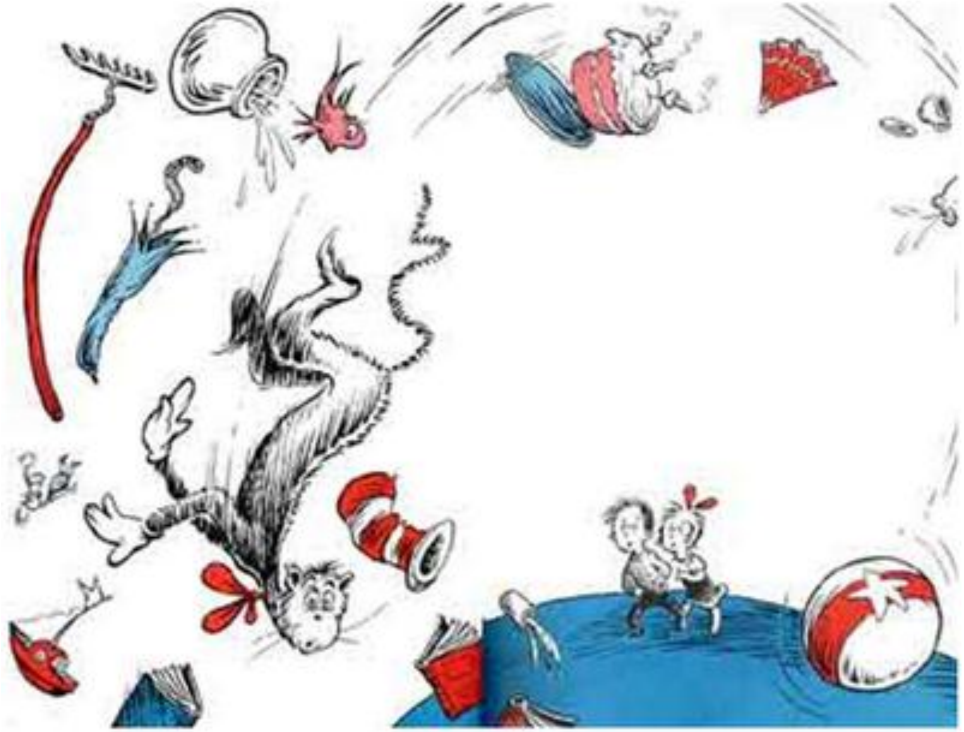
GWADW

Summary of Controls Sessions

$we\ make\ it\ look\ easy,\ but\ \ldots$



General Comments

- Controls is a new topical session for the GWADW this year
- Based on the number of participants in the controls session, we should include controls as a topical session in future GWADWs

Controls Sessions

A	System identification and modern Control
B	Optimal feedback
C	Noise feedforward and subtraction
D	Lock acquisition problems and improvements
E	Interferometer stability (Keeping the IFO Lock)
F	Next Generation Control System Architecture

- *Good sessions, good discussions, useful, but …*
- *Perhaps too much scope – not focused enough, not enough "homework" in preparation in advance?*
- *A few too many prepared talks*
- *In future GWADWs, address next generation systems (V+, A+, Voyager, Longo,…)*

Thanks to the people who helped us organizing the sessions:
Brett, Gabriele, Sheila, Keita, Jamie

Lot of work upfront in the presentations – Workshop oriented

Great cross participation:
Yuta (Kagra), Geo (Emil), Bas (Virgo), Gabriele (LIGO/Virgo), LLO (Anamaria/Den), LHO (Sheila & Keita), Ryan Fisher (DetChar)

And others we failed to mention (20+ participants per session)

Disclaimer: typos, finished the presentstion 3 minutes ago

Controls Workshop at the GWADW 2015

Abstract:

The two central days of the next GWADW meeting (http://www.ligo.caltech.edu/gwadw2015/) (May, 17-22,2015) will be organized in parallel workshops and one of these workshops will be focused on "Controls".

The goal of this DCC Page is to collect relevant information for the organization of this session.

Files in Document:

None

Topics:

- Public Talk / Colloquium
- Detector

Authors:

- Dennis Coyne
- Fabrice Matichard

Related Documents:

- LIGO-G1500202: GWADW
- LIGO-G1500663: GWADW Controls Sessions Introduction
- LIGO-G1500673: System Identification Overview & Session Goals (GWADW 2015)
- LIGO-G1500689: Discussion and comparison of classical and modern control techniques
- LIGO-G1400557: State-Space Methods for Feedback Control
- LIGO-G1500679: A summary of the Modern Controls workshop @ Caltech

Related documentation

- LIGO-G1400853: Generalized Cost Functions for Control Servo Design
- LIGO-G1400777: Noise Cancellation for Gravitational Wave Detectors
- LIGO-G1400215: Modern controls for advanced interferometers
- LIGO-G1400091: Static Feed-Forward Noise Cancellation
- LIGO-G1400095: LMS-based Adaptive Noise Cancellation
- LIGO-G1301257: Linear Quadratic Regulators for Damping Loops
- LIGO-G1200812: Noise Cancellation Techniques for Gravitational Wave Detectors
- LIGO-P1000088: Global feed-forward vibration isolation in a km scale interferometer
- LIGO-G1100542: Feed Forward Noise Reduction
- LIGO-G1000234: Feed Forward Seismic Isolation
- LIGO-G1400100: LQR Linear Quadratic Regulator - A state space optimal control technique
- LIGO-T1300301: Frequency Domain LQR
- LIGO-G1200694: Modal Damping of a Quad Pendulum for Advanced Gravitational Wave Detectors
- LIGO-G1200723: Adaptive Modal Damping of Advanced LIGO Suspensions
- LIGO-P1200057: Adaptive Modal Damping for Advanced LIGO Suspensions
- LIGO-P1100102: Modal Damping of a Quadruple Pendulum for Advanced Gravitational Wave Detectors
- LIGO-T1000458: Fitting the Quad Noise Prototype Model to Measured Data
- LIGO-G1100755: Modal Damping Notes
- LIGO-G1400567: Towards Automated Control
- LIGO-T1400672: Report from the Commissioning Workshop on Suspensions at Virgo
- LIGO-G1100161: Adaptive Control Loops for Advanced LIGO

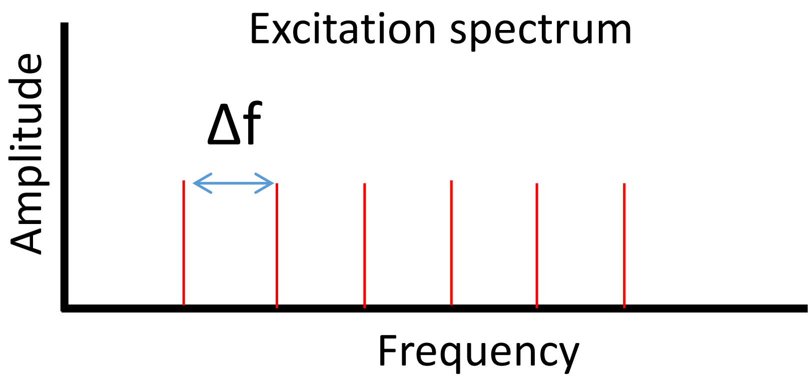
Tags: Sys IS, Optimal, Subtraction, Adaptive….
LSC Virgo Wiki Page

System Identification Overview

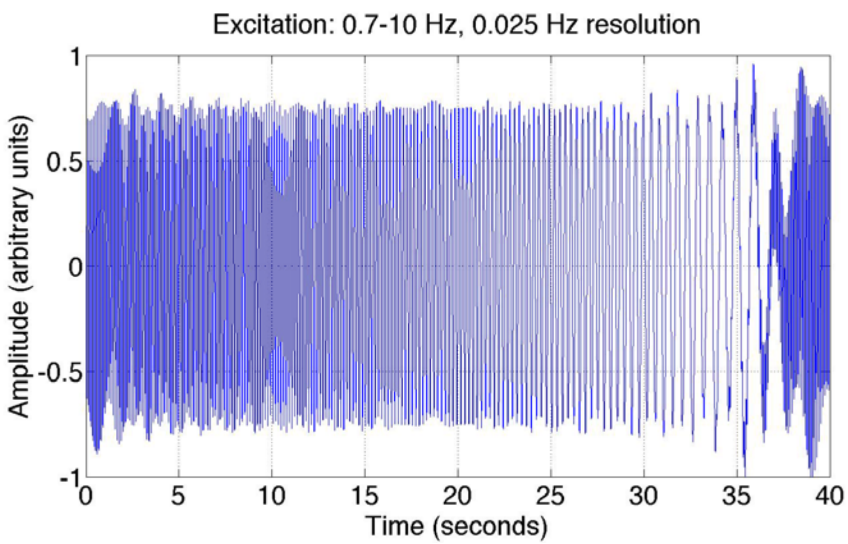
- SID is the process of developing or improving a mathematical representation of a physical system using experimental data
- Basic steps:
  - Build a physics-based model
  - Design the experiment
  - Collect the data
  - Select, filter, de-trend the data, as appropriate
  - Fit the model
  - Validate the model (compare prediction to data)
  - Iterate until converged on a validated model
- Example: SID for structural dynamics
  - Modal parameter identification
  - Building modal state space models

