Best Practices for the Development and Operation of RTN – Real-Time GNSS Networks

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ABSTRACT

Real-time GNSS networks (RTN) have been a reliable tool for precise positioning, location, and measurement since the late 1990s. From the collective body of experience of the hundreds of RTN worldwide, clear trends and best practices for development and operation have emerged. This paper examines the essential considerations for establishment of an RTN, key features to ensure its continued value, and operational models for optimal uptime and performance.

Most particularly, RTN have been commonly used in advanced economies to provide highly accurate location coordinates. These coordinates are utilized for a myriad of applications: land surveying and mapping for cadaster and land administration projects; earthquake-, tsunami-, and volcanic-warning systems; emergency response and post-event analysis; monitoring the structural integrity of critical infrastructure such as bridges and dams, and reducing the costs of large infrastructure projects by utilizing smart and precision technologies. Geospatial data infrastructure is slowly but surely becoming part of a nation's critical infrastructure. Considering the increasing importance of standardized, comprehensive and updated spatial information, it's surprising that these types of networks are often ignored or that outdated technologies are used when various government, bilateral, and multilateral agencies design projects. This paper revisits the evolution of real-time networks and outlines the most important technical considerations to deploy and manage an RTN to help these agencies in guiding their projects.

Elements examined:

- RTN components
- Features and services
- Reference framework
- Design
- Operations
- Drivers and sustainability

INTRODUCTION

Typical consumer and navigation applications for Global Navigation Satellite Systems, (GNSS[1]) are by nature imprecise without some form of augmentation or "correctors." Uncorrected GNSS results can vary from one to tens of meters depending on the hardware and local conditions. As the common sources of error for GNSS are the delays in the transit of the signals from the satellite to the user's receiver on the ground, various methods have been developed to remove as much of this error as possible. Common methods include differential solutions using one or more ground reference stations or "bases," and the provision of various models (clock delays, improved orbit, ionospheric and tropospheric data). Correctors developed from such data are delivered to the end user's field receiver, or "rover," to tighten the results to the range of centimeters—in real-time.

Real-time kinematics (RTK) [1] is an early form of corrected real-time GNSS. This is, a differential method requiring a single "base" on a static point providing corrections for one or more rovers. The results degrade over distance from the base and with variations in space weather (ionosphere) and local weather (troposphere), which often limit the operational distance from the base to 10km (6.2mi). These corrections were mostly delivered by radio pairs (another distance-limiting factor). To provide service to a large area, either there would need to be great numbers of single RTK bases or the users would need to set up a base each time. Arrays of single-base stations have been set up in some regions with some success, mostly to serve specific agricultural end-use communities, but the distance-

[1] Global Positioning System (GPS) refers to the United States' Navstar constellation of satellites, operational since the late 1970's. GNSS refers to multiple similar constellations including, but not limited to, the Glonass constellation (Russian Federation), Beidou/Compass (China), Galileo (a European consortium), etc. "GPS" has been used as a vernacular term for such satellite positioning, but both professional and consumer applications are increasingly utilizing multiple constellations. For an RTN to be successful in current and future markets, it is essential that multiple constellations are supported. For the purposes of this paper the term "GNSS" will be used.

dependent limitations of these “social networks” of RTK bases, coupled with costs for daily transportation of the base stations and security of the bases were not practical to operate over broad regions and to serve multiple end-users.

For these reasons solutions for “network RTK” [2] were developed. These real-time networks (RTN) could provide the same results as RTK but over a broader area, reduce significantly the field work and associated costs and time of deploying RTK bases and enable enhanced services to greater numbers of users and uses.

RTN COMPONENTS

The infrastructure of an RTN consists of three fundamental elements: reference stations (CORS)[2]; central processing center(s) (CPC); and access for the field users (for real-time corrections, post-observation processing files, and other network services via wireless and land-line internet).

a. CORS communications

The CPC requires a live stream of observations from each CORS; these streams contain observations from each satellite viewed. Communications from the CORS to the CPC must be low-latency, of sufficient bandwidth to accommodate multiple streams (for redundant processing), accommodate remote operation and maintenance, and have the capacity to receive static observation files (back-fill) after communications outage events. For a typical multi-constellation receiver tracking, for instance, 21 satellites at one observation per second, this would require about 1.5Kb per second, and would be multiplied for each redundant stream. It is also a best practice to have the static[3] files written on both the receivers and at the CPC for redundancy.

The CPC takes the respective observables for each one-second observation (epoch) for each receiver and each satellite and synchronizes them. Though different types of communications can be used throughout the network, latency from each CORS to the CPC cannot exceed 2 seconds without compromising this essential synchronization. Common communications methods must be contracted with guaranteed service agreements that perform with low latency and high availability. These may include wireless broadband (via cellular networks), data links via telephonic land lines, fiber networks, coaxial cable systems (cable television providers), or, in some instances, linked radio repeaters or mesh systems (e.g., 2.5GHz or 5GHz). Satellite communications have been successfully employed but may experience periods of high or frequently fluctuating latency.

