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Investigation of Lock Losses During the E2 Engineering Run

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Abstract

Many of the lock losses that occurred during the E2 Engineering Run at Hanford in November 2000 appear to have been due ultimately to insufficient dynamic range in test mass actuation, in the absence of feed-forward tidal correction, as expected. Losses occurred sooner than necessary, however, because of premature saturation in one electronics channel of the controller for the X-arm end test mass. We suspect a faulty electronics component in the circuit for the upper left coil channel of ETMX. In addition, there is strong circumstantial evidence that lock was lost on four occasions due to distant earthquakes.

Background Information

To understand our observations during the E2 run, it's useful to review briefly some background information on the interferometer running conditions and design.

First, the interferometer control system is designed to include feed-forward actuation to compensate for tidal effects, using a detailed tidal model. This actuation was not enabled during the E2 run, however, in part to allow a clean study of uncorrected tidal effects. The day-to-day swings in common-mode tidal range are of order one hundred microns[1], depending on time of month and year, which is comparable to but not much greater than the expected dynamic range ($\pm 65\ \mu$m) in longitudinal test-mass actuation[2] effective during the E2 run. Hence, even without tidal correction actuation, we expected tidally induced lock losses to occur only occasionally during the day. The dominant components in the tidal waveform have periods of approximately 12 hours (solar azimuth), 13 hours (lunar azimuth), 24 hours (solar declination), and 26 hours (lunar declination). It should be remembered that both common-mode and differential-mode tidal forces affect the arm control signals, but that common-mode amplitude is generally larger. Figure 1, generated by the E2 tidal investigation team[1], shows a fit to common-mode tidal motion, along with residuals. If actuation dynamic range is decreased by electronics offsets or by premature saturation, we expect locked stretches to be shortest where a linear combination of the curves rises or falls the steepest.

There are two complications, even in the absence of electronics malfunction, that can reduce the length of locked stretches. First, the actuation on upper test mass coils must be larger (by about 30%) than that on the lower test mass coils to compensate for pitch induced on the suspended mass by equal magnetic forces on top and bottom. Second, imperfections in initial balancing require non-zero DC offsets on some coils. In some instances, those offsets are large fractions of the dynamic range and introduce an asymmetry in effective dynamic range w.r.t. the sign of tidal drift. It should be noted that the intrinsic quietness of the Hanford test masses (at least in the absence of global length control!) means that lock is typically acquired near equilibrium, compared to the full dynamic range of actuation, i.e., the ambient swinging of the masses is small under local velocity damping.

The observations described below concern the period of E2 during which the interferometer was in recombination mode with three longitudinal degrees of freedom locked, common mode L_+ (average arm length), differential mode L_- (difference in arm lengths) and Michelson ℓ_+ (difference in Michelson cavity lengths). No attempt was made to lock the recycling ℓ_+ degree of freedom during the run. Data was also taken in 1-arm configurations with one longitudinal degree of freedom locked (the L_+ servo). In detail, for recombination, the actuation for L_+ was equal pushing on both X and Y arm end masses. Actuation for L_- was differential pushing on the two end masses, while actuation for ℓ_+ was simultaneous and equal differential pushing on input masses and end masses. This ℓ_+ actuation scheme differs from the expected final design scheme with actuation on the beam splitter and no actuation on the input masses.

Observations

We made the following observations during recombination running:

- Locked stretches had typical durations of an hour and the expected (qualitative) correlation of lock length with slope of the tidal correction inferred from the L_+ control signal was confirmed (see figure 2). Note, however, that for E2 there was not a clean separation between the common mode and differential mode control signals[3].

- Transmitted light through the Y arm tended to drift somewhat linearly with time during a locked stretch, as if a relative misalignment were getting steadily worse. At the same time, the optical levers for both pitch and yaw of the ETMY also showed steady drifts (see figure 3). We interpreted this as a mistuning of the pitch compensation during longitudinal actuation discussed above, along with an imbalance in yaw. On Saturday morning R. Schofield retuned this compensation by trial and error, much reducing the drift slope for subsequent running. We do not believe, however, that the initial ETMY mistunings contributed to lock losses.

