Microseism feed-forward correction at LLO

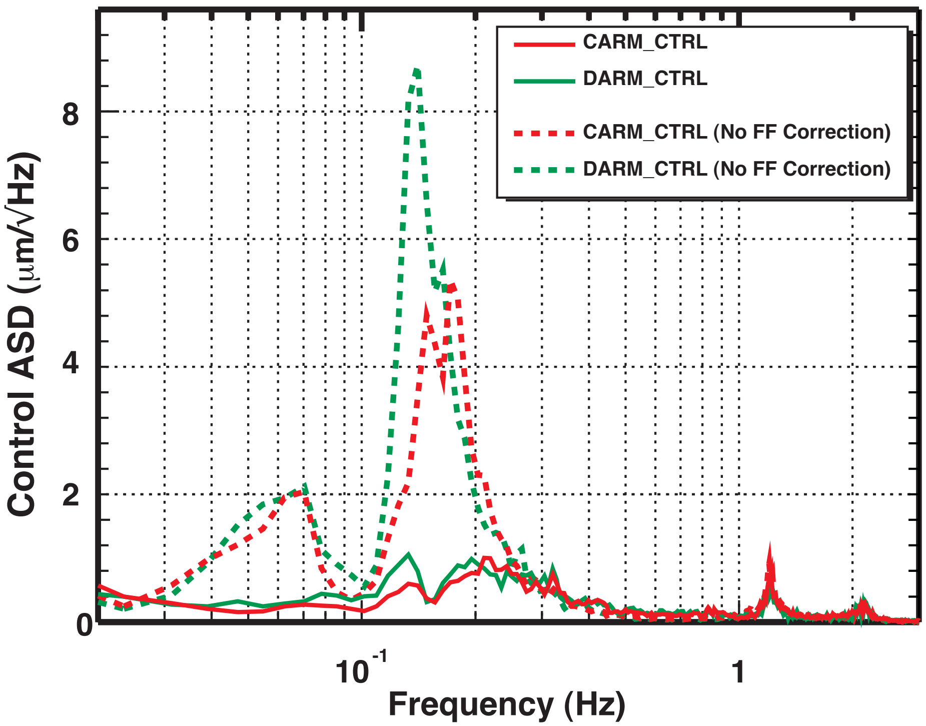
- Standing ocean gravity waves driven by storms can excite double frequency (DF) surface waves that traverse large distances on land, of several microns in amplitude and $\approx 20\ \mathrm{km}$ wavelength. This causes motion among LIGO's test masses peaking at 0.15 Hz.
- LIGO seismic isolation design provides an external fine actuation system (FAS).
  - $\pm 90\ \mu\mathrm{m}$ range for each end (or mid) station BSC payload.
  - Single DOF flexure design allows low-bandwidth correction of arm lengths, for Earth tides and the DF microseism.
- Streckeisen STS-2 seismometer signals from each building are filtered to produce differential and common-mode arm length correction signals that are applied to the FAS, largely removing the microseism independently of LSC servos.
- Filters are derived using system-identification tools, and represent a compromise between high performance at the microseism and minimal added noise elsewhere.

