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ORIGINAL ARTICLE

Modernizing and expanding the NASA Space Geodesy Network to meet future geodetic requirements

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Abstract
NASA maintains and operates a global network of Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), and Global Navigation Satellite System ground stations as part of the NASA Space Geodesy Program. The NASA Space Geodesy Network (NSGN) provides the geodetic products that support Earth observations and the related science requirements as outlined by the US National Research Council (NRC in Precise geodetic infrastructure: national requirements for a shared resource, National Academies Press, Washington, 2010. http://nap.edu/12954, Thriving on our changing planet: a decadal strategy for Earth observation from space, National Academies Press, Washington, 2018. http://nap.edu/24938). The Global Geodetic Observing System (GGOS) and the NRC have set an ambitious goal of improving the Terrestrial Reference Frame to have an accuracy of 1 mm and stability of 0.1 mm per year, an order of magnitude beyond current capabilities. NASA and its partners within GGOS are addressing this challenge by planning and implementing modern geodetic stations colocated at existing and new sites around the world. In 2013, NASA demonstrated the performance of its next-generation systems at the prototype next-generation core site at NASA's Goddard Geophysical and Astronomical Observatory in Greenbelt, Maryland. Implementation of a new broadband VLBI station in Hawaii was completed in 2016. NASA is currently implementing new VLBI and SLR stations in Texas and is planning the replacement of its other aging domestic and international legacy stations. In this article, we describe critical gaps in the current global network and discuss how the new NSGN will expand the global geodetic coverage and ultimately improve the geodetic products. We also describe the characteristics of a modern NSGN site and the capabilities of the next-generation NASA SLR and VLBI systems. Finally, we outline the plans for efficiently operating the NSGN by centralizing and automating the operations of the new geodetic stations.

Keywords Space Geodesy · Terrestrial Reference Frame · ITRF · VLBI · SLR · GNSS · DORIS

1 Introduction

Society has become highly dependent on the global geodetic infrastructure for a wide variety of applications in positioning, navigation, and timing. In addition, the global networks of Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Global Navigation Satellite System (GNSS), and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) stations support a broad range of scientific investigations and Earth observations by producing the geodetic data necessary to define the International Terrestrial Reference Frame (ITRF), measure the Earth Orientation Parameters (EOP), and determine precise satellite orbits (NRC 2010).

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Over the past several decades, NASA operated and maintained separate networks of VLBI, SLR, and GNSS stations. Guided by the recommendations of the NRC Committee on the National Requirements for Precision Geodetic Infrastructure (NRC 2010), NASA began the development of a modern NASA Space Geodesy Network (NSGN) of colocated VLBI, SLR, GNSS, and DORIS stations that will be operated as a single network. A primary objective of this modernization is to contribute to the improvement of the ITRF to reach an accuracy on a decadal scale of 1 mm with an annual stability of at least 0.1 mm/year (NRC 2018). This is an ambitious goal that represents an order of magnitude improvement over the current capability and will require significant improvements to the global geodetic infrastructure as outlined by the Global Geodetic Observing System (GGOS) (Plag and Pearlman 2009).

Guided by network simulations (Pavlis and Kuzmicz-Cieslak 2009), site assessments, and the NRC recommendations, the NASA Space Geodesy Project (SGP) adopted a tiered approach to phase-in the deployment of the NSGN and establish priorities for the development of each new station. The NSGN site selection and prioritization are driven by a variety of factors, including geology, weather, simulated impact to the ITRF and EOP, partnership arrangements, and legacy station performance and status (if existing at the site).

In the following sections, we present the significant gaps that were identified in the global geodetic infrastructure and discuss how network simulations were used to develop priorities for the NGSN strategic deployment plan. We then describe NASA's prototype next-generation geodetic site and how its design is being used to drive the overall NSGN modernization. Finally, we report on recent progress in the implementation of the next generation of NASA stations, and how NASA's new VLBI stations are being used to support the realization of the VLBI Global Observing System (VGOS) (Petrachenko et al. 2009).

2 Gaps in the global network

The current realizations of the Terrestrial Reference Frame rely on individual geodetic stations distributed around the world. Unfortunately, the current distribution is not well-balanced, with most of the VLBI and SLR stations in the Northern Hemisphere. This imbalance leads to systematic errors that degrade the accuracy of the frame and the scientific and engineering products relying on it. The NSGN deployment plan is focused on filling in the most significant gaps in the global network in order to have the largest impact toward improving the accuracy of the ITRF.

In 2011, the GGOS Bureau of Networks and Observations (BNO) issued a "Call for Participation" in forming the future GGOS core network of space geodetic observatories (Pearlman 2011). The call was very successful, resulting in numerous responses from major government agencies (including NASA) down to individual institutions seeking partnerships that would allow them to become part of the larger community (Pearlman 2012). Based on these responses, a "network model" was generated, outlining the expected state of network around five and ten years in the future. In addition to the proposed hardware and its level of performance, other ancillary information included the description of the proposed sites' characteristics and associated facilities, the likelihood of success, etc. The model was encapsulated in a digital table that was kept up to date as information trickled in over the years.

