Statewide Real-Time Global Navigation Satellite System Network Implementation

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List of Abbreviations and Acronyms

AASHTO	American Association of State Highway and Transportation Officials
ADOT	Arizona Department of Transportation
AGRC	Automated Geographic Reference Center (Utah)
AID	Accelerated Innovation Deployment (demonstration program grants (FHWA))
ARDOT	Arkansas Department of Transportation
Caltrans	California Department of Transportation
CDOT	Colorado Department of Transportation
CGNSS	continuously operating GNSS (reference station)
CORS	continuously operating reference station
DOT	department of transportation
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
FTE	full-time equivalent
GIS	geographic information systems
GNSS	global navigation satellite system
GPS	Global Positioning System
ISU	Idaho State University
IT	information technology
ITD	Idaho Transportation Department
MDOT	Michigan Department of Transportation
NCGS	North Carolina Geodetic Survey
NCN	NOAA CORS Network
NDOT	Nebraska Department of Transportation
NGS	National Geodetic Survey
NOAA	National Oceanic and Atmospheric Administration
NRTK	network real time kinematic (positioning technique)
NSRS	National Spatial Reference System
OPUS	Online Positioning User Service (NOAA)
PPK	post-processed kinematic (surveys)
PPP	precise point positioning (technique)
RTK	real-time kinematic (surveys)
RTN	real-time network
SCDOT	South Carolina Department of Transportation
SDDOT	South Dakota Department of Transportation
South Carolina RFA, Geodetic Survey	South Carolina Revenue and Fiscal Affairs, Geodetic Survey
TRB	Transportation Research Board
TxDOT	Texas Department of Transportation
VRS	virtual reference station
WisDOT	Wisconsin Department of Transportation

Executive Summary

Background

Global navigation satellite system (GNSS) real-time networks (RTNs) enable the collection of satellite data to produce real-time positioning and timing information used in earth science, engineering, construction, aerospace and other industries. Transportation agencies, including the California Department of Transportation (Caltrans), use precise positioning and timing data in a broad range of applications, from navigation and infrastructure development to land surveying.

Use of this data in future applications such as automated transportation presents an opportunity to lead or partner with other entities to implement a robust, statewide RTN. To better understand the requirements of such an effort, Caltrans was interested in learning best practices for developing, managing and implementing sustainable statewide RTN systems, including the following topics:

- Landscape, dependency and importance of existing statewide RTN systems.
- Management practices, investment, maintenance and upgrade costs for these systems.
- Return on investment to state and local governments, the scientific community and the public.
- Role these systems play in the application of advanced technologies.
- Importance of minimizing system downtime.
- Identification of system deficiencies and the mitigation strategies employed by operators.

To gather information about these topics, CTC & Associates surveyed state departments of transportation (DOTs) about their experiences and management practices related to real-time GNSS implementation. A review of in-progress and completed research about GNSS RTN best practices and management supplemented the findings of the survey.

Summary of Findings

Survey of Practice

An online survey distributed to members of the Transportation Research Board (TRB) Standing Committee on Geospatial Data Acquisition Technologies and the American Association of State Highway and Transportation Officials (AASHTO) Committee on Data Management and Analytics received 16 responses: 13 state transportation agencies, two state geodetic survey sections and one municipal utility:

State Transportation Agencies

- Arizona DOT (ADOT)
- Arkansas DOT (ARDOT)
- Colorado DOT (CDOT)
- Florida DOT (FDOT)
- Idaho Transportation Department (ITD)
- Michigan DOT (MDOT)
- Nebraska DOT (NDOT)
- Ohio DOT
- Oklahoma DOT
- Oregon DOT
- South Dakota DOT (SDDOT)
- Texas DOT (TxDOT)
- Wisconsin DOT (WisDOT)

State Geodetic Survey Sections

- North Carolina Geodetic Survey (NCGS)
- South Carolina Revenue and Fiscal Affairs, Geodetic Survey (South Carolina RFA, Geodetic Survey)

Municipal Utility

- Seattle Public Utilities

Of these agencies, three states do not currently own a GNSS RTN:

- *Colorado*. CDOT has no plans for or interest in establishing a GNSS RTN system since it partners with and uses existing RTNs from the Mesa County RTN, which covers the western half of Colorado. CDOT supplied two GNSS base stations in Region 5 (15 counties in southwestern Colorado) and also supplied base stations in Region 3 (counties in the northwestern portion of the state).
- *Michigan*. MDOT also has no plans for or interest in establishing a system.
- *South Dakota*. SDDOT does not own a GNSS RTN system, but is contemplating one. The agency currently uses Trimble's VRS Now for survey activities in the eastern half of the state. The respondent noted that an RTN would provide consistent control for DOT projects, ensuring that all projects are tied to the same control network, and would also provide better accuracy for real-time kinematic (RTK) and post-processed kinematic (PPK) surveys.

  Future implementation would involve installing a public network within the western half of the state, which is currently not covered by Trimble VRS Now. To implement a system, the agency needs buy-in from executive leadership, resources (funding and time), and dedicated employees for network setup and maintenance. If these requirements are achieved, the agency anticipates beginning implementation in the next five years.

The remaining 13 agencies participating in the survey have a GNSS RTN and provided information about their experience in six categories:

- System administration.
- Applications.
- User information.
- System costs and funding.
- Return on investment.
- Assessment and future plans.

Highlights from survey participants' responses are summarized below. More detailed information from these respondents is provided in the **Detailed Findings** section of this Preliminary Investigation.

System Administration

Key topics addressed in this portion of the survey include ownership and operation of the GNSS RTN and the continuously operating GNSS (CGNSS) reference stations, extent of GNSS RTN coverage, number and distance between CGNSS stations, relative accuracy of the GNSS RTN system, communication method between the CGNSS stations and the central processing center, alignment with the National Spatial Reference System (NSRS), and system hardware and software vendors and manufacturers.

GNSS RTN Ownership and Operation

Seven state transportation agencies participating in the survey own and operate the GNSS RTN central processing center (*Arkansas*, *Florida*, *Ohio*, *Oklahoma*, *Oregon*, *Texas*, *Wisconsin*). In Idaho, ITD and a private organization share these responsibilities. In four states, other public agencies own and operate the center: the Department of Water Resources in Arizona; a public/private cooperative in Seattle; the state geodetic survey section in North Carolina; and multiple owners in South Carolina. A private organization owns and operates the center in Nebraska.

CGNSS Ownership, Operation and Maintenance

In 10 of 13 agencies, the state DOT is either a partner or has sole responsibility for ownership, operation and maintenance responsibilities of CGNSS reference stations. Public/private organizations are partners in two states (*Idaho*, *Nebraska*) and sole owner at one agency (*Seattle Public Utilities*). A private entity is a partner in one state (*Idaho*). Other public agencies partner or have sole responsibility in eight states or agencies (*Arizona*; *Arkansas*; *Idaho*; *NCGS*; *Oklahoma*; *Oregon*; *South Carolina RFA*, *Geodetic Survey*; *Wisconsin*).

GNSS RTN Coverage

The GNSS RTN system covers the entire state in eight of the states or agencies responding to the survey (*Arkansas*; *Florida*; *NCGS*; *Nebraska*; *Ohio*; *Seattle Public Utilities*; *South Carolina RFA, Geodetic Survey*; *Wisconsin*). In the remaining five states, coverage ranges from 25% (*Arizona*) to approximately 90% (*Oklahoma*).

Number of CGNSS Stations

Respondents reported considerable variation in the number of CGNSS stations in their systems. Most responding states have 51 to 100 stations (*Arkansas*; *NCGS*; *Nebraska*; *Ohio*; *Oklahoma*; *South Carolina RFA, Geodetic Survey*) followed by 101 to 150 stations (*Florida*, *Oregon*, *Wisconsin*). ITD reported the least number of stations (25 to 30), and TxDOT reported the most (256).

Oklahoma DOT and TxDOT reported shared stations. Five of the 77 sites in Oklahoma's RTN are located in Texas. TxDOT owns 242 of the state's 256 stations and shares 14 with Louisiana State University and Oklahoma DOT.

Distance Between CGNSS Stations

The approximate distance between the CGNSS stations of responding agencies is most frequently 26 to 35 miles (*Arkansas*, *NCGS*, *Texas*, *Wisconsin*) or 36 to 45 miles (*Nebraska*; *Ohio*; *Oregon*; *South Carolina RFA, Geodetic Survey*). FDOT reported the shortest distance (15 to 25 miles) and Oklahoma DOT the longest (greater than 45 miles). The ADOT and Seattle Public Utilities survey respondents noted that the distance varies because the stations are regional (*Arizona*) or depend on local tropospheric conditions (e.g., temperature, pressure, humidity) (*Seattle Public Utilities*).

Relative Accuracy of the GNSS RTN System

The relative accuracy of the GNSS RTN systems is 1 to 2 cm for nearly all states and agencies participating in the survey (*Arizona*; *Arkansas*; *Florida*; *NCGS*; *Nebraska*; *Oklahoma*; *Oregon*; *South Carolina RFA, Geodetic Survey*; *Wisconsin*). Three agencies reported a relative accuracy less than 1 cm (*Ohio*, *Seattle Public Utilities*, *Texas*). The ITD respondent indicated a relative accuracy of 3 to 4 cm, adding that it "may be worse than indicated." The Seattle Public Utilities respondent noted that relative "is always tighter than absolute. Without asking about absolute, and whether it is 2D or 3D of R&A for both, [the response is] incomplete."

Communicating with the Central Processing Center

The CGNSS stations are most likely to use internet-based communications (11 agencies) or mobile networks (eight agencies) to interact with the central processing center. Five agencies use both methods (*NCGS*, *Ohio*, *Seattle Public Utilities*, *Texas*, *Wisconsin*). In addition to these two methods, Oregon DOT uses EarthScope NTRIP caster. None of the agencies participating in the survey used a radio signal to communicate with the central processing center.

System Hardware and Software Vendors/Manufacturers

Trimble is the most commonly used vendor for system hardware (10 agencies) and software (nine agencies) followed by Leica (hardware: six agencies; software: five agencies). Two agencies use Topcon hardware, but none of the agencies responding to the survey use Topcon software. Two agencies use Septentrio hardware, and one agency uses Septentrio software. None of the agencies responding to the survey use NavCon hardware or software.

Nine agencies use hardware from a single vendor while the remaining four agencies have purchased hardware from multiple vendors. Eleven agencies use software from a single vendor while the remaining two agencies have purchased software from multiple vendors.

Alignment with the National Spatial Reference System

Systems at 11 agencies align with the NSRS. Only the ADOT and NDOT systems do not align.

The adjustment interval of the CGNSS station positions of these 11 respondents typically varies. Four agencies adjust station positions every two to four years (*Arkansas*; *Florida*; *Oregon*; *South Carolina RFA, Geodetic Survey*), and two agencies adjust station positions annually (*Oklahoma*, *Texas*). In Oklahoma, the adjustment interval is annually because the agency continues to add sites to its network.

The adjustment interval varies at four other agencies. Both NCGS and Ohio DOT adjust station positions in line with National Geodetic Survey (NGS) changes. The Seattle Public Utilities respondent noted that the adjustment interval varies by velocities in different regions of the state. Positions are constantly monitored and when thresholds are exceeded, new positions are set. WisDOT also constantly monitors station positions and adjusts as needed. The adjustment interval in Idaho is unknown.

Applications

Respondents indicated their agencies use GNSS technology in a wide range of applications. Surveying is the primary use among participating agencies (10 agencies). The Seattle Public Utilities respondent noted the importance of asset mapping and inventory management in addition to surveying. The remaining three agencies indicated the transportation sector (*Idaho*, *Oklahoma*) and agriculture (*Ohio*) as the primary use of this data.

Other common applications where this technology is used include transportation (13 agencies), construction (10 agencies), agriculture (nine agencies), earth sciences (eight agencies), forestry (eight agencies), surveying (eight agencies) and navigation (six agencies). Fewer respondents reported using this data for atmospheric sciences (five agencies), mining (five states) and autonomous vehicles (four agencies). Geospatial data is also used by service, plumbing and dredging companies (*NCGS*) and with robotic mowers and robotic military security dogs (*Oregon*).

Potential applications for this technology were reported by eight survey respondents. FDOT is considering the technology for all of the applications described in the previous paragraph, and ITD is considering the technology for any application. Both Oregon DOT and TxDOT are considering the technology for autonomous vehicles; TxDOT is also considering it for earth sciences and navigation applications. Respondents from both South Carolina RFA, Geodetic Survey and WisDOT noted that their agencies provide this data as a service, and users then develop their own applications.

User Information

Survey respondents shared information about the current users of geospatial data available through their agencies and the data products that are provided.

Estimates of the number of GNSS RTN users that agencies' systems support were provided by 12 survey respondents, and the number varied significantly. Three states reported 250 or fewer users (*Arkansas*; *Nebraska*; *South Carolina RFA, Geodetic Survey*); two states have 2,500 to 3,000 users (*Oregon*, *Texas*); and two states have 10,000 to 12,000 users (*Florida*, *Ohio*). The number of users in three states is unknown (*Arizona*, *Idaho*, *Oklahoma*). The WisDOT respondent did not provide the total number of users but reported that the network has capacity for about 850 active users logged on simultaneously; the database can hold up to 5,000 users. Seattle Public Utilities has 2,220 user accounts with 9,600 logins.

The primary users from these 12 agencies are land surveyors (11 agencies) followed by state transportation agency staff (10 states) and university and research organization staff (nine agencies). Other common users of the system include contractors and GIS data collectors (eight agencies each), construction professionals and engineering consultants (seven states each) and agricultural professionals (six agencies). Navigation professionals (three agencies) and developers of early warning systems (one agency) are least likely to use the system. In Idaho, other primary users include the State Police, parks and recreation department, Forest Service and Bureau of Land Management.

Four agencies routinely reach out to new users (*Florida*; *Seattle Public Utilities*; *South Carolina RFA, Geodetic Survey*) or are considering reaching out to other users (*Idaho*). Outreach at Seattle Public Utilities is ongoing, and FDOT has an outreach program that focuses on geographic information systems (GIS), agriculture and utilities. ITD has a geodetic coordinator at Idaho State University (ISU) who is planning to assemble an RTN summit among interested individuals and organizations to "get some motion going" toward establishing a statewide RTN.

