Conceptual Design Part 1: Control System Design

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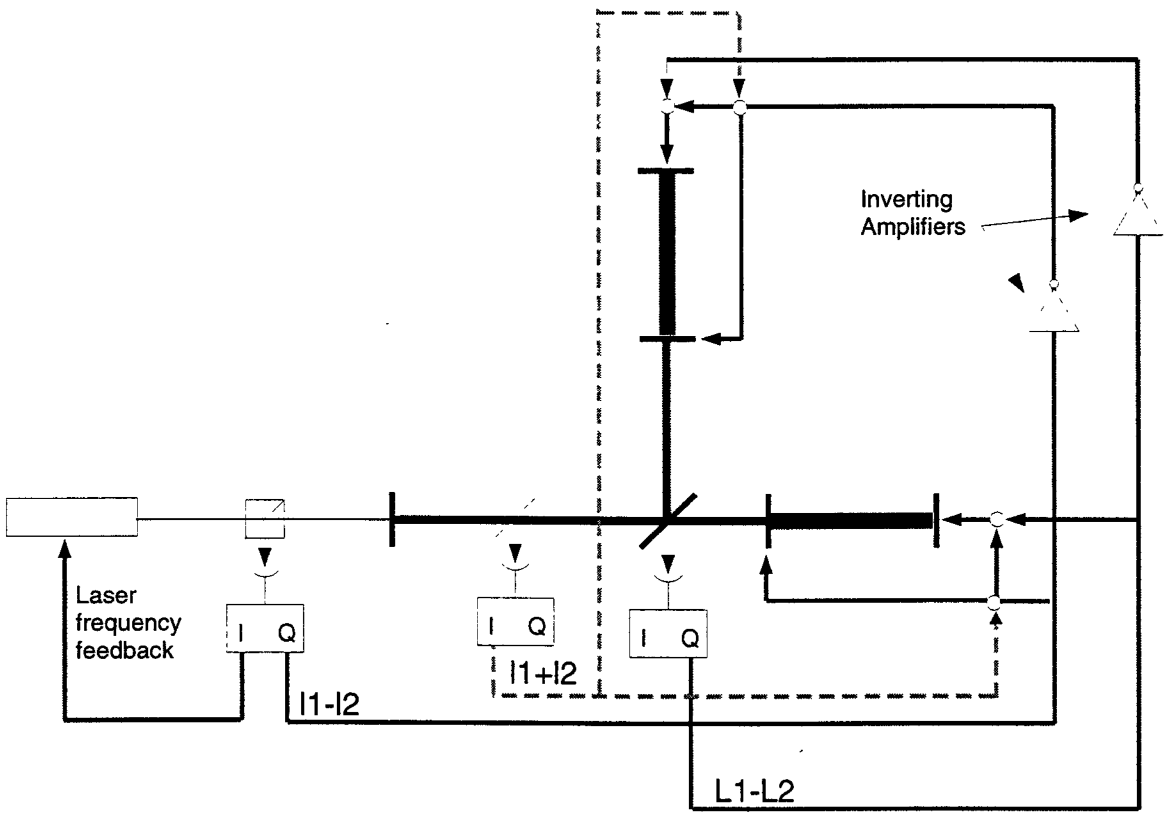
Baseline Configuration



- Actuate only the test masses (design driven by SUS)
- Sensing as shown in figure

Alternative Configurations

- Actuation (baseline is the 4 test masses)
  - ›› End test masses, beamsplitter, and recycling mirror
    - Minimizes number of signal paths
  - ›› In-board test masses, beamsplitter, and recycling mirror
    - High bandwidth signals would not be transmitted over 4 km
- Sensing
  - ›› l1+l2 sensed with non-resonant sidebands
    - Eliminates set of beam reducer optics in beam splitter chamber
  - ›› l1-l2 sensed at recycling cavity pick-off
    - Loop more robust to changes in the losses of the cavity mirrors

Length Sensing Matrix

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} \approx \begin{bmatrix} a_1 & \varepsilon_1 & 0 & 0 \\ \varepsilon_2 & a_2 & 0 & 0 \\ 0 & 0 & a_3 & \varepsilon_3 \\ 0 & 0 & \varepsilon_4 & a_4 \end{bmatrix} \begin{bmatrix} L_1 + L_2 \\ l_1 + l_2 \\ L_1 - L_2 \\ l_1 - l_2 \end{bmatrix}$$

