The NOAA CORS Network (NCN): A brief history and current status

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SUMMARY

The United States Department of Commerce's National Geodetic Survey (NGS) assembles and manages the multi-purpose, multi-agency, cooperative, GPS/GNSS continuously operating reference station (CORS) network called the NOAA CORS Network (NCN). The NCN is a cooperative effort of more than 200 federal, state, academic, and private organizations, providing publicly accessible GPS/GNSS data from more than 2000 CORS, supporting post-processed positioning activities throughout the United States and its territories. 98% of these stations are owned and maintained by NCN partners. The contributing partners freely share their GNSS measurements and station information with NGS in accordance with NGS's guidelines. NGS analyzes and archives the NCN data, and distributes it free of charge.

Since its inception in 1994, the NCN has evolved into a vital national resource that provides critical positioning information for a wide range of applications, including surveying, construction, mapping and more. The NCN has undergone significant expansion over the years, with improvements in equipment and data delivery. This paper will examine the key milestones in the NCN's history and the current state of the network.

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1. BRIEF HISTORY

The United States National Geodetic Survey (NGS) is a component of National Oceanic and Atmospheric Administration (NOAA) under the Department of Commerce (DOC). NGS traces its roots back over two centuries to the Survey of the Coast, which was established in 1807 as the first scientific agency of the US government to provide surveying and mapping services for the coastal regions of the country. It was later renamed the US Coast and Geodetic Survey (C&GS) in 1878 and then the National Ocean Service (NOS) in 1970. The C&GS component responsible for geodetic functions became known as the NGS. Over time, NGS has expanded its role to include establishing the National Spatial Reference System (NSRS) - the foundation for accurate positioning information for mapping and surveying purposes. NGS provides geodetic controls and support for other government agencies and private organizations.

Before 1994, the NSRS consisted of discrete geodetic elements including horizontal positions in latitude and longitude, or State Plane Coordinate's northing and easting, referenced to the two-dimensional North American Datum of 1983 (NAD83 (1986))[1] , and elevations in Helmert orthometric heights, referenced to the one-dimensional North American Vertical Datum of 1988 (NAVD88). These geodetic systems were developed independently, meaning that a survey monument providing accurate horizontal coordinates was not typically connected to the vertical network, nor were the elevation stations related to the horizontal reference network. Many "high accuracy" triangulation survey stations were located in remote, GPS-unfriendly areas such as mountain peaks. Easily accessible national survey control points were usually of "low accuracy", and/or had short lines-of-sight to nearby survey stations due to obstruction by radio towers, tall buildings, or similar objects. With GPS accuracy improved, the errors and misalignments in NAD83(1986) became increasingly noticeable. In the early 1990s, NGS began to reconsider its traditional approach to making the NSRS available to the nation.

Starting with Tennessee in 1989, NGS, in partnership with various institutions, worked with each state to establish regional reference frames using GPS technology, consistent with the NAD83. These GPS control points, known as the High Accuracy Reference Networks (HARN), were located in more accessible areas with less obstructed view of sky, as compared

[1] While the North American Datum of 1983 (NAD83) is 3-D in scope, NGS adopted only horizontal coordinates (latitude and longitude) for over 99% of the approximately 250,000 horizontal control points.

to the traditional “high accuracy” triangulation marks. Once a state’s HARN survey was completed, NGS conducted a statewide adjustment of the data, combining it with all archived classical geodetic surveys and local GPS projects to compute consistent positional coordinates for the associated ground mark (Snay and Soler, 2008). The establishment of the NAD83(HARN) datum demonstrated the clear need for easily accessible and highly accurate control stations to support the NSRS. Following extensive discussion in the early 1990s, NGS made the decision to set up a system of national GPS reference stations to support the HARN initiatives and local surveys, estimating the need for 100-150 sites to cover the contiguous 48 states in a 200-km grid (Spofford and Weston, 1998).

Establishing such a GPS reference station system was a significant financial challenge for NGS, as geodetic quality GPS receivers cost by then between $35,000-$50,000 each. At the same time, several federal agencies also sought to build networks of GPS base stations. The U.S. Coast Guard aimed to upgrade its radionavigation system using DGPS to enhance safe marine navigation, while the U.S. Army Corps of Engineers sought a cost-efficient navigation system for their inland waterway operations. To reduce expenses for the federal government and taxpayers, the U.S. General Accounting Office directed NGS, USCG, and USACE to coordinate their activities and equipment procurement. NGS played an advisory role, helping USCG and USACE define the necessary receiver specifications to support all three agencies’ missions.

