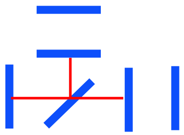
Lock Acquisition in LIGO

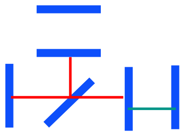
- Who am I?
  - Matt Evans
  - Caltech graduate
- What is Lock Acquisition?
  - The process by which an uncontrolled interferometer is brought to its operating point.
- Why do I care, and why should you?
  - If you can't lock your interferometer, you can't use it as a gravitational wave detector.
- This talk will focus on LIGO specifics
  - More general: Thesis on Lock Acquisition (in the DCC)
  - More accurate: InputMatrix3.c

The Lock Acquisition Path

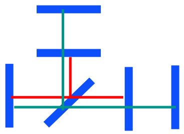
State 1 : Nothing is controlled. This is the starting point for lock acquisition.



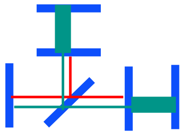
State 2 : The power recycling cavity is held on a carrier anti-resonance. In this state the sidebands resonate in the recycling cavity. (Engaged)



State 3 : One of the ETMs is controlled and the carrier resonates in the controlled arm. (Engaged + ArmXOn, or Engaged + ArmYOn)



State 4 : The remaining ETM is controlled and the carrier resonates in both arms and the recycling cavity. (Engaged + ArmXOn + ArmYOn)

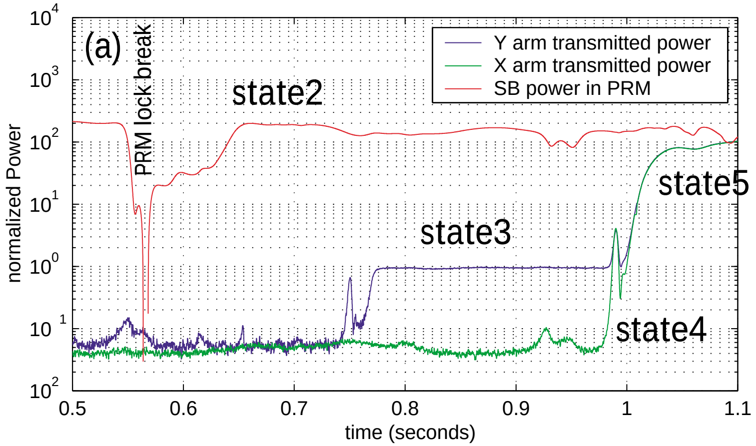


State 5 : The power in the IFO has stabilized at its operating level. End point for lock acquisition. (Engaged + ArmXOn + ArmYOn + LockOn)

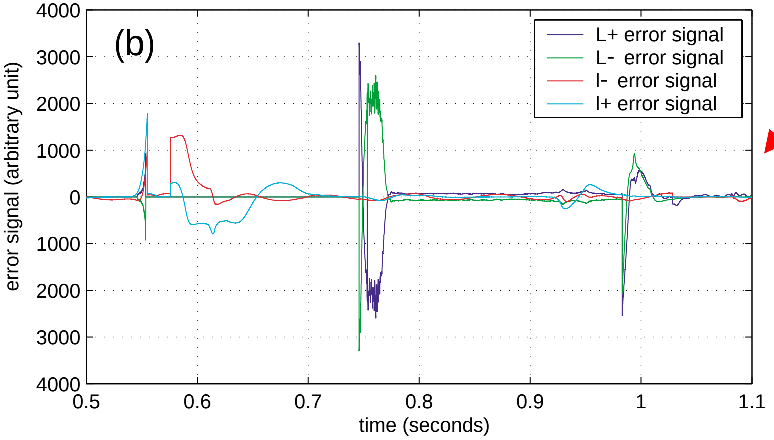
Discontinuous Changes: Triggers and Bits

- Engaged
  - Set when Spob > RecOn, reset when Spob < RecOff
  - Indicates PRM is locked, as in states 2 and above
- ArmXOn and ArmYOn
  - Set when Ptr > ArmOn, reset when Ptr < ArmOff
  - Indicates arm is locked, one in state 3, both in state 4
- LockOn
  - Set when Ptrx or Ptry > BoostOn, reset when Ptrx and Ptry < BoostOn
  - Set as state 5 is approached
  - Not really indicative of state change, but necessary to enable low frequency control loop changes