A best practice is to limit the numbers of CORS utilizing satellite communications within any sub-network to a minority of stations, not clustered together, and to have stations with low latency communications in areas of high usage. It is very important to test performance and latency of any communications method considered in the locations of proposed stations in advance of network design.

b. Central Processing Center

The CPC should consist of multiple servers with sufficient capacity to manage the processing and data storage for the network as well as to meet its expected user traffic. Modern servers (virtual or physical) have come down in cost, so robust and redundant systems are quite affordable. CPC hardware and software is not an area in which to try to save costs—cutting corners will limit automation and may result in increased operations and maintenance labor costs. Today inexpensive “cloud” servers (hosted by service providers at an offsite location) are becoming popular for RTN operations and offer advantages in scalability and redundancy.

There are commercially produced CPC software suites available. These are quite sophisticated and have been developed from decades of scientific and commercial advancements. At a minimum, the CPC software must be capable of accepting the raw observations from the CORS, processing real-time and static-file requests from multiple field users, monitoring the health and relative positional accuracy of the CORS, monitoring the quality of results and providing accounting capabilities (to manage authorized usage). CPC software must be scalable and able to accommodate modernization and expansion of GNSS constellations. Narrowly defining the list of CPC software features and capabilities to suit a single or a few end uses may

[2] Continuously operating reference stations (CORS) comprise: a stable mount (or monument) for a geodetic-grade GNSS antenna; a GNSS receiver that has been designed for continuous and remote operations; a continuous source of power (grid, generator, or solar); and robust communications links to the central processing center(s) of the RTN. The CORS must have a clear sky view free of obstructions or sources of multipath (signals bouncing off objects can contribute to poor-quality results).

[3] Static observation files contain all of the observable components of the satellite transmissions written to the memory of the receiver, typically on an hourly basis, and then in a rotation (oldest automatically removed when memory is full). These are transmitted to the CPC, often on an hourly or daily basis. These files are utilized for “post-processing,” which is a method for computing high-precision results after-the-fact in instances when the field rover does not have live communications to use the real-time correctors. Compressed formats for static files are widely utilized to reduce bandwidth and storage; these are decompressed for use automatically by post-processing software with no loss of observables. This data should be archived as the historic record.

limit the long-term value prospects for the RTN (more in the “drivers and sustainability” section below).

c. Rover access and communications

The most common form of access to the real-time correctors produced by the RTN is via internet connections—mostly wireless internet (cellular broadband, GSM, GPRS, et al). The bandwidth requirements for the individual field rover are minimal, typically never exceeding 5 GB per month. Cellular-based mobile internet is the predominant means to access an RTN; reliable and affordable but limited to cellular coverage areas.

There has been moderate success in utilizing satellite modems, but these can be subject to random and extended periods of high latency in addition to substantial data access costs to the user. Local testing is highly recommended if considering the use of satellite communications for rovers.

For areas on the fringe of cellular coverage, sometimes RTK-relay devices are used. These contain a cellular modem and a UHF or spread-spectrum radio to relay the corrections out past the limits of the cellular coverage. Some users also set up chains of radio repeaters out to job sites in areas of no-cellular, on a temporary or permanent basis.

In the past, some networks would set up banks of dial-up modems to accommodate multiple end users, but this has become obsolete with the advent of NTRIP [3] casters, which can serve hundreds of users simultaneously from each correction source of the RTN. NTRIP is a non-proprietary international protocol for user connection and authentication, and nearly every modern rover has an NTRIP client installed. Utilizing a caster rather that direct machine-to-machine (M2M) communication offers network security as all traffic can be limited to a single internet address and port. Almost without exception, there are no proprietary barriers to rovers of any brand being able to utilize any given RTN.

Rover communications is typically the responsibility of the end users, unless an RTN is being developed by and for a single enterprise. Typically the CPC design need not be concerned with end-user communications, as there are many options for the end user using internet protocols. However, cellular coverage may affect the RTN’s expected valuation and ability to attract partners and serve stakeholder constituencies (see more in the DRIVERS AND SUSTAINABILITY section below).

FEATURES AND SERVICES

Certain features of an RTN must be viewed as essential to reliably provide basic services of real-time correctors and static files for post-processing. Realistic expectations for an RTN are 99% uptime and results in the range of 2cm–5cm in 3 dimensions ((typically 1–3 cm (0.4–1.2 in) horizontal and 2–5 cm (0.8–2 in) vertical)). Successful RTN achieve such results by including more-than-minimum features (e.g., spatial integrity and environmental monitoring) with the added benefit of being able to provide ancillary services (e.g., geophysical and structural monitoring), thereby increasing the valuation of the RTN and ensuring sustainability.

Minimum features:

a. Real-time network corrections

A number of countries still utilize outdated technology to execute their projects. The most common method is to gather data and post-process the information in the office. This creates additional costs in personnel and project execution associated with gathering information and post-processing this data. All of these costs can be avoided by using real-time corrections.

