Issues in sensing and control of the 40m and Advanced LIGO optical configuration

LSC meeting, August 2004

A. Weinstein, Caltech
representing work done mostly by
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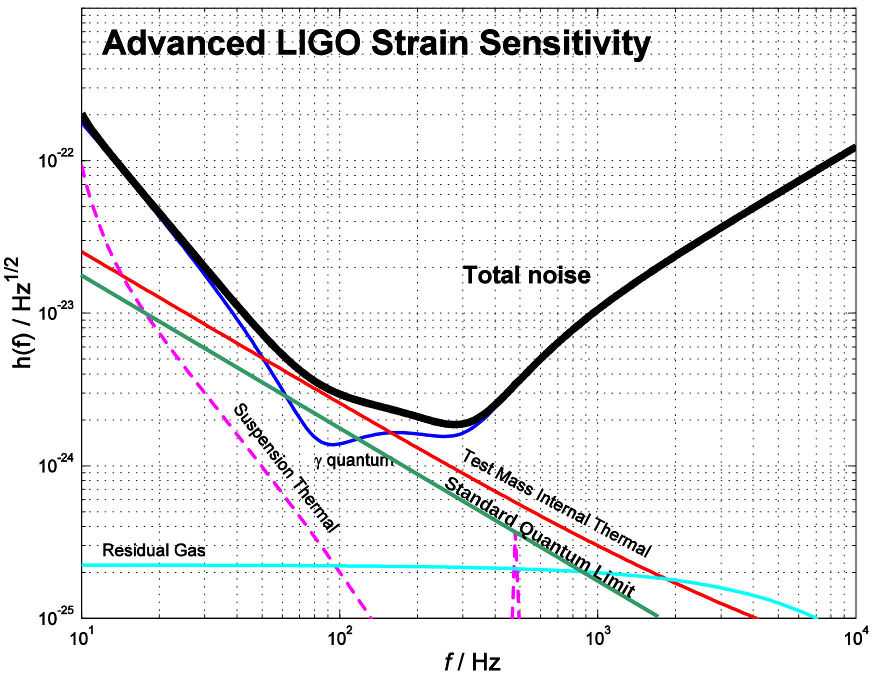
G040331-00-R

Speaker: Kentaro Somiya

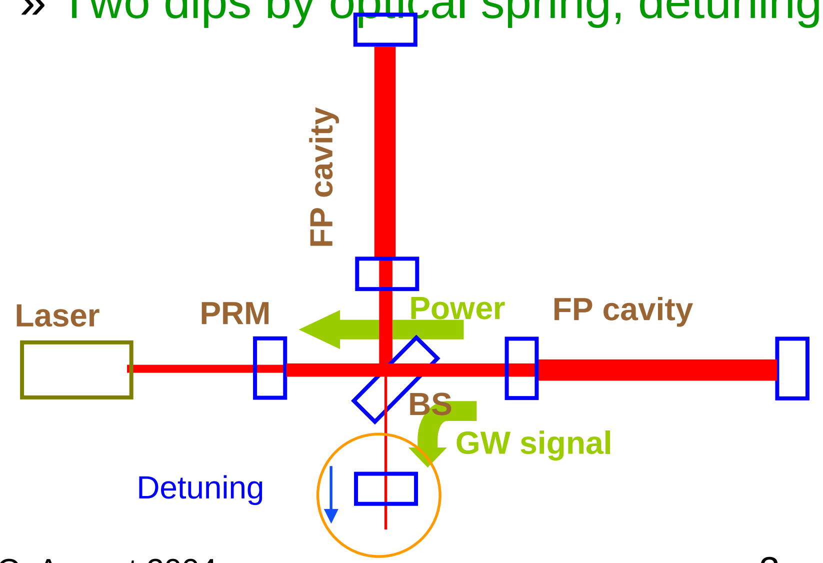
Outline

- Length sensing for 40m / AdLIGO
- Lock acquisition – the naïve way
- Lock acquisition – the dither-lock crutch
- Double demodulation
- EOMs in series: sidebands on sidebands
- EOMs in parallel: Mach-Zehnder
- Mach-Zehnder phase noise

Advanced LIGO optical configuratoin

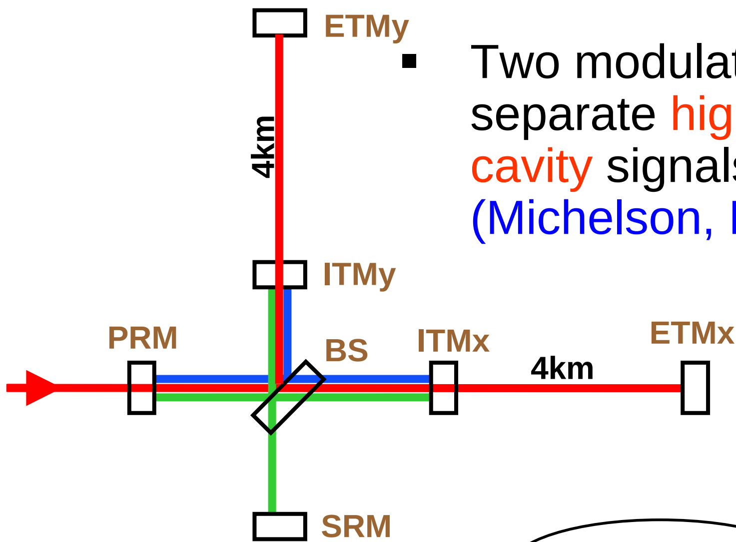


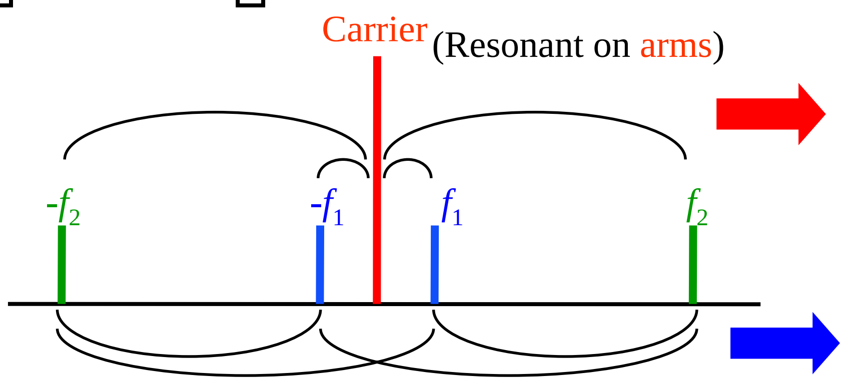
- LIGO:Power recycled FPMI
  - » Optical noise is limited by Standard Quantum Limit (SQL)
- AdvLIGO:GW signal enhancement using Detuned Resonant Sideband Extraction
  - » Can overcome the SQL ➡ QND detector
  - » Two dips by optical spring, detuning



Signal extraction for AdvLIGO

- Two modulations are used to separate high finesse, 4km long arm cavity signals from Central part (Michelson, PR, SR) signals.





- Single demodulation
- Arm information

- Double demodulation
- Central part information

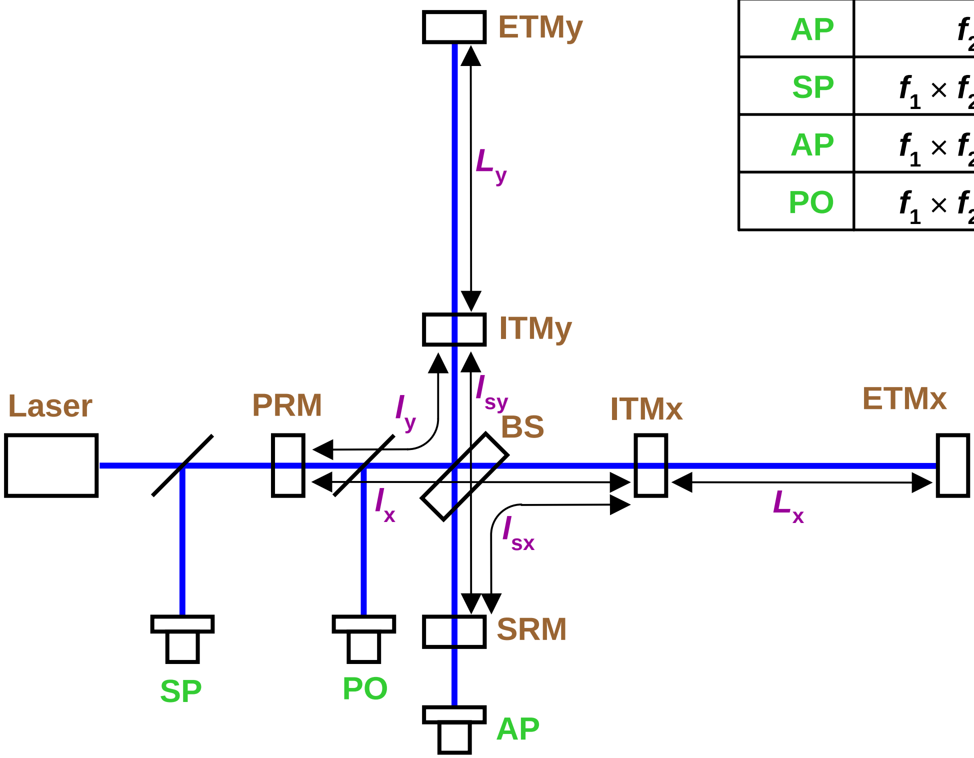
- Arm cavity signals are extracted from beat between carrier and f_1 or f_2.
- Central part (Michelson, PR, SR) signals are extracted from beat between f_1 and f_2, not including arm cavity information.

