



---

# 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  
Seiji Kawamura and Osamu Miyakawa  
G040331-00-R

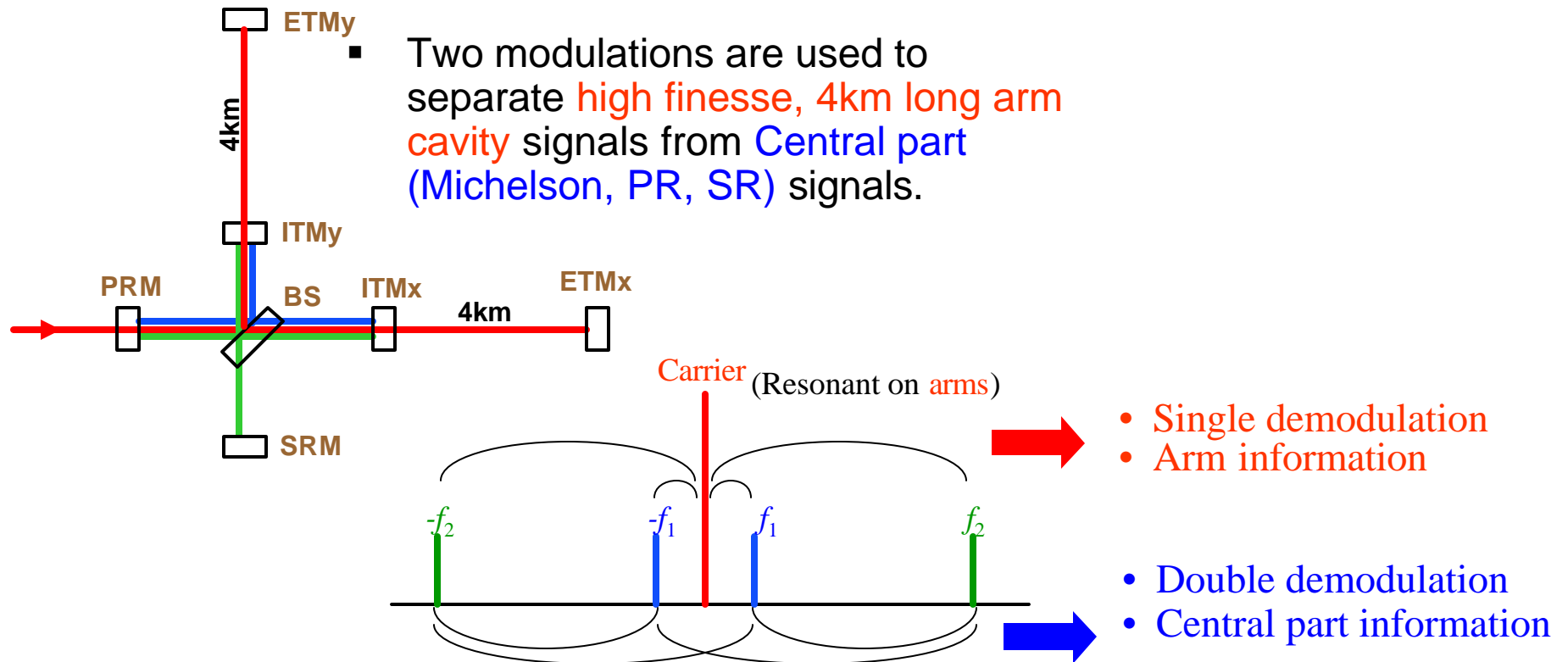


# Outline

---

- 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

# Signal extraction for AdvLIGO



- **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

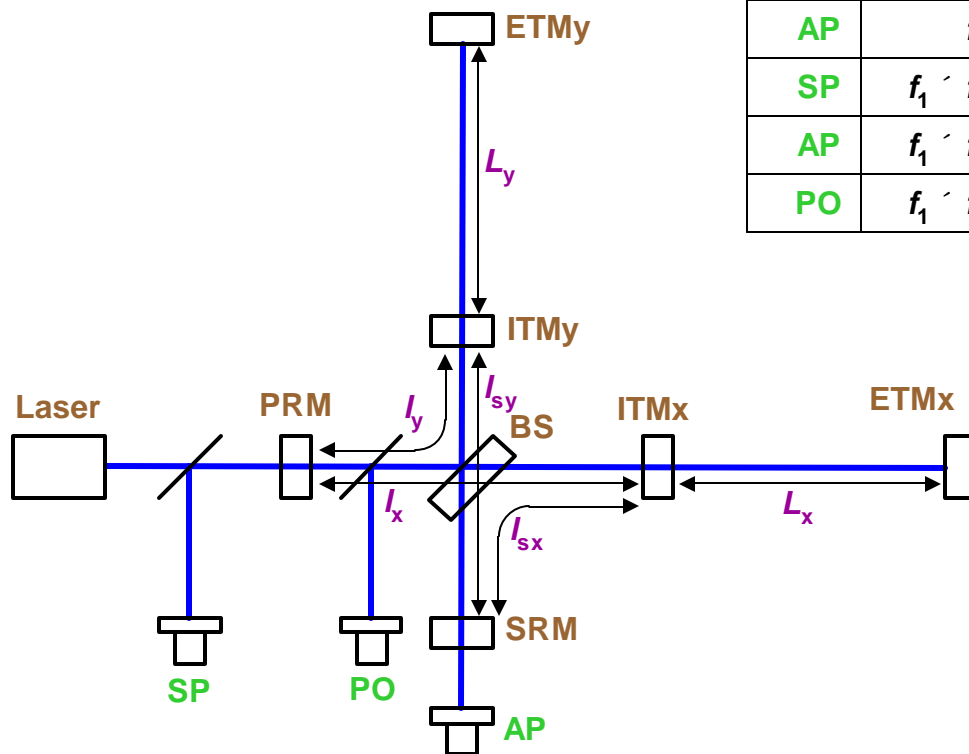
- Common of arms :  $L_+ = (L_x + L_y) / 2$
- Differential of arms :  $L_- = L_x - L_y$
- Power recycling cavity :  $I_+ = (I_x + I_y) / 2$
- Michelson :  $I_- = I_x - I_y$
- Signal recycling cavity :  $I_s = (I_{sx} + I_{sy}) / 2$

## Signal Extraction Matrix (in-lock)

Port	Dem. Freq.	$L_+$	$L_-$	$I_+$	$I_-$	$I_s$
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	$f_1 \text{ } f_2$	-1.7E-3	-3.0E-4	1	-3.2E-2	-1.0E-1
AP	$f_1 \text{ } f_2$	-6.2E-4	1.5E-3	7.5E-1	1	7.1E-2
PO	$f_1 \text{ } f_2$	3.6E-3	2.7E-3	4.6E-1	-2.3E-2	1

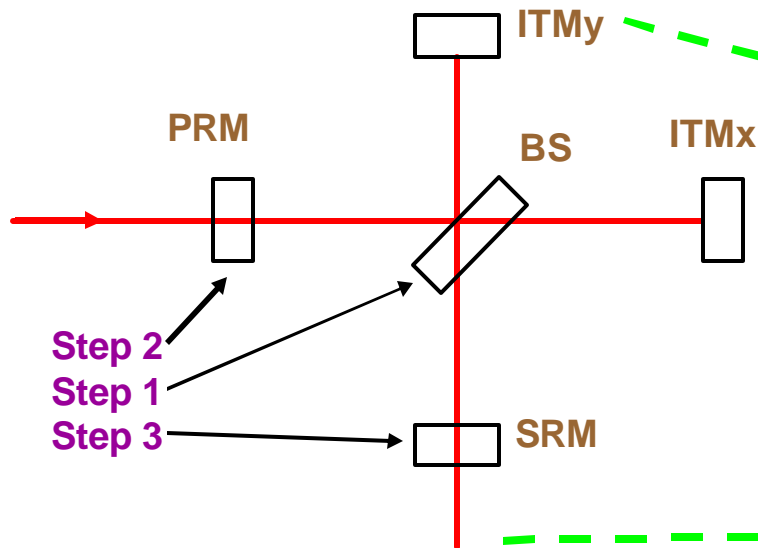
Calculated with TWIDDLE  
and with FINESSE

PO: light from BS to ITMy

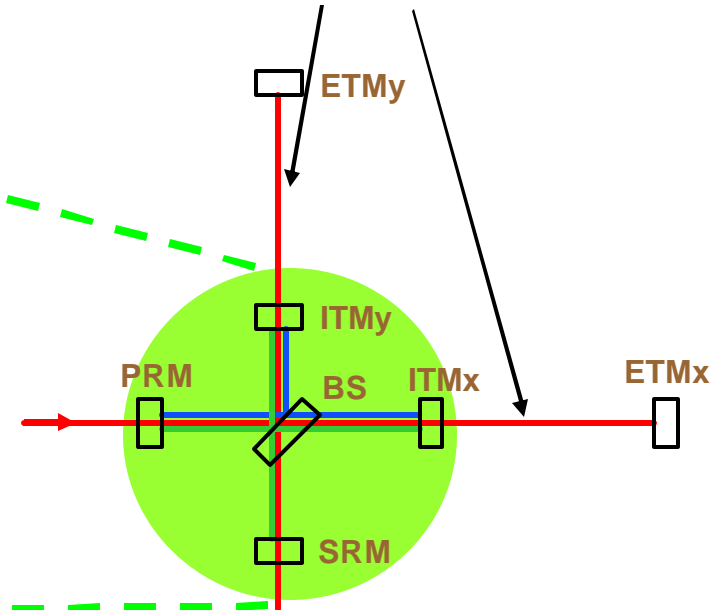


# Lock Acquisition of Detuned RSE

## 1. lock central part using beat signal between $f_1$ and $f_2$



## 2. lock arm cavities



- 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

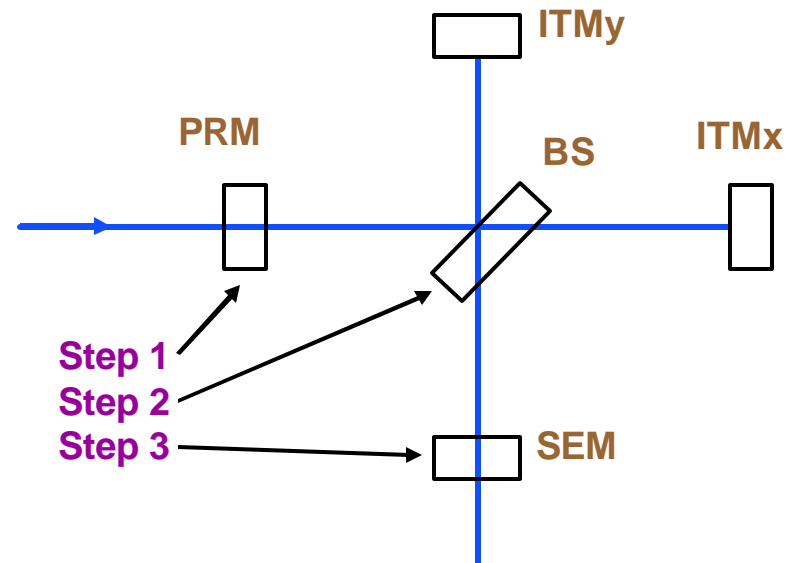
- Arm cavities: ~not disturbed by locked central part
- Central part could be disturbed by flashes of SBs in arms
- Lock each arm independently
- Switch control servo to common/differential control

# Lock Acquisition of Central Part

Ideal Procedure: Lock one by one

[for example]

- Step 1: Lock  $I_+$  robustly
- Step 2: Lock  $I_-$  robustly
- Step 3: Lock  $I_s$



