Haystack Observatory Analysis Center

Arthur Niell, Roger Cappallo, Brian Corey, Mike Titus, Chet Ruszczyk, Pedro Elosegui

Abstract Analysis activities at MIT Haystack Observatory are directed at improving the accuracy of geodetic measurements, whether these are from VLBI, GNSS, SLR, or any other technique. Analysis activities that are related specifically to technology development are reported elsewhere in this volume for the Haystack IVS Technology Development Center, although sometimes the distinction is not clear. Activities and results during the two-year period include the improvement and development of programs and procedures that are used in the analysis of VGOS data, and analysis both of the first extended series of VGOS measurements and of four sessions to determine the vector baseline between the KPGO 12-m and 20-m antennas.

1 Introduction

The past two years have seen the evolution of VGOS observing from one-hour sessions, intended primarily for developing the operational procedures for each session, to full 24-hour sessions involving three stations and four-station sessions for evaluating station performance. Contemporaneously, the correlation and post-correlation procedures have had to evolve to accommodate unanticipated conditions, largely to do with the interaction of the dispersive phase term (ionosphere) and less than optimal hardware characteristics.

MIT Haystack Observatory

Haystack Analysis Center

IVS 2015+2016 Biennial Report

In order to cope with the new observing conditions (much larger differences of TEC between stations and poor phase linearity across the full spanned RF) and with the increase in data quantity, the program *fourfit*, which extracts the delay and phase observables for each scan, was enhanced, and a new program, *fourphase*, was developed to automate one step in the generation of the coherently-combined dual-linear polarization data.

A crucial measurement for current geodetic VLBI systems is the delay on the line carrying the reference frequency to the phase calibration (phasecal) generator. Unfortunately, several of the new VGOS systems lack any Cable Delay Measurement System (CDMS), so a proxy delay based on the multitone phasecal delay has been developed as part of the effort to obtain the best accuracy from these systems.

The major analysis activity was the processing of thirteen sessions of VGOS observations using the 12-meter antenna at the Goddard Geophysical and Astronomical Observatory (GGAO) and the 18-meter Westford antenna at Haystack Observatory. These sessions provided the raw material that pointed out the need to develop many of the improvements described above, and the geodetic analysis verified the level of achievement.

2016 saw initial observations by four new VGOS antennas. The first to become operational was the 12-meter antenna at the Kokee Park Geophysical Observatory (KPGO) (Elosegui et al 2016). Test sessions with GGAO and Westford were initiated for the three other VGOS antennas at Ishioka, Japan, Wettzell, Germany (Wettzell-S), and Yebes, Spain, and the observations were analyzed to uncover problems at those sites in preparation for operations to begin in 2017.

To obtain the maximum benefit of the new VGOS systems, it is essential to tie their positions to the reference frame established by the decades of observations with the legacy S/X systems. Four sets of observations with the legacy 20-meter antenna and the new 12-meter VGOS antenna at KPGO were conducted and analyzed. These observations required the use of mixed-mode correlation of the Mark IV S/X recordings from the 20 meter and the Mark 6 broadband recordings from the 12 meter.

2 Post-Correlation Analysis

The program for estimating the delay and phase for each scan, *fourfit* (originally developed at Haystack as *frnge*), has been evolving since the earliest days of geodetic VLBI. With the implementation of the broadband systems for VGOS, a major upgrade was necessary to allow the simultaneous estimation of the group delay and the dispersive phase term due primarily to the ionosphere (dTEC). Adjustments to the algorithms for estimating the dispersive term were made both to reduce the execution time and to improve the robustness of the dTEC detection.

The program *fourphase* was developed to automate the calculation of the delay and phase differences between polarizations for each station. The application of *fourphase* to one or more strong sources from a session provides the control file for running fourfit on the full set of scans.

