The Impact of NASA's SGP and USNO on VGOS

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Abstract NASA's SGP (Space Geodesy Project) has completed a prototype core station at the Goddard Geophysical and Astronomical Observatory (GGAO) near Goddard Space Flight Center. It includes state-of-the-art VLBI, SLR, and GNSS systems as well as DORIS and a vector tie system between instruments. Broadband data have been acquired using GGAO and Westford. NASA intends to use the instruments it has developed to improve and expand the global space geodetic network. USNO has relied on VLBI for daily measurements of UT1 and is upgrading the Kokee Park station to VGOS specifications. We describe the NASA and USNO plans for implementing the next generation network.

Keywords VGOS, VLBI, DORIS, GNSS, SLR, vector ties

1 Supporting Future Requirements: NASA's Space Geodesy Project (SGP)

For years, it has been recognized that areas of science that use geodetic products, such as the International Terrestrial Reference Frame (ITRF), have a need for these products to have increased quality. For example, sea level studies will require an accuracy of 1 mm and a stability at 0.1 mm/year. This is a factor of 10–20 beyond the capability of the geodetic techniques that were standard at the beginning of the 21st century. It is estimated that ∼30 modern, integrated stations would be necessary to meet the new requirements.

In publications such as "Earth Science and Applications from Space" and "Precise Geodetic Infrastructure: National Requirements for a Shared Resource", the National Research Council has made several recommendations for accomplishing the required increases in accuracy and stability. Key recommendations are:

- upgrading U. S. stations with modern SLR and VLBI equipment,
- working with international partners to deploy additional stations,
- establishing and maintaining a high precision real-time GNSS/GPS national network,
- making a long-term commitment to maintain the ITRF, and
- continuing to support the activities of the GGOS.

NASA's response is to contribute to build a new global network of integrated geodetic stations through the Global Geodetic Observing System (GGOS) and the international services. NASA proposes to provide six to ten of these stations.

A new NASA initiative SGP started at the end of 2011 in response to the Earth Science Decadal and the National Research Council study "Precise Geodetic Infrastructure". This initiative is part of the President's Climate Initiative. GSFC has led a partnership between it and JPL. The Smithsonian Astrophysical Observatory and the University of Maryland have also participated. The initiative has two goals. The initial goal is to establish and operate a prototype next generation space geodetic station with integrated next generation SLR, VLBI, GNSS, and DORIS systems, along

1. NASA GSFC
2. USNO

with a system that provides for accurate vector ties between them (see, for example, Figure 1e). The subsequent goal is to plan and implement the construction, deployment, and operation of a NASA network of similar next generation stations that will become the core of a larger global network of modern space geodetic stations. (Ideally, this should be done in time to support the coming Decadal Survey missions.)

Fig. 1 Components of an integrated station: a) a VLBI antenna, b) Next-generation SLR station, c) GNSS station, d) a DORIS beacon, and e) vector tie equipment to connect them.

2 Contributions of a Geodetic Measurement System

Each of the four techniques of an integrated station will provide different contributions to the ITRF, as well as to other things such as determination of Earth orientation parameters. VLBI and SLR stations have a low density global distribution, while GNSS has a high-density distribution, and DORIS has a well-spaced geographic distribution. The four components interact to fully define the ITRF, with each technique providing different contributions. VLBI determines the scale of the ITRF and its orientation with respect to the ICRF. SLR determines the origin of the ITRF (the Earth's CM), the ITRF scale, and the positions (orbits) of spacecraft within the ITRF. GNSS provides precise monitoring of the Earth's polar motion and rotation rate, the positions (orbits) of space craft in the ITRF, and the position of instruments on land and sea (e.g., tide gauges and buoys and geodetic instruments). DORIS provides the positions (orbits) of spacecraft within the ITRF, and it enhances the global distribution of ITRF station positions and velocities.

The vector tie system measures the co-location of the four techniques' instruments and connects the techniques. The full definition of the ITRF provided by the four components plus the improvement of the ITRF performance provided by the vector tie system combine to well-define the origin, the scale and the orientation of the ITRF.

3 Implementation of a Prototype Integrated Station at GGAO

NASA has implemented an integrated prototype station at its GGAO facility located in Greenbelt, Maryland. Substantial progress has been made towards implementing all five components of an integrated station (VLBI, SLR, GNSS, DORIS, and the equipment to tie them together).

Figure 2 shows the first component of the GGAO integrated station—its 12-meter VGOS VLBI antenna. The rest of Figure 2 shows the key front end components and back end rack.