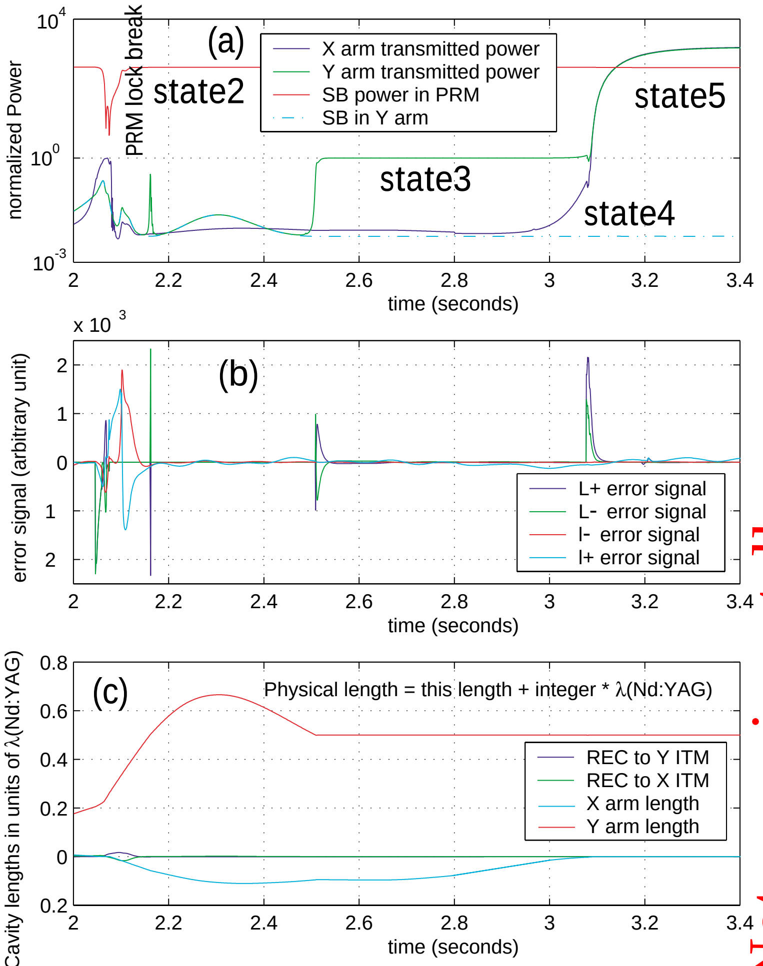
Lock Acquisition:
Real and Simulated



Arm powers are normalized by the power when one arm is locked.
SB power is normalized by the input SB power.



observable



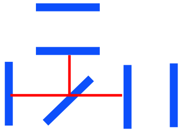
Not experimentally observable

The Sensing Matrix and Cavity Control

- Sensing Matrix
  - Expresses demodulation signal content
  - Signal amplitude
  - Local oscillator
  - Gain constant
- IFO Control
  - Invert sensing matrix to get control matrix (a.k.a. “input matrix”)
  - Use control matrix to produce error signals from demodulation signals

$$\left[REFL\_Q\right] = \left[\mathrm{glmRef}\ O_{Sref} G_S\right]\left[MICH\right]$$

The Sensing Matrix: State 2



- MICH
  - MICH is taken from REFL_Q

$$[REFL\_Q] = [\mathrm{glmRef}\ O_{Sref} G_S][MICH]$$

- PRC
  - PRC is taken from REFL_I

$$[REFL\_I] = [\mathrm{glpRef}\ O_{Sref} G_S][PRC]$$

- Signal Amplitude
  - Signal source
  - Signal gain

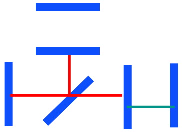
$$G_S = S_{pob} \propto \frac{A_{Srec}}{t_{RM} A_{Sin}} A_{Srec}$$

- Local Oscillator
  - Oscillator amplitude
  - Spatial overlap

$$O_{Sref} = \alpha_{SC} (r_{RM} A_{Cin} - t_{RM} A_{Crec})$$

(Note to the careful reader: many overall constants are missing.)

The Sensing Matrix: State 3



- PRC, CARM
  - Use REFL_I and AS_Q
- DARM
  - Dependent variable
- Signal Amplitude
  - Sum and difference
  - Input field changes
- Local Oscillator
  - Carrier well matched to input beam
  - AS just leakage of REC

$$\begin{bmatrix} REFL\_I \\ AS\_Q \end{bmatrix} = \begin{bmatrix} \text{glpRef}\; O_{Sref} G_S & \text{gLRef}\; O_{Cref} G_+ \\ 0 & \text{gLAsy}\; O_{Casy} G_- \end{bmatrix} \begin{bmatrix} PRC \\ CARM \end{bmatrix}$$

