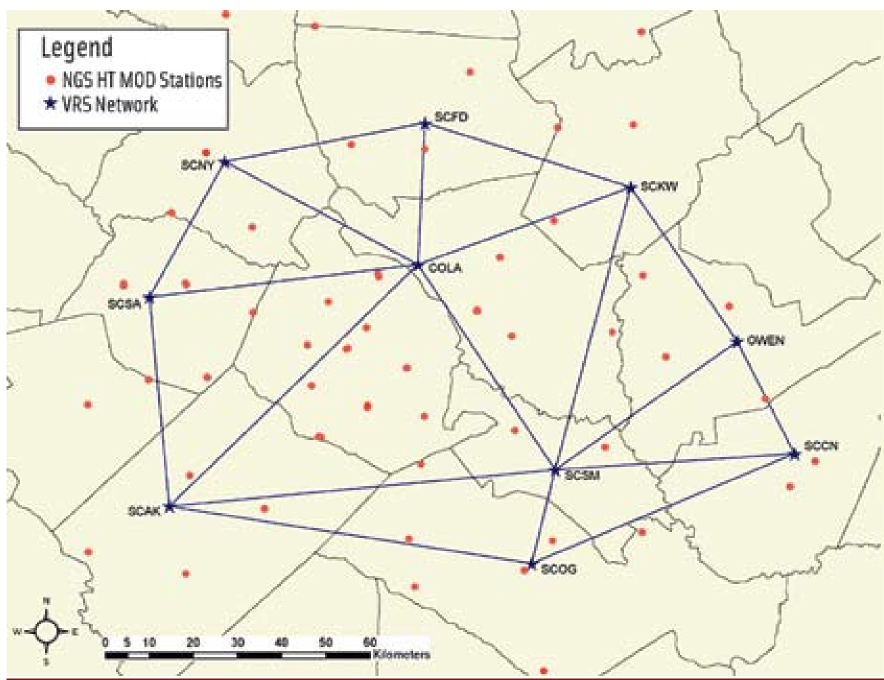


FIGURE 8 VRS Test Network

Accuracy Metrics. The design specification accuracy is just one component of the total system accuracy. The system accuracy must also include an estimate for the geodetic network accuracy and potential eccentricity of the rover over the survey mark.

NOAA Technical Memorandum NOS NGS-58, *Guidelines for Establishing GPS-Derived Ellipsoid Heights (Standards: 2 cm and 5 cm)* Version 4.3, Appendix A. – Definitions, defines two levels of accuracy. *Local (horizontal) accuracy* of a point is a value expressed in centimeters that represents the uncertainty in the coordinates of a control point relative to the coordinates of the other directly connected, adjacent control points at a 95 percent confidence level. According to the standard for 2-centimeter ellipsoid heights, this would be 2 centimeters. *Network (horizontal) accuracy* is also defined for a control point relative to the geodetic datum at a 95 percent confidence level; so, the standard for 2-centimeter ellipsoid heights would be 5 centimeters.

Although some of 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 $RMSE_r$ 95% = $(\text{Local Accuracy}^2 + \text{Eccentricty}^2 + \text{System Design}^2)^{1/2}$

A 2-D 95% Confidence Interval is equivalent to 1.7308σ

Therefore the Allowable 2-D $RMSE_r$ 95% (cm) =

$1.7308 * RMSE_r = (\text{Local Accuracy}^2 + \text{Eccentricty}^2 + \text{System Design}^2)^{1/2}$

$= (2.0*2.0 + 0.3*0.3 + 1.2*1.2)^{1/2}$

= 2.4 cm

Therefore, the 2-D $RMSE_r$ 95 percent computed from the observed values must be less than or equal to 2.4 centimeters.

The $RMSE_r$ (2-D 95%) computed from the five-minute, one-minute and five-second tests were:

1.98 cm, 2.40 cm and 2.41 cm, respectively.