Table 1 Projected accuracy of the ITRF origin, scale, and orientation after a decade of operation from two versions of the network projected to be operational 10 years from present

Network size	Origin (mm)	Scale (ppb)	Orientation (μas)
Standard (50 sites)	0.4	0.03	17.6
Extended (63 sites)	0.2	0.02	10.9

These global plans formed the basis for the development of network performance simulations that were used to assess the anticipated performance of the future network and to identify which new locations would have the largest impact on improving the ITRF over the next five and ten years. The simulations were based only on SLR and VLBI stations to keep the process simple and easily repeated; since these two techniques alone can define the ITRF with high accuracy, GNSS and DORIS were not included (although it is expected that modern, multi-constellation GNSS will be present at each site and DORIS present where available). A mix of legacy and newer technology SLR stations were included in the five-year projection, but only next-generation VLBI (VGOS) stations were used in the simulations. The legacy stations' simulated data were generated using the current productivity of these sites and assuming an average weather effect based on the results of the past decade. For the new, next-generation systems, the assumptions were based on the performance expected from such sites, i.e., 24/7 operation with minimal downtime per year and weather based on the average of the past decade for the closest available site. These two simulations indicated that the GGOS goals can be achieved by either network after a ten-year operation, with the results from the extended network's projection more than fivefold better than the set GGOS goals (Table 1).

The ten-year simulation examined two network designs: the "standard" set of stations and an "extended" set that included 13 additional sites (Fig. 1). The thirteen sites were chosen so that they could fill gaps in the standard network or evaluate the impact of their inclusion. The *standard* network

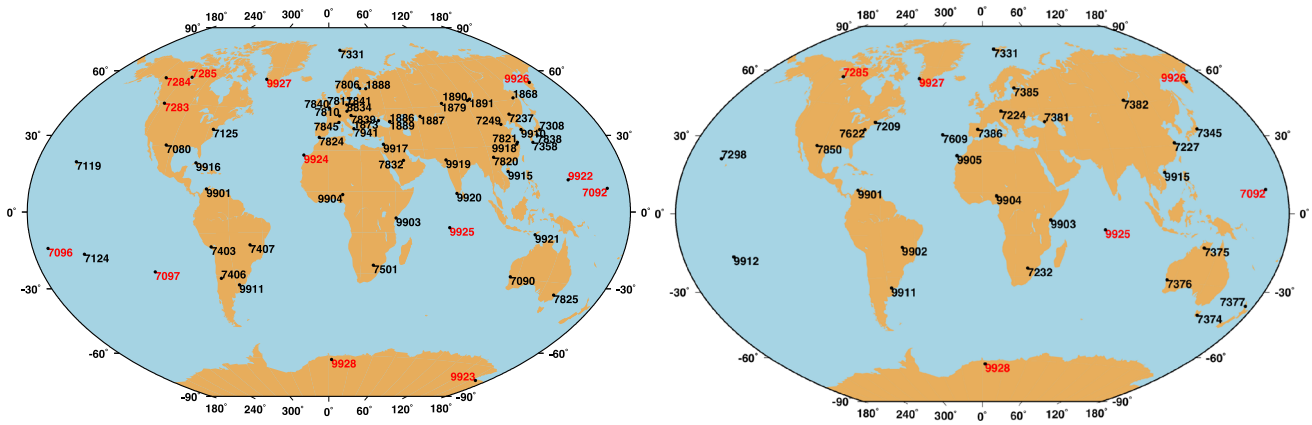

Fig. 1 SLR (left) and VLBI (right) stations used in the network simulations using the CDP-assigned identification numbers (Noll 2016) where available. The standard version comprises the black color sites, while the extended versions are those that include the red color sites. Site numbers starting with "99" correspond to future sites under consideration at locations where no SLR or VLBI system existed before

was comprised of 50 sites, all with SLR stations and 27 with VLBI stations. Some of these stations exist, but some are projected (with several being more likely than others). The *extended* network included an additional 13 SLR stations and five VLBI stations.

These additional sites were used in combination to build twenty sub-networks of a single station and in groups of up to four. Adding the sub-networks to the standard design or removing them from the extended network design, we evaluated the impact of these trade-offs on the two extreme realizations of the future GGOS core network. Individual stations were sequentially subtracted and added from the 10-year network to understand the performance impact on the frame. This analysis gave us input into the priorities that different locations around the globe would have in deciding a NSGN deployment strategy.