- V1, V3, and V4 loops are fairly uncoupled:

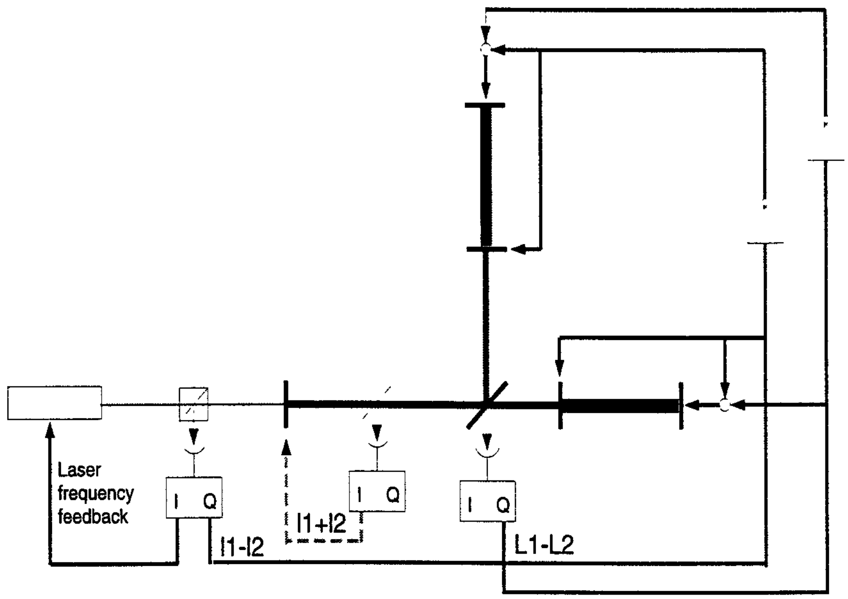
$$\frac{\varepsilon_n}{a_n} \sim \mathbf{0.01 - 0.001}$$

- V2 loop has large L_1+L_2 and small l_1+l_2 piece:

$$\frac{\varepsilon_2}{a_2} \gg 1$$

- Loop gain of (L_1+L_2) loop must be > than (l_1+l_2) loop by at least $\varepsilon_2/\mathbf{a_2}$ to provide adequate de-coupling