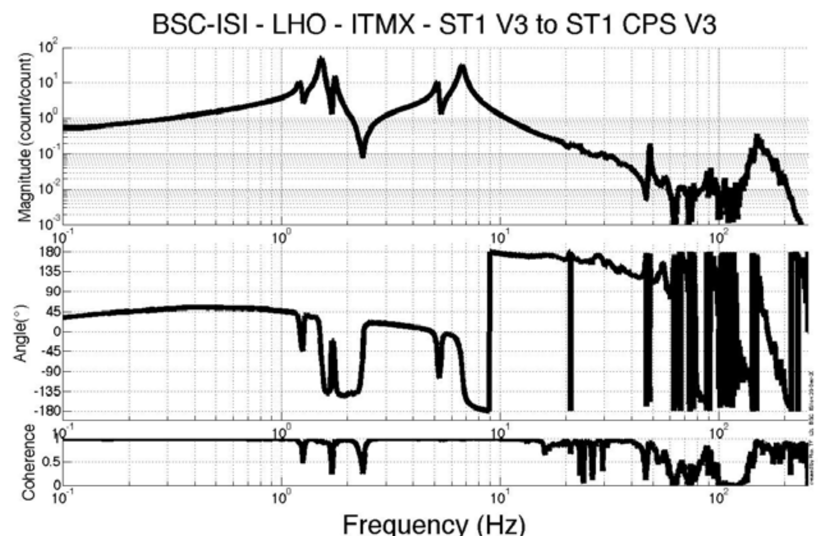
aLIGO SUS and SEI Transfer Functions

Schroeder Phase Excitations



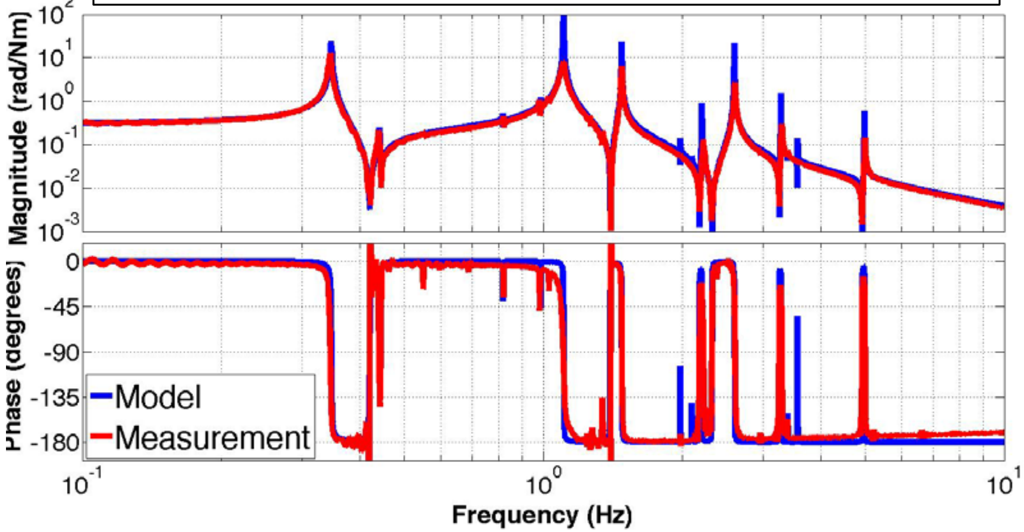
- The excitation consists of a frequency comb with a spacing of Δf
- The phase of each sine wave is set to minimize the largest excitation value
- All within MATLAB

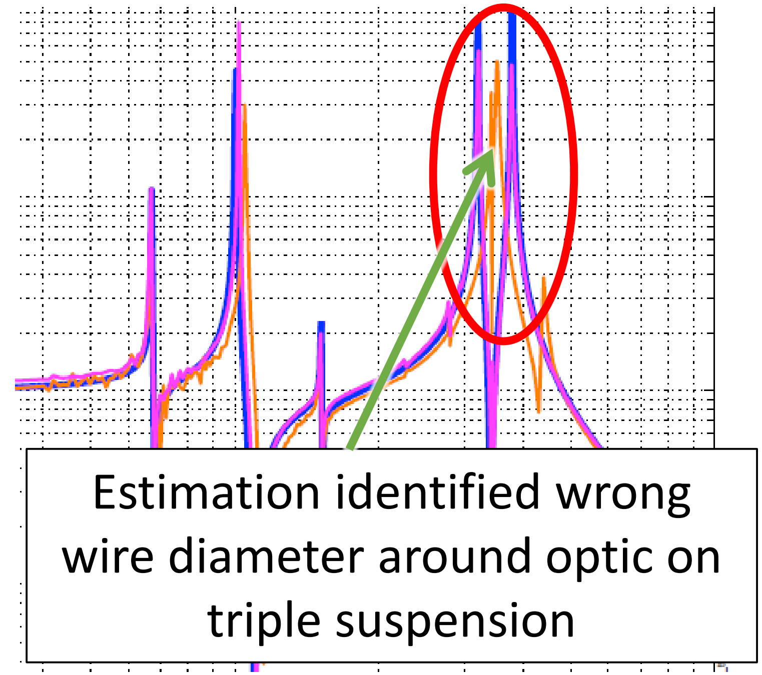




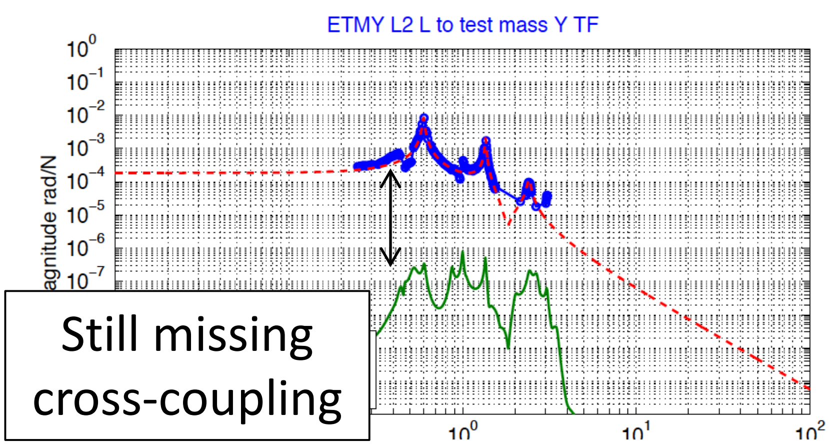
Model Fitting and Parameter Estimation

Quad SUS **After** Estimation: Pitch

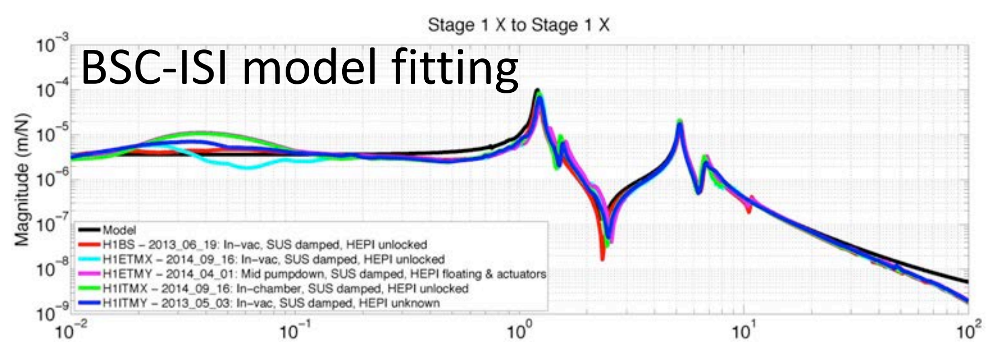




Estimation identified wrong wire diameter around optic on triple suspension



Still missing cross-coupling



BSC-ISI model fitting

Matlab's N4SID generates a state space

Brett Shapiro

A Commissioner's Cross-Coupling Wishlist

Anamaria Effler

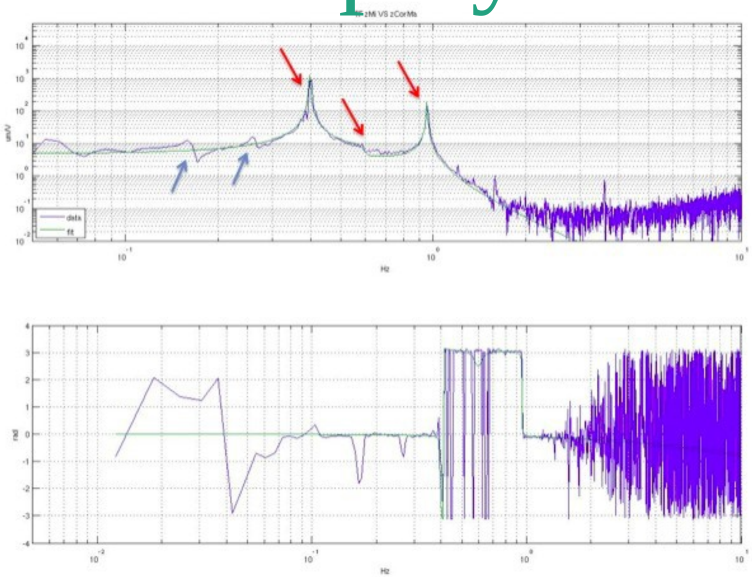
LIGO Livingston

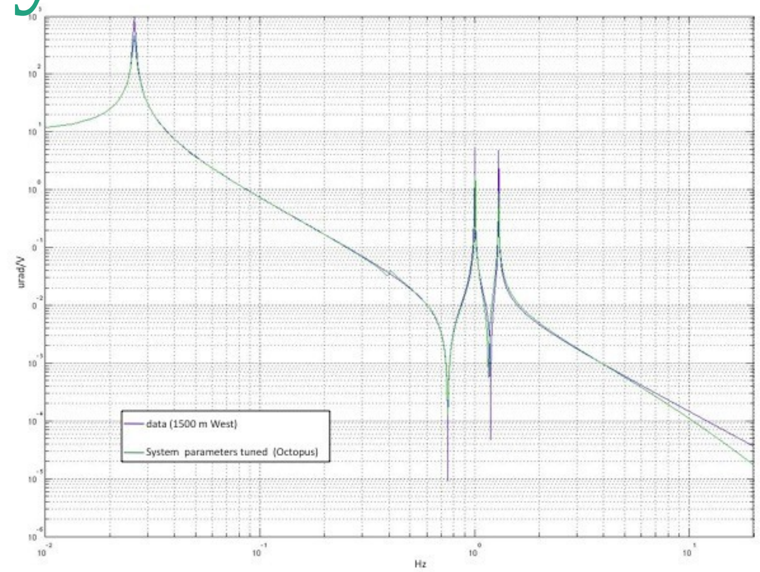
G1500676

A Commissioner’s Cross-Coupling Wishlist (a few points shown here)