Various methods for developing network corrections utilize raw, real-time synchronized observations from multiple CORS (surrounding the location of the field user) to model the sources of error and create the correctors to be applied by the user’s rover. The most common approaches are non-physically based (typically called “VRS” for “Virtual Reference Station”, or variations), master-auxiliary (MAC or variations), and FKP (Flächen Korrektur Parameter). While all approaches have proven to provide excellent results if properly implemented, there is little empirical evidence that any provide a substantial advantage over another. But it should be noted that the predominant real-time network corrector is VRS (or variants), and in many instances VRS has become a generic term for such correctors and for many RTN. At a minimum, an RTN should provide VRS (or any non-proprietary variant) with the capability of adding MAC and/or FKP (or variants) as an optional feature for users (if the RTN stakeholders request this).

The most commonly provided real-time stream formats are RTCM4 (Version 3), and CMR+. Almost without exception, GNSS rovers, including receivers used in precision agriculture and construction machine guidance systems, support RTCM 3 and/or CMR+.

[4] The Radio Technical Commission for Maritime Services (RTCM) is an international non-profit scientific, professional and educational organization. The RTCM sub-committee SC-104 develops standard formats for Differential Global Navigation Satellite Systems.

These two formats, at a minimum, should be supported by a multi-use RTN.

b. Real-time single-base corrections

Single-base corrections differ from network corrections only in that they originate from a single CORS; the output formats like RTCM 3 and CMR+ are the same and the rover processes these in the same manner. This is akin to the legacy RTK solutions where users may have otherwise set up their own temporary base. There are end uses and instances in which the user may prefer a single-base solution, or a CORS may be isolated from the main body of the RTN (e.g., a distant, offshore island). At a minimum, the same output formats of RTCM 3 and CMR+ should be offered for each CORS. An important consideration is to guarantee that the single CORS is working the same geodetic reference framework. Many RTN offer an "auto-select" option for single-base correctors, but this option is not widely desired if a full network correction is already available.

c. Network spatial integrity monitoring

An RTN will not be able to deliver results at precision higher than the positional integrity of each CORS (relative to every other CORS in the network, or functional sub-network if operated in that manner). A common threshold for RTN operation holds that at any given time, the position of any CORS relative to any other CORS should be known to within 2cm in 3 dimensions. In addition, the CORS should be constrained to a geodetic reference framework (see the REFERENCE FRAMEWORK section). If the relative integrity is inconsistent or out of such tolerances, it may affect the processing of other modeled elements and will degrade results.

It may not suffice to simply perform an initial computation (e.g., GNSS baseline processing with a least-squares adjustment) and hold those values indefinitely, as there are few regions of the world where there is zero tectonic velocity or that are free of other geo-dynamics.

The network needs to be constantly monitored for geophysical movement. Successful RTN employ multiple "motion engines" which are often offered as a standard component of CPC software. This is one of the most critical elements of network operations, especially in regions of dynamic tectonic activity. (See more in the REFERENCE FRAMEWORK section below.)

d. NTRIP, logging, and accounting

RTN system deployment may generate revenue to the RTN operator by charging for access to the data in the system, thereby providing maintenance and modernization funding. At times, however, operators choose to offer the correction services as a public good. Access control is recommended even if an RTN intends to offer free services within its own enterprise, to its partners or to the public. An NTRIP caster or casters can accommodate hundreds of simultaneous users without any appreciable processing load, and an accounting system can accommodate for-fee services (if operating under that model). Such capabilities are standard modules in CPC software suites. Session logging should be considered essential as these logs are utilized for analysis of end-use statistics and trends and to aid in troubleshooting.

e. Ionospheric condition monitoring

An RTN models signal delays due to the ionosphere and removes these as the primary source of error. Space weather events (solar flares and coronal mass ejections etc) may increase or otherwise cause fluctuations in these delays. Most space weather monitoring services provide global models based on sparse sensor arrays, but an RTN provides a very detailed local model. An RTN should have a live graphical representation of the ionospheric conditions available for both operator and end users as a planning and troubleshooting tool. It is also recommended that a tool for mapping and representing the total electron content (TEC) across the network be included.

f. Tropospheric condition monitoring

Delays due to tropospheric (local weather) conditions are also modeled and removed as sources of error but, like the ionospheric delays, there may be outliers that can affect results. As a tool for planning and troubleshooting, one of the best representations of tropospheric conditions is a map of perceptible water levels in the troposphere above the network. Tools to create these maps are offered as optional features in CPC software but should be considered essential for any RTN that is not limited to a very small geographic area as the conditions may vary over larger RTN. Such maps provide the RTN operator with the ability to determine if anomalies in results may be due to localized tropospheric effects.

g. Field results monitoring

To continually test the integrity of the results expected for end users in the field, standard field rovers are mounted in fixed locations throughout the network. Modules in the CPC software send network corrections to these test rovers and receive the returned results, which are plotted over time showing the resultant precision. These tools also log other key quality indicators from the rover. These integrity stations are a key component of quality control for an RTN.

h. Static-post files for post-processing

Users who may be working in areas of the network where real-time communications may not be available (e.g., no cellular coverage) need to have the option to post-process[5]. Static files for each CORS are typically hourly files containing all observables from each satellite in view (at the respective time) at one observation per second.