- Transmitted light through the X arm was quite flat for most of a locked stretch, but would rapidly degrade in the minutes immediately preceding lock loss (see figure 3). The yaw of ETMX as measured by the optical levers showed fairly linear drift, suggesting a small residual imbalance in left vs right actuation. The pitch of ETMX, in contrast showed relatively flat behavior until near lock loss, when the same rapid degradation seen in transmitted light would appear in pitch. This suggested saturation in one or more coils of ETMX.

- Study of the ETMX coil currents (including comparison with the well behaved ETMY coil currents) revealed that the upper left (UL) coil current behaved anomalously. While the other coil currents would suffer "software rails" as seen by the data acquisition ADC's at ± 2 V, the UL coil would consistently undergo a period preceding lock loss in which the minimum/maximum voltages read by the ADC's would drop well below 2 V in a peculiar and symmetric "exponential decay" of the min/max voltage envelope (see figures 4 and 5). This envelope itself cannot be taken at face value, since the DAQ channel is AC-coupled to the actual coil current it measures, but the anomalous behavior appeared to be a clue to malfunction in that coil. The mean UL coil current also behaved anomalously during these periods. Figure 6 shows time series for all four coils of the ETMX mass. Only the UL displays the anomalous envelope behavior. During one such period, we hooked up an oscilloscope to monitor points on the ETMX controller in the X mid station and observed severe and asymmetric railing on the UL coil monitor and moderate, asymmetric railing on UR, with little railing on LL or LR. The characteristic dominant (non-DC) frequencies estimated from the portable scope were at and above 2 kHz, outside the sampling range of the data acquisition ADC's used for these channels. We continued to observe with the scope following lock loss. During and after lock reacquisition, we saw that railing of the signals at $\pm$ 2 V nearly but did not entirely go away. It should be noted that the power spectrum for the ETMX UL coil (see figure 7) showed an odd, broad peak at about 30 Hz in contrast to the flat spectra seen for the other ETMX coils and all of the ETMY coils. This may be an artifact of inadequate anti-aliasing filters on that channel, when the channel was undergoing severe excitation at frequencies just beyond 2 kHz.

Earthquake-induced losses

A search was also carried out with the Data Monitor Tool (DMT) GlitchMon monitor (author: M. Ito) for large seismic transients in local seismometer data coincident with lock losses that also coincided with earthquakes identified by the USGS as having a magnitude >4.0 within 30° of Hanford or magnitude > 5.0 worldwide. Only 19 such quakes were reported by the USGS during the E2 run, four of which coincided with GlitchMon triggers:

Date	Time (UTC)	Lat.	Long.	Depth (km)	Mb	Ms	Location
11/09/00	05:45'54"	15.375S	173.413W	53	5.6		Tonga
11/10/00	19:14'05"	46.400N	111.380W	1	4.7		Montana
11/13/00	15:57'21"	42.542N	144.758E	33	6.1	5.6	Japan
11/14/00	03:53'01"	42.552N	144.806E	33	5.5	5.1	Japan

where Mb is the magnitude of the body wave and Ms is the magnitude of the surface wave. More detailed information on the USGS reporting service and its thresholding criteria can be found at the web site:

`http://wwwneic.cr.usgs.gov/neis/epic/epic.html`

Conclusions

- The E2 run amply confirmed the expected necessity for tidal actuation.
- The length of locked stretches was shorter than expected, however, which we attribute to DC offsets (bias settings) on coil currents.
- Evidence for repeated coil saturation is strong. One coil on one end mass was particularly susceptible and showed an anomalous behavior when saturation ensued, suggesting a faulty circuit in its controller.
- New test mass controllers have been designed and are in the pipeline for installation (one has been installed for the Hanford 2K interferometer). Feed-forward tidal actuation is planned for the next engineering that involves a full 2K interferometer.

We look forward to revisiting lock losses at Hanford once the tidal actuation and improved controllers are in place.