- Suspensions
  - Models: more realistic cross coupling predictions
  - Oplevs during testing for OSEM balancing
  - measurements of analog electronics responses
- Seismic Isolation (ISI)
  - Transfer functions to the suspensions
  - State space models
  - Better tilt-horizontal coupling estimates

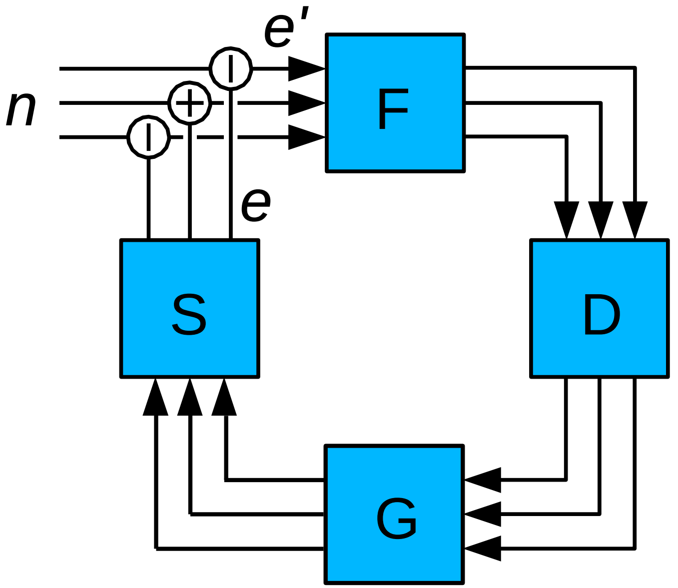
System Identification of payloads 'by hand'





- Use Octopus to get accurate model of payload (Matlab based, see LIGO-G1401229)
- Inject noise on various actuators (mirror, marionetta) and measure TF to various DOF visible by optical levers
- Tweak parameters of models until model matches measurements
- Laborious, only experts know how to do this (Paolo Ruggi, Ettore Majorana)
- Leads to deep understanding of payload mechanics, useful for design of new payloads

Measuring the optical matrix



$$e' = n + SGDFe'$$

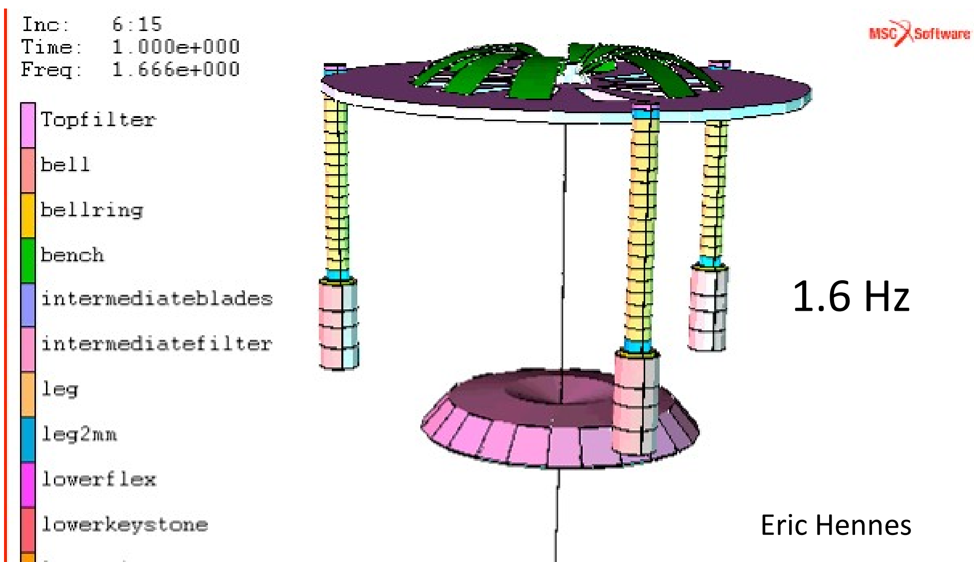
$$e' = A\,n = (1 - SGDF)^{-1}\,n$$

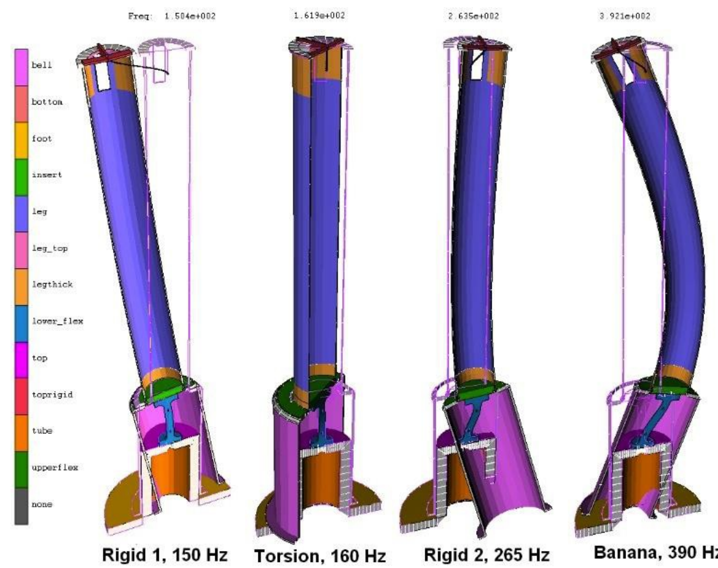
$$G = S^{-1}\left(1 - A^{-1}\right)F^{-1}D^{-1}$$

- Inject noise ***n*** on error signal ***e***, one DOF at a time, to obtain matrix of transfer functions ***A***
- Sensing matrix ***S***, loop filters ***F*** and driving matrix ***D*** are known
- Reconstruct unknown plant ***G*** with simple matrix algebra, for each frequency bin

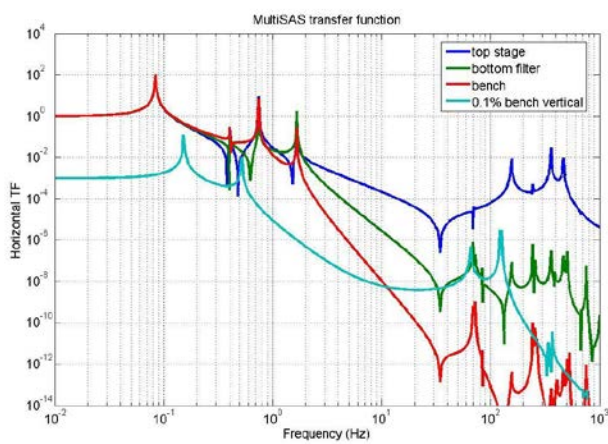
State observers and Kalman filtering

High performance vibration isolation systems





IP leg modes



Simulated Horizontal transfer function

- Tune model to measured transfer functions

G1500672

System identification with bayes theorem and non gaussian distributions

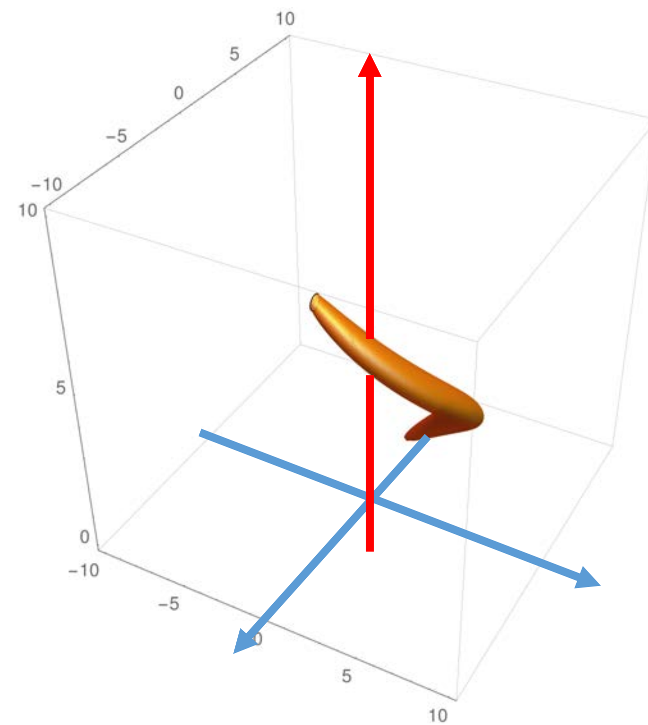
A simple example: a suspension (pendulum) with uncertain length

- Description in the phase space:

$$\dot{p} = -m\omega^2 x$$

$$\dot{x} = \frac{1}{m} p$$

- We measure the state (position and velocity). Maybe with some measurement error.
- We enlarge the space, adding the unknown parameter ω
- We model our ignorance with a joint probability distribution
- We assume we have a good model…
- …which can be used to calculate the time evolution (**RULE 1 at work**)



Giancarlo Cella

Session B: Optimal Control

- SISO filtering versus Optimal Control
- (i) Optimal controllers (ii) Observers, SNR (iii) Modal control
- LQR: Cost function, weight…
- Kalman filter

Goals:

- Already investigated, good outcome, still not used, why?
- Prospects, application
- Working groups, collaboration

Half step done…

Introduction talk (review of modern control tools, state space methods, their pros and cons)	Den Martynov

G1400557-v1   State-Space Methods for Feedback Control

$$\frac{d}{dt}\begin{pmatrix}\dot{x}\\ x\end{pmatrix}=\begin{pmatrix}-\gamma/m & -k/m\\ 1 & 0\end{pmatrix}\begin{pmatrix}\dot{x}\\ x\end{pmatrix}+\begin{pmatrix}1\\ 0\end{pmatrix}F$$

$$y=\begin{pmatrix}0 & 1\end{pmatrix}\begin{pmatrix}\dot{x}\\ x\end{pmatrix}+(0)F$$

Very detailed introduction:

- State Space methods
- Linear quadratic
- Weighting
- Augmenting the state
- Kalman
- H Infinity

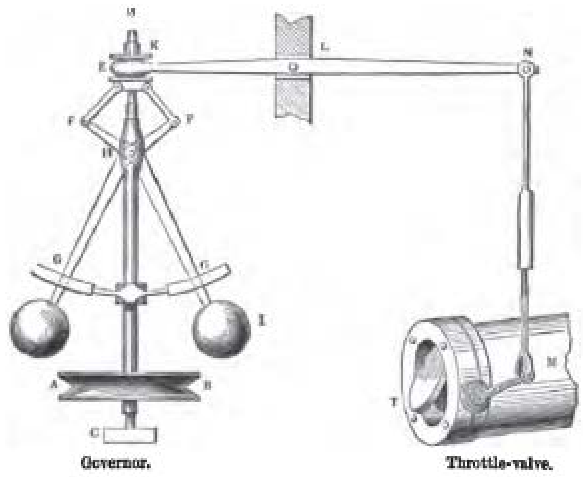
Minimize the cost function:

$$J=\int_{t_0}^{t_1}\left(x^T P x+u^T Q u\right)dt+x^T(t_1)S_f x(t_1)$$

Went other one hour, great interaction.

