Modernizing NGS's Approach to GNSS Processing

Jacob M. HECK, Bryan J. STRESSLER, Clement A. OGAJA, Andria L. BILICH, United States

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SUMMARY

The mission of the U.S. National Geodetic Survey (NGS) is to "define, maintain and provide access to the National Spatial Reference System (NSRS)." Since the advent of GPS in the late 1970s, Global Navigation Satellite Systems (GNSSs) have become dominant tools that NGS uses to maintain the NSRS and that our stakeholders use to access it. An example of the former is NGS's activities as an Analysis Center contributing ground station coordinates and velocities as well as GPS satellite orbits to the International GNSS Service (IGS). For the latter, NGS operates the Online Positioning User Service (OPUS) which provides hundreds of thousands of processing solutions every year to surveyors in the United States and across the world. In these tasks, NGS primarily uses internally-developed software called the Program for the Adjustment of GPS Ephemerides (PAGES), but this software is "showing its age" because of its limited capability to only process the legacy L1 and L2 GPS signals.

As the Galileo and BeiDou constellations become fully operational, GPS and GLONASS modernize, and regional constellations such as QZSS and NavIC come online, there will soon be over 140 satellites available for position determination. This results in improved satellite geometry that presents the potential to improve upon single constellation positioning and shorten the requisite session lengths, particularly in areas with limited sky view. New signals provide the opportunity to move beyond the dual-frequency GPS-only processing algorithms and incorporate triple-frequency methods for steps such as ambiguity fixing and ionospheric corrections. In order to use these available resources and support smarter surveying, NGS is developing new software that will replace the existing PAGES software suite for position and orbit determination, taking advantage of all the available signals and satellites in view. This software will be extensible and written in modern programming languages for easier maintenance. Ultimately, these efforts will provide multi-GNSS capability for OPUS, for monitoring of the NOAA Continuously Operating Reference Station (CORS) Network, and for GNSS orbit production for the IGS. This presentation provides an update on the development progress of the new software.

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1. INTRODUCTION

As part of its efforts to modernize the National Spatial Reference System (NSRS), the US National Geodetic Survey (NGS) will soon replace its current horizontal and vertical datums that make up the NSRS (NAD 83 and NAVD 88, respectively, among others) with a suite of plate-specific geometric reference frames and a single geopotential datum. The new NSRS reflects pivotal changes to geodetic positioning capability that have been developed in the last 40 years and will correct problems with the previous datums, in particular the non-geocentricity of the horizontal datum. The primary gateway into the new NSRS will involve using observations from GNSS.

Around this same time, the geodetic positioning satellites are modernizing and more tools are becoming available for GNSS positioning. GPS is being updated to broadcast a third frequency and several new signals, while Russia's GLONASS is also modernizing with new signals and additional satellites. China's BeiDou and the European Union's Galileo constellations are newer systems that are reaching full operational capacity and provide even more signals and more positioning capability. In addition to these global systems, regional navigation satellite systems such as QZSS (Japan) and NavIC (India) are also becoming available for positioning. These additional resources are driving the International GNSS Service (IGS) to utilize and support data from multiple constellations. In order to meet evolving demands as an analysis center for IGS, NGS is modernizing its GNSS processing operations.

Currently, NGS uses its in-house developed software called Program for the Adjustment of Ephemerides (PAGES, Schenewerk 1991) to process its GNSS data. PAGES, however, is limited to processing L1- and L2-band signals from only the GPS constellation. This limitation makes the program unable to process the newer L5-band signal of GPS as well as data from other constellations. In order to provide easier access to the new reference frames and to keep up with the techniques of other IGS analysis centers, NGS seeks to modernize its GNSS processing capability and take advantage of the new and modernized GNSS constellations which provide multiple frequencies. This is leading to the development of new multi-GNSS software to replace PAGES as the processing engine within NGS products and services.

