Haystack Observatory Analysis Center

Arthur Niell, Roger Cappallo, Brian Corey, Mike Titus

Abstract Analysis activities at Haystack Observatory are directed at improving the accuracy of geodetic measurements, whether these are from VLBI, GNSS, SLR, or any other technique. Those 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. In this article we describe upgrades to the VGOS signal chain instrumentation at GGAO12M and Westford, present a preliminary analysis of the one-hour VGOS session held in December 2014, and discuss the results and potential impact of measurements of apparent cable delays for both the GGAO12M and Westford broadband systems

1 Introduction

The broadband instrumentation for the next generation geodetic VLBI system, previously called VLBI2010 but now referred to as VGOS (for VLBI2010 Global Observing System), was implemented on a new 12-m antenna at Goddard Space Flight Center near Washington, D.C. and on the Westford 18-m antenna at Haystack Observatory near Boston, Massachusetts, USA. In October 2012, the first geodetic observing sessions were conducted using the broadband system, and in May 2013 a 24-hour session yielded measurements of correlated flux densities as well as estimation of geodetic parameters. Results from these sessions were described in previous IVS publications [1] [2].

MIT Haystack Observatory

Haystack Analysis Center

IVS 2014 Annual Report

Most of 2014 was an upgrade period for the Westford 18-m antenna broadband system. The only session with reportable geodetic VLBI results was observed on December 19, 2014.

In the area of analysis of measurements related to geodetic accuracy, several single-antenna sessions were used to determine the instrumental effects which might degrade the accuracy of the VLBI observations, such as sensitivity of cable electrical length to antenna position or motion.

In this report we highlight changes in the instrumentation that have been implemented since the previously reported results, summarize the geodetic analysis of the December session, and describe some results of the measurements made to determine the extent of uncalibrated orientation-dependent and motion-induced variations in cable electrical length.

While these activities are being reported as part of the Analysis Center activity at Haystack, the division between technology development and technique development is fuzzy. The activities that are reported here are related to analysis of the VGOS observations and validation of the technique.

The features of the VGOS system as implemented on the GGAO12M and Westford antennas are repeated here for reference:

- four bands of 512 MHz each, rather than the two (S and X) for the Mark IV systems
- dual linear polarization in all bands
- multitone phase cal delay for every channel in both polarizations
- group delay estimation from the full spanned bandwidth, which in recent sessions extends from 3.0 GHz to approximately 10.7 GHz

- simultaneous estimation of the total electron content difference (dTEC) between sites and the ionosphere-free group delay, using the phases across all four bands.

The features indicated in the last three bullets have required changes in analysis of the geodetic delays, and these have been implemented in the post-correlation software *difx2mark4* and *fourfit*.

2 Instrumentation Improvements and Observing Parameters

Several improvements were made to the instrumentation after the May 2013 session. In the Westford front end (Dewar and post-Dewar electronics), the Monitor and Control Instrumentation was rebuilt to provide more reliable and versatile functionality. But the most significant changes were the upgrades of the digital backends from RDBE-H (real samples, Mark 5B format) to the RDBE-G (complex samples, VDIF format). Internally the RDBEs were improved by the replacement of both the NRAO synthesizer and the attenuator assembly with, respectively, a much simpler Haystack-designed synthesizer and commercial attenuators. The RDBE-G also has a new personality (fpga3.0) that incorporates noise diode control; internal time-comparison of the GPS, maser 1pps, and RDBE pulse; and pulse cal extraction. Equally significant, recording is now on a single Mark 6 instead of four Mark 5Cs.

The frequencies of the four 512 MHz bands were chosen to span the range 3 GHz to 10.7 GHz with lower edges of approximately 3.0 GHz, 5.2 GHz, 6.4 GHz, and 10.2 GHz. The lower limit was chosen to avoid the effect of RFI at S-band for these initial VGOS sessions, and the high frequency limit was chosen to make use of the upper end of the available frequency range of the UpDown Converter, but to be below the frequency where the sensitivity begins to decrease significantly. The frequencies of the two intervening bands were proposed by Bill Petrachenko (private communication) to provide the best delay precision when the TEC difference between antennas is also estimated.

The frequency sequence, or ‘frequence’, within a band was changed to a minimum redundancy sequence, thus improving the delay sensitivity and reducing the sidelobes in the delay resolution function [3].

3 The Observing Session of December 19, 2014

This one-hour session, denoted X141219, was initially planned to be the first of a series of sessions for which the only objective was to develop observing procedures for the two stations, but interest evolved, and the goal was expanded to encompass all activities associated with a VGOS observing session.