The results for ITRF simulations for the different network models (Pavlis 2019) show that the SGP position, stability, and EOP requirements are projected to be met once the + 10-year (standard) network is operational. The addition of GNSS and DORIS will densify the network and is also expected to further enhance the accuracy of the ITRF. These simulations validate the importance of maintaining and expanding the NASA sites in the Southern Hemisphere in meeting the ITRF goals. They also confirm the importance of upgrading the existing NASA legacy sites and expanding the global network by at least one additional site in South America and two additional sites in Africa.

The trade-off simulations results indicate that adding or removing a single site has in general little effect; however, two sites appear to be very important in both cases (adding them or removing them): American Samoa (7096) and Easter Island (7097). The standard network benefits from the addition of McMurdo (9923) and, to a lesser extent, Whitehorse (7284). The extended network suffers when Penticton (7283) or Whitehorse (7284) is removed and, to a lesser extent, Canary Island (9924); Diego Garcia (9925); Kamtchatka (9926); Nuuk, Greenland (9927); or Troll, Antarctica (9928).

In 2017, the GGOS BNO conducted a survey of current and planned global geodetic infrastructure (Kuzmicz-Cieslak and Pavlis 2017) to re-appraise the network state five and ten years hence. The results were used to update the original "network model" making it current again, since a significant number of sites had already implemented upgrades and some of the proposed plans have changed. The new model is being used by the GGOS Standing Committee on Performance Simulations and Architectural Trade-Offs (PLATO) that is tasked to coordinate simulation studies for the evaluation of future network designs.

3 NSGN strategic plan

A strategic plan for the NSGN deployment was developed using the results of the network simulations described above. This plan recognizes the existing and projected international GGOS sites that other groups plan to implement based on the GGOS BNO survey responses and is updated periodically as these external plans change. It also considers the present NASA and NASA partnership sites as potential sites given the importance of site continuity in the ITRF and the programmatic benefits to using established international partnerships. In addition, the plan focuses on identifying candidate sites in the regions where there are voids of geodetic infrastructure and NASA has a reasonable chance of access. For each identified site, various aspects are assessed, including

1. Geological stability of the greater region, appropriate for the establishment of a core site;

2. Value added (or lost if legacy station fails) by the geodetic position for the global geodetic data products, including the ITRF, EOP, and Precision Orbit Determination (POD);
3. Site conditions including local ground stability, cloud cover, horizon, land area/terrain, and field of view;
4. Human-imposed conditions such as radio frequency (RF)/optical interference, air traffic, and neighboring interference or obstruction;
5. Political and programmatic conditions (agreement status, land ownership and control, and partnership arrangements);
6. Site accessibility, logistics, infrastructure, security, power, and communications.

The NSGN strategic plan also recognizes that the current operational network of legacy NASA stations has become increasingly challenging and costly to maintain and many of the stations are at risk of failure without significant new investments in upgrades. The loss of any of the current NASA stations was found to create a significant gap in the global network and degrade the quality of the ITRF and other geodetic products. Given the importance of continuity of sites within the ITRF, the NSGN strategic plan places a high priority on sustaining and modernizing the current capabilities over expanding the network into new regions.

A set of requirements and specifications for a typical core site (Esper 2017) were broken down into four major groups: (1) site stability/continuity, (2) site data acquisition, (3) site infrastructure, and (4) non-ITRF NASA science requirements. Aspects that were used to reject candidate sites included:

1. Unstable ground,
2. Cloud cover above 60%,
3. Insufficient land,
4. Excessive radio frequency interference (RFI) conditions,
5. Significant security issues,
6. No clear option for an agreement with the host country/institution.

The priority order for upgrading NASA's legacy sites considered four main factors: (1) domestic (USA) station replacement, (2) site impact as predicted from network performance simulations, (3) current legacy stations operational performance, and (4) assessed risk of failure for current legacy station. The deployment plans were then grouped into four Tiers as follows:

Tier 1, now underway, includes the domestic sites in Texas, Maryland, and Hawaii that already have advanced plans for near-term implementation plus a SLR station in Ny-Ålesund, Svalbard in partnership with the Norwegian Mapping Authority.

Tier 2 consists of upgrading the remaining legacy NASA VLBI and SLR sites in Australia, South Africa, Brazil, and Tahiti.

Tier 3 begins the expansion of the NASA network to new potential locations with existing NASA partners that host a NASA GNSS station, including Colombia, Kenya, and Nigeria. The completion of Tier 3 would provide the minimum standard network necessary for significantly improving the ITRF.

Tier 4 expands the network to fill in the remaining significant gaps in the global distribution, such as the remote island locations discussed above. The details of Tier 4 are highly dependent on the plans and accomplishments of the international contributions to expanding and upgrading the GGOS stations and new international partnership opportunities.

The schedule for implementing this plan is subject to the availability of funding. NASA is currently supporting the implementation of Tier 1 and advanced planning for Tier 2. Tiers 3 and 4 are not expected to begin until at least 2028 and will be revised based on how successful other organizations and nations are in implementing their contributions of improvements to the global infrastructure.