In February 1994, NGS initiated the Continuously Operating Reference Station (CORS) network with its first site, GAIT, by Trimble Navigation Corporation at the National Institutes of Standards and Technology in Gaithersburg, Maryland, on a long-term loan. Five months later, in July 1994, NGS added the second station, TMGO, at Table Mountain, Colorado. Figure 1 shows the five stations that comprised the NCN by the end of 1994.

Figure 1: The NCN in 1994, including 05 stations: GAIT (Apr 1994 - Dec 2009), RCM5 (Jun 1994 - Oct 1996), WES2 (Jun 1994 - present), TMGO (Aug 1994 - present), and PIE1 (Dec 1994 - present)

In 1995, the USCG started installing GPS receivers at their sites and finished by 1996 with around 50 stations along the coasts. NGS and USCG signed an agreement where USCG would provide data from these stations for the CORS network and NGS would provide the positioning for these stations.

The NCN gradually incorporated other federal, state, and locally sponsored CORS stations from 1995 onwards. The Texas Department of Transportation was the first state agency to join, bringing 10 well-established stations from the TX Regional Reference Point network, which greatly expanded coverage in Texas. By making contact with these agencies and arranging to exchange data, NGS expanded the NCN to 143 sites by January 1998. By 2000, the NCN had 247 operating stations, surpassing the 100-150 sites milestone. As depicted in Figure 2, the NCN has undergone significant growth since its inception, with the addition of numerous new stations over the years. As of now, the network has expanded to include over 2800 stations, a remarkable increase from its initial size of just five stations in 1994.

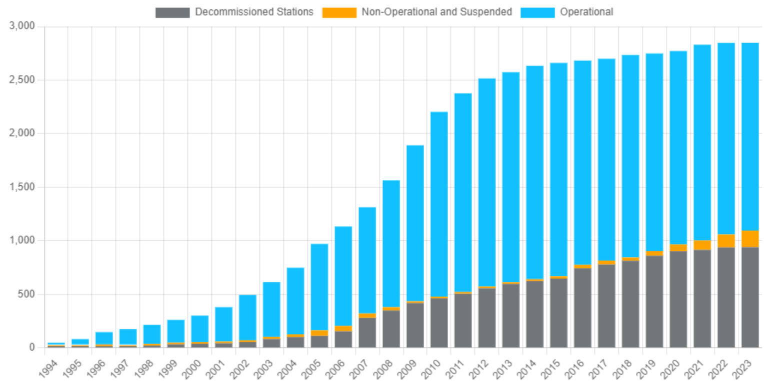

Figure 2: NCN since 1994. The NCN as of February 21, 2023: 2848 stations in total, in which:

- 1759 stations are currently providing data, classified as Operational,
- 149 stations are either Non-Operational or Suspended, i.e., haven't provided data in the last 30 days, and
- 940 stations were Decommissioned. NGS has permanently stopped ingesting data from these stations.

2. OVERALL POLICIES

Throughout the years of operation, NGS has developed a series of operating policies to ensure smooth operation. Some of these policies have been in place since the early days of the network, while others have been evolved and established in response to the growth of the network and requests from NCN providers.

- The NCN stations are independently owned and operated by individual operators who are responsible for providing and maintaining all necessary equipment. NCN station operators are also expected to share their data with NGS.
- It is important for the NCN station operators to keep NGS informed about any planned outages, changes in equipment and firmware, especially changes related to the

antenna, radome, and physical space surrounding the antenna. This information should be communicated to NGS, as soon as it is known to the operator.

- In order to maintain high data quality, an NCN station is expected to have a lifespan of at least 15 years, and this should also apply to the critical volume of space or ground surrounding the antenna. This area should remain undisturbed throughout the lifetime of the station.
- NGS is committed to making GNSS data from the NCN available to the public free of charge, and provides data in the RINEX format standard. All data collected from NCN stations are stored online, starting from the launch date of the station.
- NGS will provide station coordinates and velocities referenced in the NSRS.

3. DATA COLLECTION AND RETENTION POLICIES

The NGS/CORS branch is responsible for overseeing the collection and distribution of all NCN data. Within the CORS branch, the CORS Data Management Team (DMT) is tasked with retrieving the GNSS/GPS observations data directly from stations or from provider data centers, converting them to the Receiver INdependent Exchange (RINEX) format if necessary, performing quality assurance checks, and uploading the files to various storages for distribution.