More Information

The team's web site contains a list of starting times and durations for all E2 lock stretches (2-arm or 1-arm, depending on nominal running configuration) that lasted at least one minute. The list is derived from meta-database triggers generated by the Data Monitor Tool LockLoss program (authors: D. Chin, K. Riles) for all lock transitions during the E2 run. Additional information and the graphics files for all figures presented here may also be found at this site:

`http://blue.ligo-wa.caltech.edu/engrun/E2/Results/LockLoss/`

Acknowledgements

Aside from the "official" lock loss investigators, many other physicists in the control room contributed ideas to investigate and helped to carry out studies. A partial list includes R. Adhikari, R. Drever, R. Flaminio, R. Schofield, D. Sigg, D. Ugolini, and S. Whitcomb.

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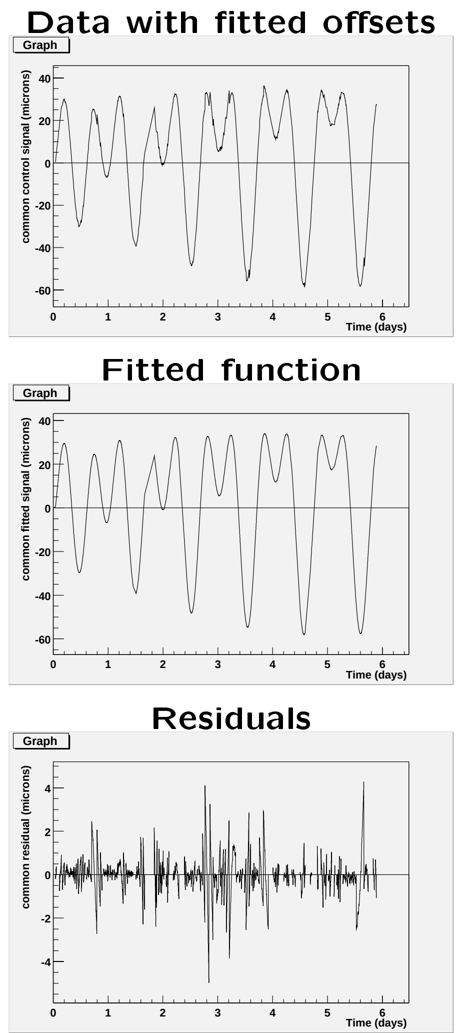
References

[1] See report of E2 investigation team on tidal effects.

[2] J. Heefner, private communication.

[3] See report of E2 investigation team on frequency noise.



Model scale factor $= -1.26$

Figure 1: Fit and residuals to common-mode tidal motion according to a detailed tidal model. Figure provided by E2 tidal investigation team.