Summary of the Caltech Workshop	Gabriele Vajente

[T1400302-v3](#) [Report from the Commissioning Workshop of Winter 2014](#)



vs

Classical Feedback Control
Frequency domain

Modern control theory
a magical solution for every problem

G1500679 A summary of the Modern Controls workshop @ Caltech

Summary of the Caltech Workshop	Gabriele

Generalized cost function

How to convince *Linear Quadratic Regulators* to do what we need?

- Frequency dependent requirements
- Arbitrary constraints on actuation
- Take the magic out of loop shape design

Kalman filter for thermal state estimation

Use a model of the mirror thermal dynamics and TCS, to build an online estimation of the thermal lensing

Optimal transfer function estimation

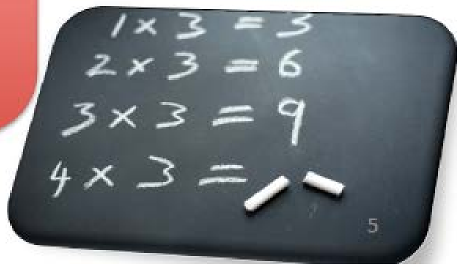
What's the smartest way to measure the response of a system, making the best use of all the things you already know about it?

Optimal filter blending

Can we make the design of filter blending automatic, based on knowledge of the noise levels and requirements?

Hierarchical control design

How to automatically design the blending for suspension control, to maximize stability and use of the actuation ranges



Time domain versus frequency domain tools

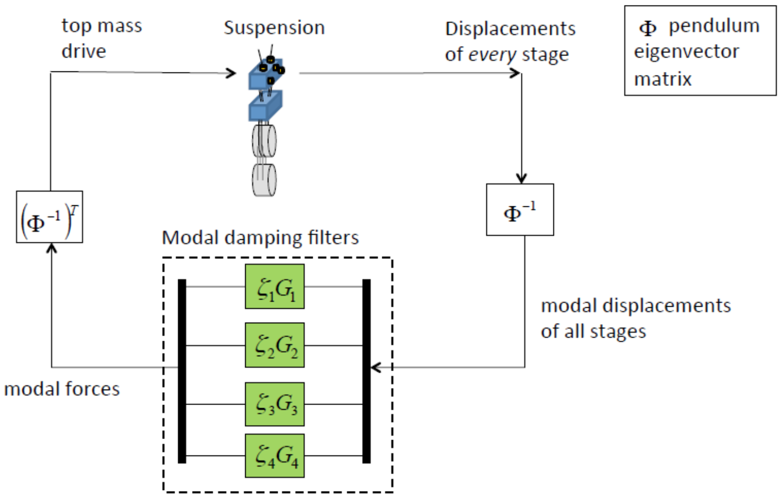
Suspension Controls, including thoughts on applicability of modern controls	**Brett Shapiro**

[G1500626-v2](G1500626-v2) Suspension Control with Thoughts on Modern Control

Can modern control be useful for the suspension systems?

2

Modal Damping with State Estimation



8

Humans (loop shaping)	Modern controls
✓ Distinguishing good and bad results Adjusting to the unexpected 'human readable' designs	MIMO systems Not subject to human biases and strategies Quantitatively 'optimal' solutions
✗ MIMO systems with many coupled loops Have individual biases and strategies	'Optimal' only in the context of the cost function Unmodeled dynamics 'human readable' designs

Concerns often heard about Modern Control (MC)

1. We're just moving the complexity of the design to the cost function.

2. It is hard to predict how a change in the cost will impact the loop.

3. The cost function does not permit the designer to include as much intuition as classical techniques like loop shaping.

My responses to those concerns

1. **"We're just moving the complexity of the design to the cost function."**

   In some cases yes. But there are cases where MC simplifies the problem. Modal damping is an example, which is actually a mix of MC and traditional loop shaping. In other cases, MC might be no more or less complex, yet provide better results. In general, keeping the cost function simple helps a lot.

Kalman filtering for vibration isolation	**Jo van den Brand**

REVIEW OF SCIENTIFIC INSTRUMENTS **85**, 034501 (2014)

State observers and Kalman filtering for high performance vibration isolation systems

M. G. Beker,[1,a)] A. Bertolini,[1] J. F. J. van den Brand,[1,2] H. J. Bulten,[1,2] E. Hennes,[1] and D. S. Rabeling[1]

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(Received 9 October 2013; accepted 11 February 2014; published online 5 March 2014)

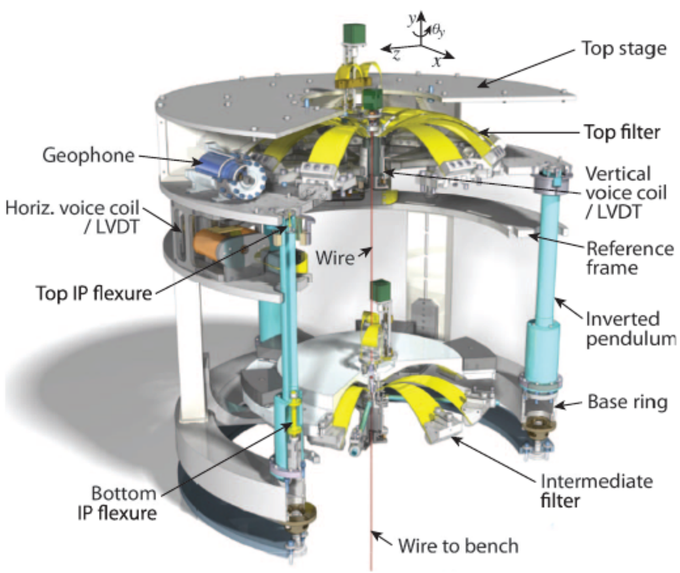
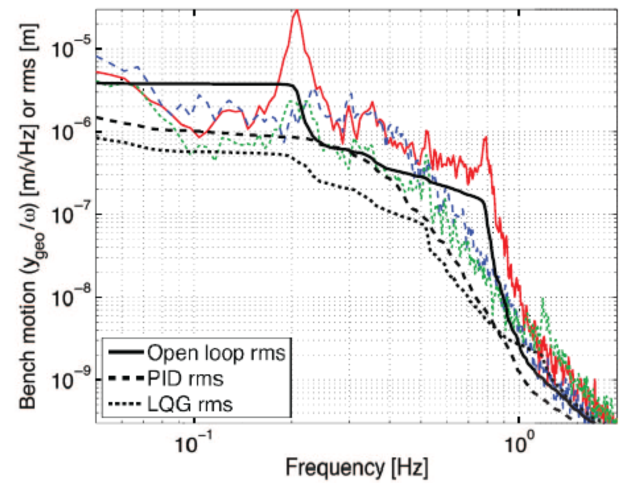


FIG. 1. An overview of the MultiSAS design. The vertical LVDT is situated at the center of the top filter and monitors the height of the intermediate filter stage relative to the top stage. A co-located vertical voice coil actuator is used to apply the vertical feedback control forces to the intermediate filter stage.

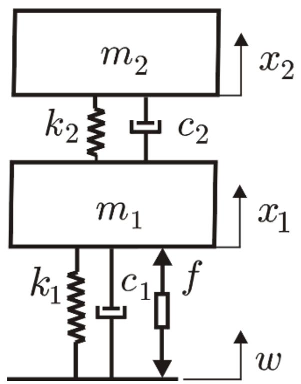


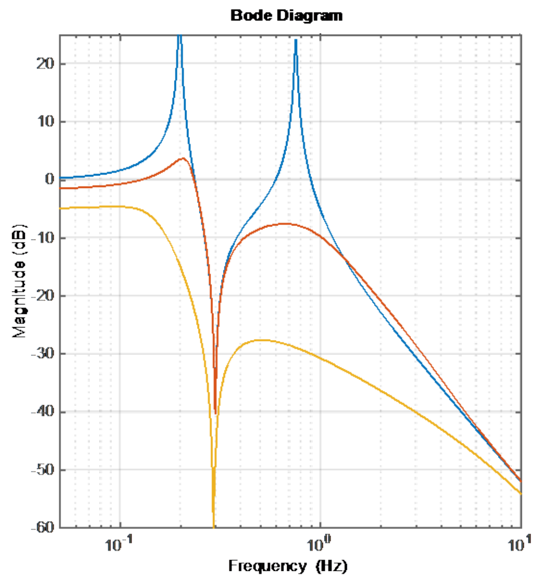
(b)

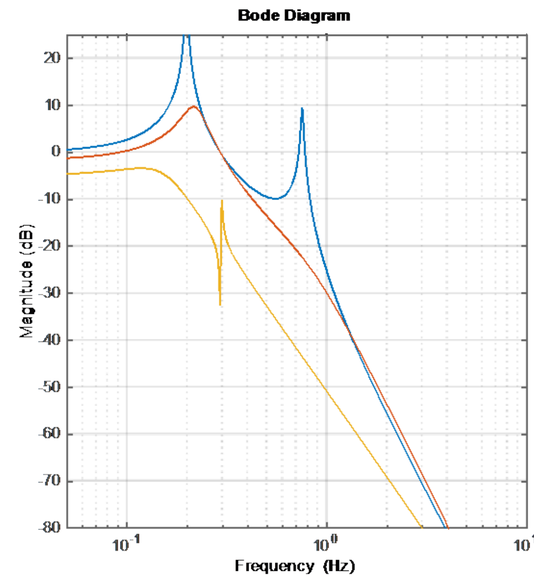
FIG. 14. MultiSAS vertical control results with environmental disturbances only. Closed loop performance plotted for the PID controller with a gain $G = 2$ and the LGQ controller designed with $Q = 100$ and $Q_d = 10$. (a) The LVDT displacement signal and the vertical ground displacement measured by the seismometer. (b) The bench displacement projected from the geophone signal and the equivalent rms motion. At frequencies below 0.1 Hz the signal is dominated by measurement noise and above 2 Hz by acoustic noise coupling to the suspended mass.