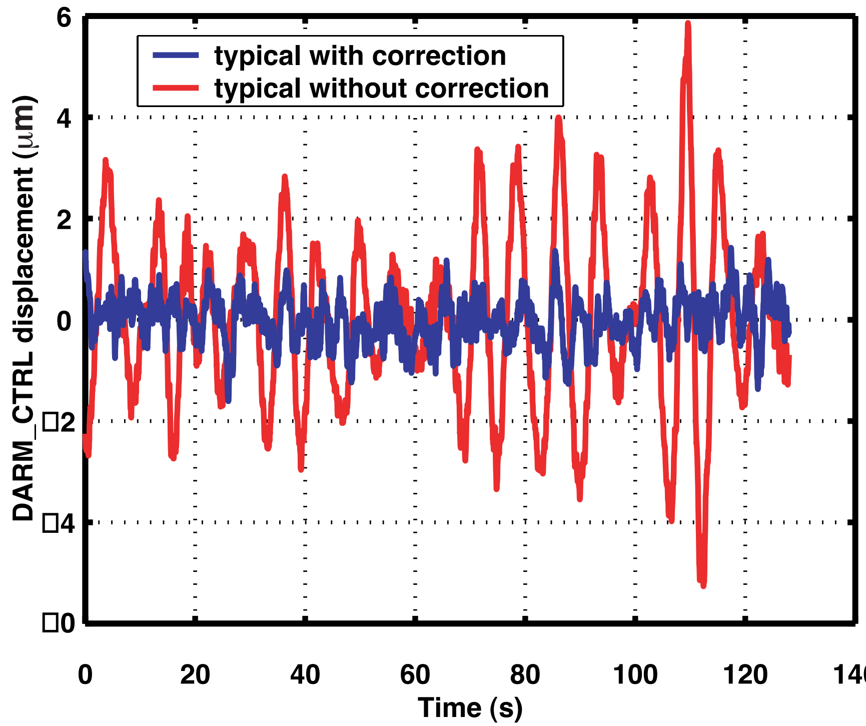
Prediction filters

- Sys-Id method fit parameters of "black-box" state space (with colored noise) to minimize variance in difference between estimate and data, weighted by data's spectral content. This was only done once, and the resulting filter set has been used ever since.
- We pre-filtered data with a bandpass, to focus fit on known microseism band.
- At very low frequencies the seismometers (or any inertial instrument) can confuse horizontal acceleration with tilt, so we cut off the filter at about 20 mHz.
- Any noise leakage to the stack modal frequencies is unacceptable, since they are rung up enough at LLO, so we cut off the signal at about 1 Hz with a high-order IIR filter.
- This bandpassing causes a fairly steep phase shift across the microseismic band, with only a narrow range of frequencies ideally removed via feed-forward. Luckily, much of the time the DF microseism looks like a narrow peak at 0.15 Hz.
- A bank of phase shifters in the GUI control panel is set up to shift the "sweet spot" up or down manually.

Noise reduction during E6

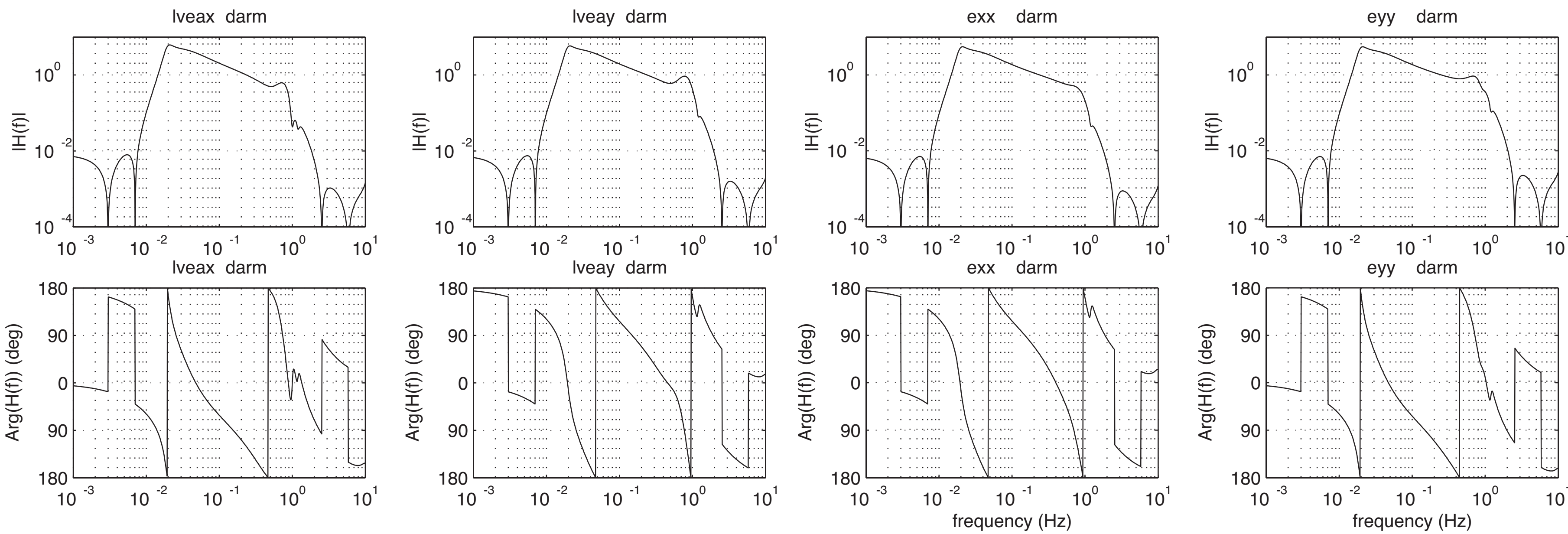
- E6 was during a period of very high *narrow* microseism, allowing a good early test.
- The use of system reduced the test mass control signal RMS (0.03 - 0.5 Hz) by $\approx 85\%$, so that this spectral band no longer dominates the control signal.