4 Prototype next-generation NSGN site

The NASA SGP completed the construction and demonstration of a prototype next-generation NSGN site at NASA's Goddard Geophysical and Astronomical Observatory (GGAO) in 2013. The site includes all four of the major space geodetic techniques: VLBI, SLR, GNSS, and DORIS, plus a Vector Tie System (VTS) that monitors the relative positions between the different geodetic stations (local-ties). A functional block diagram of the site is shown in Fig. 2 and is the basis for all the new NSGN sites (Merkowitz et al. 2016).

The next-generation SLR (NGSLR) prototype, shown in Fig. 3, successfully demonstrated a number of key performance requirements, including: daylight tracking of GNSS satellites, 1 mm level stability over an hour, and 1 mm LAGEOS normal point precision. The station performance was also compared to the legacy MOBLAS-7 station through a month-long colocation campaign (McGarry et al. 2013; Pavlis et al. 2013). Unfortunately, NGSLR was damaged by lightning in 2015 and is no longer operational.

Lessons learned from the NGSLR development are incorporated into the design of the new Space Geodesy Satellite Laser Ranging (SGSLR) stations that will be deployed as a part of the new NSGN (McGarry et al. 2018). Changes include autonomous and remote operations software and

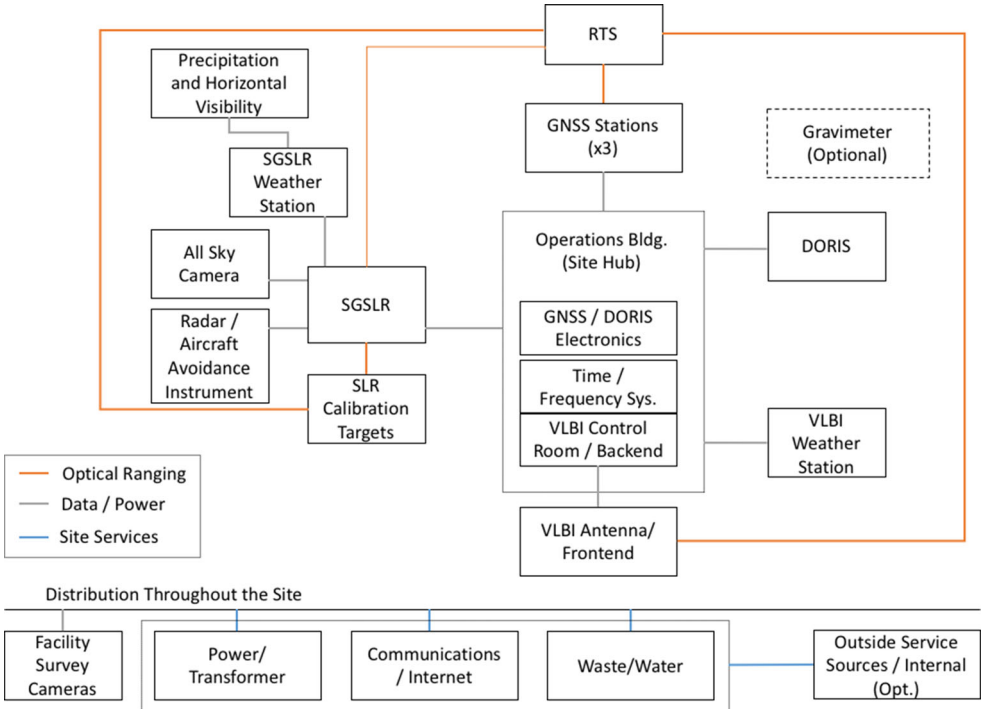

Fig. 2 Generic NSGN Site Block Diagram

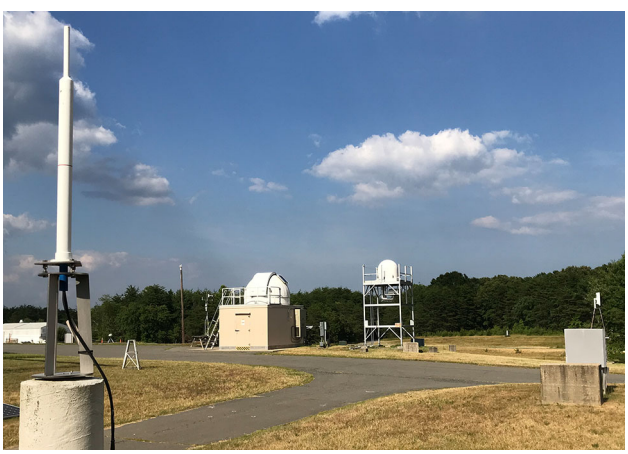

Fig. 3 DORIS beacon at GGAO with the NGSLR prototype system in the background. The SLR aircraft avoidance radar is located on the tower to the right of the NGSLR shelter

hardware, a standard on-axis Cassegrain telescope, improved optical configuration, and overall simplification and modularity for easy maintenance and technology upgrades. SGSLR is expected to achieve average range of 1 mm precision on the LAGEOS satellites and better than 2-mm range stability over a period of a year. The minimum data volume requirement for the SGSLR system is conservatively set at 45,000 Low Earth Orbit (LEO), 7000 LAGEOS, and 10,000 GNSS normal points; however, simulations have shown that the actual performance of the fully automated system is expected to be much better and on par with the best performing current stations (such as the NASA MOBLAS-5 station in Australia) given similar sky conditions (McGarry et al. 2018).

