Haystack 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, a preliminary analysis of the first geodetic sessions with the new broadband geodetic VLBI system is reported.

1. Introduction

The broadband instrumentation for the next generation geodetic VLBI system, previously called VLBI2010 but now referred to as VGOS (for VLBI2010 Geodetic Observing System), has been implemented on a new 12-m antenna at the 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 two serious geodetic observing sessions were conducted using the broadband system.

The new features for the VGOS system are:

- four bands of 512 MHz each, rather than the two (S and X) for the Mark IV systems

- dual linear polarization in all bands

- more than 30 scans per hour due to the short scans and relatively high slew rates of the smaller antennas proposed for VGOS systems

- multitone phase cal delay for every channel in both polarizations

- group delay estimation from the full spanned bandwidth ($\sim$2.2 GHz to potentially 14 GHz)

- simultaneous estimation of the group delay and the ionosphere TEC difference between sites, 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 fringe-detection software *fourfit*.

2. Observations

For these two sessions the frequency range spanned by the four bands was limited by the hardware capability at the time of the observations. The lower band edges for the lowest and highest bands were chosen to be 3200 MHz and 9344 MHz. A simulation by Bill Petrachenko found that the best frequencies for the other two bands were 5248 MHz and 6272 MHz.

While the goal for the VLBI2010 systems is to reduce the scan length to the minimum in order to obtain the greatest temporal density of scans, for these sessions the minimum scan length was chosen to be 30 seconds to ensure high SNR. This was necessary because of uncertainty in the measured sensitivity of the antennas and in the scaling factors used for the SEFDs in *sked*. These considerations resulted in an observation rate of approximately 33 scans per hour, about double the usual IVS R1 schedule.

A problem that was not anticipated until observations were first made with the MV3 proof-of-concept system at GGAO is the strong impact of the SLR aircraft avoidance radar on the VLBI system. The radar signal, at about 9.3 GHz, is strong enough to damage the VLBI front end. It is now known that the VLBI antenna must avoid pointing too close to the radar when the SLR system is tracking. This means that a cone of the sky with an opening angle of about 40 degrees must be excluded.

The two six-hour sessions were scheduled for October 4 and 5, 2012. On the first day the SLR systems at GGAO did not observe, so the radar was off and a mask on the sky available to the VLBI observations was not required. On the second day the SLR system was observing, the radar was on, and the VLBI schedule avoided the danger zone. The same number of observations was obtained on the two days, but there is a decrease in geometric strength on the second day along the direction to the SLR system (azimuth 195°) because of the loss of scheduled observations in that direction.

Each of the four bands was sampled and formatted in an RDBE-H digital backend running FPGA code version 1.4 which produced eight 32 MHz channels in each polarization. The output from each RDBE was recorded on a Mark 5C.

Phase calibration pulses were injected between the feed and the low noise amplifier to produce tones every 5 MHz in the spectrum.

3. Correlation and Observable Extraction (Fourfit)

The data were correlated on the DiFX software correlator at Haystack Observatory. A separate correlation pass was required for each band, although both the polarization parallel-hands and cross-hands of a scan were correlated at the same time. For each scan fourfit was used to obtain a coherent fit to all phase and amplitude observables for all one-second accumulation periods in the scan.

The instrumental delay from the pulse cal injection point to the digitization point was corrected within *fourfit* for each channel using all of the phase cal phases in that channel.

The estimation of the coherent amplitude, delay, and TEC difference was achieved using recent improvements in the program *fourfit*. The new processing requires several steps.

The steps are:

a) *fourfit* the H and V polarizations separately for each band to obtain amplitude, delay, phase, and delay rate (eight values of each); b) merge the data from the four bands and two polarizations into one file; c) input an *a priori* station delay from the point of phase cal pulse insertion on the antenna to the digitization point in the control room based on the length of the cable; d) input an *a priori* difference in TECs between the sites; for this session the estimation appears to be insensitive to the value used; more work is needed on how to generate the *a priori* value; e) *fourfit* the merged data for each polarization for one or more strong sources to verify (or adjust) the station delays and to determine the phase and delay offsets among the bands; f) *fourfit* the merged data for all bands and polarizations for a combined amplitude, the coherent delay (called pseudo-I delay because it is analogous to the I Stokes parameter), phase, delay rate, and ΔTEC.

The extracted observables were exported to GSFC, where a database was generated by David Gordon; this required modification of the *dbedit* software in order to bring in the delay with ionosphere (charged particle dispersion) already estimated.

4. Analysis

The geodetic analysis was done using *nuSolve*, a new GUI-based program for editing and parameter estimation that is being developed by Sergei Bolotin of NVI, Inc. *nuSolve* was used because of the potential to model the clocks and atmospheres as stochastic processes. However, for the period covered by this report the temporal modeling of all parameters was piecewise linear (PWL). The estimated parameters for the results reported below are the position of GGAO12M, and atmosphere zenith delays and gradients and clock values for both sites. Various time intervals from two hours down to ten minutes were tested for all of the atmosphere and clock parameters. This process was applied to H, V, and I for both sessions. However, the H and V delays did not include estimation of the ionosphere.