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



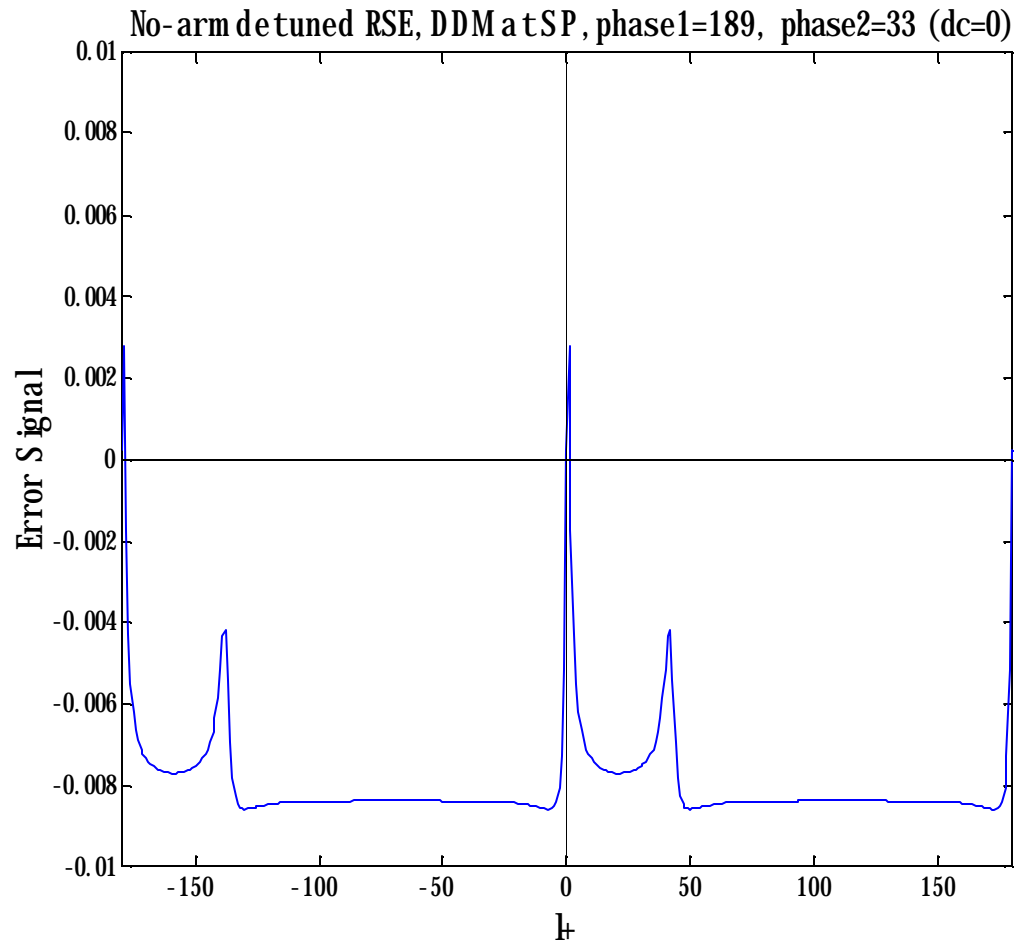
# Strategy for central part

---

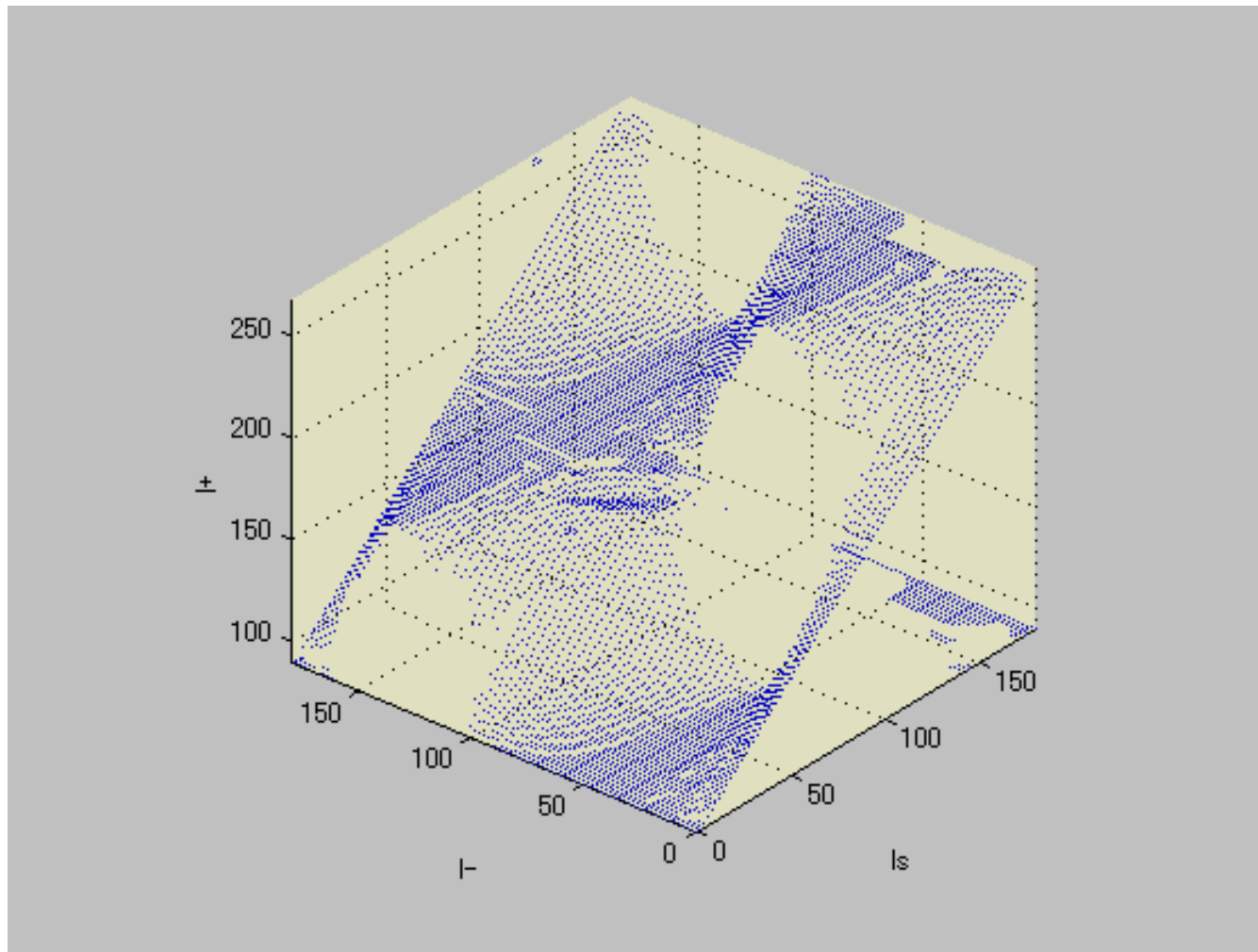
- Ideally, lock one DOF at a time, robust against other (2) DOF's varying randomly as the mirrors swing
- look for a servo-able signal (crossing zero at desired point, relatively insensitive to values of other DOFs)
- See how robust the signal is when the other 2 DOFs vary across their phase space uniformly; 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 3<sup>rd</sup> 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!



# Quality of I+ Signal (dc=0, I+:Max)

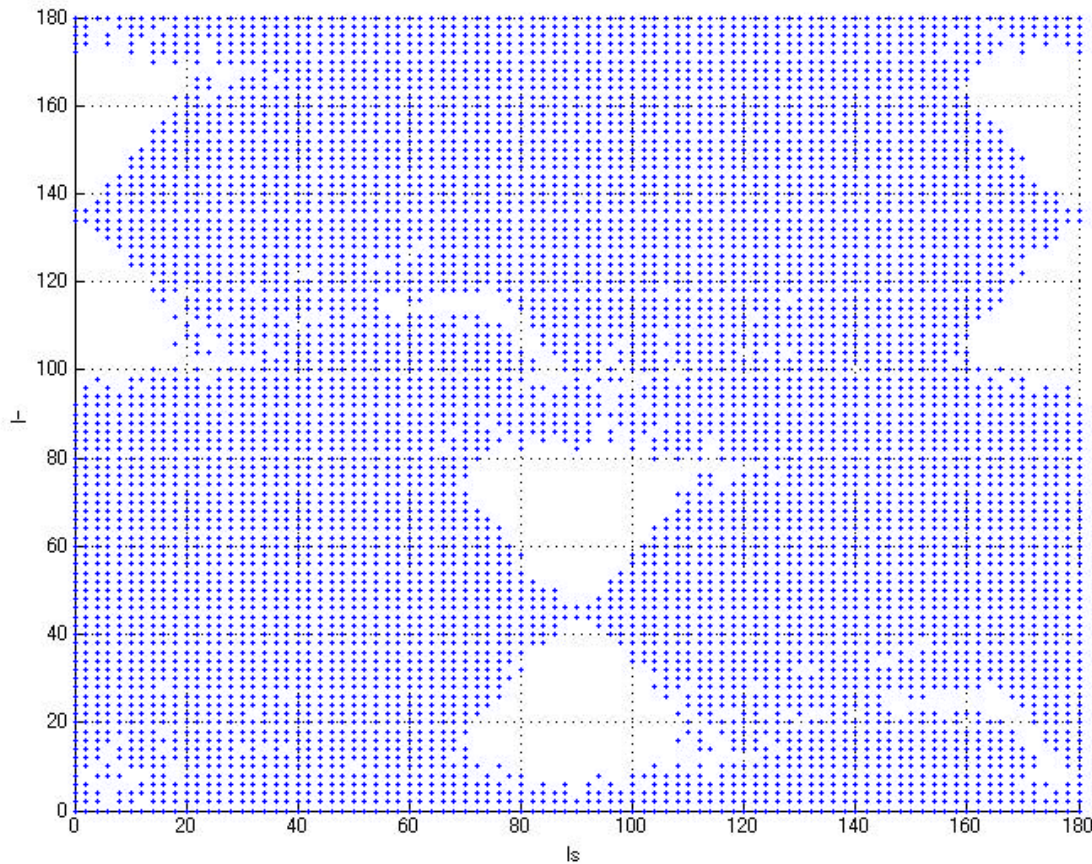


# I+ Signal lockable surface



I+ DOF may not lock exactly where you want it (for carrier resonance in PRC), but as the DOFs come under control, the locked phase will adiabatically “walk” to where we want it.

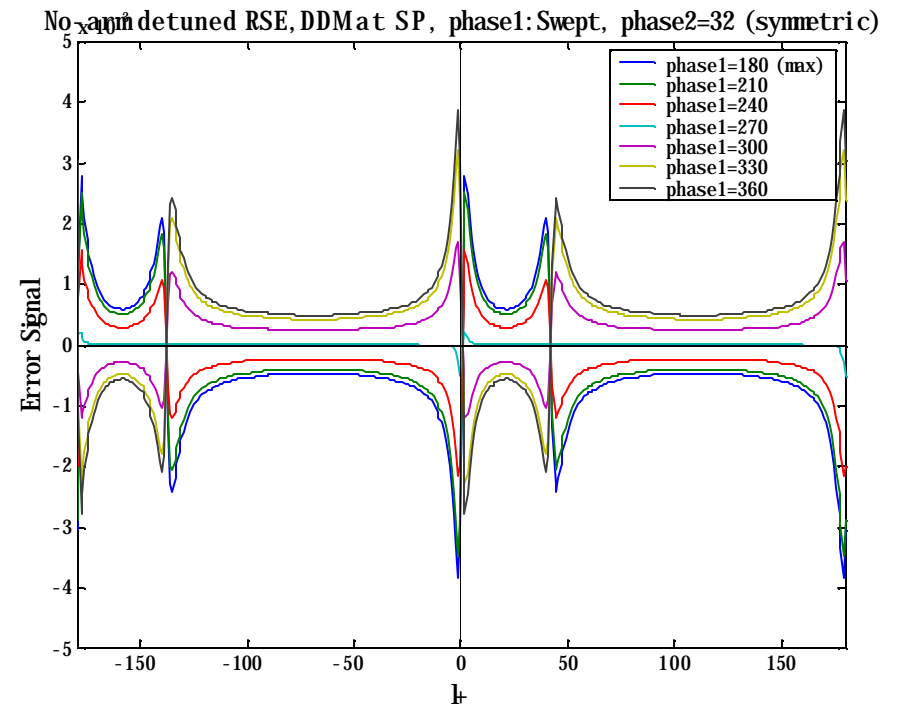
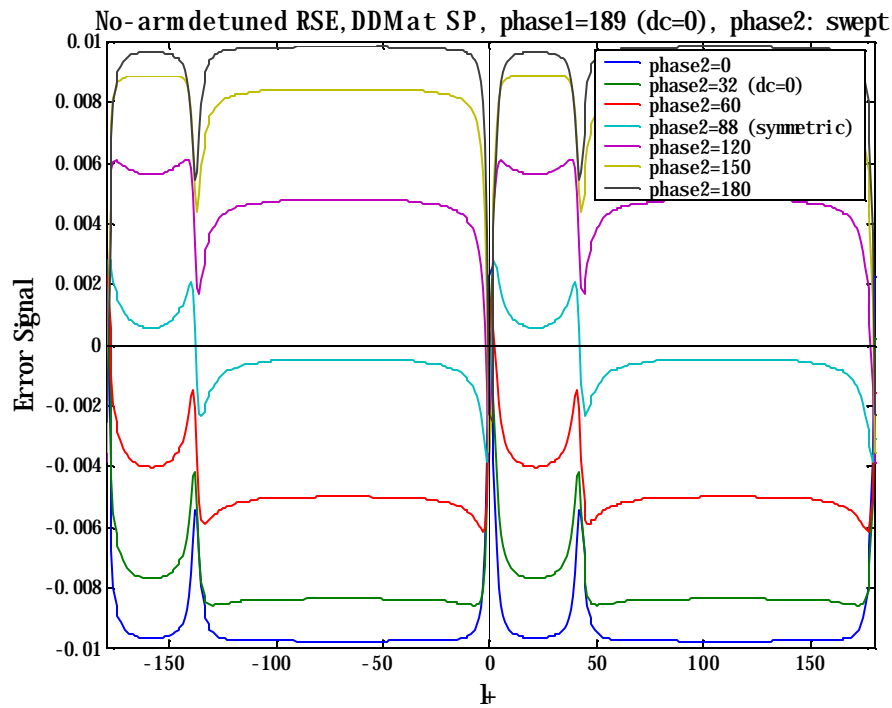
# I+ Signal lockable surface



