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Statewide GNSS-RTN Systems: Current Practices

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Abstract

The applications of geospatial technologies and positioning data embrace every sphere of modern-day science and industry. With technological advancement, the demands for highly accurate positioning services in real-time led to the development of the Global Navigation Satellite System—Real-Time Network (GNSS-RTN). 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.

Keywords

Real-Time Network, Geospatial Data, Practice Survey, Current Practices, Business Models, Real-Time Correction

1. Introduction

Geographic science and technologies are transforming every aspect of industry and revolutionizing the world. Significant technological advances have been made in global navigation satellite systems (GNSS) which include the GPS (U.S. global positioning system) and its counterparts: GLONASS (Russia), Galileo (Europe), QZSS (Japan), and BeiDou (China) [1]. The applications of geospatial data embrace every sphere of modern-day science and industry where geographical positioning matters [2]. The list includes navigation, agriculture, logistics and transportation, ecology, forestry, mining, and many others. In the early 1990s, the GPS was declared open for civilian use, however, the errors in the positioning data were relatively high for many applications. To deal with this issue of errors, GPS Real-Time Kinematic (RTK) technology emerged, and the use of GPS-RTK became vital in various applications which require accurate location data in real-time. However, the performance and accuracy of the traditional GPS-RTK are limited due to the distance between a reference station (a.k.a. base station) and a roving receiver (user device). The GPS-RTK is a positioning technique that uses a fixed base station placed at a known location which transmits correction to the rover to improve accuracy and minimize errors. The accuracy and reliability of the GPS-RTK measurements degrade with the increase in baseline length (*i.e.*, base-to-rover distance) due to distance-dependent errors and biases [3]. To overcome the limitation of the baseline length of the traditional GPS-RTK technique and with the advancement in GNSS technology, the GNSS-RTN concept was introduced in the mid-1990s [4]. The GNSS-RTN is a satellite-based positioning system using a network of ground receivers (also called base stations, reference stations, or continuously operating reference stations (CORSs)) to improve the accuracy of corrections in positioning data. This concept is shown in **Figure 1**. The network of reference stations extenuates and alleviates the spatially-correlated atmospheric and satellite orbit biases [5], and

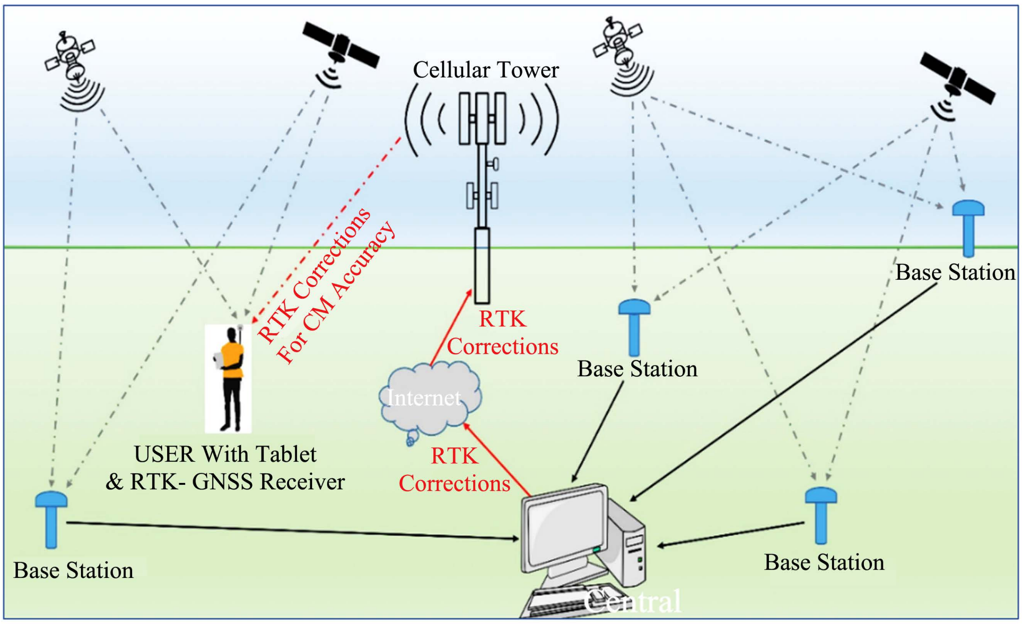

Figure 1. Concept of GNSS-RTN operation, reprinted from Anatum [14].

improves the accuracy and precision of geospatial positioning through real-time corrections sent from a central processing center to a rover. The utilization of ground sensors enables systems to have a range of 1 to 5 centimeters in accuracy, compared to a range of 1 to 10 meters when sensors are not utilized [6].

GNSS-RTN has found applications in precision agriculture, survey-grade applications, construction engineering projects, municipal infrastructure, emergency management, infrastructure asset management, environmental studies, transportation, and other fields [7]. As the accuracy and precision of positioning data continue to enhance with developments in technology and such data or services become more accessible to users, more applications can utilize the positioning data that the GNSS-RTN systems can produce [8] [9].

Since the advent of GNSS-RTN technology, national networks have been established in many countries around the world, especially in developed countries. Here in the U.S., statewide (or partial) networks have been established in more than half of the 50 states with the respective state Departments of Transportation (DOTs) being key players in developing and operating many of these networks [10]. While significant research has been conducted on the components and working technology of the GNSS-RTN systems [11] [12] [13], only a little attention has been given to aspects concerning the planning, building, operating, and managing of these systems.

Background

The body of literature is quite limited with respect to current practices regarding GNSS-RTN systems. California Department of Transportation (Caltrans) carried out a survey of only six statewide GNSS-RTN systems in 2015 and reported that most of the GNSS-RTN systems were owned by the state department of transportation (DOT) with CORSs ownership varying between the public and private sectors. Furthermore, most CORSs were located on public land and operating costs are funded by the state agency as most of the networks do not charge access fees from users. While return on investment was not formally investigated in the surveyed states, Florida DOT did calculate $964,360 in annual savings [15]. Another study reported that the Washington State Reference Network (WSRN) is a cooperative of about 80 different partners spanning the public and private sectors. However, joining the cooperative requires contributing at least one station to the network. Access to static files is free, while access to real-time corrections requires being either a partner or a subscriber, which requires an annual fee to help cover operations costs. Seattle Public Utilities hosts the central processing center for the network, provides stations to the network, and serves as a point of contact for WSRN matters. Additionally, Central Washington University is also an important partner in providing infrastructure, expertise, and a backup central processing center [16].

A brief overview of international practices regarding GNSS-RTN is also important. Jenssen *et al.* (2016) reported about CORSnet-NSW, a GNSS-RTN system owned by the Government of New South Wales in Australia [17]. CORSnet-NSW also engages in data-sharing agreements with neighboring states to provide adequate coverage. The Government owns the system and conducts all the maintenance and operations. Raw data is sold to three companies, while CORSnet-NSW subscriptions are sold through 16 authorized providers. Raw data is also made available to various positioning efforts including the Asia-Pacific Reference Frame [17]. Similarly, Bakici *et al.* (2017) reported the business plan for the Turkish National Permanent GNSS Network-Active (CORS-TR). The CORS-TR system consists of 146 stations spread around Turkey and Northern Cyprus. The system is jointly operated by the General Directorate of Land Registry and Cadastre (GDLRC) and General Command Mapping (GCM). The executive board holds the power to determine access fees; principles of access for educational institutions; principles of maintaining and marketing the system; and plans for investment, research, and development. System setup cost was $6.6 million, while operating costs fluctuate and are covered by service fees. In 2016, revenue totaled $1.5 million, while operating costs totaled $270,000. Most users (63.96% of the 8455 total users as of February 2017) were from the private sector [18].

These aforementioned studies offer valuable information on GNSS-RTN systems, however, there are certain limitations such as studies based on only one or very few GNSS-RTN systems and lacking best practices or guidelines in building, operating, and managing the GNSS-RTN networks. This lack of information and guidance was the main impetus for the current study. The study aims to gain a better understanding of how the existing networks in the U.S. are being managed and operated by different states, including the range of location services offered and user access charges, if any. Such information would help state agencies and private entities in making informed decisions as they build, expand or manage their own GNSS-RTN systems.