Discussion and comparison of classical and modern control techniques	**Christophe Collette**

LIGO-G1500689: [Discussion and comparison of classical and modern control techniques]







- Robustness: For equivalent performance, LQG is more robust to plant variations than aggressive PID.
- Noise rejection: Modal approach (+ Kalman estimator) is flexible to apply high gain to low frequency, and small gain to high frequency modes
  ➔ less noise injection

Modern control, general outcome:

Progress in out understanding of these tools

Potential applications where modern control could be better than the traditional way

Not proven yet, but good evidence in several cases

Not used yet on the detector?

Partly because our systems are designed to be diagonal and are well instrumented.

"Don't rely on controls to fix design issues"

- Equivalent performance than traditional control for SISO systems
- Useful for combining signals and minimize noise
- More Robust
- Handling cross couplings – MIMO systems
- Keeping the momentum

Session C: Feedforward and noise subtraction

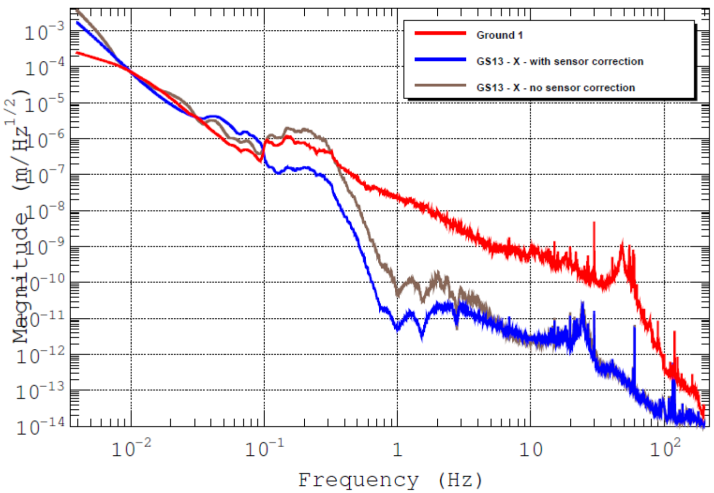
Already made the step…

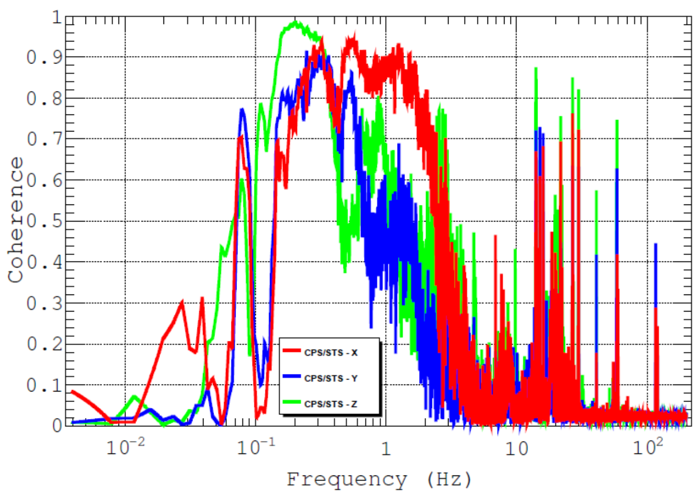
- The standard way (rely on intuition, identify the sensor path, identify the correction path, implement)
- The optimal way (array of sensors, linear regression, least square minimization, Wiener…)
- Results already obtained

Goals:

- Where do we stand (Past results, current work)
- Prospects, applications
- Instrumentalist and DetChar
- Automating
- Adaptive

Sensor correction in seismic and suspensions	Fabrice





Some questions:

1) How to make the best use of our array of sensors?

2) How do make used of our array of witness sensors, vertical axis as rotation sensors, tilt sensors?

3) Are we using the good target sensors?

4) How do we search for coherence?

5) Toolbox for the linear regression, Wiener implementation?

6) Going adaptive for non stationary processes?

Data mining tools: hot to find channels that can be used for subtraction; how to tackle non stationary noises and couplings?	Gabriele Vajente

G1500682-v1 Data mining: how to find channels to feed-forward

Top 20 coherences at all frequencies

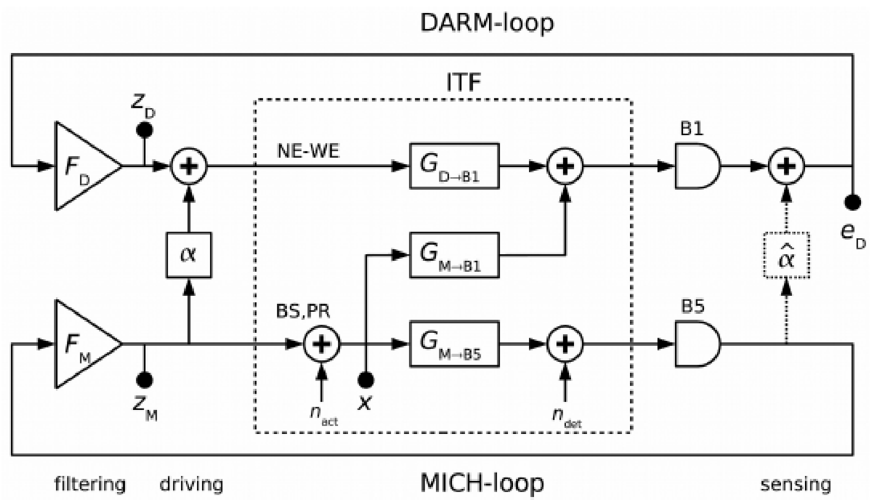
GPS 1108981336 (Thu Feb 26 10:22:01 2015 UTC) + 600 s