Community-wide studies aimed at defining the next-generation geodetic VLBI system (Niell et al. 2006; Petrachenko et al. 2009) concluded that to meet emerging geophysical requirements (Plag and Pearlman 2009), three key elements are required: fast-slewing antennas, broadband signal chains, and efficient correlators. Antennas need to slew fast (6 and 12 degrees per second in elevation and azimuth angle, respectively) across the entire visible sky to reduce atmospheric errors—the primary limitation to station position accuracy. Signal chains need to be broadband (2–14 GHz) to have sufficient sensitivity to detect a large (over 100) sample of compact radio sources over short integration times (about 10 s). Efficient correlators and correlator methods are required to interferometrically combine the data from the individual stations. Once continuously operating, the VGOS extended network is expected to produce several petabytes of data per day.

A 12-m-diameter, fast-slewing VLBI antenna equipped with a broadband signal chain was implemented at GGAO in 2013 (Ma et al. 2014) and is shown in Fig. 4. The 18-m Westford antenna at the MIT Haystack Observatory in Massachusetts was also furnished with a broadband signal chain to form a 600-km-long VGOS baseline that, coupled to the correlator at MIT, constitutes a well-suited test bed for VGOS research advancement. A 24-h VLBI observing session was

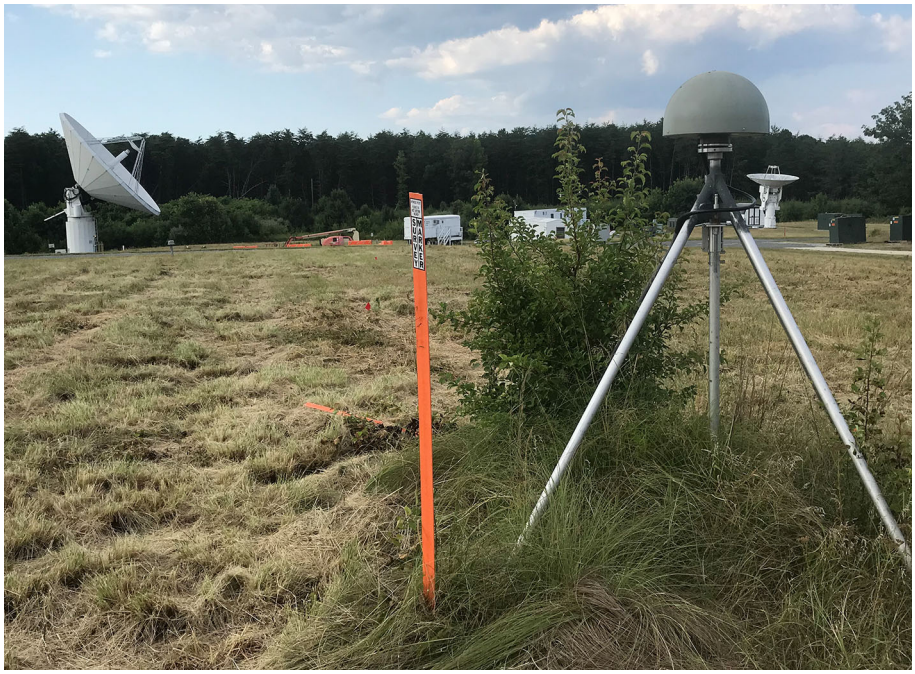

Fig. 4 North GNSS station (GODN) at GGAO with the 12-m VGOS antenna in the back left

performed in May 2013 between GGAO and Westford to demonstrate the performance and operational capabilities. The analysis of this first VGOS geodetic session successfully produced millimeter-level estimates of the ~600-km baseline between GGAO and Westford (Niell et al. 2014). The Westford-GGAO VGOS baseline has been observing regularly since December 2014 following an approximately 15-day duty cycle of observations, correlation, and data analysis. The estimated baseline length from the set of observing sessions through January 2017 yielded a weighted root-mean-square scatter of length residuals about the mean of 1.6 mm (Niell et al. 2018), demonstrating VGOS feasibility and showing significant promise toward the realization of a high-precision, global VGOS network.