2. Study Approach

To better understand the current practice in establishing and operating the GNSS-RTN systems at the national level, an online questionnaire survey was developed and sent to the GNSS-RTN system owners/operators or state DOTs in 37 states (13 states either have no GNSS-RTN system and/or no contact details available) across the U.S. The questionnaire survey was created and administered using Qualtrics survey software. The survey consisted of 23 questions divided into two sections, system general information and system operation [19]. The general information section involved system attributes such as system ownership, hardware and software used, geographic coverage, system products, user types, and other general information. The system operation section involved other aspects such as system costs, funding mechanisms, user access charges, and public-private partnerships. Besides the practice survey, virtual interviews were conducted with the representatives of two major manufacturers/vendors of GNSS-RTN products and services.

3. Results and Analysis

3.1. GNSS-RTN Survey

After sending the survey to 37 states (13 states either have no GNSS-RTN system and/or no contact details available), thirty-eight respondents submitted the survey representing 34 states and 30 GNSS-RTN systems (4 states with two responses and 4 states with no GNSS-RTN system). The duplicate responses were removed and the response from the manager of GNSS-RTN was considered. Only five responses were incomplete, however, they provided answers for the majority of survey questions, thus included in the analysis. Out of the 30 respondents from the 30 different states, as shown in Figure 2, twenty-seven responses were from public agencies and only three responses were from private entities.

The following section summarizes the information, on national practices of the statewide GNSS-RTN operations and management, gathered from 30 different states in the U.S. The responses are organized by using the different question topics included in the survey.

System Characteristics (ownership, # of CORs, spacing, etc.)

1) GNSS-RTN Ownerships

As GNSS-RTN is a fairly expensive system, in terms of both initial and operational costs, it is, therefore, imperative to know about the ownership of the statewide GNSS-RTN system and its components to ascertain the trend of investment made by agencies and/or entities. A question was asked about the

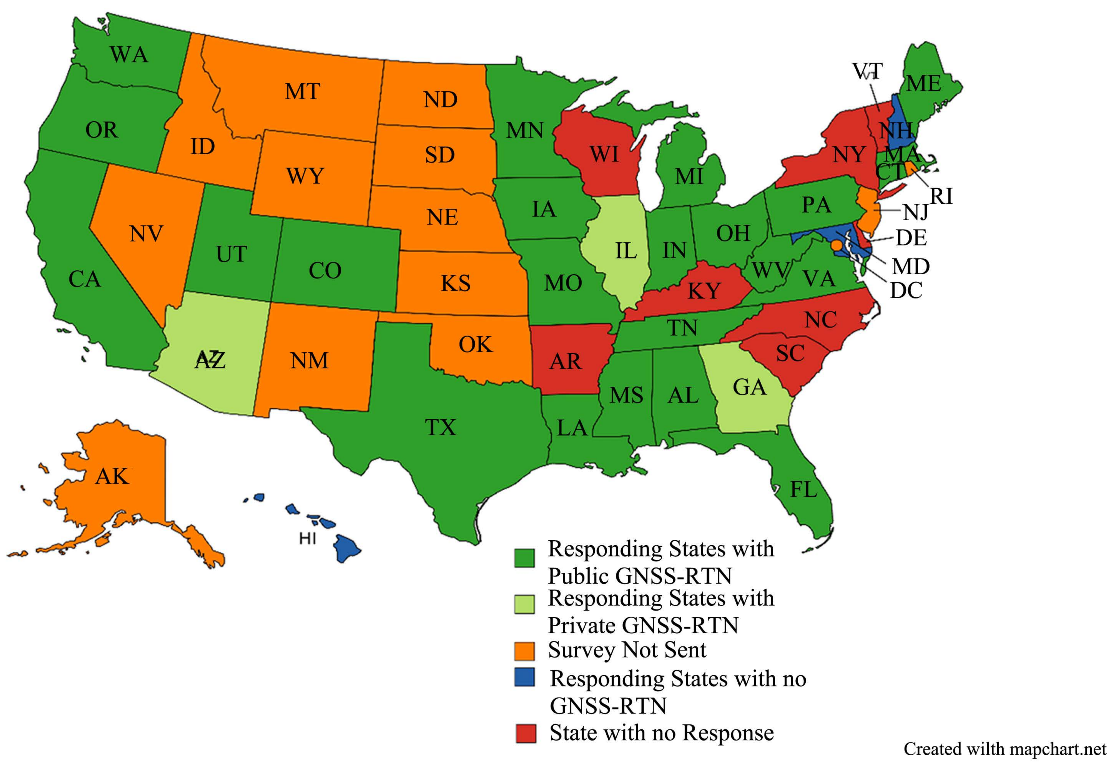

Figure 2. U.S. states surveyed map (Map Source: mapchart.net).

ownership of the GNSS-RTN central facility (central processing center) and the CORSs in the network. The responses show that the central processing centers (CPCs) in 80% of the corresponding states are owned by public agencies. Regarding the ownership of CORSs in respective states, 40% of respondents indicated that the CORSs are owned by both public and private entities, while around 57% of respondents indicated that the CORSs are owned solely by the public agency. Most of the state Departments of Transportation (DOT), who responded to the survey, own the CPC and operate the statewide GNSS-RTN system. They also own most but not all of the CORSs within their respective networks. The results for system ownership are shown in **Figure 3(a)** and **Figure 3(b)**.

2) GNSS-RTN Technology Suppliers/Vendors

Besides ownership of the system, various companies or vendors are involved in providing products and services of GNSS technology and GNSS-RTN components worldwide. However, it is important to acquire information on major vendors/suppliers of the GNSS-RTN products and services in the U.S. This information would assist some states in the planning of future GNSS-RTN systems within their jurisdictions. To collate information on the vendors/suppliers for GNSS-RTN systems in different states, questions were asked about the companies that supplied hardware for CORSs, hardware for the central processing facility, and the software for the GNSS-RTN system. The complete response options were: *Trimble*, *Leica*, *NavCon*, *TopCon*, *and Others* (*where respondents can write in text*). It was allowed to select multiple options if more than one company has provided products or services to the statewide GNSS-RTN system. Based on the responses from GNSS-RTN owners/operators, the top three companies that provide hardware for CORSs in the U.S. are Trimble, Leica, and TopCon as illustrated in **Figure 4**. The same three companies were the major suppliers of software and hardware for the central facility of the GNSS-RTN systems.

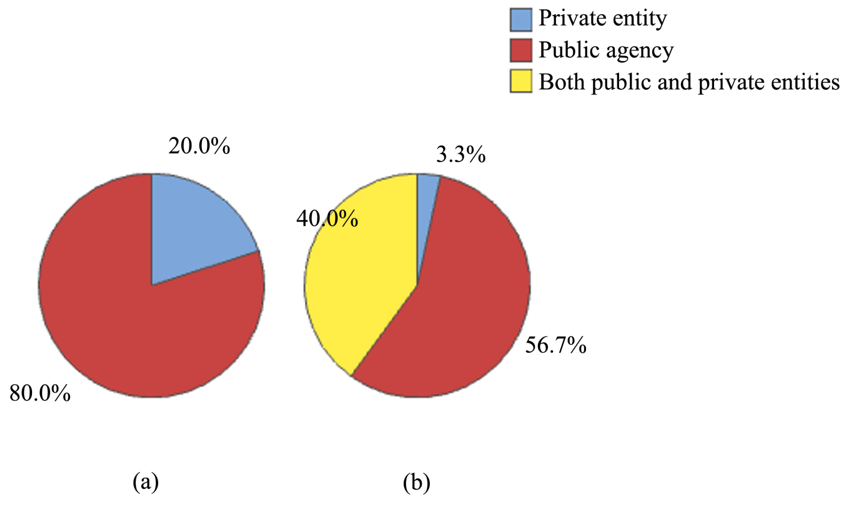

Figure 3. Ownership of GNSS-RTN (a) Central facility; (b) CORSs in the networks.