Three data products are commonly provided to end users: post-processed data (12 states), real-time coordinates (11 states) and network connection (11 states). Eight of the 13 agencies responding to the survey provide all three of these end products. Oregon DOT also provides single-base correctors, and Seattle Public Utilities provides streams through partnerships for autonomy solution developers/providers and adjacent RTNs.

Nine of the 13 agencies typically provide the data as a public service to users (*Arizona*, *Arkansas*, *Florida*, *Idaho*, *NCGS*, *Ohio*, *Oregon*, *Seattle Public Utilities*, *Wisconsin*). Seven agencies provide the data to contractors (*Idaho*; *Nebraska*; *Ohio*; *Oklahoma*; *Seattle Public Utilities*; *South Carolina RFA, Geodetic Survey*; *Texas*). Seattle Public Utilities and TxDOT respondents noted that static data is open to all public users. Seattle Public Utilities also provides real-time data to partners, members of the science community and academia, training and demonstration professionals, and research and development staff. All others pay a subscription fee. ITD and South Carolina RFA, Geodetic Survey also require subscriptions.

System Costs and Funding

Ten survey respondents estimated the cost, when available, of system startup, annual operation and maintenance, upgrades and network expansion, and other related activities. System startup date and network size are among the variables influencing these costs. For example, the earliest startup date noted among these respondents was 2000 and the most recent was 2012.

Funding to support their GNSS RTNs is typically received from federal (one state) and state (11 states) funds and user fees (four states). Nearly half of these agencies fund their systems through multiple sources. Four states rely on other funding. For example, in addition to a one-time user fee of $500, NCGS has created a continuously operating reference station (CORS) fund to collect donations in support of the network (with some limitations on who can donate). In addition to state funds, Oregon DOT receives data from EarthScope and other public agencies. Instead of federal or state funding, Seattle Public Utilities receives a combination of direct partner investments in infrastructure and nonpartner subscription revenue.

Nine of the 13 agencies responding to the survey do not charge a fee for user access. Three agencies charge an annual subscription fee (*Idaho*; *Seattle Public Utilities*; *South Carolina RFA, Geodetic Survey*). NDOT users get access based on the amount of NDOT bases in the network. NCGS has a one-time $500 fee for two logins; additional logins are charged a $250 one-time fee. At Seattle Public Utilities, nonpartners pay subscriptions.

Return on Investment

Five survey respondents described the data and methods used to measure the benefits of investing in the GNSS RTN (*Arkansas*; *NCGS*; *Seattle Public Utilities*; *South Carolina RFA, Geodetic Survey*; *Wisconsin*).

Data that is typically used to measure system benefits includes number of RTN and post-processing users (*NCGS*; *South Carolina RFA, Geodetic Survey*); accuracy (*Wisconsin*); data downloads (*NCGS*); length of time using the RTN (*NCGS*); self-supporting system, directly investing any revenue exceeding operations costs into infrastructure upgrades (*Seattle Public Utilities*); cost and time savings resulting from not purchasing and continually setting up local base stations and moving them as needs require (*Wisconsin*); and user satisfaction from construction inspectors, who have given “very positive feedback” about the data providing “much easier access to survey-grade measurements” (*Arkansas*).

Although the Oregon DOT and TxDOT respondents indicated that their agencies don’t measure their systems’ return on investment, both respondents described data used to measure system benefits. The Oregon DOT respondent cited the time saving for crews, the single-coordinate system, system accuracy and the benefit to multiple groups within the agency and throughout the state. The TxDOT respondent also cited time savings and system accuracy, as well as safety improvements and the increase in users over 20 years (from 25 to 2,500 users).

Among the remaining eight agencies that currently do not measure system benefits, only FDOT is planning to assess the return on investment in the future. Currently the agency is identifying the data and methods needed for this analysis.

Assessment and Future Plans

Key successes and challenges establishing a GNSS RTN were described by survey respondents, in addition to operations and maintenance best practices and vision statements for their systems' future operations.

Successes with the GNSS RTN Startup

Twelve survey respondents described the successes of their agencies' efforts to establish a GNSS RTN, including:

- **Partnerships** (*Idaho*, *Nebraska*, *Ohio*, *Oregon*).
- **User satisfaction** (*NCGS*, *Oregon*, *Seattle Public Utilities*).
- **Funding** (*Arkansas, Florida*, *Seattle Public Utilities*).
- **Accuracy and reliability** (*Florida*, *Texas*), including precise positioning (*Seattle Public Utilities*, *Texas*), reliability (*Florida*), and extensive coverage and strong infrastructure (*Texas*).
- **Access to real-time data** (*Texas, Wisconsin*).
- **Growth of the RTN system** (*Florida*; *South Carolina RFA, Geodetic Survey*).
- **Reduced road construction costs** (*South Carolina RFA, Geodetic Survey*).

The Oklahoma DOT respondent noted that establishing a GNSS RTN has been "a long process." The agency started this process about 10 years ago, building the equipment into the budget each year.

Challenges with the GNSS RTN Startup

The challenges these agencies have faced in establishing a GNSS RTN include:

- **Communication and coordination with partners**, including information technology departments (*Arkansas*, *Florida*, *NCGS*, *Ohio*).
- **Internet availability and station location** (*Arkansas*; *Florida*; *Nebraska*; *Oklahoma*; *Oregon*; *South Carolina RFA, Geodetic Survey*; *Texas*).
- **Buy-in** (*Seattle Public Utilities*, *Texas*).
- **Funding** (*Idaho*).
- **Station reliability and accurate positions** (*Texas*).
- **Establishing correct protocols** (such as spacing and user needs) at startup (*Wisconsin*).
- **Testing for anticipated accuracies** (*Wisconsin*).
- **Developing an overall statewide strategy** that requires minimal changes during development (*Wisconsin*).

Best Practices

Respondents provided a wealth of information about best practices related to GNSS RTN operations and maintenance, which are summarized in Table ES1. Eleven respondents shared practices addressing initial startup, day-to-day operations and future considerations.

Table ES1. Best Practices for GNSS RTN Operations and Maintenance

State/Agency	Best Practice
Arkansas	• Provide documentation to assist with connection to the network. • Automate password reset if user loses or forgets it. • Include an FAQs document on the website. (ARDOT is currently creating this resource for its website.)
Florida	• Locate stations at government facilities only. • Align stations with the NSRS frequently. • Perform field research into new methodologies.
Idaho	Let others do the RTN work.
NCGS	Train all field staff to install and maintain CORS.
Nebraska	Provide constant communication between users and operators.
Ohio	Perform annual maintenance and site inspections.
Oklahoma	• Let the consultant handle network operations with support from the agency. • Perform a monthly OPUS Project submission on all sites to determine if the site is moving or stable. [OPUS is National Oceanic and Atmospheric Administration's Online Positioning User Service, which provides free access to high-accuracy NSRS coordinates.] • Inspect each site annually. • Monitor the weather, looking for extreme weather events in the area of the site. Then conduct field inspections of the site and run an OPUS Project [submission] on affected sites. (***Note***: Oklahoma DOT lost its first site to a tornado last year.)
Oregon	Use quality GNSS mounts for station stability.
Seattle Public Utilities	For quality assurance and quality control: • Provide geodetic monitoring, on-board base monitoring, rover monitoring and science partner monitoring. • Request user feedback.
Texas	• Perform regular system monitoring. Continuously monitor network performance to quickly identify and resolve issues. • Conduct routine maintenance. Schedule regular maintenance checks for hardware and software to ensure optimal functionality.
Wisconsin	Perform planned equipment and software upgrades to more seamlessly keep current with technology developments.

Vision for the Future

Ten agencies and/or partners participating in the survey have created a vision for the future of their RTN systems. These plans contain three common themes:

Network expansion

- *ARDOT*: Keep adding CORS from adjacent states to optimize network near the [state] borders.
- *ITD*: Obtain legislative and leadership interest in a state agency expanding or taking over responsibility of a statewide RTN. (Currently, interest is low.)
- *NCGS*: Continue adding CORS.
- *Oklahoma DOT*: Provide border-to-border coverage in Oklahoma.

Service to network users

- *NCGS*: Continue to serve the users of our network.
- *Oklahoma DOT*: Open the network to anybody who wants to use the network, free of charge.
- *South Carolina RFA, Geodetic Survey*: Provide the best real-time GNSS services to customer base.

System maintenance and updates

- *Ohio DOT*: Maintain the system to the best of our ability, and continue to work with NGS and Trimble to keep the system modernized.
- *Oregon DOT*: Upgrade to NATRF2022 and additional constellations.
- *Seattle Public Utilities*: Partner with autonomy providers to offer hybrid network real-time kinematic/precise point positioning solutions.
- *TxDOT*: Partner with contractors and vendors to align RTN use with internal state DOT rover refresh; equipment maintenance; and correction for surveying, terrestrial, mobile and aerial mapping, and construction machine control for large projects.
- *WisDOT*: Keep the system up to date and current.

Outreach to Select State Transportation Agencies

Several respondents noted that establishing partnerships is key to the successful operation of a GNSS RTN. In a follow-up effort to the survey, CTC contacted survey respondents whose agencies partner with other organizations in owning and operating the GNSS RTN central processing center and/or CGNSS reference stations to better understand the value of interagency partnerships in successfully implementing statewide or regionwide GNSS RTN. Five respondents described their agencies' experiences, frequently noting several benefits, including efficiency and expanded coverage:

Arkansas Department of Transportation

- **Efficiency**. Partnering with municipalities or entities in Arkansas has limited the needed hardware purchases and added redundancy to the network. Usually the municipality had already incurred the cost of the hardware, and the data sharing improves the solution for all partners.

- **Expanded coverage**. Data sharing with adjacent states has "extend[ed] the envelope" of the virtual reference station (VRS) solution beyond the state border. Where data isn't shared with adjacent states, the real-time solution is subject to a parts per million error similar to a single base solution for a certain distance beyond the envelope of GNSS reference stations.

Idaho Transportation Department

- **Access to data stream**.
- **Efficiency**. The agency is able to provide data without needing to set up additional bases.
- **Expanded coverage**. Data sharing improves service to all users.

Nebraska Department of Transportation

- **Expanded coverage**. Currently 25 of the 39 CGNSS reference stations owned by NDOT are part of NGS's CORS network. In an agreement with Midwest RTK, HPRTK and Topcon Positioning Systems, NDOT provides access to its base stations in exchange for licenses to use their VRS networks. NDOT is also working to expand the number of its base stations to meet the needs of the department. NDOT rarely works with other agencies in the state when dealing with the bases, but the Nebraska State Patrol and other agencies use the licenses from the VRS networks. All sections of NDOT, including Maintenance, Design and Construction, are responsible for operating the 39 bases.

North Carolina Geodetic Survey

- **Efficiency**. Partnering with the National Park Service allows both agencies to avoid duplicating CORS in the same general area and provides a seamless connection between networks.
- **Expanded coverage**. NCGS shares data with SCDOT and Tennessee DOT, providing coverage to North Carolina, South Carolina and Tennessee users working along state borders. This arrangement also provides a seamless connection between networks.
- **Additional monitoring**. After a level 5 earthquake occurred in the northwest corner of the state, NCGS installed additional CORS in the area to monitor conditions. The partnership with EarthScope provided further expertise in earthquake monitoring.

Oklahoma Department of Transportation

- **Staffing support**. Oklahoma DOT staff shortages hampered network operation and maintenance. Partnering allows the agency to use state employees to maintain the sites, continue providing network access at no cost to users and maintain the integrity of the data. Because of staff shortages, the agency also does not make any network adjustments. But it does review and approve each adjustment its partner performs.
- **Expanded coverage**. The agency has also partnered with TxDOT for data exchange, giving both Texas and Oklahoma users border-to-border coverage. Oklahoma DOT is currently reaching out to ARDOT to arrange a similar data exchange.

Related Research and Resources

A literature search of publicly available domestic in-progress and published research identified publications that are organized into three categories:

- Previous Preliminary Investigations.
- Statewide systems.
- Related research.

Tables summarizing these publications are presented by topic area beginning on page 15. Each table provides the publication or project title, the year of publication if research is completed, and a brief description of the resource. Significantly more detail about each resource can be found in the **Detailed Findings** section of this report.

Gaps in Findings

While survey respondents provided a significant amount of information about their GNSS RTN systems, overall response to the survey was limited, with only 13 agencies describing their experience with these systems. In addition, the literature search uncovered minimal research about implementation and management of statewide RTN systems.

Next Steps

Moving forward, Caltrans could consider:

- Engaging with agencies responding to the survey for further information about their experiences.
- Following the efforts of ITD as it attempts to gain buy-in for a statewide RTN.
- Reaching out to NCGS for information about its assessment of real-time and post-processing users in measuring the benefits of its GNSS RTN system.

Table ES2. Previous Preliminary Investigations

Publication or Resource (Year)	Excerpt from Abstract or Description of Resource
Statewide Real-Time Global Positioning System or Global Navigation Satellite System Network Implementation (2015)	Presents the results of interviews with representatives of six state DOTs that had well-established RTNs: FDOT, Minnesota DOT, New York State DOT, Oregon DOT, Washington State DOT and WisDOT.

Table ES3. Statewide Systems

Publication or Resource (Year)	State/City	Excerpt from Abstract or Description of Resource
Implementing and Testing a Real Time Network Positioning System for Connecticut Department of Transportation: Advanced Continuously Operating Reference Network (ACORN) (2022)	Connecticut	Presents Connecticut DOT's system, which "has evolved from only serving static data to also serving streaming real-time messages that allow roving global navigation satellite system (GNSS) receivers (such as the U.S. NAVSTAR Global Positioning System [GPS]) to determine centimeter-accuracy positions in real time."
ACORN FAQ (undated)	Connecticut	Provides general information about the state's network, including registration and login details.
Iowa Real-Time Network (undated)	Iowa	Describes the evolution of this system since 2006.
Iowa Statewide RTK-GPS Network Deployment Project (2008)	Iowa	Describes findings from the 2006 business model study that laid the groundwork for the system's implementation.
MnCORS GNSS Network (undated)	Minnesota	Provides general information about the MnCORS GNSS Network.
MnCORS GNSS Network Frequently Asked Questions (2025)	Minnesota	Addresses common user questions about network access and operation.
Analyze Business Models for Implementation and Operation of a Statewide GNSS-RTN (2022)	Montana	Provides information to support state efforts to plan and implement the Montana GNSS-RTN system.
Supporting Dataset: Analyze Business Models for Implementation and Operation of a Statewide GNSS RTN (2024)	Montana	Supplements the content provided in the previous citation.
North Carolina Continuously Operating Reference Stations (CORS) Network (2024)	North Carolina	Provides 2023 data used to assess the economic benefits of the network.
Research in Progress: Automated Methods for Correcting ODOT's Real-Time GNSS Network for Survey and Post-Disaster Recovery (2024)	Oregon	Describes the objective of this research to develop a near real-time methodology for automatically flagging and correcting reference stations that are misaligned with NSRS.
Best Practices for the Development and Operation of Real-Time GNSS Networks (2017)	Seattle	Examines the "essential considerations for establishment of an RTN, key features to ensure its continued value, and operational models for optimal uptime and performance."