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

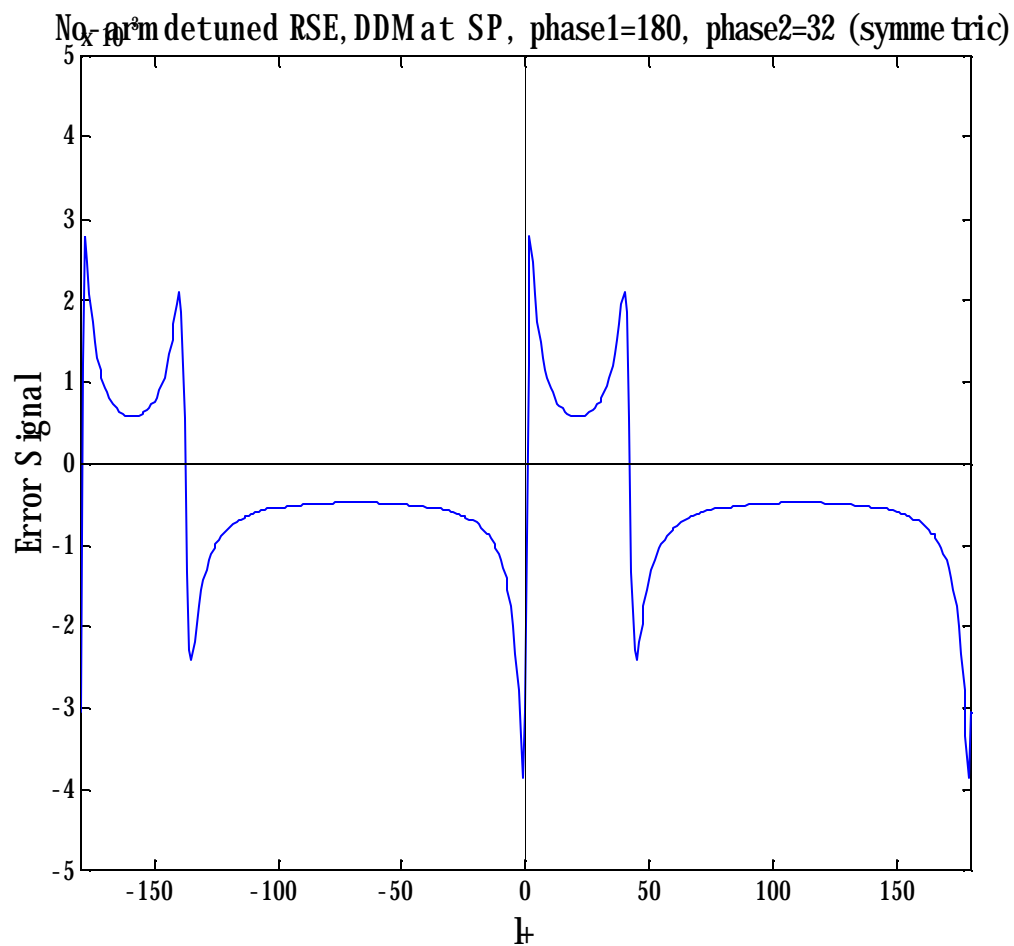


# Dependence of I+ Signal on Demodulation Phases

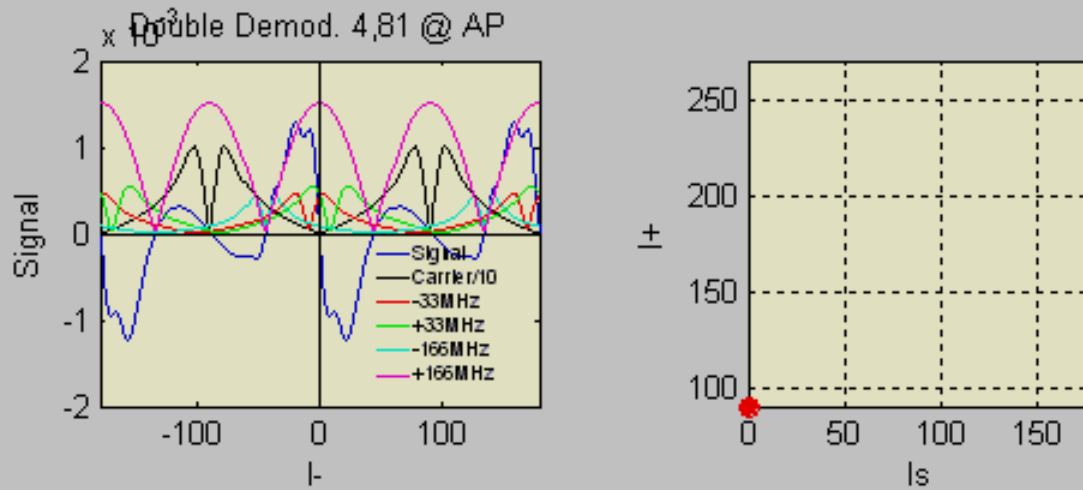




# Quality of I+ Signal (Symmetric, $dc \neq 0$ )

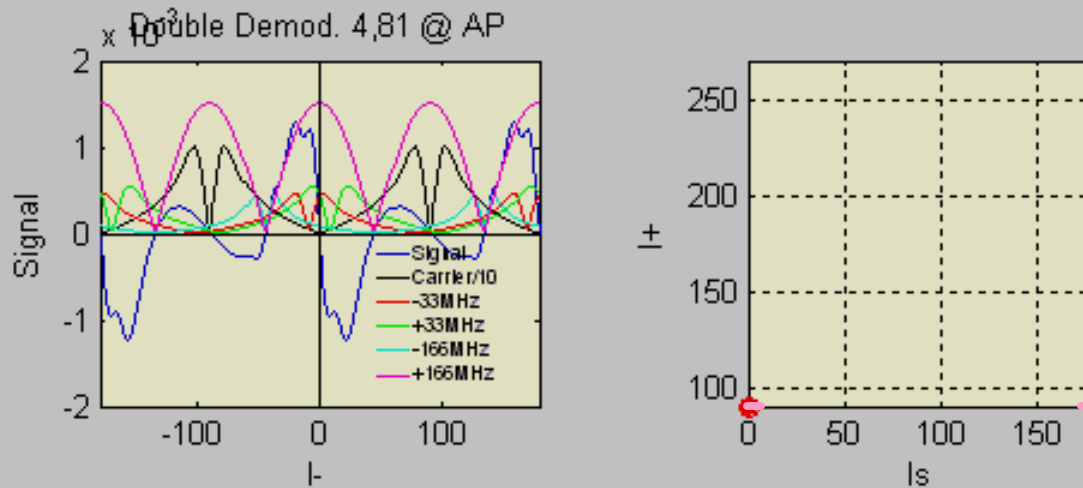


# Original I- signal



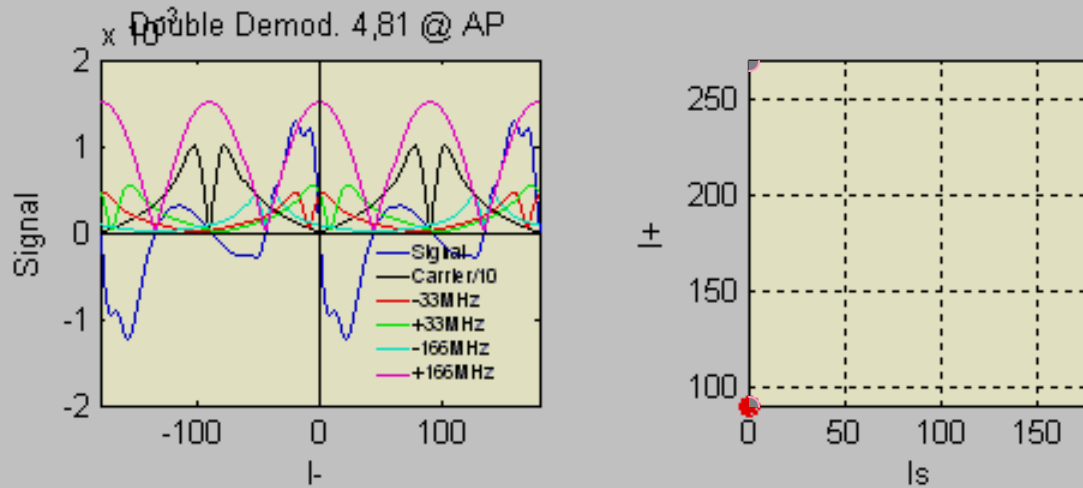
- Good I- signal with Is and I+ lock

# Original I- signal



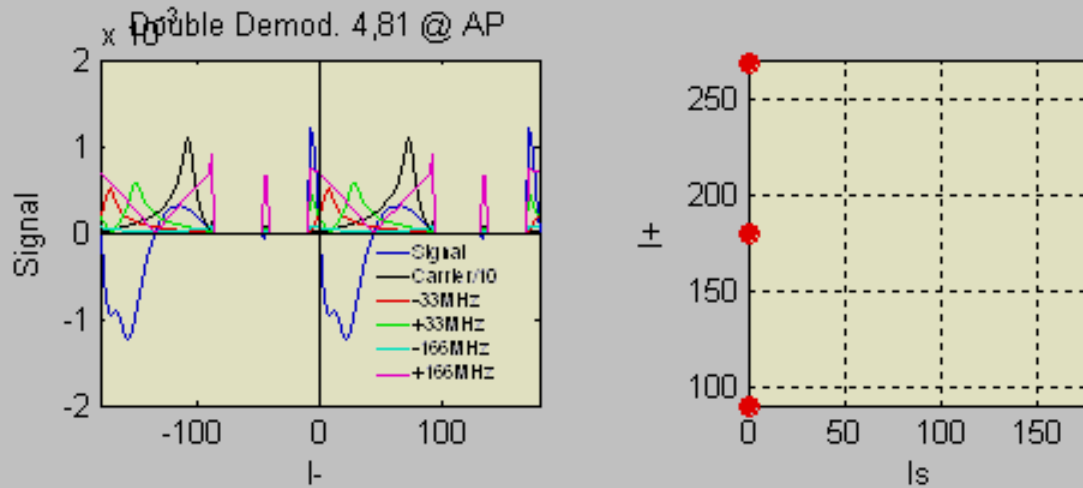
- Good I- signal with I<sub>s</sub> and I<sub>+</sub> lock
- Good I- signal with 178 ~ 2 deg. of I- and I<sub>+</sub> lock. ( ~2% of line)

# Original I- signal



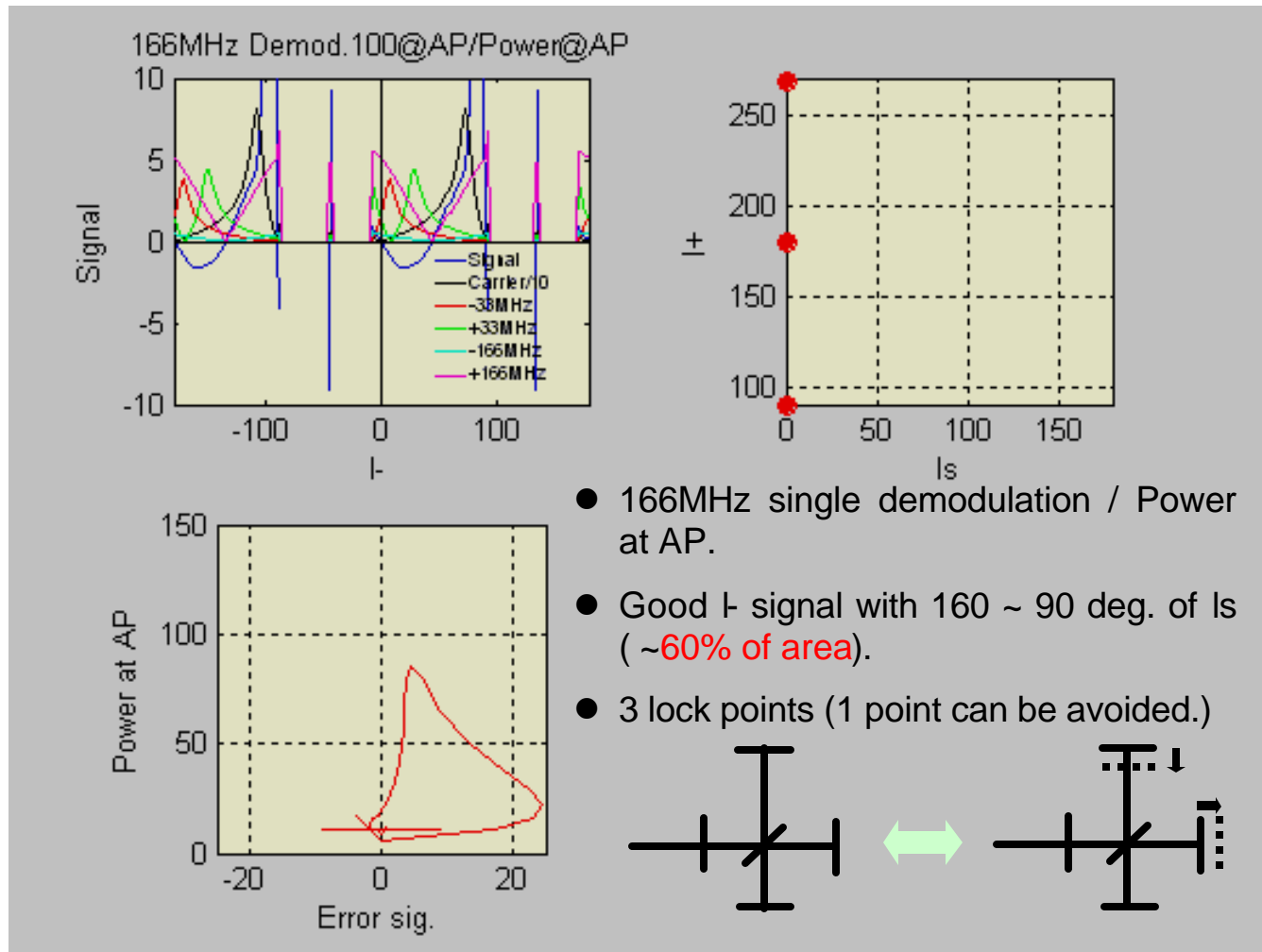
- Good I- signal with Is and I+ lock
- Good I- signal with 178 ~ 2 deg. of I- and I+ lock. ( ~2% of line)
- No good signal obtained except for I+ around lock. ( ~0.04% of area)

# I- signal with I+ lock

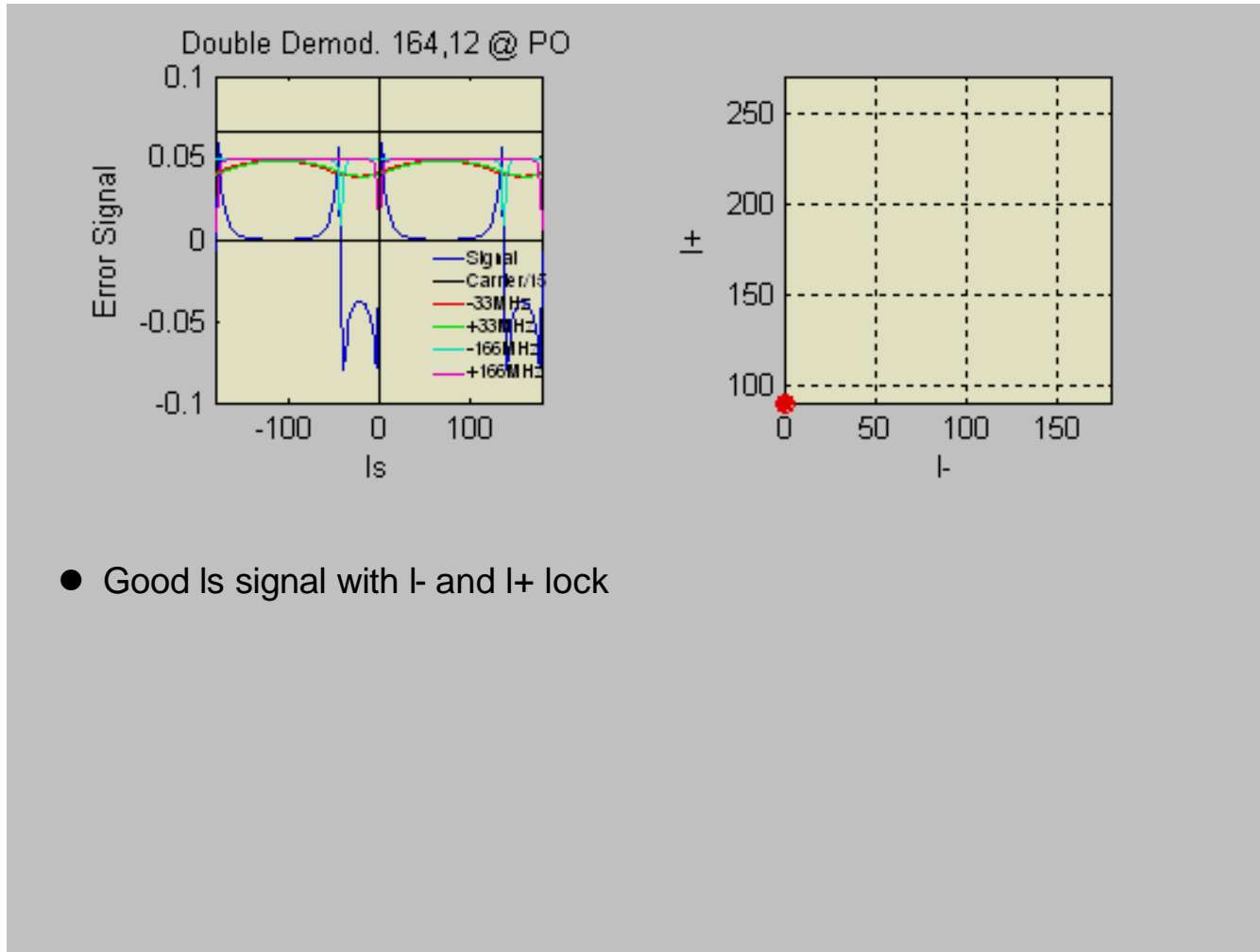


- Good I- signal with 150 ~ 5 deg. of I+. ( ~20% of area)
- Disturbed by peaks of +/-33MHz