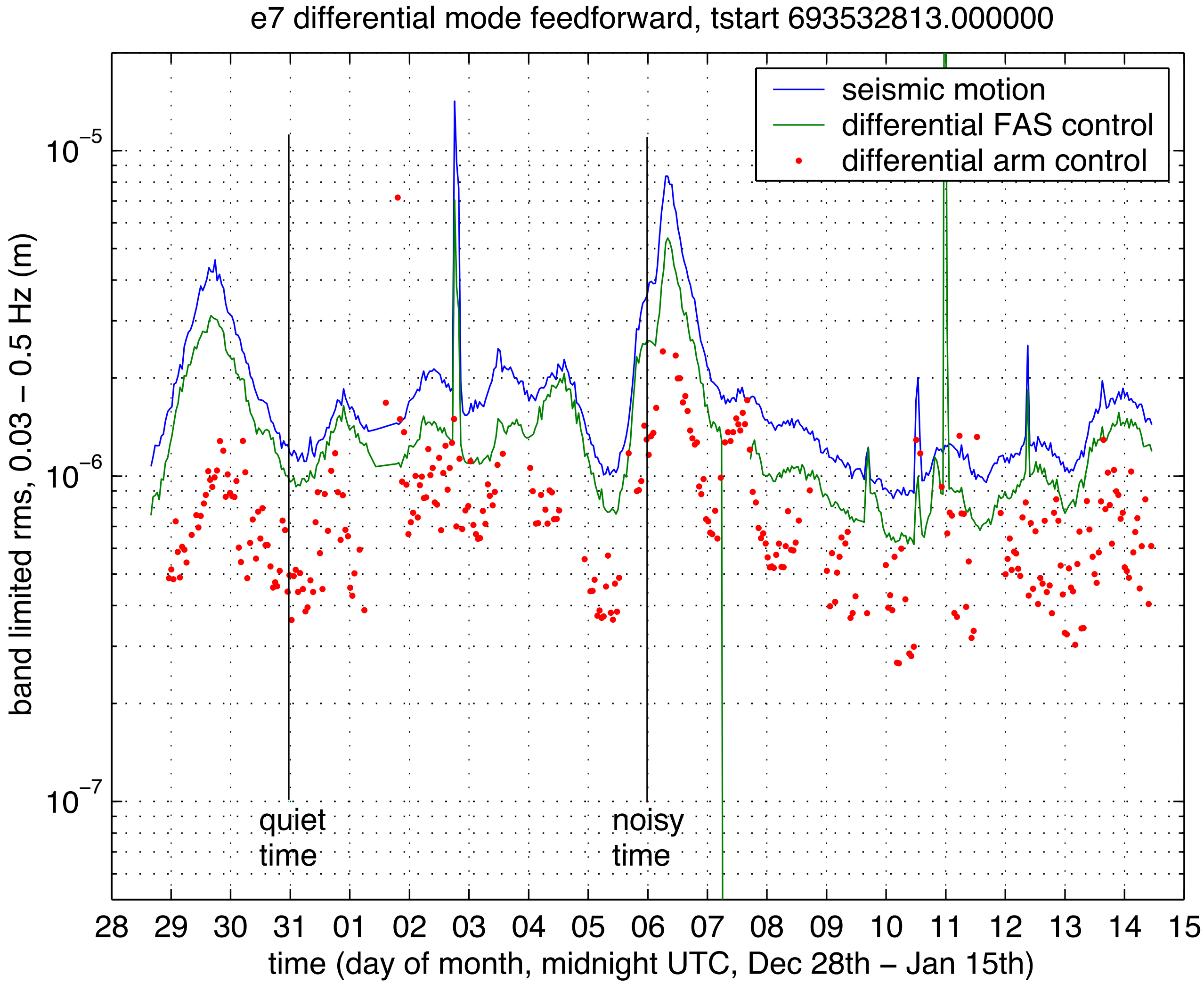
FF predictor shapes

- Since the STS-2 seismometers have a velocity readout, one expects the filters that can best predict the differential test mass displacement will look like integrators over the relevant band. They do, albeit with some variation to optimize noise performance.
- Extra operator-switched phase shifter sections allow variation over tens of degrees to accommodate changing microseism. In practice these are rarely used.