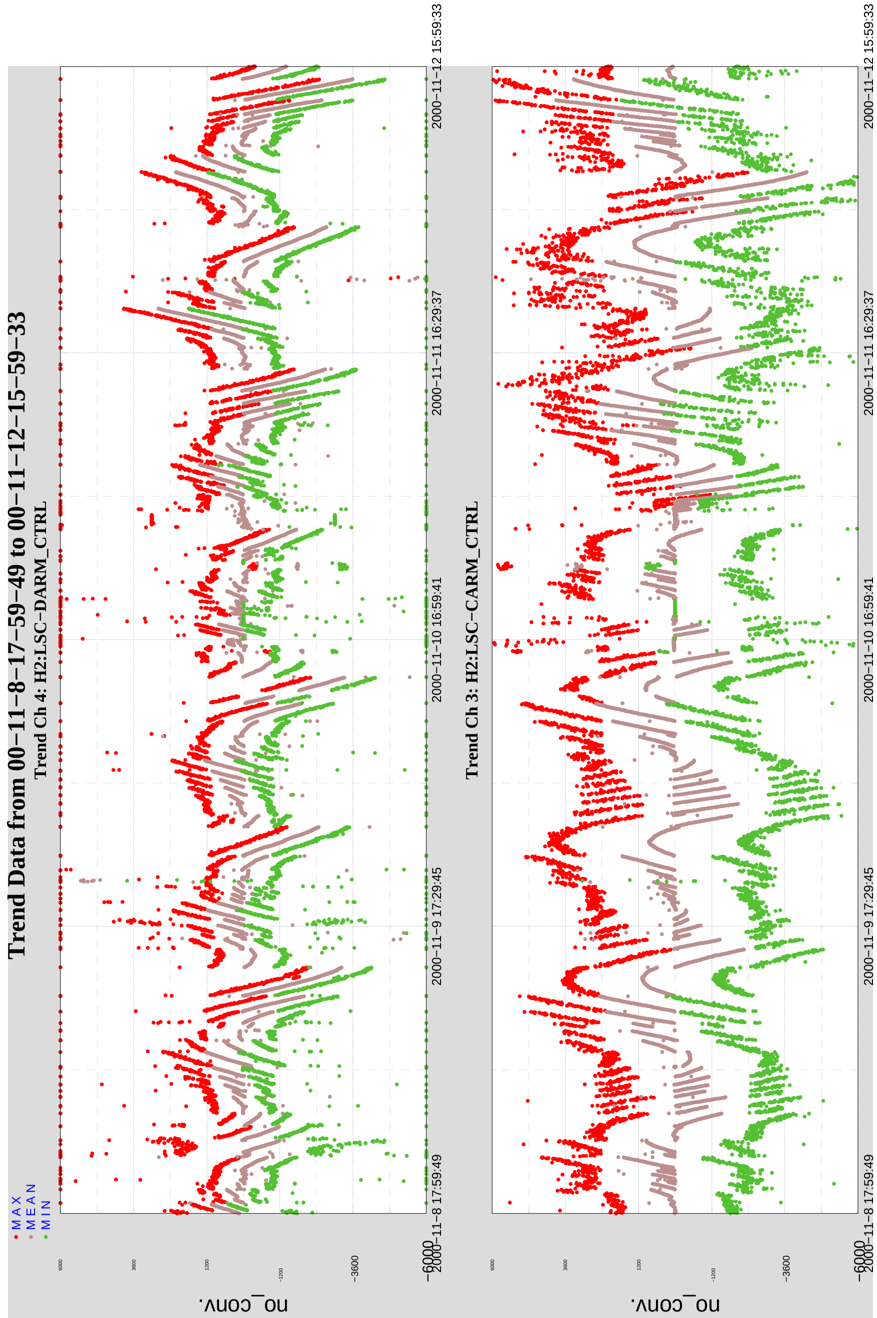


Figure 2: Time series (four days) of common mode and differential mode arm control signals. Sharp breaks indicate lock losses. The expected qualitative correlation is observed here between length of lock and slope of the (dominant) common mode control signal.