Table ES4. Related Research

Publication or Resource (Year)	Excerpt from Abstract or Description of Resource
Statewide GNSS-RTN Systems: Current Practices (2023)	Presents information on the best practices or guidelines in building, operating and managing GNSS-RTN networks.
High-Level Assessment of Statewide GNSS-RTN Business Models (2023)	Assesses eight business models using three criteria: state control, sustainability and state/agency costs to help state agencies "make informed decisions as they build, expand or manage their own GNSS-RTN systems."
GNSS-RTN Role in Transportation Applications: An Outlook (2022)	Presents an overview of GNSS-RTN technology, applications in the transportation sector and considerations about using this technology in advanced transportation applications.
Tale of Two RTNs: Rigorous Evaluation of Real-Time Network GNSS Observations (2018)	Evaluates GNSS RTN using data collected from NGS surveys in South Carolina and Oregon.

Detailed Findings

Background

Global navigation satellite system (GNSS) real-time networks (RTNs) are a collection of sensors that continuously gather, process and transmit satellite data from a central processing center via the internet to produce real-time positioning and timing information. These tools have applications in many industries that require precise positioning and timing data, such as earth science, engineering, construction and aerospace. In agriculture, precise data is used to help maximize crop yield. This data aids the scientific community in monitoring seismic activity, sea-level rise, early earthquake activity and climate change. Transportation agencies, including the California Department of Transportation (Caltrans), use precise positioning and timing data in a broad range of applications, from navigation and infrastructure development to land surveying.

Caltrans continues to evaluate its growing reliance on real-time positioning for transportation project delivery and asset management and for future applications such as automated transportation. Use of this data in a growing number of diverse applications may present an opportunity for the agency to lead or partner with other entities on the implementation of a robust, statewide RTN in California. Before pursuing this opportunity, the agency requires a better understanding of the development, management and implementation of existing, sustainable statewide RTN systems. Specifically, Caltrans was interested in information about:

- Landscape, dependency and importance of existing statewide RTN systems.
- Management practices, investment, maintenance and upgrade costs for these systems.
- Return on investment to state and local governments, the scientific community and the public.
- Role these systems play in the application of advanced technologies.
- Importance of minimizing system downtime.
- Identification of system deficiencies and the mitigation strategies employed by operators.

Below is a presentation of information gathered about these topics. The materials and experience discussed in this investigation were gathered through a survey of state departments of transportation (DOTs) and a review of in-progress and completed research.

Survey of Practice

An online survey sought information about experiences and management practices related to real-time GNSS implementation. Members of the Transportation Research Board (TRB) Standing Committee on Geospatial Data Acquisition Technologies and the American Association of State Highway and Transportation Officials (AASHTO) Committee on Data Management and Analytics received the survey.

Sixteen agencies responded to the survey: representatives from 13 state transportation agencies, two state geodetic survey sections and one municipal utility.

State Transportation Agencies

- Arizona DOT (ADOT)
- Arkansas DOT (ARDOT)
- Colorado DOT (CDOT)
- Florida DOT (FDOT)

- Idaho Transportation Department (ITD)
- Michigan DOT (MDOT)
- Nebraska DOT (NDOT)
- Ohio DOT
- Oklahoma DOT
- Oregon DOT
- South Dakota DOT (SDDOT)
- Texas DOT (TxDOT)
- Wisconsin DOT (WisDOT)

State Geodetic Survey Sections

- North Carolina Geodetic Survey (NCGS)
- South Carolina Revenue and Fiscal Affairs, Geodetic Survey (South Carolina RFA, Geodetic Survey)

Municipal Utility

- Seattle Public Utilities

Survey questions are provided in Appendix A. Survey results are summarized below in two topic areas:

- Agencies with GNSS RTNs.
- Nonusers of GNSS RTNs.

Agencies with Global Navigation Satellite System Real-Time Networks

Thirteen agencies participating in the survey have a GNSS RTN:

- ADOT
- ARDOT
- FDOT
- ITD
- NDOT
- NCGS
- Ohio DOT
- Oklahoma DOT
- Oregon DOT
- Seattle Public Utilities
- South Carolina RFA, Geodetic Survey
- TxDOT
- WisDOT

Detailed information about agency experience with GNSS RTN is summarized below in six categories:

- System administration and information.
- Applications.
- User information.
- System costs and funding.
- Return on investment.
- Assessment and future plans.

System Administration and Information

Information presented in this section describes typical ownership, operation and maintenance practices of GNSS RTN central processing centers and continuously operating GNSS (CGNSS) reference stations; the area of the state covered by the GNSS RTN; number of CGNSS stations in the GNSS RTN and the approximate distance between them; relative accuracy of the GNSS RTN system; method used by the CGNSS stations to communicate with the central processing center; details about system hardware and software along with vendors and manufacturers; and alignment to the National Spatial Reference System (NSRS).

GNSS RTN Ownership and Operation

In the majority of the states participating in the survey, state transportation agencies are sole owners and operators of the GNSS RTN central processing center (seven states). In Idaho, ITD and a private organization share these responsibilities. Other public agencies own and operate the center in four states: the Department of Water Resources in Arizona; a public/private cooperative in Seattle; the state geodetic survey section in North Carolina; and multiple owners in South Carolina. The South Carolina RFA, Geodetic Survey and South Carolina DOT (SCDOT) share ownership of the network; Trimble Network Managed Services manages daily maintenance and software. A private organization owns and operates the center in Nebraska. Table 1 summarizes survey results.

Table 1. GNSS RTN Central Processing Center: Ownership and Operation

State/Agency	Private Organization	State DOT	Other Public Agency	Description
Arizona			X	Arizona Department of Water Resources
Arkansas		X		
Florida		X		
Idaho	X	X		
NCGS	X		X	NCGS
Nebraska	X			
Ohio		X		
Oklahoma		X		
Oregon		X		
Seattle Public Utilities			X	Public/private cooperative operated by a public utility
South Carolina RFA, Geodetic Survey			X	• *Ownership*: South Carolina RFA, Geodetic Survey and SCDOT. • *Daily maintenance and software*: Trimble Network Managed Services.
Texas		X		
Wisconsin		X		
Total	**3**	**8**	**4**	

CGNSS Ownership, Operation and Maintenance

In more than one-half of the agencies describing experience with a GNSS RTN (seven agencies), multiple entities share ownership, operation and maintenance responsibilities of CGNSS reference stations. The state DOT is either a partner or has sole responsibility in 10 of the 13 agencies; a public/private organization is a partner in two states (*Idaho*, *Nebraska*) and sole owner in one agency (*Seattle Public Utilities*); and a private entity is a partner in one state (*Idaho*).

Other public agencies partner or have sole responsibility in eight states. In Arkansas, some continuously operating reference stations (CORS) are operated by local municipalities, and adjacent states are incorporated into the statewide network. Oklahoma DOT's Survey Division owns the network and maintains the sites, while a consultant is responsible for network adjustments and data storage. WisDOT CGNSS stations outside of the state are managed by Michigan, Minnesota and Iowa DOTs.

NCGS shares data with EarthScope, a community of professionals that "advance[s] understanding of the Earth and its physical systems by democratizing access to geophysical instrumentation, observations and practices" (see *Related Resource* below). The Oregon DOT respondent noted that its RTN is a partner network of GNSS stations in which EarthScope is a huge contributor. Table 2 summarizes survey results.

Table 2. GNSS CORS: Ownership, Operation and Maintenance

State/Agency	Private Entity	Public/Private Organization	State DOT	Other Public Agency	Description
Arizona				X	Arizona Department of Water Resources
Arkansas			X	X	• Some CORS operated by local municipalities. • Adjacent states incorporated into the statewide network.
Florida			X		
Idaho	X	X	X	X	Idaho State University
NCGS				X	• Majority by NCGS. • CORS data also shared with South Carolina RFA, Geodetic Survey; Tennessee DOT; National Park Service; and EarthScope (see *Related Resource* below).
Nebraska		X	X		
Ohio			X		
Oklahoma			X	X	• Oklahoma DOT's Survey Division owns the network and maintains the sites. • A consultant adjusts the network and stores all data.
Oregon			X	X	• Oregon DOT's RTN is a partner network of GNSS stations in which EarthScope is a significant contributor.
Seattle Public Utilities		X			
South Carolina RFA, Geodetic Survey			X	X	South Carolina RFA, Geodetic Survey
Texas			X		

State/Agency	Private Entity	Public/Private Organization	State DOT	Other Public Agency	Description
Wisconsin			X	X	Stations outside of state are managed by Michigan, Minnesota and Iowa DOTs.
Total	**1**	**3**	**10**	**8**	

Related Resource:

GNSS Realtime Data, EarthScope Consortium, undated.
https://www.earthscope.org/data/gnss-realtime/
From the webpage: We provide real-time GNSS data streams over the NTRIP protocol [Networked Transport of RTCM via Internet Protocol] for both commercial and noncommercial use. These streams originate from multiple sources, including the Network of the Americas (NOTA) and partner organizations. The data are transmitted as raw GNSS in RTCM 3.3 [Radio Technical Commission for Maritime Services 3.3] and BINEX [binary exchange] formats at a rate of 1 Hz. These formats include data from all constellations and signals, although individual receivers may only transmit a subset. RTCM 3.3 streams are provided using the MSM7 [Multiple Sign Messages 7] message type. A small number of stations also provide onboard point positioning solutions in NMEA GGK or GSOF format. [***Note***: NMEA GGK is a National Marine Electronics Association format; GSOF is a proprietary format from Trimble.]

GNSS RTN Coverage

In eight of the states or agencies responding to the survey, the GNSS RTN covers the entire state (*Arkansas; Florida; NCGS; Nebraska; Ohio; Seattle Public Utilities; South Carolina RFA, Geodetic Survey; Wisconsin*). In the remaining five states, coverage ranges from 25% (*Arizona*) to approximately 90% (*Oklahoma*). In Oklahoma, recent partnerships with TxDOT and discussions with ARDOT to partner have enhanced coverage. The TxDOT respondent noted that gaps in coverage occur in unpopulated areas of the western portion of the state. (***Note***: The respondent shared a statewide map of RTN coverage, which has been shared with the Caltrans panel.) Table 3 summarizes survey results.

Table 3. GNSS RTN Coverage Area

State/Agency	Entire State	Portion of State	Description
Arizona		X	25%-50%
Arkansas	X		
Florida	X		
Idaho		X	45%
NCGS	X		
Nebraska	X		
Ohio	X		

State/Agency	Entire State	Portion of State	Description
Oklahoma		X	• Approximately 90% of the state. • Recent partnership with TxDOT now provides complete coverage on Oklahoma's southern and western borders. • Trying to partner with ARDOT to cover Oklahoma's eastern border.
Oregon		X	80%
Seattle Public Utilities	X		
South Carolina RFA, Geodetic Survey	X		
Texas		X	Network gaps in unpopulated areas of west Texas.
Wisconsin	X		
Total	**8**	**5**	

Number of CGNSS Stations

The number of CGNSS stations in each responding agency's GNSS RTN varied considerably: from 25 to 30 stations (*Idaho*) to 256 stations (*Texas*). Most responding agencies have 51 to 100 stations (*Arkansas; NCGS; Nebraska; Ohio; Oklahoma; South Carolina RFA, Geodetic Survey*) or 101 to 150 stations (*Florida, Oregon, Wisconsin*). Shared stations between Oklahoma DOT and TxDOT were noted in the survey results. The Oklahoma DOT respondent reported 77 sites in the state's RTN, five of which are located in Texas. The TxDOT respondent noted that of the state's 256 stations, 242 are owned by TxDOT and 14 are shared with Louisiana State University and Oklahoma DOT. Table 4 summarizes survey results.

Table 4. Number of CGNSS Stations in the GNSS RTN

State/Agency	1-50	51-100	101-150	151-200	200+	Description
Arizona	X					44 stations
Arkansas		X				51 stations
Florida			X			104 stations
Idaho	X					Estimating 25-30 stations
NCGS		X				99 stations
Nebraska		X				51 stations in the network; 39 are owned and operated by the state.
Ohio		X				66 stations
Oklahoma		X				77 stations: • 72 sites in Oklahoma • 5 sites in Texas
Oregon			X			140 stations
Seattle Public Utilities				X		170 stations
South Carolina RFA, Geodetic Survey		X				60 stations

State/Agency	1-50	51-100	101-150	151-200	200+	Description
Texas					X	256 stations: • 242 TxDOT-owned stations • 14 stations shared with Louisiana State University and Oklahoma DOT
Wisconsin			X			120 stations
Total	**2**	**6**	**3**	**1**	**1**	

<u>Distance Between CGNSS Stations</u>

Among survey respondents, the approximate distance between CGNSS stations is most frequently either 26 to 35 miles (*Arkansas, NCGS, Texas, Wisconsin*) or 36 to 45 miles (*Nebraska; Ohio; Oregon; South Carolina RFA, Geodetic Survey*). One agency respondent each reported distances of 15 to 25 miles (*Florida*), more than 45 miles (*Oklahoma*) or unknown (*Idaho*). The survey respondents from both ADOT and Seattle Public Utilities noted that the distance varies because the stations are regional (*Arizona*) or depend on local tropospheric conditions (e.g., temperature, pressure, humidity) (*Seattle Public Utilities*). Table 5 summarizes survey results.