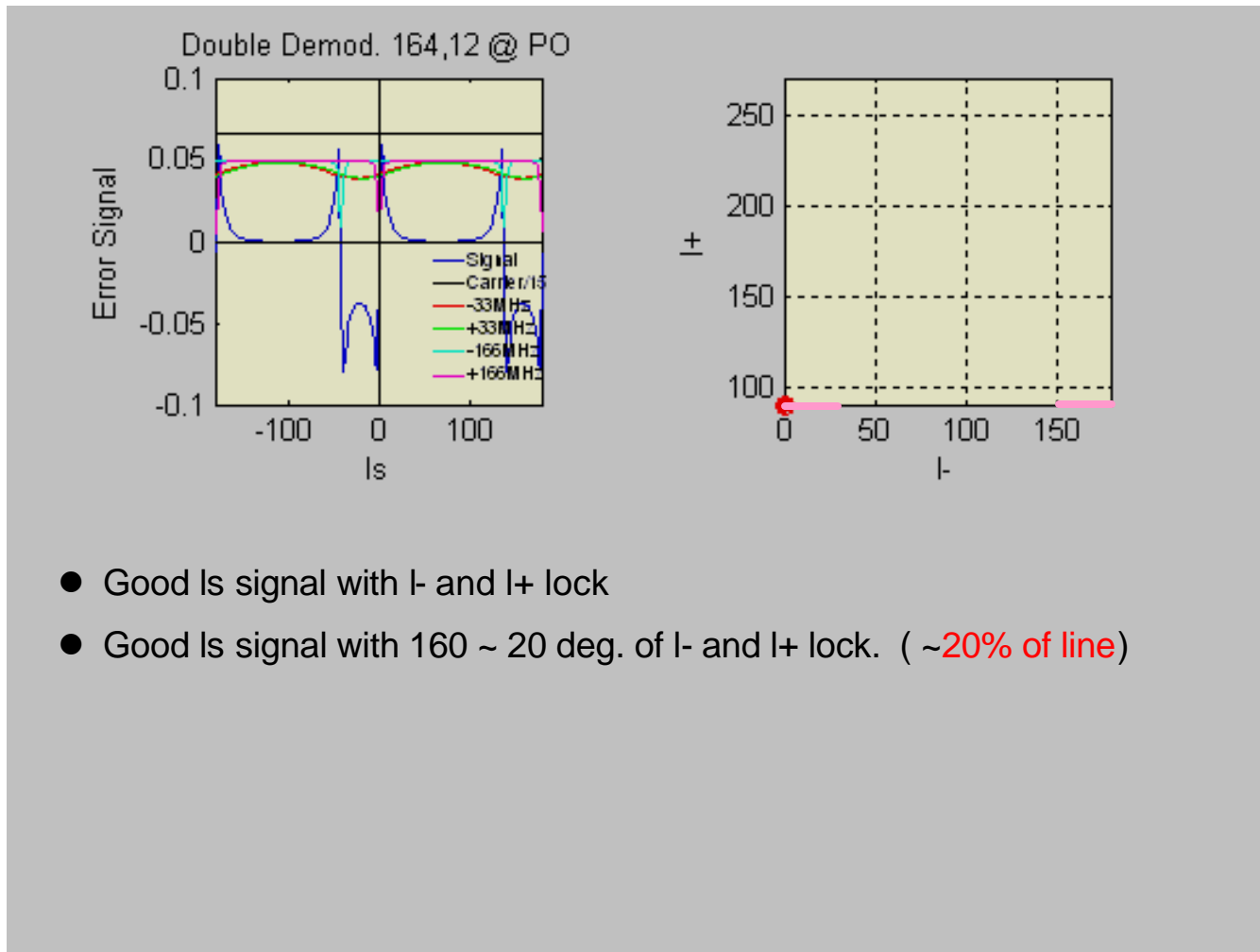
# I- signal with I+ lock



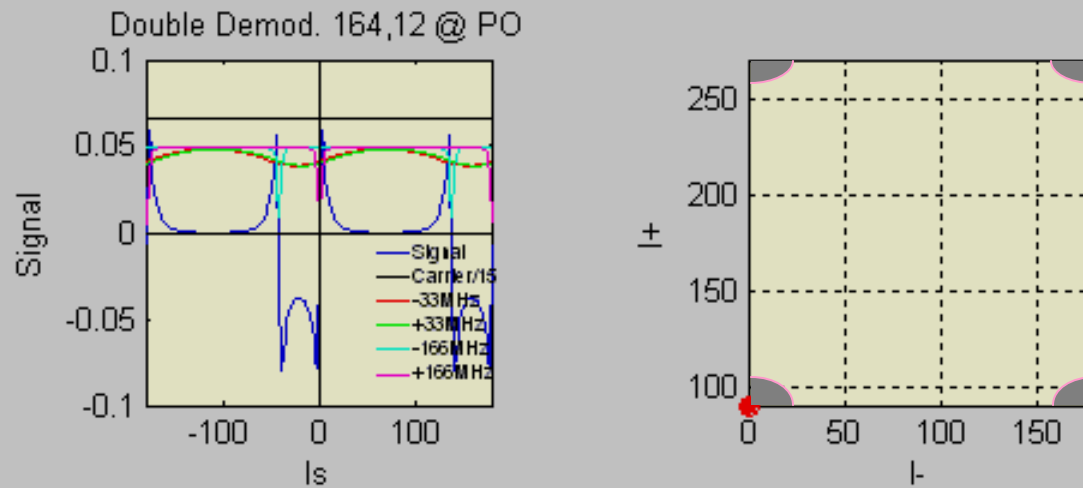
# Original $I_s$ signal



# Original $I_s$ signal

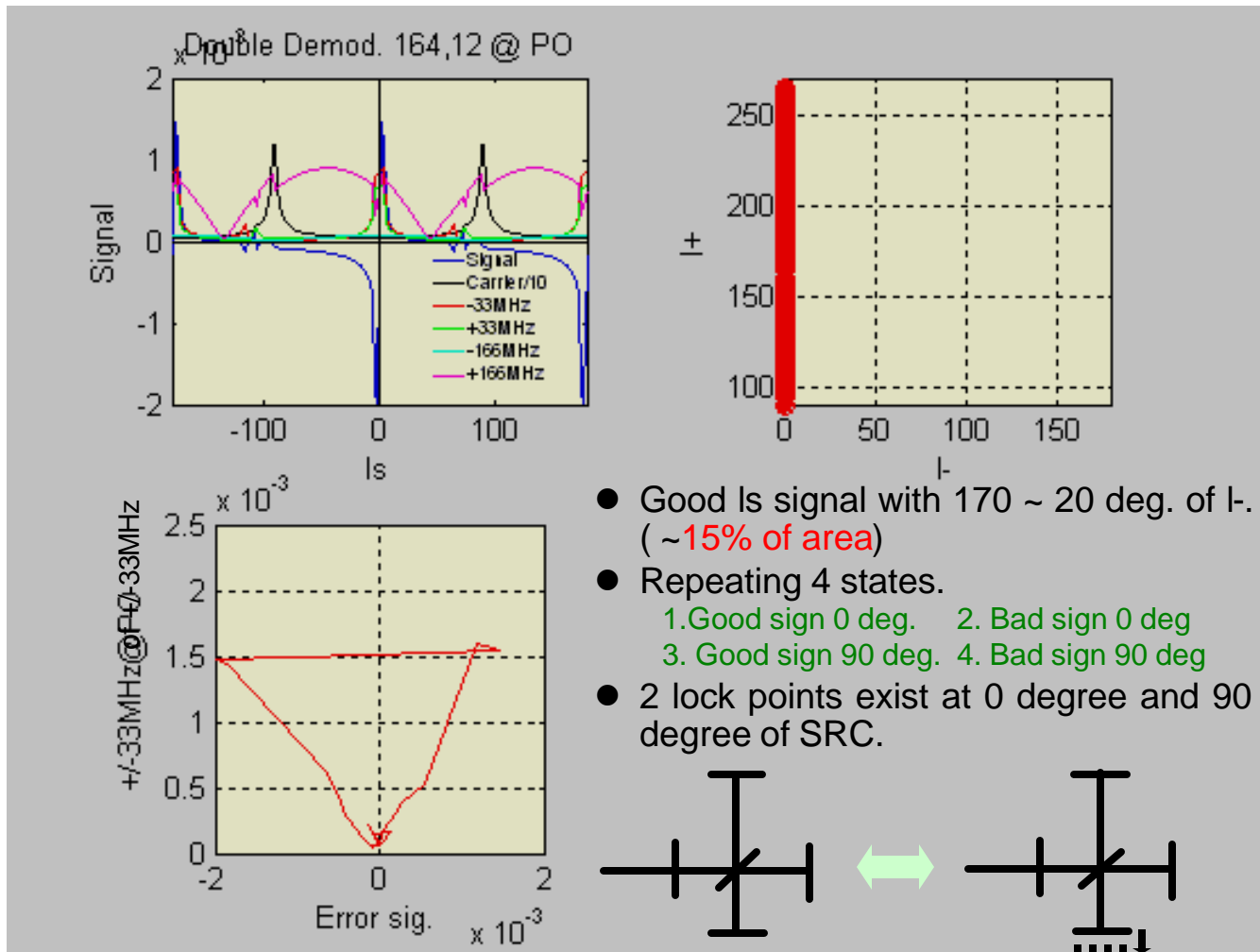


# Original Is signal



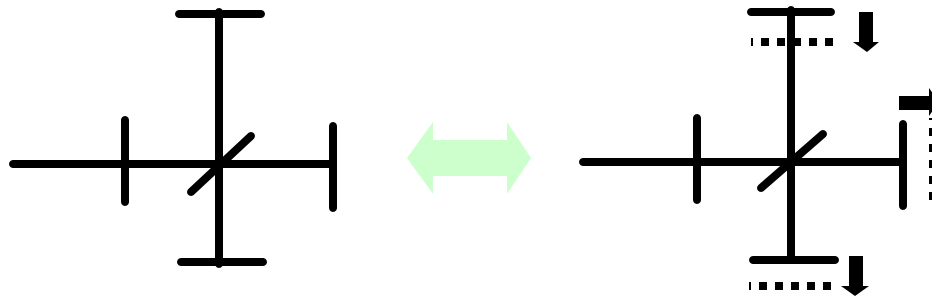
- Good  $I_s$  signal with  $I_-$  and  $I_+$  lock
- Good  $I_s$  signal with 160 ~ 20 deg. of  $I_-$  and  $I_+$  lock. ( ~20% of line )
- No good signal obtained except for  $I_+$  around lock. ( ~2% of area )

# Is signal with I+ lock



# Lock acquisition procedure

1. I+: double demodulation 88,180 deg. @ SP 80%
  2. I- : 166MHz single demodulation 100 deg. @AP / Power @ AP 60%
  3. Is : double demodulation 164,12 deg. @ SP 15%
- Total lock area  
 $80\% \times 60\% \times 15\% = 8\%$
  - 2 lock states exist, but no way to distinguish them

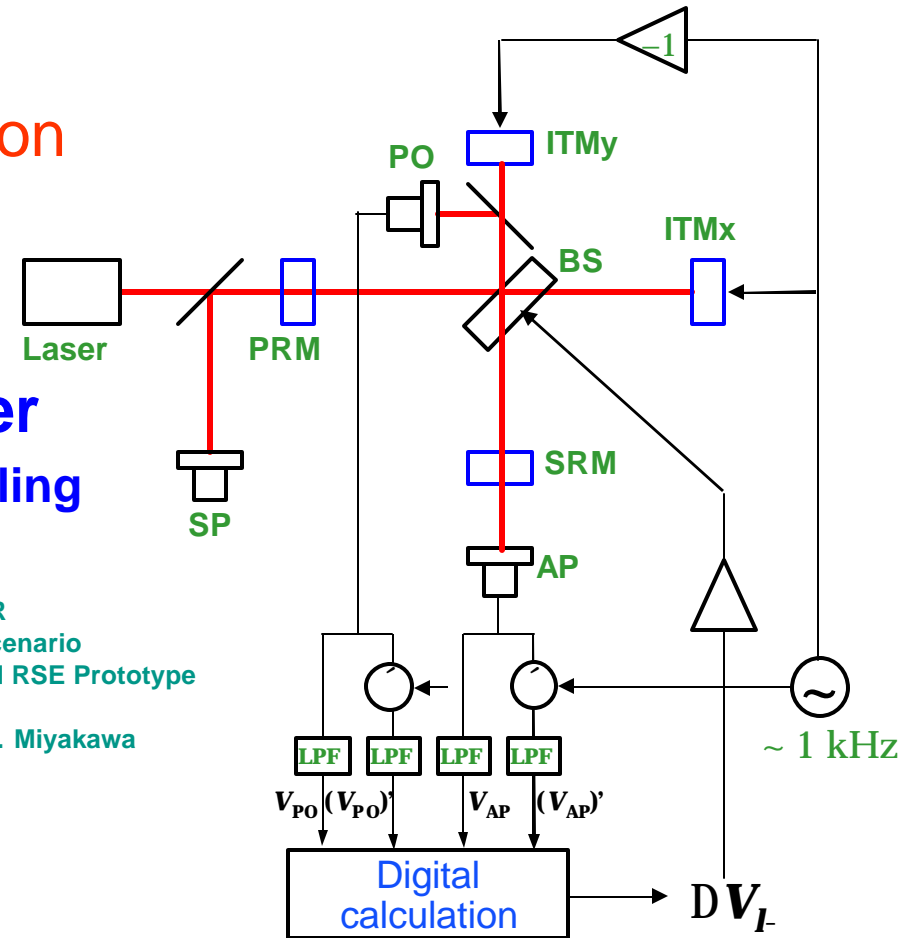


- Unfortunately, no easy way to lock central part directly using the original double demodulation
- **Dither locking for  $l_-$  signal**
- **Divide signal by inside power**
  - » Good cancellation of power recycling

$$\Delta V_{l_-} = \frac{d}{d l_-} \left( \frac{V_{AP}}{V_{PO}} \right)$$

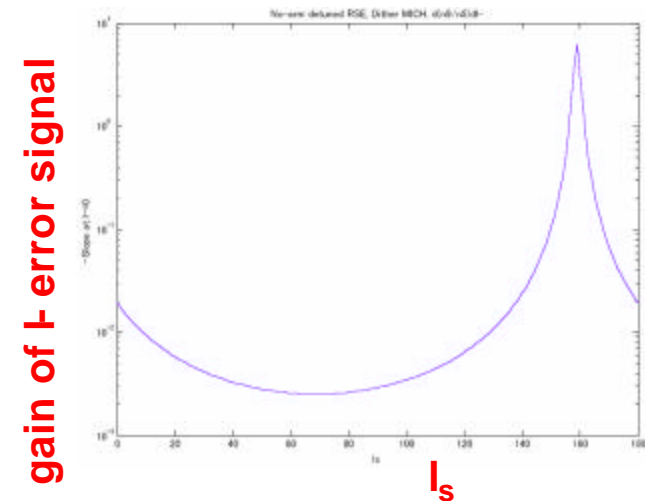
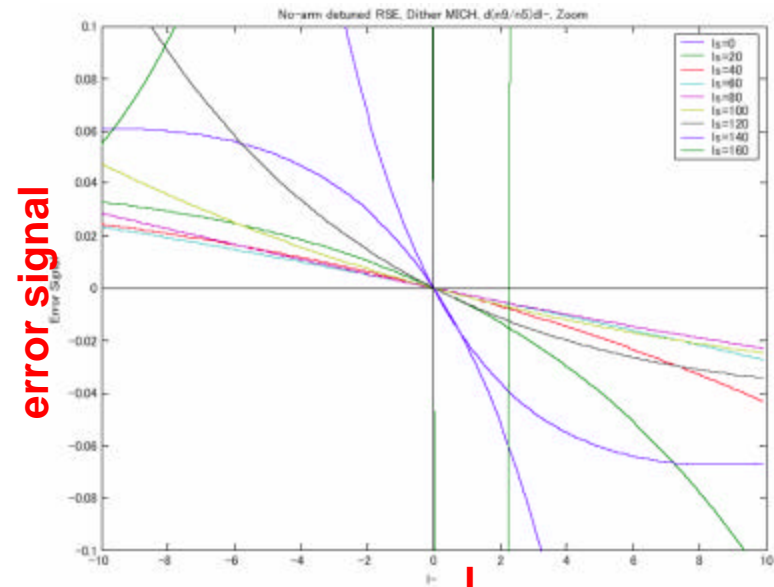
$$= \frac{V'_{AP} V_{PO} - V_{AP} V'_{PO}}{V_{PO}^2}$$

