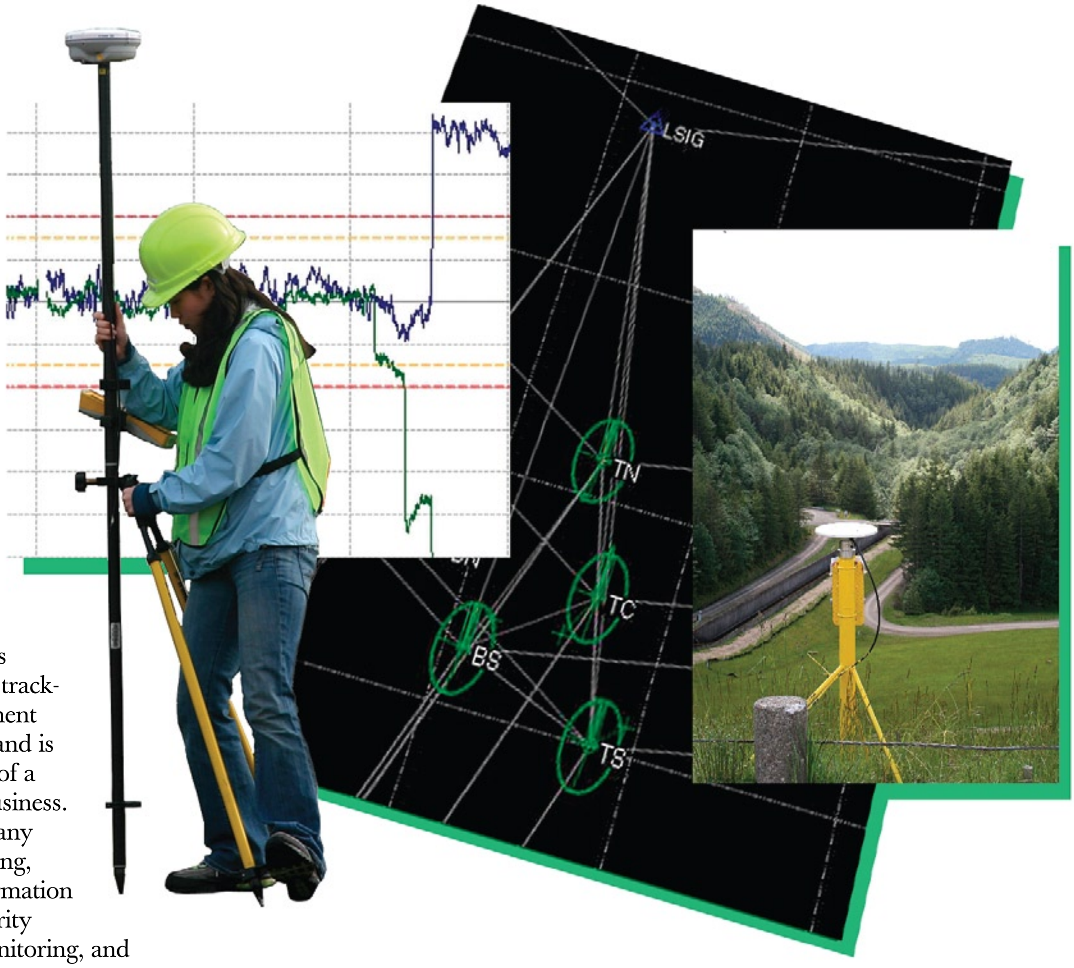

RTN–101:

Monitoring with RTN (Part 15)

"Measure what is measurable, and make measurable what is not so."

—Galileo Galilei, Philosopher, Astronomer and Mathematician

>> By Gavin Schrock, LS

Monitoring is essentially tracking movement over time and is often part of a surveyor's regular line of business. Such tasks are known by many names: subsidence monitoring, deflection monitoring, deformation monitoring, structural integrity monitoring, compliance monitoring, and more. These tasks support a wide range of disciplines, including construction, public safety, environmental studies, geophysical studies, post-disaster evaluations, planning and development; the list grows as customers come up with new and sometimes challenging needs.