These files are often stored in a compressed format (to save on storage space and to reduce data usage for transfer back-fill files after communications outages). The RTN should have the option of collecting at higher rates (e.g., 10 observations per second) when requested for specialized needs (e.g., aerial survey or mobile mapping).

End-users will process these static files with their own surveying and/or geodesy software packages, or online processing services.

i. Custom static file request system

To accommodate multiple users who may desire different format static files, an online custom static file order application should be a standard feature for the RTN. Such a service will allow users to choose multiple CORS for any given time period and duration, the observation rate they plan to process at, and the format they desire. The RTN will convert the files from the internal compressed format and bundle them for multiple CORS for download by the requesting user.

j. Web portal

The RTN generates much useful information for the end user to check the status and quality of the RTN services and to access static files. These can and should include plots of network health indicators, like ionospheric conditions, total electron content (TEC), perceptible water and geometric integrity of the CORS, and outputs from any field quality monitoring stations. The users should be able to view any notices from the RTN operators, view session logs from their own activities, see a live status map of CORS, and be able to download custom static and virtual file orders.

A complete and effective web portal for users is the key to reducing operations customer support loads. Users can access services and find answers to nearly any question they would have otherwise had to call the operator to resolve. The web portal should also link to instructional and educational materials and answers to frequently asked questions.

Recommended additional features

k. Virtual static files for post-processing

Virtual observation files are an additional type of static observation files that are uniquely provided by RTN. These are utilized in the same manner as standard static files for post-processing, and by the same end-user surveying and geodesy programs, but have an advantage in that relatively shorter observation session durations can yield the same results as much longer standard static sessions.

These virtual static files are requested by the user (through a web interface). When the user enters the rough location where they collected the observations on their rover, the RTN applies the same modeling as it would for a real-time solution and creates a static file for that location. The user then downloads and processes in the same manner as a standard file.

l. Online post-processing

RTN-hosted online post-processing can be a valuable service to provide for the same reasons a user might seek to post-process observations: to work in areas without real-time communications, to provide redundancy checks, or to establish geodetic control,.

Some RTN suites offer this service as an optional module. Users upload their field static files for a given period and location, the CPC searches for static files in its archive from CORS surrounding that location, and a post-processing session is initiated (applying pre-defined optimal settings). The results are then emailed to the user available for download (via their secure login).

REFERENCE FRAMEWORK

The reference framework of an RTN exists on two levels: (1) relative integrity internal to the network of RTN CORS; and (2) constraints to a published or otherwise official geodetic reference system (often called "datum"). For the latter, if a specific reference system is not required, then the RTN's

[5] Post-processing is a method by which the observables from each satellite observed by the rover and base(s) are recorded in static data files at each receiver. These observations are processed together after-the-fact to compute a position for the rover (at the time of data collection) from processed baselines and subsequent adjustments (if applicable). There are post-processing methods for short observation times (low-precision needs) to long session (hours) to multiple session (over days or weeks) for higher-precision applications. Prior to the advent of real-time methods, post-processing was the default method for precise GPS uses. It is still widely used for the highest precision needs like project control and geodetic networks.

external constraints should be to a global system (e.g., WGS84/ITRF/IGS) for operational considerations.

One of the most potentially problematic elements of an RTN is that of maintaining relative spatial integrity between the CORS. Modern RTN provide multiple motion engines, both real-time and post-processed, to check the relative integrity. An RTN operator should employ a tiered system of these motion engines; some to detect long-term trends (e.g., tectonic plate movement), and others to detect sudden movements of the CORS (e.g., a local disturbance of the antenna mount, such as a landslide or a vehicle collision). Monitoring long-term velocities is important in determining if/when a CORS positon should be re-computed and updated to maintain overall network integrity.

Primary stakeholders of the RTN may desire the results to be derived relative to a specific global, regional, national, or state reference framework. Indeed, many RTN worldwide serve as the active control component of their respective locales. To serve as many end-user constituencies as possible (thereby ensuring broad valuation and better long-term prospects for stakeholder support of the RTN), a best practice is to constrain the CORS to a respective official national or global reference system, then to support other desired references via multiple outputs (e.g., different NTRIP sources for each station or subnet).

In addition to monitoring and updating from movement due to tectonic velocities—and this may be substantial and rapid in many regions of the world—the RTN operator must be able to establish new positions rapidly after sudden or catastrophic events (e.g., earthquakes, volcanic eruptions). In the event of an earthquake it may be difficult to determine which CORS in a network have not moved due to the event. Another feature of modern RTN are Precise Point Positioning (PPP[6]) options for the reference stations and the CPC software. Some CPC providers offer PPP as an option (both internet-served and from commercial satellites). This is a valuable tool for the operator, both as a redundant check for maintaining spatial integrity of the CORS, and for post-tectonic-event validation and updated coordinate generation.

