**Servo Project Progress Report**
**Dates covered: 1/20/07 to 2/16/07**
**D. Clark**

At last report, we had planned the following activities:

1. Meet with Keith Powell to discuss results and formulate controller iteration design plan.
2. Pursue system identification and simulation as needed to predict the telescope plant response, including verification of open-loop response now that the telescope configuration has changed (*f/9* to *f/5*).
3. Develop controller design changes (filters, gains, etc.) to bring the controller into working order.
4. Test controller iteration with xPC Target test machine for initial verification.
5. Turn over to Trebisky for inclusion in the mount computer code infrastructure.
6. Test VxWorks implementation with the remainder of commissioning checklist items.

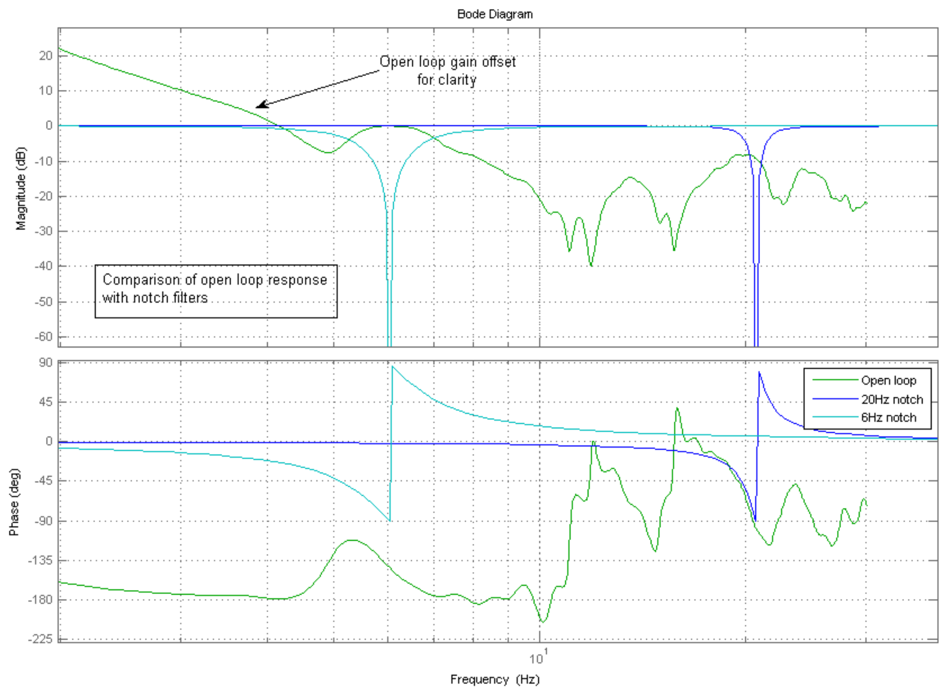
For item 1, Powell indicated a willingness to help on an ad-hoc basis, but with the caveat that he could not be paid due to his work hours being at maximum for students while he remains busy working on CAAO-related activities. He has, however, been available for occasional consultation.