The allowable Vertical RMSEv (95%) is:

$1.96*RMSE_v = (\text{Local Accuracy}^2 + \text{Eccentricty}^2 + \text{System Design}^2)^{1/2}$

where a 1-D 95% Confidence would be 1.96σ

or

$1.9600*RMSE_v = (2.0*2.0 + 0.3*0.3 + 2.4*2.4)^{1/2} = 3.1$ cm.

The RMSEv (95%) computed from the five-minute, one-minute and five-second tests were:

2.25, 2.39, and 2.40 cm, respectively.

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.

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

Although the RMSE values all suggest that the design criteria were met, the standard deviations for the sample groups are inversely proportional to the sample period. SCGS recommends no less than three-minute sample periods in order to obtain accurate and reliable elevations.

Conclusions: Who Benefits?

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?

The number one user is predicted to be engineering and construction companies engaged in highway construction. At last count, approximately 100 earth-moving machines in the state rely on local base station RTK for three-dimensional machine guidance. The number of different job sites is limited by the number of available local base stations, estimated to be 25 at this time.

With the VRS network, every earth-moving machine can be at a different job site because the network eliminates 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. VRS will also eliminate the degradation of accuracy caused by the distance (1-2 ppm) between local base station and earth-moving machines.

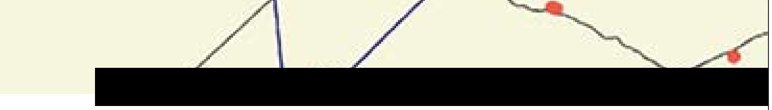
Three-dimensional guidance works by first creating a digital terrain model for the project site. The model is loaded into a computer display in the cab of the earth-moving machines. The GNSS receivers at each tip of the blade provide actual position of the blade. The computer calculates the difference between the three-dimensional surface and the actual blade position. It then sends the proper correction — adjustments to pitch and tilt — to the hydraulics controlling the blade position.

GPS control is accurate enough for sub-grade tolerances of approximately 2 centimeters. Using additional sensors such as lasers or robotic total stations, earth-moving machines are capable of fine grade tolerances of 1 centimeter.

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-decimeter positional accuracy for peanut farmers would reportedly enable an increased 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.

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.

The mapping community is also a major player in VRS. Real-time sub-foot accuracy without postprocessing is possible. A great deal of activity is foreseen



in infrastructure mapping. The GNSS constellation will provide consistent coordinates and more satellite signals in an urban canyon environment and also allow the rover to work closer to tree canopies.

How much does it cost? The final estimate is $1.6 million to build the 45-station South Carolina GNSS network, including hardware installation. This estimate includes sufficient spare base receivers and antenna mounts in the case of natural disasters, such as a large hurricane, in order to minimize interruption of service.

Because the state has paid for this portion of the project, the only remaining recurring costs are for yearly hardware and software maintenance and license fees. SCGS plans to implement a $600 per year user fee on October 1, 2007. Based on a minimum of 50 users, all maintenance and licensing costs can be recouped. Assuming 150 users, the entire 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 (TSC2) data collector, which has a Bluetooth wireless connectivity to the R8 and cell phone.

The VRS network servers based in Columbia 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 kernel of the **Trimble** GPSNet 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.

Authors

Lewis A. Lapine <lew.lapine@scgs.sc.gov> graduated from The Ohio State University with a degree in geodesy and photogrammetry. His doctorial thesis dealt with the integration of kinematic GPS and aerial photography that minimizes the requirement for ground control in the aerotriangulation process. He is the former director of the National Geodetic Survey and is currently chief, South Carolina Geodetic Survey. He has 37 years experience in geodesy.

Matthew J. Wellslager <matt.wellslager@scgs.sc.gov> graduated from The University of South Carolina with a degree in geography. His master's thesis deals with GPS positional accuracy in a multipath environment. He is a former chief of a National Geodetic Survey GPS field party and currently works for the South Carolina Geodetic Survey as program manager for the South Carolina Virtual Reference Station Network. He has 23 years experience in geodesy and geographic information systems. IG