The fundamental goal of most monitoring tasks is to show relative changes: evaluating the relativity of multiple observations of the same points, while adding a temporal component. The first three "D's" of positioning are the XYZ; the fourth "D" is time. Whether the client is interested purely in the horizontal displacement, the vertical, or both, the goal is the same: repeat observations within the prescribed positional tolerances and temporal units. This could be millimeters to feet; whatever the client specifies (but it is often a good policy to work in tolerances higher than requested).

Much of this subject will not be new to most surveyors, but now there are more tools at our disposal. The advent of total stations, robotics, and laser scanning saw a renaissance in monitoring. Beyond surveying instruments, a great many other solutions have been developed for specific monitoring needs. The seeming simplicity of some belies their amazing capabilities; strain gauges and tilt sensors are common for structural integrity needs. Others

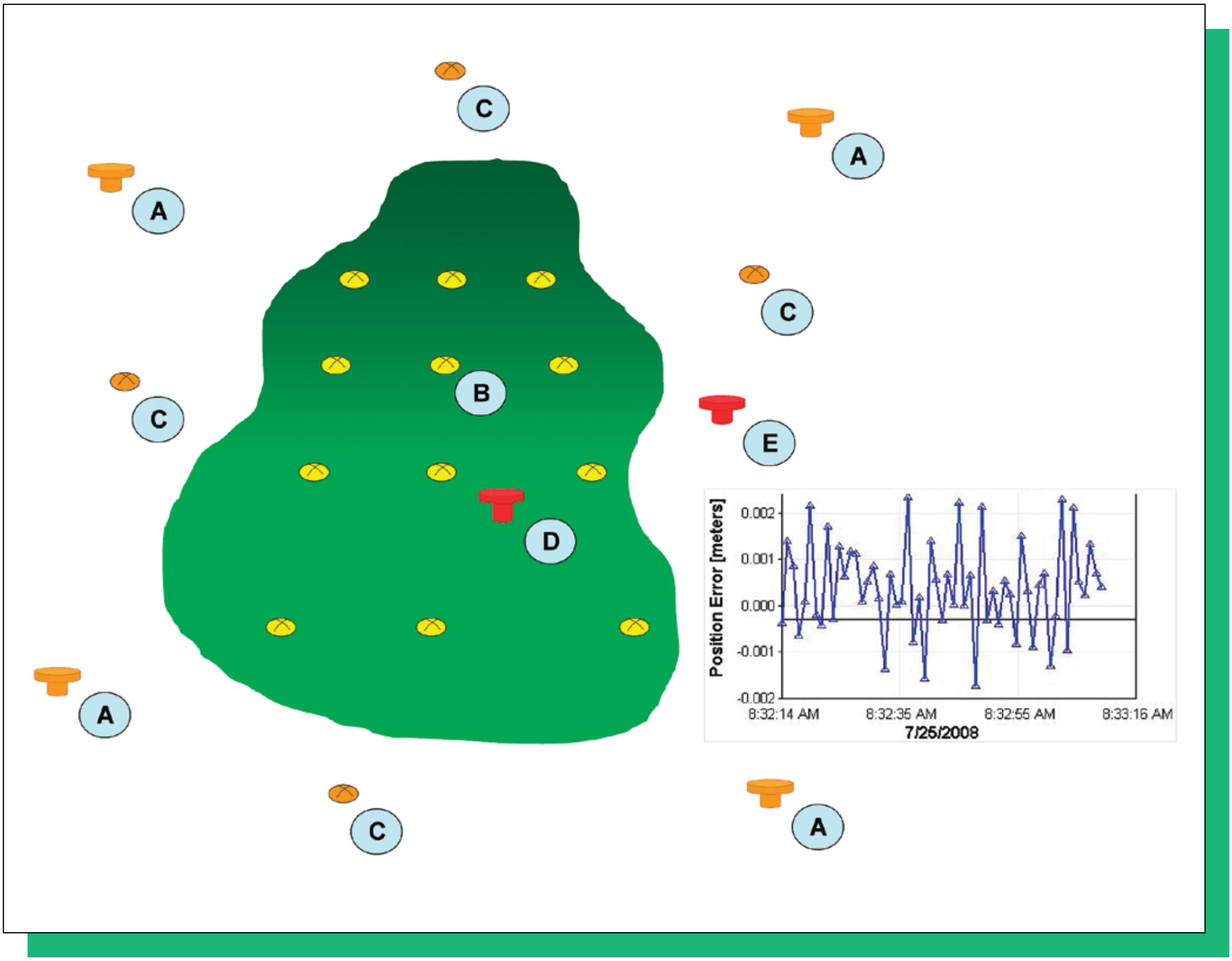

Figure 1 In this example of an RTN-based subsidence monitoring project, any combination of the following elements may be employed:

A — Existing RTN CORS; monitored for network integrity
B — Points to be observed periodically with a rover
C — Existing monuments for a site calibration
D — Continuously operating monitoring rover (COMR on-site)
E — Continuously operating monitoring rover (COMR off-site) with a live graph from a rover integrity monitor (inset)

border on science fiction: fiber optic lines that can detect strain conditions of any regions along their length, radio ranging systems, sonic, gravimetric, and geomagnetic (in the not-so-distant future). Sophisticated monitoring software suites have also been developed to manage one or more of these tools.

Satellite-based positioning has been utilized for monitoring even in its earliest incarnations. GPS brought a tool that could contrast positions over wide areas at much reduced costs compared to conventional, even considering the long observation times needed to yield higher precisions. Code-based, and some code-carrier-based "near-real-time" systems have been employed for more than a decade; the observations being processed as they are written to static files and served up to a suite designed for such purposes.