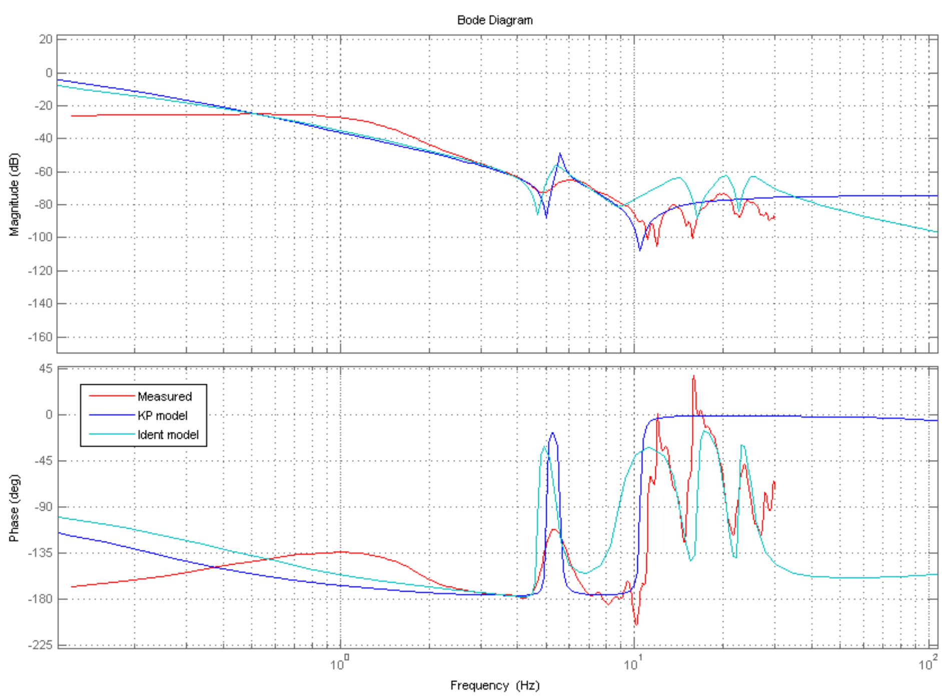
For items 2 and 3, the work focused on a) design of flexible-mode compensation filters at 6 and 20Hz to properly reduce the effects of the resonances on the controller stability, and b) development of a new telescope model that predicts the instability seen with the hardware.

First, an evaluation copy of The Mathworks' Filter Design Toolbox was acquired. This toolbox contains m-file scripts and a small GUI for designing a number of advanced filter types, as well as those (relatively) low-order filters needed for modal notch filters in our application.

Using the open-loop data taken on 1/18/07 (*f/9* Red Channel) using our standard transfer-function estimation tools, and the Filter Design Toolbox, two new notch filters were generated for the 6 and 20Hz structural modes. These filters were centered on the measured modal-frequency centers, but their Q was set conservatively, as lower Q (i.e. broadening the filter notch) gets expensive in terms of phase loss, and could result in closed-loop instability if the phase margin of the controller gets degraded by too much.

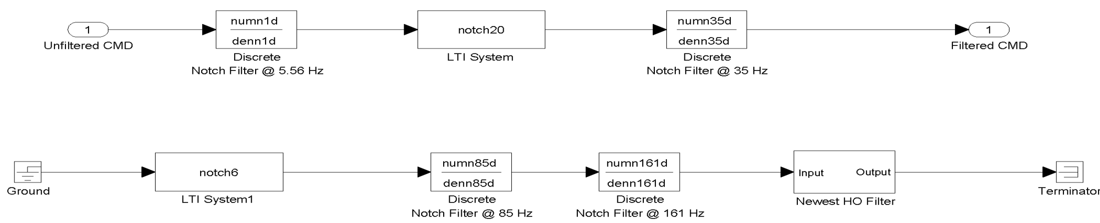
Once the initial filter design was complete, the next thing was to check their operation in simulation to ensure that the controller would work as expected when running the actual hardware. Again, using the measured open-loop data and the System Identification Toolbox, a new mathematical model of the elevation axis was generated and tested in simulation. While this new model is not particularly true to the measured open-loop magnitude response, it does at least more closely match the actual phase response, which is important for stability analysis.



Above, we have comparisons of the notch filter responses with the open-loop measurements, then a comparison of the measured open-loop response with the two models that have been used for design and analysis, the original one developed by Keith Powell, and the new one from the System Identification Toolbox.

For simulation, the new identified model correctly predicted a 20Hz oscillation when using the usual set of flexible-mode compensation filters in the controller. To properly simulate the time response of the telescope, changes were made to the filter bank layout, adding the new 20Hz notch filter and deleting others to properly maintain the closed-loop phase margin for simulations.