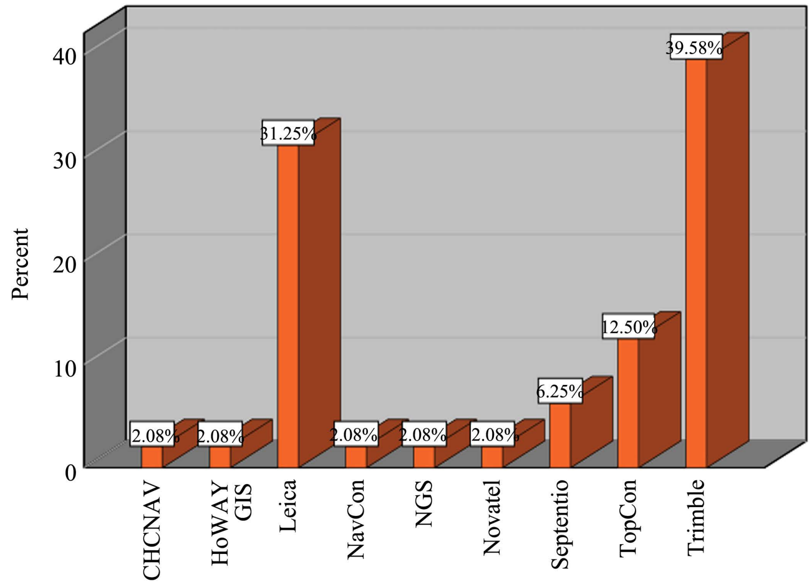

Figure 4. Companies providing hardware for CORSs in the U.S.

3) Network Size and Extent

It is crucial to identify the current practices of the coverage area of the GNSS-RTN system in each state, the number of CORSs deployed, and the inter-CORS spacing in the network. These factors not only influence the economic feasibility of the GNSS-RTN system, but are important determinants of the accuracy of the spatial data. The lower the spacing between CORSs, the higher the accuracy of the spatial data and the higher the cost of the GNSS-RTN system. The GNSS-RTN owners/operators were asked about the *total number of CORSs that are part of the statewide GNSS-RTN system* (*including CORSs owned by entities other than the GNSS-RTN system owner*/*operator*), *GNSS-RTN coverage* (*whole State or part of the State*), and the *average spacing between CORSs in their respective GNSS-RTN systems*. The respondents reported numbers of CORSs as low as 10 stations in Connecticut to as high as 240 stations in Texas. These results, shown in **Figure 5**, clearly indicate that larger states have a higher number of CORSs in their systems, which is anticipated. Moreover, regarding the coverage area of the network in each state, the responses indicated that approximately 86% of the states have GNSS-RTN coverage in 'whole State', whereas only 14% of the state GNSS-RTN systems cover part of the state. The responses are illustrated in **Figure 6**.

On enquiring about spacing between CORSs, the responses indicated that approximately 90% of statewide GNSS-RTN systems in the U.S use CORSs with a spacing of less than 70 km, on average. The results of the responses are presented in **Figure 7**.

System Operations and Services—Business Model

4) System Communications

One of the important elements of the GNSS-RTN system is the communication between the CPC and the CORSs for data correction. Different communication

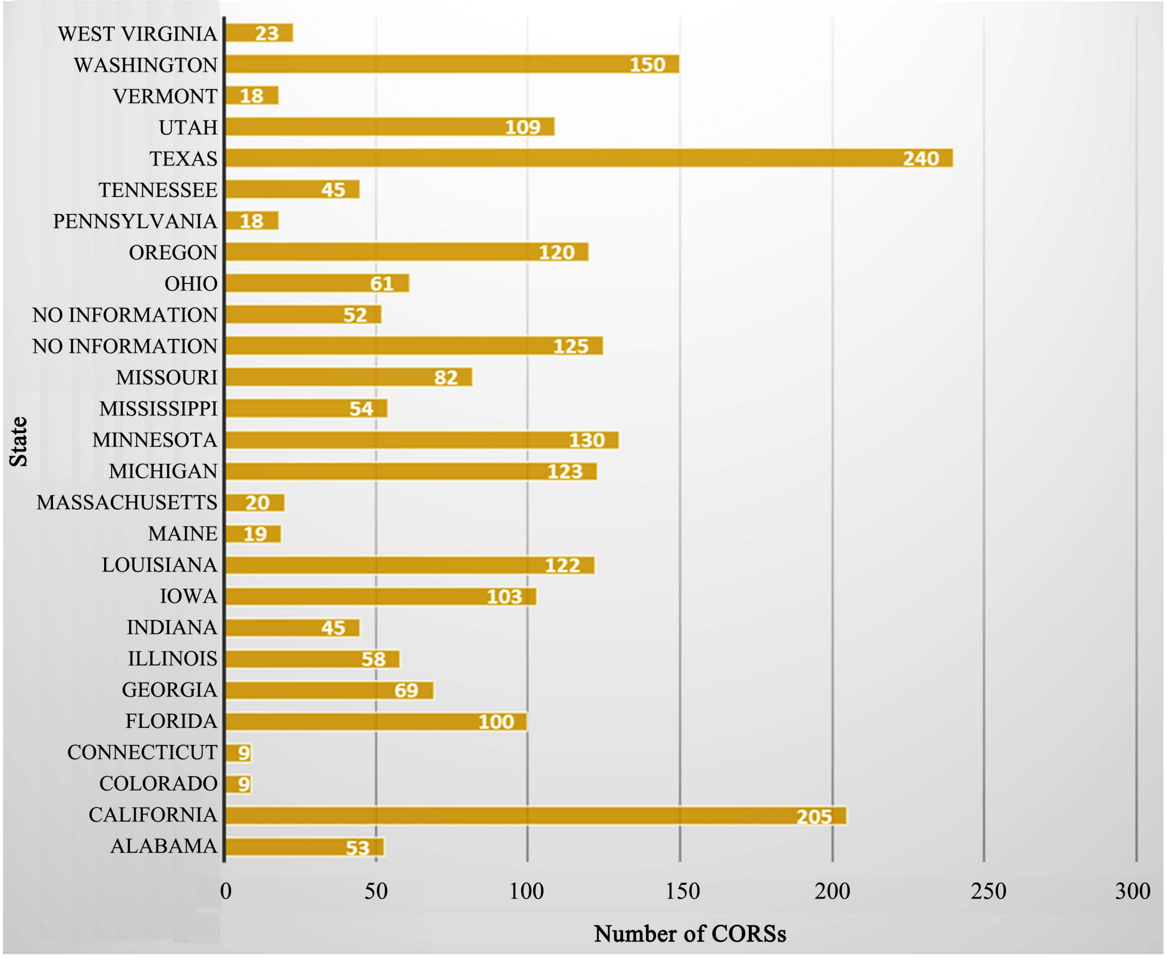

Figure 5. Number of CORSs in each state.

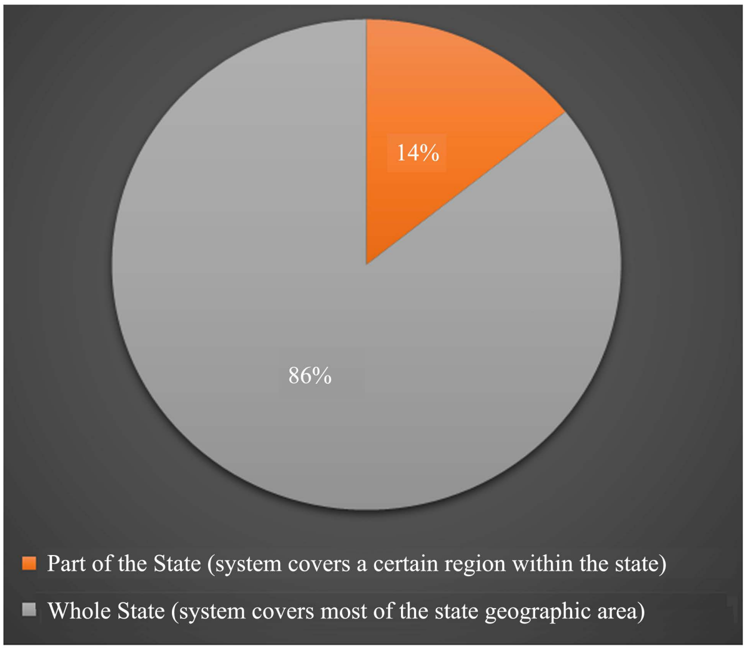

Figure 6. GNSS-RTN coverage in the state.