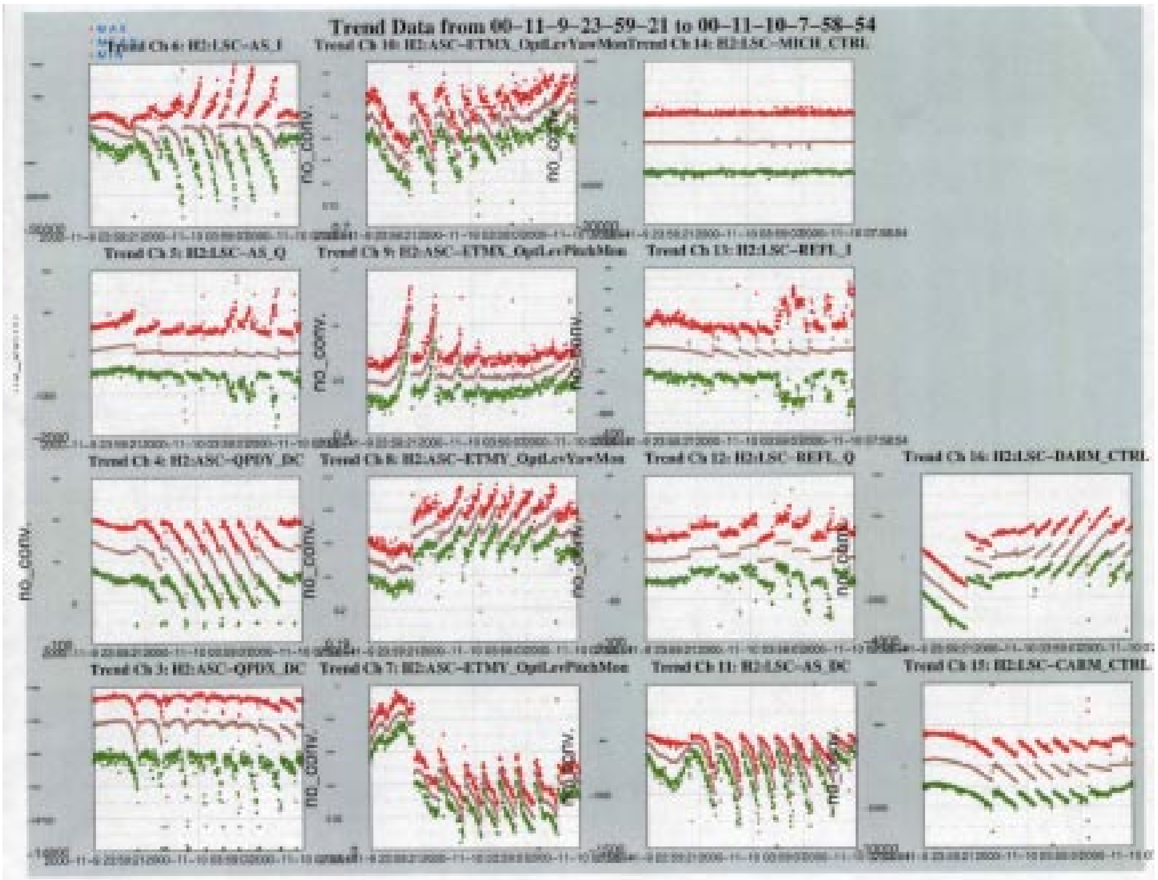


Figure 3: Time series of various channels during multiple lock stretches. The sharp breaks in the transmitted arm powers (bottom plots in 1st column) and in the arm control signals (4th column) indicate lock losses. The 2nd column shows yaw and pitch monitors for the end masses, where linear drifts indicate residual imbalance in ETMX and ETMY coil control matrices and where the non-linear behavior (seen most strongly in the ETMX pitch) suggests coil saturation.