2. **NGS PRODUCTS AND SERVICES**

The backbone of the National Spatial Reference System (NSRS) after 2022 will be the Continuously Operating Reference Station (CORS) Network (NGS, 2019). Stations within the NOAA CORS Network (NCN, see Figure 1) provide direct access to the NSRS. The NCN is a partnership between over 200 agencies, universities, and other groups (Snay & Soler, 2008). These stations continuously log GPS and other GNSS data from permanent stations. There are over 2700 active and decommissioned stations within the NCN. Recently the data from these stations were reprocessed as part of the REPRO2 effort, resulting in new position and velocity solutions at 3050 stations within NCN and the IGS Network (Saleh et al., in review).

A subnetwork of primary stations within the NCN to maintain long-term consistency between the NSRS and ITRF will be known as the NOAA Foundation CORS Network (NFCN). These stations are to be operated by NGS (or through an agreement with other Federal agencies) and will have long, continuous time series, have demonstrated high stability, and provide even coverage across the United States and its territories. Many are planned to be co-located at sites with other geodetic measuring techniques such as DORIS, SLR, or VLBI. Each of the tectonic plates where the United States has significant civilian populations will have at least three Foundation CORS locations in order to solve for the Euler pole parameters. By design, stations in the NFCN will collect all available GNSS signals being broadcast. NGS will submit all Foundation CORSs for inclusion in the global IGS Network.

As an analysis center within IGS, NGS computes station positions and orbits for the GPS constellation that are then contributed to the IGS analysis center coordinator for the combined weekly solution. Also as part of IGS, NGS performs GPS antenna calibrations in order to solve for phase center offsets (PCOs) and phase center variations (PCVs) that improve positioning accuracy. These are distributed via the ANTEX file format.

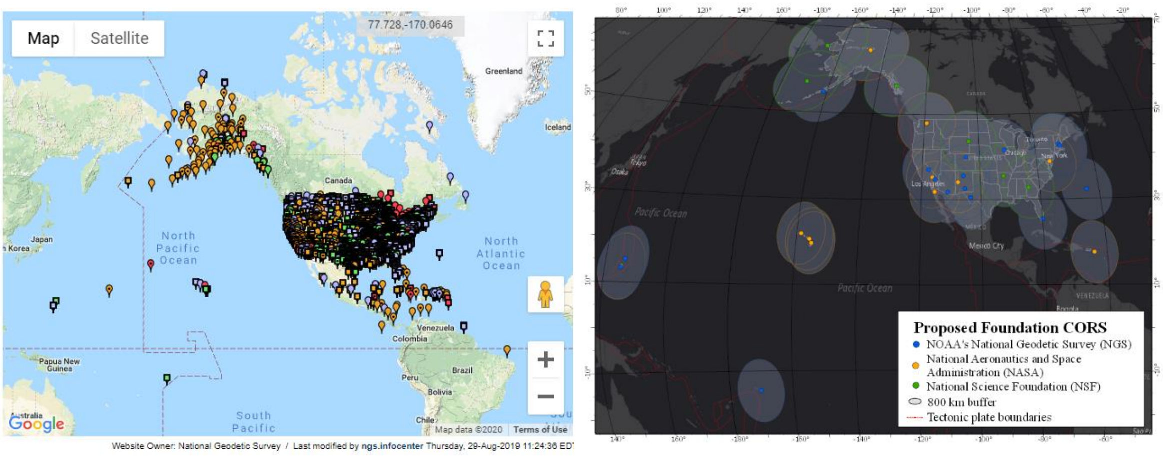

Figure 1. Continuously Operating Reference Stations (CORSs) managed by NGS. (left) The NOAA CORS Network has over 1700 active stations that are maintained by over 200 partner groups. (right) The Foundation CORS Network is the backbone of the NSRS.