While RTK has been used for monitoring since its introduction, there were still valid concerns; most commonly cited are concerns about vertical precisions and the potential for error in setting bases. RTK has gotten better, and while some may argue that short baseline RTK and network corrected RTK (RTN) yield similar results, RTN has a few more things going for it that can take monitoring to the next level.

Why RTN?

"What is monitoring the monitor?" Prime among the advantages of RTN for monitoring is the inherent integrity of the RTN itself. An RTN will only perform optimally only if the stations can maintain the strictest of relative positional tolerances–often a maximum of 10mm 3D across the entire RTN. A maxim for RTN repeated *ad nauseam* throughout this series is "one can only expect one-centimeter precisions from observations if every RTN CORS maintains one-centimeter or better relative network integrity."

Beyond the network-based correctors for RTK, the RTN should also be providing static files for post-processed applications. Even if you suspect the base coordinates of a particular RTN, you could always develop your on coordinates for the group of stations around your monitoring project with the same static data (this is a good practice).

A good RTN is monitoring itself continuously, and this provides a stable

base (or set of bases) to provide the "control" for your project. Movement of RTN CORS due to natural geophysical forces is also tracked by this continuous monitoring (but more about this in a subsequent installment). These factors are known, and may or may not need to be considered in designing your monitoring project, depending on the time span and whether you are working in a geophysically active part of the country or not.

Even the vertical component can produce well within the 1cm range, but (like anything surveyors do) only if thoughtful approaches are applied.

Periodic Monitoring with RTN

The concept is quite simple–repeat observations on the same points periodically. Often the only values that count are the differences between the respective observations. The client may specify that the deliverables be expressed relative to some datum, and this is handled by ties through known control: levels, traverses, and calibrations. Conventional methods lend themselves well to this approach, but often at a prohibitive cost. Efforts to utilize lower cost methods bring fears of the results getting lost in the inherent noise of the respective solution.