Table 5. Approximate Distance Between CGNSS Stations

State/Agency	15-25 miles	26-35 miles	36-45 miles	45+ miles	Unknown	Other	Description
Arizona						X	Varies widely. CORS are regional.
Arkansas		X					
Florida	X						
Idaho					X		
NCGS		X					
Nebraska			X				
Ohio			X				
Oklahoma				X			
Oregon			X				
Seattle Public Utilities						X	Varies depending on local tropospheric conditions. Approximately 19 miles (30 km) in some areas.
South Carolina RFA, Geodetic Survey			X				
Texas		X					
Wisconsin		X					
Total	**1**	**4**	**4**	**1**	**1**	**2**	

<u>Relative Accuracy of the GNSS RTN System</u>

Nearly all of the survey respondents indicated that the relative accuracy of their GNSS RTN system is 1 to 2 cm (nine agencies). Three survey respondents indicated the accuracy was less than 1 cm (*Ohio, Seattle*

Public Utilities, Texas), and one survey respondent indicated the relative accuracy was 3 to 4 cm (*Idaho*). The Seattle Public Utilities respondent added that relative "is always tighter than absolute. Without asking about absolute, and whether it is 2D or 3D of R&A for both, [the response is] incomplete." The ITD respondent added that accuracy "may be worse than indicated." None of the survey respondents reported a relative accuracy of 5 cm or more. Table 6 summarizes survey results.

Table 6. Relative Accuracy of the GNSS RTN System

State/Agency	<1 cm	1-2 cm	3-4 cm
Arizona		X	
Arkansas		X	
Florida		X	
Idaho			X
NCGS		X	
Nebraska		X	
Ohio	X		
Oklahoma		X	
Oregon		X	
Seattle Public Utilities	X		
South Carolina RFA, Geodetic Survey		X	
Texas	X		
Wisconsin		X	
Total	**3**	**9**	**1**

<u>Communicating with the Central Processing Center</u>

The CGNSS stations of the agencies responding to the survey are most likely to use internet-based communications (11 agencies) or mobile networks (eight agencies) to interact with the central processing center. Five agencies use both methods (*NCGS, Ohio, Seattle Public Utilities, Texas, Wisconsin*). Oregon DOT uses three methods: internet-based communications; mobile network; and EarthScope NTRIP caster (see *Related Resource*, page 21). None of the agencies participating in the survey used a radio signal to communicate with the central processing center. Table 7 summarizes survey responses.

Table 7. Communication Method Between CGNSS Stations and Central Processing Center

State/Agency	Internet	Mobile Network	Other	Description
Arizona		X		
Arkansas	X			
Florida	X			

State/Agency	Internet	Mobile Network	Other	Description
Idaho	X			
NCGS	X	X		
Nebraska	X			
Ohio	X	X		
Oklahoma		X		
Oregon	X	X	X	EarthScope NTRIP caster
Seattle Public Utilities	X	X		
South Carolina RFA, Geodetic Survey	X			
Texas	X	X		
Wisconsin	X	X		
Total	**11**	**8**	**1**	

System Hardware and Software Vendors

Survey respondents identified the vendor or manufacturer that supplied the GNSS RTN hardware and software. Responses are summarized below.

System Hardware: Vendors and Manufacturers

Nine agencies use hardware from a single vendor while the remaining four agencies have purchased hardware from multiple vendors. Trimble is the most commonly used vendor (10 agencies) followed by Leica (six agencies) and Topcon (two agencies). Two agencies also use hardware from Septentrio. None of the agencies responding to the survey use hardware from NavCon. The **References** section following these summaries provides links to the websites of vendors noted by survey respondents. Table 8 summarizes survey responses.

Table 8. System Hardware: Vendors and Manufacturers

State/Agency	Leica	Topcon	Trimble	Other	Description
Arizona	X				
Arkansas			X		
Florida	X				
Idaho	X		X		
NCGS			X		
Nebraska			X		
Ohio		X	X		
Oklahoma	X				
Oregon	X		X	X	Septentrio
Seattle Public Utilities	X	X	X	X	Septentrio

State/Agency	Leica	Topcon	Trimble	Other	Description
South Carolina RFA, Geodetic Survey			X		
Texas			X		
Wisconsin			X		
Total	**6**	**2**	**10**	**2**	

References

Leica Geosystems, https://leica-geosystems.com/en-us/products/gnss-systems.

Septentrio, https://www.septentrio.com/en.

Topcon Positioning Systems, https://www.topconpositioning.com/us/en/solutions/technology/infrastructure-products/gnss-bases-and-rovers.

Trimble Geospatial, https://geospatial.trimble.com/en/products/hardware/gnss-systems.

System Software: Vendors and Manufacturers

Eleven of the 13 agencies responding to the survey use software for their GNSS RTNs from a single vendor while the remaining two agencies have purchased software from multiple vendors. Again, among survey respondents, Trimble is the most commonly used vendor (nine agencies) followed by Leica (five agencies). Oregon DOT also uses software from Septentrio. None of the agencies responding to the survey use NavCon or Topcon software. See the **References** section above for access to the vendor websites. Table 9 summarizes survey results.

Table 9. System Software: Vendors and Manufacturers

State/Agency	Leica	Trimble	Other	Description
Arizona	X			
Arkansas		X		
Florida	X			
Idaho	X	X		
NCGS		X		
Nebraska		X		
Ohio		X		
Oklahoma	X			
Oregon	X		X	Septentrio
Seattle Public Utilities		X		
South Carolina RFA, Geodetic Survey		X		
Texas		X		
Wisconsin		X		
Total	**5**	**9**	**1**	

Alignment with the National Spatial Reference System

Survey respondents from 11 agencies reported that their agencies' systems align with the NSRS. Only the ADOT and NDOT systems do not align.

These 11 respondents described the adjustment interval of the CGNSS station positions. Four of the agencies adjust station positions every two to four years (*Arkansas; Florida; Oregon; South Carolina RFA, Geodetic Survey*), and two agencies adjust station positions annually (*Oklahoma, Texas*). The Oklahoma DOT respondent added that currently the adjustment interval is annually because the agency continues to add sites to the network.

The adjustment interval varies at four other agencies: NCGS, Ohio DOT, Seattle Public Utilities and WisDOT. Both NCGS and Ohio DOT adjust station positions in line with National Geodetic Survey (NGS) changes. Seattle Public Utilities and WisDOT adjust positions as needed. The Seattle Public Utilities respondent noted that the adjustment interval varies by velocities in different regions of the state. Positions are constantly monitored and when thresholds are exceeded, new positions are set. WisDOT constantly tests station positions and adjusts as needed. The adjustment interval in Idaho is unknown. None of the respondents reported using an interval of more than five years. Table 10 summarizes survey responses.

Table 10. CGNSS Station Position Adjustment Interval

State/Agency	Annually	Every 2-4 Years	Other	Description
Arkansas		X		
Florida		X		
Idaho			X	Unknown
NCGS			X	When NGS revises a position of one of the agency's CORS.
Ohio			X	When NGS revises a position. (Most stations are part of the National Oceanic and Atmospheric Administration (NOAA) CORS Network (NCN), which ties directly to the NSRS.)
Oklahoma	X			Still adding sites to the network, so currently adjust annually.
Oregon		X		
Seattle Public Utilities			X	Varies by velocities in different regions of the state. Positions are constantly monitored and when thresholds are exceeded, new positions are set.
South Carolina RFA, Geodetic Survey		X		
Texas	X			
Wisconsin			X	As needed based on constant testing of station positions.
Total	**2**	**4**	**5**	

Applications

Information about agency use and applications for geospatial data are presented below in three categories:

- Primary application of geospatial data.
- Other applications using GNSS RTN technology.
- Potential applications of GNSS RTN technology.

Primary Application of Geospatial Data

Among survey respondents, surveying is the predominant use of geospatial data using GNSS RTN technology (10 agencies). Oklahoma DOT and ITD indicated the transportation sector as the primary use, although the ITD respondent clarified that as a representative of the transportation sector, he was unfamiliar with other applications within the agency. Agriculture is the primary use by Ohio DOT, and at Seattle Public Utilities, asset mapping and inventory management in addition to surveying are the primary uses. Table 11 summarizes survey responses.

Table 11. Primary User Segments of Geospatial Data

State/Agency	Agriculture	Asset Mapping	Inventory Management	Surveying	Transportation
Arizona				X	
Arkansas				X	
Florida				X	
Idaho					X
NCGS				X	
Nebraska				X	
Ohio	X				
Oklahoma					X
Oregon				X	
Seattle Public Utilities		X	X	X	
South Carolina RFA, Geodetic Survey				X	
Texas				X	
Wisconsin				X	
Total	**1**	**1**	**1**	**10**	**2**

Other Applications Using GNSS RTN Technology

Survey respondents indicated their agencies use GNSS technology in a wide range of applications. All 13 noted the use of geospatial data from this technology within the transportation sector. Other common applications included construction (10 agencies), agriculture (nine agencies), earth sciences (eight agencies), forestry (eight agencies), surveying (eight agencies) and navigation (six agencies). Fewer respondents reported using this data for atmospheric sciences (five agencies), mining (five agencies) and autonomous vehicles (four agencies). Geospatial data is also used by service, plumbing and dredging companies (*NCGS*) and with robotic mowers and robotic military security dogs (*Oregon*).

Agencies participating in the survey that reported use among the most applications were NCGS (11 applications) and FDOT, Ohio DOT, Seattle Public Utilities and South Carolina RFA, Geodetic Survey (nine applications each). Table 12 summarizes survey responses.

Table 12. Other Applications Using GNSS RTN Technology

State/Agency	Agriculture	Atmospheric Sciences	Autonomous Vehicles	Construction	Earth Sciences	Forestry	Mining
Arizona					X		
Arkansas	X			X	X	X	
Florida	X	X	X	X		X	X
Idaho	X						
NCGS	X	X	X	X	X	X	X
Nebraska				X			
Ohio	X	X	X	X	X	X	X
Oklahoma							
Oregon	X			X	X	X	
Seattle Public Utilities	X	X	X	X	X	X	X
South Carolina RFA, Geodetic Survey	X	X		X	X	X	X
Texas				X			
Wisconsin	X			X	X	X	
Total	**9**	**5**	**4**	**10**	**8**	**8**	**5**

Table 12. Other Applications Using GNSS RTN Technology, Continued

State/Agency	Navigation	Surveying	Transportation	Other	Description
Arizona			X		
Arkansas	X		X		
Florida	X	X	X		
Idaho		X	X	X	Unsure of all applications using RTN
NCGS	X	X	X	X	Service, plumbing and dredging companies
Nebraska			X		
Ohio		X	X		
Oklahoma		X	X		
Oregon	X	X	X	X	Robotic mower and robotic military security dog
Seattle Public Utilities		X	X		
South Carolina RFA, Geodetic Survey	X	X	X		

State/Agency	Navigation	Surveying	Transportation	Other	Description
Texas			X		
Wisconsin	X		X		
Total	**6**	**8**	**13**	**3**	

Potential Applications of GNSS RTN Technology

Eight survey respondents also described applications that their states are considering for future use to expand the implementation of this technology. FDOT is considering the technology for all 10 of the applications described in the previous sections, and ITD is considering the technology for any application. Both Oregon DOT and TxDOT are considering the technology for autonomous vehicles; TxDOT is also considering it for earth sciences and navigation applications. Both South Carolina RFA, Geodetic Survey and WisDOT provide this data as a service, and users then develop their own applications. Two agencies — NDOT and Oklahoma DOT — are not considering other applications at this time.

User Information

This section presents information about the current users of geospatial data and the data products that are provided.

System Users

The information presented below describes the number of current users supported by an agency's system, the primary users of geospatial data and agency plans to reach out to other users.

Number of Users

Twelve survey respondents estimated the number of users that their agencies' systems support. That number varied significantly, ranging from 80 (*Arkansas*) to approximately 12,000 users (*Florida*). The WisDOT respondent did not provide the total number of users but reported that the database can hold up to 5,000 users, but the network has the capacity for about 850 active users to be logged on simultaneously. The number of users at ADOT, ITD and Oklahoma DOT is unknown. Table 13 summarizes survey responses.

Table 13. Number of GNSS RTN Users

State/Agency	1-1,000	1,001-5,000	5,000+	Unknown	Other	Description
Arizona				X		
Arkansas	X					80 simultaneous users
Florida			X			Approximately 12,000 user accounts
Idaho				X		
Nebraska	X					125+
Ohio			X			10,800
Oklahoma				X		
Oregon		X				3,000

State/Agency	1-1,000	1,001-5,000	5,000+	Unknown	Other	Description
Seattle Public Utilities					X	2,200 user accounts; 9,600 logins
South Carolina RFA, Geodetic Survey	X					250 simultaneous users
Texas		X				Approximately 500 organizations and 2,500 users
Wisconsin					X	Network capacity for about 850 users logged on simultaneously. Database can hold up to 5,000 users.
Total	**3**	**2**	**2**	**3**	**2**	

Primary Users

Among 12 of the 13 survey respondents, the primary users of the system are land surveyors (11 agencies) followed by state transportation agency staff (10 agencies) and university and research organization staff (nine agencies). Other common users of the system include contractors and GIS data collectors (eight agencies each), construction professionals and engineering consultants (seven agencies each) and agricultural professionals (six agencies). Navigation professionals (three agencies) and developers of early warning systems (one agency) are least likely to use the system. Other primary users in Idaho include the State Police, parks and recreation department, Forest Service and Bureau of Land Management. The agencies with users representing the most sectors are Ohio DOT; Seattle Public Utilities; South Carolina RFA, Geodetic Survey; and WisDOT. Table 14 summarizes survey responses.