The schedule was generated using *sked*. As reported last year, because *sked* does not yet have the capability to account for the antenna performance at all four bands, the SEFDs at both S-band and X-band as used in *sked* for the two antennas were adjusted to allow use of the R1 session parameters. The 100 strongest sources were selected from the catalog of good geodetic sources. The minimum elevation was set to 5° for both antennas (although it was subsequently discovered that the minimum usable elevation for GGAO12M is 6.25°). Furthermore, for GGAO a cone with half-angle of about 20° centered on the direction to the SLR site to the southwest was masked out to avoid potential damage to the LNAs by the SLR aircraft avoidance radar. A minimum scan length of 30 seconds was set, and the minimum SNR was set to 15 for both bands. As generated by *sked* the average observed scan length was 31 seconds, and the average number of scans per hour was 48. The observed SNRs for the coherent fit of all bands and both polarizations range from 38 to 375 with a median value of 83. From these numbers it is clear that for future sessions the minimum observation time can be significantly reduced if the goal is a minimum SNR of 20. Of course weaker sources can also be introduced to improve the sky coverage.

The process for the geodetic analysis of the session is described in the Haystack Observatory Analysis Center Annual Report for 2013 [4]. Briefly summarized, the correlator output from each of the four bands is processed with *fourfit* to determine that the same clock offset model can be used and that the data quality is acceptable; the four bands are combined in one file using *fourmer*; the delay and phase offsets between polarizations are obtained from one or more strong sources using one polarization of GGAO12M as the reference; *fourfit* is run on the combined data from all four bands, including both polarizations, to determine a single delay observable; the *fourfit* output is converted to a database and meteorological data are added, and parameter estimation is done using *nuSolve*.

For the *nuSolve* analysis, because this is only a one-hour session, the model parameterization was relatively simple. The estimated parameters were the clock behavior at GGAO, the position of GGAO, and the atmosphere zenith delays and gradients at both stations. The clocks and atmospheres were modeled as piecewise-linear (PWL) functions using the default constraints from *nuSolve*. The post-fit delay residuals are shown in Figure 1. The WRMS is 5.6 psec.

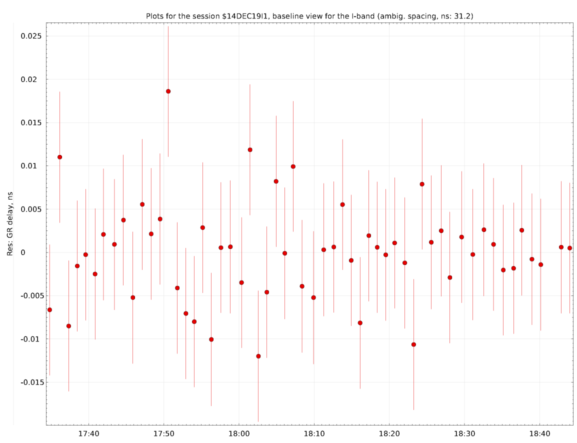

Fig. 1 Group delay post-fit residuals for X141219 after re-weighting. The weighted RMS value is 5.6 psec. The horizontal axis is time, spanning the 72 minutes of the session. The vertical axis is delay in nanoseconds, from -0.020 to +0.025.

The uncertainties for the position components of GGAO are sensitive to the length of the segments of the clocks, zenith wet delays, and gradients. The solution corresponding to Figure 1 used four segments for each of clocks and ZWDs and two segments of gradients in the one hour session. The resulting uncertainties for GGAO in Up, East, and North are 6.1, 2.5, and 1.6 mm.

4 Uncorrected Delays Due to Antenna Motion

As mentioned in last year's report, the two sites do not yet have delay measurement instrumentation for the cable carrying the 5 MHz reference signal from the maser to the phase calibration generator in the front end. Any variation of delay in this cable would thus produce an uncorrected variation in the observed delay. If this variation is correlated with antenna position, it may result in an error in the estimated position. The most common problem is for the delay to vary due to cable stretching with motion in elevation or in azimuth (or both), although change related to thermal variation as solar illumination varies might have a small effect.

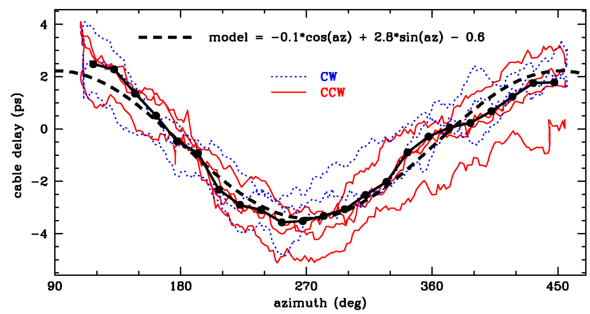

Fig. 2 Azimuthal variation of Westford 5 MHz one-way cable delay on June 20, 2014 measured with a Mark IV cable cal system. Each thin line represents the delays measured while the antenna slewed ∼345° in one direction, with dotted lines = CW and solid lines = CCW; data have been smoothed with ∼20° boxcar averaging. Heavy solid curve and points are medians of unsmoothed data in 15° bins, and heavy dotted line is a best-fit sinusoid. Azimuth limits at Westford are 90° and 470°.