A series of trials with varying intervals for atmospheres, atmosphere gradients, and clocks indicated that consistent results and minimum RMS delay scatter could be obtained using 20-minute intervals for the atmosphere zenith delays and clocks and 40 minutes for the atmosphere gradients. The default constraints included in the nuSolve setup were not adjusted. Outliers were excluded in an iterative process of estimation, outlier rejection, and re-estimation, leaving approximately 140 of the original 178 points in the solution. These observations should be examined carefully to determine if the cause for being an outlier can be ascertained.

The delay uncertainties for all observations have a median value of less than one picosecond. After arriving at a set of estimated parameters and retained observations, the additional quadratically-added delay required to obtain chi-square per degree of freedom of 1.0 was calculated within nuSolve (a process known as re-weighting). The additive delay value for both sessions is about 12 psec. This is not unexpected due at least in part to the PWL parameterization of the atmosphere and clock values.

5. Results

The H and V polarization observables are statistically independent as far as system noise is concerned, and thus they provide two separate solutions. However, other sources of noise, such as the atmosphere delay, source structure and positions, and clock variations, are almost completely correlated. Therefore the agreement of the estimated parameters for H and V should be much better than the formal uncertainties. On the other hand, the I solution, for which the delay is a combination of all polarization products, may differ slightly because the TEC difference between the stations was estimated.

The topocentric offsets from the *a priori* position for GGAO12M, as well as the changes in baseline length, are shown in Figure 1. The agreement among the components and length for H and V is reasonable, but the differences for I among the components on the two days is larger than expected. One possible source of the additional scatter is the estimation of the ionosphere. The additional ionosphere delay parameter, which is a quadratic function of frequency, makes the estimated parameters susceptible to systematic phase errors among the different bands. Clearly, a closer look at the data is required.

Delays obtained from the multiple phasecal tones in each channel indicate that there is a large dependence on the direction the antenna is pointing for both Westford and GGAO12M. If the variations were in the signal path from the receiver to the digital back end, the multitone delays would correct them. However there is evidence that the variation occurs in the 5 MHz uplink cable,
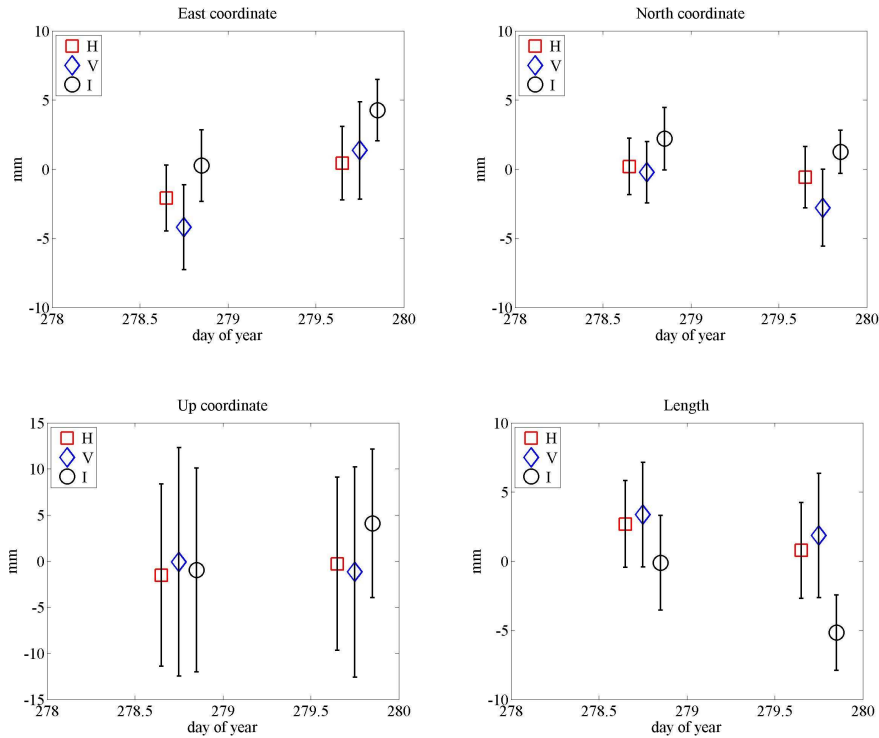
Figure 1. Adjustments to the topocentric position of the GGAO12M antenna and to the length of the baseline. Ionosphere was estimated for I but not for H and V.

in which case it is not corrected. Most of the variation is in azimuth for Westford. Discovery of this effect emphasizes the need for a cable calibration system for the broadband antennas.

6. Outlook

Regular broadband observations using the 12-m and Westford are scheduled to begin in mid-2013. Operational procedures for correlation and data analysis (correlator/fourfit/solve) for both stand-alone Broadband observations and Broadband-Mark IV observations need to be developed.

In order to facilitate development of these procedures we hope to install the new *openDB/ calc/solve* data handling and parameter estimation packages at Haystack. This will allow us to experiment with, understand, and verify the entire data chain from scheduling through parameter estimation.

Acknowledgements

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