5 DOF for length control

Common of arms : $L_+ = (L_x + L_y) / 2$
Differential of arms : $L_- = L_x - L_y$
Power recycling cavity : $l_+ = (l_x + l_y) / 2$
Michelson : $l_- = l_x - l_y$
Signal recycling cavity : $l_s = (l_{sx} + l_{sy}) / 2$

Signal Extraction Matrix (in-lock)

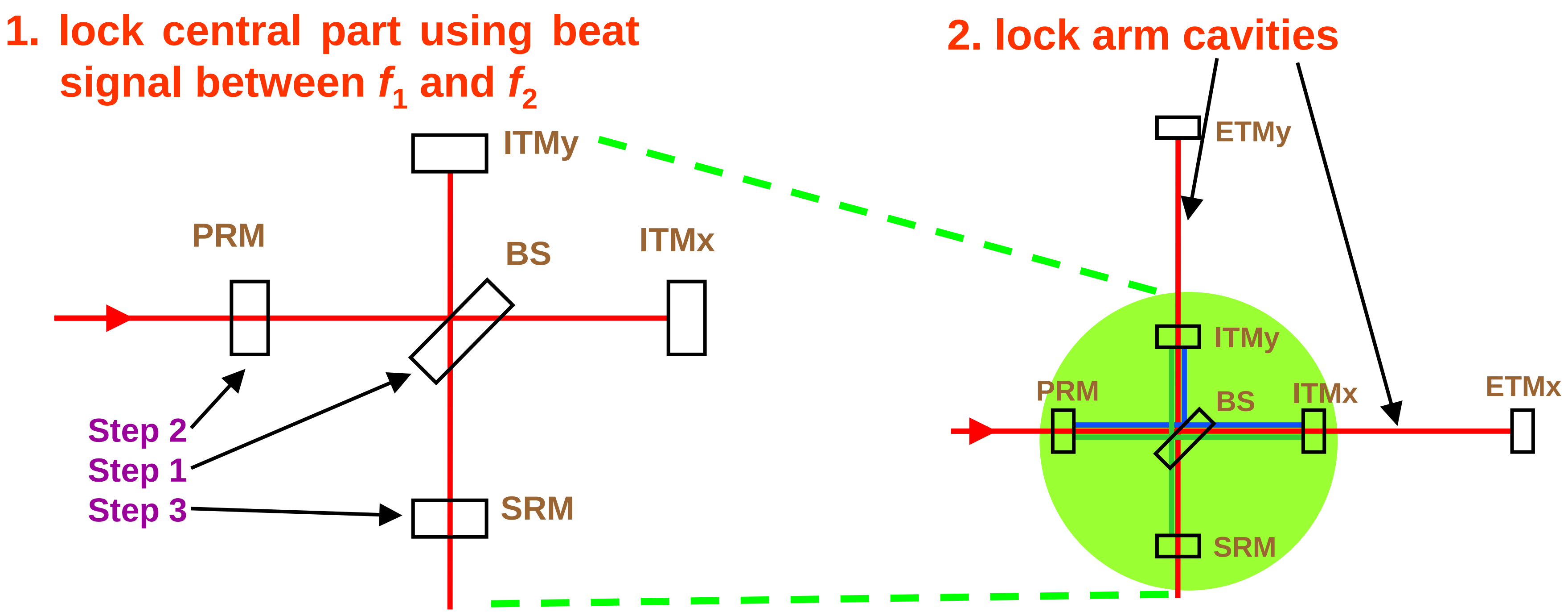
Port	Dem. Freq.	L_+	L_-	l_+	l_-	l_s
SP	f_1	1	-3.8E-9	-1.2E-3	-1.3E-6	-2.3E-6
AP	f_2	-4.8E-9	1	1.2E-8	1.3E-3	-1.7E-8
SP	$f_1 \times f_2$	-1.7E-3	-3.0E-4	1	-3.2E-2	-1.0E-1
AP	$f_1 \times f_2$	-6.2E-4	1.5E-3	7.5E-1	1	7.1E-2
PO	$f_1 \times f_2$	3.6E-3	2.7E-3	4.6E-1	-2.3E-2	1



Calculated with TWIDDLE
and with FINESSE

PO: light from BS to ITMy

Lock Acquisition of Detuned RSE



- Central part: ~not disturbed by lock status change of arm cavity
- Find primary signal not disturbed by the other two DOFs
- Find secondary signal not disturbed by the residual DOF

- Arm cavities: ~not disturbed by locked central part
- Central part could be disturbed by flashes of SBs in arms
- Lock each arm independently
- Switch control servo to common/differential control

Lock Acquisition of Central Part

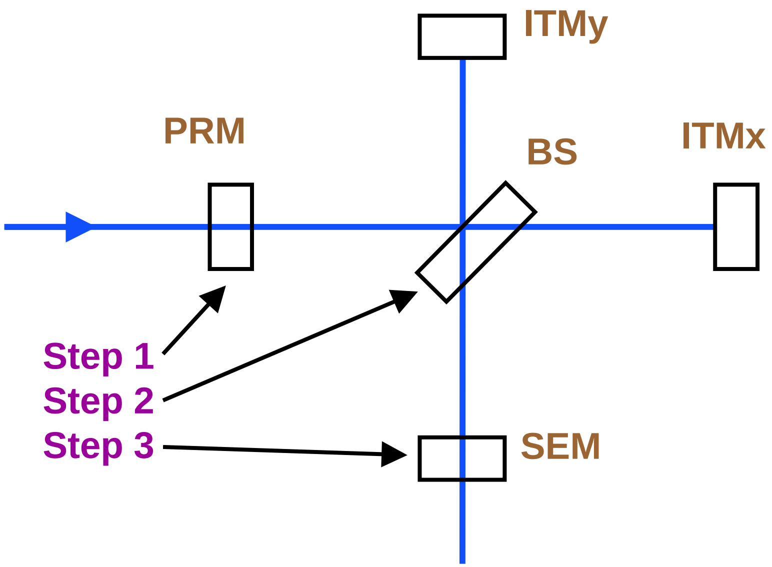
Ideal Procedure: Lock one by one

[for example]

Step 1: Lock l_+ robustly

Step 2: Lock l_- robustly

Step 3: Lock l_s

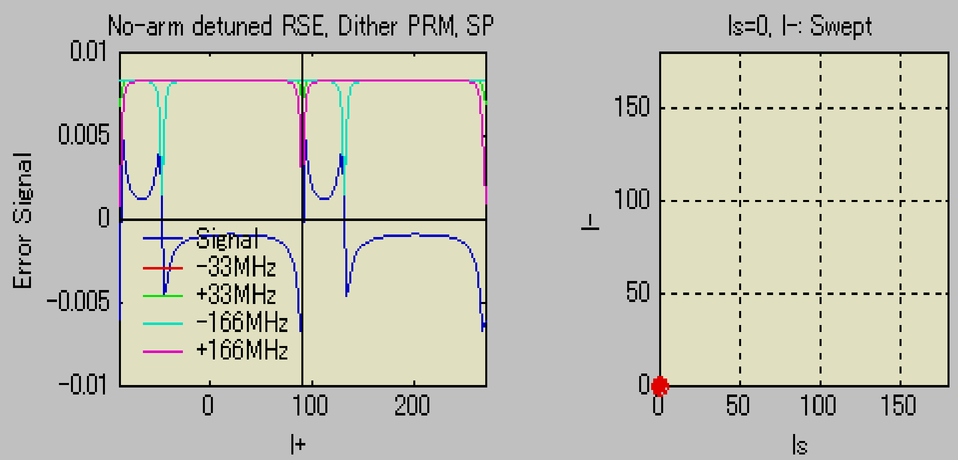


- Find primary signal not disturbed by the other two DOFs
- Find secondary signal not disturbed by the residual DOF

Strategy for central part

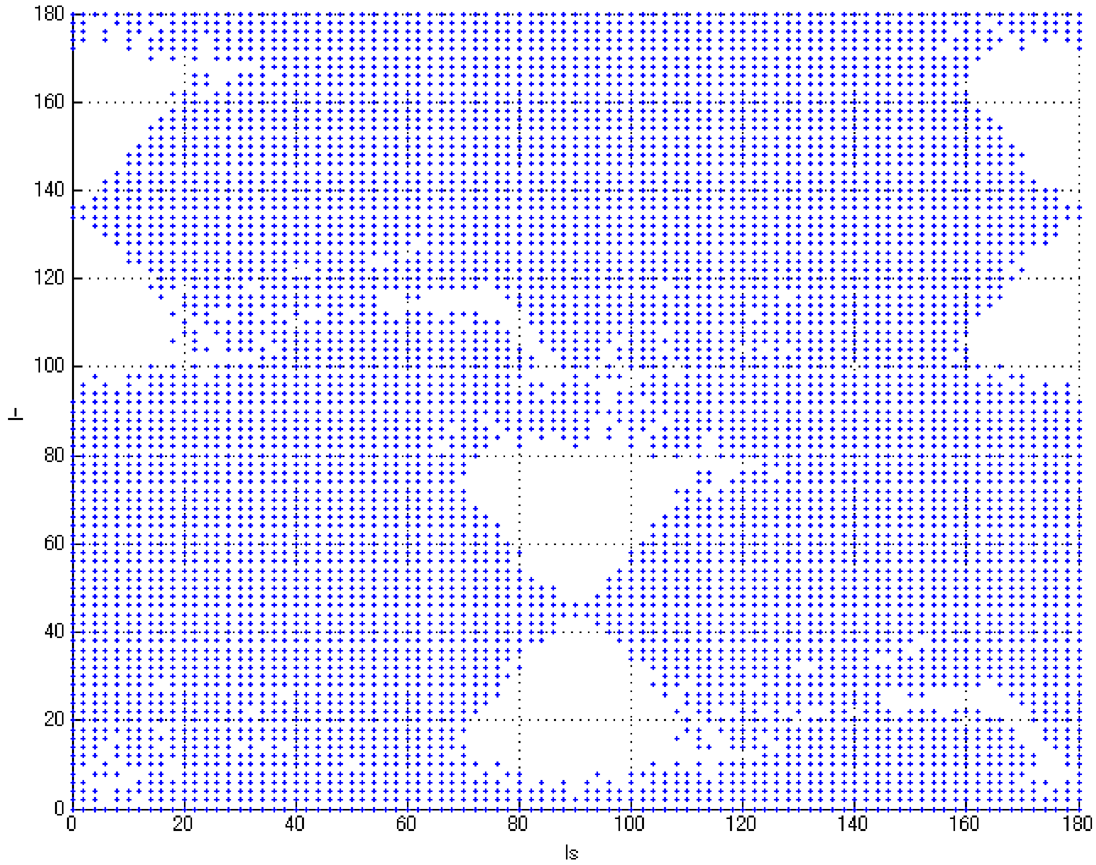
- Ideally, lock one DOF at a time, robust against other (2) DOF's varying randomly as the mirrors swing
- look for a servo-able signal (crossing zero at desired point, relatively insensitive to values of other DOFs)
- See how robust the signal is when the other 2 DOFs vary across their phase space uniformly;
  quantify what fraction of the time a good signal exists
- then examine a second DOF, see if a good signal exists for significant fraction of the time.
- Then, check that signal exists for 3rd DOF.
- Try this for all (6) possible ordering of DOFs.
- Fiddling with demod phases can help.
- Outcome – possible, but may need to wait a LOOONG time
- When arms are unblocked, RF sidebands resonating in arms can knock central part out… start all over.
- Upshot: no robust method found!

l+@SP, Symmetric



- Four SBs resonate at different points
- Good signal obtained when +f2 resonates
- Signal for –f2 resonance has an opposite polarity
- Disturbed when +f2 and –f2 resonate at the same point
- Signals for ±f1 resonance can be cancelled by proper DDM phases, which coincide with the phases for symmetric signal

l+ Signal lockable surface



- l+ can be locked 80% of area.
- Feedback l+ signal to laser frequency for fast locking.