Figure 3a shows the second component of the GGAO integrated station—its Next Generation SLR station with key personnel that have contributed to its development. The station has successfully completed a two-year development effort in which it demonstrated four key performance requirements. These were tracking the LAGEOS satellites with $\sim$mm-level precision, robust day time and night time satellite ranging from the LEO to GNSS altitudes (up to 22,000 km), maintaining system stability of under 1 mm (RMS) for over an hour, and operating semi-automatically. As one test, NGSLR and MOBLAS-7 simultaneously tracked the LAGEOS satellites, and NGSLR achieved excellent agreement with MOBLAS-7 with millimeter-level precision. Figure 3b shows NGSLR in the process of the simultaneous tracking.

Two new GNSS stations, GODN and GODS ("Goddard North and South"), form the third compo-

Fig. 2 Components of the VGOS VLBI system at GGAO: (top left) 12-m antenna, (top right) the cryogenic front end components, (middle left) a view of the quad ridge feed horn, (bottom left) low noise amplifier, and (bottom right) the fully assembled rack of the back end components.

Fig. 3 a) NGSLR station and key personnel in its development and support. b) NGSLR (left) and MOBLAS7 (right) perform simultaneous ranging on a LAGEOS satellite.

nent of the GGAO integrated station. They have been collecting data since 2012-01-17. Figure 4a shows the old GODE station, and Figure 4b shows the GODS station on a deep drilled braced monument. The stations are multi-constellation (i.e., they are compatible with GPS, GLONASS, and Galileo). The accuracy of GODN and GODS was tested by comparing the GODN—GODS baseline length calculated from GPS measurements taken by GODN and GODS to the baseline length measured by a local tie survey.

The fourth GGAO station component, a DORIS beacon shown in the foreground of Figure 5a, has been located at GGAO since June 2000. The GGAO

Fig. 4 GNSS stations: a) GODE and b) deep drilled braced monument GODS.

beacon is part of a global network of ∼57 stations, shown in Figure 5b. The beacons emit at 2 GHz and 400 MHz. The observable is dual-frequency one-way Doppler. DORIS receivers are located on altimeter satellites (e.g., TOPEX/Poseidon, Jason-1 and Jason-2, ENVISAT, Cryosat-2, and SARAL) and on remote sensing satellites (e.g., SPOT-2, SPOT-3, SPOT-4, and SPOT-5). DORIS receivers will be installed on future satellites, including Jason-3, SENTINEL-3, Jason-CS, and SWOT.

Fig. 5 a) The GGAO DORIS beacon (foreground). b) The global DORIS network.

The final component of the integrated station is its Vector Tie System (VTS). The VTS is a combination of a precise local-tie survey and a periodic monitoring system for measuring site stability. The system has demonstrated sub-millimeter accuracy at GGAO. The ability of the monitoring system to operate semi-autonomously has been demonsrated. It was able to find and identify a target prism, verify the prism correction, and process distance measurements to correct for atmospheric conditions. Figure 6a shows the robotic total station. Figure 6b schematically represents the local ties between the geodetic techniques at GGAO.

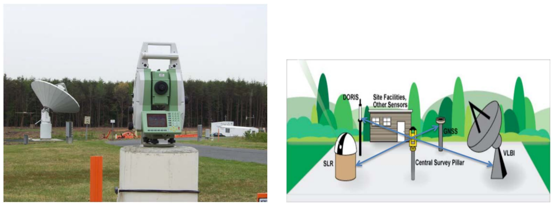

Fig. 6 a) The GGAO robotic total station. b) Diagram of the local reference frame tie to all geodetic stations at GGAO.

4 SGP Site Selection Strategy

The Global Geodetic Observing System (GGOS) has issued a call for participation in the Global Geodetic Core Network. This network is intended to be a foundation for measuring the Earth System, and it is intended to be a contribution to the Global Earth Observation System of Systems (GEOSS). To complement this call, the SGP has developed a strategy for developing a network of integrated stations. Based on simulations of a 32 site network, the SGP has developed a conceptual global site distribution as a starting point for identifying coverage by regions. The identification of actual sites to fill in this grid has three levels of focus. Consideration will be given to existing and projected sites of international groups, if the sites meet the required technological standards. Existing NASA and NASA partnership sites will also be examined as potential participants. An effort will be made to seek candidate sites with a reasonable chance of success in under-populated regions. The process for examining each candidate site will be to:

- examine the value that the site's geodetic position will add to the network,
- examine site conditions such as ground stability and typical cloud cover,
- examine human-imposed conditions such as RF/optical interference and air traffic,
- examine political and programmatic conditions, such as land ownership and control, the potential for an agreement and partnership arrangements, and
- examine site accessibility, logistics, infrastructure, security, power, and communications.

After examination, each site will be qualified as a good or a bad candidate. Three areas—French Polynesia, South America, and Africa—are under consideration by SGP using these criteria to fill existing gaps in the global distribution.