Table 14. Primary Users of System

State/Agency	Agricultural Professionals	Construction Professionals	Contractors	Early Warning System Developers	Engineering Consultants	GIS Data Collectors
Arizona						X
Arkansas	X	X	X		X	X
Florida						
Idaho					X	X
Nebraska						
Ohio	X	X	X		X	X
Oklahoma		X	X		X	
Oregon	X	X	X			
Seattle Public Utilities	X	X	X	X	X	X
South Carolina RFA, Geodetic Survey	X	X	X		X	X
Texas			X			X
Wisconsin	X	X	X		X	X
Total	**6**	**7**	**8**	**1**	**7**	**8**

Table 14. Primary Users of System, Continued

State/Agency	Land Surveyors	Navigation Professionals	State DOT Staff	University/ Research Staff	Unknown/ Other	Description
Arizona	X					
Arkansas	X		X	X		
Florida	X					
Idaho	X		X	X	X	State Police, parks and recreation, Forest Service, Bureau of Land Management
Nebraska			X			
Ohio	X	X	X	X		
Oklahoma	X		X	X		
Oregon	X		X	X		
Seattle Public Utilities	X		X	X		
South Carolina RFA, Geodetic Survey	X	X	X	X		
Texas	X		X	X		
Wisconsin	X	X	X	X		
Total	**11**	**3**	**10**	**9**	**1**	

Outreach to New Users

Four agencies responding to the survey routinely reach out to new users or are considering reaching out to other users:

- FDOT has an outreach program focusing on geographic information systems (GIS), agriculture and utilities.
- ITD is currently planning an RTN summit in Idaho. The respondent noted that Idaho has a geodetic coordinator on staff at Idaho State University (ISU) who is planning to assemble a meeting with interested individuals and organizations this year to see if Idaho can "get some motion going" to establish a statewide RTN. (*Contact*: Cory Scoffield, PLS geodetic analyst/coordinator, GIS Training and Research Center, Idaho State University, 208-282-3606, coryscoffield@isu.edu.)
- At Seattle Public Utilities, outreach is ongoing.
- South Carolina RFA, Geodetic Survey's subscription service is available to anyone interested in precision positioning.

Data Products

The discussion below describes the data products provided to end users and access to those data products.

Data Products for End Users

Three data products are commonly provided to end users: post-processed data (12 agencies), real-time coordinates (11 agencies) and network connection (11 agencies). Eight of the 13 agencies responding to the survey provide all three of these end products. In addition to these products, Oregon DOT also provides single-base correctors, and Seattle Public Utilities provides data streams through partnerships to autonomy solution developers/providers and adjacent RTNs. Table 15 summarizes survey responses.

Table 15. Data Products Provided to End Users

State/Agency	Real-Time Coordinates	Network Connection	Post-Processed Data	Other	Description
Arizona	X		X		
Arkansas	X	X	X		
Florida	X	X	X		
Idaho	X	X	X		
NCGS		X	X		
Nebraska	X	X	X		
Ohio	X	X	X		
Oklahoma	X	X			
Oregon	X	X	X	X	Single-base correctors.
Seattle Public Utilities	X	X	X	X	Data streams (via partnerships) to autonomy solution developers/providers and adjacent RTNs
South Carolina RFA, Geodetic Survey	X		X		
Texas	X	X	X		
Wisconsin		X	X		
Total	**11**	**11**	**12**	**2**	

Method for Providing Data Products

Agencies use the following methods to provide data products:

- As a public service to users.
- Internally to state DOT.
- Internally to other public agency.
- To private entities.
- To contractors.

Nine of the 13 agencies provide the data as a public service to users (*Arizona, Arkansas, Florida, Idaho, NCGS, Ohio, Oregon, Seattle Public Utilities, Wisconsin*). Seven agencies provide the data to contractors (*Idaho; Nebraska; Ohio; Oklahoma; Seattle Public Utilities; South Carolina RFA, Geodetic Survey; Texas*). Seattle Public Utilities and TxDOT noted that static data is open to all public users. Seattle Public Utilities also provides real-time data to partners, members of the science community and academia, training and demonstration professionals, and research and development staff. All others pay a subscription fee. ITD and South Carolina RFA, Geodetic Survey also require subscriptions. Table 16 summarizes survey responses.

Table 16. Methods for Providing Data Products to End Users

State/Agency	Public Service	Internally: State DOT	Internally: Other Public Agency	Private Entity	Contractor	Other	Description
Arizona	X						
Arkansas	X						
Florida	X						
Idaho	X			X	X	X	Subscription required
NCGS	X						
Nebraska		X	X	X	X		
Ohio	X	X	X	X	X		
Oklahoma		X	X		X		
Oregon	X					X	Oregon Real-time GNSS Network (ORGN) NTRIP Caster
Seattle Public Utilities	X	X	X	X	X	X	• Static data shared with all users. • Real-time data open to partners, science, academia, training and demo, and research and development. • All others pay subscriptions.
South Carolina RFA, Geodetic Survey				X	X	X	Anyone with a subscription to the RTN.
Texas		X	X		X	X	Static files shared with all public users.
Wisconsin	X						
Total	**9**	**5**	**5**	**5**	**7**	**5**	

System Costs and Funding

Survey respondents presented cost and funding information for a variety of topics, including cost estimates for various activities, sources of GNSS RTN funding and cost recovery mechanism.

Cost Estimates

Ten survey respondents estimated the cost, when available, of system startup, annual operation and maintenance, upgrades and network expansion, and related activities. Table 17 summarizes survey responses.

Table 17. Cost Estimates for GNSS RTN Systems

State/Agency	System Startup	Annual Operation and Maintenance	Upgrades and Network Expansion	Other
Arizona	Unknown	Unknown	Unknown	
Arkansas	$1.5 million	$120,000 (software maintenance, 1 full-time equivalent (FTE) to manage the network, 1-2 sensors replaced annually)	$20,000 for additional nodes required to add CORS from adjacent states	
Florida	• Startup: 2012 • $1,343,500	Current costs: $803,656, not including salaries	$27,000/station	
Idaho	Unknown	Unknown	Unknown	Unknown
NCGS	Depends on network size	$400,000	$200,000	Equipment insurance (which depends on network size): Approx. $30,000
Nebraska	Unknown (no records)	$20,000 (estimate)	$50,000 (estimate)	Estimates based on state-owned and -operated bases, not operating the network
Ohio		$65,000	$30,000-$45,000	
Oregon		Leica Spider Customer Care Package, 2 year: $167,000	Upgrade GPS L2C and GLONASS: $482,000	
Seattle Public Utilities	• Startup: 2001 • First corrections: 2002	Operations (labor, software license, communications): $250,000 annually	Varies; typically $180,000-$230,000 annually for continuous upgrade cycle	Training and miscellaneous: $10,000-$15,000
South Carolina RFA, Geodetic Survey	• Startup: 2008 • More than $2 million (equipment, servers, hardware, contractual services)	• Trimble contract: Approx. $250,000 • Hardware maintenance as needed • Last networkwide receiver upgrade (in 2023): Approx. $1.5 million	• Upgrades: Usually every 5 years • Expansion: When possible	
Texas	• Startup: 2006 • $250,000	Approx. $1 million/year	Approx. $10 million over 20 years	

State/Agency	System Startup	Annual Operation and Maintenance	Upgrades and Network Expansion	Other
Wisconsin	• Startup: 2000 • Costs: Unknown	Software: $25,000/ year (primary level vendor support, software updates, mobilization costs to resolve technical issues, periodic maintenance)	• $15,000/new receiver and antenna • $10,000/installation of CORS geodetic-grade braced monuments	

Funding Sources

Nearly half of the agencies fund their GNSS RTN systems through multiple sources, including federal and state funds and user fees. Eleven of the 13 agencies receive funding from the state. Only one agency (*Arkansas*) receives federal funding. In addition to a one-time user fee of $500, NCGS has created a CORS fund to collect donations that support the network (with some limitations on who can donate). In addition to state funds, Oregon DOT receives data from EarthScope and other public agencies. Instead of federal or state funding, Seattle Public Utilities receives a combination of direct partner investments in infrastructure and nonpartner subscription revenue. Table 18 summarizes survey responses.

Table 18. Funding for GNSS RTN Systems

State/Agency	Federal Funds	State Funds	User Fees	Other	Description
Arizona		X			
Arkansas	X	X			
Florida		X			
Idaho		X	X		
NCGS		X		X	• *One-time user fee*: $500. • *Donations*. Agency has created a CORS fund to collect donations to support the network. Some limitations on who can donate.
Nebraska		X	X	X	State funds used to maintain and operate the bases owned by NDOT.
Ohio		X			
Oklahoma		X			
Oregon		X		X	Partner-supplied data (EarthScope (see *Related Resource*, page 21) and other public agencies).
Seattle Public Utilities			X	X	• Mix of direct partner investments in infrastructure and nonpartner subscription revenue. • No direct state or federal funding.

State/Agency	Federal Funds	State Funds	User Fees	Other	Description
South Carolina RFA, Geodetic Survey			X		
Texas		X			
Wisconsin		X			
Total	**1**	**11**	**4**	**4**	

Cost Recovery Mechanism

Nine of the 13 agencies responding to the survey do not charge a fee for user access. Three agencies charge an annual subscription fee (*Idaho; Seattle Public Utilities; South Carolina RFA, Geodetic Survey*). NDOT users get access based on the amount of NDOT bases in the network. NCGS has a one-time $500 fee for two logins; additional logins are charged a $250 one-time fee. At Seattle Public Utilities, nonpartners pay subscriptions. Table 19 summarizes survey responses.

Table 19. Cost Recovery Mechanisms Among Agencies

State/Agency	Annual Subscription Fee	Fee Based on Access	No Fee	Other	Description
Arizona			X		
Arkansas			X		
Florida			X		
Idaho	X				
NCGS				X	• One-time $500 fee for two logins. • Additional logins: $250 one-time fee.
Nebraska		X	X	X	Access based on number of NDOT bases in network.
Ohio			X		
Oklahoma			X		
Oregon			X		
Seattle Public Utilities	X			X	Nonpartners pay subscriptions.
South Carolina RFA, Geodetic Survey	X				
Texas			X		
Wisconsin			X		
Total	**3**	**1**	**9**	**3**	

Return on Investment

In this section, survey respondents discussed measuring the benefits of investing in the GNSS RTN, including the data and methods used to measure the benefits.

Measuring the Benefits of GNSS RTN Investments

Five agencies responding to the survey have measured the benefits of the investments made in their GNSS RTN:

- ARDOT
- NCGS
- Seattle Public Utilities
- South Carolina RFA, Geodetic Survey
- WisDOT

Data Used to Measure System Benefits

The respondents from these five agencies noted the data used to measure system benefits:

- **Number of RTN and post-processing users** (*NCGS; South Carolina RFA, Geodetic Survey*). The NCGS respondent noted the OPUS users of NC CORS. [OPUS is NOAA's Online Positioning User Service, which provides free access to high-accuracy NSRS coordinates. See *Related Resource* below.] The South Carolina RFA, Geodetic Survey respondent cited network renewals and continued growth of subscriptions to the RTN.
- **Accuracy** (*Wisconsin*). Agricultural users are more precise in planting and harvesting pathways, reducing fuel consumption.
- **Cost and time savings** (*Wisconsin*). The respondent noted the costs and time saved by users by not purchasing and continually setting up local base stations and moving them as needs require.
- **Data downloads** (*NCGS*).
- **Length of time using RTN** (*NCGS*).
- **Self-supporting system** (*Seattle Public Utilities*). Any revenue exceeding operations costs is directly invested in infrastructure upgrades.
- **User satisfaction** (*Arkansas*). Construction inspectors have provided "very positive feedback," noting that the data "has given them much easier access to survey-grade measurements."

Note: Although the respondents from Oregon DOT and TxDOT indicated that their agencies don't measure the benefits of the investments made in the GNSS RTN, both respondents described data used to measure system benefits: time saving for crews (*Oregon, Texas*); system accuracy (*Oregon, Texas*); single-coordinate system (*Oregon*); benefit to multiple groups within the agency and throughout the state (*Oregon*); safety improvements (*Texas*); and the increase in users over 20 years (from 25 to 2,500 users) (*Texas*).

Methods Used to Measure the Benefits

User satisfaction and the growth in the number of users are key indicators used to measure the benefits of the GNSS RTN among these five agencies. ARDOT finds it "very difficult" to quantify the financial return on investment and primarily relies on user satisfaction. NCGS conducts a study each year using the number of users for real time and post-processing. The respondent from South Carolina RFA, Geodetic Survey noted that it maintains its entire RTN using annual subscription and renewal fees. No state funding is provided. He added that the growth shows the benefits of the network. Seattle Public Utilities measures the benefits based on usage and multipliers for various end-use applications. The WisDOT respondent noted that the cost savings "seem obvious," but no direct study has been attempted.

Note: Again, although the Oregon DOT and TxDOT respondents indicated that their agencies don't measure the benefits of the investments made in the GNSS RTN, both respondents described methods to measure benefits. The Oregon DOT respondent cited cost and time savings, efficiency and data accuracy. The TxDOT respondent cited intangible cost savings (such as data processing time, data download and post-processing time); consistent quality of real-time, corrected data collection; saved lives from reduced time in the right of way; and lower contractor bids for survey deployments.

Related Resource:

> **OPUS: Online Positioning User Service**, National Geodetic Survey, National Oceanic and Atmospheric Administration, May 2025.
> https://geodesy.noaa.gov/OPUS/about.jsp
> *From the website*: NOAA's Online Positioning User Service (OPUS) provides free access to high-accuracy National Spatial Reference System (NSRS) coordinates. OPUS uses the same software which computes coordinates for the nation's geodetic control marks and the NOAA CORS Network (NCN).

Agencies Planning to Measure the Benefits of GNSS RTN Investments

Of the eight agencies currently not measuring the return on investment of their GNSS RTN systems, only FDOT plans to measure these benefits in the future. The agency is currently determining the data and methods to use for this analysis.

Assessment and Future Plans

Below is information survey respondents provided about the key successes and challenges establishing a GNSS RTN, best practices for operations and maintenance, and the agency's vision for the future.

Successes with the GNSS RTN Startup

Twelve of the 13 survey respondents described their agencies' successes establishing a GNSS RTN. Success was frequently measured in terms of access and user satisfaction, accuracy and reliability, funding support and partnerships.

Access and User Satisfaction

Real-time access to users was noted by several respondents, including TxDOT, where users have immediate access to data for timely decision-making. In North Carolina, the RTN supports many sectors — from a one-person company to large companies. Access in Wisconsin is available to users 365 days a year, 24 hours a day at no cost. The Oregon DOT respondent also cited the importance of providing services free to the public, and Seattle Public Utilities respondent reported user satisfaction.

Accuracy and Reliability

TxDOT noted the high accuracy of its GNSS RTN, achieving precise positioning for users in various applications. Strong infrastructure has also been achieved. The agency deploys "a reliable network of base stations for extensive coverage." FDOT also reported increased accuracy and improved reliability, and Seattle Public Utilities noted meeting precision goals.