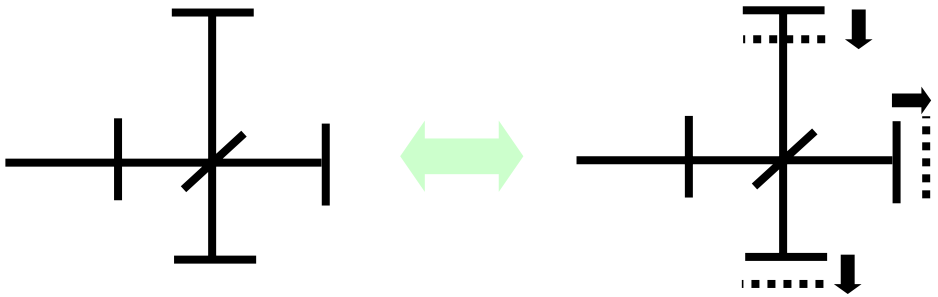
Lock acquisition procedure

1. l+: double demodulation 88,180 deg. @ SP 80%
2. l- : 166MHz single demodulation 100 deg. @AP / Power @ AP 60%
3. ls : double demodulation 164,12 deg. @ SP 15%

- Total lock area

  80% x 60% x 15% = 8%

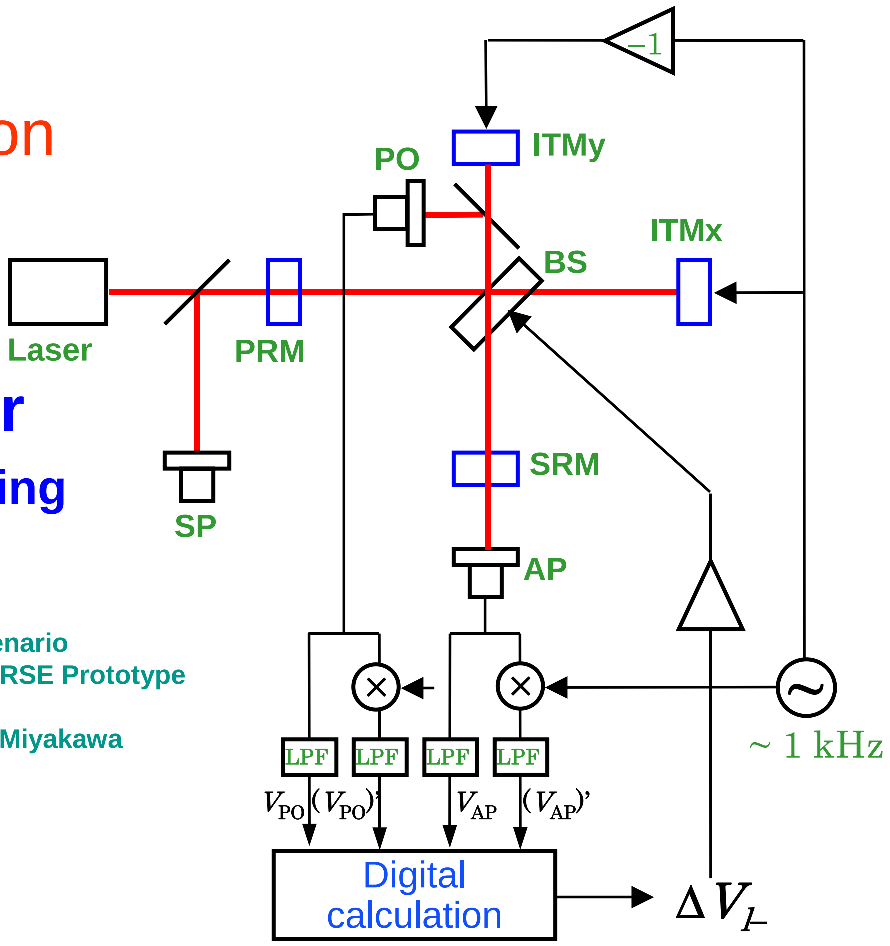
- 2 lock states exist, but no way to distinguish them



Looking for good signal for lock acquisition

- Unfortunately, no easy way to lock central part directly using the original double demodulation

- **Dither locking for l_- signal**
- **Divide signal by inside power**
  - » **Good cancellation of power recycling**

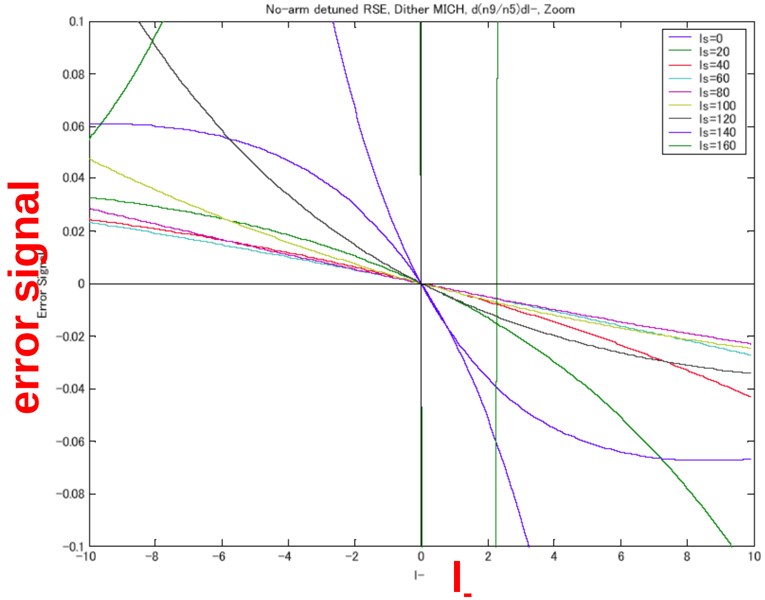


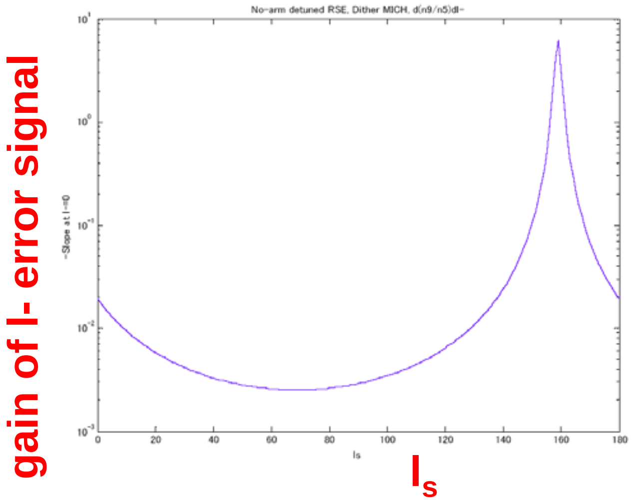
$$\Delta V_{l-} = \frac{d}{d\,l_-}\left(\frac{V_{AP}}{V_{PO}}\right) = \frac{V'_{AP}V_{PO} - V_{AP}V'_{PO}}{V_{PO}^{\;2}}$$

LIGO-T040081- 02- R
Lock Acquisition Scenario
for the 40m Detuned RSE Prototype
I. Central Part
S. Kawamura and O. Miyakawa

Gain of dither locking signal

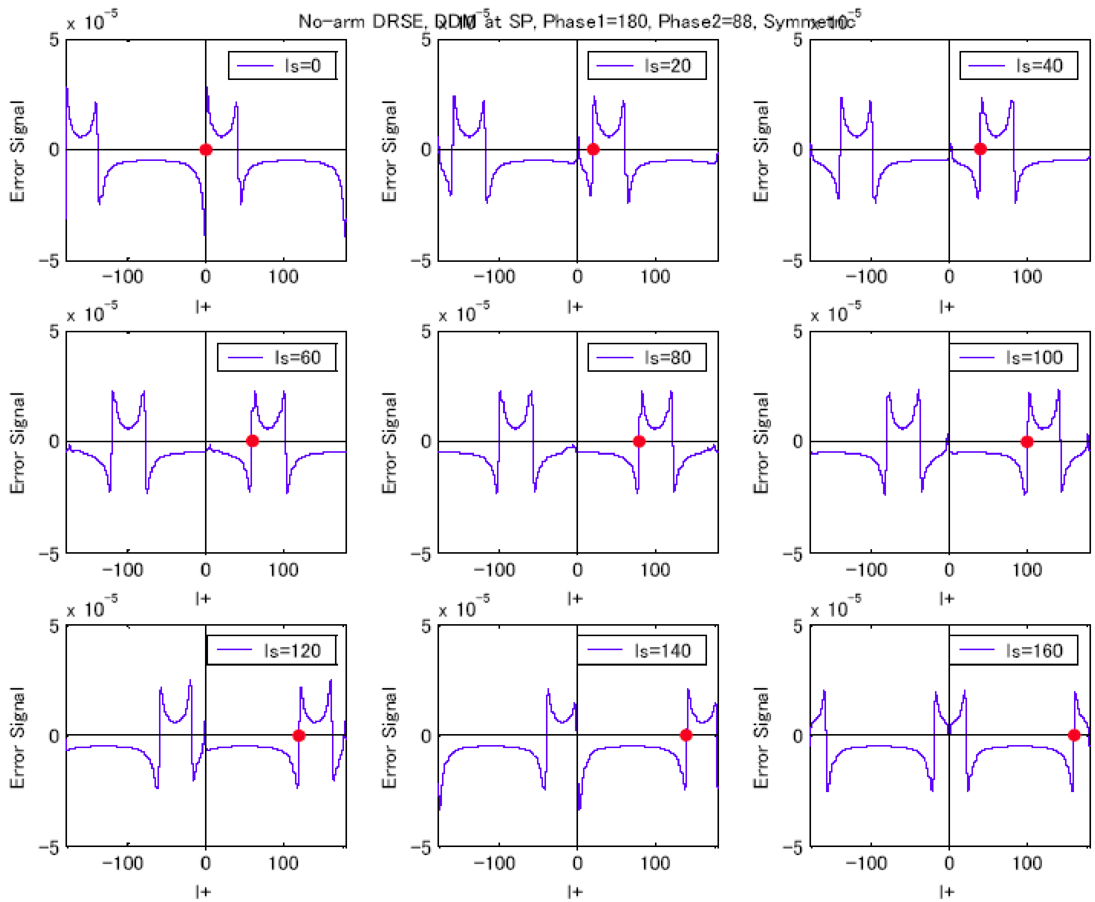
- l- dither locking signal gain depends strongly on ls
- But polarity of signal is always the same
- Can handle this with a limiter…
- l- dither locking signal doesn't depend on l+ at all!
- Signal is degraded by presence of RF sidebands… turn them down low (Γ<0.02) to acquire dither lock, then ramp them back up.