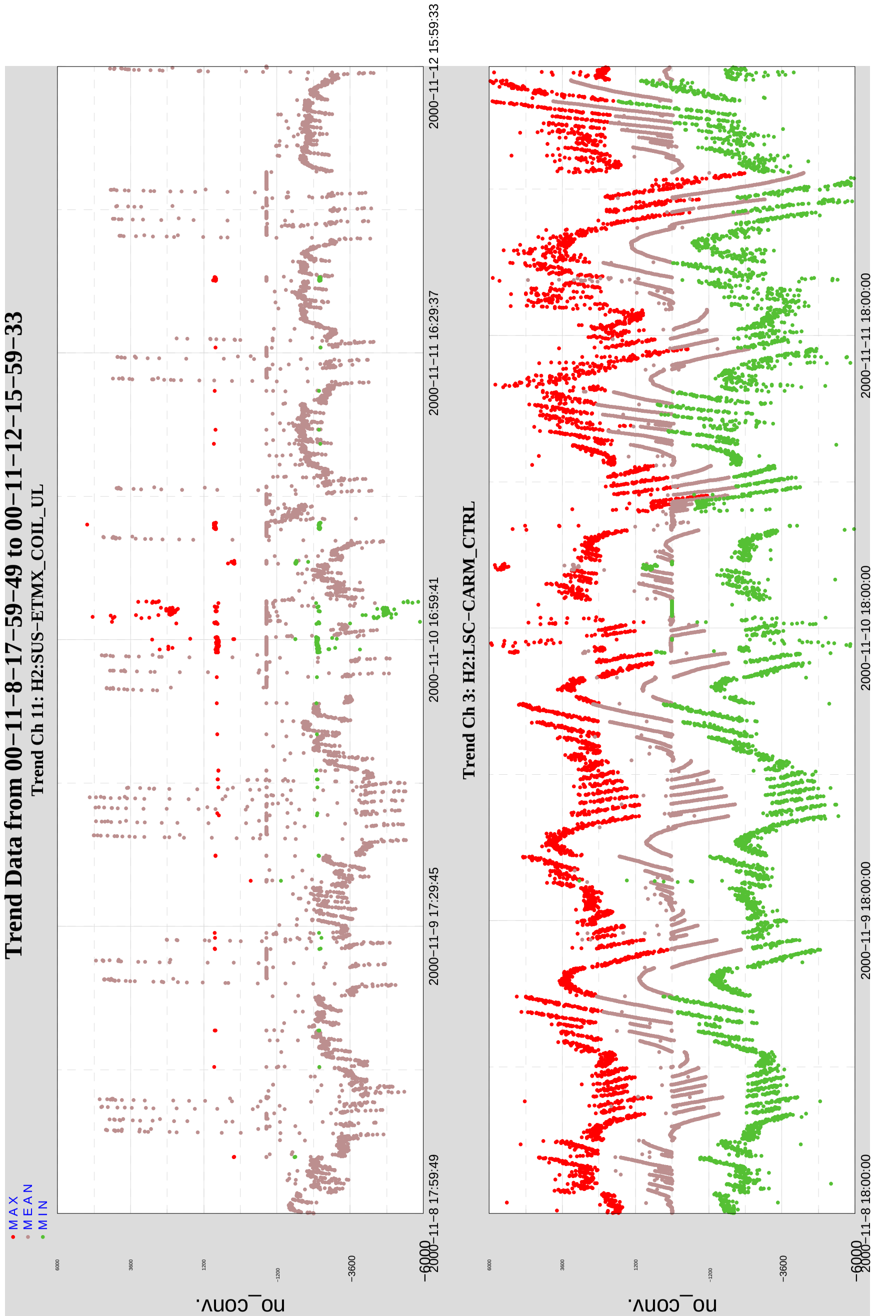


Figure 4: Time series (four days) of current in the ETMX upper left coil and of the common mode arm control signal during multiple lock stretches. The mean coil current shows in many cases an anomalous behavior in the few minutes preceding lock loss. Because the corresponding DAQ channel was AC coupled to the actual current signal, the envelope cannot be taken literally, but does give a clue to underlying malfunction.