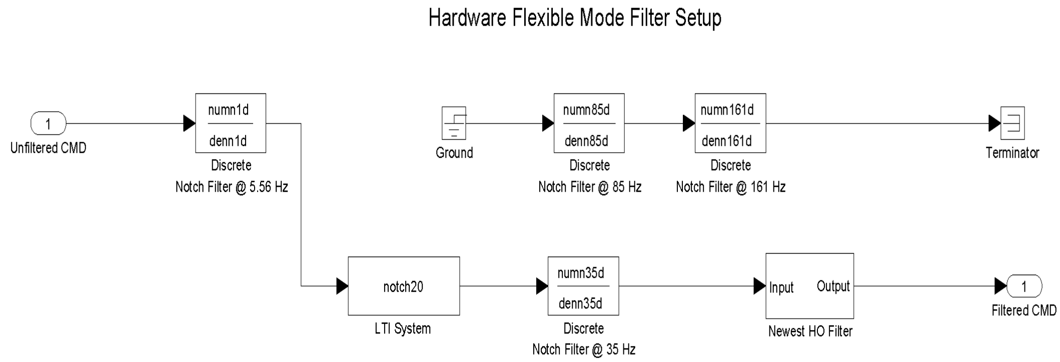

Simulation Flexible Mode Filter Setup

The normal filter setup is to use every filter in this image in series, except for those marked notch6 and notch20, which are the new modal filters.

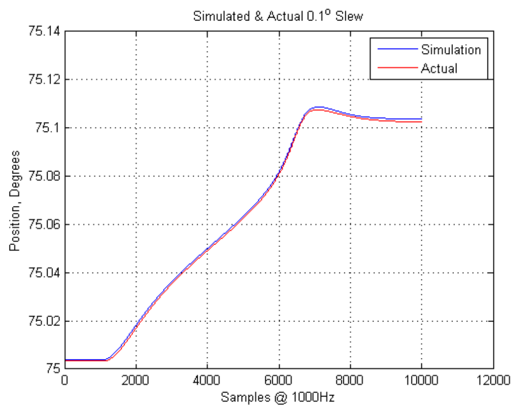
No changes to the controller other than to insert the new 20Hz notch filter were made to prepare the controller for testing in hardware with the xPC Target system. On 2/12/07, the xPC Target controller was tested with the new filter(s) while *f/9* was still installed on the telescope to take advantage of having the same telescope configuration as the last set of tests on 1/18/07.

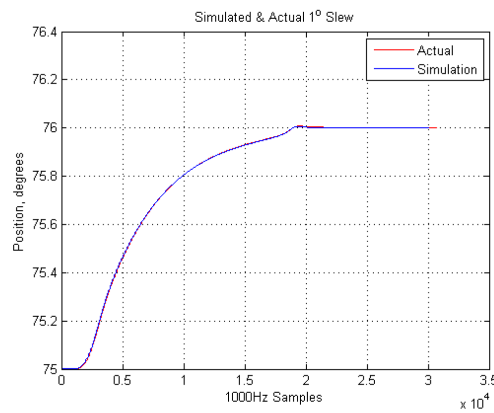
First, the controller was built and run using the same filters and gains as the January tests to verify that the 20Hz instability was still present; this was indeed the case. Next, the filters were arranged as the simulation, the code was rebuilt, and the controller restarted. The telescope had a very loud ~200Hz oscillation at startup, so the filter bank was rebuilt with the “newest HO filter”, which is a high-order rolloff filter for just those high frequencies, and the controller was then stable.

There is, however, a very disconcerting startup oscillation when the amplifiers are turned on and the controller started which results in ~0.3° oscillation in the telescope for about 10 seconds, then damps out and stops. This is most likely a controller initialization problem that has one or more integrators wound up early in the startup process. Solving this particular issue will require more investigation.