The geodetic aspects of RTN operation may be among the most difficult for a new operator to master; typically some education in geodesy is required. Partnerships with national geodetic entities and scientific entities that may also be hosting GNSS CORS are highly recommended (see DRIVERS AND SUSTAINABILITY section). Some CPC software vendors also offer hosting, operations, and monitoring services; these are also a recommended resource for geodetic expertise (see OPERATIONS section, paragraph g. – Hosted RTN operations and services).

DESIGN

The design of any RTN must be customized to some degree as local or combinations of local and regional factors may be somewhat unique—needs of the stakeholders, geography and climate, communications and power resources, funding and operational models are but a few considerations. Fortunately, the nearly two decades of RTN development and installations have yielded some fundamental design considerations. There are some great guidelines developed by entities that operate hundreds of CORS (for scientific and official geodetic purposes); such guidelines are consistent with the criteria for what constitutes an optimal RTN CORS [4] [5].

a. **Central Processing Center**

   Redundant and robust processing power is the key to the design of the CPC. Standard server hardware and operating systems (e.g., most commercial CPC software suites are designed to operate on Windows Server) as well as hosted servers are quite affordable. Redundant servers at a separate location, hosted and cloud servers are highly recommended. Sending redundant streams of observations from each CORS to primary and backup servers provides your users with seamless and continuous service.

   Hosting of CPC and CORS-to-CPC communications through enterprise or government agency networks has often proven to be problematic for RTN operations. As such entities often have very complex and strict security concerns, the internal internet connectivity environment may change at any time and may cause lengthy interruptions to CORS-to-RTN streaming and end-user connections. Working with commercial communications providers is likely the realistic choice for CORS communications over a wide region; the security risks are minimal, both CORS and the CPC offer multiple security options, and running them outside of an enterprise network will minimize hazards to those as well.

[6] Precise Point Positioning is a GNSS positioning method that derives global positions relative to global reference systems to centimeter precisions (but typically with a long initial convergence time). This is achieved by applying enhanced clock and orbit data (or “products”), derived from global arrays of tracking stations) to a receiver’s own local observations. These clock and orbit products are delivered to receivers in real-time, either by internet connections or via transmission from commercial satellites. There are also online services where users can submit observations files for online PPP processing. There are academic and commercial PPP services, with the latter deriving the clock and orbits from their own global tracking networks and typically offering a broader range of options than academic services (e.g., multi-constellation support, real-time and satellite transmission of clock and orbit products). As the reference for PPP is truly global and does not rely on local CORS and differential methods, PPP is well suited to global or regional geodetic work, and scientific studies (e.g., plate tectonics studies). Initial convergence times and challenges in vertical results typical of PPP make it less attractive for most real-time uses.

b. Receivers and antennas

There are classes of GNSS receivers specifically designed for use as a CORS—high precision, high quality, multi-constellation support, low power consumption, network boards for connection as an internet device, and web-based user interfaces for operations.

RTN can accommodate multiple models of receivers as CORS; while it is not necessary for every CORS to be of the same brand/model, there are advantages to the operator in having the same receiver characteristics and in being able to fully benefit from certain features of their CPC software suite in having receivers with a broad range of features. Selection of CORS receivers and antennas is not an area of RTN design for much compromise and cost cutting.

Geodetic-grade antennas are essential, as they provide optimal multipath rejection. It is advisable to apply absolute antenna models, like those commissioned by the International GNSS Service (IGS)[7]. If your RTN is utilizing a mix of receiver brands/models, it is not advisable to utilize the antenna offset models provided by the manufacturers (they sometimes use different methods for determining offset) and it is advisable to use the respective IGS models for each to provide consistency.

If possible, it is advisable to avoid enclosing an antenna in a protective dome or cone unless there are theft or vandalism concerns. Antenna models for domes can vary a lot, and unless you can have each antenna/dome individually modelled (there are commercial services that can do this to IGS standards but at cost), there may be small but not insignificant variations. While choke rings have been the gold standard, there are geodetic-grade antennas that are low profile, are fully enclosed (eliminating the need for a dome), and have been shown to perform as well as many (often more costly) choke-ring antennas.

Geodetic-grade antennas are typically powered by a low current running though the coaxial antenna cables. Antennas may be as much as 100m (328ft) from the receiver (a best practice is to accommodate the placement of the receiver in a secure and environmentally appropriate enclosure, or inside a building). Low-loss antenna cable is recommended, and there are good all-weather cable types available (the antenna cable does not necessarily need to be placed in conduit). In-line lightning arrestors are recommended to protect receivers. Cable length limits are typically 100m, and while signal boosters may work, they should only be used if no there are no other options.

c. Enclosures, power, and communications

The power consumption of the components of a CORS can be quite modest; purpose-designed CORS receivers are generally under 4W, and there may only need to be one additional device for communications (modem or relay radio). If AC power is available, a 5-amp circuit will typically suffice. Most of the purpose-designed CORS receivers have internal batteries that may last as long as 2–3 days in the event of power outages (logging will continue), but your communications devices do not, so backup power packs (or batteries with trickle chargers) are recommended.

If no AC is available, solar arrays (12V or 24V) serve CORS quite successfully. Some the providers of CORS GNSS equipment also provide pre-engineered solar arrays with enclosures and backup batteries—these enclosures are designed to accommodate the GNSS receivers and some ancillary communications equipment.