The island of Tahiti in French Polynesia has been evaluated. Some infrastructure for an integrated station already exists there at Punaaula. An SLR station, NASA's MOBLAS-8, has operated there since 1997, and the existing site has a co-located GNSS station and DORIS beacon. There is an existing agreement with CNES and the University of French Polynesia (UFP), and discussions are underway for a partnership. But the current site is not tenable, so a new site must be identified. Vairao has been identified as a potential location. Figure 7a shows the locations of Punaaula (larger section of the island) and Vairao (smaller section). Figure 7b and 7c show the actual locations at Punaaula and Vairao, respectively.

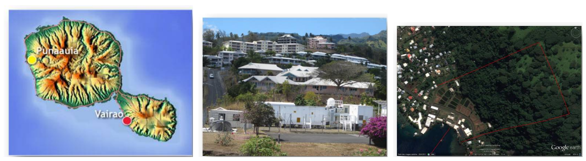

Fig. 7 a) Two station locations on Tahiti. Local conditions on Tahiti at b) Punaaula and c) Vairao.

Several South American sites are possible, as shown in Figure 8a. Discussions are underway with Colombia's Instituto Geográfico Agustín Codazzi (IGAC), and possible sites have been identified, including Barrancas and Marandua. Discussions are also underway with Brazil's National Institute for Space Research (INPE) concerning sites in Brazil, such as one near Brasilia. Several meetings have been held, and NASA is working with them on organization and presentation material. BKG's Transportable Integrated Geodetic Observatory (TIGO) (Figure 9b) is in the process of concluding operations at Concepcíon Chile and moving to a new site at La Plata, Argentina. There are existing SLR stations at Arequipa and San Juan but no SGP plans for augmentation at this time.

Two sites in Africa (Figure 8b) at Malindi, Kenya and Toro, Nigeria are under discussion. NASA and the Italian Space Agency (ASI) have begun discussions about forming a partnership to operate a site at Malindi (Figure 10a). NASA has no current agreement with ASI, but it has a long history of cooperation, and an agreement process is underway. Malindi is an established site with a large reservation funded by Italy,

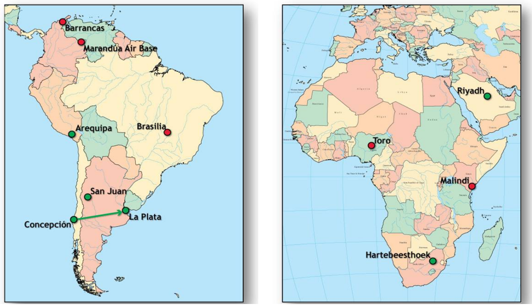

Fig. 8 Candidate integrated sites in a) South America and b) Africa.

Fig. 9 SLR stations in Argentina: a) San Juan and b) TIGO (moving to La Plata).

with a large staff and an existing ESA GNSS receiver. Discussions are also underway between NASA and Nigeria's National Space Research and Development Agency (NSRDA) about a partnership site at Toro (Figure 10b). This is also an established site which has a GPS station and a significant number of staff performing space geodesy. The Toro site was offered under the GGOS Call for Proposal.

Fig. 10 Candidate African sites at a) Malindi, Kenya and b) Toro, Nigeria.

5 Upgrade to an Existing Site (KPGO, Hawaii)

USNO (U. S. Naval Observatory) has relied on VLBI for daily measurements of UT1, so it is funding a new VGOS system at the Kokee Park Geophysical Observatory (KPGO) at Kokee Park, Hawaii, USA. KPGO is a well-established VLBI site with a long history of data. But a drawback for SLR is that it typically has very cloudy skies. A second Hawaiian site, Haleakala, is located ∼380 km from KPGO. This site typically has clear skies and has a long history of SLR operations, but it will be very difficult to build a VGOS station nearby. The strategy is to use multitple GPS baselines to determine the co-location vector. Figure 11 shows the locations and local conditions at KPGO and Haleakala.

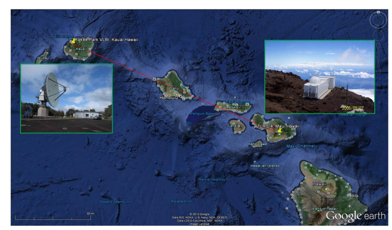

Fig. 11 Positions of KPGO and Haleakala, Hawaii with inset pictures of a) KPGO and b) Haleakala.

NASA and USNO are forming a partnership to build the new KPGO VGOS station. The SGP has completed an environmental categorical exclusion for two potential locations. USNO has awarded a contract to InterTronic Solutions to build a 12-m class antenna. The PDR was held on January 28 and 29. USNO has asked NASA to provide project oversight, site preparation, and signal chain development. Pad design will be done by a GSFC contractor. Pad construction will be done by NAVFAC or by a GSFC contractor. Signal chain fabrication, installation, integration, and testing will be done by MIT/Haystack Observatory. The new station will become an operational VGOS station as part of the new NASA Space Geodesy Network in 2016.

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