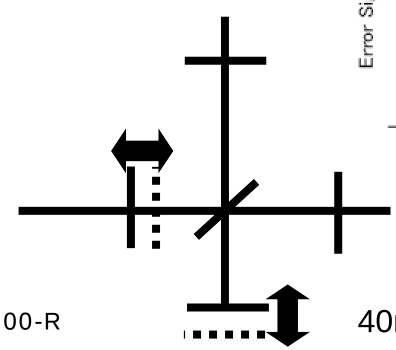




Lock l+ with DDM at SP

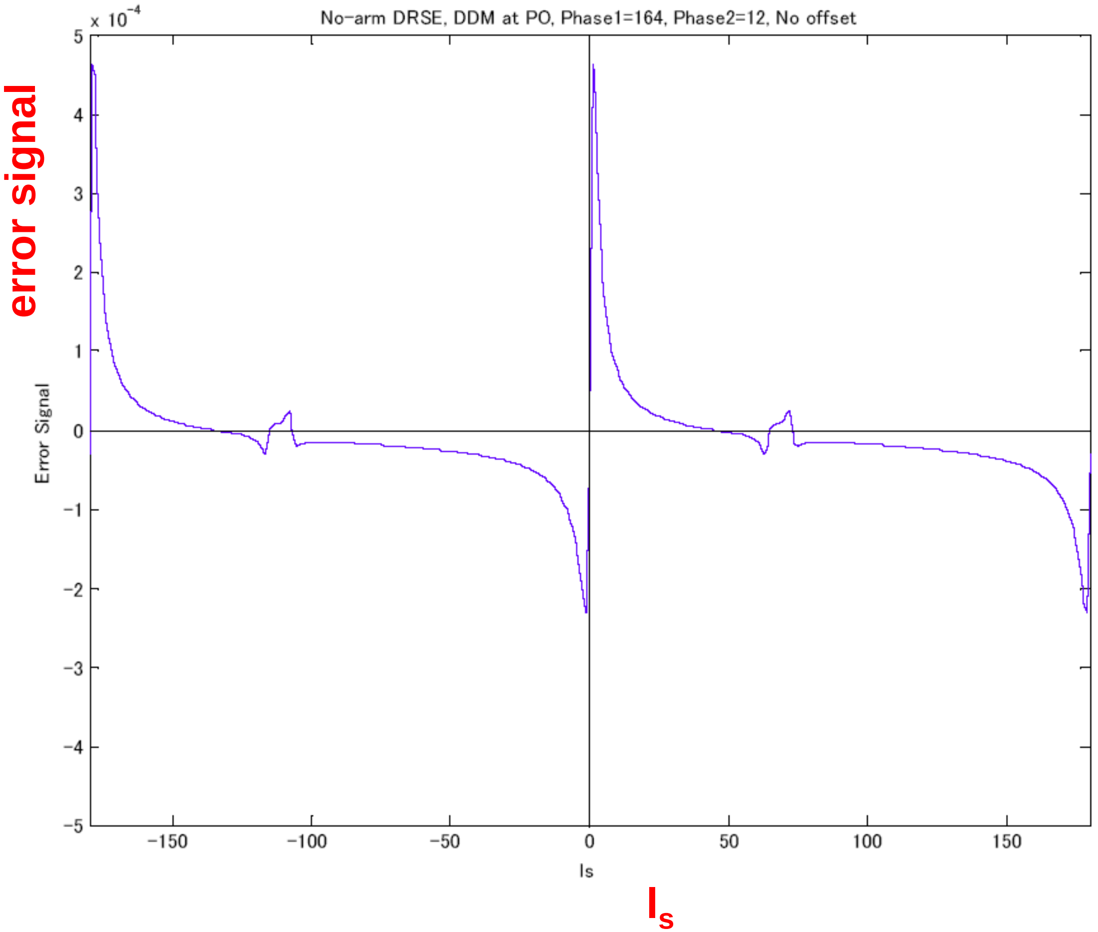
- With l- dither-locked, there's always a good l+ signal, for all values of ls.
- Feedback l+ signal to laser frequency for fast locking.
- The locking point may not be at l+ = 0^{o} !
- The PRM follows the swinging of the SRM; this signal keeps the combined cavity locked.
- Then, once ls is locked, we'll recover l+ = 0^{o}.





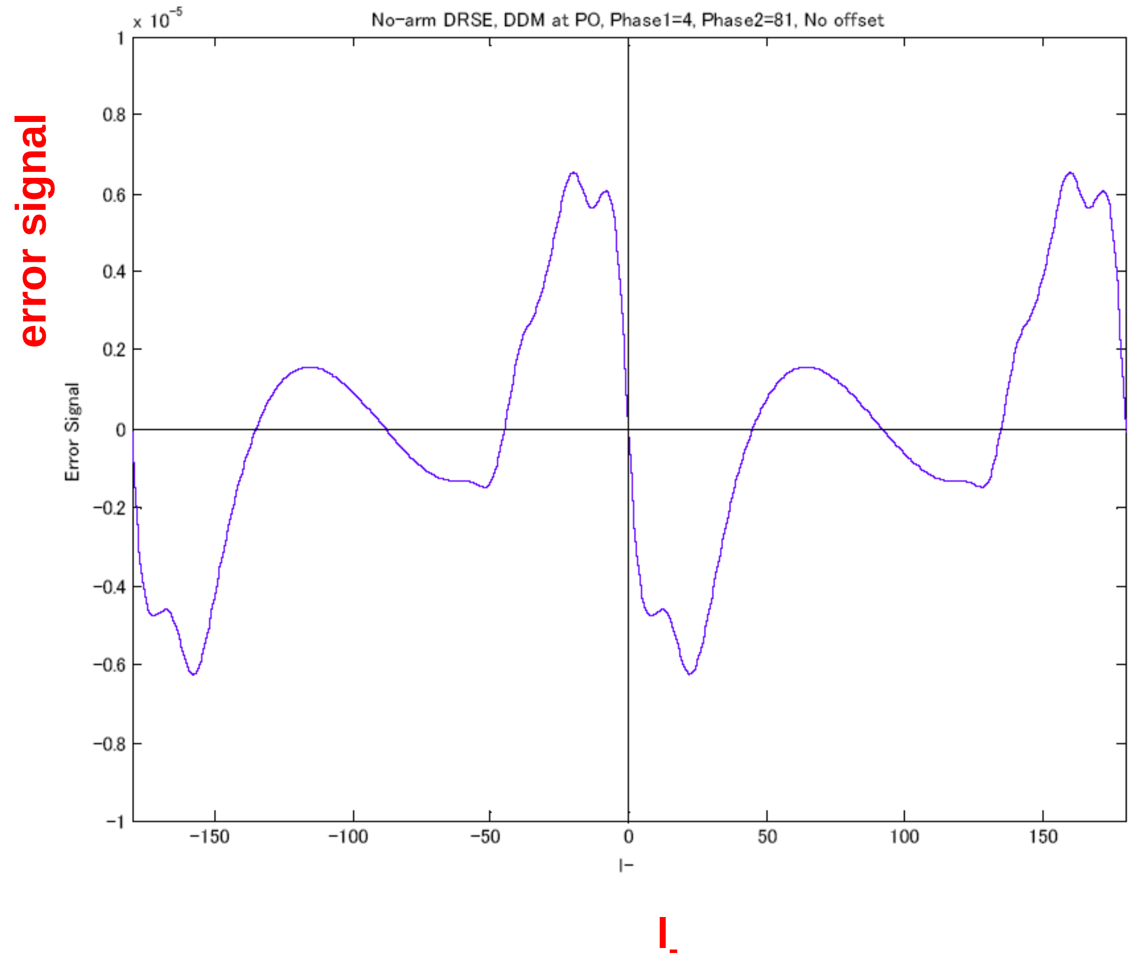
Lock ls with DDM at PO

- With l- dither-locked, and l+ DDM-locked to ls, there's a good error signal for locking ls at the desired point (0^o with respect to RF, detuned wrt carrier).
- Final step:



Switch to l- with DDM at AP

- Central part final step: Switch the *l*– control signal from the dither signal to the DDM signal at the AP
- The smooth transfer of the control signal can be done using the conventional technique: superimpose the DDM signal to the dither signal, and then remove the dither signal
- Then, on to the arms!



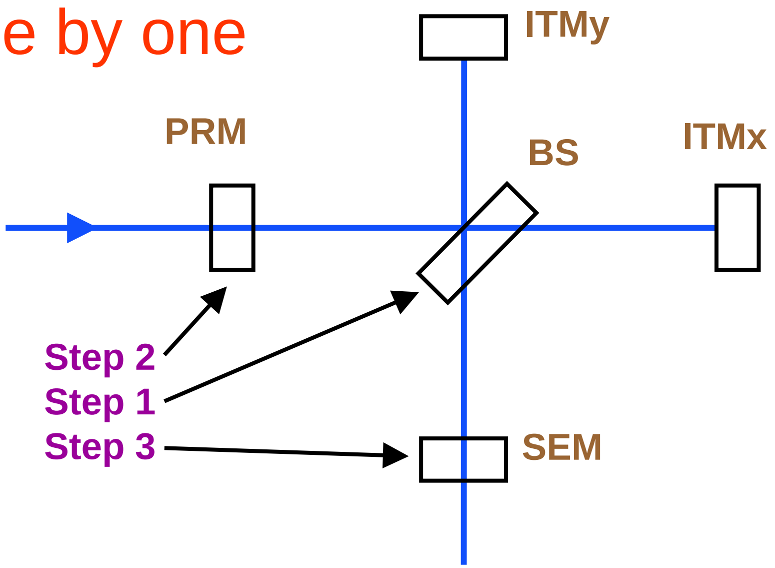
Lock Acquisition of Central Part

Ideal Procedure: Lock one by one

Step 1: Lock *l*- robustly

Step 2: Lock l_+ robustly

Step 3: Lock l_s



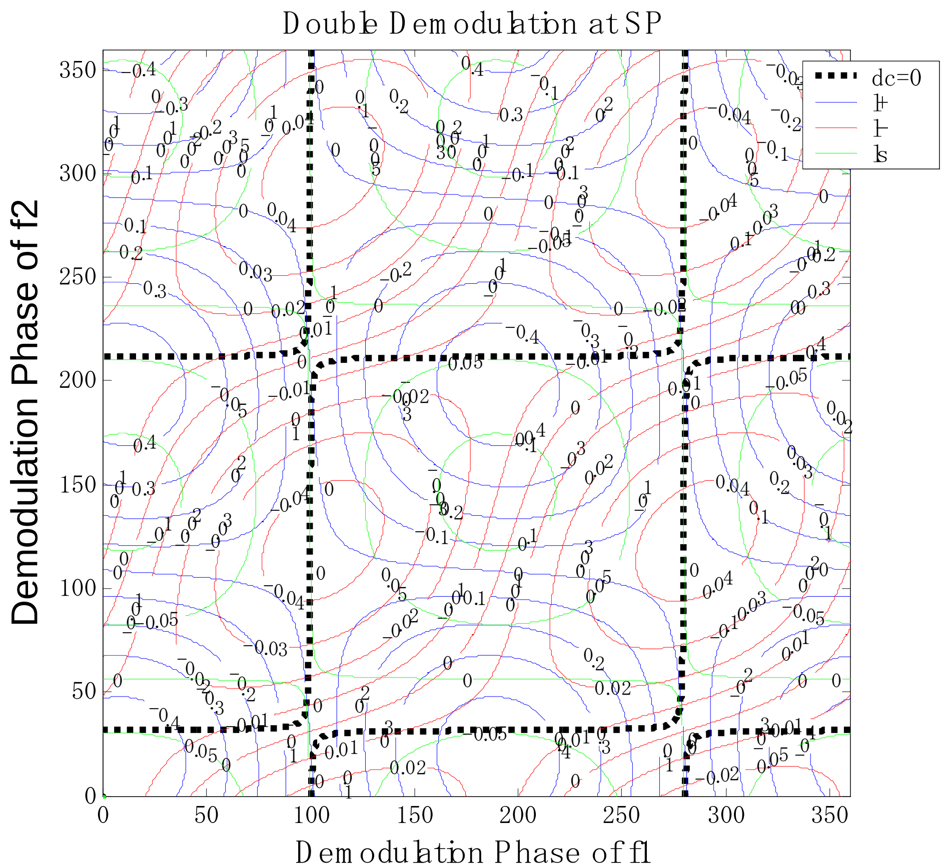
1. l-: dither, @ $\frac{S_{AP}P_{SP} - S_{SP}P_{AP}}{P_{SP}^{2}}$ with low modulation:100%
2. l+ : double demodulation 88,180 deg. @ SP :100%
3. ls : double demodulation 164,12 deg. @ PO :100%