3 Antenna Polarization Stability

The differences in delay and phase between the two linear polarizations for each station were monitored from the earliest observations, and they have exhibited extraordinary stability, at the level of a few picoseconds of delay and ten degrees of phase over long periods of time. The delay difference appears to provide a parameter for monitoring otherwise undetectable changes that might have occurred in the broadband instrumentation.

4 Cable Delay Measurement Proxy

The multiple phasecal tones within a band provide a measure of the delay from maser to recorder, including the uplink path for the reference frequency to the phasecal. The uplink cable is subject to stresses from the motion of the antenna that result in changes in delay that, if left uncorrected, can introduce systematic offsets in the estimated geodetic parameters, such as station position. Because there is no CDMS for the GGAO 12 meter, and none is planned for the near future, procedures were developed to measure the azimuth and elevation dependence of the phasecal delay and to apply the results as corrections in the geodetic analysis. This technique can also be used for other systems that lack (at least temporarily) a needed CDMS, such as the 13.2-meter VGOS antennas at Wettzell.

The dependence of the phasecal multitone delay on azimuth for GGAO at one epoch is shown in Figure 1. The delay correction for a scan is obtained by interpolation of the median value to the azimuth of an observation. Because the delay changes due to both wear and environmental conditions, the orientation dependence is measured approximately monthly.

Because the cable delay value is such an essential component of the final geodetic estimation, the usage and accuracy are of interest as Analysis Center activities.

5 Geodetic Analysis

The vgosDb structure is used for the geodetic databases, which are created at Haystack from the data that were correlated and subsequently processed through *fourfit* using the *fourphase* results. The analysis is done with nuSolve, including the use of the appropriately formatted proxy cable delay file (see description in Niell et al., 2016). Both the vgosDb suite of programs and nuSolve are installed and in use at Haystack and will be run on all VGOS sessions processed there.

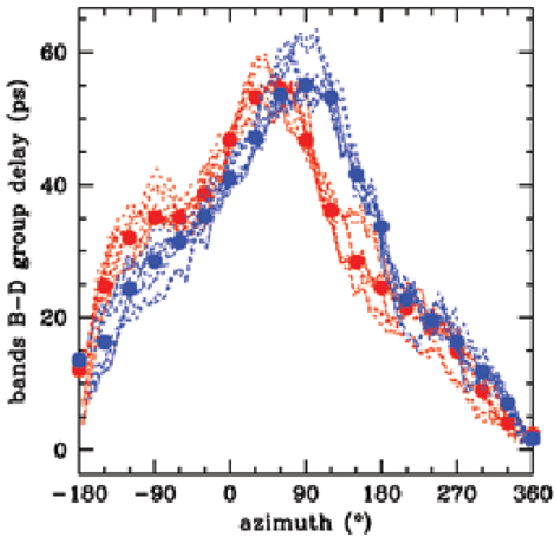

Fig. 1 GGAO12M phasecal multitone delay measurements as a function of azimuth with median values. The averages of the clockwise (blue) and counter-clockwise (red) values were used as nodes for piecewise linear interpolation in azimuth.

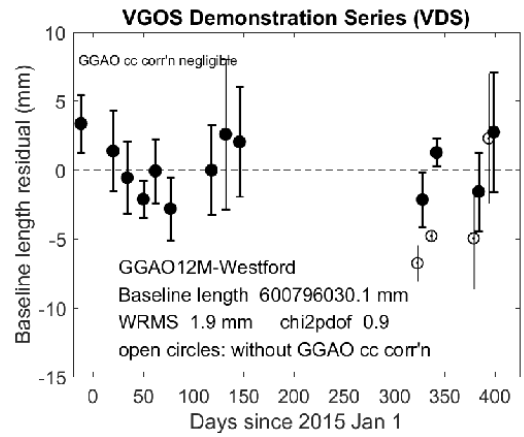

Fig. 2 Baseline length between GGAO12M and Westford VGOS antennas from 2014 December through 2016 February. Solid circles: either no cable delay correction at GGAO12M (first nine sessions) or with cable delay correction when azel dependence was significant (last four sessions). Open circles: length of baseline with no cable delay correction applied for GGAO. No cable delay correction was made for Westford.