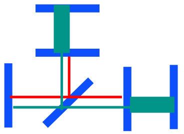
$$DARM = \pm CARM$$

$$G_+ = \frac{P_{trx} + P_{try}}{A_{Crec}} \qquad G_- = \frac{P_{trx} - P_{try}}{A_{Crec}}$$

$$O_{Cref} = r_{RM} A_{Sin} - \alpha_{SC} t_{RM} A_{Srec}$$

$$O_{Casy} = \alpha_{SC} A_{Srec}$$

The Sensing Matrix: States 4 and 5



- MICH
  - » Switches from REFL_Q to POB_Q (lmPO bit)

$$\begin{bmatrix} REFL\_Q \\ POB\_Q \end{bmatrix} = \begin{bmatrix} \text{glmRef}\, O_{Sref} G_S \\ \text{glmPob}\, O_{Spob} G_S \end{bmatrix} [MICH]$$

- PRC, CARM, DARM
  - » 3x3
  - » G_- vanishes
  - » Singularity

$$\begin{bmatrix} REFL\_I \\ POB\_I \\ AS\_Q \end{bmatrix} = \begin{bmatrix} \text{glpRef}\, O_{Sref} G_S & \text{gLRef}\, O_{Cref} G_+ & \text{gLRef}\, O_{Cref} G_- \\ \text{glpPob}\, O_{Spob} G_S & \text{gLPob}\, O_{Cpob} G_+ & \text{gLPob}\, O_{Cpob} G_- \\ 0 & \text{gLAsy}\, O_{Casy} G_- & \text{gLAsy}\, O_{Casy} G_+ \end{bmatrix} \begin{bmatrix} PRC \\ CARM \\ DARM \end{bmatrix}$$

- Local Oscillator
  - » POB also leakage of REC
  - » similar to POX or POY in state 5

$$O_{Spob} = \alpha_{SC} A_{Crec}$$

$$O_{Cpob} = \alpha_{SC} A_{Srec}$$

Measuring the Sensing Matrix Element

- Gain Ratios
  - These “constants” are measured directly
  - Represent hardware gain (optical and electrical)
  - Errors introduced by clipping and other uncompensated effects
- Amplitudes
  - Derived from power measurements (S_{pob}, P_{trx} , P_{try})
  - Calibration necessary (NSPOB, NPTRX , NPTRY)
  - Errors introduced by clipping and sideband imbalance
- Spatial Overlap Coefficient
  - Changes due to thermal lensing and alignment
  - Estimated by input spatial overlap
  - Robust in simulation

$$\alpha_{SC} \approx \frac{1 - r_{RM} r_{MICH}}{t_{RM}} \frac{A_{Srec}}{A_{Sin}} \propto \sqrt{S_{pob}}$$

Improved Mode Overlap due to Thermal Lensing

- PRM is nears optimally coupled for SBs
  - » O_{Cref} small and noisy
  - » CARM small and noisy in REFL_I
  - » O_{Cpob} larger with higher NSPOB
  - » CARM larger in POB_I

$$O_{Cref} = r_{RM} A_{Sin} - \alpha_{SC} t_{RM} A_{Srec}$$

$$\propto r_{RM} A_{Sin}^2 - (1 - r_{RM}) S_{pob}$$

$$O_{Cpob} = \alpha_{SC} A_{Srec} \propto S_{pob}$$

- State 4 singularity happens later
  - » Near NSPOB = NPTR
  - » Currently crossed quickly at low NPTR
  - » Later means slower and more difficult to cross
- Use non-resonant SBs on reflection?

Conclusion

- Lock acquisition components
  - Acquisition path (states 1 through 5)
  - Sensing matrix
    - Equations for elements along the path
    - Amplitude, gain and mode-overlap estimators
  - Control matrix is inverse of sensing matrix
- Thermal lensing
  - Affects lock acquisition
    - Cold vs. hot should have same gain ratios
    - Singularity duration increases with better mode matching
  - Affects lock maintenance
    - CM loop may need to use POX or non-resonant SBs
- and now for a shameless SimLIGO plug…

SimLIGO
“Best possible noise curve”

- Perfect optical surfaces
  - H1 as built curvatures, reflectivities and losses
  - Thermal lens nearly optimal
  - No clipping or scattering
- More, cleaner power
  - 5W at the RM with no intensity noise
  - Uses all of the light at the AS port
- No electronics noise except digitization
  - All control loops active (LSC and ASC)
- Result: close to SRD
  - Starting point for time domain noise study
  - Still some work to be done

SimLIGO
More Realistic Noise Curve

- Full Strength SimLIGO Hanford Seismic Noise
  - Close to H1 observed
  - SRD seems optimistic
- Electronics noises present, but
  - No noise from dampers (OSEM or OL)
  - Rev A1 dewhiteners on all test masses
- CM loop not present in SimLIGO
  - Frequency noise not present
  - Intensity noise not present
- Still 5W in, but only 1 AS PD