Test Case Detection Mode Design

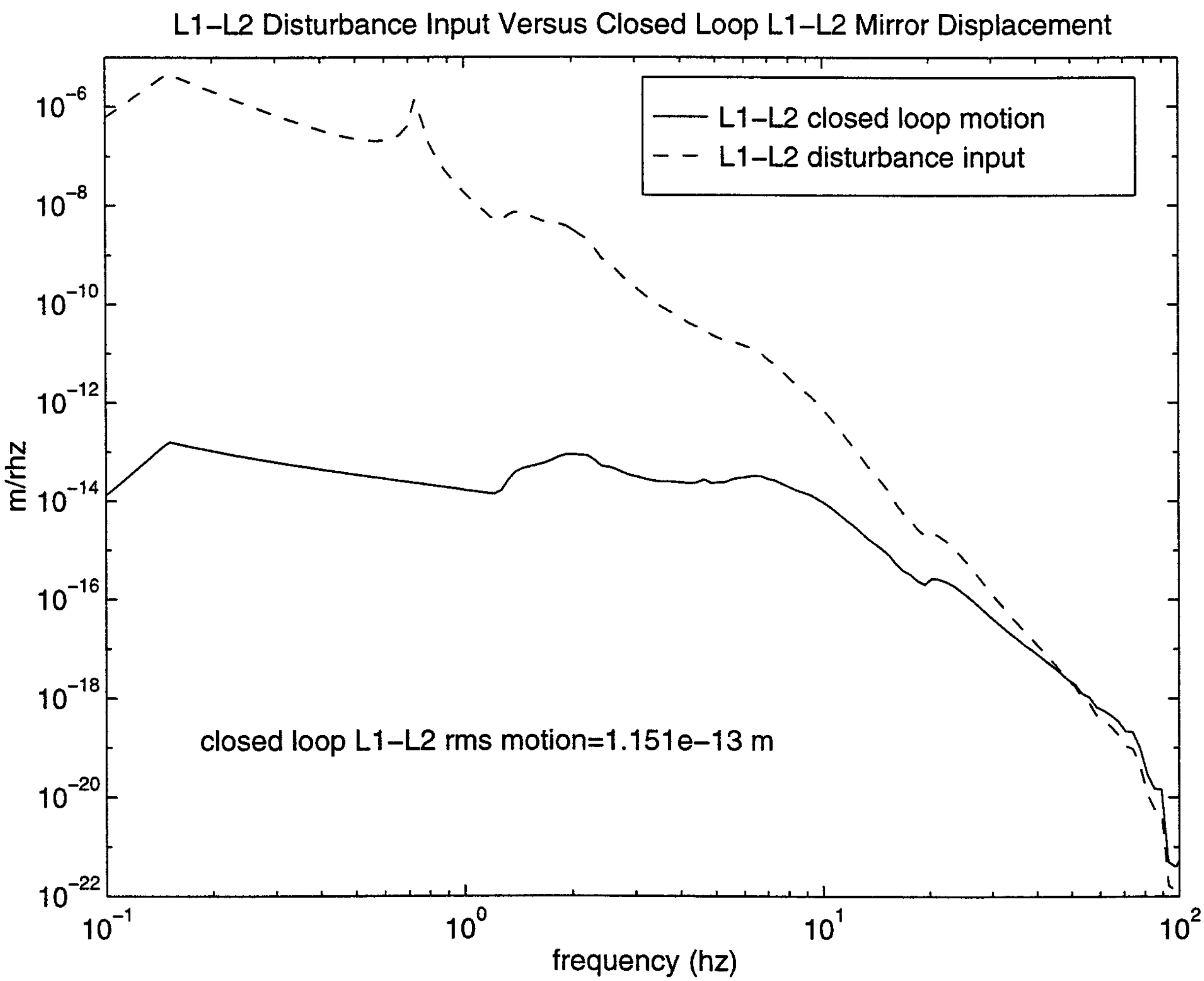


- Low frequency design driver (<10 Hz):
  - ››Reduction of RMS motion (mainly at microseismic peak)
  - ››Loop gain ratio requirement of (L1+L2) and (I1+I2) loops
- Mid-frequency design driver (10<f<100 Hz)
  - ››Shot noise feedthrough of I_1-I_2 loop into gravity wave band
  - ››Loop gain ratio requirement of (L1+L2) and (I1+I2) loops
- High frequency design driver (f>100 Hz)
  - ›› loop gain attenuation so test mass resonances don't ring
  - ›› frequency noise suppression