Switch to design control topology, open shutter, lock arms

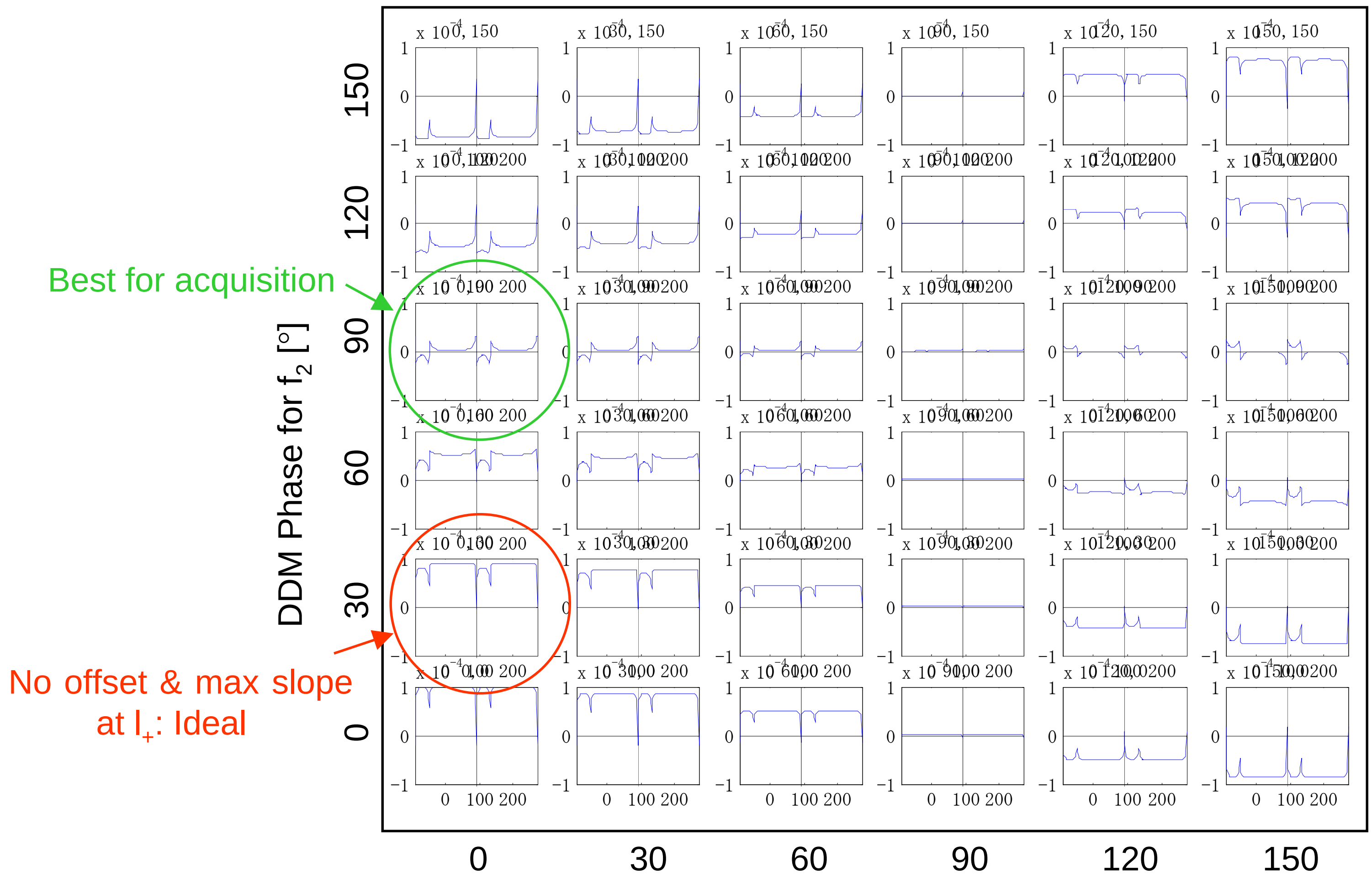
Double Demodulation

- Double Demodulation used for I_+, I_-, and I_s
- Demodulation phases optimized to suppress DC and to maximize desired signal

[S.Kawamura, “Signal Extraction Matrix of the 40m Detuned RSE Prototype”, LIGO-T040010-00-R (2004)]

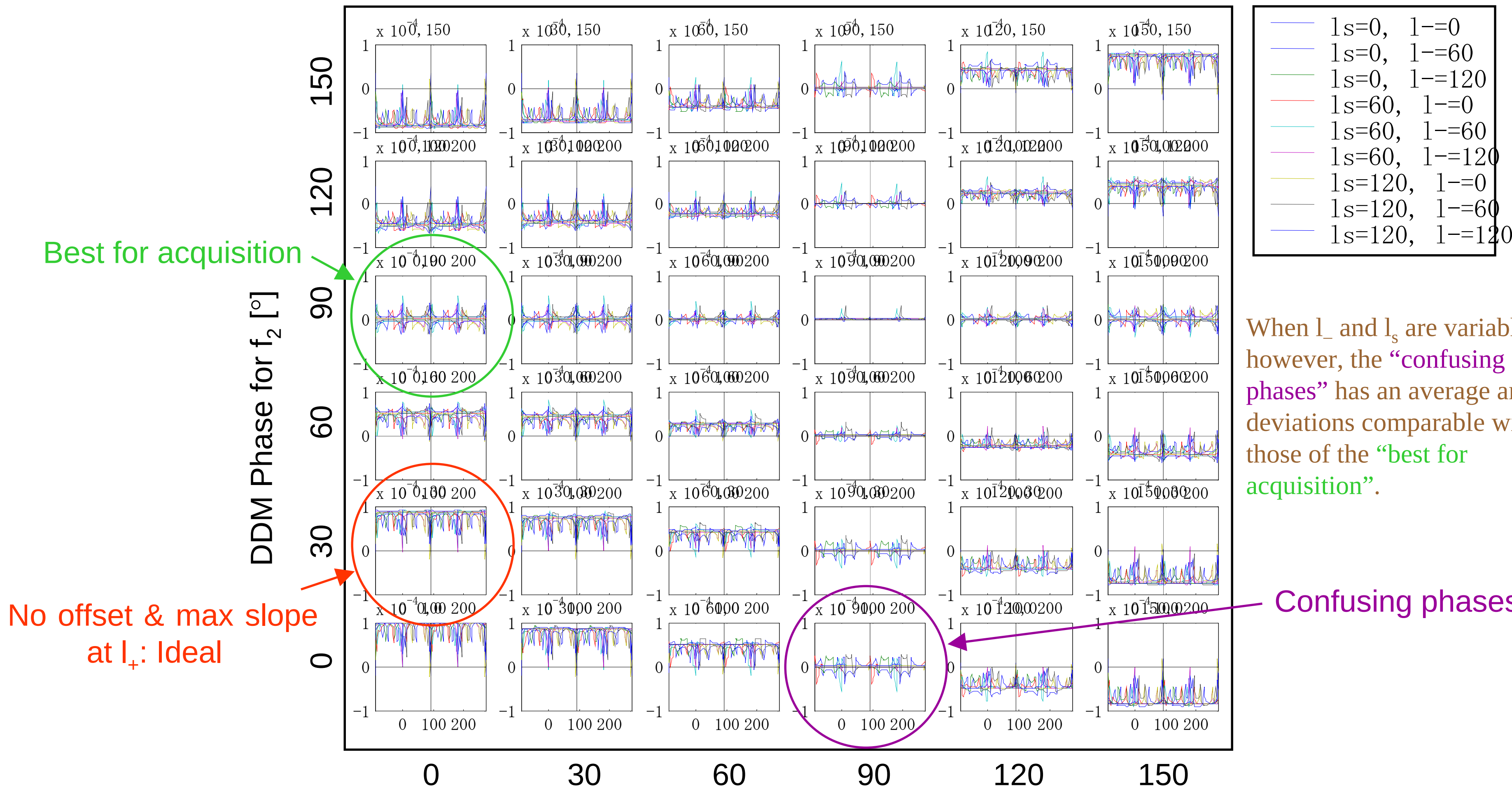


Dependence of l_+ Error Signal at SP on DDM Phases (l_-, l_s: Ideal)



The l_+ error signal for the "best for acquisition" looks unique. It has a zero average and maximum deviations (among the zero average ones).

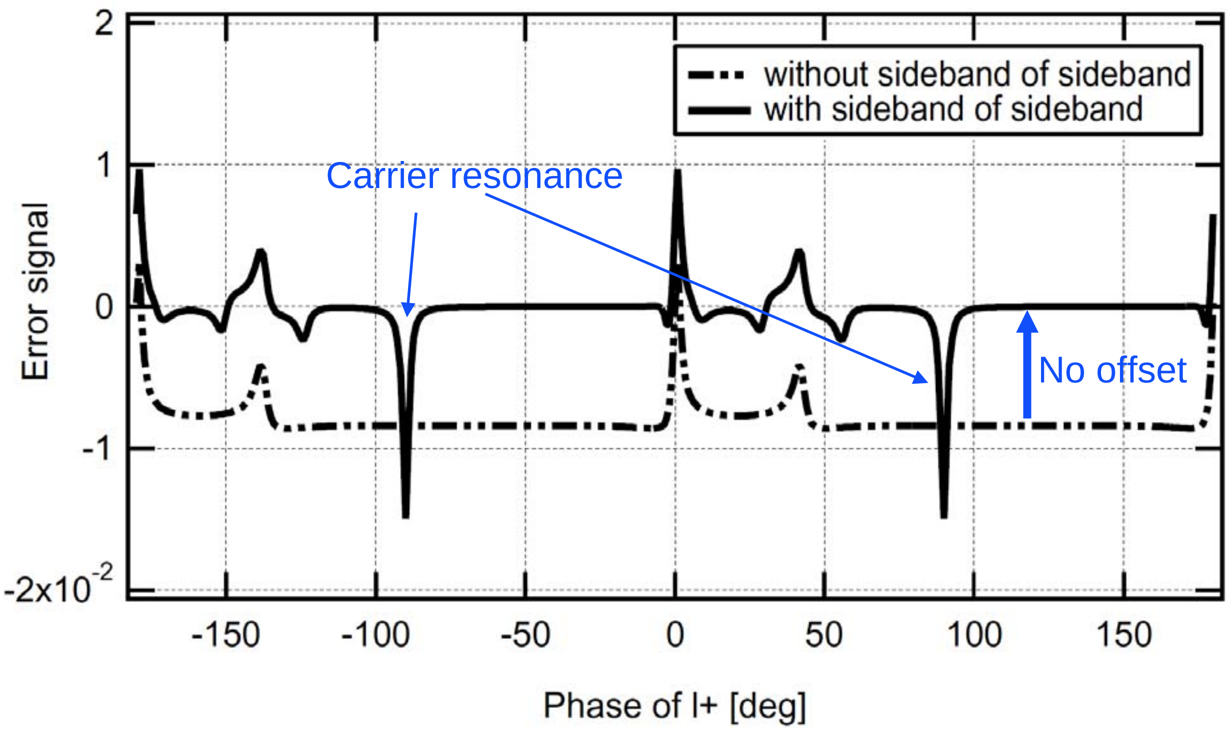
Dependence of l_+ Error Signal at SP on DDM Phases (l_-, l_s: Variable)



When l_- and l_s are variable, however, the "confusing phases" has an average and deviations comparable with those of the "best for acquisition".