This must be approached like a scientific study, working under strictly controlled (pardon the pun) conditions, conditions as closely repeated as possible for each subsequent observation. Of course the old argument that GPS could never yield proven repeatability might otherwise preclude its use for monitoring (depending on how cynical one is, nearly any positioning method could be ripped apart and criticized). It is true that no matter how hard one may try to repeat all conditions of a GPS observation, one would ultimately fail because those satellites will never be in the same place twice, under the same atmospheric conditions, etc. Like many other measurement solutions employed by surveyors, the proofs ultimately are results based. (**Figure 1**)

Well designed conventional and real-time monitoring projects will share many of the same elements as conventional monitoring projects: exterior control (or CORS), good monumentation, and some check mechanisms. Each monitoring project assumes some element to be held as "stable" to compare the suspected unstable elements. The RTN may serve as the control element. You may be working calibrated (localized) to local control, or applying a GEOID difference model (though you better be confident in the regional consistency of such models), or you may be working purely in ellipsoid values (which is what GPS gives you by default). Any of these may be valid, depending on the project,

Figure 2 Elements of an ongoing monitoring initiative at an earthen water supply dam near Seattle include the following:

- A — Existing RTN CORS of the Washington State Reference Network
- B — Continuously operating monitoring stations (COMR); dual frequency receivers with geodetic antennae and dual axis tilt sensors
- C — Test table calibration station
- D — COMR at the toe of 2:1 slope
- E — COMR Station on 5:1 slope

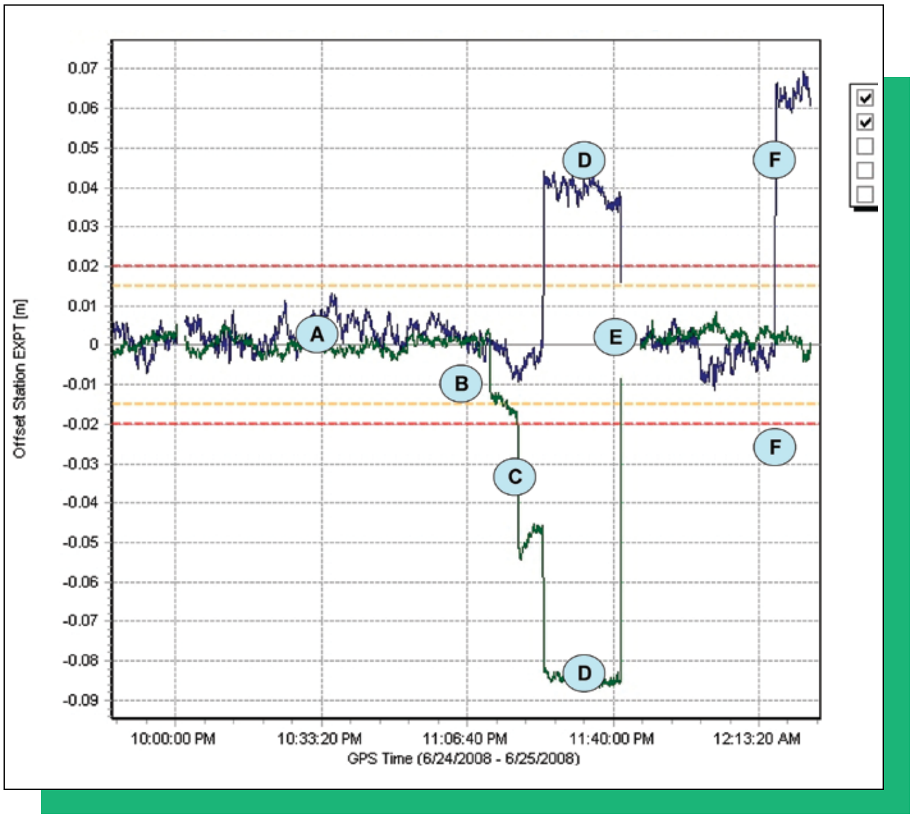

Figure 4 A standard report from the integrity manager shows results of one of series done on the test table:

A — Noise from the table
B — 1cm north shift
C — 4cm north shift
D — 4cm north x 4cm west shift
E — Reset test
F — Return to original position. Note red and yellow alarm tolerance lines set.

as the differences over time are most important values, almost regardless of convention, and as long as you have applied the same method each time.