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



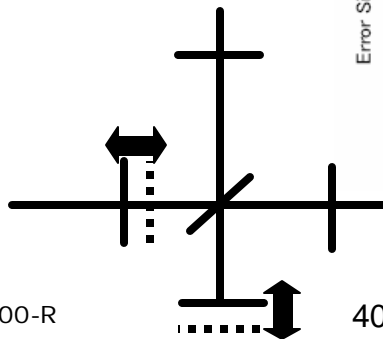
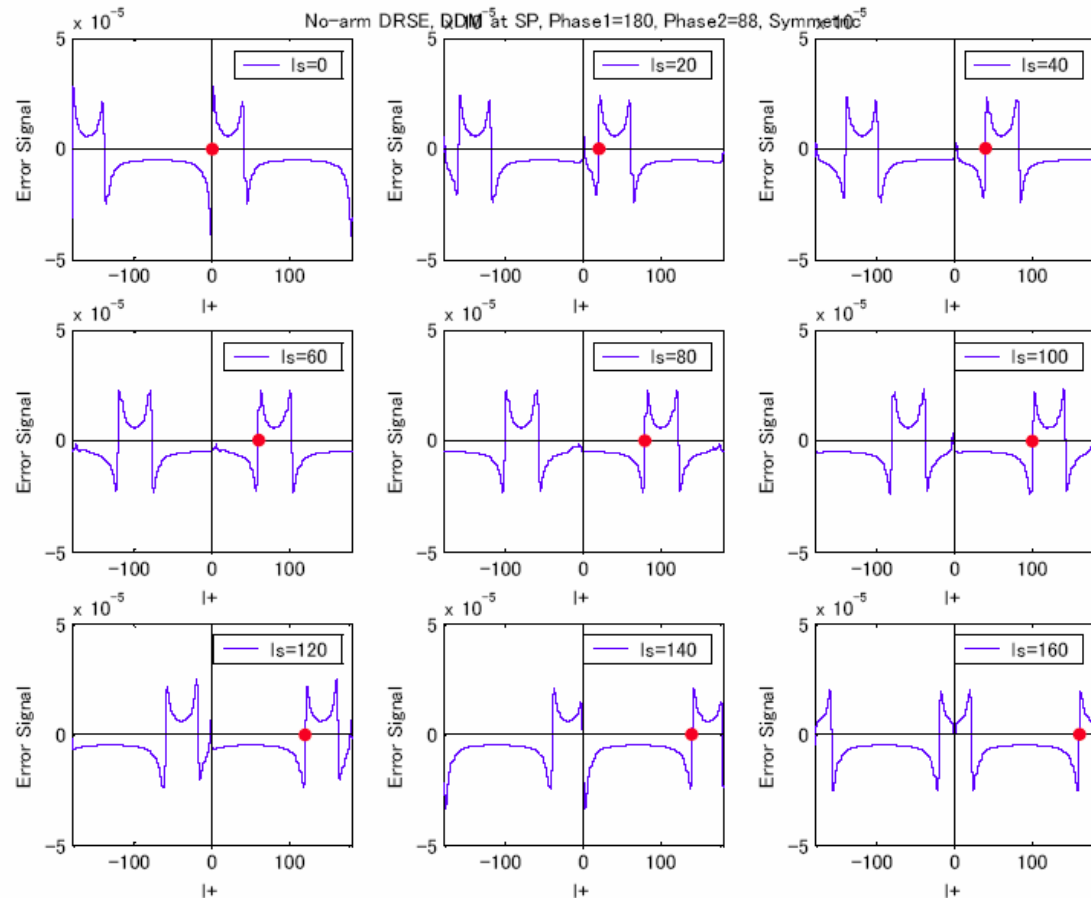
# Gain of dither locking signal

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



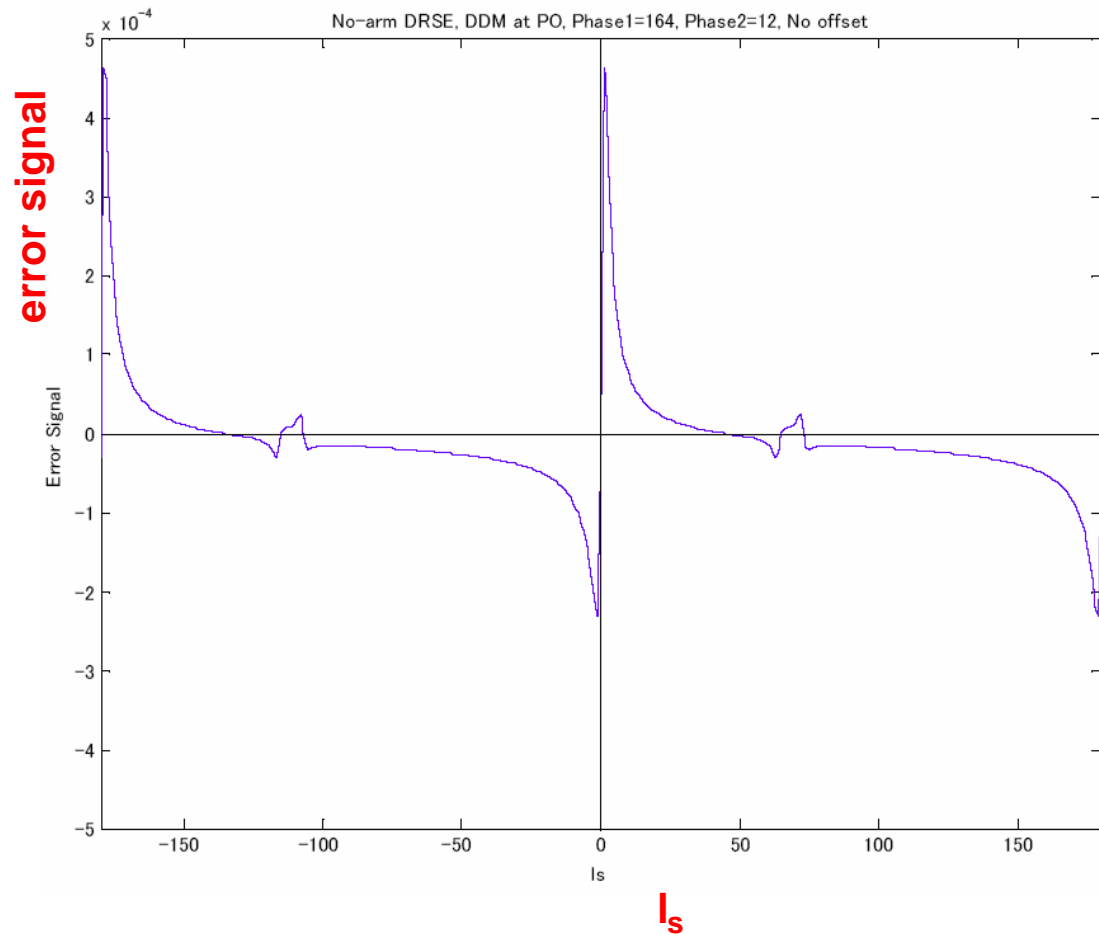
# Lock I+ with DDM at SP

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



# Lock Is with DDM at PO

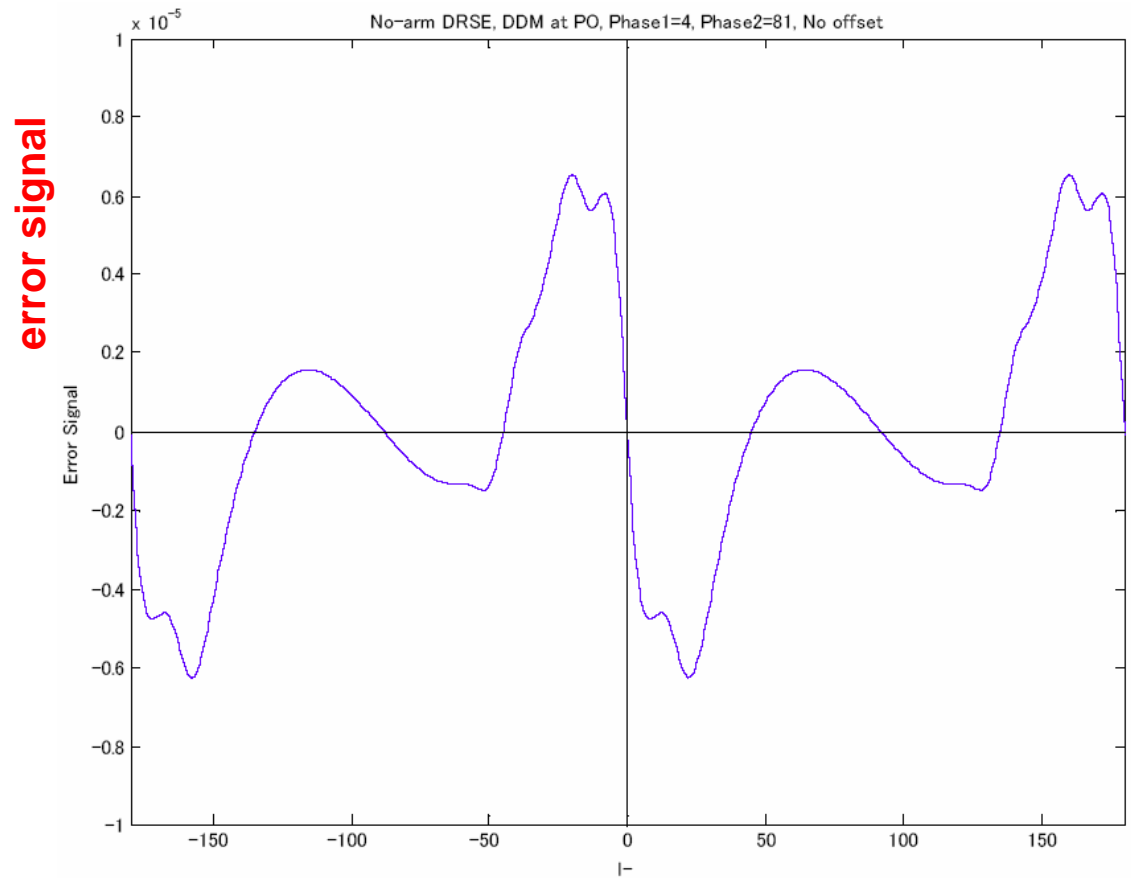
- With I- dither-locked, and I+ DDM-locked to Is, there's a good error signal for locking Is at the desired point (0° with respect to RF, detuned wrt carrier).
- Final step:





# Switch to I- with DDM at AP

- Central part final step:  
Switch the  $I-$  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!



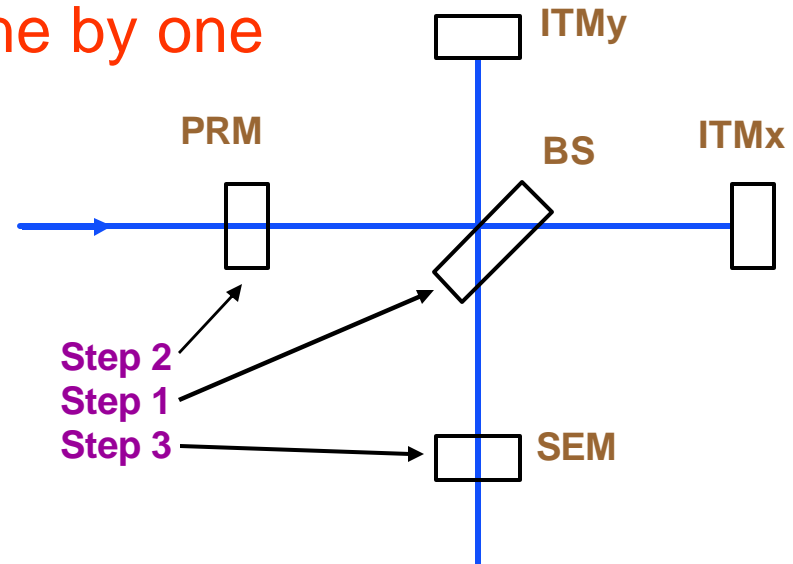
# Lock Acquisition of Central Part

Ideal Procedure: Lock one by one

Step 1: Lock  $I_-$  robustly

Step 2: Lock  $I_+$  robustly

Step 3: Lock  $I_s$



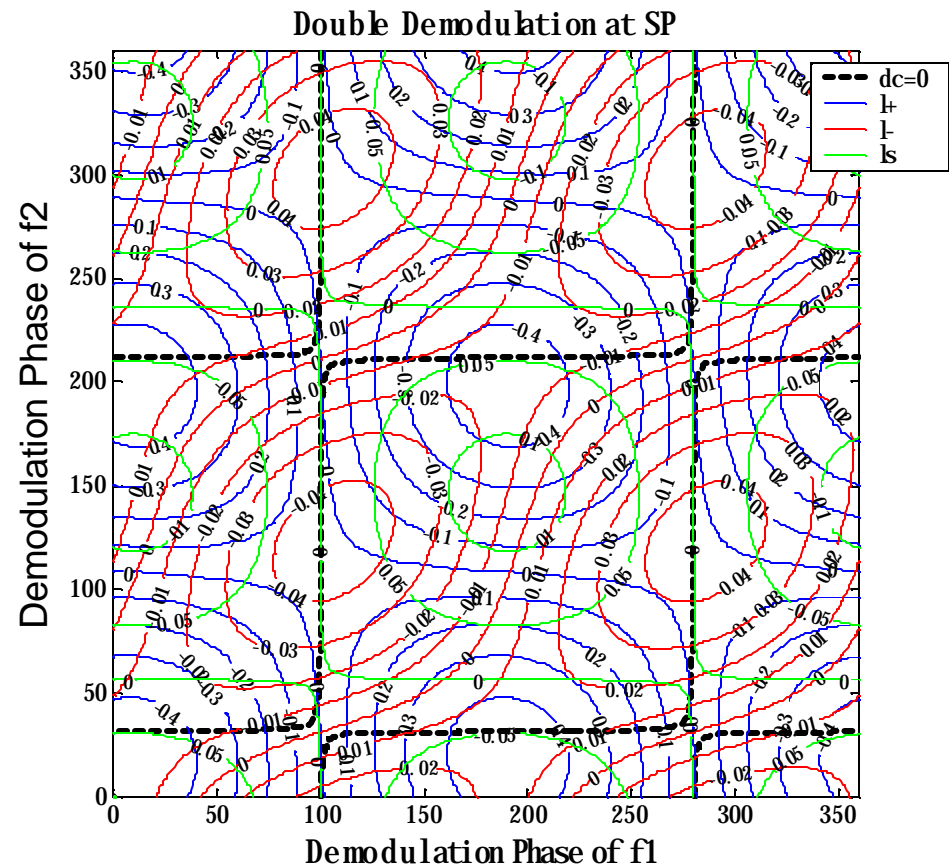
1.  $I_-$ : dither, @  $\frac{S_{AP}P_{SP} - S_{SP}P_{AP}}{P_{SP}^2}$  with low modulation: 100%
2.  $I_+$ : double demodulation 88,180 deg. @ SP : 100%
3.  $I_s$ : double demodulation 164,12 deg. @ PO : 100%