- NGS must be able to retrieve GNSS/GPS observation data via the Internet;
- All file names and associated dates must be recorded with respect to GPS time, not local time;
- Directory structure at a remote station must follow the RINEX file name convention, and shall be placed in either:
    - /base_directory/native/yyyy/ddd/ssss/<RINEX-file-name > for raw and/or proprietary format;
    - /base_directory/rinex/yyyy/ddd/ssss/<RINEX-file-name> for RINEX format;
- The GNSS data collected at NCN stations are made available to the public by NGS in RINEX format;
- Hourly files, which comprise one hour of data from a remote station, are collected every hour and typically made available within minutes after the end of the hour. However, these hourly files are only retained for two days;
- Daily files, comprising a continuous 24-hour record of data from 00:00 to 23:59:59 in GPS time, are either collected directly from remote stations or merged from available hourly files. These files are made available for download from NGS servers within a few minutes to a few hours following the end of the UTC Day. They are kept permanently and available in two formats:
    - GNU gzip-compressed of data in the Hatanaka-compression RINEX format;
    - GNU gzip-compressed of data in RINEX format.

    However,
    - After 30 days, daily files are decimated to 30s sampling rate;
    - After 06 months, only gzip-compressed files of daily data in Hatanaka-compression RINEX format are provided.

- For RINEX version 2 data, NGS utilizes UNAVCO's TEQC software on incoming data for quality checking purposes. Quality of daily data generated by TEQC -qc command are stored with daily data files.
- Navigation data files are available only for sites that NGS submits to the IGS network.

Meteorological data files are available only for sites with meteorological sensors (MET packs) attached to GNSS receivers.

4. PRODUCTS AND ACCESS

NGS offers public access to all data that has been collected from the NCN since February 09, 1994, which includes GNSS/GPS observation, daily broadcast ephemerides, station logs, and NGS-published coordinates and velocities for each station. All data obtained through the NCN are available to the public via the Internet.

The NCN Data Flow is illustrated in Figure 3, which outlines the various pathways through which users can access GNSS/GPS observation data collected from the NCN. One way to obtain NCN data is by downloading it directly from the station providers, who are responsible for collecting and archiving the data at each individual station. This approach is often preferred by users who require real-time or near-real-time data and need to access the most current information available.

Alternatively, users can access NCN data through various online storage options provided by NOAA/NGS and other sources, including:

- NOAA-NCN bucket on AWS at: https://noaa-cors-pds.s3.amazonaws.com/index.html via NOAA Open Data Dissemination Program (NODD).
- NGS server: https://geodesy.noaa.gov/corsdata/
- The National Centers for Environmental Information (NCEI) via NOAA's Comprehensive Large Array-data Stewardship System (CLASS) information technology system for downloading original at-sampling rate RINEX data from 2004 to present (30-day delay), at: https://www.avl.class.noaa.gov/saa/products/search?datatype_family=CORS

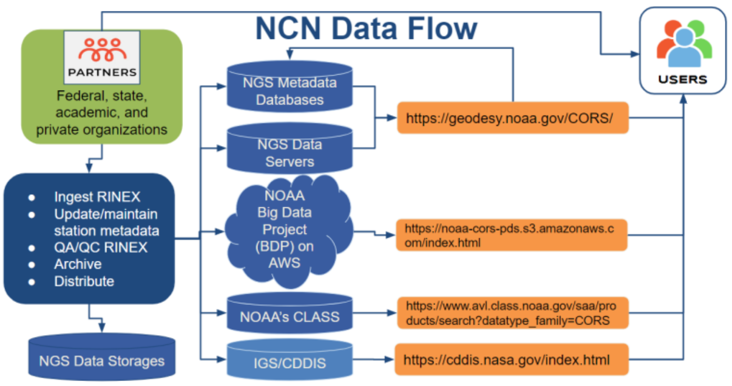

Figure 3: NCN Data Flow.

These online storage options offer users a convenient and reliable means of accessing historical and current data from the NCN. Additionally, a limited number of NCN stations also function as IGS (International GNSS Service) stations, which means that their data can be accessed through the IGS/CDDIS data center.

5. PARTICIPATING AGENCIES

The NCN is a collaborative effort between a diverse range of organizations including federal, state, and local governments, academic institutions, and private industry. This representation provides a broad range of expertise and ensures that the NCN is not reliant on any single agency, communication system, or type of equipment. However, this diverse participation requires closer communication with all involved parties.

As of February 22, 2023, NGS has received contributions from 223 organizations, resulting in a total of 2848 stations. The contributions from these organizations have been distributed across various partner types, each making a significant contribution to the overall size and scope of the network.