If a CORS is housed near or on a stable building, an enclosure may not be needed; but if the CORS equipment must be operated in a remote location, standard environmental enclosures (commercially available through electrical and communications equipment suppliers) work well. Purpose-designed GNSS CORS receivers and antennas are designed to operate in temperature ranges as wide as –40ºC to +65ºC (–40ºF to +149ºF), but other components (e.g., modems, switches, routers, and back-up power) may not—check specifications. Pre-engineered enclosures are vented and protect the equipment from the elements, but you may need to add a small thermostat-controlled fan in hot and humid locales, and/or a small trickle-heater for very cold conditions.

d. Antenna mounts

Stability of the antenna mount and a sky view clear of constructions and multipath hazards are both equally important for an RTN CORS. It is recommended that test observations be performed at any candidate sites. This should include several sessions of at least 24 hours each, and the results analyzed in surveying or

[7] IGS – The International GNSS Service is a cooperative of scientific and governmental entities that operates a global GNSS tracking network providing what have become the internationally accepted and applied standard clock and orbit data products. The IGS also provides absolute antenna models for most high-precision GNSS antennas to foster consistency in processing for geodetic and timing uses.

geodetic-processing software or with analysis tools of a publicly available tool like TEQC[8].

High-precision receivers and geodetic antennas may detect and reject a significant amount of multipath (i.e. signals bouncing off objects) but there may be strong and persistent sources of multipath from objects above and below the plane of the antenna. An antenna mounted above the metal roof of a building may not necessarily be problematic; test observations can reveal suitability. A setting (typically 10º) is made in the receiver to mask out signals from satellites that are close to the horizon or local sky-view hazards. Azimuth-dependent masks, a feature in some modern CORS receivers and/or CPC software suites, allow the operator to selectively mask around specific sky-view or multipath hazards.

A mount for the antenna, whether on the ground or on a building, should include a levelling adapter and a locking mechanism (anti-theft). A ground mount (e.g., drill-brace, tiered concrete pillar, driven pole or beam, etc.) should extend below any layer that may be susceptible to seasonal frost or other dynamics that may affect the near-surface layers. Bedrock is preferable. Seeking expertise from geologists is recommended.

A building mount can be quite stable, if the structure sits on bedrock, is of sufficient mass, or is of solid concrete construction, etc. Again, testing is recommended. Once in operation, the CPC software should be monitoring the movement of the mount precisely; any movement trends, seasonal, diurnal, or other will be detected. It may surprise some that buildings initially thought of as low-stability can perform well, and otherwise solid-appearing buildings may not.

Some operators will employ tilt sensors or accelerometers as part of proposed mount/site tests. There are CORS receivers that also house large motion sensors (seismology sensors); these can serve seismological research (adding more stakeholders) as well as monitor the stability of the site.

The previously noted guidelines [4] [5] present some of the most common ground mounts and best practices for selecting antenna mount sites

e. Communications

See RTN COMPONENTS section, paragraph a.– CORS Communications, for communications considerations and options.

f. CORS spacing

Most network RTK solutions provided by CPC software suites will perform well with a nominal CORS spacing of 50–70km (31–43mi). There are, however, RTN that have set CORS farther apart but with the understanding that, during some heightened space weather events, users in those areas may be temporarily unable to work. Some RTN choose to keep CORS in and around high-use areas closer together for redundancy.

Unlike communications networks (cellular, radio), it is not necessary to put CORS on hill or mountain tops (unless there are sky-view advantages). Adjacent CORS of greatly varied elevation change or crossing regions of dramatic tropospheric (weather) variations can pose network processing challenges. For these reasons, operators may place stations closer together or operate different parts of the RTN as functional "sub networks" (see OPERATONS section, paragraph a. – Geodetic determinations and monitoring).

It is a good practice to seek insights from RTN operators in regions of similar terrain, plate tectonic velocities, and climate as your proposed RTN. CPC software, services and solution providers are also a good resource.

OPERATIONS

Although there have been significant advances in the automation of certain aspects of RTN operations, you will need multiple qualified and trained operators, or you should seek hosted operations via contract. The duties and requisite skills of an operator are diverse and significant.

a. Geodetic determinations and monitoring

RTN operators should have a background in geodetic surveying or have a partner in the network or a consultant experienced in geodesy. Even if a partner or consultant computes initial positions for the RTN, the operators must have a fundamental understanding of geodetic dynamics of the region and be able to analyze CORS monitoring data to determine if and when to re-compute and update CORS positions.