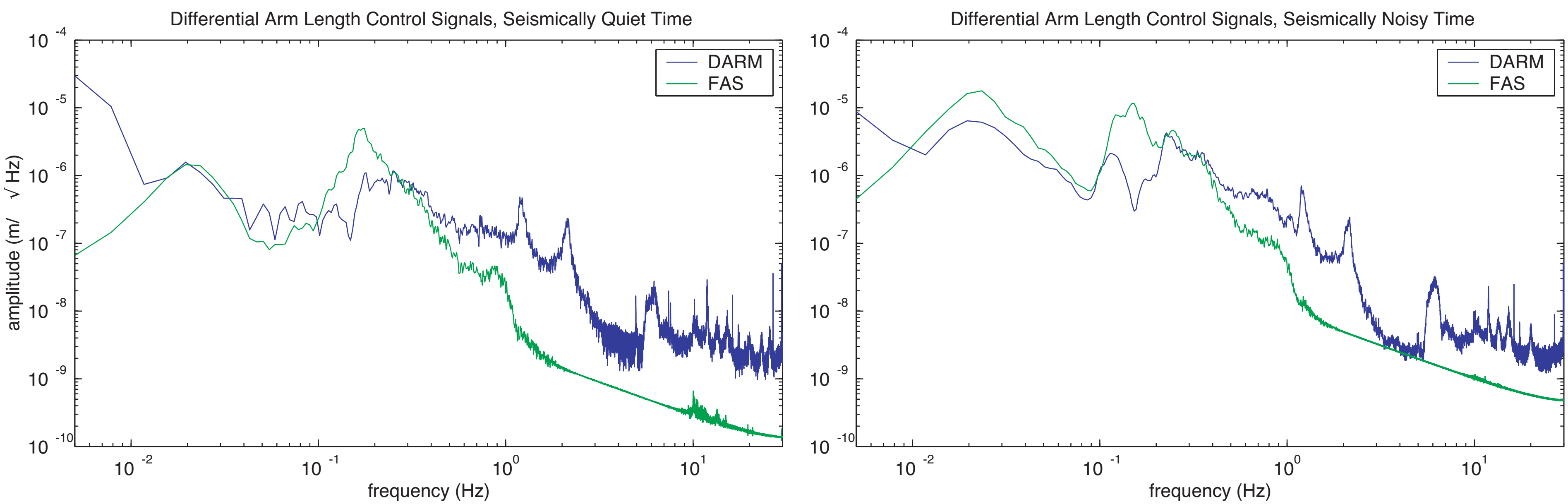
Long-term study during E7

- During the two-week E7 run, the FF system remained largely untouched and operational.
- Unfortunately, the Earth provided us with a challenging microseism for much of the run; the peak was not narrow, but spread itself up to 0.2 or 0.3 Hz, where our filter's phase was wrong.
- Still, the FF system reduced the needed test mass control signals in the 0.03 - 0.5 Hz band by a factor of a few most of the time.
- During a particularly noise time, the operators and scientists were convinced that the FF was doing more harm than good and turned it off. They were mistaken, as can be seen in the next slide. . .


e7 differential mode feedforward, tstart 693532813.000000
seismic motion
differential FAS control
differential arm control
band limited rms, 0.03 – 0.5 Hz (m)
10^{-5}
10^{-6}
10^{-7}
quiet time
noisy time
28 29 30 31 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15
time (day of month, midnight UTC, Dec 28th – Jan 15th)

Disturbance character during noisy vs. quiet times

- Noisy period has more energy in higher frequencies, where FF isn't as effective.



Improvement possibilities

- After LLO retrofit, active isolation in 1 - 3 Hz band may allow less aggressive lowpass filtering and better performance above 0.2 Hz.
- Adaptive Sys-Id may allow less operator involvement (which is rare, but would probably help).
- Hanford needs to be fitted with the system, so new things may emerge.