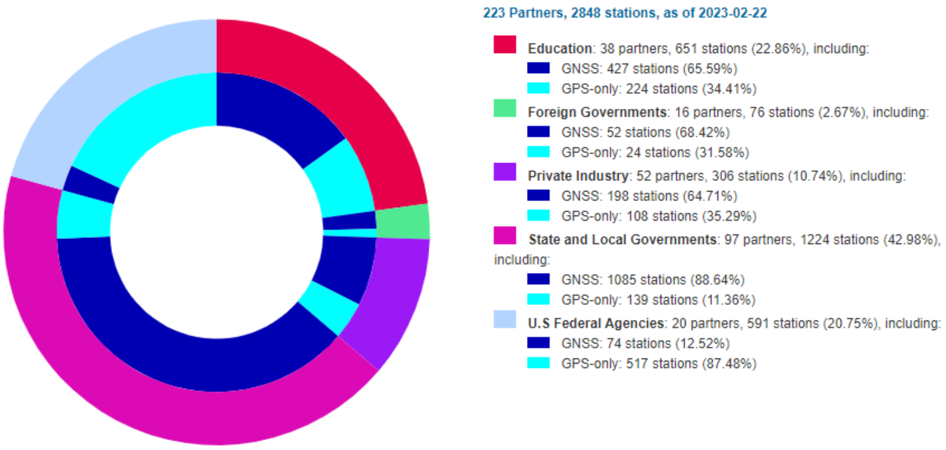

Figure 4: NCN Partners as of February 22, 2023.

The NCN's top 10 contributors are listed in Table 1. The Texas Department of Transportation was the first state agency to join NCN in 1996 and is the third highest contributor with 181 stations. The U.S. Coast Guard is the second highest contributor with 394 stations, however it had switched off the last Differential Global Positioning System (DGPS) signals on June 30, 2020, after more than 25 years of service. It is clear that state and local governments are the top contributors to the network, accounting for the largest portion of stations and demonstrating their commitment to supporting this critical infrastructure.

Responsible Agency	**Total**	**Op.**	**Non-Op.**	**Sus.**	**Decom.**
UNAVCO	502	385	117	2	18

U.S. Coast Guard (USCG)	394				394
Texas DOT	181	147			34
Michigan DOT	108	98	3		7
SmartNet North America	103	76	4		23
North Carolina Geodetic Survey	96	74	1		21
Missouri DOT	92	71			21
Ohio DOT	66	48			18
Minnesota DOT	61	48	5	1	7
U.S. National Geodetic Survey	56	24	12	2	18

Table 1: Top 10 NCN contributors.

It's worth noting that 125 partners (56% of all NCN partners) have contributed just one station each. Examples include the Indiana University Bloomington, who contributed the IUCO station in May 2000, and Lake County, Illinois who contributed the LCDT station since October 2001. Meanwhile, NGS owns and operates 56 stations in total, accounting for approximately 2% of the total stations in NCN. Among these, there are 23 GNSS and 1 GPS stations classified as Operational, 12 Non-Operational, 2 Suspended, and 18 Decommissioned stations.

Regardless of the number of stations each partner's contribution to the NCN, each contribution is important and valuable for enhancing the quality and accuracy of the NSRS.

6. CURRENT STATUS

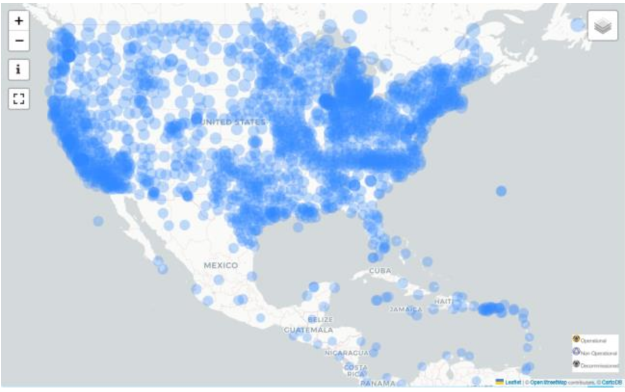

Figure 5: NOAA CORS Network 70-km coverage on mainland

Figure 5 illustrates the geographic contribution in the lower 48 states of the United States. The NCN stations are concentrated along the coastlines, with many stations located in states such as California, Texas, Alabama, Florida, New Jersey, and New York. These states have a high density of stations due to their location and the importance of the ports, shipping, and transportation infrastructure. The network is heavily congested in states such as North Carolina, Tennessee, Missouri, Michigan, and Indiana due to their population, infrastructure and economic importance. On the other hand, the network is thin in the mid-western states such as North Dakota, Montana, South Dakota, Wyoming, Colorado, and Kansas due to their lower population density and less infrastructure.