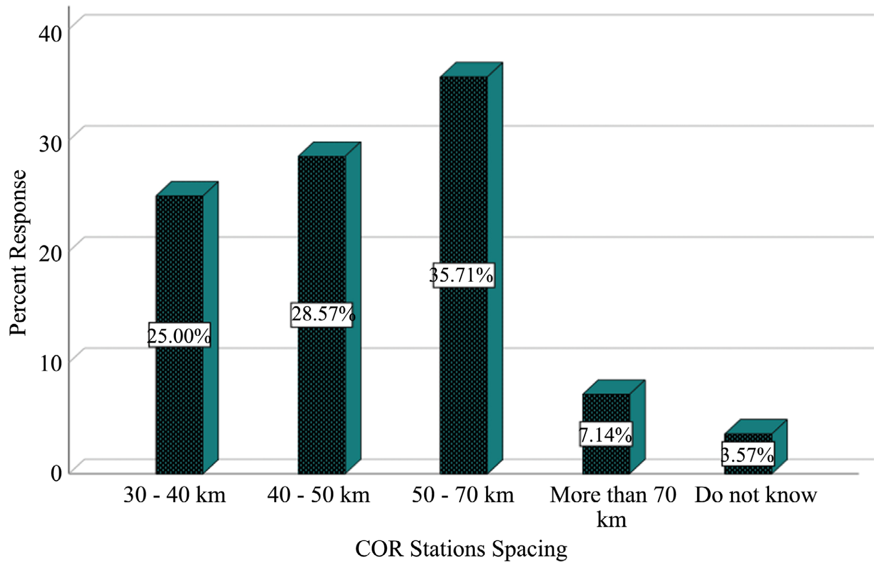

Figure 7. Percent RTN systems based on CORSs spacing.

means or methods can be used to connect the CORSs with the central facility based on the availability of the communications services in the area. Therefore, a question was included about c*ommunication methods currently in place to connect CORSs to the central facility/server.* The respondents were provided with the following response options: *mobile cellular network*, *internet-based communication*, *radio signal-based*, *and Others* (*where respondents can write in text*). Based on the responses of the operators/owners of current statewide GNSS-RTN systems in the U.S., most of the networks use the internet or both internet and mobile cellular network for communication between CORSs and the central processing facility. A few states also use radio signals for communication as shown in Figure 8.

5) System Products and Users

Although the GNSS-RTN technology is currently utilized in a few industries such as precision farming, construction industry, mining, and land surveying, the implications of highly accurate real-time location services would be far-reaching and more critical to many advanced transportation applications. To get a better understanding of statewide GNSS-RTN spatial data services offered to end-users, a question was asked about *the system products/services*. The following options were provided: *corrected coordinates* (*Real-time*), *network corrections* (*Real-time*), *post-processed data* (*Static*), *and Others* (*where respondents can write in text*). The responders were allowed to check multiple options if the network offers multiple products or services to the users. The results of the responses to this question are shown in Figure 9. The results indicate that approximately 66% of the statewide GNSS-RTN systems provide corrected coordinates (real-time), network corrections (real-time), and post-processed data (static), whereas approximately 17% of the statewide GNSS-RTN systems provide only network corrections (real-time), and post-processed data (Static).

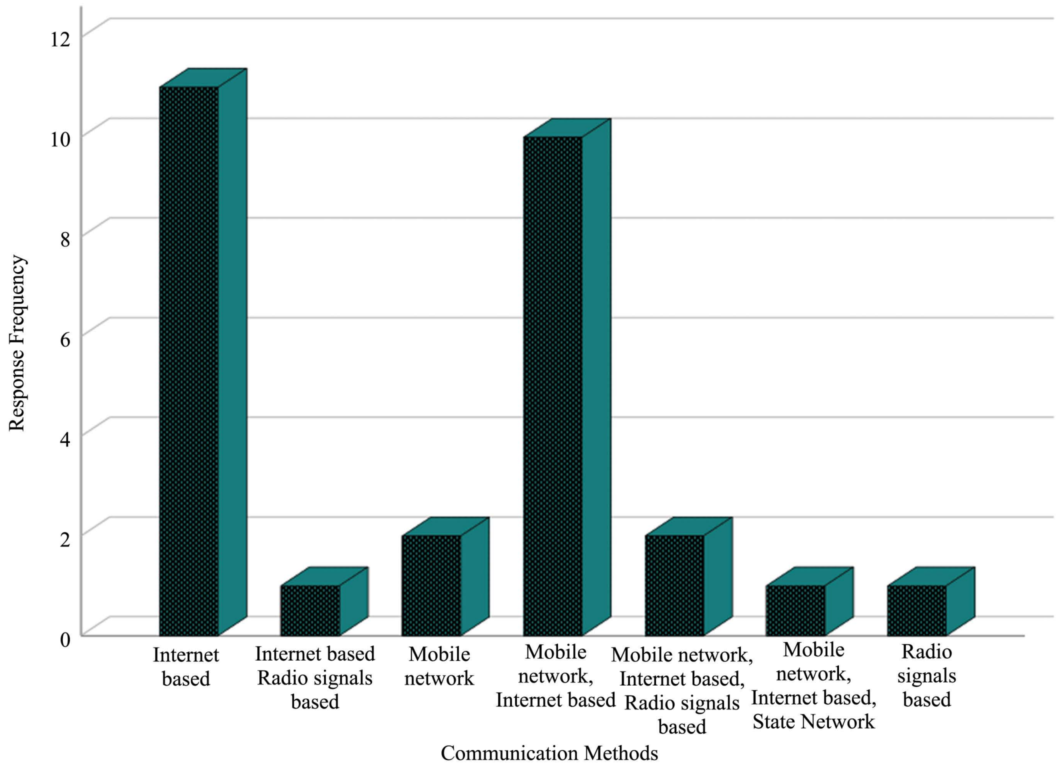

Figure 8. Methods used for communication between CORSs and central facility.

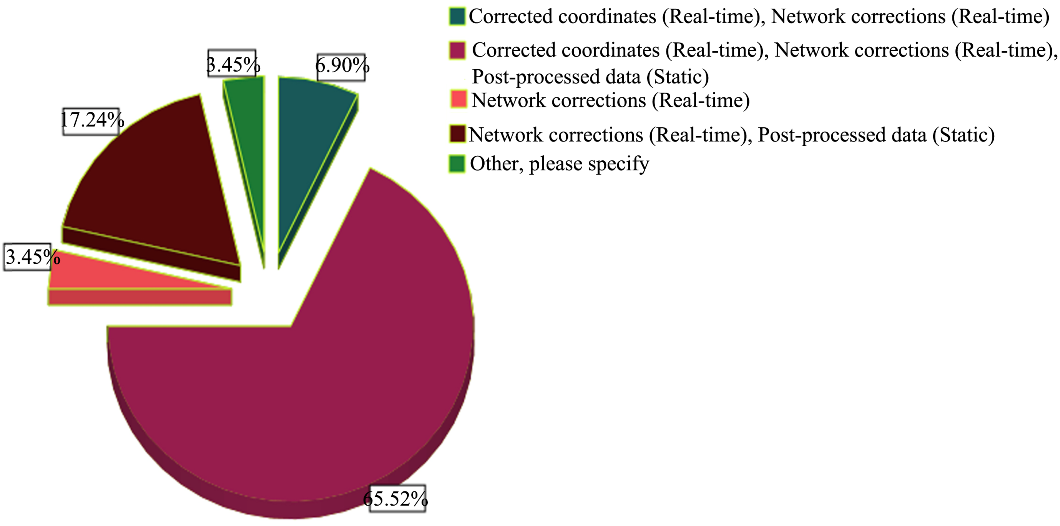

Figure 9. Products of GNSS-RTN available to users.

Moreover, some statewide RTN systems also provide the following products (responded as Other):

- Virtual Rinex
- User statistics
- Real-time & historical tracking of rovers for clients
- Online post-processing solutions
- Observation streams for science and industry

6) Level of Accuracy

The main purpose of establishing the GNSS-RTN system is to offer highly accurate location services. Besides gaining information about products offered by statewide GNSS-RTN systems, a question was asked about the location data accuracy provided by the statewide GNSS-RTN system. Four options were provided: accuracy of *2 - 4 cm*; *4 - 6 cm*; *6 - 8 cm*; *and more than 8 cm*. Twenty-seven out of 30 respondents indicated that their statewide GNSS-RTN system offers an accuracy of 2 - 4 cm as shown in **Figure 10**. Two respondents reported an accuracy of 4 - 6 cm, and one respondent skipped this question. This high percentage of responses (90%) for high accuracy in location data (*i.e.*, 2 - 4 cm) is consistent with the fact that the majority of the statewide GNSS-RTN systems have CORS spacing lower than 70 km as discussed earlier.