Frequency [Hz]	Top channels									
0.00	ASC-X_TR_B_PIT_OUT_DQ (0.44)	ASC-X_TR_A_PIT_OUT_DQ (0.43)	ALS-C_TRX_A_LF_OUT_DQ (0.43)	SUS-ETMX_L2_WIT_P_DQ (0.40)	SUS-ETMX_L3_OPLEV_PIT_OUT_DQ (0.39)	ASC-AS_B_RF45_Q_PIT_OUT_DQ (0.36)	ASC-AS_A_RF45_Q_PIT_OUT_DQ (0.35)	ASC-AS_B_RF36_I_PIT_OUT_DQ (0.33)	LSC-REFLAIR_B_RF27_I_ERR_DQ (0.33)	ASC-AS_B_RF45_I_PIT_OUT_DQ (0.31)
0.50	ASC-X_TR_B_PIT_OUT_DQ (0.33)	ASC-AS_B_RF45_Q_PIT_OUT_DQ (0.32)	SUS-ETMX_L3_OPLEV_PIT_OUT_DQ (0.32)	ASC-X_TR_A_PIT_OUT_DQ (0.31)	ALS-C_TRX_A_LF_OUT_DQ (0.31)	ASC-AS_A_RF45_Q_PIT_OUT_DQ (0.31)	ASC-AS_B_RF36_I_PIT_OUT_DQ (0.30)	ASC-AS_B_RF45_I_PIT_OUT_DQ (0.28)	ASC-AS_A_RF45_I_PIT_OUT_DQ (0.27)	ASC-REFL_A_DC_YAW_OUT_DQ (0.25)
1.00	SUS-OMC_M1_NOISEMON_LF_DQ (0.34)	SUS-OMC_M1_NOISEMON_SD_DQ (0.32)	SUS-OMC_M1_MASTER_OUT_LF_DQ (0.26)	SUS-OMC_M1_MASTER_OUT_RT_DQ (0.25)	SUS-OMC_M1_VOLTMON_LF_DQ (0.24)	SUS-OMC_M1_VOLTMON_RT_DQ (0.23)	ASC-AS_B_RF36_I_PIT_OUT_DQ (0.18)	ASC-AS_B_RF45_I_PIT_OUT_DQ (0.17)	ASC-AS_B_RF45_Q_PIT_OUT_DQ (0.16)	ASC-AS_A_RF45_Q_PIT_OUT_DQ (0.16)
1.50	SUS-OMC_M1_MASTER_OUT_SD_DQ (0.48)	SUS-OMC_M1_NOISEMON_SD_DQ (0.44)	SUS-OMC_M1_VOLTMON_SD_DQ (0.44)	SUS-OMC_M1_DAMP_Y_IN1_DQ (0.42)	ASC-AS_B_RF45_I_YAW_OUT_DQ (0.41)	SUS-OMC_M1_NOISEMON_LF_DQ (0.41)	SUS-OMC_M1_MASTER_OUT_LF_DQ (0.40)	SUS-OMC_M1_MASTER_OUT_RT_DQ (0.40)	ASC-AS_A_RF45_I_YAW_OUT_DQ (0.39)	SUS-OM3_M1_MASTER_OUT_UL_DQ (0.39)
2.00	LSC-ASAIR_B_LF_OUT_DQ (0.25)	LSC-ASAIR_A_LF_OUT_DQ (0.25)	ASC-AS_B_DC_SUM_OUT_DQ (0.23)	ASC-AS_A_DC_SUM_OUT_DQ (0.23)	SUS-ETMX_M0_DAMP_L_IN1_DQ (0.13)	ASC-AS_B_RF36_I_YAW_OUT_DQ (0.12)	SUS-OM1_M1_DAMP_Y_IN1_DQ (0.11)	SUS-ETMX_R0_DAMP_L_IN1_DQ (0.10)	SUS-ITMX_L1_WIT_L_DQ (0.10)	SUS-OM3_M1_MASTER_OUT_LR_DQ (0.10)
2.50	LSC-ASAIR_A_RF45_I_ERR_DQ (0.77)	LSC-XARM_IN1_DQ (0.77)	LSC-ASAIR_B_LF_OUT_DQ (0.60)	LSC-ASAIR_A_LF_OUT_DQ (0.59)	ASC-AS_A_DC_SUM_OUT_DQ (0.56)	ASC-AS_B_DC_SUM_OUT_DQ (0.55)	SUS-ETMX_M0_DAMP_L_IN1_DQ (0.50)	SUS-ETMX_R0_DAMP_L_IN1_DQ (0.40)	ASC-X_TR_A_YAW_OUT_DQ (0.25)	ASC-X_TR_B_YAW_OUT_DQ (0.24)
3.00	LSC-XARM_IN1_DQ (0.85)	LSC-ASAIR_A_RF45_I_ERR_DQ (0.85)	LSC-ASAIR_B_LF_OUT_DQ (0.81)	LSC-ASAIR_A_LF_OUT_DQ (0.80)	ASC-AS_A_DC_SUM_OUT_DQ (0.78)	ASC-AS_B_DC_SUM_OUT_DQ (0.78)	SUS-ETMX_M0_DAMP_L_IN1_DQ (0.65)	SUS-ETMX_R0_DAMP_L_IN1_DQ (0.52)	ASC-X_TR_A_YAW_OUT_DQ (0.50)	ASC-X_TR_B_YAW_OUT_DQ (0.48)
3.50	LSC-XARM_IN1_DQ (0.89)	LSC-ASAIR_A_RF45_I_ERR_DQ (0.89)	LSC-ASAIR_B_LF_OUT_DQ (0.88)	LSC-ASAIR_A_LF_OUT_DQ (0.88)	ASC-AS_A_DC_SUM_OUT_DQ (0.87)	ASC-AS_B_DC_SUM_OUT_DQ (0.87)	SUS-ETMX_L1_WIT_L_DQ (0.42)	SUS-ETMX_R0_DAMP_L_IN1_DQ (0.35)	SUS-ETMX_M0_DAMP_L_IN1_DQ (0.35)	ASC-X_TR_A_YAW_OUT_DQ (0.18)
4.00	LSC-ASAIR_B_LF_OUT_DQ (0.95)	ASC-AS_A_DC_SUM_OUT_DQ (0.95)	ASC-AS_B_DC_SUM_OUT_DQ (0.95)	LSC-ASAIR_A_LF_OUT_DQ (0.94)	LSC-XARM_IN1_DQ (0.91)	LSC-ASAIR_A_RF45_I_ERR_DQ (0.91)	SUS-ETMX_L1_WIT_L_DQ (0.49)	ASC-Y_TR_A_NSUM_OUT_DQ (0.38)	SUS-ETMX_M0_DAMP_L_IN1_DQ (0.36)	ASC-Y_TR_B_NSUM_OUT_DQ (0.33)
4.50	LSC-ASAIR_B_LF_OUT_DQ (0.92)	ASC-AS_A_DC_SUM_OUT_DQ (0.92)	ASC-AS_B_DC_SUM_OUT_DQ (0.92)	LSC-ASAIR_A_LF_OUT_DQ (0.87)	LSC-ASAIR_A_RF45_I_ERR_DQ (0.77)	LSC-XARM_IN1_DQ (0.77)	SUS-ITMX_M0_DAMP_L_IN1_DQ (0.31)	SUS-ITMX_M0_MASTER_OUT_F2_DQ (0.25)	SUS-ITMX_M0_VOLTMON_F3_DQ (0.25)	SUS-ITMX_M0_MASTER_OUT_F3_DQ (0.24)
5.00	ASC-AS_A_DC_SUM_OUT_DQ (0.85)	ASC-AS_B_DC_SUM_OUT_DQ (0.84)	LSC-ASAIR_B_LF_OUT_DQ (0.83)	LSC-ASAIR_A_LF_OUT_DQ (0.64)	LSC-XARM_IN1_DQ (0.37)	LSC-ASAIR_A_RF45_I_ERR_DQ (0.37)	SUS-ITMX_M0_MASTER_OUT_F2_DQ (0.16)	ASC-AS_A_RF45_Q_YAW_OUT_DQ (0.15)	SUS-ITMX_M0_MASTER_OUT_F3_DQ (0.15)	SUS-ITMX_M0_NOISEMON_F2_DQ (0.15)
5.50	ASC-AS_A_DC_SUM_OUT_DQ	ASC-AS_B_DC_SUM_OUT_DQ	LSC-ASAIR_B_LF_OUT_DQ	SUS-BS_M2_VOLTMON_LR	SUS-BS_M2_VOLTMON_UL	SUS-BS_M2_MASTER_OUT	SUS-BS_M2_MASTER_OUT	ASC-AS_A_RF45_I_PIT_OUT	SUS-OM2_M1_MASTER_OUT	SUS-OM2_M1_MASTER_OUT

BruCo: Brute Force Coherence (**LIGO-G1500230**)

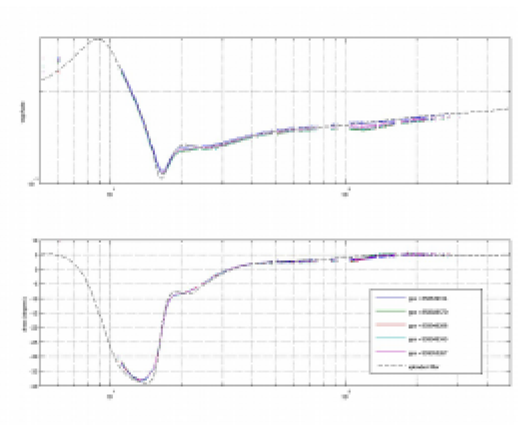
Feed forward of auxiliary degrees of freedom | Bas Swinkels

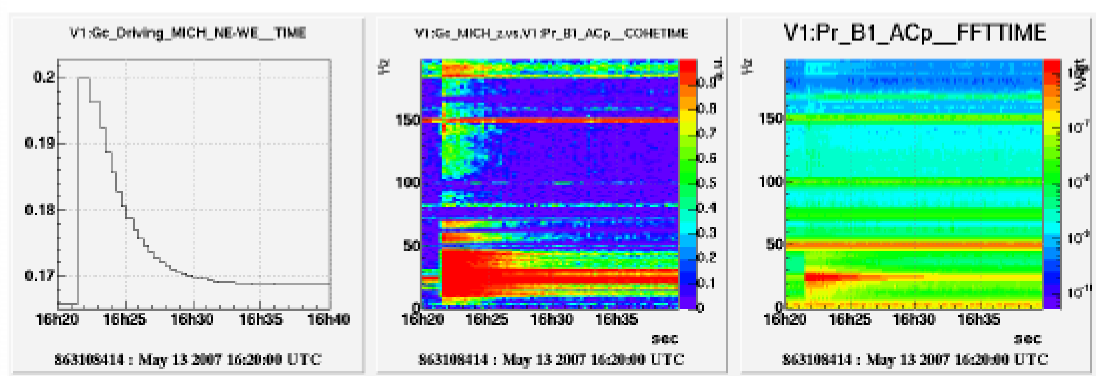
LIGO-G1500680: Subtraction of auxiliary DOF noise



- Advanced Virgo
- Online versus offline

- Servo amplitude of alpha-filter to zero this signal





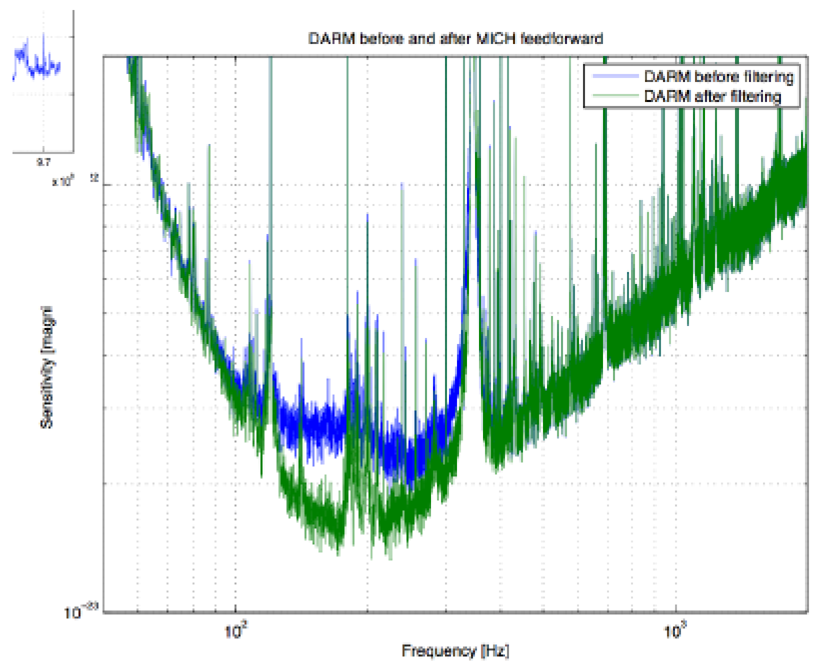
Online subtraction pipeline, and bilinear noise coupling	**Keita Kawabe**