One of the most popular tools that NGS provides to the public is the Online Positioning User Service (OPUS, Soler et al., 2010). Released online in 2001, OPUS has steadily grown in popularity, providing over 600,000 solutions in 2018 to users from all over the world. OPUS takes a user submission of a RINEX file plus information about the equipment used to collect the data, and computes a position from three independent, single baseline solutions. The results, including coordinates in the latest reference frame and plane coordinates, are then emailed to the user. Figure 2 shows the home screen of the OPUS web interface.

Figure 2. The home screen of the Online Positioning User Service (OPUS). https://www.ngs.noaa.gov/OPUS/

3. GNSS MODERNIZATION

As early as the 1960s when the United States Navy launched the TRANSIT satellites, position determination on the ground has been possible using manmade satellites. In the late 1970s, GPS was launched and shortly afterward began being used by civilians for positioning purposes. Determining a position on the surface of the earth went from taking months of field observation to minutes. This allowed for geodetic organizations around the world to use it in setting up and maintaining their geodetic networks.

Now in addition to GPS, there are several other GNSS constellations available to use for positioning. As Table 1 outlines, there are four global constellations of GNSS that are at or near full operation as of 2020. Adding two other regional navigation systems, there are upwards of 140 satellites available in orbit that can be used for positioning.

Table 1. Information about each GNSS constellation, including country, year of first launch, current number of satellites, full constellation number of satellites, orbit types, and frequencies. MEO = Medium earth orbit (~20,000 km above earth, ~12 hour orbital period) GEO = Geostationary orbit (remains above the same place in the equatorial plane) IGSO = Inclined GeoSynchronous orbit. https://www.gnssplanning.com/#/satellites as of 2020-02-05.

Name	**Country**	**Began**	**Current Satellites**	**Nominal Constellation**	**Type**	**Frequencies**
GPS	USA	1978	31	30	MEO	L1, L2, L5
GLONASS	Russia	1982	24	24	MEO	G1, G2, G3
Galileo	European Union	2005	24	30	MEO	E1, E5a, E5b, E5a+b, E6
BeiDou	China	2007	48	35	MEO (27),GEO (5), IGSO (8)	B1, B1-2, B2a, B2b, B2a+b, B3
QZSS	Japan	2010	4	4	IGSO	L1, L2, L5
NavIC	India	2013	6	7	3 GEO,4 GSO	L1, S-band
TOTAL			137	130		

Some of the benefits of GNSS modernization include more signals and more satellites. Added signals are expected to improve tropospheric and ionospheric modeling, while added satellites increase skyview and allow for surveying in locations that were previously inaccessible with satellite techniques. Figure 3 shows an example of improved sky coverage when collecting data from all four of the global constellations.