7) Number of Users and User Access Charges

The statewide GNSS-RTN system provides highly accurate location services to public and private users. Although the GNSS-RTN location data is currently being used in many applications across multiple disciplines, the number of users is only expected to increase in the future. To obtain information about the users who benefit from the statewide GNSS-RTN, a question was asked about *the average number of users of the GNSS-RTN system in terms of: the total system users*; *users with annual subscriptions*; *and users with less-than-a-year subscriptions.* Responses are summarized in Error! Reference source not found. which shows that Colorado's GNSS-RTN system had the highest number of users, an average of 10,000 total users. The number of users of statewide GNSS-RTN in Ohio, Florida, Michigan, and Minnesota varied in a range from approximately 5000 to 7700. A few states reported equal numbers of total users and annual subscriptions as shown in **Figure 11**, indicating that they only offer annual subscriptions to access the network. Further, many states offer access to system products free of charge thus showing the total number of users only.

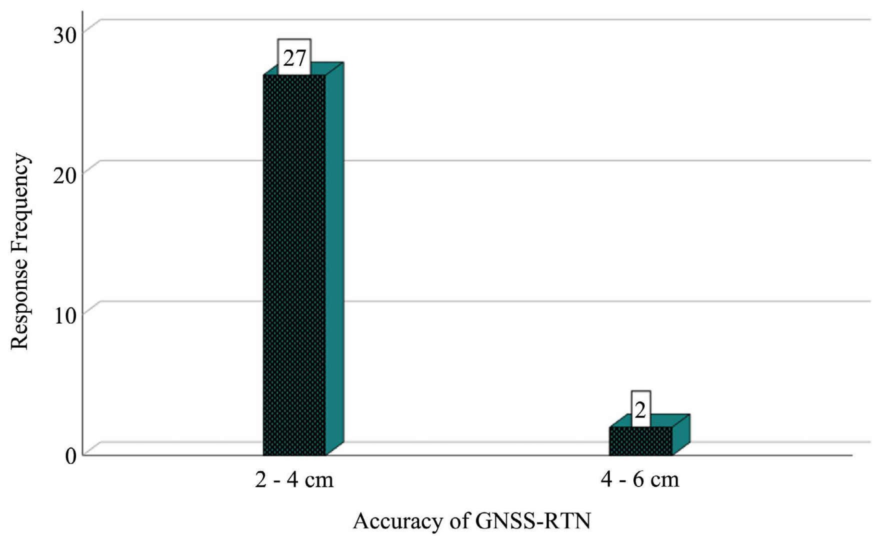

Figure 10. Accuracy of statewide GNSS-RTN system.

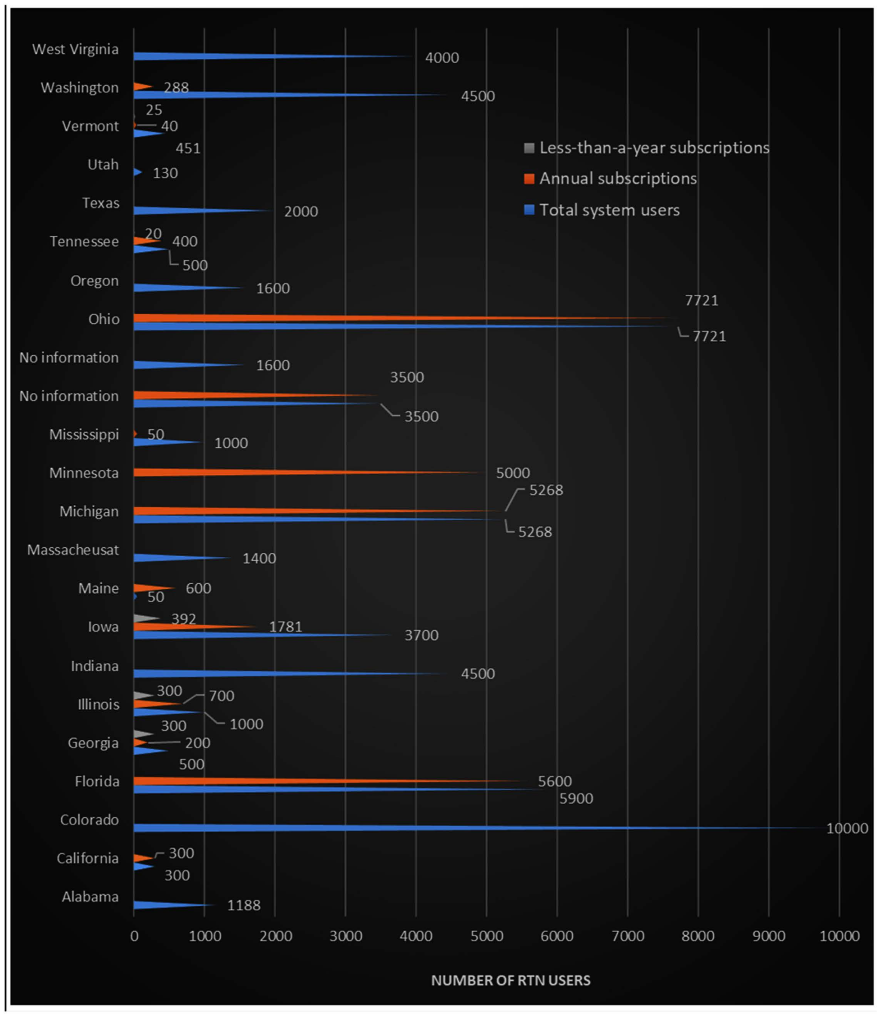

Figure 11. Number of users of statewide GNSS-RTN system.

Given the high operational cost of the GNSS-RTN systems, it is essential to know about the rules and charges of accessing the statewide GNSS-RTN system. The system owners/operators were asked about the *charges of users' access to the statewide GNSS-RTN system with the following options: free of cost; annual subscription fee; less-than-a-year subscriptions fee; charges based on access duration; charges based on data-size download; and others* (*where respondents can write in text*). The respondents were allowed to select multiple options [check all that apply] if they have different rules or packages for different users. The current statewide GNSS-RTN systems differ in their access rules, however, most of the states offer free access to the networks. Approximately 60% of statewide GNSS-RTN systems' access is entirely free of charge for both public and private users. Table 1 summarizes the details of charges/rules for accessing the GNSS-RTN systems in different states. In California, direct access is only available to Municipalities. Public departments can access data from state-owned stations via the partner California Real-Time Network (CRTN). Colorado DOT offers free access to public departments and private users pay an annual subscription fee

Table 1. Rules/charges for accessing GNSS-RTN system.

Charges to Access RTN	Response Frequency	Percent (%)
Annual subscription fee	1	3.6
Annual subscription fee, Less-than-a-year subscriptions fee, Charges based on access duration	1	3.6
Annual subscription fee, Less-than-a-year subscriptions fee	1	3.6
Annual subscription fee, Other, please specify:	2	7.1
Free of cost	17	60.7
Free of cost, Annual subscription fee	1	3.6
Free of cost, Annual subscription fee, Less-than-a-year subscriptions fee	1	3.6
Free of cost, Annual subscription fee, Less-than-a-year subscriptions fee, Charges based on access duration, Other, please specify:	1	3.6
Free of cost, Annual subscription fee, Other, please specify:	1	3.6
Other, please specify:	2	7.1

through private vendors. Similarly, the GNSS-RTN system in Pennsylvania is only accessible for DOT and private users can access private GNSS-RTN based on the subscription fee. The Utah Reference Network GPS (TURN-GPS) requires an annual subscription to access TURN-GPS for location services. The respondents from Washington state reported that users access the network based on annual subscriptions, however, the majority of the users are cooperative partners in the statewide network who have access to the network free of charge. In addition, two respondents selected the "Other" option, one from California and the other from Pennsylvania. The respondent from Pennsylvania reported that access is only provided to DOT employees and private users access private GNSS-RTN systems through subscriptions.