Loop Gains and RMS Motion

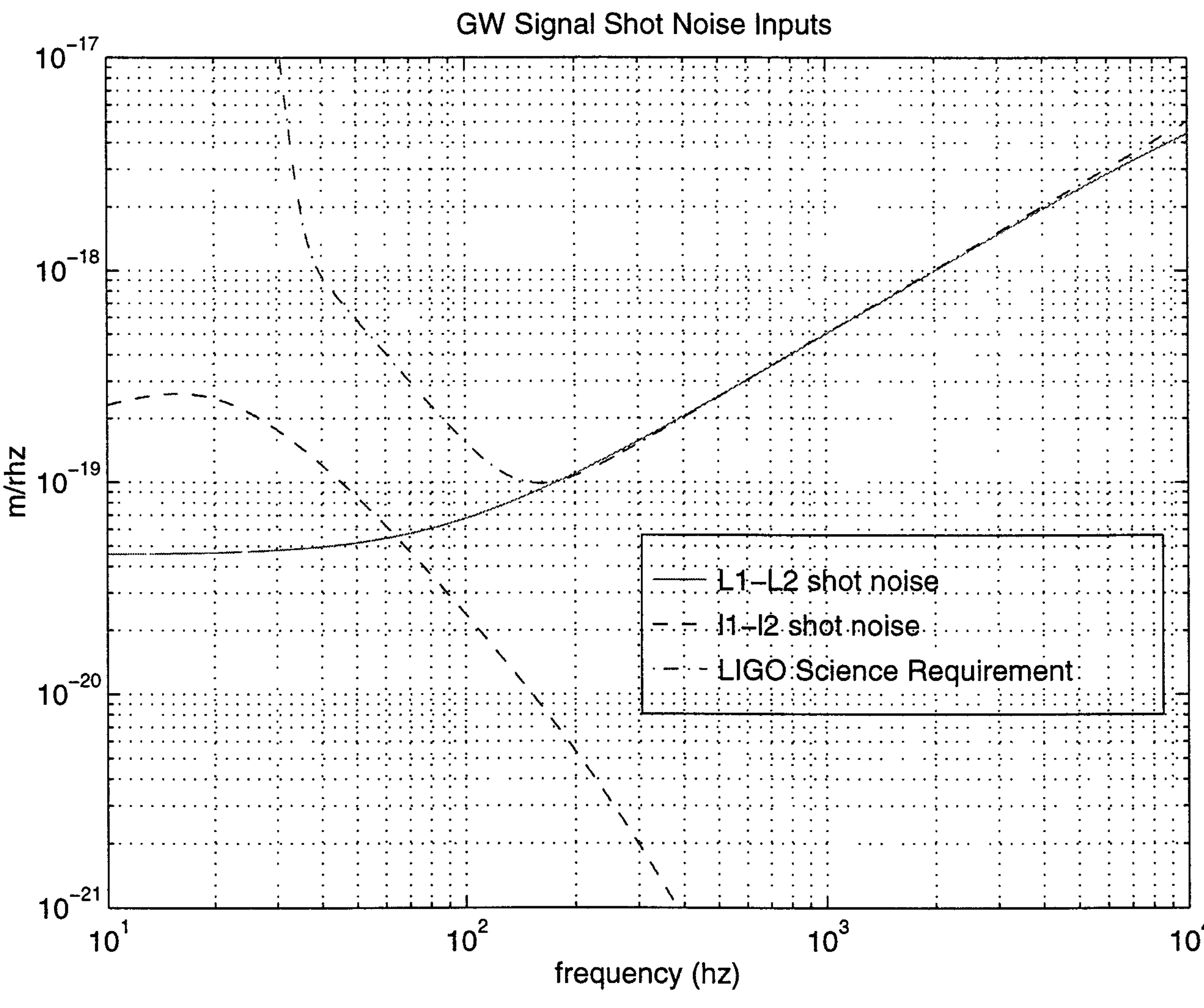
	Laser loop	l_1+l_2 *loop*	L_1-L_2 *loop*	l_1-l_2 *loop*
Loop Gain at 1 Hz	10^6	$3x10^3$	$3x10^6$	$2x10^3$
Unity Gain Frequency in Hz	10^4	55	140	22
Phase Margin	45^o	46^o	36^o	40^o
Gain Margin	8	3	4	7
Gain at 8 kHz	~1	$2x10^{-8}$	10^{-5}	10^{-8}
RMS Requirement (mrms)	$2.5x10^{-12}$ (equivalent)	$1.6x10^{-10}$	10^{-12}	$1.3x10^{-10}$
RMS Motion (mrms)	$8x10^{-13}$ (equivalent)	$1.2x10^{-11}$	$1.15x10^{-13}$	$1.5x10^{-10}$

Example Plot of Closed Loop Motion (L1-L2 Loop)



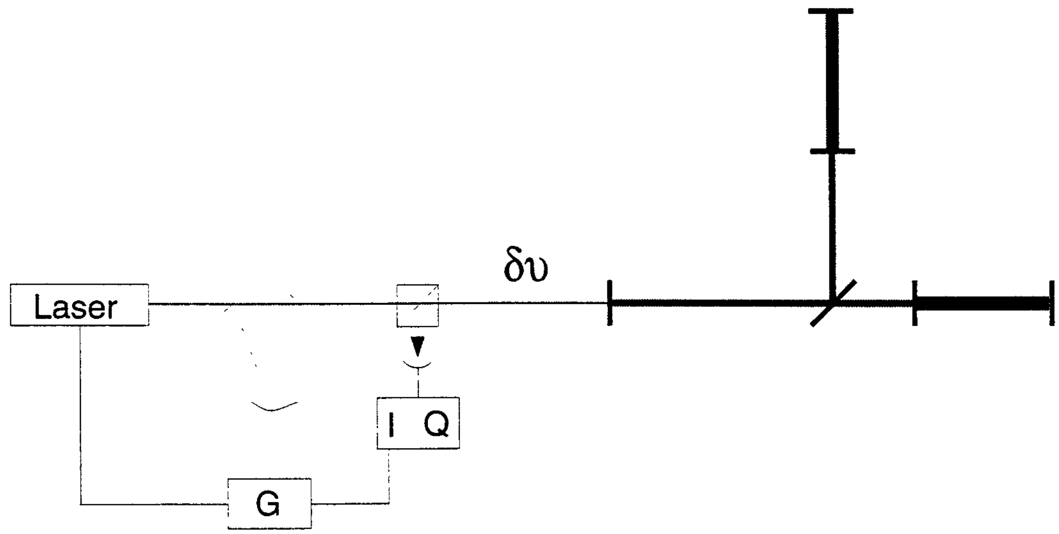
- Disturbance Input: Livingston spectrum filtered through baseline stack and suspension design