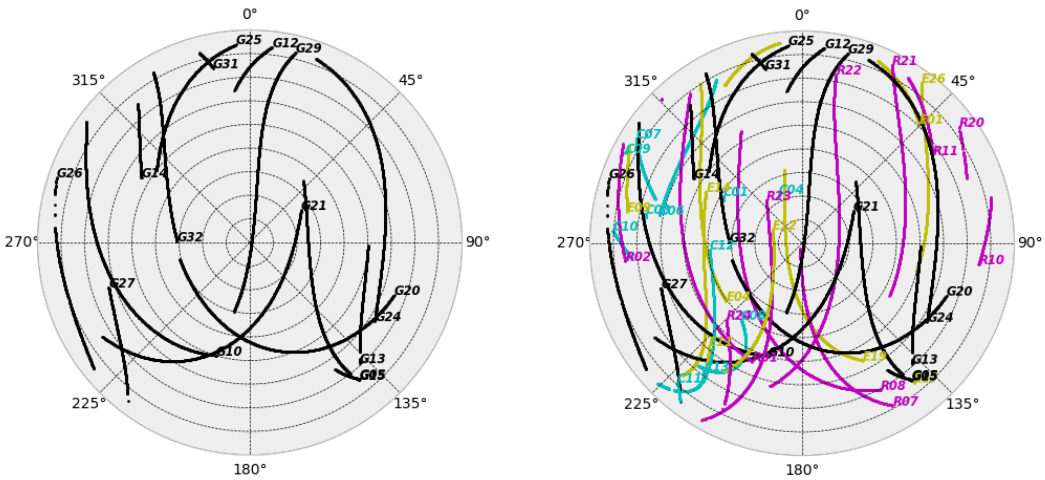

Figure 3. An example of satellite skyview during a 4-hour observation session from station XMIS in Christmas Island, Australia. (left) The GPS satellites within view. (right) GPS, GLONASS, Galileo, and BeiDou stations within view.

Similarly, precise point positioning (PPP) results often demonstrate the possible improvements in positioning accuracy and convergence time when using multiple constellations. Previously, we evaluated several new multi-GNSS PPP packages that are available through the GPS Toolbox (Stressler et al., 2018b). When compared to the IGS weekly solution, the GAMP software (Zhou et al., 2018), which builds upon the open-source RTKLib, demonstrated an average improvement in positioning accuracy when new constellations were included in the solutions. For the same data sets, the Matlab-based PPPH software (Bahadur & Nohutcu, 2018) yielded notable improvements in convergence time when additional constellations were included. These results along with the GPS+GLONASS results for the same data sets from the NRCAN CSRS-PPP program (https://webapp.geod.nrcan.gc.ca/geod/tools-outils/ppp.php) are shown in Figure 4. Although the software that NGS is developing will be initially intended for baseline processing, the results from these PPP programs show how additional satellites and signals improve positioning. As multi-GNSS products and processing techniques mature in the coming years, the improvements in GNSS positioning should become even more apparent.

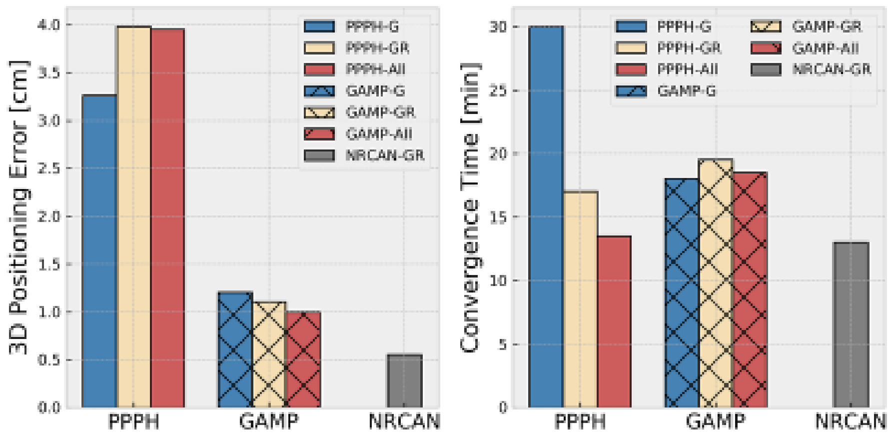

Figure 4. (left) 3D positioning error computed from 24-hour sessions using PPP softwares PPPH, GAMP, and NRCan PPP when processing with GPS-only (G), GPS+GLONASS (GR), and all available constellations. (right) Convergence time comparisons using the different softwares and different constellation combinations.

New constellations and signals provide many benefits for positioning, however, there are challenges that go along with these changes. Additional observables bring a need for new data products and quality control tools which means that new code needs to be written to account for all of these changes. Some products, like antenna calibrations for the newer signals and combined multi-GNSS final orbit products, are still in need of development. IGS has already developed some pre-processing tools to edit RINEX files and analyze signal quality that perform some of the functions of TEQC (Estey & Meertens, 1999). GFZRNX (Nischan, 2016) and GNUT/ANUBIS (Vaclavovic & Dousa, 2016) are public tools developed as part of IGS's Multi-GNSS Experiment (MGEX, Montenbruck et al., 2017) that can quality check the RINEX data and modify it to the latest format prior to the start of processing. NGS has incorporated these tools into the workflow for GNSS data management for its RINEX 3 capacity.