8) GNSS-RTN System Management Costs

As the GNSS-RTN system is comprised of CORSs and the CPC, and multiple owners may exist for different system components, it was important to ask about the entity (or entities) responsible for different operating costs. To learn about the current practice regarding the party responsible for maintenance, IT services, etc., questions were asked about *the party responsible for the cost of the following items*: *user and IT support*; *communication between central facility and CORSs*; *maintenance of the central facility*; *and maintenance of CORSs.* The options provided were: *central facility owner*, *CORSs owner*, *and Others* (*where respondents can write in text*). The results of the responses to these questions are summarized in **Figure 12**. For user and IT support service costs, the owners of central facilities are responsible for this cost in around 64% of all the statewide GNSS-RTN systems. In a few states such as California, Massachusetts, Texas,

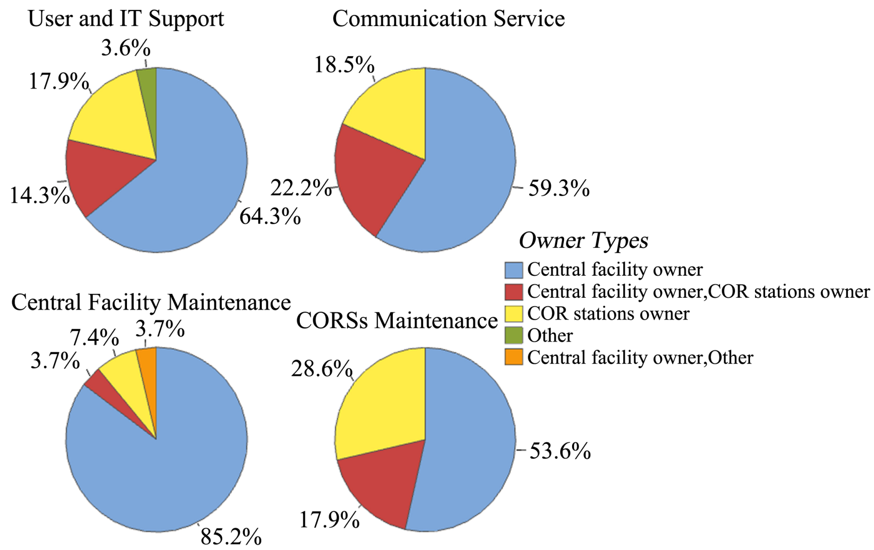

Figure 12. Entity responsible for various costs of RTN system.

and Vermont, the state DOTs are operating statewide GNSS-RTN systems with private partners (who own some CORSs), hence, CORSs owners are also sharing the responsibility of the cost of user and IT support services.

The central facility and CORSs are connected and communicate primarily via the internet, cellular network, or both. These services cost a fair share of the operation costs. Most of the responding states have the central facility owners responsible for the cost of communication services between the CPC and the CORSs, however, around 22% of the respondents reported that CORSs' owners also share the responsibility of the communication cost with the central facility owners. In a few states including Utah and West Virginia, only CORS owners are responsible for the cost of communication between the central facility and the CORSs.

In regard to central facility maintenance costs, the results of the survey indicate that approximately 85% of central facility owners are responsible for the maintenance costs of the central facility. In Texas, both the central facility's owner and CORSs' owners share the responsibility for the cost of maintenance of the central facility. Whereas in Vermont, the central facility owner and the state agency of Digital Services are responsible for the maintenance of the central facility. As for the CORSs' maintenance costs, it is found to be the responsibility of the central facility owners in most of the states (53.6% of total responses). However, CORSs owners are also responsible in several states (28.6% of total responses) such as Colorado, Maine, Massachusetts, West Virginia, and Mississippi. In five states including California, Oregon, Texas, Vermont, and Washington, the central facility owners and CORSs owners are responsible for the maintenance costs of their own CORSs.

9) GNSS-RTN System Revenue

To better understand the business models for GNSS-RTN systems included in this survey, the respondents were asked about the revenues of the GNSS-RTN system from any users' fees or subscription charges. A more meaningful way to know about the revenues of the system is to ask in terms of the total system operation costs covered by users' fees. The owners/operators of the GNSS-RTN system were queried about the revenues collected from users in terms of total system operation costs recovery. The respondents provided information that is quite surprising as presented in **Figure 13**. Most of the state agencies (17 out of 26 respondents) reported revenues generated from users' fees of "*0% of total system operation cost*" which indicates that these states provide access to the statewide GNSS-RTN system free of charge for all users. Two states, Tennessee, and Mississippi recover "*1% to 20% of the total operation cost*" of the GNSS-RTN system from users' fees. The GNSS-RTN system in Arizona, Illinois, and Georgia are privately owned networks (AZGPS, AZ; Kara Co. Inc, IL; eGPS Solution Inc, GA) and reported that users' subscription charges make "60% to 80% of total operation cost", "80% to 99% of total operation cost", and "total cost of system operation", respectively. Furthermore, the revenues obtained from user fees in the states of Louisiana, Utah, and Washington cover the total cost of statewide GNSS-RTN system operation.

10) Funding Sources

Significant resources are required for establishing, operating, and maintaining a statewide GNSS-RTN system. To get information on funding sources of current statewide systems in the United States, questions were asked to specify the funding sources for the establishment of the GNSS-RTN system, its operations, and maintenance, with options provided: *Federal funds*, *State funds*, *Users/subscription fee*, *and Others* (*where respondents can write in text*). Many of the GNSS-RTN systems in responding states were established using state funds (11 out of 27 responses), however, 8 RTN systems also received federal funds along with state funds as shown in **Figure 14**. Only two statewide GNSS-RTN systems were built on federal funds. Tennessee state RTN system was established using

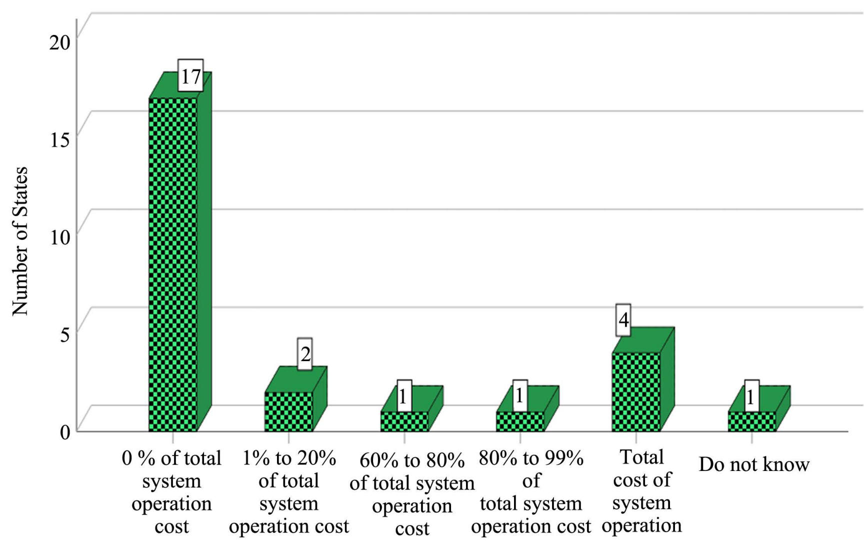

Figure 13. Revenues from user fees/charges as a percent of total system operation costs.

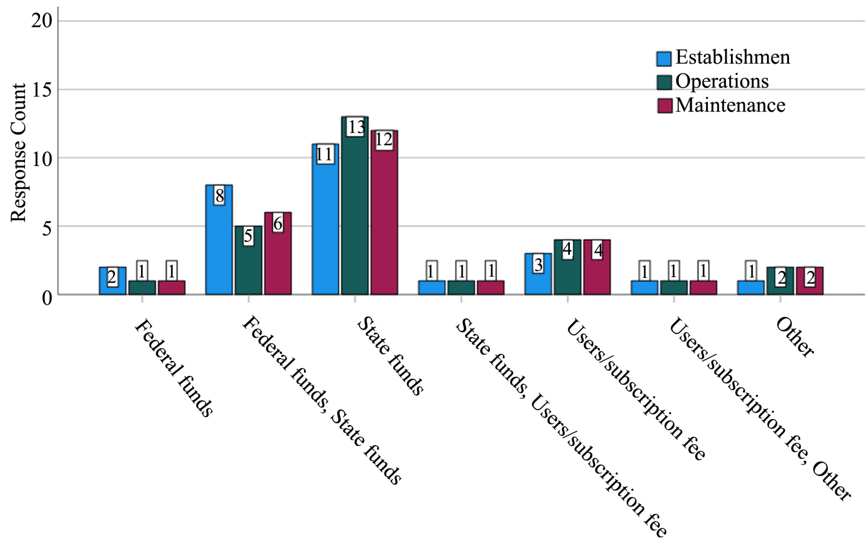

Figure 14. Sources of funds for RTN systems.

state funds and users' fees. The Washington state GNSS-RTN was funded by an initial investment of the Seattle Public Utilities, partners' contributions, and users' subscription fees. "*Other*" funding source reported by a respondent (owner of a private network) from Georgia is "private business ownership for profit".