As of February 23, 2023, the NCN has a total of 2848 stations. Among these, 1756 stations (approximately 61.76% of the total NCN stations) are actively providing RINEX data in the last 30 days and are classified as Operational stations. However, there are 144 stations that have not been providing data for the last 30 consecutive days and are classified as Non-Operational. Additionally, NGS has temporarily suspended data ingestion from 8 stations with known issues for long durations. The station providers and NGS's CORS branch are collaborating to identify reasonable solutions for these stations. A total of 940 stations are classified as Decommissioned from which NGS has permanently stopped ingesting data.

The classification of NCN stations by operating status is illustrated in Figure 6, which provides a visual representation of the distribution of operational, non-operational, suspended, and decommissioned stations across the network.

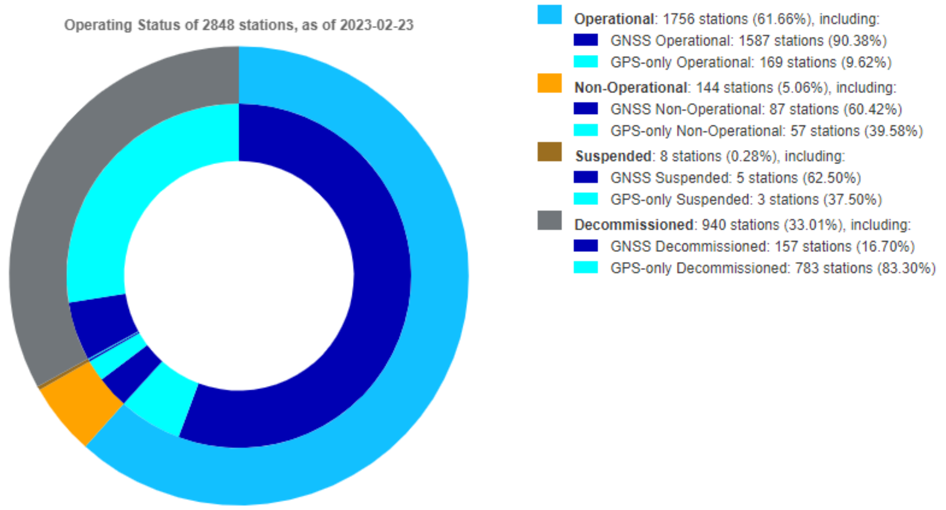

Figure 6: NCN by operating status.

Out of the total 2848 NCN stations, approximately 61.66% or 1587 stations, are classified as Operational and are providing GNSS observations data. Within this group, 782 stations are tracking GPS+GLONASS constellations, 779 stations are tracking GPS+GLONASS+Galileo constellations, and a few stations are also tracking Beidou and regional constellations like

QZSS. The ability to track multiple constellations is particularly important for high-precision positioning applications, as it allows for improved accuracy and availability of signals. Figure 7: NCN by supported satellite constellation, illustrates the distribution of NCN stations across the different satellite constellations. As shown in this figure, there are 169 Operational stations providing GPS-only observations. The majority of these GPS-only stations are over 10 years old. The oldest and most remarkable station is UNAVCO's SEDR located in Washington state, which has been in operation for 25 years and remains stable and functional.

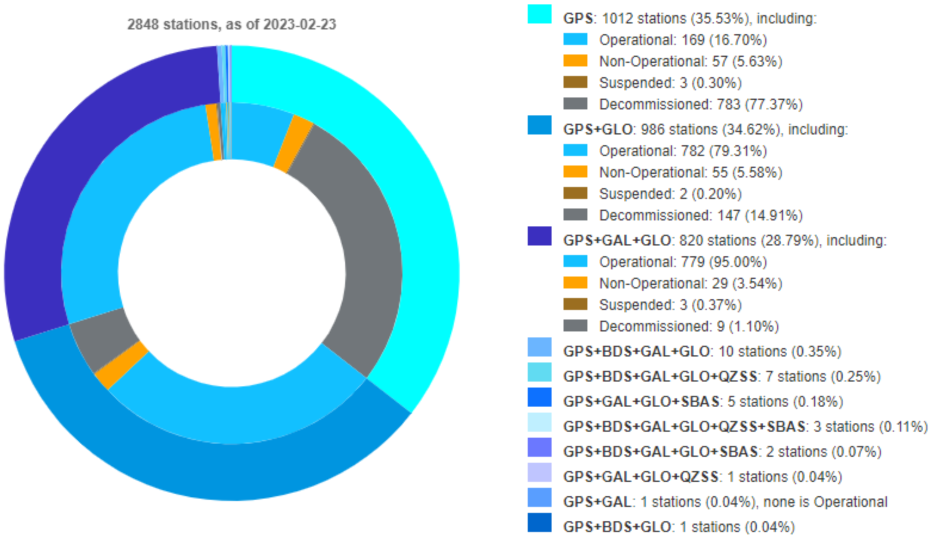

Figure 7: NCN by supported satellite constellations.