In 2014, the 5 MHz cables at both sites were replaced because the old cables exhibited strong azimuthal delay dependence of 20-30 ps. Significant reduction in the azimuth variation was achieved at both sites, as shown in Figures 2 and 3. At Westford the azimuth dependence is well described by a sinusoid of amplitude ∼3 ps. If VLBI data are left uncorrected for this effect, a shift in the local E-W position of ∼1 mm will result. At GGAO the delay variation over azimuth is ∼1 ps with the LMR-400UF cable and ∼8 ps with the RG-214 cable. Hysteresis effects of order 2-3 ps are present with the RG-214 cable, as seen in the differences between the CW and CCW data; these effects make it difficult to model the variations. A further complication to modeling is the fact that the GGAO delays are the sum of uplink and downlink delays, whereas corrections should only be made for the uplink delay. At present the LMR-400UF cable, with its smaller azimuth dependence and hysteresis, is used to carry the 5 MHz signal. The elevation delay dependence (not shown) is $<\sim 1$ ps at both sites.

It is clear from cable delay measurements conducted over the last few years that the 5 MHz cables can degrade over time scales of months to years, in the sense of developing stronger azimuth variations and hysteresis effects. Until permanent cable measurement systems are installed at both sites, periodic monitoring of the cable delays will be carried out to check for changes in the orientation dependence.

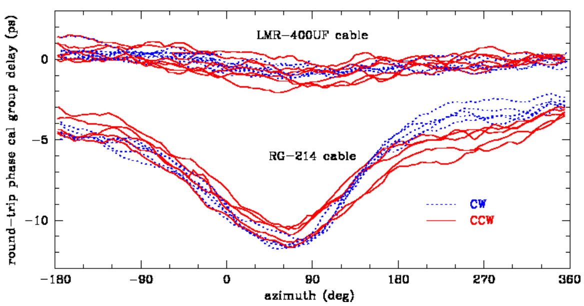

Fig. 3 Azimuthal variation of the GGAO 12-m round-trip cable delay on December 5, 2014 for two different 5 MHz cables. Delay is the group delay of the phase cal phases over a 500 MHz span and represents the sum of the delays in the uplink 5 MHz coax cable and the downlink RF optical fiber. Data have been smoothed with 20° boxcar averaging. Azimuth limits on the 12 m are -180° and 360°.

5 Outlook

Observations using the GGAO12M and Westford antennas are scheduled to become more frequent beginning in January 2015 with the initiation of the VGOS Demonstration Series. This series will initially be a set of six bi-weekly sessions of nominally one hour duration using the same observing configuration as was used for the X141219 session. The goal for the observations is to develop and demonstrate the full data path for a VGOS session, from schedule to analysis. Based on the degree of success of those sessions, the duration of a session and the frequency of further observations may be increased. Other session parameters, such as length of scan and the band frequencies, will also be investigated. By mid-year, monthly twenty-four hour sessions are expected to be conducted.

Acknowledgements

We thank the Broadband Development group for their efforts in constructing, implementing, and operating the systems at GGAO and at Westford and for assisting in the testing and observations; John Gipson for guidance in getting sked to work; David Gordon for getting the broadband output into databases; and Sergei Bolotin for developing *nuSolve* and getting it to work with the new broadband observable.

References

1. Niell et al., First Broadband Results with a VLBI2010 System, IVS 2012 General Meeting Proceedings, NASA/CP-2012-217504, D. Behrend and K. D. Baver (eds.), 13-17, 2012. http://ivscc.gsfc.nasa.gov/publications/gm2012.
2. Niell et al., VGOS Operations and Geodetic Results, IVS 2014 General Meeting Proceedings "VGOS: The New VLBI Network", D. Behrend, Karen D. Baver, and Kyla L. Armstrong (eds.), 97-101, Science Press (Beijing). ISBN 978-7-03-042974-2, 2014. http://ivscc.gsfc.nasa.gov/publications/gm2014.
3. Rogers, A. E. E., Effective Bandwidth for Phase Delay Measurements, Radio Sci., 5, 1239-1247, 1970.
4. Niell et al., Haystack Observatory Analysis Center, in International VLBI Service for Geodesy and Astrometry 2013 Annual Report, edited by K. D. Baver, D. Behrend, and K. L. Armstrong, NASA/TP-2014-217522, 276-279, 2014. http://ivscc.gsfc.nasa.gov/publications/ar2013/index.html.