Funding Support

In 2017, ARDOT received grant funding from the Federal Highway Administration (FHWA) Accelerated Innovation Deployment (AID) Demonstration program, which allowed for the rapid expansion of the network. Successes noted by other agency respondents were obtaining recurring funding (*Florida*) and functioning as a self-supportive cooperative (*Seattle Public Utilities*).

Partnerships

A key success reported by respondents was the establishment of partnerships. The ITD respondent noted that in the absence of support from the Idaho Legislature (and since providing an RTN system is not a charge of ITD), the private surveying community has been partnering with the Utah TURN system (see *Related Resources*, page 42) to host CORS that are included in that system. A few ITD sites provide facility access to the TURN CORS.

By 2015, a nine-county area in the state had been covered. Nine CORS stations set up in nine eastern Idaho counties were providing real-time corrections for use in machine-controlled grading (automated machine guidance). In an unofficial partnership with the local ISU campus, ITD aided in establishing CORS at the campus, at a high school in Bingham County, and at the Boise and Coeur d'Alene regional office facilities. These stations were established for use by the ITD survey personnel, but the data streams have been feeding into the Leica SmartNet system.

In addition, stations at the ITD maintenance facilities provided power and internet connectivity to the Utah RTN system. The Utah Geospatial Resource Center then installed a CORS at some of ITD's maintenance facilities, and those data streams have been included in the Utah Automated Geographic Reference Center's (AGRC's) RTN system.

[***Note***: By agreement with Leica SmartNet, all ITD-owned CORS have been streaming to the SmartNet system for nearly 10 years. This agreement was established because key staff members familiar with CORS were retiring, and the stations needed to be monitored and maintained. SmartNet has completed these tasks in exchange for the data streams. Last calendar year, SmartNet upgraded all receivers with new receivers.]

The NDOT respondent cited the value of the partnership with the private owner of the network and the department, adding that the State of Nebraska and the owner are in negotiations about operating the network in the future. The Ohio DOT respondent cited the "healthy working relationship" with the state's information technology (IT) department, and the Oregon DOT respondent noted the cost savings by partnering with others.

More information about the value of partnerships is presented in **Outreach to Select State Transportation Agencies**, beginning on page 48.

Other Successes

Among the successes reported by respondents was the growth of RTN systems. The FDOT respondent cited the "densified network" of reference stations, and the South Carolina RFA, Geodetic Survey respondent noted continued growth within the land surveying sector, precision agriculture and better land use management.

Also noted was lowering costs of SCDOT road construction (*South Carolina RFA, Geodetic Survey*).

For some agencies, establishing a GNSS RTN may require taking the long view. The Oklahoma DOT respondent noted that it has been "a long process." The agency started this process about 10 years ago, building the equipment into the budget each year.

Challenges with the GNSS RTN Startup

These same 12 survey respondents also described the challenges that their agencies have faced while establishing the GNSS RTN. Issues related to communicating and coordinating with partners, especially IT; internet access and station location; funding; and agency buy-in were reported.

Communication and Coordination with Partners

Several respondents reported issues working with partners, including IT (*Arkansas, Florida, NCGS, Ohio*). The ARDOT respondent noted challenges with the initial coordination with IT to open ports and allow outside data into its network. Similarly the Ohio DOT respondent wrote that obtaining a "healthy working relationship with IT" was challenging. However, once the department understood the importance of the system and all the inner workings of the Trimble software, the relationship has been "great." The FDOT respondent reported the need to encourage software developers and IT to communicate. NDOT also has communication issues with the network owner and NGS.

Internet Availability and Station Location

In some areas of Arkansas, the respondent noted that internet availability was poor. However, access has since improved. Establishing and maintaining functional network servers were reported by FDOT. The Oregon DOT respondent noted challenges maintaining and monitoring the network. The South Carolina RFA, Geodetic Survey respondent cited network security, and finding stable and secure reference station locations with internet access.

According to the Oklahoma DOT respondent, providing statewide coverage will be "a big challenge to overcome." The agency began establishing the network by hosting CORS sites at Oklahoma DOT facilities. But the agency has "just about cover[ed] the state with our facilities, so know we are going to have to partner with other state agencies or private sector people to fill in the gaps." The NDOT respondent also noted a challenge setting up base locations. TxDOT reported difficulties with effective technical support and maintenance for the network.

Funding

In Idaho, the biggest challenge has been obtaining funding to expand the system of CORS. Expansion has been occurring "piecemeal" by both SmartNet and Utah TURN, but many areas in Idaho are not covered by "anything resembling reasonable baseline distances from a CORS."

Legislative support for establishing an Idaho RTN has also been lacking. Grants to obtain funding for an Idaho RTN were written in 2007, 2009, 2012 and 2022, but they all failed. The respondent also noted that much of the populated areas are covered by commercially available RTNs, and that interest in a state agency expanding or taking over responsibility for a statewide RTN is low. ITD personnel would need to see a return on investment in some measurable form, or at least usage counts and statistics. Funding is needed to implement a statewide RTN and when that will occur is unknown.

Buy-In

Some agencies reported issues achieving buy-in to the need for a network. The Seattle Public Utilities respondent noted that in the early days of the RTN, there was skepticism about the technology, which dissipated after a few years. State agencies also would not provide support initially, so the agency had to “go cooperative.” (Currently, the state uses the network.) The TxDOT respondent noted difficulties encouraging users to switch to GNSS RTN and educating them on its benefits.

Additional Challenges

TxDOT reported issues with station reliability and accurate positions. The WisDOT respondent reported challenges with deciding correct protocols (such as spacing and user needs) at startup, and testing for anticipated accuracies. The respondent also noted developing an overall statewide strategy that required minimal changes during development.

Related Resources:

SmartNet Network Coverage, SmartNet North America, undated.
https://www.smartnetna.com/coverage_network.cfm
Network coverage in North America is presented in this map.

TURN GPS, Utah Geospatial Resource Center, undated.
https://gis.utah.gov/products/turn/
From the website: The Utah Reference Network (TURN) is a high-precision global navigation satellite system (GNSS) reference network providing real-time corrections and data for post-processing. Our network consists of permanently located GPS receivers installed across Utah and portions of Idaho, Wyoming and southern Nevada that generate real-time, high-accuracy GNSS positioning. These receivers send their data using the Networked Transport of RTCM via Internet Protocol (NTRIP) to a central system that analyzes the input to adjust and correct the data to provide the most accurate locations, usually down to centimeter level. Our network uses the Trimble Pivot VRS Platform.

Recent TURN GPS Network Highlights, Sean Fernandez, Utah Geospatial Resource Center, July 15, 2024.
https://gis.utah.gov/blog/2024-07-15-turn-gps-network-highlights/
Featured in this blog post are the most recent advancements and updates in the agency’s GPS network “that enhance the precision and reliability of real-time GPS corrections in Utah and some surrounding states.” Highlights include GNSS solutions, network upgrades and activity with partner agencies.

Best Practices

Respondents provided a wealth of information about best practices related to GNSS RTN operations and maintenance. Eleven respondents shared practices addressing issues related to initial startup (e.g., train all field staff to install and maintain CORS), day-to-day operations (e.g., conduct regular system monitoring and routine maintenance) and future considerations (e.g., perform field research into new methodologies). Table 20 summarizes survey responses.

Table 20. Best Practices for GNSS RTN Operations and Maintenance

State/Agency	Best Practice
Arkansas	• Provide documentation to assist with connection to network. • Automate password reset if user loses or forgets it. • Include an FAQs document on the website. (ARDOT is currently creating this resource for its website.)

State/Agency	Best Practice
Florida	• Locate stations at government facilities only. • Align stations with the NSRS frequently. • Perform field research into new methodologies.
Idaho	Let others do the RTN work. [***Note***: The respondent added that "it is arguable whether this is a 'good' practice."]
NCGS	Train all field staff to install and maintain CORS.
Nebraska	Provide constant communication between users and operators.
Ohio	Perform annual maintenance and site inspections.
Oklahoma	• Let the consultant handle network operations with support from the agency. • Perform a monthly OPUS Project submission on all sites to determine if the site is moving or stable. • Inspect each site annually. • Monitor the weather, looking for extreme weather events in the area of the site. Then conduct field inspections of the site and run an OPUS Project [submission] on affected sites. (***Note***: Oklahoma DOT lost its first site to a tornado last year.)
Oregon	Use quality GNSS mounts for station stability.
Seattle Public Utilities	For quality assurance and quality control: • Provide geodetic monitoring, on-board base monitoring, rover monitoring and science partner monitoring. • Request user feedback.
Texas	• Perform regular system monitoring. Continuously monitor network performance to quickly identify and resolve issues. • Conduct routine maintenance. Schedule regular maintenance checks for hardware and software to ensure optimal functionality.
Wisconsin	Perform planned equipment and software upgrades to more seamlessly keep current with technology developments.

Vision for the Future

Ten agencies and/or partners participating in the survey have created a vision for the future of their RTN system. The common focuses of these plans are continuing to expand the network, serving network users, and maintaining and updating systems. Responses from survey participants are provided below:

- **ARDOT**: Keep adding CORS from adjacent states to optimize network near the [state] borders. (The system is for the most part built out within the state.)
- **ITD**: Obtain legislative and leadership interest in a state agency expanding or taking over responsibility for a statewide RTN. (Currently, interest is low.)
- **NCGS**: Continue adding CORS and serving the users of our network.
- **Ohio DOT**: Maintain the system to the best of our ability, and continue to work with NGS and Trimble to keep the system modernized.

- **Oklahoma DOT**: Provide border-to-border coverage in Oklahoma, and then open the network to anybody who wants to use the network, free of charge.
- **Oregon DOT**: Upgrade to NATRF2022 and additional constellations.
- **Seattle Public Utilities**: Partner with autonomy providers to offer hybrid network real-time kinematic/precise point positioning (NRTK/PPP) solutions.
- **South Carolina RFA, Geodetic Survey**: Provide the best real-time GNSS services to customer base.
- **TxDOT**: Partner with contractors and vendors to align RTN use with internal state DOT rover refresh; equipment maintenance; and correction for surveying, terrestrial, mobile and aerial mapping and construction machine control for large projects.
- **WisDOT**: Keep the system up to date and current.

State Resources

Below are documents and other resources associated with responding agencies' GNSS RTN that were either provided by survey respondents or sourced through an online search.

Arizona

Arizona Continuously Operating Reference Station Network — AZCORS, State of Arizona, undated.
https://www.azwater.gov/hydrology/azcors
Information about the management and operation of the Arizona Continuously Operating Reference Station Network is available at this website, including a map of the network and user registration information.

AZCORS — Site Overview, Arizona Department of Water Resources, undated.
https://azcors.azwater.gov/sbc/Account/Index?returnUrl=%2Fsbc%2F
At this site, users may subscribe to real-time and RINEX data products in the AZCORS network.

Arkansas

Real Time Network, Arkansas Department of Transportation, undated.
http://gps.ardot.gov/
Users can log in to ARDOT's RTN at this website. Access to a sensor map is also available.

Control Surveys, Surveys Division, Arkansas Department of Transportation, undated.
https://ardot.gov/divisions/surveys/control-surveys/
This website includes a list of ARDOT CORS network stations.

Florida

Florida Permanent Reference Network (FPRN), Florida Department of Transportation, undated.
https://www.fdot.gov/geospatial/FPRN.shtm
Access to maps, services and user registration is available at this webpage.

Idaho

SmartNet North America, undated.
https://www.smartnetna.com/coverage_network.cfm
A map of SmartNet network coverage and subscription information are available at this website. By agreement with Leica SmartNet, all ITD-owned CORS have been streaming to the SmartNet system for nearly 10 years.

TURN GPS[The Utah Reference Network], Utah Geospatial Resource Center,
https://gis.utah.gov/products/turn/
The Utah Reference Network (TURN) "network consists of permanently located GPS receivers installed across Utah and portions of Idaho, Wyoming and southern Nevada." This website provides subscription and connection to the network, maps to the TURN network and sensors, and other resources.

Nebraska

Seiler Geospatial Midwest RTK Network — Nebraska, Seiler Instrument Company, undated.
http://www.mwrtk.net/Map/SensorMap.aspx
A map of sensors located in Nebraska and adjacent states is presented on this webpage.

North Carolina

North Carolina GNSS CORS and Real-Time Network, North Carolina Geodetic Survey, undated.
https://rtn.nc.gov/
From the website: The North Carolina GNSS CORS and Real-Time Network can provide GNSS correction data to users wanting accurate and precise GNSS positioning and navigation. Users can obtain the GNSS correction data either for post-processing or real-time applications. For post-processing applications, a user will need a CORS data download subscription. For real-time applications, a user will need [an] RTK service login subscription. A user will first need to register so a user account can be created for their organization. Select the Register link on the left. There is no cost for a CORS data download subscription. There is a cost for a RTK service login subscription. The first RTK service login has a $500 one-time cost. The cost for a second RTK service login is included with the cost for the first. After the second, each RTK service login has a $250 one-time cost.

Ohio

Statewide Cooperative Real-Time GNSS Network, Office of CADD and Mapping Services, Ohio Real Time Network, Ohio Department of Transportation, undated.
https://ortn.dot.state.oh.us/trimblepivotweb/
Access to user login and the sensor map is available from this webpage.

Oklahoma

CORS Data, Survey Division, Oklahoma Department of Transportation, undated.
https://www.odot.org/survey/corsdata.php
A listing of state CORS sites is available at this website.

Oregon

Oregon Real-Time GNSS Network, Geometronics Unit, Oregon Department of Transportation, undated.
https://www.oregon.gov/odot/ORGN
From the website: The Oregon Department of Transportation's Geometronics Unit develops and operates the Oregon Real-time GNSS Network — a network of continuously operating GNSS reference

stations. Our team is responsible for enhancing and maintaining the vertical and horizontal geodetic control infrastructure across the state of Oregon.

The ORGN consists of GNSS continuously operating reference stations that provide real-time kinematic correctors to field GNSS users over the internet. GNSS users, who are properly equipped to take advantage of these correctors, can survey in the field to the one centimeter horizontal accuracy level in real time.

Seattle Public Utilities

Washington State Reference Network, State of Washington, undated.
http://www.wsrn.org/
http://wsrn3.org/
Login and network information are available at these websites.