4. PROGRESS AT NGS

Given all of these updates to the tools available for satellite positioning and the changing requirements within the geodetic community to go along with these updated tools, NGS is in the process of modernizing its products and services for the surveying public. Rewriting a decades-old software package brings about a terrific opportunity to modernize the approach to data processing and reduction. PAGES was written specifically for single-constellation dual frequency data processing in an earlier era when computers were limited in their ability and programming languages were less developed. For the new software, modules are being written in C++, which gives an object-oriented capability for easier maintenance and extensibility. Supporting scripts and plotting utilities are being developed in Python, a well-supported modern scripting language. In order to maintain documentation that is easier to read, Doxygen is used in the development process. Atlassian’s JIRA software is used to keep track of updates to the software as they are needed, and Subversion is used for version control on the programs. Unit tests are developed to verify that each class is working properly at the granular level, resulting in fewer problems as the program grows more complex.

To date, the GNSS Software team has developed various modules for reading and utilizing data from standard GNSS file formats (e.g., RINEX, SP3, ANTEX). To assess the quality of the broadcast ephemeris for each of the four main constellations (GPS, GLONASS, GALILEO, and BeiDou), we compared satellite positions and clock offsets from broadcast navigation files to those interpolated from precise orbit files (Stressler et al., 2018a). Satellite ephemerides for each constellation are available as part of MGEX through several IGS analysis centers. Precise orbits are provided in sp3 files and broadcast orbits are available in RINEX format. This study showed very similar agreement between the precise and broadcast ephemeris within about an hour of the reference epoch.

As Figure 5 shows, the average 3D error is minimized for the longest amount of time (over 2 hours) for GPS, with Galileo and BeiDou also agreeing at the meter level for over an hour before and after the time of ephemeris. Galileo broadcast orbits agree the best with the precise orbits close to ephemeris time (within less than a meter), while BeiDou and GLONASS differ by several meters.

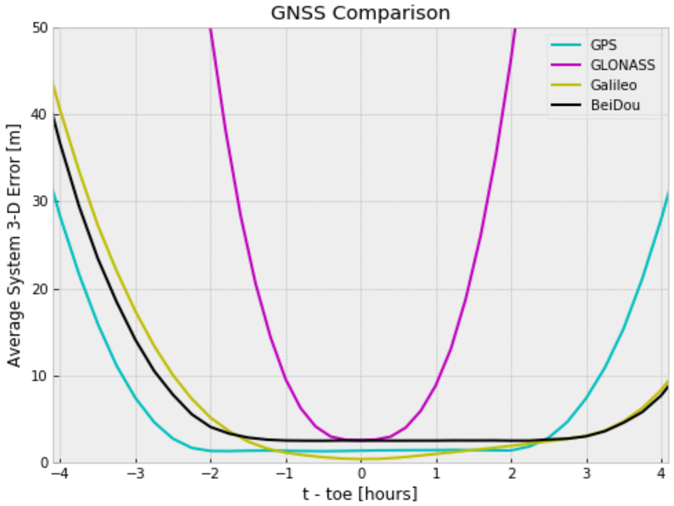

Figure 5. A comparison of the system 3D error of each of the constellations. The average 3D error is minimized for the longest amount of time (+ 2 hours) for GPS, with Galileo and BeiDou also agreeing at the meter level for over an hour before and after the time of ephemeris.

Additional signals (such as GPS L5 or GLONASS L3) help with showing the quality of the signal received. Triple-frequency observations can be used to form several different linear combinations to estimate the contributions of code and phase multipath.. Figure 6 shows how the source frequency of phase biases identified in triple frequency phase multipath combinations can be determined by comparing different code multipath combinations.