Double demodulation signal of I_+

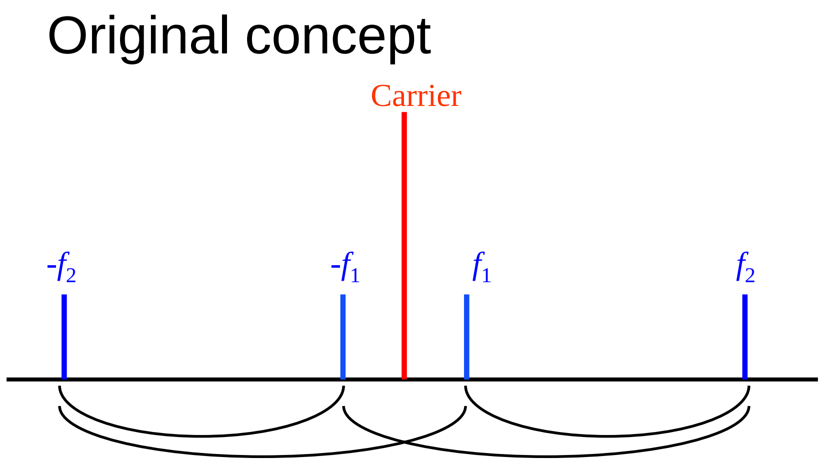
- What we expected
  - » Big offset when cavity is not locked
  - » No disturbance from carrier
- What we have seen
  - » No offset
  - » Big disturbance from carrier

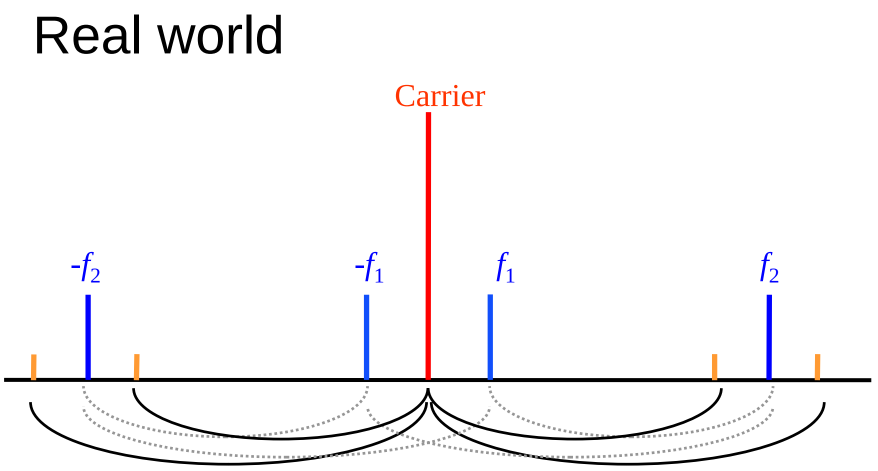


Mach-Zehnder noise

- Effect of sidebands on sidebands
- Mach-Zehnder design
- Obvious noise sources
- Phase noise introduced by Mach-Zehnder (pointed out by Matt Evans, analyzed by Seiji)

Disturbance by sidebands of sidebands





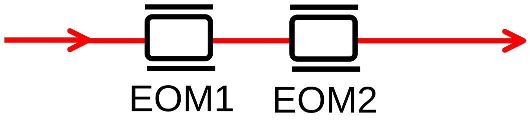
- Sidebands of sidebands are produced by two series EOMs.
- Beats between carrier and $f_2 \pm f_1$ disturb central part.

Port	Dem. Freq.	L_+	L_-	l_+	l_-	l_s
SP	f_1	1	-3.8E-9	-1.2E-3	-1.3E-6	-2.3E-6
AP	f_2	-4.8E-9	1	1.2E-8	1.3E-3	-1.7E-8
SP	$f_1 \times f_2$	-1.7E-3	-3.0E-4	1	-3.2E-2	-1.0E-1
AP	$f_1 \times f_2$	-6.2E-4	1.5E-3	7.5E-1	1	7.1E-2
PO	$f_1 \times f_2$	3.6E-3	2.7E-3	4.6E-1	-2.3E-2	1

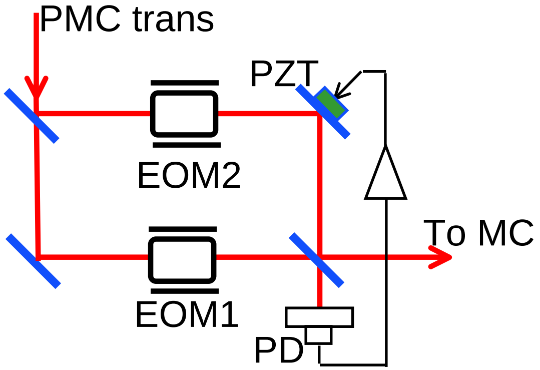
Port	Dem. Freq.	L_+	L_-	l_+	l_-	l_s
SP	f_1	1	-1.4E-8	-1.2E-3	-1.3E-6	-6.2E-6
AP	f_2	1.2E-7	1	1.4E-5	1.3E-3	6.5E-6
SP	$f_1 \times f_2$	7.4	-3.4E-4	1	-3.3E-2	-1.1E-1
AP	$f_1 \times f_2$	-5.7E-4	32	7.1E-1	1	7.1E-2
PO	$f_1 \times f_2$	3.3	1.7	1.9E-1	-3.5E-2	1

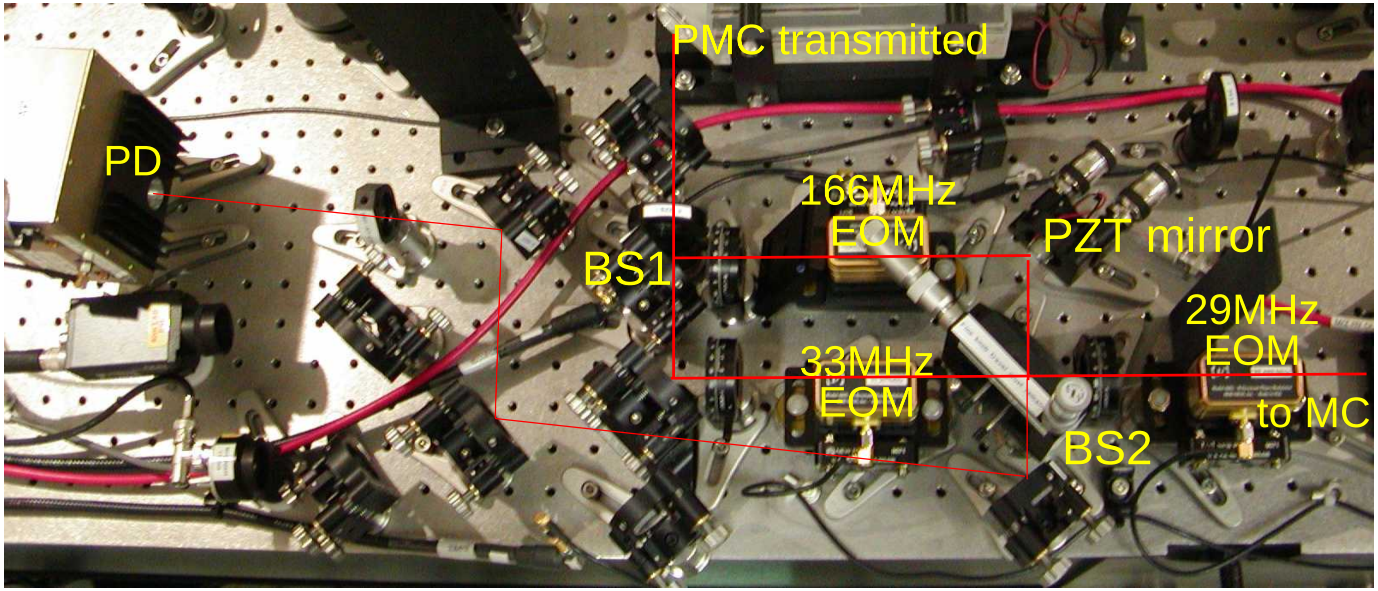
Mach-Zehnder on 40m PSL to eliminate sidebands of sidebands

Series EOMs
with sidebands of sidebands



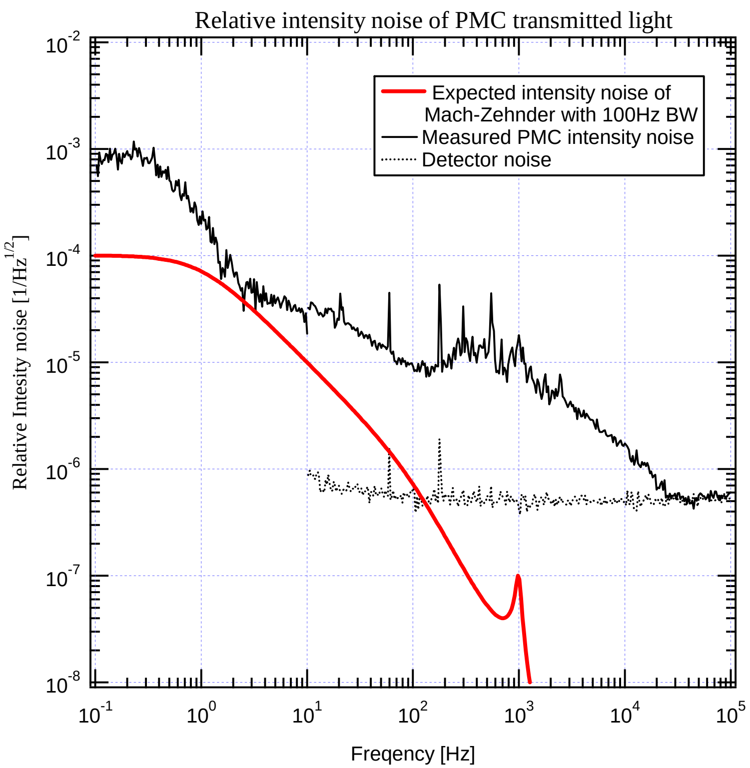
Mach-Zehnder interferometer
no sidebands of sidebands from beginning





Additional noise caused by M-Z interferometer

- Intensity noise
  - » Band width=100Hz
  - » Not a problem.