A thorough radio frequency interference (RFI) study was performed at GGAO to ensure a suitably quiet environment for the broadband VGOS station and mitigate any significant disturbances (Hilliard et al. 2013). The 9.4-GHz radars used by the SLR aircraft avoidance laser safety systems at GGAO (see Fig. 3) are particularly threatening to the VGOS station because direct pointing of the radar at the VGOS antenna could potentially damage the VGOS receiver. To mitigate this risk, a software pointing mask was implemented in both the SLR and VGOS systems to prevent either station from pointing at the other. Unfortunately, this masking reduces the observable sky for both techniques. Future improvements to the SGSLR and VGOS systems will include direct communication between them to enable real-time pointing coordination that will significantly reduce the size of the mask. In addition, strategic placement at new sites can help avoid the need for pointing masks altogether by taking advantage of natural terrain features and radio blocking barriers (buildings, etc.) that prevent a clear line-of-sight between the two systems. NASA is also looking at alternative methods for aircraft safety that would eliminate this problem, but currently only the radar-based system is approved for use within the USA.

Lessons learned from the GGAO VGOS development are incorporated into the design of the new NSGN VGOS stations along with changes due to a different antenna manufacturer and some technology obsolescence. In addition, two key implementations that will bring GGAO (and future sites) to full VGOS compliance include doubling its four broadband digitizers up to 1-GHz sampling capability and adding a Cable Delay Measurement System (CDMS) to calibrate instrumental delays and phases associated with the cable carrying hydrogen maser signal.

Two modern multi-constellation GNSS stations (GODN and GODS) were also installed at GGAO on deep drill braced monuments and meet the International GNSS Service (IGS) standards. The GNSS-measured baseline length between GODN and GODS was compared to VTS measurements and was found to be in agreement with the sub-millimeter level (Desai et al. 2013). Each new NSGN site will also include at least 2–3 similar commercially available multi-constellation GNSS stations capable of real-time data streaming.

A DORIS station at the GGAO has operated since June 2000 as part of the global DORIS network (Fagard 2006; Moreaux et al. 2016). The latest installation is a 1.8-m high concrete pillar with a 0.4-m tripod that provides the antenna support (Fig. 3). This type of monumentation was shown to have the highest stability for the stations of

the DORIS network (Saunier 2016). The station beacon transmits radio signals at 2036.25 MHz (the 2 GHz channel) and 401.25 MHz (the 400 MHz channel) that are observable by satellites equipped with DORIS receivers (Auriol and Tourain 2010). The possible installation of DORIS beacons at the new NSGN sites will depend on many factors including local RF restrictions and the geographic requirements of the DORIS network set by the French Centre National d'Études Spatiales (CNES) and National Institute of Geographic and Forest Information (IGN).

The installation of the DORIS beacon at the GGAO accommodates the DORIS system requirements while minimizing the potential for interference with the VLBI receiver. The mark-to-mark distance between the DORIS antenna reference point and the VLBI 12-m reference point is 222.657 m, as determined through a geodetic survey in 2012. In addition to distance, the local topography as well as the legacy MOBLAS-7 SLR station structure provide natural shielding between the two systems. Nearby structures especially metallic towers that are located within the visibility cone for the DORIS beacon can degrade the signal received at the satellite and increase the noise in the DORIS data (Yaya and Tourain 2010). To improve the DORIS data quality from the Greenbelt station, at the request of the CNES, a tall tower close to the DORIS beacon (that protruded into the cone of visibility for DORIS up to 46° elevation), which noticeably degraded the DORIS data, was removed on June 22, 2009. The use of RF shielding/blocking material placed at strategic locations was also investigated at GGAO to mitigate the impact of RFI from DORIS on the broadband VLBI measurements (Hilliard et al. 2013). The compatibility of DORIS at the GGAO site is thus assured by a combination of distance and judicious placement.

Robotic Total Stations (RTS), other supplemental instrumentation (such as tilt meters), and comprehensive precise local-tie surveys were used at GGAO as part of the VTS to determine estimates of the site stability. The RTS (Fig. 5) performed regular semi-automated measurements to a series of preselected target prisms. The system demonstrated the ability to locate and identify the target prisms, verify the prism correction, and process range measurements correcting for atmospheric conditions. Since the layout of each NSGN site will be different, the VTS design at each site will need to be tailored to the specific site's configuration.

Fig. 5 Robotic Total Station (RTS) at GGAO that is part of the site's Vector Tie System (VTS)

5 NSGN implementation

5.1 Hawaii deployment

NASA and the United States Naval Observatory (USNO) have a long-standing partnership on the development and operations of a 20-m VLBI antenna at NASA's Kōke'e Park Geophysical Observatory (KPGO) on Kauai, Hawaii, as part of the National Earth Orientation Service. Several GNSS stations and a DORIS beacon are also located at the site. NASA and USNO partnered to implement a VGOS station at KPGO that incorporates lessons learned from the GGAO prototype. For example, the 12-m antenna at KPGO includes an upgraded antenna feed relative to GGAO to cover the high-frequency end of the VGOS range, integrates an up-down-converter that better matches the expanded frequency range, and incorporates a CDMS.