An RTN may be operated in functional subnets for the reasons noted in the DESIGN section, paragraph f.– CORS spacing, but also because different regions of a wide-area CORS may be subject to varied rates of

[8] TEQC (translation, editing, quality check) is developed by the non-profit science company Unavco as a toolkit for working with GNSS observation files of many formats. This command-line software has companion tutorials. It can be downloaded at no charge at www.unavco.org/software/data-processing/teqc/teqc.html

tectonic plate velocity. Subnets are often more practical to manage geodetically than an entire region (e.g., country or state). This is not problematic for the end users as they will find correction sources for each region on the NTRIP caster(s) or the RTN.

b. Information technology and communications

Operation of the CPC software, installation, upgrades, software maintenance, and performance monitoring requires that operators be well versed in the following fields: information technology, database management, server operations, internet protocols, and working with the various communications technologies employed by the RTN.

c. GNSS science and technology

An RTN represents some of the most advanced GNSS processing and analysis tools in commercial use. For operators to be able to analyze results, monitor data, and troubleshoot potential problems, it is essential that they understand fundamentals of the science of GNSS, keep current with the modernization of GNSS signals and constellations, and understand the processes employed to reduce the effects of standard sources of error inherent to GNSS observations.

d. Management

An RTN operator will often have to manage authorized usage, logins, accounts, partnership and user agreements, maintenance of CORS, contracts, permits for CORS sites, software and hardware upgrades, and customer support. Interpersonal skills are also essential.

e. Customer support

If an RTN is established and running, the end users will inevitably contact the RTN for support. Field uses of RTN corrections for high-precision GNSS equipment also require specific skills and knowledge on behalf of the field user. While operation and configuration of their field equipment is their own responsibility, end users will rightly contact the RTN with questions about accounts, status of the RTN, the reference framework, updates, quality indicators, web portal features and other services provided by the RTN. Support calls from individual users tend to decrease as the user gains experience, but can be frequent initially. The operator should also be versed in the general use of representative GNSS field equipment to better help in troubleshooting and support requests.

f. Primary and backup operators

Unless the RTN is quite small (e.g., 3–5 stations) and serves only a single enterprise and/or end user or a limited end-user community, you will need more than one operator. Operators for large and multi-use RTN are essentially on-call for network operations year-round and around-the-clock.

A backup operator need not be as well versed in all aspects but should perform the day-to-day duties often enough to keep current in the operations of the RTN to be able to troubleshoot an optional operating state in case the primary operator is unavailable.

g. Hosted RTN operations and services

CPC software developers offer contract services for design and development of RTN, through installation, maintenance, redundancy services and operations. Such services are becoming popular and, for many RTN stakeholder communities, can represent substantial cost savings in reduction of RTN overhead.

RTN owners and stakeholder constituencies often have difficulty in identifying, training, and retaining qualified operators. Unless the RTN is willing to commit to a full-time operator or operators and to ensure succession of operators in the event of operator job changes, a hosted service is highly recommended. This is particularly important during the execution of projects to avoid delays from RTN networks not being operational and guarantee on-time performance.

Hosted services can operate the RTN's CPC remotely, or host a CPC and redundant CPC at their facilities or in the cloud. Typically the vendor is hosting multiple RTN, and has full-time operators who are well trained and have a knowledge base of operations, upgrade, support and troubleshooting that would take a new operator many years to gain.

DRIVERS AND SUSTAINABILITY

An RTN needs stakeholders that realize sufficient value to support initial establishment and ongoing operations. Many RTN emerge from an initial limited but immediate set of needs and stakeholders, but see growth and a wider set of stakeholders once established.

a. RTN uses

The end uses for RTN are broad, and have been growing since RTN were first introduced in the 1990s. Uses include, but are not limited to:

- Land Surveying and Geodetic Surveying
- Construction, Machine Control, and Grading

- Heavy Construction, Structural Assembly, and Construction Inspection
- Compliance Inspection, Grade Checking, and Site Safety
- GIS, Resource Mapping, Utility Location and Clearances
- Preliminary Engineering and Engineering Studies
- Mobile Mapping, Aerial Mapping, and UAVs
- Asset Inventory, Physical Plant, and Infrastructure Inventory
- Dams, Bridges, Buildings, and Structural Integrity Monitoring
- Geophysical Studies, Tectonic Plate Movement Research
- Earthquake, Tsunami, and Volcanic Warning Systems
- Landslide Monitoring, Geological Deformation
- Communications Networks and Utility Infrastructure
- Atmospheric Studies, Ionospheric and Tropospheric Modeling
- Precise Navigation, Snowplow Guidance, and Maritime Portage
- Rail, Port, Mining, and Airport Operations
- Intelligent Transportation, and Route Delineation
- Incident Mapping, Emergency Response, and Post-Event Analysis
- Environmental Mapping and Monitoring
- Disaster Preparedness, Recovery and Reconstruction
- Precise Guidance, Hazard Clearances, and Precise Geofencing
- Forensics, Scene Investigation, and Incident Mapping
- Archaeology, Restoration, and Monument Preservation
- Science, Timing, and Robotics

b. Initial establishment funding

Infrastructure costs, if borne by one entity for an entire RTN, could be substantial—receivers, antennas, site permits and leases, communications and power hardware, mounts, servers, and CPC software. For example, a 50-station network could see costs in millions of dollars (USD). For this reason, many networks use phased development. It is often the case that, once an RTN is in place and running successfully, attracting additional stakeholders will follow.