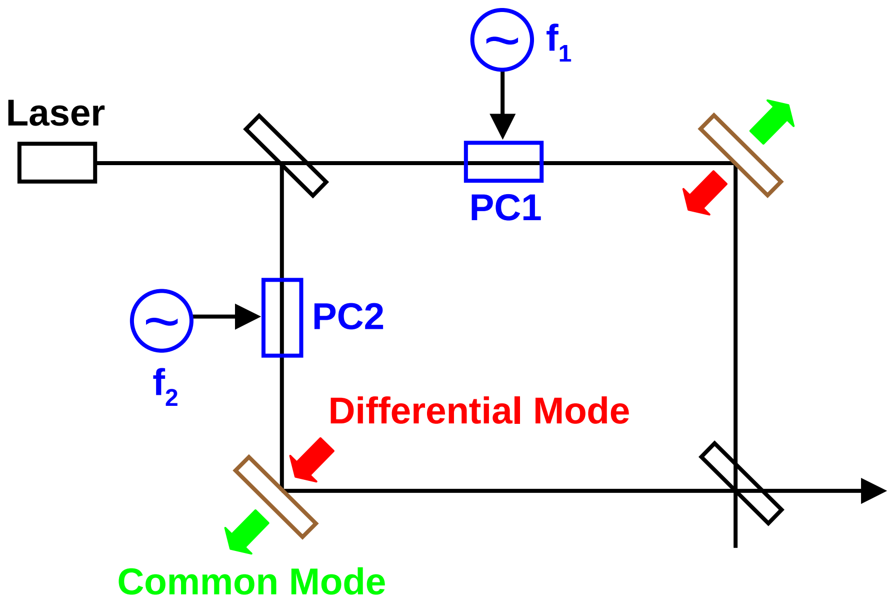


This will be suppressed by a servo.

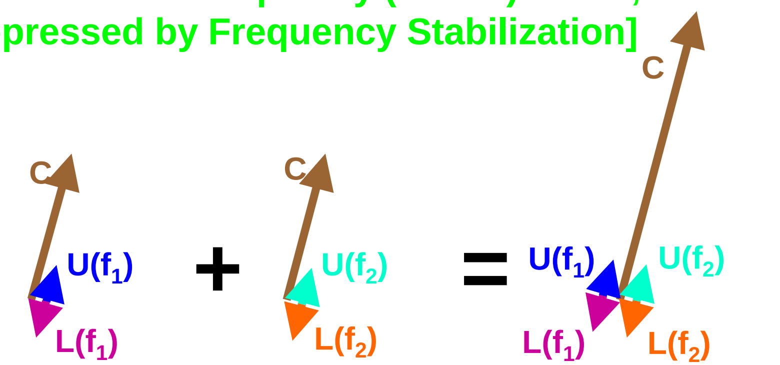
- Mode matching
  - » Will be a loss at MC, not a problem.
- Frequency noise
  - » By Doppler shift or beam jitter, not a big issue.
- Carrier phase fluctuation caused by shake of EOMs
  - » Will be shown on demodulation phase, probably OK.

Two Effects of Mach Zehnder Mirror Motion

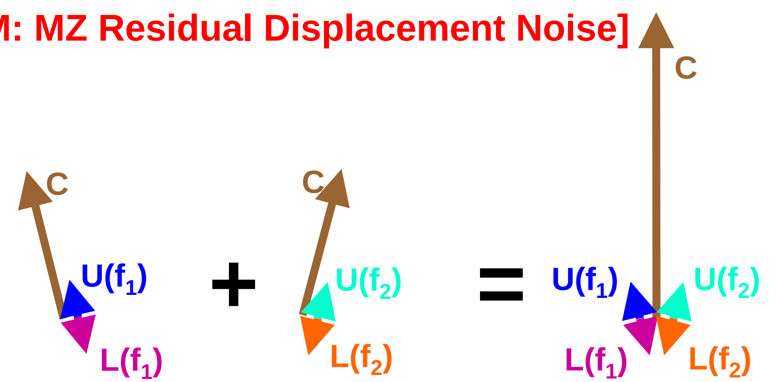
Seiji Kawamura,
following suggestion by Matt Evans



[CM: Same as Frequency (Phase) Noise, Suppressed by Frequency Stabilization]



[DM: MZ Residual Displacement Noise]



Two Mechanisms of the MZ Noise for the Detuned RSE Interferometer

- Direct mechanism

  * zero at DC when there is no carrier at AP

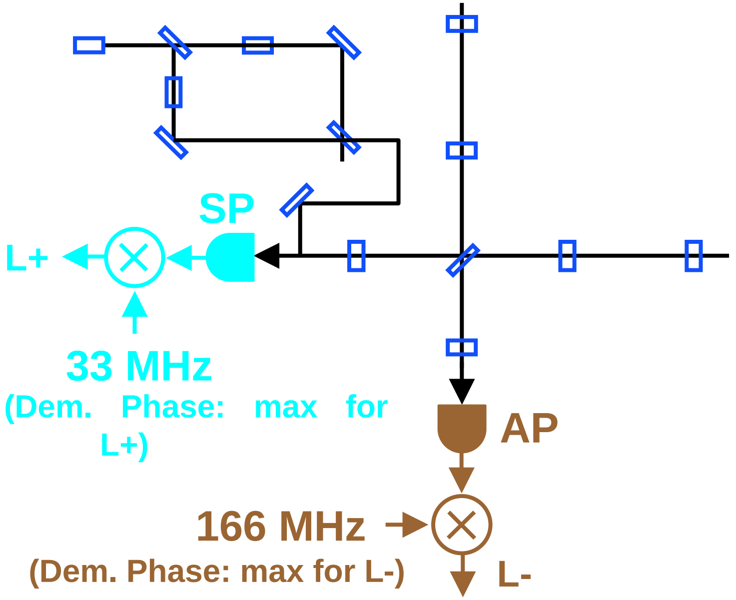
  * more coupling with more carrier at AP

- Via frequency stabilization

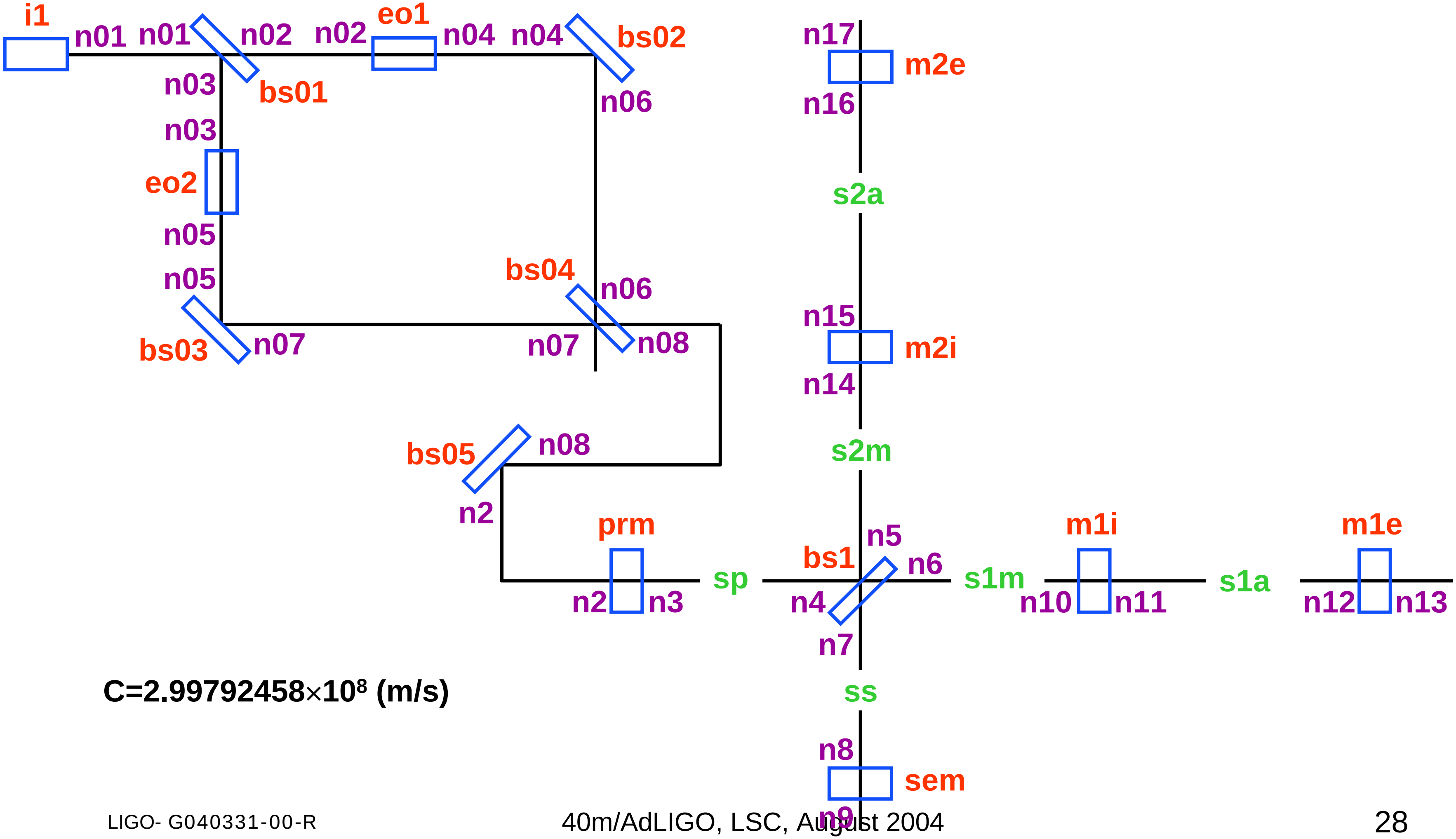
  * exists only within the frequency stabilization bandwidth

  * MZ noise is detected at SP and is imposed on the frequency (phase) noise of the laser by the frequency stabilization feedback system