South Carolina

South Carolina Real Time Network, South Carolina Revenue and Fiscal Affairs Office, undated.
https://rfa.sc.gov/programs-services/geodetic/rtnstatus
From the website: Ensures accurate, real-time positioning for improved efficiency for engineering, surveying, automated road construction, precision agriculture, mining, and golf course maintenance via 43 Global Navigation Satellite System (GNSS) receivers installed throughout the state.

In addition to the 43 receivers in South Carolina, data is received from two receivers in Georgia and [10] receivers in North Carolina. Each receiver is connected via the internet to the SC RTN primary server and emergency backup servers utilizing cloud-based technology. Satellite data from the GPS, GLONASS, Galileo and BeiDou constellations are collected and processed every second. Users connect to the servers via mobile cellular service and use the processed information in combination with GNSS data that they are collecting in the field to obtain corrected positions and elevations accurate to approximately 0.02 m (0.06 ft) horizontally and 0.04 m (0.13 ft) vertically in real time. South Carolina was one of the first states to implement this technology, at this scale.

Texas

TxDOT RTN, Texas Department of Transportation, undated.
https://txrtn.txdot.gov/
Access to user login and the sensor map is available from this webpage.

Wisconsin

WISCORS (Wisconsin Continuously Operating Reference Station) Network, Wisconsin Department of Transportation, undated.
https://wisconsindot.gov/Pages/doing-bus/eng-consultants/cnslt-rsrces/tools/wiscors/default.aspx
From the website: The Wisconsin Department of Transportation (WisDOT) Geodetic Surveys Unit is developing a statewide Global Navigation Satellite System (GNSS) reference station network, called the Wisconsin Continuously Operating Reference Stations (WISCORS) Network. This network consists of over 115 permanent GNSS reference stations that can provide GNSS corrections to mobile users in real-time. Mobile users properly equipped to take advantage of these GNSS corrections can position in the field to the 2 centimeter accuracy level in real-time.

The mission of the WisDOT Geodetic Surveys Unit is to apply state-of-the art methods of precise positioning and advanced geodetic techniques to establish and maintain the horizontal and vertical geodetic control infrastructure across the state of Wisconsin. A principal objective in that mission is the establishment and operation of a permanent GNSS CORS network in Wisconsin.

Nonusers of Global Navigation Satellite System Real-Time Networks

Among agencies responding to the survey, three states do not currently own a GNSS RTN: Colorado, Michigan and South Dakota.

SDDOT is contemplating one and currently uses Trimble's VRS Now within the eastern half of the state for survey activities. The respondent noted that an RTN would provide consistent control for DOT projects, ensuring that all projects are tied to the same control network. An RTN would also provide better accuracy for real-time kinematic (RTK) and post-processed kinematic (PPK) surveys. Future implementation would install a public network within the western half of the state, which Trimble's VRS Now does not cover. Before implementing a system, the agency needs buy-in from the executive team, resources (money and time) and dedicated employees to set up and maintain the network. If this implementation were to move forward, the agency anticipates beginning in the next five years.

Colorado and Michigan have no plans for or interest in establishing a system. The CDOT respondent added that the agency partners with and uses existing RTNs from the Mesa County RTN, which essentially covers the western half of the state. In Region 5 (15 counties in southwestern Colorado), CDOT supplied two GNSS base stations that are part of the Mesa County network. In Region 3 (counties in northwestern Colorado), CDOT also partners with Mesa County and supplied base stations. Since that partnership has been successful, CDOT has not had a need to develop its own system.

State Resources

Colorado

Real-Time Virtual Reference Network (RTVRN), Mesa County (Colorado), 2024.
https://www.mesacounty.us/departments-and-services/public-works/gps-survey/real-time-virtual-reference-network-rtvrn
From the website: The Mesa County RTVRN is a service that provides real-time corrections to GPS/GNSS devices in surveying, construction, agriculture, mapping and science industries. The Mesa County Real-Time Virtual Reference Network has 33 [b]ase stations, 17 of which are NGS CORS [s]tations. The current reference frame for this network is NAD83 (2011). The RTVRN is a free service to the public.

South Dakota

Trimble VRS Now, Trimble Geospatial, undated.
https://geospatial.trimble.com/en/products/correction-services/trimble-vrs-now
From the website: Trimble VRS Now correction service is proven and cost-effective, delivering instant access to network-RTK corrections via cell signal.

Outreach to Select State Transportation Agencies

As noted in the previous section, establishing partnerships is a key success reported by several agencies participating in the survey. In a follow-up effort, CTC contacted survey respondents whose agencies partner with other organizations in owning and operating the GNSS RTN central processing center and/or CGNSS reference stations to better understand the value of interagency partnerships in successfully implementing statewide or regionwide GNSS RTN. Five respondents described the benefits to their agencies:

Arkansas Department of Transportation

- **Efficiency**. Partnering with municipalities or entities in Arkansas has been helpful primarily by limiting the hardware purchase for ARDOT and by adding redundancy to the network. In most cases, the municipality had already incurred the cost of the hardware, and the data sharing just improves the solution for all partners.

- **Expanded coverage**. Data sharing with adjacent states has been beneficial to each state by "extending the envelope" of the Virtual Reference Station (VRS) solution beyond the state border. The respondent noted that where data isn't shared with adjacent states, the real-time solution is subject to a parts per million error similar to a single base solution for a certain distance beyond the envelope of GNSS reference stations.

Idaho Transportation Department

- **Access to data stream**.
- **Efficiency**. The agency is able to provide data without needing to set up additional bases.
- **Expanded coverage**. Data sharing improves service to all users.

Nebraska Department of Transportation

- **Expanded coverage**. Currently 25 of the 39 CGNSS reference stations owned by NDOT are part of NGS's CORS network. In an agreement with Midwest RTK, HPRTK and Topcon Positioning Systems, NDOT provides access to its base stations in exchange for licenses to use their VRS networks. NDOT is also working to expand the number of its base stations to meet the needs of the department.

  The respondent added that NDOT rarely works with other agencies in the state when dealing with the bases, although the Nebraska State Patrol and other agencies use the licenses from the VRS networks. But all sections of NDOT, including Maintenance, Design and Construction, are responsible for operating the 39 bases.

North Carolina Geodetic Survey

- **Efficiency**. The partnership with the National Park Service allows both agencies to avoid duplication of CORS in the same general area. This arrangement provides a seamless connection between networks.
- **Expanded coverage**. NCGS shares data with SCDOT and Tennessee DOT so that users of the North Carolina, South Carolina and Tennessee networks who are working along the state borders are surrounded by CORS instead of working on the edge of their networks. This arrangement also provides a seamless connection between the networks.

- **Additional monitoring**. After North Carolina experienced a large earthquake (level 5) in the northwest corner of the state, NCGS installed additional CORS in the area to monitor conditions. The partnership with EarthScope provided additional expertise in earthquake monitoring.

Oklahoma Department of Transportation

- **Staffing support**. Oklahoma DOT lacks the employees to run and maintain the network. Partnering allows the agency to maintain the sites with state employees. The respondent added that "with Oklahoma's leadership wanting to cut the size of state government, it was very important to find the right partnership to run our RTN network. We wanted to maintain the 'no cost to the user' aspect of the network and maintain the integrity of the data. I think we have a good partnership built and have been able to maintain each site ourselves."

  The agency also does not make any network adjustments because of a lack of employees. But it does review each adjustment its partner performs and gives its approval to that adjustment. (***Note***: Oklahoma does one adjustment each year.)

- **Expanded coverage**. The agency has also partnered with TxDOT for data exchange, giving both Texas and Oklahoma border-to-border coverage. Oklahoma DOT is currently reaching out to ARDOT to arrange the same type of data exchange.

Note: According to the respondent, Oklahoma DOT recently went through "our first con with having a partnership run our network." It experienced its first network outage, which lasted for three days, with not much communication from its partner. The respondent believes that most of the issues have been "worked out with our partner in case this problem happens again."

Related Research and Resources

A literature search of publicly available domestic in-progress and published research identified publications that are organized into the following topic areas:

- Previous Preliminary Investigations.
- Statewide systems.
- Related research.

Previous Preliminary Investigations

Statewide Real-Time Global Positioning System or Global Navigation Satellite System Network Implementation, Preliminary Investigation, California Department of Transportation, February 2015.
https://dot.ca.gov/-/media/dot-media/programs/research-innovation-system-information/documents/preliminary-investigations/real-time-gps-networks-pi-a11y.pdf
This Preliminary Investigation presents the results of interviews with representatives of six state DOTs that had well-established RTNs at the time of publication:

- *FDOT*: Florida Permanent Reference Network (FPRN).
- *Minnesota DOT*: Minnesota Continuously Operating Reference Station Network (MnCORS).
- *New York State DOT*: New York State Spatial Reference Network (NYSNet).
- *Oregon DOT*: Oregon Real-Time GPS Network (ORGN).
- *Washington State DOT*: Washington State Reference Network (WSRN).
- *WisDOT*: Wisconsin Continually Operating Reference Stations network (WISCORS).

Statewide Systems

Below are resources addressing existing or planned statewide systems in seven states: Connecticut, Iowa, Minnesota, Montana, North Carolina, Oregon and Washington.

Connecticut

Implementing and Testing a Real Time Network Positioning System for Connecticut Department of Transportation: Advanced Continuously Operating Reference Network (ACORN), Thomas Myer and Ronald Tellier, Connecticut Department of Transportation, March 2022.
https://rosap.ntl.bts.gov/view/dot/62775
From the abstract: The Connecticut Department of Transportation (CTDOT) has evolved its Continuously Operating Reference Stations (CORS) from only serving static data to also serving streaming real-time messages that allow roving global navigation satellite system (GNSS) receivers (such as the U.S. NAVSTAR Global Positioning System [GPS]) to determine centimeter-accuracy positions in real time.

Related Resource:

> **ACORN FAQ**, Connecticut DOT, undated.
> https://portal.ct.gov/dot/-/media/dot/aec/const_inspection/acorn_faq.pdf
> This brief document provides general information about the state's network, including registration and login details.

Iowa

Iowa Real-Time Network (IaRTN), Iowa Department of Transportation, undated.
https://iowadot.gov/rtn/
From the website: In 2006, the Iowa Department of Transportation conducted a business model study to examine the potential models for the deployment and operations of a statewide Real Time Kinematic (RTK) Global Positioning System (GPS) network. The study results helped the Iowa DOT develop a business model that best suited the DOT's and the State of Iowa's needs. Under the selected model, the network uses existing Iowa DOT facilities and wide area network (WAN) communications infrastructure. In addition, the DOT owns the network hardware and software, maintains the hardware, and contracts out the network software support/service.

After a thorough evaluation process, including a written proposal and installation of demonstration networks by competing firms, Leica Geosystems was selected to install and support the IaRTN. The first 80 base stations were installed in the last half of 2008, and the network went online Feb. 2, 2009. Data from the IaRTN base stations along Iowa's borders are shared with other DOT RTK networks in Minnesota, Missouri and Wisconsin. In return, those three networks share the data from their base stations along the Iowa border with the IaRTN. The sharing enhances all three networks along the border areas. Currently the network consists of 103 base stations (83 Iowa DOT sites, 10 Minnesota DOT sites and 3 Wisconsin DOT sites).

In 2018, the network hardware was replaced, and the operating software was upgraded to take advantage of new technology not available in 2008. The network was upgraded to a Global Navigation Satellite System (GNSS) network, using the satellite constellations of the United States (GPS), Russia (Glonass) and the European Union (Galileo). The network provides users centimeter positioning statewide. The Iowa DOT uses the centimeter positioning for surveying, engineering and geographical information system (GIS) applications, along with machine control. The network is also available to federal, state, county, city, quasi-public and private sector users without charge. Machine control by the agricultural sector is one of the biggest network users.

Related Resource:

> **"Iowa Statewide RTK-GPS Network Deployment Project,"** Iowa Department of Transportation, April 11, 2008.
> https://rosap.ntl.bts.gov/view/dot/17115
> This presentation describes findings from the 2006 business model study that laid the groundwork for the agency's implementation of IaRTN.

Minnesota

MnCORS GNSS Network, Land Management, Minnesota Department of Transportation, undated.
https://www.dot.state.mn.us/surveying/cors/
From the website: The Continuously Operating Reference Station Network is a cooperative effort between MnDOT, other state agencies and institutions, counties, cities and private enterprises with the goal of providing Global Navigation Satellite System (GNSS) corrections [statewide].

Using signals from all available GNSS satellites, and receivers at over 140 known positions, MnCORS is able to continuously provide survey grade positioning corrections.

Related Resource:

MnCORS GNSS Network Frequently Asked Questions, Land Management, Minnesota Department of Transportation, last updated February 2025.
https://www.dot.state.mn.us/surveying/cors/mncors_faq.html
This online document addresses a range of topics, including registration procedures, equipment requirements, data access and plans for network expansion.

Montana

Analyze Business Models for Implementation and Operation of a Statewide GNSS RTN, Ahmed Al-Kaisy, Rafael Teixeira, Sajid Raza and Benjamin Meyer, Montana Department of Transportation, October 2022.
https://doi.org/10.21949/1518323
From the abstract: The Global Navigation Satellite System (GNSS), commonly known as the global positioning system, has become one of the fastest-growing emerging technologies delivering location services to various sectors. The applications of geospatial data span every sphere of modern-day science and industry where geographical positioning matters. The list includes navigation, agriculture, surveying, construction, transportation, forestry, mining and many others. The accuracy and precision of geospatial data using the GNSS Real-Time Network (RTN) technology enable advanced applications in many fields where geospatial data is used; and open the doors for new applications such as the emerging autonomous systems in transportation, mining and agriculture. This research project is intended to provide information that would help the state's efforts in the planning and implementation of the Montana GNSS-RTN system. Four major tasks were completed for this project, namely, state-of-the-art review, state-of-the-practice assessment, characterizing Montana existing GNSS-RTN infrastructure, and identifying and cataloging viable business models for statewide GNSS-RTN systems.

Related Resource:

Supporting Dataset: Analyze Business Models for Implementation and Operation of a Statewide GNSS RTN, Ahmed Al-Kaisy and Sajid Raza, Montana Department of Transportation, December 2024.
https://doi.org/10.21949/1530069
This dataset supplements the content in the previous citation.