Repeatability of results is the prime concern most have with the use of RTK for monitoring. How can we best prove the repeatability? Large numbers of observations is one method for statistical analysis, or sampling with conventional methods for comparison (still a good idea), and/or monitor the RTK process itself directly… the latter is fast becoming the solution of choice.

The COMR

How do you test the RTK process itself for repeatability over time, short of running round the clock over the life of the monitoring project? Just that easy! You set up a Continuously Operating Monitoring Rover (COMR). The concept is the same as CORS except that a COMR is a client of the RTN, just like any mobile rover except that it is set it up on a more solid mount, initializes to the RTN, and sends the corrected positions back to the RTN (or a rover monitor program).

A dual-frequency receiver simply needs to have an RTK engine onboard, though there are some options in some monitoring suites for server-side RTK (more later), and some means of live communications (typically an Internet connection). The COMR does not need a controller or survey software attached; it can be a very simple setup.

Whichever mount you use for a COMR, you just need to be confident that it will not move over the span of the project. The corrected positions feed into a software application like the Rover Integrity Monitor, an add-on module for the Trimble GPSNet RTN software suite. A typical implementation to support a periodic monitoring project that will utilize RTN is to set one up on the "stable" part of the project. Even better is to also have another one on the "unstable" region of the project. If your local RTN offers such a service, this can produce not only a live feed representing current network precision, but can show displacements over time.

Figure 3 Controlled movement tests; displacements marked on a graph sheet on a level table.

But if a COMR can provide such feedback live, wouldn't it be great to do entire monitoring projects with live data? There are now options that go far above and beyond the concept of COMR.

The COMS

A shortcoming of some periodic monitoring projects is the wide periods between observations. Often the only way to effectively study trends and to work with subtle movements that would otherwise be lost in the noise of the method employed is to take frequent observations. How about every second?

A Continuously Operating Monitoring Station (COMS) can provide raw observations to integrity monitoring software, like the Trimble Integrity Manager, which has several motion engines for processing the observations relative to other existing CORS. It does this in real-time and/or automated post-processed modes, and then analyzes with any number of filtering options. Such suites are already utilized by some RTNs to monitor their CORS (but more on this in a subsequent installment). While some of these services can run as standalones, monitoring "mini-RTNs" on their own, the option for connecting to and holding rigorously monitored RTN CORS is widely viewed as a best practice.

A delegation from the Mapping Agency of Vietnam on a study tour of the Washington State Reference Network and the monitoring operations at the dam site, June 2008. Asia has seen a rapid rise in monitoring initiatives. These include such critical issues as plate tectonics, critical slopes, slide areas, water tables, tsunami warning systems, dam safety, subsidence, structural integrity, and monitoring of offshore drilling platforms.

It might be impractical (more likely cost prohibitive) to place a full COMS on each feature or point you are tasked to monitor (the client may want dozens or hundreds). Many (including myself) have experimented with devices that cycle between many antennae with one receiver, but with questionable results. Still, the best option for great numbers of points is robotic, so if some of the points observed in each set are targets on COMS, then you have the best of both worlds.