  * The imposed frequency noise is detected at AP

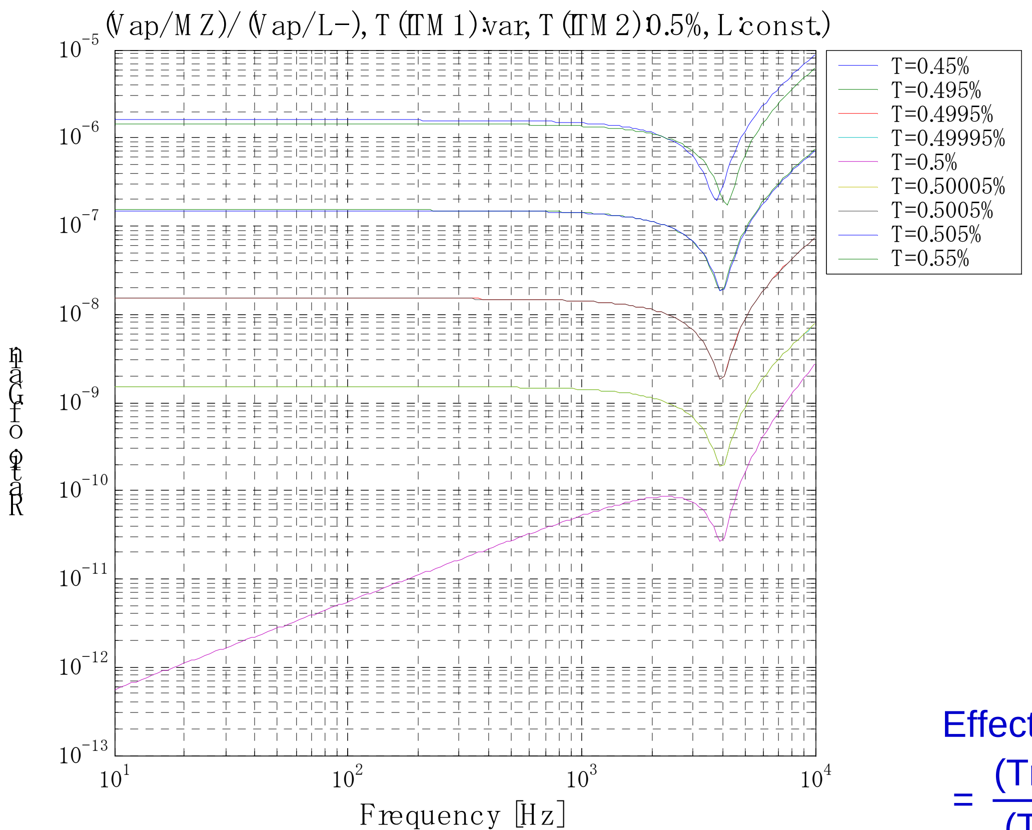


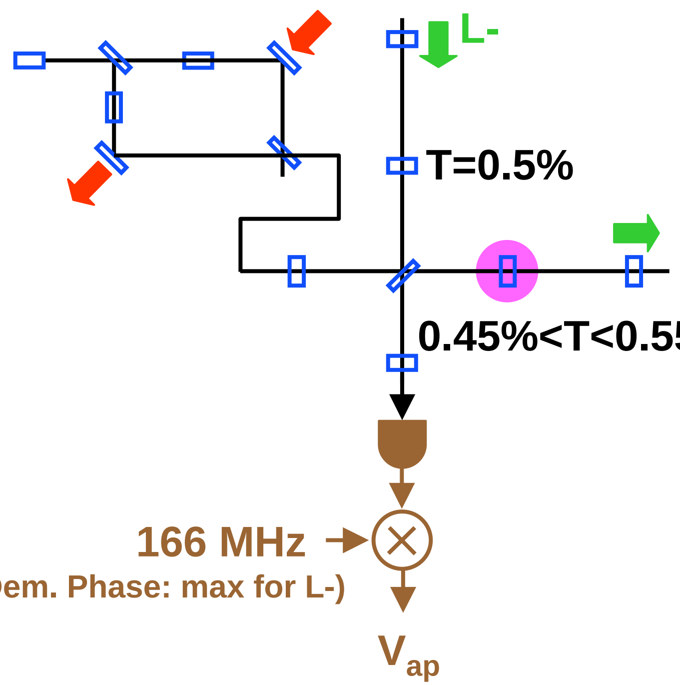
Simulation using FINESSE



C=2.99792458×10^8 (m/s)

Direct mechanism

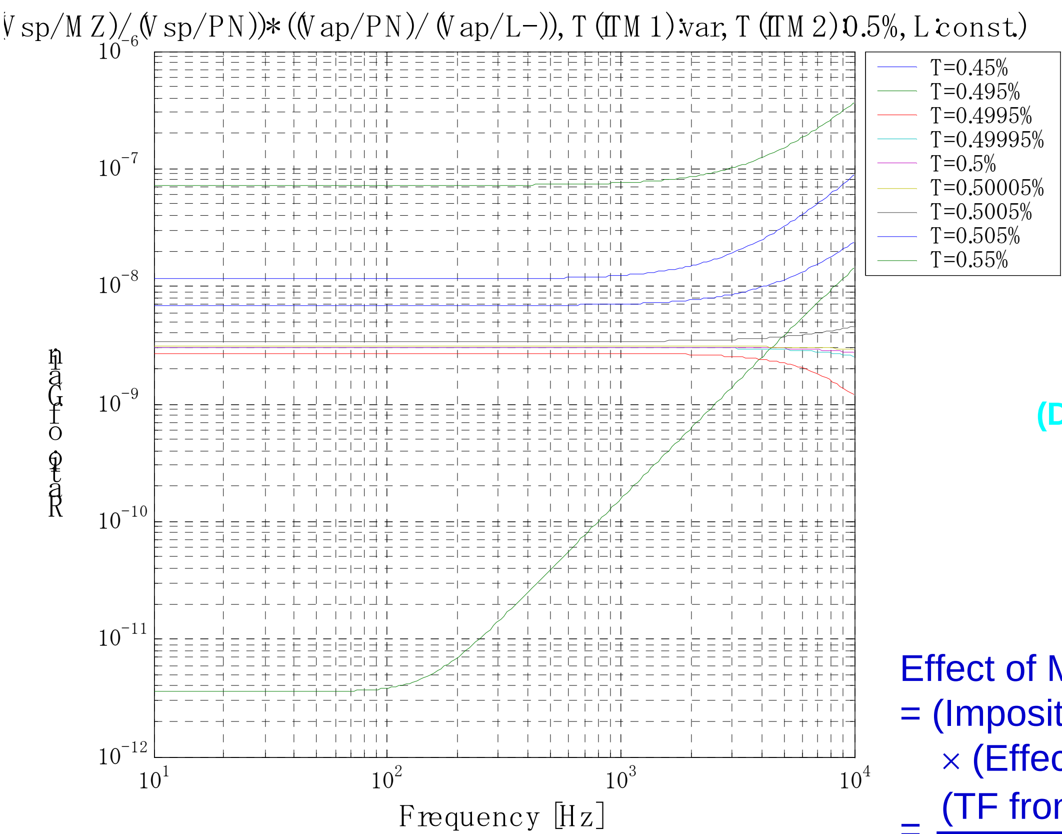


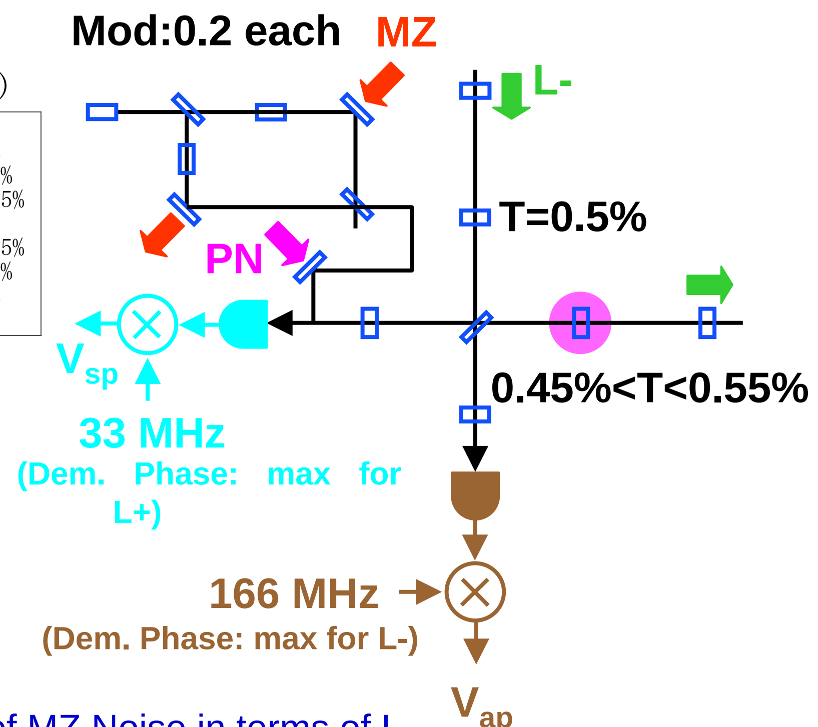


Effect of MZ Noise in terms of L-

= (Transfer Function from MZ to Vap) / (Transfer Function from L- to Vap)

Via Frequency Stabilization





Effect of MZ Noise in terms of L-

= (Imposition of MZ on PN by Frequency Stabilization)

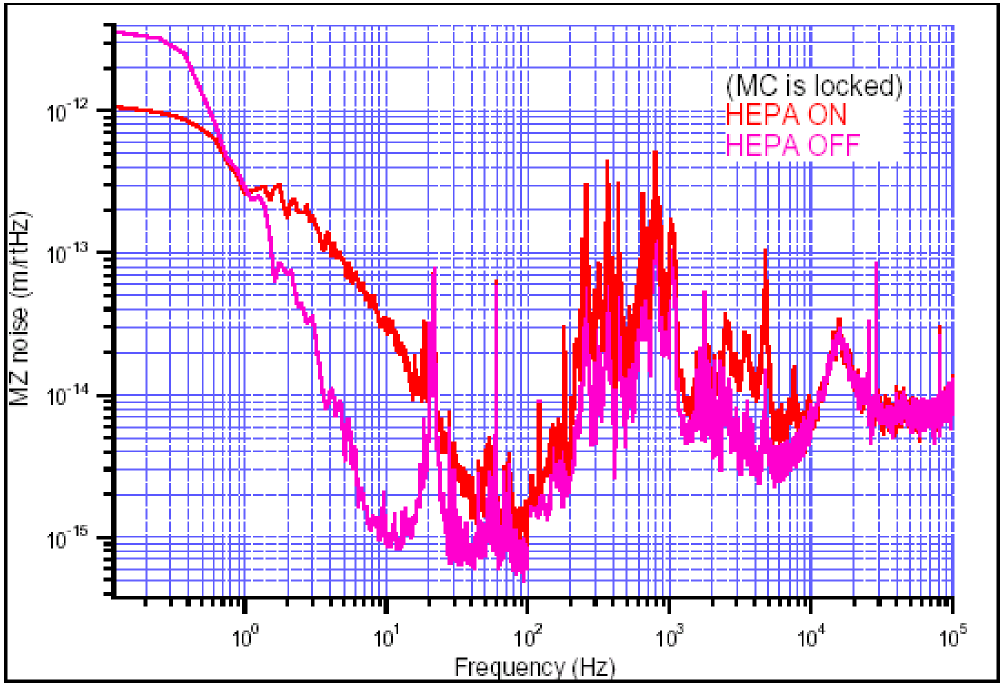
× (Effect of PN in terms of L-)

$$= \frac{(\text{TF from MZ to Vsp})}{(\text{TF from PN to Vsp})} \times \frac{(\text{TF from PN to Vap})}{(\text{TF from L- to Vap})}$$

Quick Results

- The direct mechanism gives 10^{-6} coefficient with some worst imbalances in T.
- It means that the MZ noise should be suppressed to 10^{-13} m/rHz in order to suppress the L- noise to 10^{-19} m/rHz.
- The noise via frequency stabilization is smaller than that with the direct mechanism.

Actual Noise



- The peaks around 1 kHz could produce non-negligible L- noise.
- Could be improved by Implementing a phase correcting PC to expand the bandwidth (Currently only a PZT is used).

More Investigations Necessary

- The noise effect should be estimated with various imbalances of the interferometer
- The effect for the DC readout scheme should be estimated
- Estimate for Advanced LIGO
- Simulation with E2E

Summary

- Ready to try lock acquisition scheme:
  - » Lock central part (l-, l+, ls) first, with blocked arms
  - » l- dither locking is a crutch to get all 3 degrees of freedom locked, one at a time
  - » lock arms without disturbing central part
- Eliminated sidebands on sidebands with Mach-Zehnder
- Concern about phase noise introduced by Mach-Zehnder

Hope we succeed in locking detuned RSE very soon!