North Carolina

North Carolina Continuously Operating Reference Stations (CORS) Network, Gary Thompson, *64th Meeting of the Civil GPS Service Interface Committee*, September 16-17, 2024.
https://www.gps.gov/cgsic/meetings/2024/thompson.pdf
In addition to general information about the North Carolina CORS network, this presentation provides 2023 data used to assess the economic benefits of the network and funding information (see Slides 21 and 22).

Oregon

Research in Progress: Automated Methods for Correcting ODOT's Real-Time GNSS Network for Survey and Post-Disaster Recovery, Oregon Department of Transportation and Federal Highway Administration, start date: November 2022; expected completion date: September 2025.

Note: The most recent quarterly report for this project, dated August 1, 2024, is available at https://www.oregon.gov/odot/Programs/ResearchDocuments/spr856qr.pdf.

Project description at https://rip.trb.org/View/1897254
From the project description: The main objective of this research is to develop a near real-time methodology for automatically flagging and correcting ORGN reference stations that are misaligned with the satellite based National Spatial Reference System (NSRS). The objective of this study will be achieved by: (1) Investigating alternative techniques and methodologies used for monitoring permanent static GNSS networks such as precise point positioning (PPP); (2) Developing, in collaboration with NOAA's National Geodetic Survey (NGS), the necessary algorithms and workflow, which will include recommended best practices for housing and disseminating raw GNSS data, for the purpose of automatically adjusting and aligning the ORGN to the NSRS; (3) Identifying optimal statistical variables and tolerances to quantify the health of ORGN base stations; and (4) Producing a web-based graphical user interface(s) sharing updated ORGN coordinates and time-series plots for ORGN operators and surveying practitioners.

Washington

"Best Practices for the Development and Operation of Real-Time GNSS Networks," Gavin Schrock, *Surveying and Land Information Science*, Vol. 76, Issue 2, pages 119-130, 2017.
https://www.researchgate.net/publication/321677041_Best_practices_for_the_development_and_operation_of_real-time_GNSS_networks
From the abstract: 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 used 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 using 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 is 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 GNSS networks and outlines the most important technical considerations to deploy and manage an RTN to help these agencies in guiding their projects. Elements examined: (1) RTN components (2) Features and services (3) Reference framework (4) Design (5) Operations (6) Drivers and sustainability.

Related Research

Note: Selected authors of the three journal articles cited immediately below participated in the October 2022 Montana study cited on page 52.

"Statewide GNSS-RTN Systems: Current Practices," Sajid Raza and Ahmed Al-Kaisy, *Journal of Geographic Information System*, Vol. 15, No. 1, pages 73-97, February 2023.
https://www.scirp.org/journal/paperinformation?paperid=123016
From the abstract: While there is numerous published information on the technical aspects of the GNSS-RTN technology, information on the best practices or guidelines in building, operating and managing the GNSS-RTN networks is lacking in practice. To better understand the current practice in establishing and operating the GNSS-RTN systems, an online questionnaire survey was sent to the GNSS-RTN system owners/operators across the U.S. Additionally, a thorough review of available literature on business models and interviews with representatives of two major manufacturers/vendors of GNSS-RTN products and services were conducted. Study results revealed a great deal of inconsistency in current practices

among states in the way the GNSS-RTN systems are built, operated and managed. Aspects of the diversity in state practices involved the business models for the GNSS-RTN systems besides the technical attributes of the network and system products. The information gathered in this study is important in helping state agencies make informed decisions as they build, expand or manage their own GNSS-RTN systems.

"High-Level Assessment of Statewide GNSS-RTN Business Models," Ahmed Al-Kaisy and Sajid Raza, *International Conference on Transportation and Development 2023: Transportation Planning, Operations and Transit*, pages 424-437, 2023.
Citation at https://doi.org/10.1061/9780784484883.038
From the abstract: The applications of geospatial technologies and positioning data embrace every sphere of modern-day science and industry where geographical positioning matters. Among all other fields, geospatial technology plays a remarkable role in the transportation sector and has the potential to play an even more critical role in future autonomous transportation systems. In this regard, the GNSS-real-time network (GNSS-RTN) technology is promising in meeting the needs of automation in most advanced transportation applications. The GNSS-RTN is a satellite-based positioning system that uses a network of reference stations to provide centimeter-level accuracy in positioning data in real time. The technical aspect and working technology of GNSS-RTN are widely studied; however, only limited research has been conducted on the various GNSS-RTN business models currently in use nationally and internationally. Therefore, this study aims at assessing the various GNSS-RTN business models currently used in practice as well as those that are deemed potentially viable but have not yet moved to practice. Eight different business models were cataloged and used in the current assessment. All business models were assessed using three criteria: state control, sustainability and state/agency costs. The findings of this research are important in helping state agencies make informed decisions as they build, expand or manage their own GNSS-RTN systems.

"GNSS-RTN Role in Transportation Applications: An Outlook," Sajid Raza, Ahmed Al-Kaisy, Rafael Teixeira and Benjamin Meyer, *International Conference on Transportation and Development 2022: Transportation Planning and Workforce Development*, pages 182-195, 2022.
Citation at https://doi.org/10.1061/9780784484340.017
From the abstract: Geospatial location service is not only used in measuring ground distances and mapping topography, but has also become vital in many other fields such as aerospace, aviation, natural disaster management and agriculture, to name but a few. The innovative and multi-disciplinary applications of geospatial data drive technological advancement toward precise and accurate location services available in real-time. Although the real-time network (RTN) technology is currently utilized in a few industries such as precision farming, construction industry and land survey, the implications of precise real-time location services would be far-reaching and critical to many advanced transportation applications. The global navigation satellite system (GNSS)-RTN technology, introduced in the mid-1990s, is promising in meeting the needs of automation in most of the advanced transportation applications. This article presents an overview of the GNSS-RTN technology, its current applications in transportation-related fields, and a perspective on the future use of this technology in advanced transportation applications.

"Tale of Two RTNs: Rigorous Evaluation of Real-Time Network GNSS Observations," Mahsa Allahyari, Michael Olsen, Daniel Gillins and Michael Dennis, *Journal of Survey Engineering*, Vol. 144, Issue 2, 2018.
Citation at https://ascelibrary.org/doi/10.1061/%28ASCE%29SU.1943-5428.0000249
From the abstract: To evaluate the accuracy of shorter-duration RTN GNSS observations and their potential for use as a source for establishing geodetic control, data collected from two National Geodetic Survey (NGS) surveys in South Carolina and Oregon were studied in detail. This article explores

the horizontal and vertical accuracy of real-time observations as a function of observation duration, examines the influence of the inclusion of Globalnaya Navigazionnaya Sputnikovaya Sistema (GLONASS) observables, compares results from real-time kinematic (RTK) positioning using a single base station versus a network of base stations, and assesses the effect of baseline length on accuracy. Thirty-eight passive marks were repeatedly observed with GNSS using [an] RTN in the two study areas for a variety of different observation times, ranging from 5 s[econds] to 15 min[utes]. An optimal real-time observation duration was found in the range of 180 to 300 s[econds]. The real-time data acquired using a network of base stations tended to be more accurate and precise than single-base RTK data, especially vertically. Further, the addition of GLONASS observables helped obtain more fixed solutions at longer baseline lengths than solutions based solely on global positioning system (GPS) observables and showed a slight improvement in accuracy, particularly for stations with poorer satellite visibility.

Contacts

CTC engaged with the individuals below to gather information for this investigation.

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Appendix A: Survey Questions

The online survey represented below was distributed via email to members of the Transportation Research Board Standing Committee on Geospatial Data Acquisition Technologies and to the American Association of State Highway and Transportation Officials Committee on Data Management and Analytics.

Caltrans Survey on Statewide Real-Time Global Navigation Satellite System Network Implementation
The California Department of Transportation (Caltrans) is gathering information about the implementation of a statewide global navigation satellite system (GNSS) real-time network (RTN). Caltrans is particularly interested in gaining an improved understanding of the landscape, dependency and importance of existing statewide RTNs.

The survey below inquires about your agency's experiences and management practices related to real-time GNSS implementation. We estimate the survey will take approximately 20 minutes to complete. We would appreciate receiving your responses by January 28, 2025.

If someone else in your agency would be more appropriate to address questions related to this issue, please forward this survey to that person.

The final report for this project, which will include a summary of the responses received from all survey participants, will be available on the Caltrans website.

If you have questions about completing the survey, please contact Carol Rolland at carol.rolland@ctcandassociates.com. If you have questions about Caltrans' interest in this issue, please contact Tori Kanzler at tori.kanzler@dot.ca.gov.

Thanks very much for your participation.

(Required) Please provide your contact information.

Name:
Agency:
Division/Title:
Email Address:
Phone Number:

Note: Responses to the question below determined how respondents were directed through the survey.

(Required) Does your state have a global navigation satellite system (GNSS) real-time network (RTN)?

- Yes (Skipped the respondent to **System Administration and Information**.)
- No, but we are contemplating a GNSS RTN. (Skipped the respondent to **Interest in Establishing a GNSS RTN** and **Wrap-Up**.)
- No, and we have no plans for or interest in establishing a GNSS RTN. (Skipped the respondent to **Wrap-Up**.)

System Administration and Information

1. Please indicate who owns and operates the GNSS RTN central processing center. Select all that apply.
    - Private organization
    - State DOT
    - Other public agency (Please describe.)
2. Please indicate who owns, operates and maintains the continuously operating GNSS (CGNSS) reference stations. Select all that apply.
    - Private entity
    - Public and private organizations
    - State DOT
    - Other public agency (Please describe.)
3. Please describe the extent of the area covered by the GNSS RTN.
    - Entire state
    - Portion of the state (Please estimate the area of the state covered.)
4. Please indicate the number of CGNSS stations in the GNSS RTN.
5. Please indicate the approximate distance between CGNSS stations.
    - 15 to 25 miles
    - 26 to 35 miles
    - 36 to 45 miles
    - More than 45 miles
    - Unknown
    - Other (Please describe.)
6. Please indicate the relative accuracy of the GNSS RTN system.
    - Less than 1 centimeter
    - 1 to 2 centimeters
    - 3 to 4 centimeters
    - 5 or more centimeters
7. Please indicate the method used by the CGNSS stations to communicate with the central processing center. Select all that apply.
    - Internet-based communications
    - Mobile network
    - Radio signal
    - Other (Please describe.)
8. Please identify the vendor/manufacturer that supplied the system **hardware**. Select all that apply.
    - Leica
    - NavCon
    - Topcon
    - Trimble
    - Other (Please identify.)
9. Please identify the vendor/manufacturer that supplied the system **software**. Select all that apply.
    - Leica
    - NavCon
    - Topcon
    - Trimble
    - Other (Please identify.)
10. Is the system aligned to the National Spatial Reference System (NSRS)?
    - Yes (Please respond to Question 11 below.)
    - No
11. If the system aligns to the NSRS, what is the adjustment interval of the CGNSS station positions?
    - Annually
    - Every two to four years
    - More than five years
    - Other (Please describe.)

Applications

1. Please select the ***primary use*** of geospatial data using GNSS RTN technology in your state. Select one response.
    - Agriculture
    - Atmospheric sciences
    - Autonomous vehicles
    - Construction
    - Earth sciences
    - Forestry
    - Mining
    - Navigation
    - Surveying
    - Transportation sector
    - Other (Please describe.)
2. Please identify any ***other applications*** where this technology is used in your state. Select all that apply.
    - Agriculture
    - Atmospheric sciences
    - Autonomous vehicles
    - Construction
    - Earth sciences
    - Forestry
    - Mining
    - Navigation
    - Surveying
    - Transportation sector
    - Other (Please describe.)
3. Please indicate any ***other applications that your state is considering*** for this technology. Select all that apply.
    - Agriculture
    - Atmospheric sciences
    - Autonomous vehicles
    - Construction
    - Earth sciences
    - Forestry
    - Mining
    - Navigation
    - Surveying
    - Transportation sector
    - Other (Please describe.)

User Information

1. Please indicate the number of users that the system supports.
2. Please describe the primary users of the system. Select all that apply.
    - Agricultural professionals
    - Construction professionals
    - Contractors
    - Developers of early warning systems
    - Engineering consultants
    - GIS data collectors
    - Land surveyors
    - Navigation professionals
    - State DOT staff
    - University and research organization staff
    - Unknown
    - Other (Please describe.)
3. Is your agency considering reaching out to other users?
    - No
    - Yes (Please describe this outreach.)
4. Please indicate the data products that are provided to end users. Select all that apply.
    - Real-time coordinates
    - Network correction
    - Post-processed data
    - Other (Please describe.)
5. Please indicate how the data products are provided. Select all that apply.
    - As a public service to users
    - Internally to state DOT
    - Internally to other public agency
    - To private entities
    - To contractors
    - Other (Please describe.)

System Costs and Funding

1. Please provide an estimate of costs for the following activities.
    - System startup:

- Annual operation and maintenance:
- Upgrades and network expansion:
- Other (Please describe.):

2. Please describe how the GNSS RTN is funded in your state. Select all that apply.
    - Federal funds
    - State funds
    - User fees
    - Other (Please describe.)
3. Please indicate whether a cost recovery mechanism is in place for user access. Select all that apply.
    - Annual subscription fee
    - Fee based on access
    - No fee
    - Other (Please describe.)

Return on Investment

1. Has your agency measured the benefits of the investments made in the GNSS RTN?
    - No (Please respond to Question 2 below.)
    - Yes (Please respond to Questions 3 and 4 below.)
2. Does your agency have plans to measure the benefits of these investments?
    - No
    - Yes (Please describe your agency's plans.)
3. What data is used to measure system benefits?
4. What method(s) does your agency use to measure the benefits?

Assessment and Future Plans

1. Please describe the key successes of your agency's efforts in establishing a GNSS RTN.
2. Please describe the key challenges experienced with the GNSS RTN startup.
3. What best practices has your agency adopted related to GNSS RTN operations and maintenance?
4. Has your agency and/or partners created a vision for the future of the system?
    - No
    - Yes (Please describe.)
5. Please provide links to documents associated with your agency's GNSS RTN. Send any files not available online to carol.rolland@ctcandassociates.com.

Interest in Establishing a GNSS RTN

1. Please briefly describe your agency's interest in establishing a GNSS RTN.
2. What does your agency need to implement a GNSS RTN?
3. When do you anticipate beginning implementation?

Wrap-Up

Please use this space to provide any comments or additional information about your previous responses.