Regarding funding sources for the operation of the statewide GNSS-RTN system, somewhat similar responses were received. The operating costs of approximately 50% of statewide GNSS-RTN systems were entirely funded by the respective states. Furthermore, 5 out of 27 GNSS-RTN systems (approximately 20%) also received federal funds along with state funds for regular operations. Only Tennessee's GNSS-RTN system operating cost was funded by the state funds and users' subscription fees. The operations of statewide GNSS-RTN systems in Illinois (a private network), Louisiana, Utah, and Arizona (a private network) were fully funded by users' charges. The respondent from Washington state reported that the operating cost of the GNSS-RTN system is mainly funded by users' fees, however, some partners contribute to software upgrades and other miscellaneous costs. These findings are summarized in Figure 14. The GNSS-RTN system requires regular maintenance of CORSs and the central facility. When asked about the funding sources for maintenance purposes, the respondents provided somewhat similar responses as those for the funding source of operation costs. The results are shown in Figure 14.

Most of the statewide GNSS-RTN systems are managed and operated in-house by state agencies. This requires assigning resources and staff to oversee the daily operations of the RTN system. It is essential to know the resources and staff (in terms of full-time equivalent - FTE) required for the in-house GNSS-RTN system operation. Therefore, operators of the current statewide RTN systems in various states were asked about the number of FTE staff assigned to the daily operations of the RTN system. The responses indicated that the number of FTE staff assigned for operating the RTN system varied between 0.75 FTE and 5

FTE. Specifically, around 34% of responses indicated 1 FTE, 21% reported 2 FTE, 25% reported 3 FTE, 8% reported 1.5 FTE, and 4% each for 0.75, 4, and 5 FTE. A summary of the responses to this question is illustrated in **Figure 15**.

GNSS-RTN systems, the GNSS-RTN owners/operators were asked if they included existing CORSs in establishing their statewide networks. The responses are summarized in **Figure 16**, illustrating that 14 out of 25 states (56%) incorporated existing CORSs, 8 out of 25 states (32%) did not incorporate existing CORSs, 2 respondents (8%) reported that there were no existing CORSs in their states, and one respondent selected "Other" option and reported CORSs owned by adjacent states and municipal organizations within the state were incorporated in the statewide GNSS-RTN system.

To learn whether incentives were provided to the owners of the already existing (private) CORSs incorporated into statewide networks, the operators/owners of the 15 statewide GNSS-RTNs that incorporated the existing CORSs were asked if they had been providing any incentives to the owners of the CORSs and the nature of the incentives. Most of the respondents (73%) reported that they did not provide any incentives to the owners of existing CORSs as shown in **Figure 17**. Some states reported providing incentives to the owners of private CORSs in various forms such as unlimited access to data, access to value-added services, one free subscription per CORS, educational opportunities for schools that host CORSs, and reduced subscription charges.

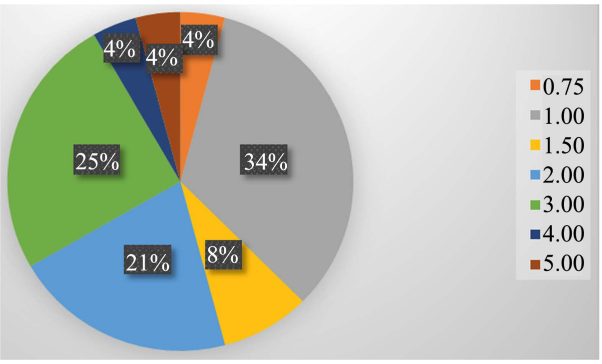

Figure 15. Staff assigned to RTN system for daily operations (In terms of FTE).

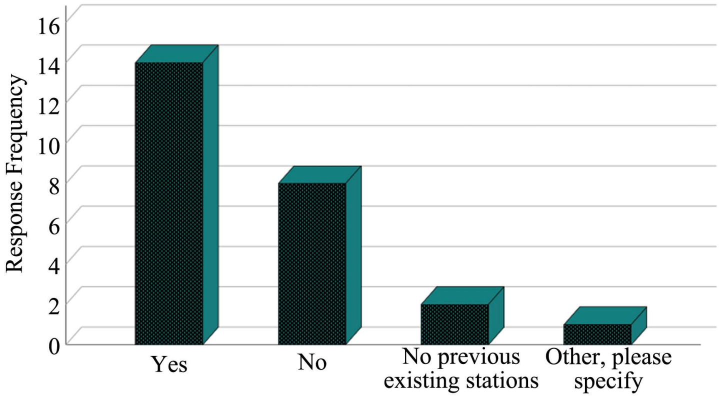

Figure 16. Incorporation of existing CORSs in statewide RTN systems.

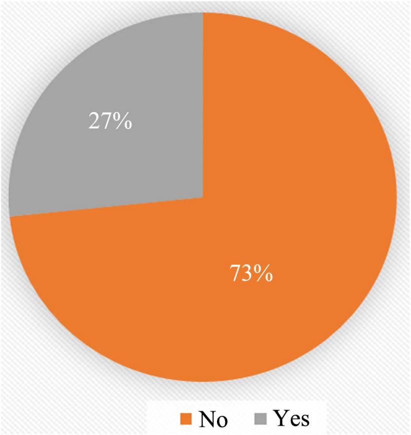

Figure 17. Incentives to owners of private CORSs.

3.2. Business Models for Statewide GNSS-RTN System

This section summarizes the potentially viable business models identified in previous studies, the practice screening survey, and the interviews with the representatives of manufacturers/vendors of GNSS-RTN products and services. The models are numbered in sequence without necessarily following a specific order.

3.2.1. Business Model 1

In this model, the state agency owns the GNSS-RTN system and is responsible for all the costs associated with building and operating the system providing free access to all users.

The main advantage of this business model is that the state has full control over the system (the state has almost full ownership of the system). However, the state is responsible for all costs associated with building, operating, and maintaining the system. This model has the potential to improve user engagement by providing end users with free access to all data and system products. The study conducted by Caltrans in 2015 estimated a total annual cost of the statewide GNSS-RTN system equivalent to roughly $580,000, and an annual benefit equivalent to roughly $38.5M [15].

3.2.2. Business Model 2

In this model, the state owns the CPC facility and part of the CORSs within the state while other CORSs are owned by other state partners including private entities. Operation and maintenance costs are borne by the owners of system components, *i.e.*, the state is responsible for operating and maintaining the CPC and state-owned CORSs, while other partners are responsible for maintaining their CORSs.

Being the owner of the majority of the system infrastructure, allows the state to have good control over the network. This model involves a public-private partnership in which private entities own, operate, and maintain the remaining CORSs needed to complete the statewide network. The public-private partnership requires agreements in place between the state agency and all other system partners. Similar to the first model, this model provides access to all system users free of charge, which can potentially increase the number of end users.

3.2.3. Business Model 3

This business model shares a great deal of similarity with business model 2 except that the public agency which owns and operates the CPC does not necessarily own any notable portion of the CORSs network. The Washington state CORS network, called the Washington State Reference Network (WSRN), is owned by a cooperative of more than 80 partners (cities, counties, utilities, state agencies, and private partners). The Seattle Public Utilities (SPU), one of the partners in the cooperative, owns the CPC and is responsible for its operation and maintenance costs. Operation and Maintenance costs for each CORS are the responsibility of that station's owner [20].

In this model, an entity can be a partner of the cooperative by providing, operating, and maintaining one or more CORSs. Similar to the previous two models, a public agency is responsible for addressing any technology-related cost of the network and to implement, operate, and maintain the CPC. This model also requires agreements between all partners of the network and the operating agency. The strategy used to deliver data in this model differs from the first two models by requiring an annual subscription fee for all non-partner end users. The revenues generated by the paid subscriptions are used to cover some of the operating costs of the network. The level of control the state has over the system is still reasonable (but less than the previous two models) given that a public agency is operating and maintaining the CPC.