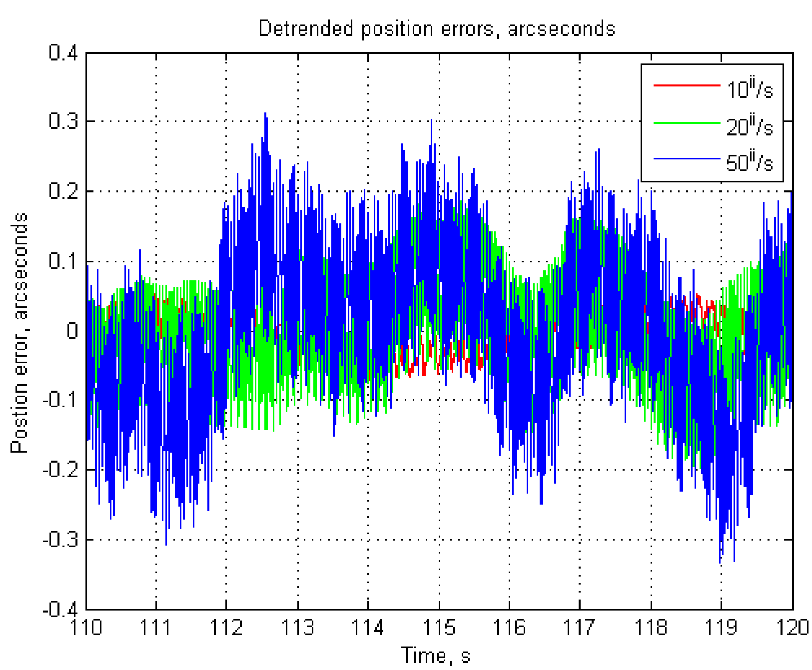



Once the controller was set up and working, the initial testing was done using the Java GUI developed in January for testing slew and track behavior of the controller. Below are comparisons of the time-simulation of slews and the actual slew results:

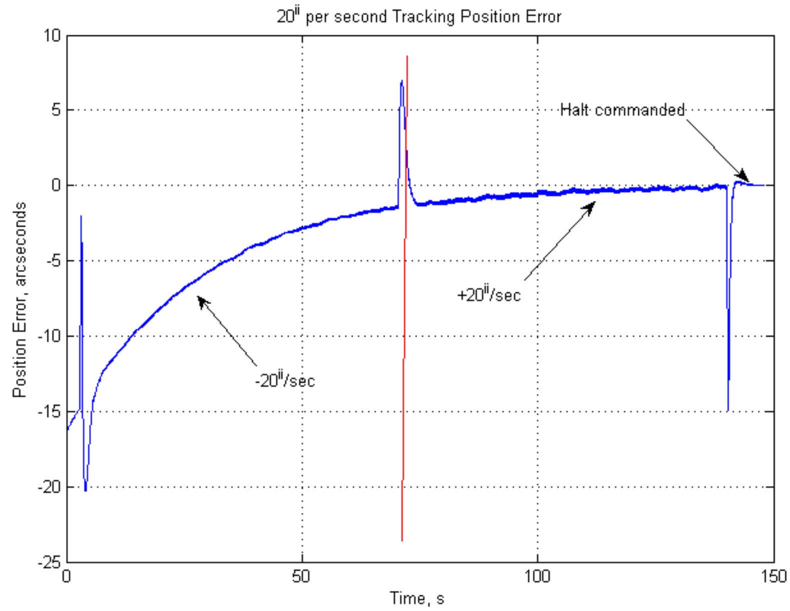


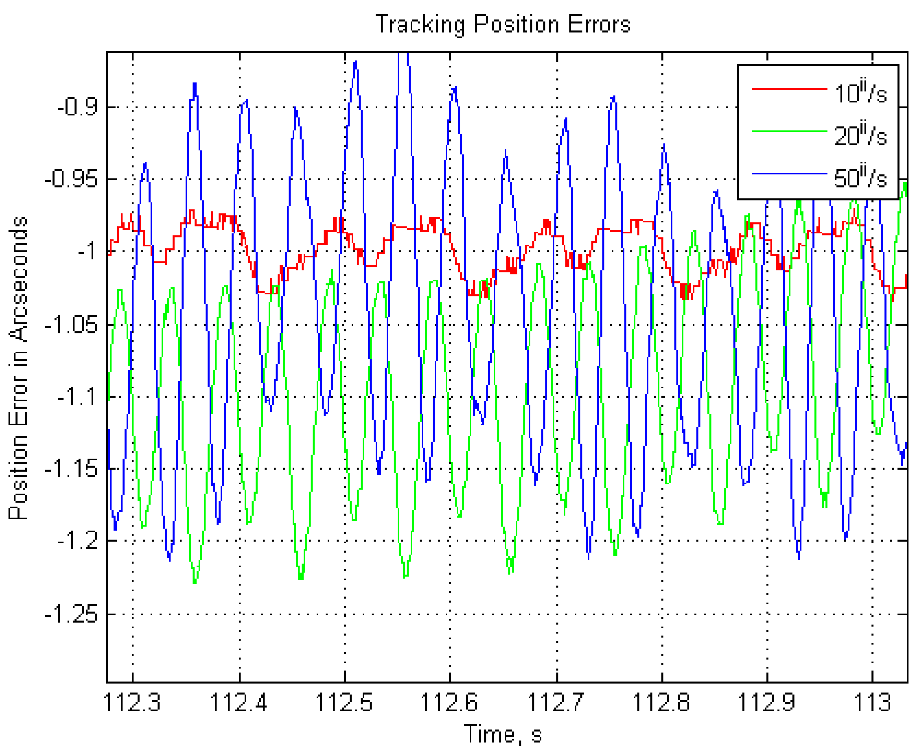

Slews of up to 20° were done; data was collected for 0.1, 0.5, 1.0, and 10° slews, with good agreement with the simulation with all of them. The Java GUI was then used to command constant-speed tracking at 10, 20, and 50 arcseconds/second.  A detrended subset of the position error signal is shown here:



Below is the position error signal while tracking at ±20 arcseconds/second. The telescope balance is obviously favoring one direction over another, and the slow rise time of the error signal towards zero is indicative of integral gain that is too low.




Clearly low-frequency periodic structure can be seen in the data. This will require further investigation to determine its source; an early suspect may be torque ripple on the elevation motors. But, for these short tracking periods, the standard deviation of the position errors are 0.1255 arcseconds, 0.3819 arcseconds, and 0.6455 arcseconds for the

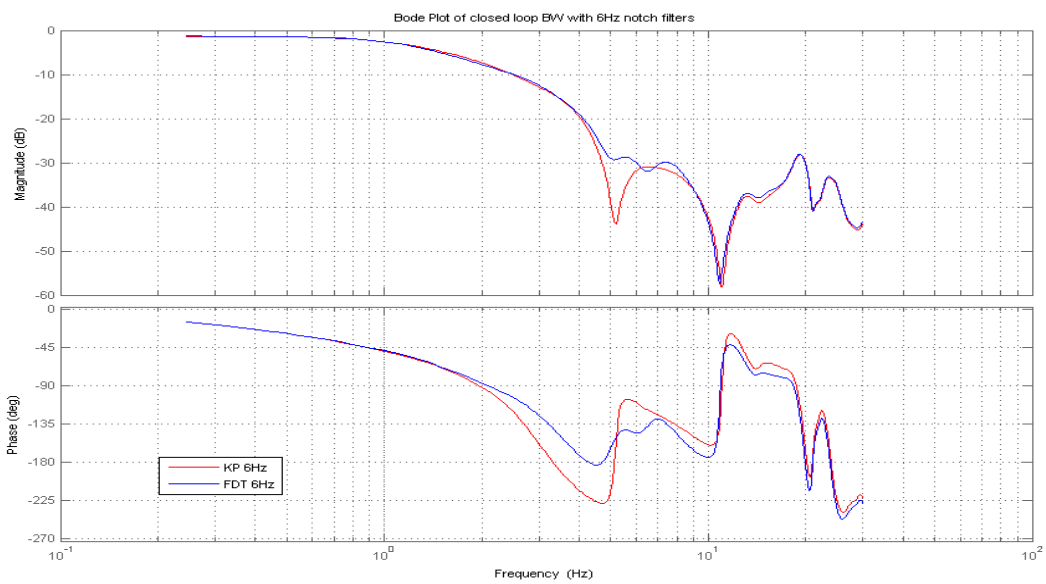


10, 20, and 50 arcsecond/second rates, respectively. Inspecting the PSD of the data shows that the 20Hz modal frequency crops up in the two faster rates, increasing in a non-linear fashion with velocity. This can be seen in the above magnification of the time data.