Switch to design control topology, open shutter, lock arms

# Double Demodulation

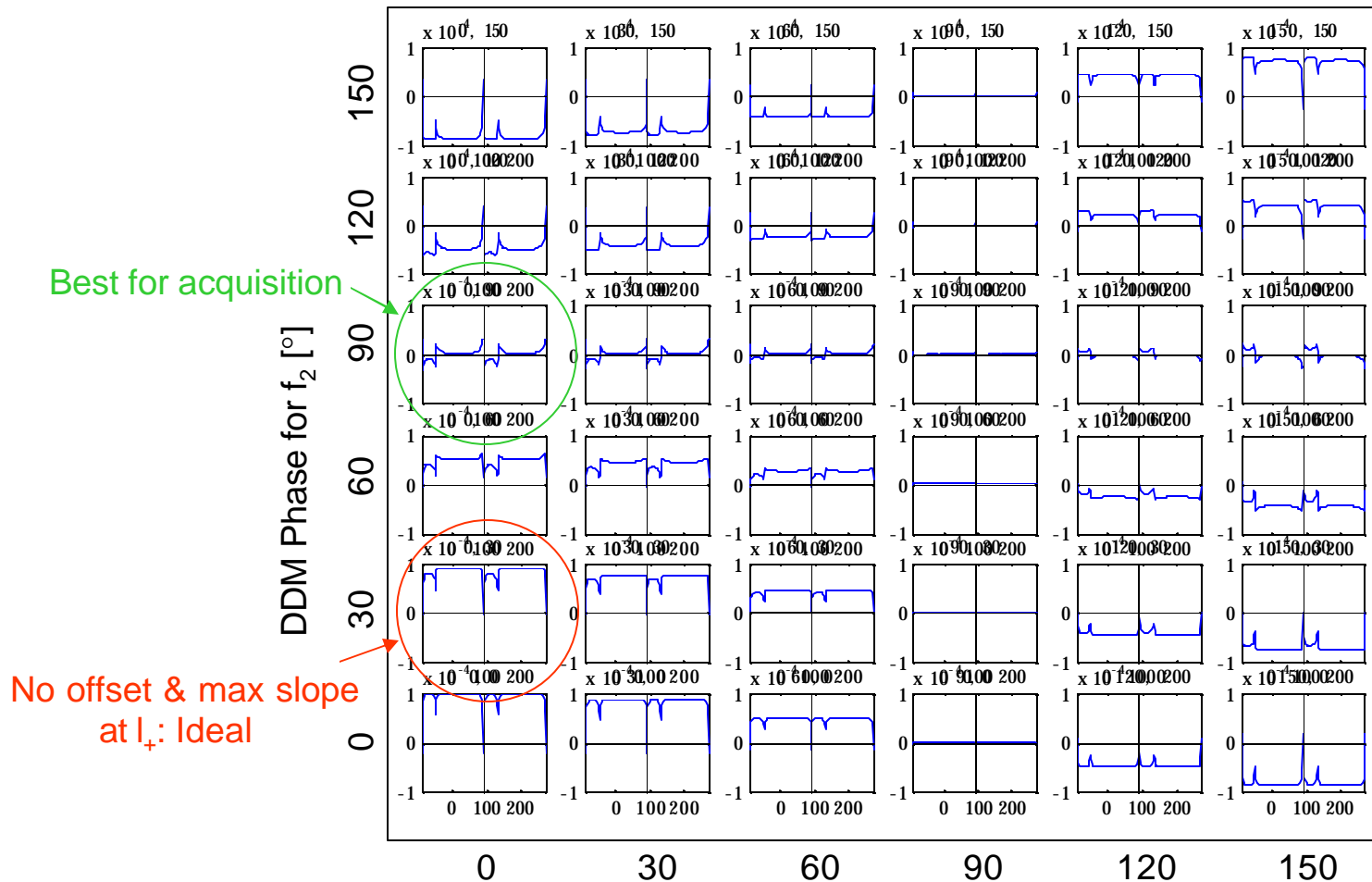
- Double Demodulation used for  $I_+$ ,  $I_-$ , and  $I_s$
- Demodulation phases optimized to **suppress DC** and to **maximize desired signal**

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





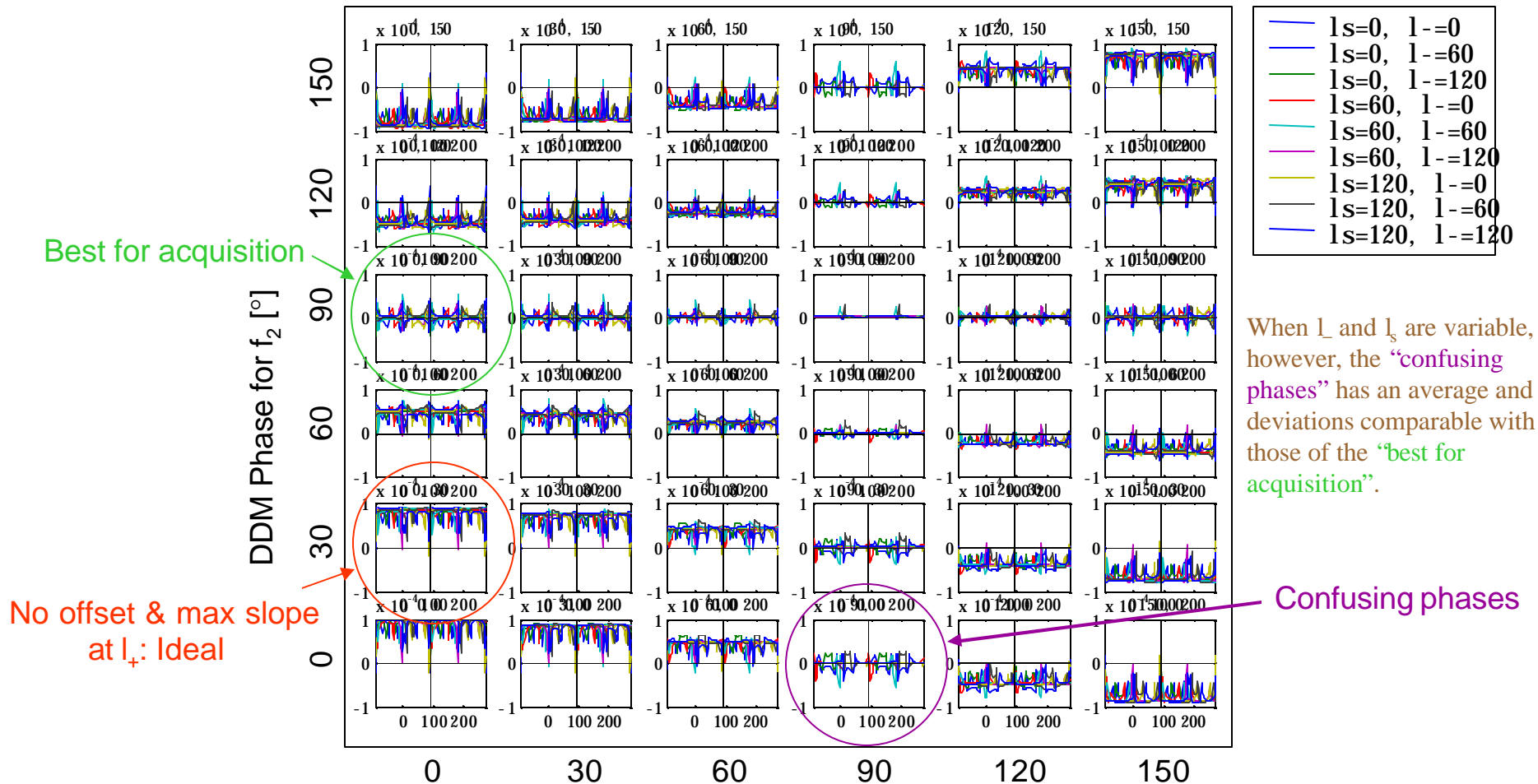
# Dependence of $I_+$ Error Signal at SP on DDM Phases ( $I_-, I_s$ : Ideal)



The  $I_+$  error signal for the “best for acquisition” looks unique. It has a zero average and maximum deviations (among the zero average ones).

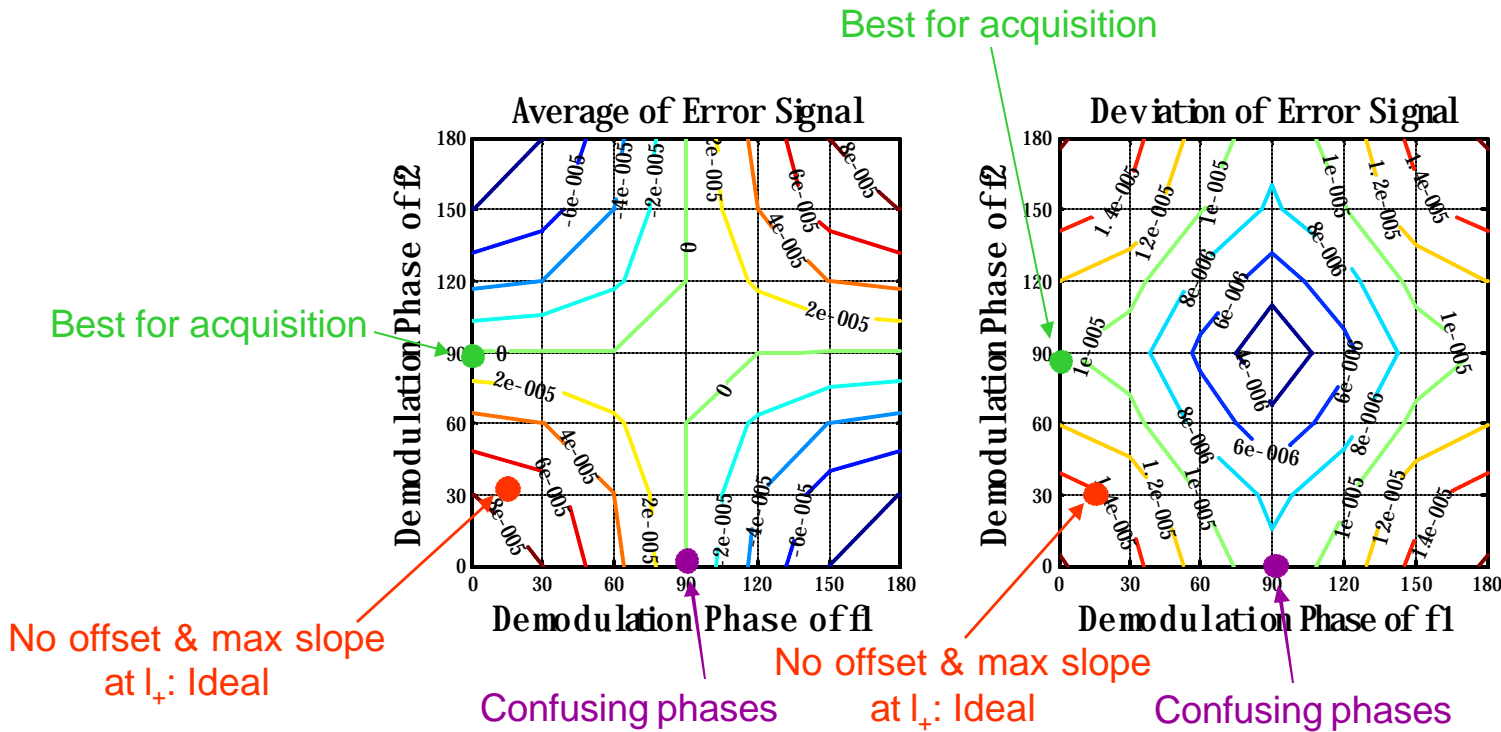


# Dependence of $I_+$ Error Signal at SP on DDM Phases ( $I_-, I_s$ : Variable)





# Dependence of Average Value and Deviation of DDM Signal at SP on DDM Phases ( $I_+$ , $I_-$ , $I_s$ : Free)



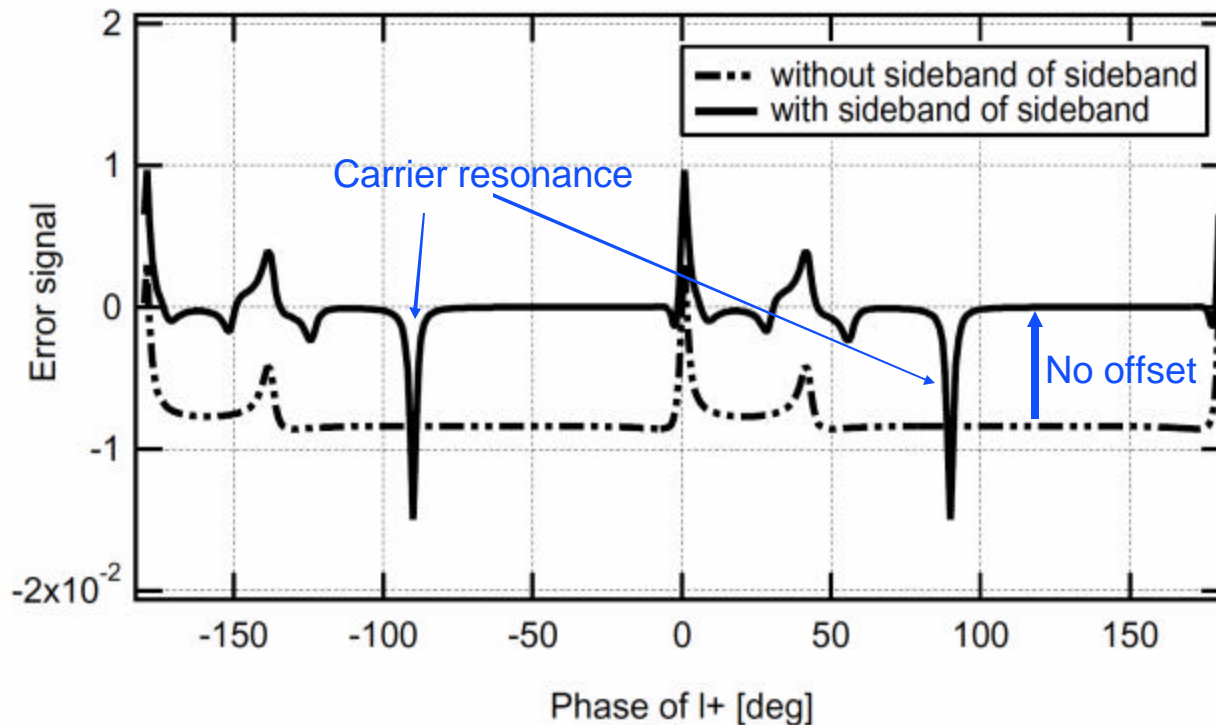
Indeed, when all the DOF are freely swinging, the “confusing phases” also gives a zero average and almost maximum deviations (Among the zero average ones).

Nevertheless it is possible to reach the “best for acquisition” by the following procedure.

