PRFPMI locking assessment as MIMO system

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Abstract

- Report on my recent experimental activities

- The problem of the lock acquisition of PRFPMI is the two as below
  1. We cannot reduce the CARM offset due to the CARM couplings to PRCL and MICH
  2. We cannot hand off the CARM control from ALS to RF (= REFL 1f)

- The first problem (CARM offset problem) was solved by
  - Improving CARM ALS control for higher control bandwidth

- The second problem (Handing off problem) is not solved yet, currently working on
  - Model the servo as MIMO system that has cross-coupling between 4 DoFs
  - Using Finesse (Numerical simulation) to model the plant

- In this seminar, I will show the details for the two problem. I would appreciate if you share your opinions, especially for the second, handing off problem.

Contents

- Introduction of our PRFPMI
- First problem: PRMI 3f-locking breaks during CARM offset reduction
- Second problem: Breaks of locking during handing off CARM control to RF
- Summary

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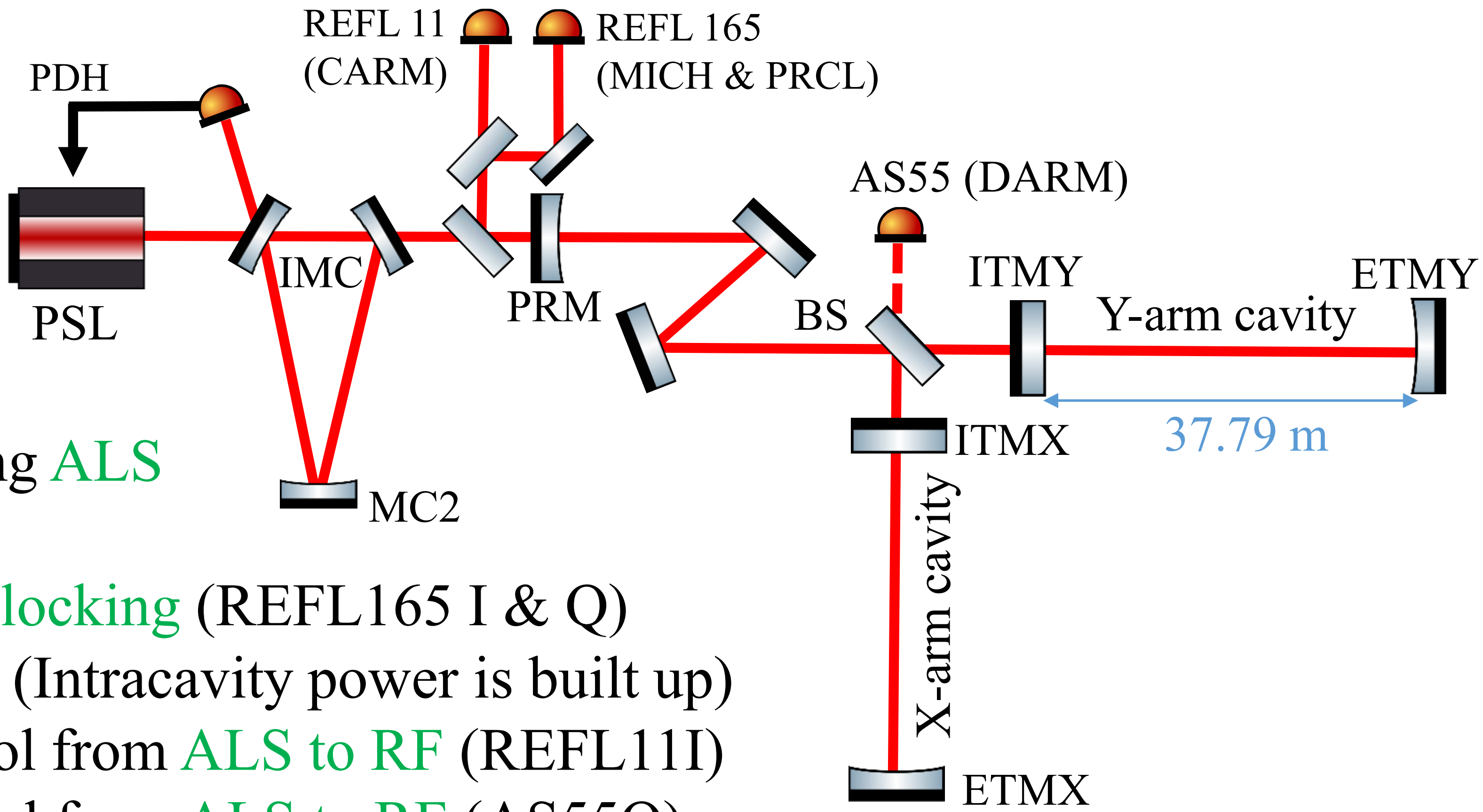
Experimental setup



