Haystack Observatory Analysis Center

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Abstract Analysis activities at Haystack Observatory are directed towards improving the accuracy of geodetic measurements, whether these are from VLBI, GNSS, SLR, or any other technique. Those analysis activities that are related to technology development are reported elsewhere in this volume. In this report we present some preliminary results of an analysis of a 24-hour broadband VGOS session from May 22, 2013. The data were calibrated to obtain correlated flux densities at X-band for a subset of the sources, and a geodetic solution was obtained. Both analyses led to improvements in the DiFX correlator and the post-correlation software.

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 the Goddard Space Flight Center near Washington, D.C., USA, 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. Results from these sessions were described in last year's Analysis Center Annual Report. In this report we highlight the procedures for obtaining correlated flux densities and baseline results for a 24-hour session on May 22, 2013.

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IVS 2013 Annual Report

The features of the VGOS system are repeated here for reference:

- four bands of 512 MHz each, rather than the two (S and X) for standard IVS sessions
- dual linear polarization in all bands
- multitone phase cal delay for every channel in both polarizations
- simultaneous estimation of the total electron content difference (dTEC) between sites along with the ionosphere-free group delay using the phases across all four bands spanning 3.2 GHz to approximately 8.8 GHz for this session.

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

2 The Observations

The main objective of the 24-hour session on May 22, 2013 was to validate the quality of the calibration of correlated flux densities on the GGAO12M-Westford baseline. Since the largest number of potential comparison values is from the S/X observations of the geodetic VLBI program, the highest frequency band was chosen to lie within the range of the geodetic X-band, covering approximately 8.3 – 8.8 GHz. The frequencies of the other three bands were the same as used in October 2012, covering 512 MHz beginning at 3.2, 5.2, and 6.3 GHz. S-band was not observed because the presence of RFI was likely to severely limit the validity of any calibration.

The schedule was generated using *sked*. Because *sked* does not yet have the capability to account for the broadband parameters, the SEFDs at both S-band and X-band 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. A minimum scan length of 30 seconds was set, and the minimum SNR was 15 for both bands. The minimum elevation was set to 5°, and a cone about the SLR site to the southwest of the GGAO antenna was masked out to avoid potential damage to the LNAs by the SLR aircraft avoidance radar. The average scan length observed was 31 seconds, and the average number of scans per hour was 48.

The signal chain consisted of a QRFH feed, low noise amplifiers, and phase calibration injection in the payload near the focus for both antennas, and four Up-Down Converters, RDBE-Hs, and Mark 5C recorders in the control room. These are described more completely in Niell et al (2012).

3 Correlated Flux Density Measurements

The correlated flux density S_c for each observation was obtained from the correlation coefficient ρ as:

$$S_c = b * \rho * \sqrt{(SEFD1 * SEFD2)} \qquad (1)$$

where

- b= 1.13 for DiFX correlator (Cappallo, private communication)
- SEFD1,2 = System Equivalent Flux Density for GGAO and Westford at the time of the observations.

The SEFDs in the 8 GHz band (X-band) were obtained for each scan by scaling the on-source power level at the time of each observation to the on-source minus off-source power difference for CasA. The measurements for CasA were made before, after, and near the middle of the session. However, the elevations of the source at the beginning and end were too low for useful measurements, so only the mid-session value was used for calibrating the correlated flux densities. The CasA power was corrected for partial resolution of CasA because the angular size is not negligible compared to the half-power beamwidths of the two antennas. This method of estimating the SEFD is valid provided the system gain does not vary between the observation epoch and the CasA measurement epoch, so that system power tracks system temperature. Analysis of the phase cal amplitudes at the two stations showed that the gain variations were small.

The weather was stormy at Westford, and the system power varied by more than a factor of two during the first ten hours. Water on the Westford radome was largely responsible for the higher power levels. Besides affecting system temperature, variations in the thickness of the radome water layer or in atmospheric attenuation at either site can also cause variations in signal transmission loss from quasar to antenna feed. Corrections to the correlation coefficients were made for this latter effect.

Instead of displaying the correlated flux densities, we show, for twelve of the strongest sources and for the vertical polarization (V-pol), the ratios between the correlation coefficient for each scan of each source and the median value for that source using all of the data for the 24 hours (Figure 1). The three frames are for a) the observed correlation coefficients directly from the correlator; b) the same but multiplied by the square root of the product of the (equivalent of the) system temperature; c) and further corrected for absorption by the atmosphere and by a radome water layer using a simple model. The larger scatter for the first ten hours exhibited in 1c) is thought to be due to incomplete correction for variations in system temperature and absorption by the radome. For the last 14 hours, except possibly for the source 3C418 (blue crosses), the ratios are consistent with the sources being unresolved (no change in correlated flux density with baseline orientation). Because this is expected for good geodetic sources on this short baseline, the result is supportive of the calibration procedure.