1. Adjust  $\theta_2$  to minimize the average.
2. Adjust  $\theta_1$  to maximize the deviation.

# 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

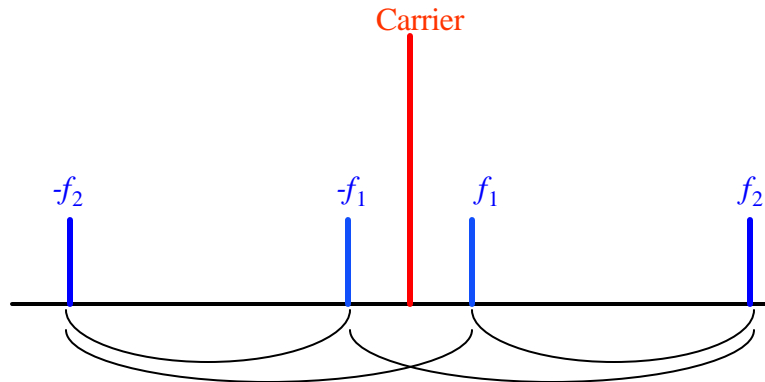
---

- 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)

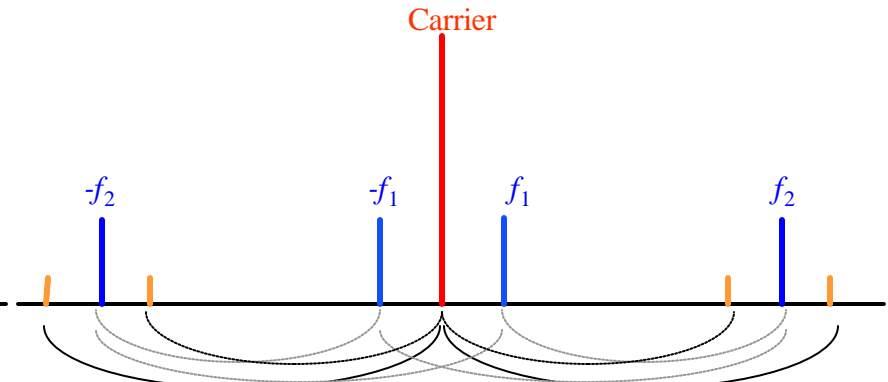


# Disturbance by sidebands of sidebands

Original concept



Real world



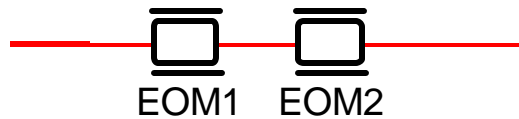
- Sidebands of sidebands are produced by two series EOMs.
- Beats between carrier and  $f_2 \pm f_1$  disturb central part.

Port	Dem. Freq.	$L_+$	$L_-$	$I_+$	$I_-$	$I_s$
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	$f_1 \sim f_2$	-1.7E-3	-3.0E-4	1	-3.2E-2	-1.0E-1
AP	$f_1 \sim f_2$	-6.2E-4	1.5E-3	7.5E-1	1	7.1E-2
PO	$f_1 \sim f_2$	3.6E-3	2.7E-3	4.6E-1	-2.3E-2	1

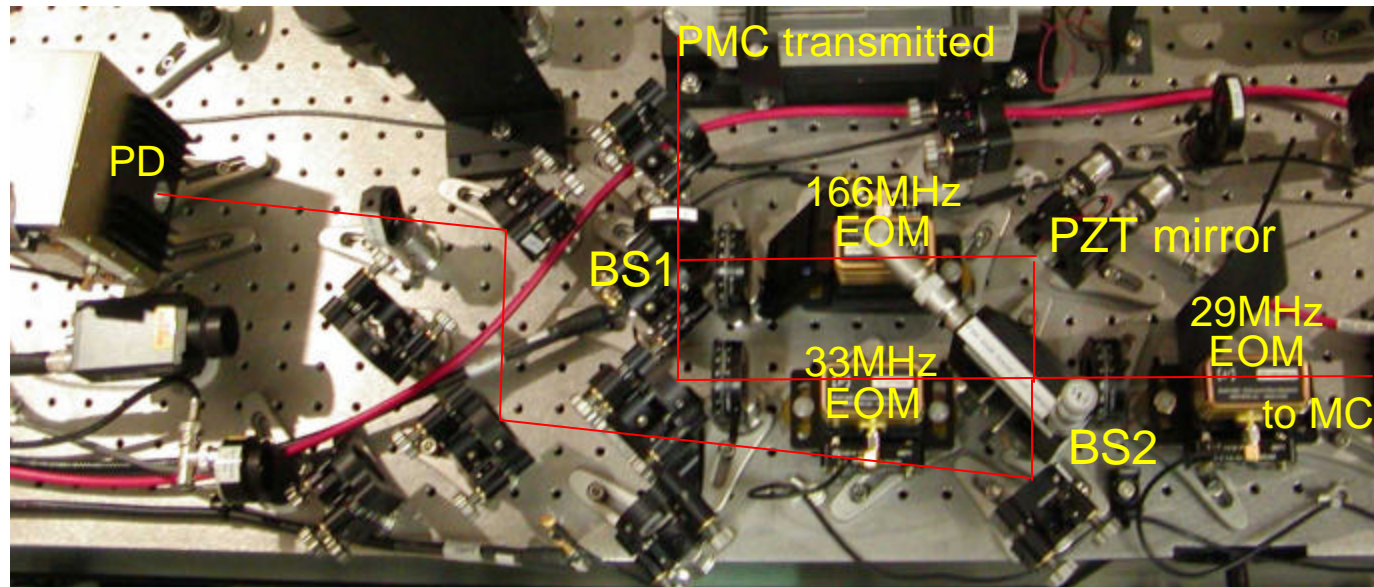
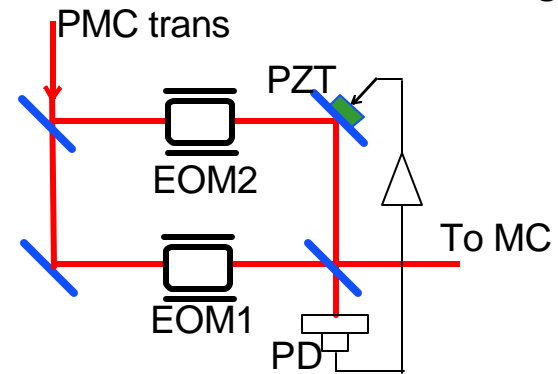
Port	Dem. Freq.	$L_+$	$L_-$	$I_+$	$I_-$	$I_s$
SP	$f_1$	1	-1.4E-8	-1.2E-3	-1.3E-6	-6.2E-6
AP	$f_2$	1.2E-7	1	1.4E-5	1.3E-3	6.5E-6
SP	$f_1 \sim f_2$	7.4	-3.4E-4	1	-3.3E-2	-1.1E-1
AP	$f_1 \sim f_2$	-5.7E-4	32	7.1E-1	1	7.1E-2
PO	$f_1 \sim f_2$	3.3	1.7	1.9E-1	-3.5E-2	1

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

Series EOMs  
with sidebands of sidebands

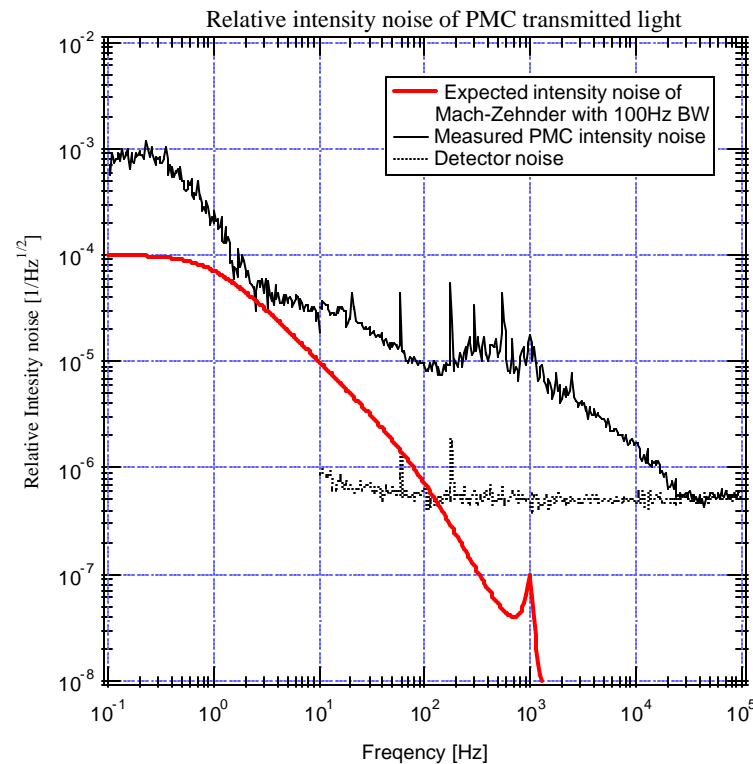


Mach-Zehnder interferometer  
no sidebands of sidebands from beginning



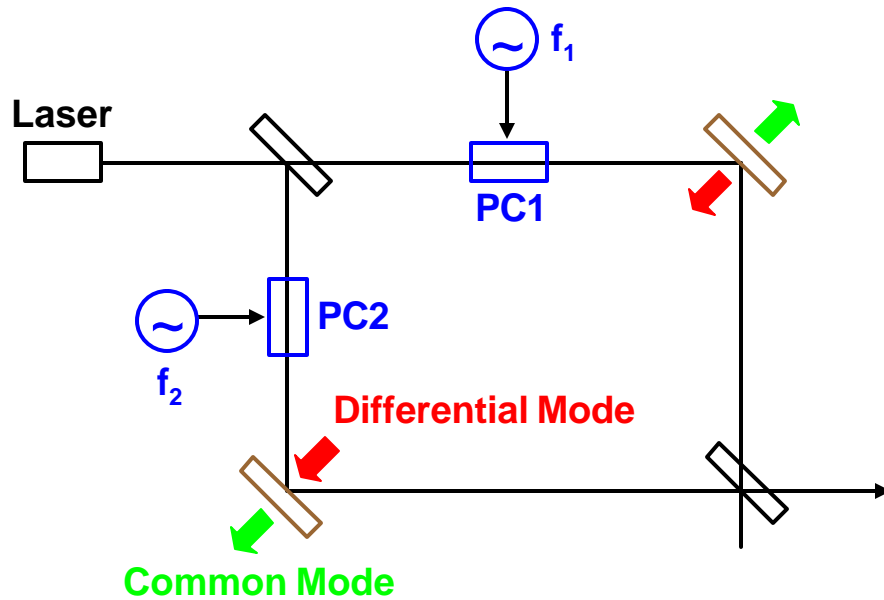
# Additional noise caused by M-Z interferometer

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

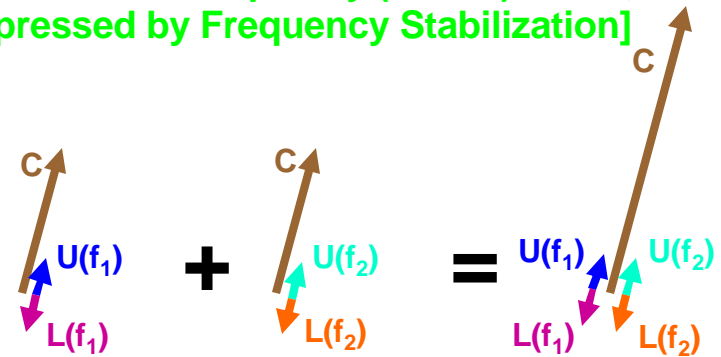


# Two Effects of Mach Zehnder Mirror Motion

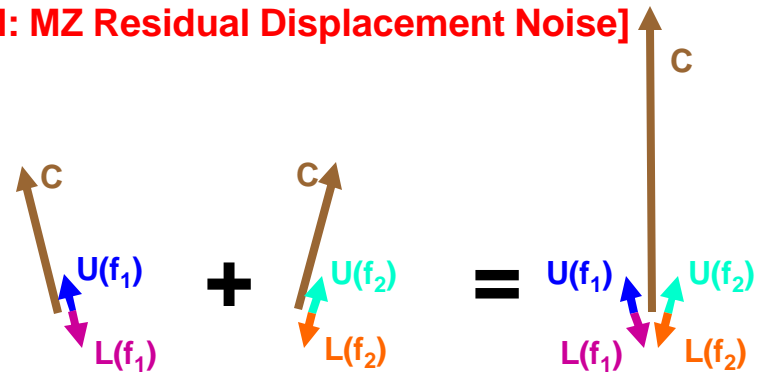
Seiji Kawamura,  
following suggestion by Matt Evans



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



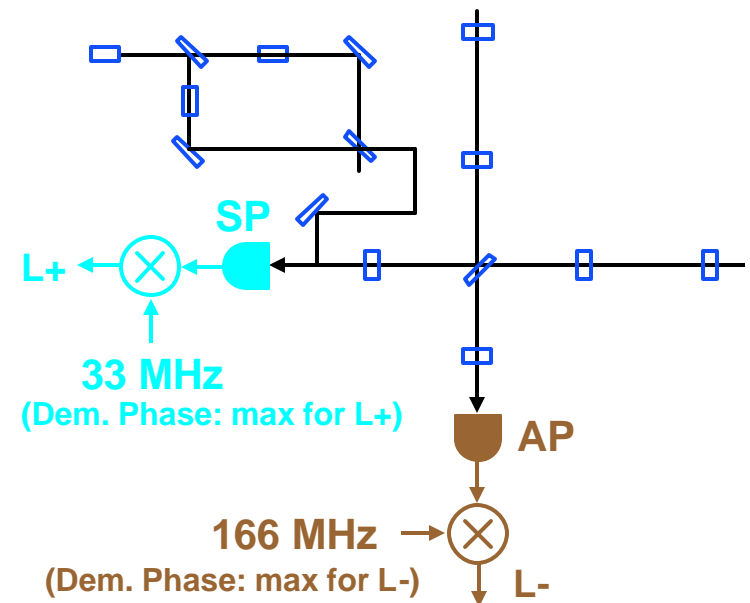
[DM: MZ Residual Displacement Noise]