3.2.4. Business Model 4

In this business model, the state agency has full ownership of the system, *i.e.*, the CORSs network and the CPC, however, the system is operated using a private company/corporate. All costs associated with operating and maintaining the system are the responsibility of the state agency. This was one of the business models proposed by GNSS-RTN manufacturers/vendors to the state of Iowa as part of planning the statewide GNSS-RTN system [21]. This model is very similar to business model 1, except that the state would use a private vendor for operating and maintaining the system.

Similar to business model 1, this model involves considerable initial and annual costs borne by the state. As the system is completely owned by the state, the state maintains a high level of control over the system. Contracts and/or agreements between the vendor and the state agency are required. User engagement is estimated to be high with this model, as users have access to system products free of charge.

3.2.5. Business Model 5

This model suggests a strong public-private partnership with a vendor, in which the vendor installs all remaining CORSs needed to complete the network and utilizes its own CPC to process and deliver location data to end users. In this model, it's the vendor's responsibility to cover all costs of the CPC and vendor-owned CORSs, leaving only the operating and maintenance costs of other CORSs as the responsibility of CORSs owners. This model also considers a subscription/user fee as a source of revenue for the vendor. While this model requires negligible initial investment and annual costs by the state, it also provides the state with lower control over the network. This model was reported of being used in Australia and the United Kingdom [22].

3.2.6. Business Model 6

This business model is based on public-private partnership and was discussed as part of the interviews with the technology vendors/manufacturers' representatives (Leica and TopCon representatives) [10]. In this model, the state would establish the CORSs network (alone or with partners) while the private vendor would host and manage the network using their infrastructure. The state network in this model would contribute to the private vendor network, and in return, the vendor would provide the state agency with access to the network data and services in the form of an agreed-upon number of network subscriptions. The agency in this model has the freedom to use those subscriptions in any way they see fit including selling some subscriptions to private users. One variation of this model is for the state to control access to the network by purchasing additional subscriptions at discounted prices and selling those to "other" users usually at a higher market price.

The main advantage of this business model is the use of a CPC that is owned, operated, and maintained by a private vendor, to host the network. This will remove a significant proportion of the initial and running costs that would otherwise be borne by the state agency. However, this requires the state to have agreements with owners of existing CORSs (and may have to provide incentives in the process) and build the remaining CORSs needed to complete the network. While this model significantly reduces the amount of state investment in the GNSS-RTN system, it provides the state with a lower level of control over the system.

3.2.7. Business Model 7

This business model is also based on a public-private partnership that was discussed during the interviews with technology vendors' representatives [10]. In this model, the state would establish the CORSs network (alone or with partners) and will be responsible for the costs of operating and maintaining the network. The vendor would host and manage the network using their infrastructure but with full state control on operating the statewide network. The state network in this model will not be incorporated/added to the vendor's private network, and the vendor has no access to the state network. The state will pay the vendor annual fees for hosting and managing the network using a fixed-term agreement. The state is free to decide who can access the network and can impose fees for different products and user types within the state.

This business model shares many similarities with the previous model in regard to the ownership of the CORSs network and the network hosting infrastructure. The CORSs needed to complete the network are implemented, operated, and maintained by the state (alone or with partners), and the vendor uses its infrastructure to host the network. The operating costs of the system including network hosting costs, which are borne by the state, could be significant.

3.2.8. Business Model 8

In this business model, a technology vendor would establish, operate and maintain the GNSS-RTN system and provide hosting and management services through their own networks. The vendor would develop and use a business model for marketing the positioning data services to end users including public and private entities. In this model, the system is 100 percent owned by the vendor and the state plays no role in establishing, operating, and maintaining the system. A variation of this model is to have a consortium of private companies as the owners and operators of the GNSS-RTN system instead of a single technology owner such as the CORS-RTK network across the whole of France [22].

The main advantage of this model is the lower financial responsibility for the state. Like other end users, state agencies would need to purchase subscriptions to satisfy their GNSS-RTN data needs. However, this model provides no control to the state over the system, which may not serve the best interests of the state (e.g., inconsistent or incomplete geographic coverage of the state).

3.3. Selection of Business Models: Major Considerations

Three major factors are believed to influence the adoption of a business model for establishing and operating a statewide GNSS-RTN system. These factors are:

1) State control over the system,

2) Sustainability of the business model, and

3) Costs borne by state/agency.

State control refers to the level of control the state has on the prospective GNSS-RTN system being planned and built to align with the state's best interests [23]. The ownership of the GNSS-RTN infrastructure largely determines the level of control a state agency has over the statewide GNSS-RTN system. The ownership combination of system components varies among states, partners, and vendors, and so does the level of control the state has in each of the models. Similarly, a sustainable business model refers to a model that would help the state maintain and provide the desired level of location data service over time within available resources. For sustainability, the lower the running costs the higher the sustainability of the system. Furthermore, having user access charges would help the state recover all or some of the operating and maintenance costs, which should result in improved sustainability. Similarly, the financial obligation of the state towards the initial operating costs of a GNSS-RTN system is a major consideration in the selection of the most appropriate business model to best serve the agency's goals and interests.

4. Findings and Recommendations

This paper presented the results of state-of-practice screening to document the current practices in building, operating, and managing the GNSS-RTN systems both nationally and internationally. The study involved a thorough literature review, a practice survey for owners/operators of GNSS-RTN systems in the US, and interviews with major vendors of GNSS-RTN products and services in the US.

The major findings of this study are summarized below.

- The practice survey revealed a great deal of inconsistency among states in the way the GNSS-RTN systems are built and operated. The lack of national guidance in this regard could partly be behind the lack of uniformity in states' current practices.
- Most of the statewide GNSS-RTN systems surveyed are public with the majority being owned and operated by the state Departments of Transportation (DOTs). Only three networks (10% of the systems surveyed) are owned and operated by private entities. Around 86% of these systems provide coverage throughout the whole state geographic area.
- Approximately, 90% of statewide GNSS-RTN systems in the U.S. are based on CORSs with an average spacing of fewer than 70 km thus providing highly accurate location data (2 - 4 cm accuracy).
- Around 60% of the GNSS-RTN systems surveyed offer entirely free access to both public and private users (17 out of 27 respondents). However, private networks as well as some of the state-owned networks charge user access fees. Products delivered to users are in the form of corrected coordinates (real-time), network corrections (Real-time), post-processed data (Static), and occasionally virtual Rinex.
- The owners of central processing centers are responsible for user and IT support service costs in approximately 64% of the GNSS-RTN systems surveyed. In addition, the central facility owners are generally responsible for the cost of CPC maintenance. In many instances, the CPC owners are also responsible for the cost of communication between the central facility and CORSs (around 60% of the systems surveyed).
- The funding sources for the establishment of the public GNSS-RTN systems surveyed are either only state funds or some federal funds along with state funds. However, the funding sources for the daily operation of GNSS-RTN systems are state funds and/or users' fees.
- Two-thirds of the systems surveyed (67%) reported staffing needs equivalent to 2.0 FTE or fewer for day-to-day system operations.
- Approximately 50% of the systems surveyed did incorporate the already existing CORSs in their networks. Some states provide incentives to the owners of private CORSs in various forms such as unlimited access to data, access to value-added services, free subscriptions, and reduced subscription charges.
- Eight different business models of a statewide GNSS-RTN system are cata-

loged with detailed descriptions. Three main factors are identified that influence the adoption of any specific business models for a statewide GNSS-RTN system. These factors are: state control of the GNSS-RTN system, sustainability of the business model, and costs borne by the state/agency.

The role of the GNSS-RTN system will only be increasing in the future and state governments are expected to play a bigger role in assuring that high-precision GNSS data with reasonable sampling rates are available throughout their jurisdictions. Although more than half of the states have already established statewide (or partial) GNSS-RTN systems, the geographical coverage of all the states is a major hurdle for some applications. The fact that many of these applications concern the public domain (e.g., highway transportation), the federal government is also expected to play an active role in helping states achieve full implementation of the technology in time to support some of the advanced emerging applications (e.g., autonomous vehicles). Part of this role is for the federal government to publish and provide technical assistance on system interoperability standards to allow for an effective national network. The authors also recommend further research into the economic benefits of the GNSS-RTN data for existing and future applications which would help the states in making appropriate decisions in embracing the technology and in updating and expanding the existing networks. This study is focused on GNSS-RTN systems only in the U.S. which is a major limitation of this research. The authors recommend performing a similar study at a global level and synthesizing a comprehensive report on current practices of GNSS-RTN systems in different countries.

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Conflicts of Interest

The authors declare no conflict of interest.

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