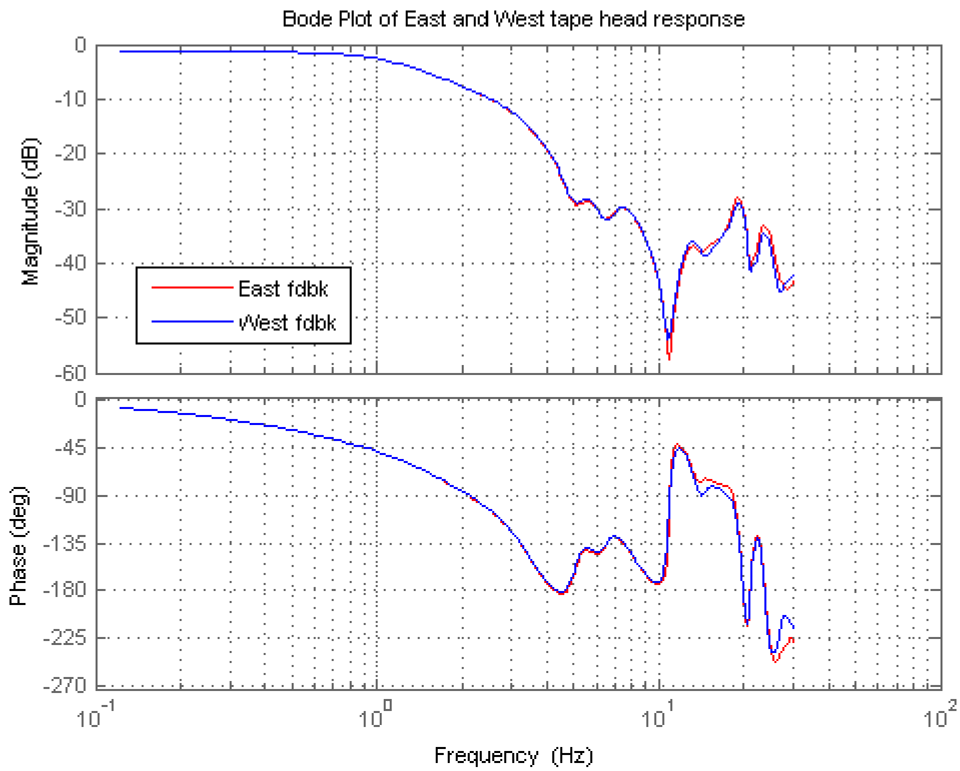
Once the slew and track time data were collected, it was time to move on to collection of frequency-response data. In this case, the command pre-processor was disconnected from the controller command signal input, and a chirp signal input scaled to 0.01° peak was connected. The controller bandwidth can then be directly measured by comparing the input command signal with the actual telescope motion from the encoders. A further test, injecting the chirp signal into a summing junction with the DAC signal and measuring the response, i.e. disturbance rejection, was not pursued in the interest of time. Several measurements of the closed-loop command signal response were done: a) with the new 20Hz filter and the “standard” 6Hz filter, b) with both the new 6Hz and 20Hz filter in place, and c) with the loop closed on the West tape encoder, instead of the East unit.

This allowed investigation of the effect of the two new filters, and verification that both tape encoders do in fact, have the same frequency response. At present, the tape encoders have different mounts; closing the loop on both eliminates any question that bringing the West unit up to the same standard as the East will have any effect on the servo loop performance. It is planned to install the new-style mount on the West unit soon due to its superior alignment ability and concomitant improvements in encoder output signal quality.