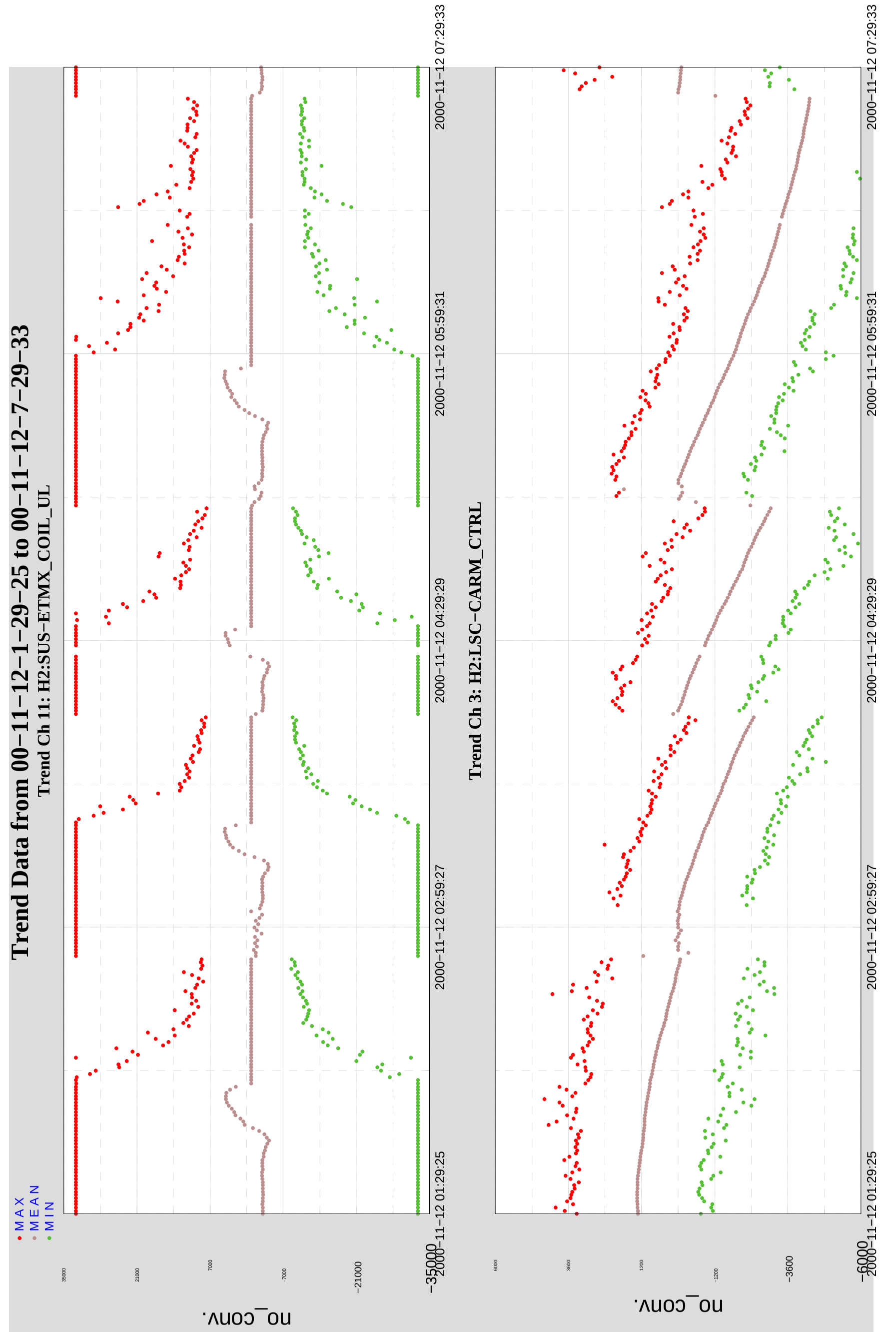


Figure 5: Magnification of four consecutive lock losses shown in preceding figure, showing odd "decay" of coil current envelope (min/max).