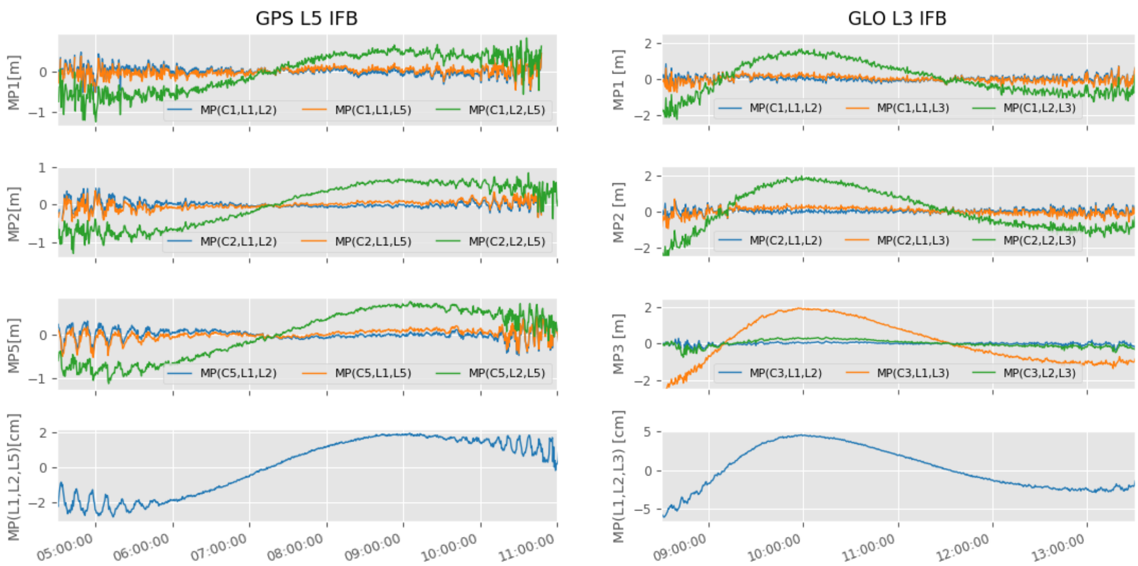

Figure 6. Code multipath combinations for GPS (left) and GLONASS (right). Subplots (a)-(c) show the different permutations of code multipath combinations using different carrier frequencies. By comparing these combinations to the triple frequency phase combinations (d), we are able to tease out the source frequency of the phase biases. For example, the pattern of GPS MP(C5,L2,L5) in (c) matches that of MP(L1,L2,L5) while MP(C5,L1,L2) does not. From Stressler et al., 2019.

One significant area of NGS operations that is already seeing improved results from the new software tools is in the antenna calibration program. With a new 6-axis robot arm, NGS is improving its capability to perform absolute antenna calibrations. As the software develops for multi-constellation processing, improvements are being made to the antenna calibrations that NGS performs. The IGS publishes type mean values to the ANTEX file for use in routine data processing. Many IGS antenna calibrations are only available for the L1 and L2 frequencies, whereas at NGS we can experimentally calibrate the newer L5 frequency as shown for a Septentrio Choke Ring SEPCHOKE_B3E6 in Figure 7. With the modernization of GPS, L5 calibrations will become very important for improved position determination. Until recently, NGS could only perform GPS antenna calibrations but now has GLONASS calibrations that compare very closely with the results from the IGS type mean as shown in Figure 8 for the same Septentrio antenna.