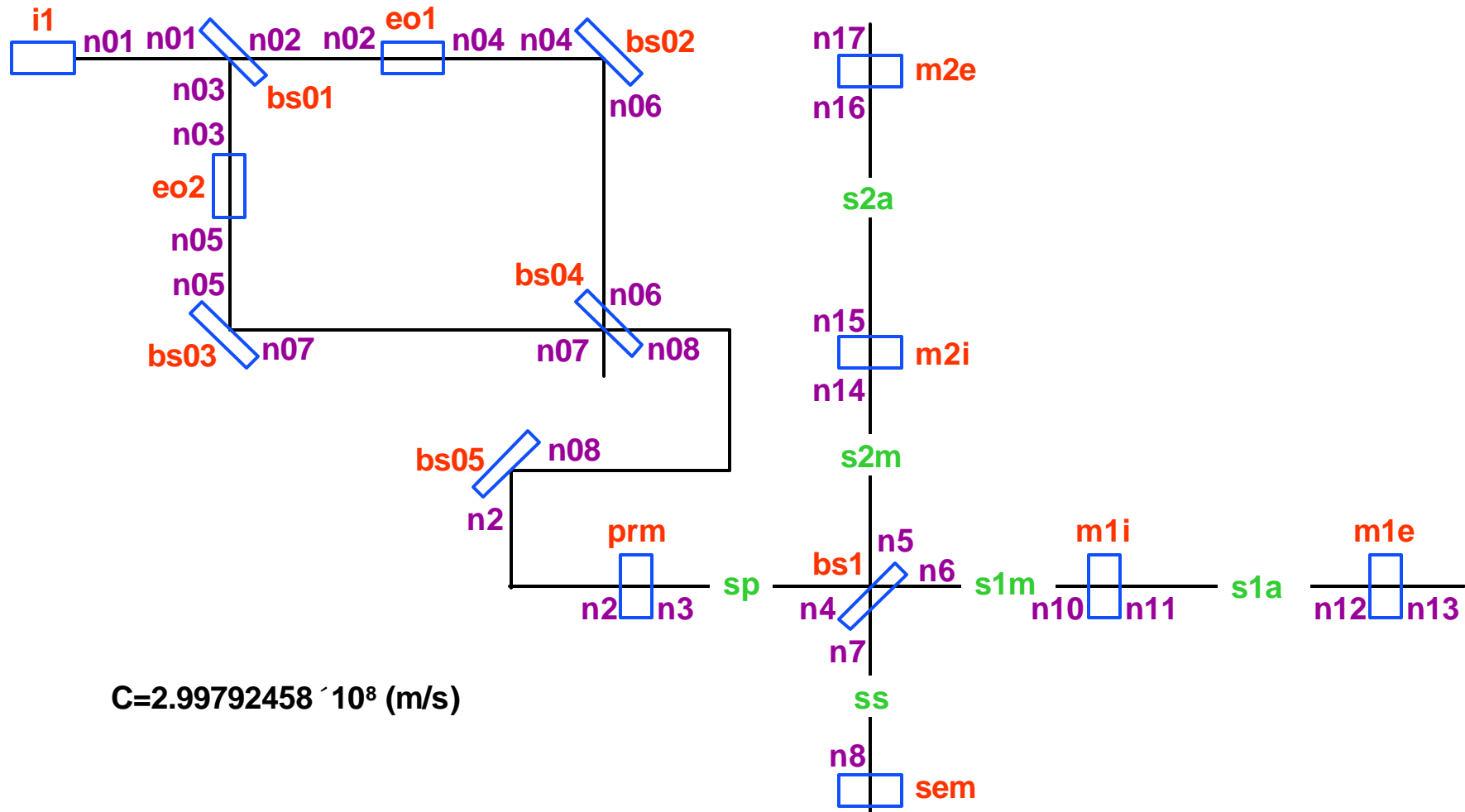
# Two Mechanisms of the MZ Noise for the Detuned RSE Interferometer

- 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



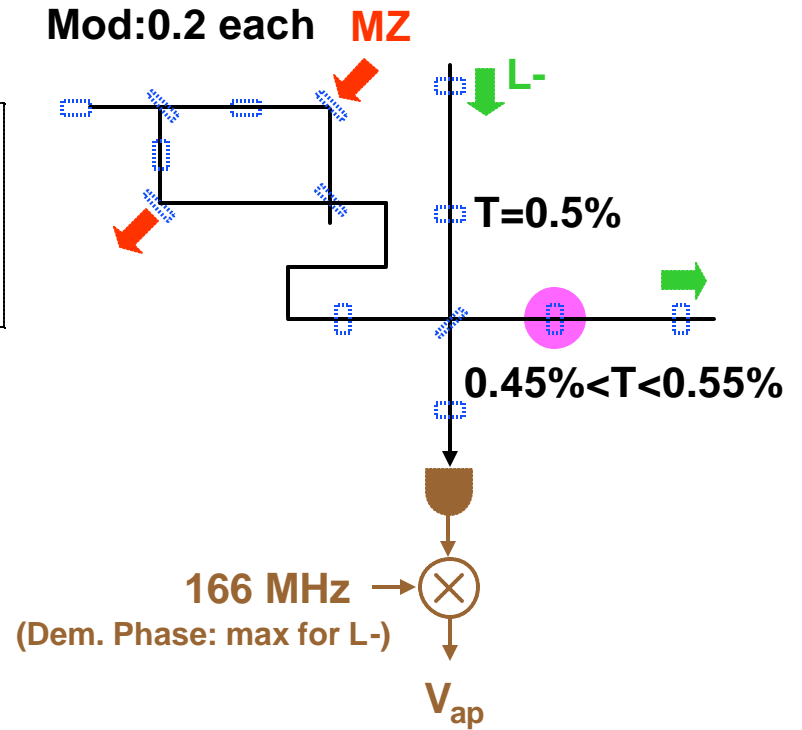
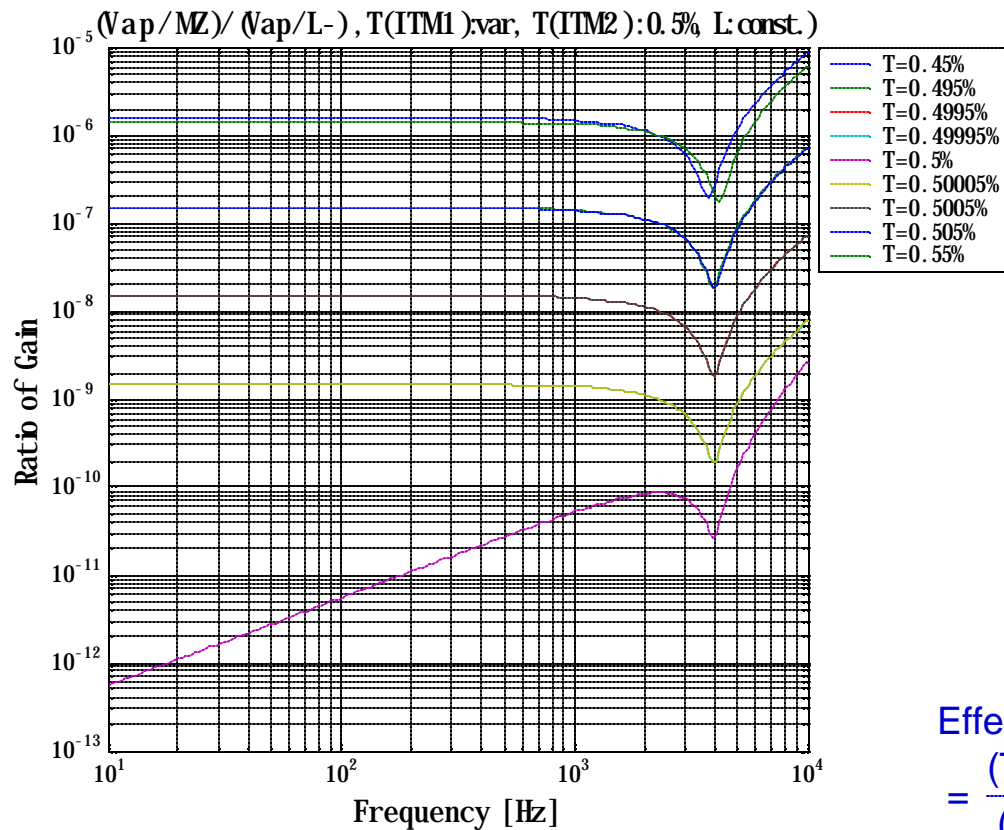


# Simulation using FINESSE



$C=2.99792458 \times 10^8 \text{ (m/s)}$

# Direct mechanism

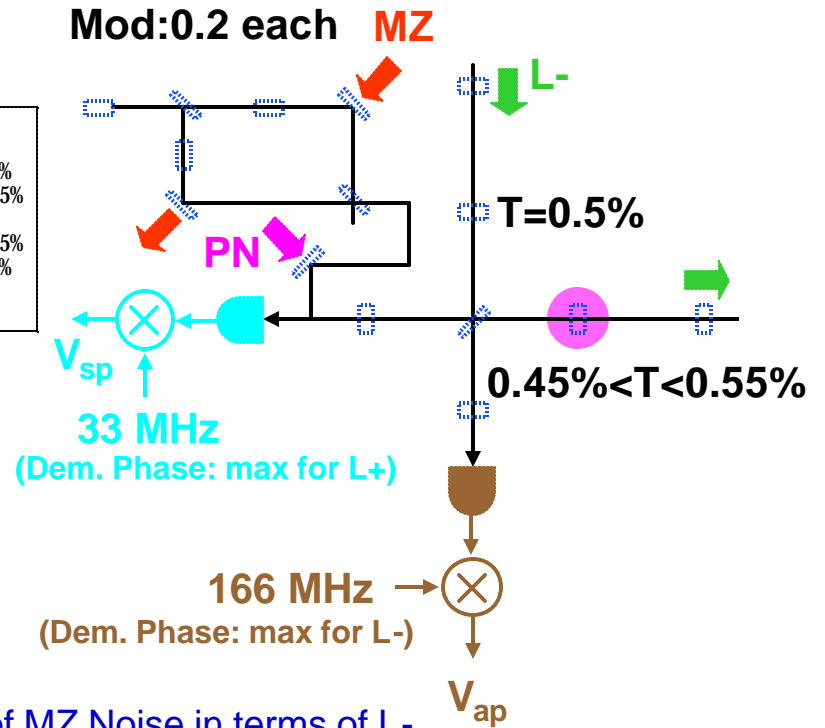
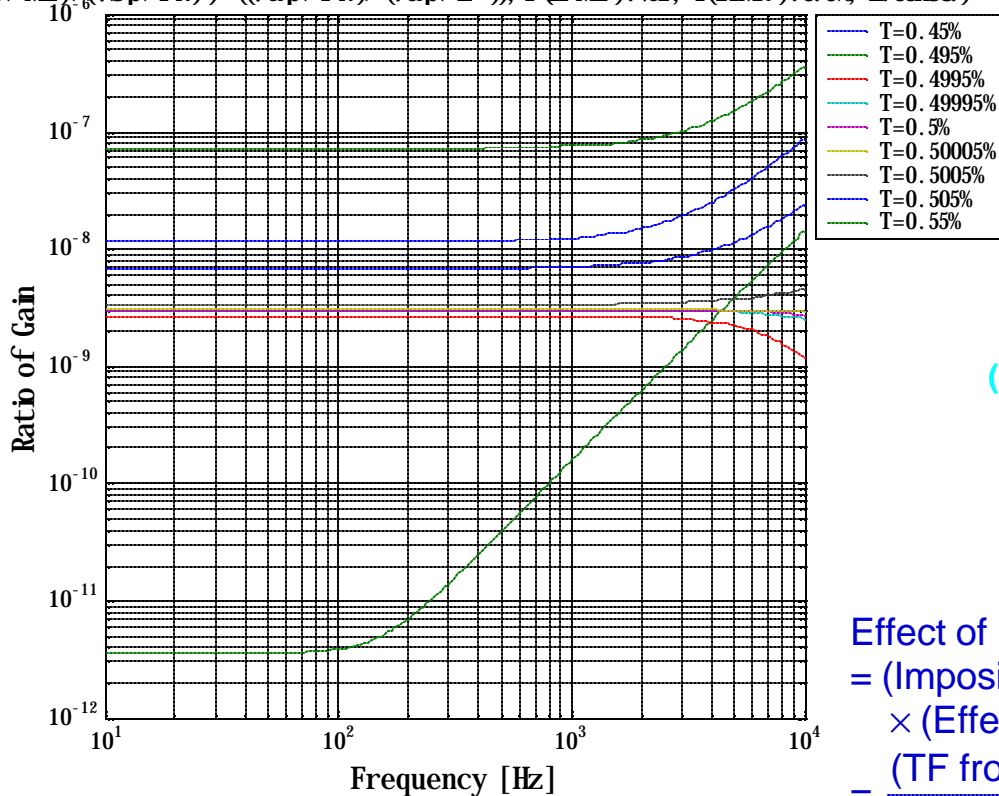


Effect of MZ Noise in terms of L-

$$= \frac{\text{(Transfer Function from MZ to V}_{ap}\text{)}}{\text{(Transfer Function from L- to V}_{ap}\text{)}}$$

# Via Frequency Stabilization

$V_{sp}/MZ) / (V_{sp}/PN) * (V_{ap}/PN) / (V_{ap}/L-), T(TM1):var, T(TM2):0.5\%, L:const.)$



Effect of MZ Noise in terms of L-  
 = (Imposition of MZ on PN by Frequency Stabilization)  
 × (Effect of PN in terms of L-)  

$$= \frac{(\text{TF from MZ to } V_{sp})}{(\text{TF from PN to } V_{sp})} \times \frac{(\text{TF from PN to } V_{ap})}{(\text{TF from L- to } V_{ap})}$$

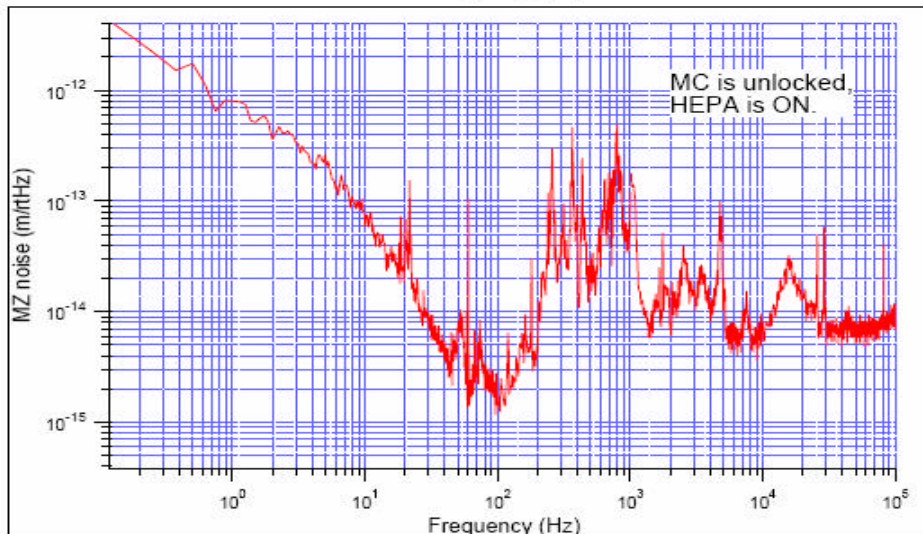
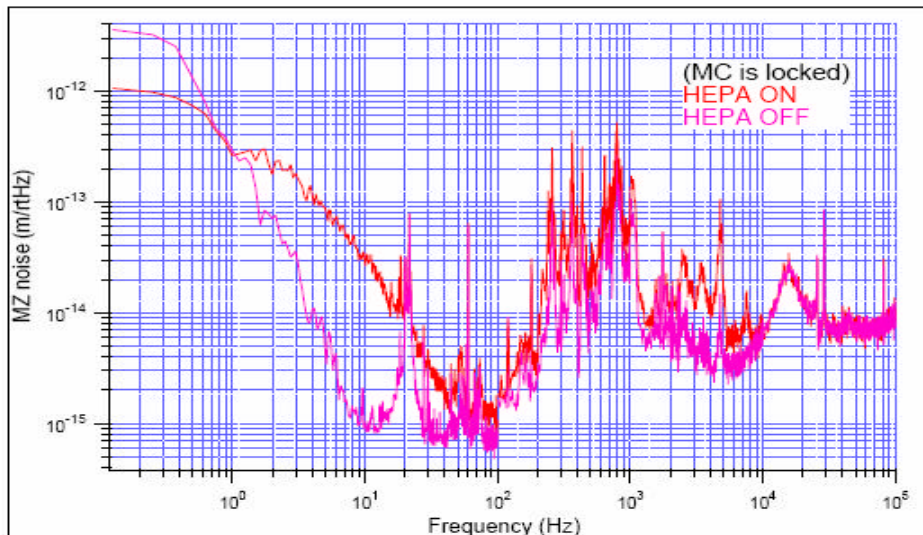


# Quick Results

---

- 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



- No evidence for MC -> FSS path.
- 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 (I-, I+, Is) first, with blocked arms
  - » I- 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!***