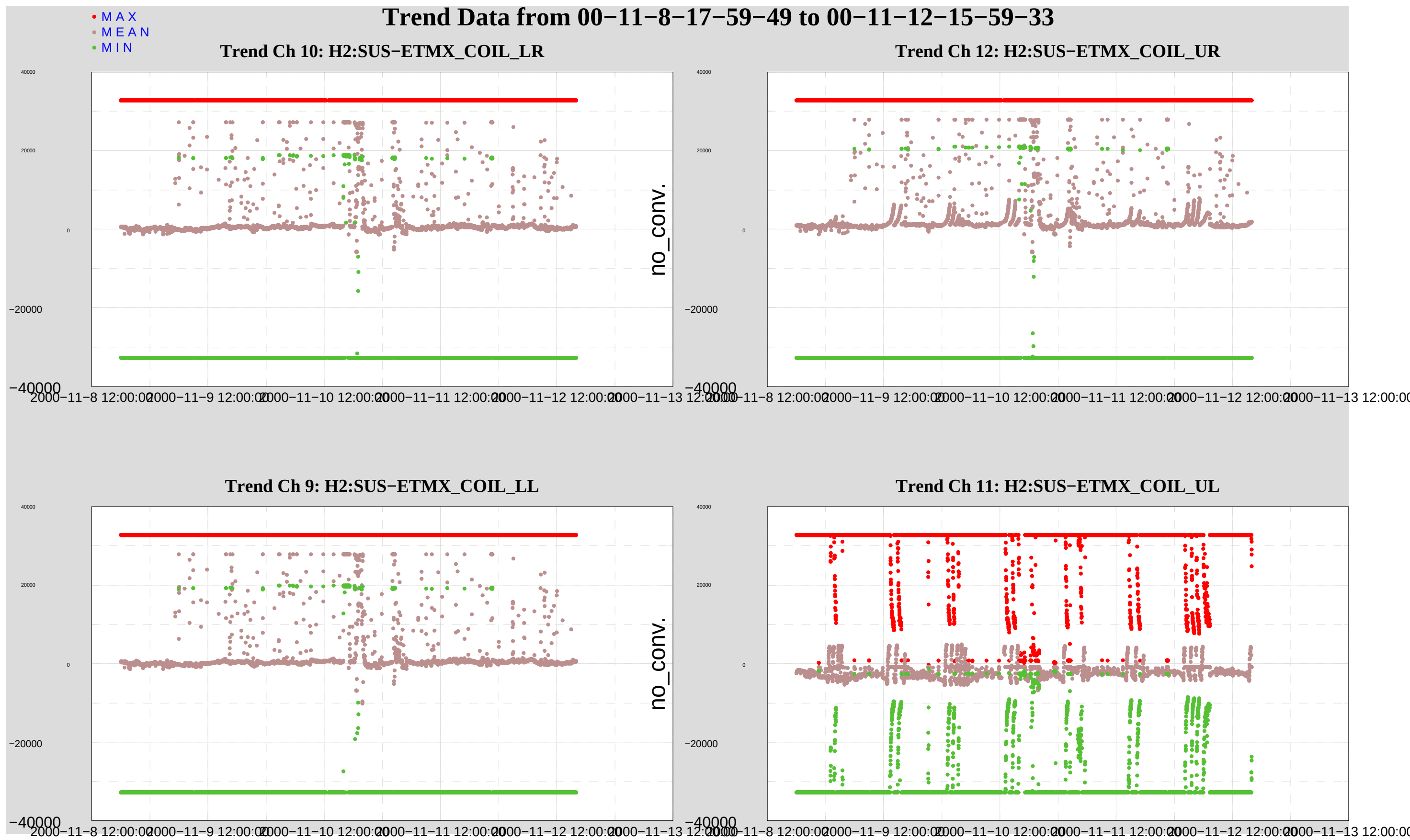


Figure 6: Sample time series for all four coils of ETMX mass.

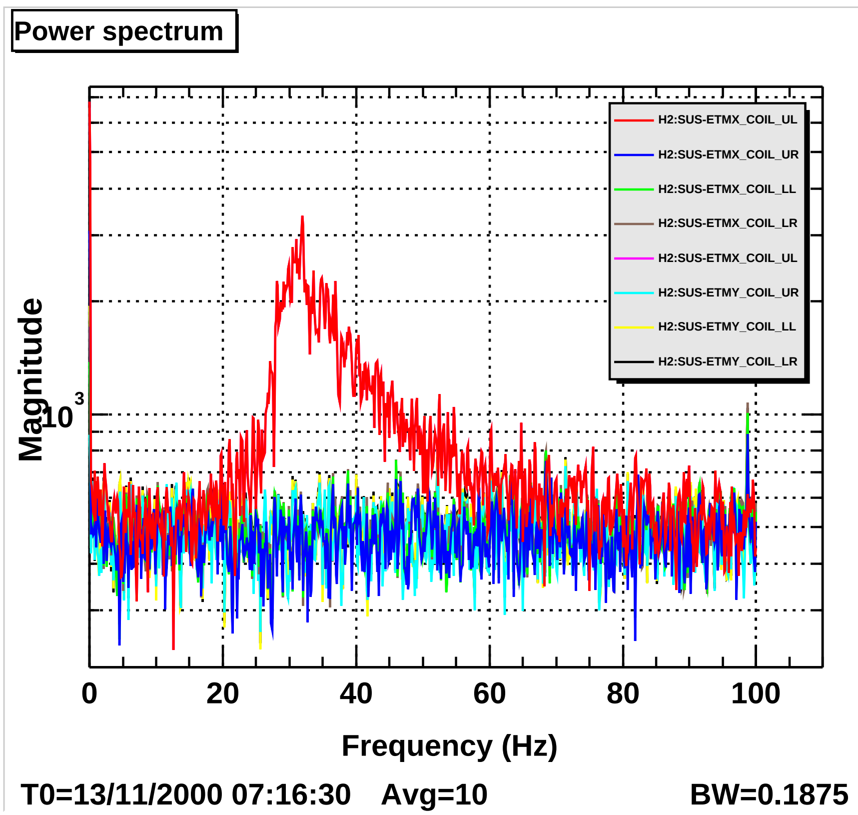


Figure 7: Spectra of coil currents for both end masses. The UL coil in ETMX shows an anomalous and broad low-frequency peak (possibly an alias of a high-frequency peak).