[G1500664-v1](G1500664-v1)   Post-Facto Noise Subtraction, Bilinear Coupling

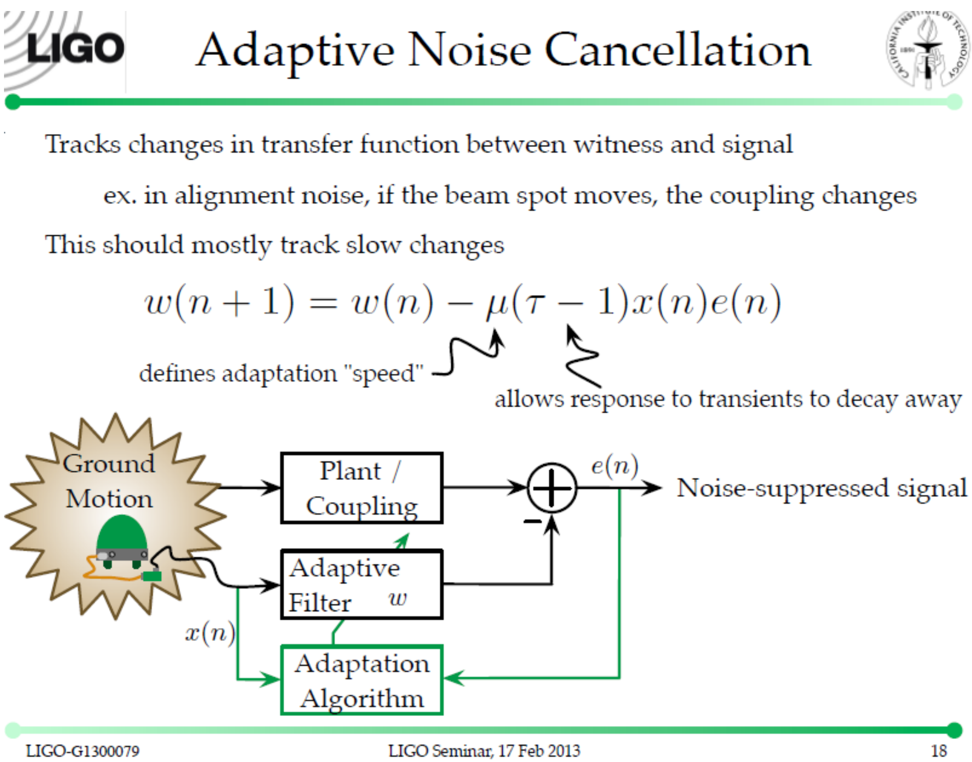
Reducing the input noise, and the coupling, and feed forward in real time:

1. Post--facto noise subtraction pipeline
2. Possibility of subtracting bi--linear (and potentially tri--and higher order) coupling.

- Reviewed examples
- Talked about adaptive techniques
- Existing tools
- Work to be done
- Adapt to some other noise sources



Feedforward at LLO and 40m, adaptive feed forward	Denis Martynov



Described the work done

Good results

Though the FIT subtraction not as good at the SUS resonance

MICH/SRCL subtraction depends a lot on the centering of the beam. OK at Virgo, limited at LIGO. Lesson for the future.

How useful would it be at the sites? How do we make that happens?

[G1300079-v1](G1300079-v1) Noise Cancellation for Gravitational Wave Detectors

Ryan Fisher

DetChar & Commissioning Tools

- Goal: Collect a set of vetted tools in one place so they get used
- Plan: Create an Approved/Complete Tools wiki
- Organized by Category
- Organizers: Ryan Fisher, Fabrice Matichard, Gabriele Vajented, Dennis Coyne, Bas Swinkels

"Vetting" Requirements

- SVN or GIT checkout of code available
- A set of instructions that allows a user to start from nothing and end up with an expected output
- A set of instructions on how to change the inputs or configurations to get different desired outputs
- Description of what the tool is useful for and what you get out of it
- Any limitations (location, software) or package requirements on running it
- The tool should be vetted by a volunteer from DetChar or elsewhere

What Kinds of Tools?

- First set:
  - BruCo - Brute force correlation code
  - Excavator - correlate auxiliary channels with glitches
  - wDQ - used to simplify generating Omega Scans for glitch follow-up
- Desired:
  - Non-stationary noise
  - Bi-Linear and Non-Linear coupling analysis
  - Weiner statistic/adaptive analysis calculation
  - Spectral tools

Feedforward/Subtration, general outcome

- Good review of auxiliary degrees of feedom (using similar tools…)
- Solving non stationarity
- Search for non linearity, bi-linear couplings
- Adaptive tools
- **Need to generalize the search for coherence**
- **Making the tools available**
- **Wonderful collaborative effort**
- **To do list**
- **Things are in motion**

Summary D: Lock Acquisition Problems & Improvements Acquisition overview/problems & discussions

- aLIGO (Shiela Dwyer, Keita Kawabe (LHO); Anamaria Effler (LLO))
  - Lock acquisition is deterministic for the arms (ALS) but stochastic for DRMI
  - Works most of the time; acquires in 15-30 min
  - Reasons for lock difficulty:
    - Poor initial alignment (drift)
    - Mode hopping
    - Bounce & roll modes not adequately damped sometimes (plant drifts)
    - CARM depends on RC gain
    - High winds (LHO)
      - causes DRMI lock to take more time
      - with high ETM green transmission, ALS arm lock problems
  - Simulation:
    - Optickle (and derivatives), E2E

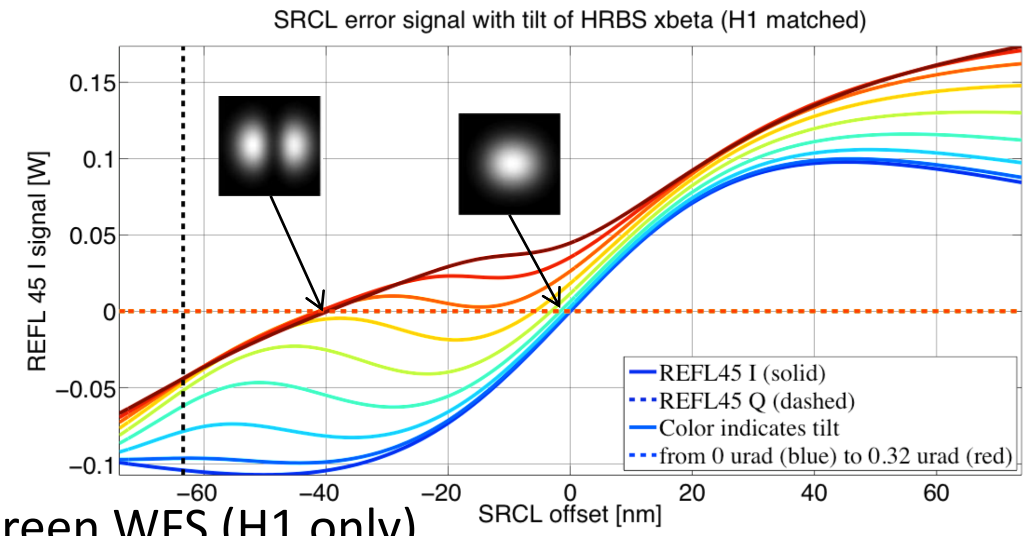
Summary D: Lock Acquisition Problems & Improvements Acquisition overview/problems & discussions (continued)

- Virgo (Gabriele Vajente, Bas Swinkels)
  - iVirgo Thermal transients in ITM at full lock caused drift
    - solution was to wait ~10 minutes
    - Lower absorption for aVirgo
  - Planning to use same variable finesse locking technique, but don't yet have a solution for SRC
  - Added high frequency RF sidebands (132 MHz) for use in lock acquisition – less sensitive to aberrations (thermal et. al.)
  - Plan to use guided lock acquisition (ala TAMA) if needed
    - aVirgo arm cavity finesse is 450 (was 150 for iVirgo)
    - Simulation indicates that guided lock acquisition may not always be needed
  - Digital demodulation
  - Simulation:
    - E2E, Optickle, Finesse (for thermal)

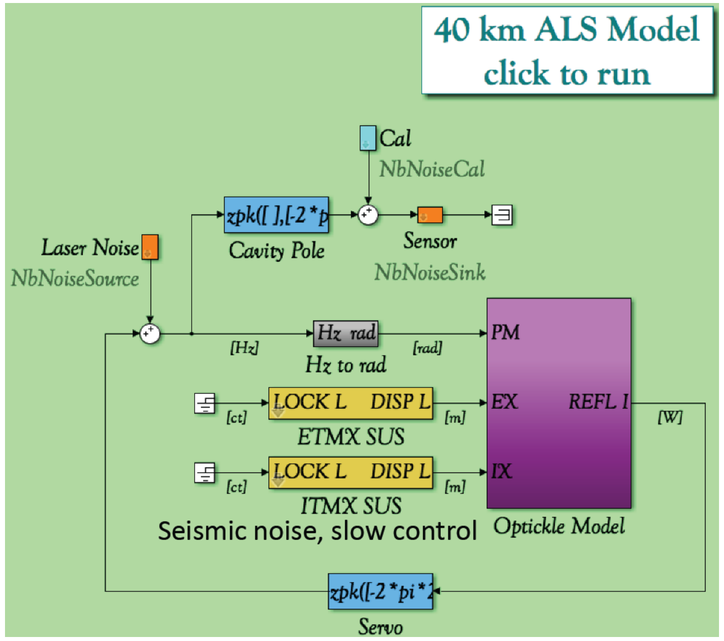
Summary D: Lock Acquisition Problems & Improvements Acquisition overview/problems & discussions (continued)

- Geo (Emil Schreiber, [Hartmut Grote])
  - “only” 3 DOFs, but PR factor is higher
  - Automated, guided, stochastic locking for each DOF in sequence
    - PRC → Michelson (with 2kHz detuned SRC via heterodyne) → SRC
    - Then OMC beacon lock acq.; switch on slow controls (alignment, power ramp up, …)
    - ~3 – 5 min total for lock sequence
  - No (significant) lock acquisition problems
- KAGRA (Yuta Michimura)
  - Same basic approach as for aLIGO, with 2 differences:
    - Inject green ALS beam through PR2/SR2 (rather than fiber to ETMs)
    - Non-resonant SB for DRMI instead of 3f (AM, not PM)

Summary D: Lock Acquisition Problems & Improvements



- Mode Hopping Problems (Paul Fulda)
  - ALS
    - Causes: Low finesse; alignment
    - Solutions: improved SEI performance (tuning); ALS green WFS (H1 only)
    - Will replace ETMs with proper green transmission
  - H1 DRMI (but not L1)
    - Causes: Alignment; mode matching; Gouy phase; Cross-coupling
    - Solutions: improve alignment, increase HOM separation
    - Would be good to measure RC optics with better ROC accuracy
- Simulation for Commissioning/Controls (Chris Wipf)
  - SimulinkNB – noise budget tool
  - Example application: ALS for 40 km long arm (FSR @3kHz)
  - Tool for designers and commissioners



Summary D: Lock Acquisition Problems & Improvements

- Bayesian approach for locking high finesse cavities (Manuel Marchiò, Giancarlo Cella)
  - Apply force outside of resonance (to slow down the optic) based on a dynamics model
  - State space (position, velocity) Guassian distribution + linear dynamics → Kalman filter estimator
  - Use transmitted power to know that you are passing a TEM00 resonance
  - Plan to include PDH off-resonance signal with particle filter (sum of Gaussians) method
  - Could this approach work for DRMI, for a more deterministic lock?