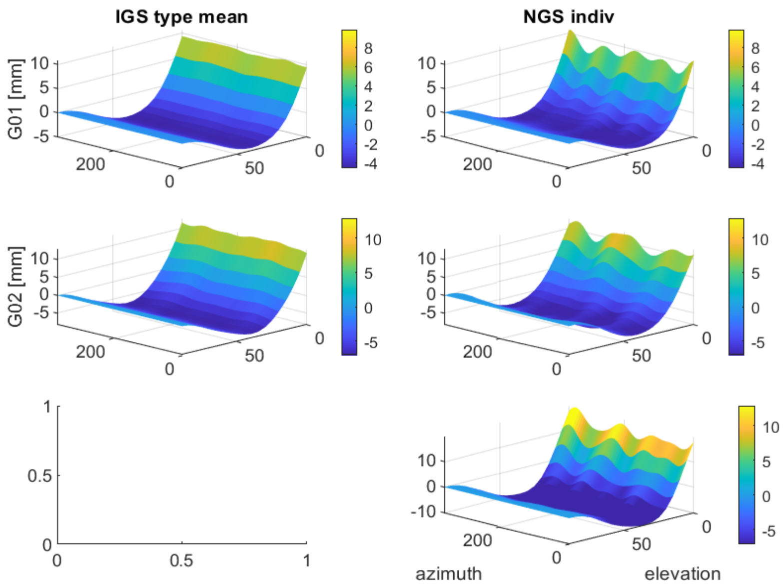

Figure 7. Phase center variations for a Septentrio Choke Ring antenna comparing the IGS calibrations (left) and the NGS calibrations (right).

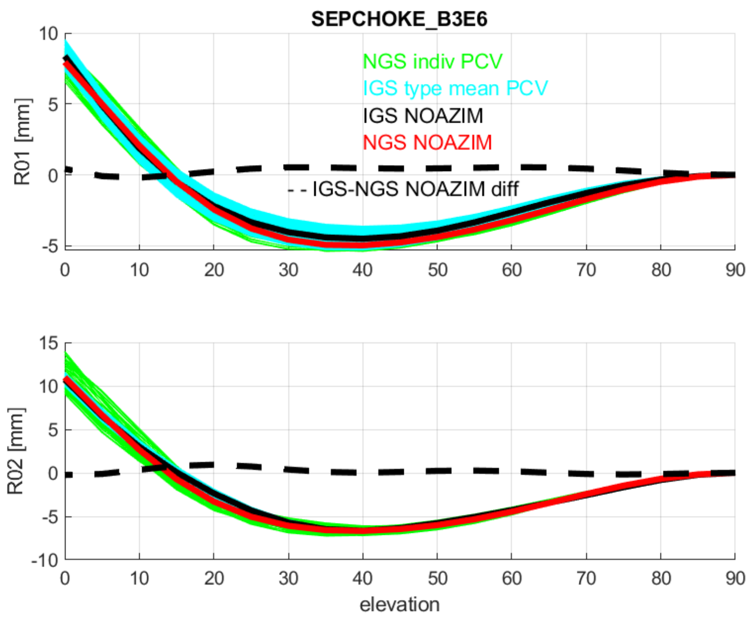

Figure 8. Comparison of GLONASS antenna calibrations as determined by IGS and NGS for signals R01 and R02.

5. SUMMARY

As part of NSRS modernization, NGS is developing new software for processing multi-constellation GNSS. The software will eventually replace the legacy PAGES software in many NGS operations including OPUS, orbit production, and CORS quality monitoring. Using the extra satellites that are available along with the added frequencies should improve the positioning accuracy of OPUS and will allow for better positioning within locations with limited sky view. These changes will result in better tools available to the surveying public that surveyors can easily incorporate into their workflows.

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BIOGRAPHICAL NOTES

Jacob Heck, Bryan Stressler, Clement Ogaja, and Andria Bilich are all Geodesists in the Geosciences Research Division at NOAA's National Geodetic Survey and are members of the GNSS software development team.

CONTACTS

Dr. Jacob M. Heck
NOAA's National Geodetic Survey
1315 East-West Highway
Silver Spring, MD
UNITED STATES
Tel. +1 240 533 9686
Email: jacob.heck@noaa.gov
Web site: https://geodesy.noaa.gov