5.1 GGAO12M-Westford VDS Sessions

As projected in the 2014 Haystack IVS Annual Report (Niell et al., 2015), the VGOS Demonstration Series (VDS) of primarily one-hour sessions was initiated in 2014 December. Thirteen sessions were successful through 2016 February. The sessions were scheduled, coordinated, correlated, and analyzed through to a geodetic solution by Haystack personnel. Due to lack of time, the proxy cable delay values for GGAO12M were applied to only the last four sessions. For the first nine sessions, the 5 MHz cable at GGAO showed less than a few picoseconds of variation with antenna orientation, so any correction in the baseline length is expected to be less than one millimeter. For the last four sessions, application of the proxy cable delay reduced both the WRMS scatter of the baseline lengths and the post-fit group delay residuals, supporting the validity of the proxy concept. As can be seen in Figure 2, the weighted RMS of the cable-delay-corrected length residuals is slightly less than 2 mm with a chi-squared per degree of freedom of about 1.

5.2 Kokee12m

A major milestone was reached during the past two years. The first operational VGOS system was completed at KPGO as a joint USNO/NASA/Haystack project, consisting of a commercial 12-meter antenna and a broadband signal chain designed and constructed by Haystack. As the developer of the signal chain, it was the responsibility of Haystack to validate the geodetic performance of the antenna and broadband receiver. Six validation sessions of six to 24 hours were conducted with GGAO12M and Westford. Only preliminary geodetic solutions have been completed.

Four sessions, ranging in length from one hour to 22 hours, were observed using the Kokee 12-meter and 20-meter antennas to obtain a VLBI tie of the 12-meter antenna's position to the 20-meter antenna. The broadband frequencies for the 12-meter antenna were changed from the standard VGOS values to provide overlap with the fixed frequencies of the 20-meter S/X Mark IV system. Both the S-band and X-band data were correlated on the DiFX correlator at Haystack using mixed-mode, but only the X-band data were analyzed, because the ionosphere difference between the antennas is negligible. After some modifications to *fourfit*, the four sessions yielded a three-dimensional local tie with a precision of approximately 1 mm.

6 Analysis Challenges

At this point (2017 January), implementation of the broadband delay capability that enables the VGOS concept still has several tasks that need development or understanding in order to attain an operational network.

- Work towards automation of the correlation and post-correlation processing of over 1,000 scans per session for each baseline.
- Improve the cable-delay proxy procedure and accuracy.
- Account for, and reduce, phase non-linearity across the bands.
- Understand the sampler delay *a priori* differences between bands for different cable types.
- Develop procedures for calculating correlated flux density by band.

7 Outlook

During the next biennium we will address the challenges of the previous section. In addition, the size of the VGOS network and the diversity of antenna systems will increase, and new challenges will certainly present themselves. Although not discussed explicitly, it is imperative to combine the VGOS and legacy networks in order to optimally incorporate the VGOS stations into the ITRF established by the legacy stations. The procedures for accomplishing this are not fully developed, although they are being worked on.

Acknowledgements

We thank the many people who have worked to implement the VGOS stations and bring them to operations.

References

1. Elosegui et al., Accuracy evaluation of the next-generation VLBI systems from first observations (paper G41B-1016), AGU Fall Meeting, San Francisco, 2016.
2. Niell et al., Haystack Observatory Analysis Center, in International VLBI Service for Geodesy and Astrometry 2014 Annual Report, edited by K. D. Baver, D. Behrend, and K. L. Armstrong, NASA/TP-2015-217532, pp. 225–228, 2015.
3. Niell et al., VGOS observations with Westford, GGAO, and the New Station at Kokee, Hawaii, IVS 2016 General Meeting Proceedings "New Horizons with VGOS" Edited by Dirk Behrend, Karen D. Baver, and Kyla L. Armstrong NASA/CP-2016-219016, pp. 44-48, 2016.