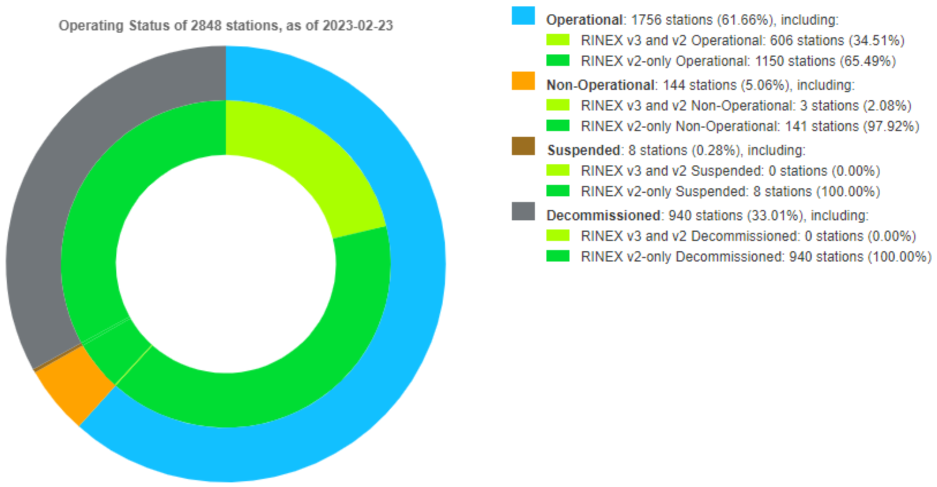

Figure 8: Available RINEX products from the NCN.

The GNSS/GPS observation data from NCN stations is available in different formats, and Figure 8 categorizes these stations based on the RINEX products they provide. Since 2020, NGS has been gradually collecting RINEX v3 data and making it available to the public via NGS's web servers at https://geodesy.noaa.gov/corsdata/beta/rnx/ . Out of the 1756 stations that are currently producing RINEX data, 606 stations (~34.51% of the Operational stations) provide both RINEX v3 and RINEX v2 data. In cases where stations only offer RINEX v3 data, NGS converts it to RINEX v2 and archives both formats. At present, there are 1150 Operational stations (approximately 65.5% of the total Operational stations) that NGS retrieves RINEX v2 data only. NGS is working on the RINEX v3 QA/QC workflow for quality control, and collaborating with the station providers to introduce more RINEX v3-capable stations to NCN.

Approximately 42.56% of the total 2848 NCN stations, or 1212 stations, provide data at a 1-second sampling rate. Of these, 943 stations are Operational, accounting for 53.7% of the 1756 Operational stations. Additionally, there are 562 Operational stations that provide data at a 15-second sampling rate, and 69 Operational stations provide data at a 30-second sampling rate. Figure 9: NCN by Sampling Rate (seconds) provides further information about each operating group.

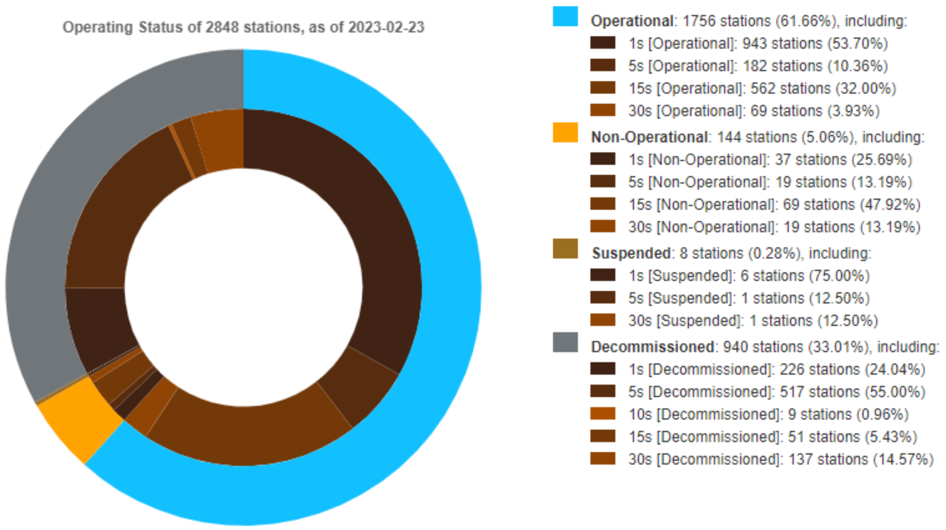

Figure 9: NCN by Sampling Rates (seconds)