On February 1, 2016, the new KPGO antenna saw "first light" using several strong radio source calibrators such as Taurus and Cassiopeia. On February 5, 2016, it participated in coordinated interferometric observations with the broadband systems at Westford and GGAO; thus, forming two baselines in excess of 7000 km, to make the world's first three-way broadband VLBI measurement.

A geodetic tie between the old legacy antenna and the new VGOS antenna (Fig. 6) was then measured through a series of VLBI observations prior to the replacement of the 20-m antenna's main bearing. The geodetic tie effectively places the new antenna in the ITRF via the coordinates of the old antenna, which has been an ITRF-defining station since 1993. Besides obtaining estimates for the short (31 m) intra-KPGO baseline vector, these types of VLBI observations are special because they involve both the legacy and next-generation architectures. This "mixed-mode" observing, when applied to the global network, will help to bridge seamlessly the transition from legacy to VGOS over the next few years.

Fig. 6 New 12-m VGOS antenna at NASA's Kōke'e Park Geophysical Observatory (KPGO) on Kauai, Hawaii is shown (left) alongside the legacy 20-m VLBI antenna (right)

The KPGO VGOS station is now operational and regularly participates in observations such as the VGOS trial sessions with Westford and GGAO as well as other international stations as they come online. Preliminary estimates of baseline length scatter about the weighted mean from observations spanning about 2 years between KPGO and the other two NASA stations suggest few-millimeter-level precision. These estimates will continue to improve as VGOS analysis methods mature. In December 2017, the KPGO station participated in the VLBI "CONT17" continuous campaign, 5 days of continuous observing with 5 other VGOS stations, marking the first time the new VGOS network will contribute to official geodetic data products.

Unfortunately, KPGO typically has very cloudy skies making it a poor location for a SGSLR station. Therefore, the SGP decided the site of NASA's legacy TLRS-4 SLR station at the Haleakala Observatory on Maui is the best location for a Hawaiian SGSLR station. Consequently, the tie between the sites will need to be made using the GNSS stations at each location to form a "single" Hawaii NSGN site (a "hybrid" Core site). The new Haleakala SGSLR station is slated for implementation as the final Tier 1 SLR station.

5.2 Texas deployment

The McDonald Observatory near Fort Davis was selected as a new NSGN site because of its long history in SLR, geological stability, low radio frequency interference environment, and relatively clear skies. The SGSLR station will be located on Mount Fowlkes near the legacy McDonald Laser Ranging System (MLRS) (Shelus 1985). The VGOS station will be located near the observatory visitor center in the valley area about 100 m below (about 8° in elevation) and 800 m west of the SGSLR station. A benefit of this layout is that the SGSLR aircraft avoidance radar will never have to point down the hill making it unnecessary to implement pointing masks between the two stations.

Additional GNSS stations are being installed near the VGOS and SGSLR stations. A network of control points and monuments for RTS are also being installed at two locations to tie the stations together as part of the site's VTS.

The new VGOS station is scheduled to be installed and become operational at MGO in early 2019. Components of the SGSLR station will be installed starting in 2019 with commissioning of the station planned for the beginning in 2020.

5.3 Space Geodesy Network Operations Center (SGNOC)

All of the new geodetic stations are being designed with a high level of automation such that they can ultimately operate nearly autonomously. A centralized remote operations capability is currently under development (an initial demonstration using the GGAO prototype stations was performed in 2014) to be able to remotely command and monitor these systems. An overview of the new Space Geodesy Network Operations Center (SGNOC) is shown in Fig. 7.

The SGNOC operations concept contains several critical elements. First, site parameters are shared (e.g., published) through the network interface and become visible to registered users (operators, engineers, etc.). The SGNOC archives and trends monitoring data with the data files residing at the SGNOC itself and at other collaborating data centers. The SGNOC acts as a monitoring, command, and control center for fully automated systems in the field. It also supports