Shot Noise Performance for Auxiliary Length Control Servos



- Michelson l1-l2 shot noise ~16% of LIGO sensitivity between 40-140 Hz

Frequency Noise Suppression



	f = 100 Hz	f = 10 kHz
δυ Requirement	**10^{-7} Hz/Hz$^{1/2}$**	**$4x10^{-6}$ Hz/Hz$^{1/2}$**
δυ from IFO Shot Noise	10^{-7} Hz/Hz$^{1/2}$	$3.3x10^{-6}$ Hz/Hz$^{1/2}$
δυ with IFO Feedback "Off"	10^{-4} Hz/Hz$^{1/2}$ (MC thermal noise)	10^{-5} Hz/Hz$^{1/2}$ (MC thermal noise and shot noise)
δυ with IFO Feedback "On"	$5x10^{-9}$ Hz/Hz$^{1/2}$ (loop gain=$2x10^{4}$)	10^{-5} Hz/Hz$^{1/2}$ (loop gain=1)

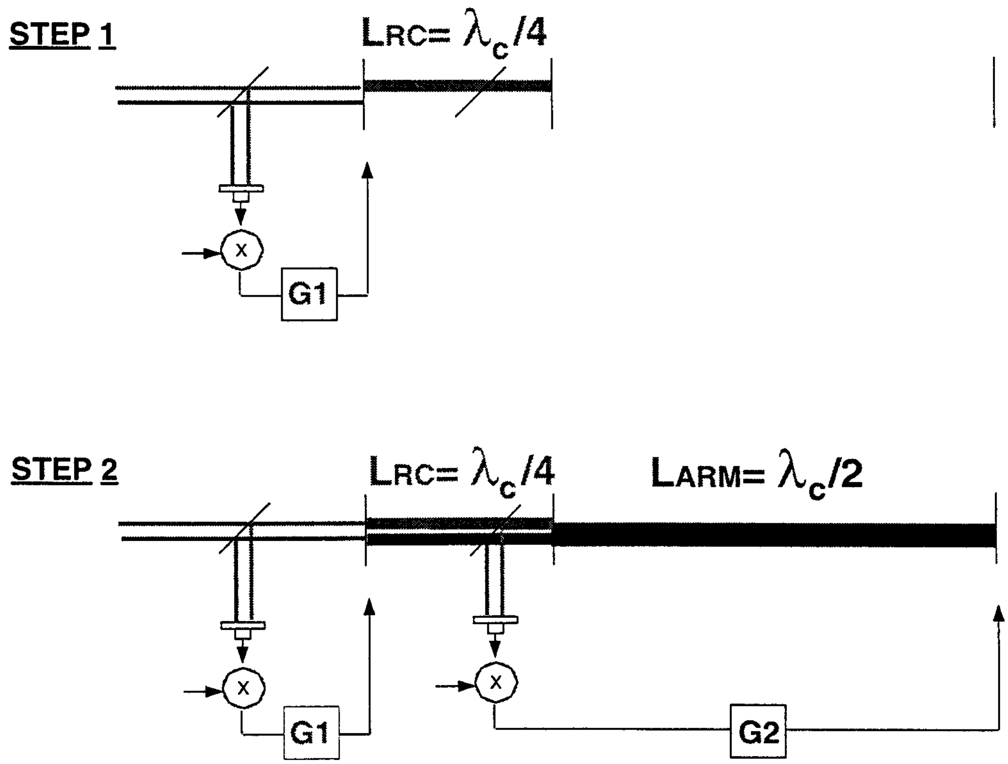
Concept for Acquisition Mode

- Concept based on coupled cavity acquisition model

    ›› cavities lock in natural sequence (sidebands first)