Like a CORS, a COMS would need to be solidly mounted. I have seen such things as rods-duct-taped-to-bridges, which might surprisingly work, but one might wonder how much of the movement is in the mount (the old bipod/tripod issue). One may be limited in how "beefy" a mount may be possible at a particular site. In the example below there was prohibition as to how much the post or braces of each mount could penetrate the core of the earthen dam (the core being 4'-6' below the surface). While the mount contacted the core, just how much could shifts in the surface layer affect the integrity of the mount? Taking a cue from folks who have been monitoring lava flows with antennae on long poles, a 2-axis tilt sensor was added to the mount. The tilt sensor results are added to the observation data of many receivers, and/or sent directly to integrity monitoring suites. (**Figure 2**)

This particular monitoring project site was chosen to fully test the capabilities of the integrity monitoring options. The nature of movement in this particular earthen dam is subtle (while some other earthen and concrete dams are designed to deflect in the order of tenths of feet), so it has historically been difficult to distinguish actual movement from the quarterly optical observations, or from the generalized plate movement, or from some newly suspected localized geodynamic effects.

A multi-level approach was taken. First, the statewide RTN was monitored with multiple CORS common to both the NGS and academic institutions tracking plate tectonic movements. Holding some of those, smaller sub-networks within the RTN were monitored for relative integrity. RTN CORS in the sub-network around the subject site could then be held as control.

For the project, a standard RTN CORS from the state network sits up in bedrock on one end of the dam, with four other RTN CORS within 30 km. Five COMS were placed on the structure; 3 on the crest, and one each on the toe of the 2:1 slope and on the 5:1 lower slope. Many months of data were gathered in the Integrity Manager for automated daily, weekly, and monthly post-processed analysis, a network integrity engine (that runs continuous loop closures between stations), and further with two real-time modes.

A rapid motion engine provides long baseline options (up to 200km), watching for changes in velocity in the range of centimeters in the span of minutes. This is being used in India to monitor offshore islands for tsunami warnings, in New Guinea to keep an eye on volcanoes, and in the South China Sea to monitor subsidence of drilling rigs. This is well suited for adding alarms.

The real-time option that really shone in the dam project was the RTK Engine; this is essentially server-side RTK, but with the ability to hold multiple stations. As it turns out, the integrity of the surrounding RTN is so tight that the real-time solution typically had noise under 5mm. As a side test of the RTN, VRS check shots were taken on the control that had been established with weeks of static data, yielding 3D results under 3mm.

Controlled Movement Tests

A major impetus for real-time monitoring of this particular site is to enable rapid post-event analysis in case of earthquakes (not uncommon in the region), or effects other natural forces. Therefore it was crucial to test the effects of displacements that could be expected as a result of such events. (**Figure 3**)

Rather than wait for an actual earthquake, a test table was set up. A geodetic antenna was set on a tribrach, and centered optically over an existing mark through a hole in a leveled table. The displacements were measured on a graphed sheet (aligned to grid north) set on the table (later scanned into CAD). (**Figure 4**)

The results were within a few millimeters of measured each time, and reaction times for the RTK engine were within seconds. This far exceeded expectations of the client. The months of the COMS observations are then contrasted with data from other elements such as water level, temperature, wind load, regional plate tectonics series (derived from CORS that include some common to the RTN).

A New Market

There are definitely some new twists to an old market, with newer markets opening up all the time. Monitoring is booming worldwide with renewed emphasis on public safety issues (in many countries which previously overlooked such concerns). Coastal regions are being watched more closely, and even economic downturns have driven the market for structural integrity monitoring; those who may be forced to maintain existing infrastructure in lieu of costly replacements.

Sadly, to some degree this is another case of many of the coolest projects being managed by (and sometimes executed by) the clients, academia, experts in the nature of the type of movement being studied, engineers, or other non-surveyors. Who is best qualified to understand the nature of positioning? Surveyors, of course.

Again, this is a ball that surveyors should not drop. Surely it is time to fully explore and perfect these new lower costs alternatives. The needs for monitoring are not going away, especially those with statutory or regulatory drivers. The more parties that can afford monitoring, the more will be monitored.

Gavin Schrock is a surveyor in Washington State where he is the administrator of the regional cooperative real-time network, the Washington State Reference Station Network. He has been in surveying and mapping for more than 25 years and is a regular contributor to this publication.