There are few large RTN (>25 CORS) that have been funded by one entity for a limited or single end use that realize sufficient cost benefits to sustain the network. Smaller RTN may be able to make such a model work. Among the best options for funding the initial infrastructure investment in the RTN (without having to cut corners and compromise quality) are: (1) to seek partners to leverage existing CORS; (2) to seek partners willing to contribute; or (3) to partner with an RTN service provider that might be willing to help establish the RTN and to operate it in exchange for being able to charge non-partners for usage to cover operations costs. For developing countries, however, it is often the case that funding an RTN may realize significant cost benefits for other large projects. Thus, it is recommended that funding agencies integrate these networks into their projects.

There are some end uses for RTN that may only occur in certain high-usage areas of a geographic region—often in only the most heavily populated areas. If the goal is to develop an RTN to cover large regions, such as a whole country or state, it is important to seek partners who have a stake in even the remote areas of the entire region; science, natural resources, agriculture, transportation, and other government agencies often do.

c. Recurring costs

To ensure high-quality results and long-term viability of the RTN, a program of ongoing modernization should be set in place with a schedule for software, receiver and antenna upgrades. Some components may work for many years beyond their design life, but may become obsolete and unable to take advantage of GNSS signal and constellation modernization.

Annual costs may include: software maintenance contracts, server maintenance contracts, operator labor and training costs, receiver maintenance contracts, site leases and permits, communications data subscriptions, CORS maintenance and repairs, loss and damage replacements, contributions to an upgrade fund, and more. In a single-entity model, these costs will be borne solely by that entity; a subscription model for users outside the enterprise or non-partners is not uncommon. If partners or hosts for individual or groups of CORS are willing to bear the initial infrastructure cost and their recurring costs, this can be in exchange for use of the entire RTN.

d. Partnering with the scientific community

The use of GNSS for geologic, geodetic, and atmospheric research has seen the establishment of arrays of CORS by academic institutions and/or scientific cooperatives of institutions engaged in such research; for example, the study of plate tectonics [6] [7]. Some of these arrays began before the advent of RTN. Partnering with the stakeholders in these scientific arrays has often proven to be the most mutually beneficial of partnerships.

Researchers are mostly very desirous of data from a wider array of sensors, and RTN often provide a greater density. Partnering on existing scientific CORS will provide the live-streaming capabilities many may have lacked, and the RTN can provide a conduit to a broader group of stakeholders with an increased valuation and resources to apply to these overlapping arrays.

e. Partnering with geodetic reference frameworks
With the costs of establishing and maintaining physical "passive" geodetic control increasing, and with many legacy control networks falling into obsolescence, the desire for "active" control networks (GNSS) has risen. Stewards of national or regional geodetic reference frameworks may already be partnering with their respective regional scientific and academic communities. Well-designed and operated RTN often become an active arm of the reference framework. The RTN benefits from the geodetic expertise and resources of such partners in establishing positions for CORS, in maintaining their spatial integrity and in updating accordingly.

f. Partnering with transportation departments
Another class of entities (public and private) that have broad interests over wide regions includes transportation departments, rail companies, and utilities. These entities are typically heavy users of RTN (once established). They may have some GNSS infrastructure to contribute, and have facilities all over the region for CORs sites (often secure, with internet communications and power). In fact many RTN began with, or are wholly operated by departments of transportation.

g. Commercial hosting and partnerships
There are a number of examples in which RTN infrastructure was established by scientific and/or governmental entities (for their own uses), but where the RTN data has been leased to commercial entities for paid correction services; this provides revenue to maintain the RTN. Another model is to find an RTN service to operate the RTN in exchange for allowing them to charge for subscriptions. RTN correctors have value beyond cost savings through internal use and, unless an RTN owner or owners leverage this potential revenue, it may be difficult to withstand the ups and downs of enterprise budget cycles.

h. Challenges
Although the rapid growth of RTN worldwide is solid evidence of their cost-benefit and utility, there are still parties and entities that will resist their establishment.

Legacy high-precision positioning, location, and navigation methods are mostly more labor intensive and expensive. The practitioners of costly legacy methods may not wish to pass on the cost savings that RTN can provide to their clients and may openly resist. Those with security concerns may be few, but it only takes a few people in upper echelons of the decision-making process to stop an RTN. There are concerns that somehow criminal or terrorist actors will utilize the RTN, but this has never been shown to be the case in all of the years of RTN use worldwide. Positioning is not unique to RTN and high precision does not outwardly hold any advantage for nefarious actors that they could not otherwise obtain via other less expensive and less complex means.

CONCLUSIONS

RTN have become a standard tool in developed economies worldwide. However, developing economies more often than not need to upgrade and utilize readily available technologies to improve their geospatial data infrastructure through an RTN. High-precision positioning is truly a new type of utility and should become a must-have component of a nation's critical infrastructure. When properly deployed, updated RTN can realize billions of dollars in cost savings over the many years of their existence.

Any initiative to develop an RTN in the present day can benefit from the nearly two decades of development and experience gained by the hundreds of RTN globally. A new RTN will be implemented at lower costs and without the struggles of its predecessors.

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