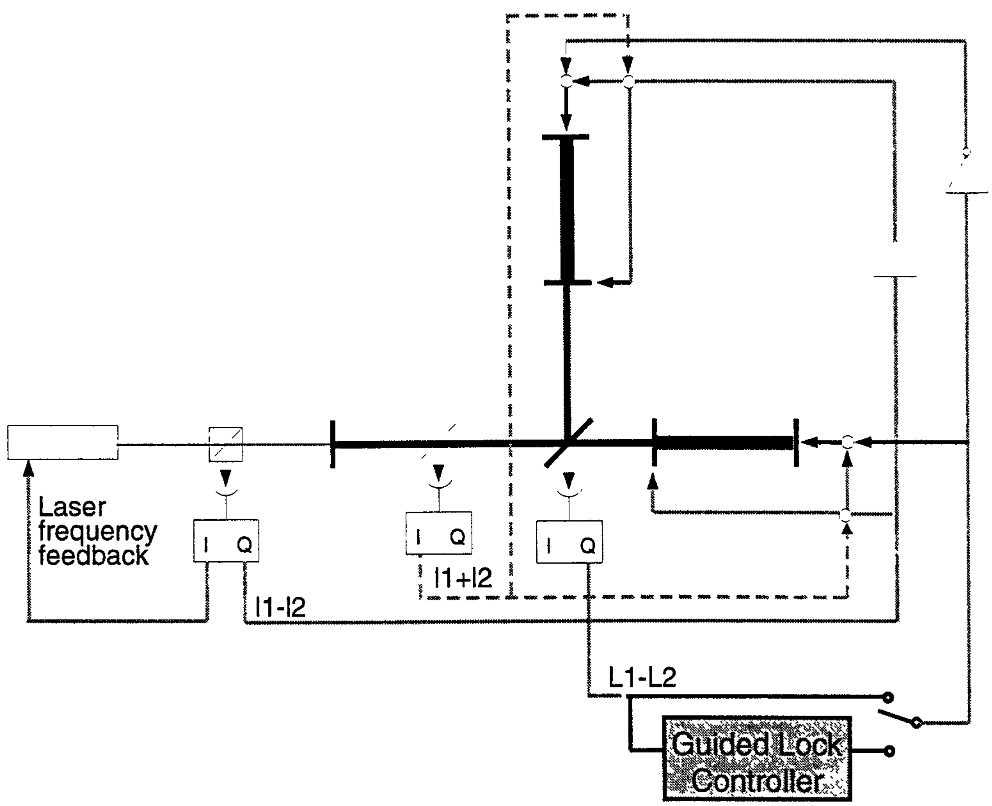
    ›› Threshold velocity is high for recycling cavity (broad fringe)

    ›› Threshold velocity lower for arm cavity acquisition unless bandwidth is very high (i.e. laser loop)



Concept for Acquisition Mode (cont.)

- Projected locking behavior for recycling
  - ›› l_1-l_2 and l_1+l_2 have high threshold velocity (broad fringes)
  - ››L_1+L_2 has high threshold velocity (high BW servo)
  - ››L_1-L_2 loop has low threshold velocity (~same as 40m)
- Resulting configuration similar to Detection mode but with “Guided Lock” in L1-L2 loop



Concept for Acquisition Mode (contd.)

- Other differences from Detection Mode
  - ››Reduced low frequency gains (important for RMS reduction not acquisition)
  - ››Increased bandwidths (bandwidths important, not gain)
  - ››Unconditionally stable filters (get more gain and phase margin so believe acquisition will be more robust)
  - ››Switching system between Acquisition and Detection modes servos based on 40m switching design

Issues To Be Resolved

- Final decision on Detection mode configuration
- Completion of Acquisition Model to verify threshold velocities and conceptual design
- Systems engineering approach to resolve laser frequency noise issues