4 Geodetic Analysis

The four bands were correlated independently and were first analyzed separately with the delay-estimation program *fourfit* to verify that the correlation was correct before being combined into one data set. Phase cal was applied using the ‘multitone’ option in

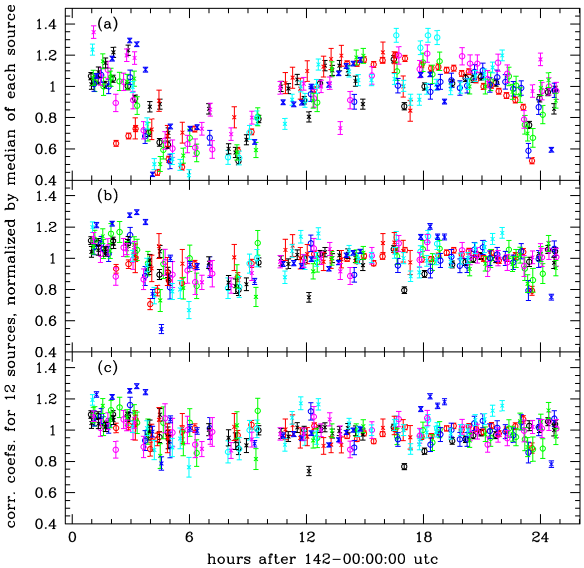

Fig. 1 The correlation coefficient ratios to the median values at X-band for twelve sources: a) correlation coefficients from the correlator; b) correlation coefficients corrected for on-source power; c) furthur correction for atmospheric and radome loss.

fourfit which calculates the delay for each 32 MHz channel from the six or seven tones spaced 5 MHz apart. The four bands, each having two polarizations, were then combined into one file using *fourmer*; then *fourfit* was used to coherently estimate the group delay for all four bands and to obtain the coefficient of the inverse frequency dependence of the phase which is attributed to the differenced Total Electron Content (dTEC) between the two stations. With the application of multitone phase cal delay, there were no cycle ambiguities.

In order to process the observed delays through *calc* to obtain the observed-minus-model residuals, it was necessary to modify the program *dbedit* (D. Gordon, private communication) to accept delays obtained from 64 channels and from which the dispersive term had already been removed. The data were then analyzed using the program *nuSolve* which is in development by Sergei Bolotin to serve initially as a preprocessor for batch-mode *solve* processing but ultimately as a replacement for *solve*.

For the *nuSolve* analysis, because this is only a single 24-hour session, the model parameterization was relatively simple. Only the clock behavior at GGAO, the position of GGAO for the day, and the atmosphere zenith delays and gradients at both stations were estimated. The clock and atmospheres were modeled as stochastic processes using the default process values from *nuSolve*. Tests were made for comparison using piecewise linear functions with intervals of ten minutes and longer, but the fits were not as good after reweighting.

Short of having a series of observations on different days with which to assess the repeatability of observations with the two antennas, a similar comparison can be made with independent segments within a session. Therefore the 24-hour session was separated into independent six-hour segments. With the high observed scan rate, there were still over 250 useful observations in each segment. This is comparable to the number of scans per station for a full 24 hours in an IVS session.

The length estimates for the full 24 hours and for each of the six hour segments are shown in Figure 2.

Independent measurements of this baseline were made in two six-hour sessions in October 2012 (Niell et al.). The agreement for successive days for the independent polarizations was at the millimeter level. While it would be tempting to compare the baseline length of this May 2013 session, there is reason to refrain: measurements of the phase cal delay obtained from the multitone phase cal processing for both sessions showed a strong dependence of delay on azimuth for the Westford antenna, although the range of variation was different by a factor of about two. For the May 2013 data, the range of delay was about 50 psec, while for October 2012 it was about 25 psec.

Since an uncorrected variation of azimuthal instrumental delay would be interpreted in the estimation process as an apparent error in the horizontal position of the antenna, it is not useful to compare the baseline lengths for the 2012 and 2013 sessions. In the future a cable delay measurement system will be deployed at the sites to reduce these errors to a negligible value (see the Technology Development Center Report for Haystack Observatory, Beaudoin et al, this volume).

5 Outlook

Observations using the 12 m and Westford are expected to become more frequent beginning in mid-2014. The correlation and data analysis chain (correlator/*fourfit/solve*) for the stand-alone broadband VGOS

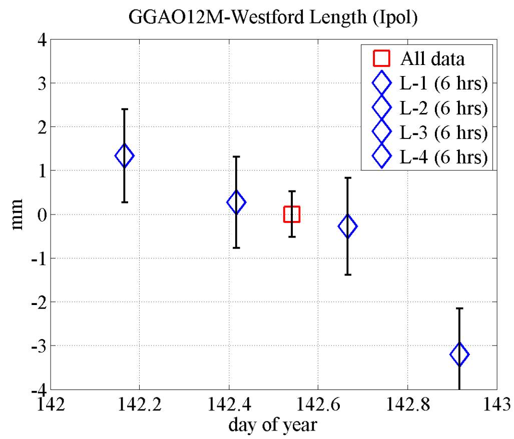

Fig. 2 Baseline length between Westford and GGAO12M on 2013 May22. Red square: solution for all 24 hours of data; blue diamonds: independent six hour segment analyzed with the same parameterization as the full 24-hour solution.

observations and for the mixed broadband-Mark IV observations needs to be developed and made operational.

As a first step in facilitating these developments *nuSolve* has been installed at Haystack and was used for most of the geodetic analysis described in this report. A next step will be to begin to use the vgosDB format, followed by installation of the full *calc/solve/nuSolve* suite of programs.

Acknowledgements

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References

1. Niell et al., “First Broadband Results with a VLBI2010 System”, IVS 2012 General Meeting Proceedings, edited by D. Behrend and K. Baver, NASA-CP-2012-217504, pages 13-17.