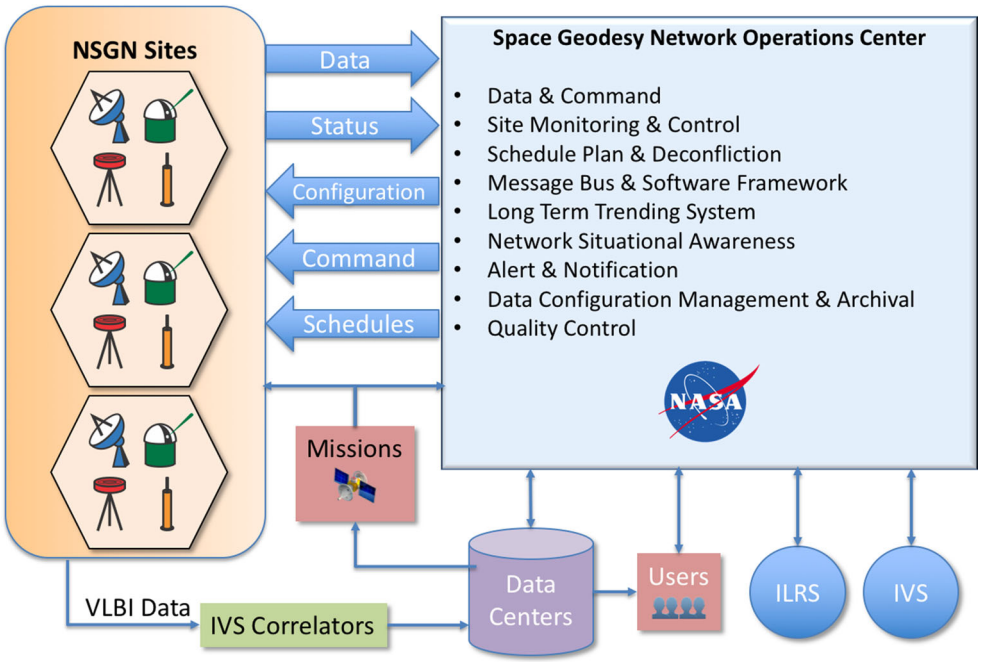

Fig. 7 Centralized operations of the NSGN will be performed using a virtual Space Geodesy Network Operations Center and will provide various levels of access for users and the geodetic community

remote station control of partially automated systems. The SGNOC will also interface with the existing global geodetic infrastructure, such as the geodetic data centers.

A central aspect of the SGNOC is making the elements of the network function coherently. The network itself is subdivided into the following major physical elements, each of which may be further subdivided: stations, sites, data transport, and operations. The SGNOC is functionally in charge of network operations, which includes real-time status monitoring, alert notification, command, scheduling of network assets, trending, and data archiving. In addition, it handles network management functions, such as delivery of control commands, delivery of station (science and engineering) data, network service requests (e.g., trending data), network asset configuration (e.g., health and data acquisition status of stations, sites, communications), accountability reporting (out of service reports, maintenance logs, etc.), and safety and security regulations (NASA and local). In addition, sustaining engineering services are conducted by skilled engineers in their respective areas, in charge of carrying out engineering data analysis, predicting and resolving anomalies, resolving maintenance calls, and improving operations.

5.4 VLBI Global Observing System (VGOS)

The final aspect of the NSGN strategic plan is focused on the successful transition from legacy VLBI to VGOS. Regular VGOS test sessions are being performed with the available stations to gain experience and improve performance. The VGOS station at KPGO has been a significant step forward in that the long baselines enable the kind of geodetic science studies, such as source structure geodetic imaging, to which short baselines are largely insensitive. However, a fully populated global network will be required to fully meet the GGOS goals. Over the last year, VGOS stations in Spain (Yebes), Germany (Wettzell), and Japan (Ishioka) have started to come online, and Onsala (Sweden) and few others are following suit. All stations are still working toward becoming fully operational and participate regularly in the current biweekly VGOS test sessions. All the available VGOS stations participated in the successful CONT17.

Numerous other VGOS stations are expected to become operational over the next few years, most immediately Onsala, MGO, Hobart (Australia), and Ny-Ålesund (Norway). To take advantage of the existing stations and bring in new VGOS stations as they come online, NASA has developed a plan to move the network toward an operational state. The first step in this plan is to complete the analysis of the CONT17 data and address any lessons learned. A plan for UT1 VGOS observing will then be developed. Several legacy–VGOS mixed-mode sessions are being considered for the end of 2018 to start connecting the two networks. In early 2019, the VGOS correlation methods developed by MIT should be mature enough to begin the rollout to other International VLBI Service for Geodesy and Astrometry (IVS) correlation centers, thus moving the community significantly closer toward regular and robust VGOS observations.

6 Summary

The implementation of a new NSGN has begun based on the successful demonstration of the prototype core geodetic site at GGAO in Maryland. The new network is designed to meet the demanding requirements set out by the NRC and GGOS to support improvements to the ITRF, EOP, and POD. NASA completed the implementation of a new VGOS station in Hawaii and has demonstrated the viability of the VGOS concept using its network of three broadband VLBI stations. New VGOS and SGSLR stations are now being built to establish a modern NSGN site at the McDonald Observatory in Texas by the year 2020 followed soon thereafter by a SGSLR station at the Norwegian Mapping Authority's core site in Ny-Ålesund, Svalbard. Advanced plans are also being made to upgrade the other legacy NASA sites and fill in gaps in the global geodetic network.

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