D: Lock Acquisition Problems & Improvements: *goals/questions*

- From each interferometer, gather a compendium of
  - lock acquisition problems
  - Locking metrics & statistics
- Discuss approaches to address each lock acquisition problem and their relative merits and success to date
- Are the pre-lock auxiliary systems (OptLev, ALS, TCS, …) adequate, or are improvements necessary?
- Shouldn't future interferometers be designed to observe and control all DOF (bounce, roll, violin modes)?
- Would we benefit from embedding independent sensing/actuation into the interferometers for routine diagnostic measurements & characterization?
- Which lock acquisition problems can & should be pursued on small scale research interferometers?
- SIMULATION TOOLS
- STOCHASTIC LOCKING NOT GOOD

Summary E: Interferometer Stability
Lock Loss Causes

- aLIGO (Keita Kawabe, Shiela Dwyer (LHO); Anamaria Effler (LLO))
  - We can automatically detect lock loss, but not the cause (yet)
  - Detchar has a tool for auto plotting signals of typical interest just preceding a lock loss event
    - Will make auto & publish
  - Clear need for better local sensing of poorly controlled (damped) modes: roll, bounce, violin modes
  - Not yet clear if the limited actuation authority for these modes is stable/reliable or not (i.e. do we also need better actuation?)
    - Depends on alignment & beam position
    - Bounce & roll don't change at LLO; stable with good alignment
    - Find good alignment based on RC gains (automated procedure)
  - Inspiral range creeps down (sometimes) – thermal?
  - Leading lock loss causes at LLO:
    - Parametric Instability
    - EQs every 2-3 days
  - Saturation
    - Detchar is working on ODC checks on saturation
    - DAQ system has automatic saturation detection code

Summary E: Interferometer Stability Lock Loss Causes (continued)

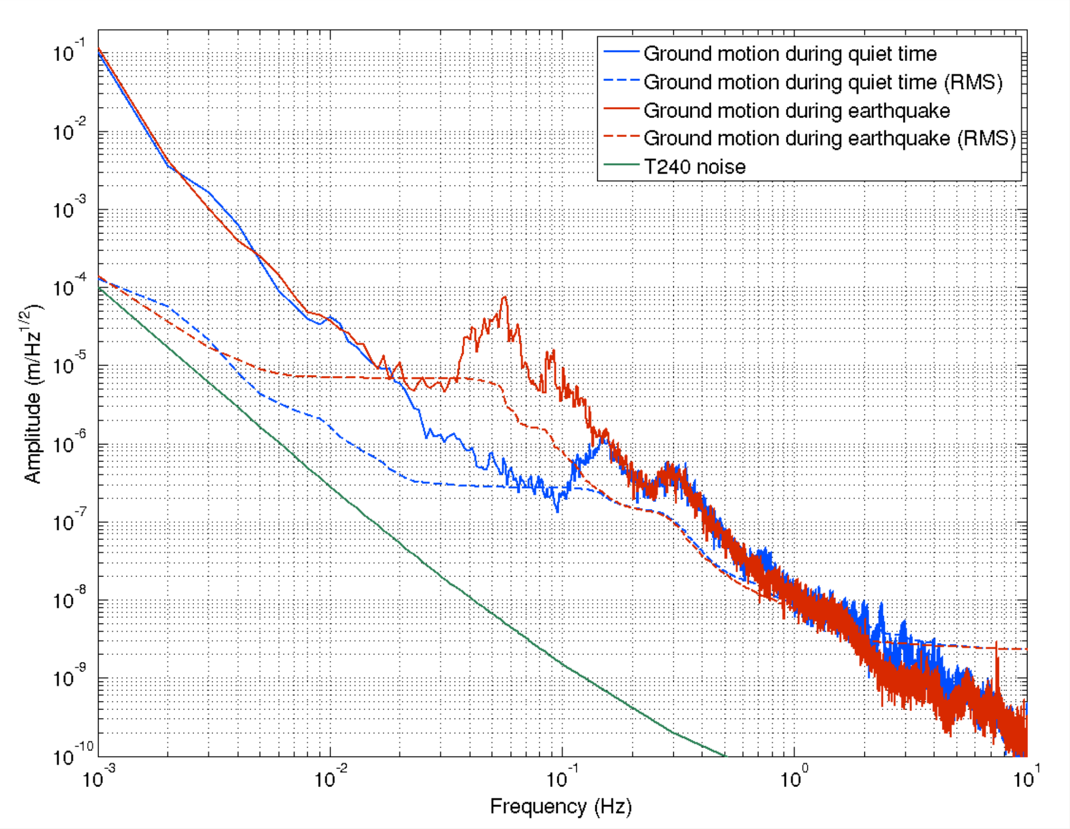
- Virgo (Bas Swinkels)
  - Reviewed VSR1 – 3 lock/unlock statistics
  - Improved caused lock loss events from 1-2/week (mag 6, Indonesia) to 1 per 2-3 weeks (mag 7, Indonesia)
  - VSR3: 90% locked, 80% science, 143 hr longest lock
  - Maintenance period (typ 4 hr/week) was largest contributor
  - Instrument/hardware reliability comparable to maintenace
- Geo (Emil Schreiber)
  - Auto lock loss detection (& plotting) and re-acquire

Summary E: Interferometer Stability

- Ground Tilt (Krishna Venkateswara)
  - Wind induced gnd tilt is significant for LHO (> 20 mph, 15% time)
  - Optic yaw response in high wind
    - Might be bilinear coupling with mis-centered beam?
    - Could be mis-balanced coil drivers
    - Investigate ISI to SUS cross-coupling, esp. yaw
    - Suggestion to simulate wind (high amplitude motion in ISI) to discover coupling path
    - LIGO pursuing a 2nd Beam Rotation Sensor (BRS) for LHO testing
- TCS (Alastair Heptonstall)
  - Plan to maintain ITM/CP thermal lens with CO2 laser when main beam losses lock – Operator sets thermal lens power with Guardian
  - Need to separately tune SRC & PRC (Virgo does this already for PRC) – LIGO considering the addition of a "ring heater" (or similar) to SR3 & PR3

Summary E: Interferometer Stability

- Earthquakes (Sebastien Biscans, et. al.)
  - LIGO has a few unlocks per week
    - (maybe same order of magnitude for Virgo)
  - Tilt is not well known for EQs
  - Displacement ASD high < 0.1 Hz
  - LIGO ISI platform (apparently) tilts a lot in response
  - ISI platform trips on S-wave or surface waves , approx. 30 min typ from EQ p-wave → time to prepare
    - With USGS network at least a few min warning for "all" EQs
    - EQ Monitor (Jan Harms, Michael Coughlin) can predict to amplitude factor of 4 & 1-2 sec arrival
    - Reduce digital gain & increase analog gain
    - What to do to prepare & ride-out a mild EQ, e.g. higher blend freq.
    - Each EQ is different; requires testing. LASTI?



E: Interferometer stability (maintaining lock) *goals/questions*

- Gather a compendium of lock loss event causes
  - Do we have detchar infrastructure for automatic detection, logging, and calculation of statistical metrics?
- Discuss approaches to address each lock loss cause and their relative merits and success to date
- Are the lock loss prevention auxiliary systems adequate, or are improvements necessary?
- Would we benefit from embedding independent sensing/actuation into the interferometers for environment sensing?
- Which lock loss problems can & should be pursued on small scale research interferometers?

Summary F: Next Generation Control System Architecture

- How can we improve controls infrastructures to facilitate development of "modern" or "advanced" controls?
- Rolf Bork and Bas Swinkels gave brief overviews of the current aLIGO and aVirgo controls infrastructure

- Leverage commercial off-the shelf (LIGO: server-class computers, PCIe I/O, Beckhoff, RT linux patch, EPICs, etc.)

vs

- flexibility and control of custom (Virgo: DSPs, TOLM, ALP, etc.)
  - Both can work.
  - Virgo hopes to move from ALP to Tango. Should LIGO move from EPICs to Tango to leverage the entire LVC community?
  - No group conclusions; not really all the right people/expertise

Summary F: Next Generation Control System Architecture

- We then heard from people working on controls technology about what they would like to see:
    - Increase availability to modern/advanced algorithms that are ready to move beyond R&D (e.g. drop in "RCG part"):
        - State Space/LQR
        - Kalman filters
        - LQG adaptive algorithms (prototyped at 40m Lab)
    - Adaptation rate < loop rate
        - Leverage multiple processors to offload adaptive calculations from front-ends, or
        - multi-rate front-end calculations
    - Increase accessibility, e.g. reduce hardware requirements, to facilitate development of prototypes, simulations, etc.
    - Modularity and flexibility in the infrastructure is the key to facilitating future controls development
    - Build a set of canonical problems (e.g. SUS angular control) and matching algorithms (e.g. Kalman filter) to develop a super-set of control system requirements
    - Couple the control system design tool (RCG for LIGO) directly to a simulation (e.g. SimPlant prototype at 40m Lab)

Final Comments

- How can we as a community share and sustain a growing expertise in the application of advanced/modern controls to GW interferometer systems?
  - LVC wiki pages for Controls
    - Get a critical mass
    - Share examples, code, experiences
  - Regular LVC (virtual) meetings on Controls
    - Perhaps an “official” LVC working group on controls?
  - Detchar “gold star” vetted tools wiki page
- In future GWADWs:
  - Address next generation systems (V+, A+, Voyager, Longo, …)
  - Consider truly advanced techniques, with adequate prep (NN, deep learning, …)