First up is a comparison of the two 6Hz notch filters:




Next, closing the loop on the two tape heads:



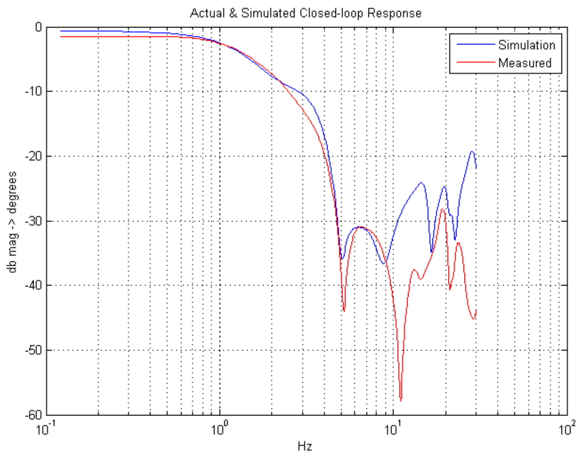

Clearly, there's no practical difference in using the two tape heads. Inspection of the closed-loop response reveals these facts:

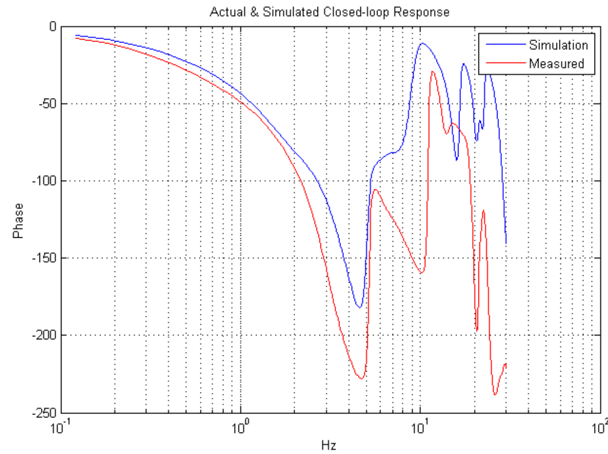
1. The servo loop bandwidth is ~1Hz. This is probably too low for comfort in science observing.
2. The 6Hz filter notch is correctly centered on the modal frequency, since it has nearly-equal sidelobes around the center frequency. This filter needs to have lower Q to suppress more of the modal frequency response. As it is, it allows more phase margin than the original filter.
3. The 20Hz filter notch, on the other hand, is not centered, since it has unequal sidelobes, and it also needs lower Q to capture more of the modal energy. Caution will be necessary to ensure that adjustment of the filter characteristics does not result in an unstable control loop.

The controller as it is now, while needing more optimization, *could*, in theory, be released for implementation as the MMT elevation controller. It is stable and behaves as expected in slewing and tracking. This is not recommended; optimization of the controller would be of great benefit. The optimizations needed are:

1. The notch filter responses need to be adjusted to more closely correspond to the modal response of the elevation axis.
2. The controller gains should be increased to raise the closed-loop bandwidth.
3. Any startup oscillation in the VxWorks implementation should be dealt with; it is potentially hazardous to personnel and equipment. It is expected that this problem is mainly with the xPC Target version, as we have not heretofore seen large startup excursions while testing the VxWorks version.

Below are comparisons of the actual and simulated closed-loop response:




Using the model to drive design optimizations is clearly possible, keeping in mind the general lack of fidelity above 8Hz, as shown above. More work in this direction is needed. Also, we need verification of the controller robustness w.r.t. implementation with the *f/5* telescope configuration, to ensure a "comfort zone" when attempting to use the controller with *f/15*, which is considerably more fragile than either of the other configurations.

Activities for the next period:

1. Adjust notch filters as necessary to optimize performance.
2. Increase servo loop gains and verify simulation results.
3. Measure *f/5* configuration response with the same controller setup as used for *f/9* to characterize changes (if any) to the telescope response.
4. Measure new controller gains and filters on hardware.
5. Prepare for actual deployment of improved controller.