According to Figure 10, the majority of the 1756 Operational stations in the NCN collect data on an hourly basis, accounting for 74.72% or 1312. On the other hand, 442 Operational stations collect data on a daily basis. It is worth noting that only four stations, all owned by NGS: ASPA, PRMI, NYBP and NPRI collect data on a 30-minutes basis, in which NYBP is classified as Non-Operational due to missing data since June 17, 2022, and NPRI is suspended due to missing data since October 04, 2021. ASPA is currently providing both RINEX v2 and v3 data.

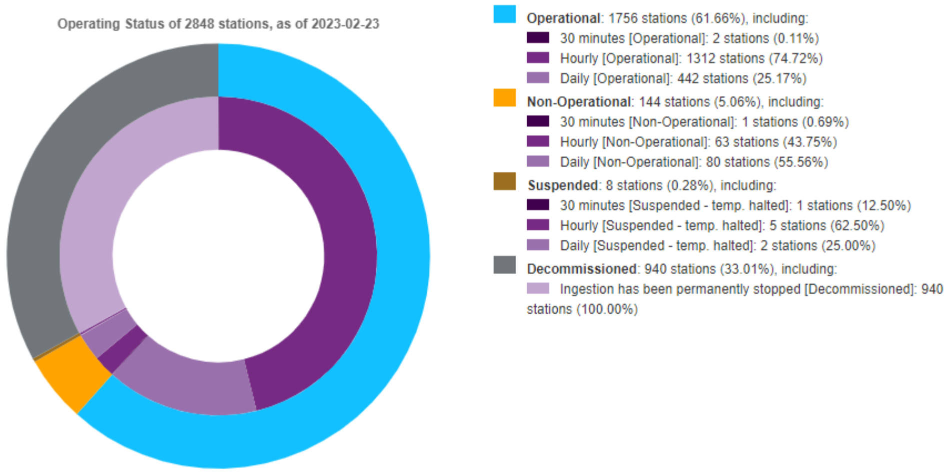

Figure 10: NCN by Ingestion Frequency

7. NOAA FOUNDATION CORS NETWORK (NFCN)

As previously mentioned, the NCN stations are installed and operated by different collaborators, resulting in varying configurations to meet specific application needs, and may be disconnected at any time. To ensure a long-term consistency between the NSRS and the International Terrestrial Reference Frame (ITRF), it is crucial to maintain a set of reference frame sites at the highest standard to archive a robust, enhanced, and long-lasting national reference frame. This set of reference frame sites, classified as the NOAA Foundation CORS Network (NFCN), is designed to provide the reliable "backbone" for the NCN. The positions of all NCN stations that do not belong to the NFCN will be adjusted to the NFCN in order to maintain the integrity of the entire NCN.

The NFCN is a federally controlled network that will ensure a high level of operational readiness. It is considered critical infrastructure and is the result of a collaborative effort between multiple government agencies, including NOAA/NGS, NASA, National Geospatial Intelligence Agency (NGA), and the National Science Foundation (NSF). As of February 23, 2023, there are 25 stations included in the NFCN, which is depicted in Figure 11, illustrating the network's 800-km coverage.

NFCN Performance Goals:

- Formal agreements signed with partners for project support.
- All NGS-owned NFCN are submitted for inclusion in the IGS network.
- Stations provide definitional support for the ITRF and plate rotation models.
- Site surveys conducted to International Earth Rotation and Reference Systems Service (IERS) standards are repeated on a 5-year cycle at each station.
- Target Operational Time:
    - Network availability >90% at all times;
    - Individual station down time < 14 days;

Figure 11: NOAA Foundation CORS Network (NFCN) 800-km coverage. As of February 23, 2023, there are 25 stations in the NFCN.

NFCN Station Guidelines:
To maintain high-quality GNSS data within the target area of the NFCN, every new installation or adoption of an NFCN must adhere to the strict IGS site guidelines and meet the following requirements:

- Collocation: All existing sites that use space geodetic techniques (SLR, VLBI, or DORIS) will have a collocated NFCN station.
- Density: New stations will be installed or adopted to fulfill the spacing criteria of 800 km within the Foundation CORS target area, after the collocation criteria are met.
- Euler: New stations will be installed or adopted to increase the minimum number of NFCN to 3 on each of the 4 tectonic plates of interest, after the above criteria are met.
- Gap Filling: New stations will be installed or adopted on a case-by-case basis to fill any gaps in coverage, once the above criteria are met. Gap coverage outside the United States and its Territories will be done in consultation with the IERS and any appropriate governments.

Funding for the NFCN program has been limited since its inception. However, in 2022, the NFCN program received enough program funding from the Bipartisan Infrastructure Law (BIL) to complete the installation of the remaining NGS's owned NFCN stations. These efforts will begin in the summer of 2023, and we anticipate it taking about four years to complete. During this time, NGS will focus on new NFCN installations, but also upgrading the hardware at existing NGS-owed CORS, as well as looking for opportunities to provide reliability and redundancy in the NFCN.

Also, since FY2020, NGS and NGA started to collaborate on the installation of NFCN stations at ten National Radio Astronomy Observatory's (NARO) Very Long Baseline Array

(VLBA) stations. NGS's responsibility will be to install three braced monuments at each VLBA location, while NGA providing high-rate tracking receivers (HRTR), antennas, cables and lightning protection and grounding systems.

8. CONCLUSION

The NOAA CORS Network (NCN) has continued to expand and improve since its inception in 1994, expanding from just five stations to a total of 2848 stations as of February 23, 2023. As a reliable and free source of GPS/GNSS data, the NCN has become a valuable asset for high-precision positioning and other geodetic applications throughout the United States and its territories.

Out of the 2848 stations, approximately 61.67% or 1587 stations are currently providing RINEX data in the last 30 days, with 61.66% of these stations having the capability to track multiple constellations. The GPS/GNSS observation data from NCN stations is available in various formats, with RINEX v3 data gradually being collected since 2020. Currently, 34.51% of operational stations provide both RINEX v3 and RINEX v2 data. NGS is working on the RINEX v3 QA/QC workflow for quality control and introducing more RINEX v3-capable stations to the network.

This success is thanks to the collaborative efforts of a broad range of organizations, including federal, state and local governments, academic institutions, and private industry. This diversity ensures the network's resilience, as it is not reliant on any single agency, communication system, or type of equipment. To ensure the NCN's continued success, effective communication among all stakeholders is crucial. NCN station providers must recognize their vital role in maintaining the network and must collaborate closely with NGS to ensure its continued success for years to come.

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BIOGRAPHICAL NOTES

John Galetzka is a geologist from California who served in the Army's 2nd Ranger Battalion and studied geological sciences at the University of Oregon. He worked at the US Geological Survey, California Institute of Technology, and University NAVSTAR Consortium, where he built continuous GPS networks and conducted CORS and geodetic imaging projects in various locations. Currently, he is the CORS Branch Chief at NGS and mentors students on using low-cost UAV and RTK GNSS equipment to create maps and models in challenging environments.

Ira Sellars has been working as a CORS Analyst in the NGS/SRSD/CORS branch since April 2019. Prior to this role, she taught cartography and GIS at the University of Social Sciences and Humanities, Ho Chi Minh City, in Vietnam, and conducted research on geovisualization and digital atlas. Sellars later became a Visiting scientist at NGS/RSD under University Corporation of Atmospheric Research (UCAR), and worked as the sole programmer for the NOAA/NOS Vertical Datum Transformation software for nine years.

Will Freeman has been working as an engineer with NOAA since 2004. He was a construction project manager for the National Weather Service and since 2019, he has been working for the National Geodetic Survey (NGS) as the Continuously Operating Reference Stations (CORS) and Foundation CORS program manager. Prior to joining NOAA, Will worked 14 years as an engineer supporting the Navy in construction and environmental compliance management.

Francine Coloma has been working as a geodesist with NOAA in the NGS/SRSD/CORS branch since March 2015. Before becoming a Federal employee, she supported NOAA NGS/SRSD/CORS under the University of Colorado (CU) Cooperative Institute for Research in Environmental Sciences (CIRES) in Boulder, CO as an Associate Scientist. Coloma has also worked at the National Snow and Ice Data Center (NSIDC) in Boulder, CO and collaborated with the University of Hawaii at Hilo (UHH) Center for the Study of Active Volcanoes (CSAV) and the USGS Hawaiian Volcano Observatory (HVO) on volcanic deformation monitoring.

Lijuan Sun is a geodesist who works in the NGS/SRSD/CORS branch, where she is responsible for maintaining metadata, publishing new NCN stations, and monitoring existing NCN stations. She has been affiliated with NOAA as a contractor since 2002 and has previously worked as a programmer analyst for various NOAA divisions, including Satellite Services Division (2002-2004), Weather Service Hydrology Lab (2004-2005), and NGS (2005-2015). Following her extensive experience as a contractor, she was eventually hired as a federal employee in NGS.

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