- Phase modulation
  - $f_1 = 11$ MHz
  - $f_2 = 55$ MHz ($= 5f_1$)
- Lock acquisition procedures are
  1. Lock CARM and DARM using ALS
  2. Apply CARM offset
  3. Lock MICH and PRCL by 3f-locking (REFL165 I & Q)
  4. Reduce the CARM offset to 0 (Intracavity power is built up)
  5. Handing off the CARM control from ALS to RF (REFL11I)
  6. Handing off the DARM control from ALS to RF (AS55Q)
- Actuators for each DoF
  - CARM: MC2 ((IMC length), PSL-IMC PDH loop is on, so the PSL frequency is actuated)
  - DARM: ETMX – ETMY
  - MICH: -PRM + $\sqrt{2}$ BS
  - PRCL: PRM

Note: Other sensors are there (such as POP, AS DC, BHD), but abstracted because they are not used in today's seminar

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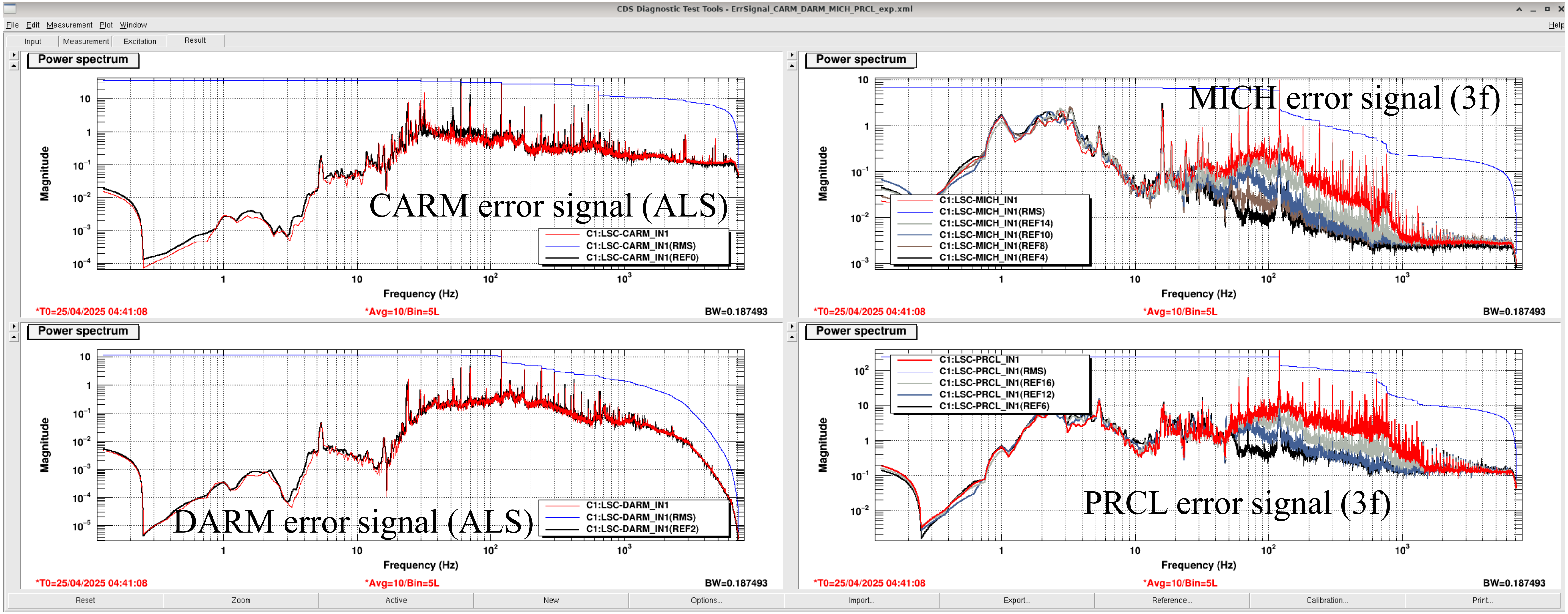
Problem in the CARM offset reduction

As reducing CARM offset, Arm motion (CARM and DARM) comes to couple to PRMI motion (PRCL and MICH)
Then, PRCL and MICH error signal are contaminated (10 Hz – 1 kHz)



CARM High Bandwidth with hierarchy control

Our strategy so that CARM motion does not mix into the PRCL and MICH is increasing the control bandwidth of ALS CARM and getting higher gain at 10 Hz to 1 kHz

For this purpose, we installed fast path in the ALS CARM control. That actuates the PSL frequency

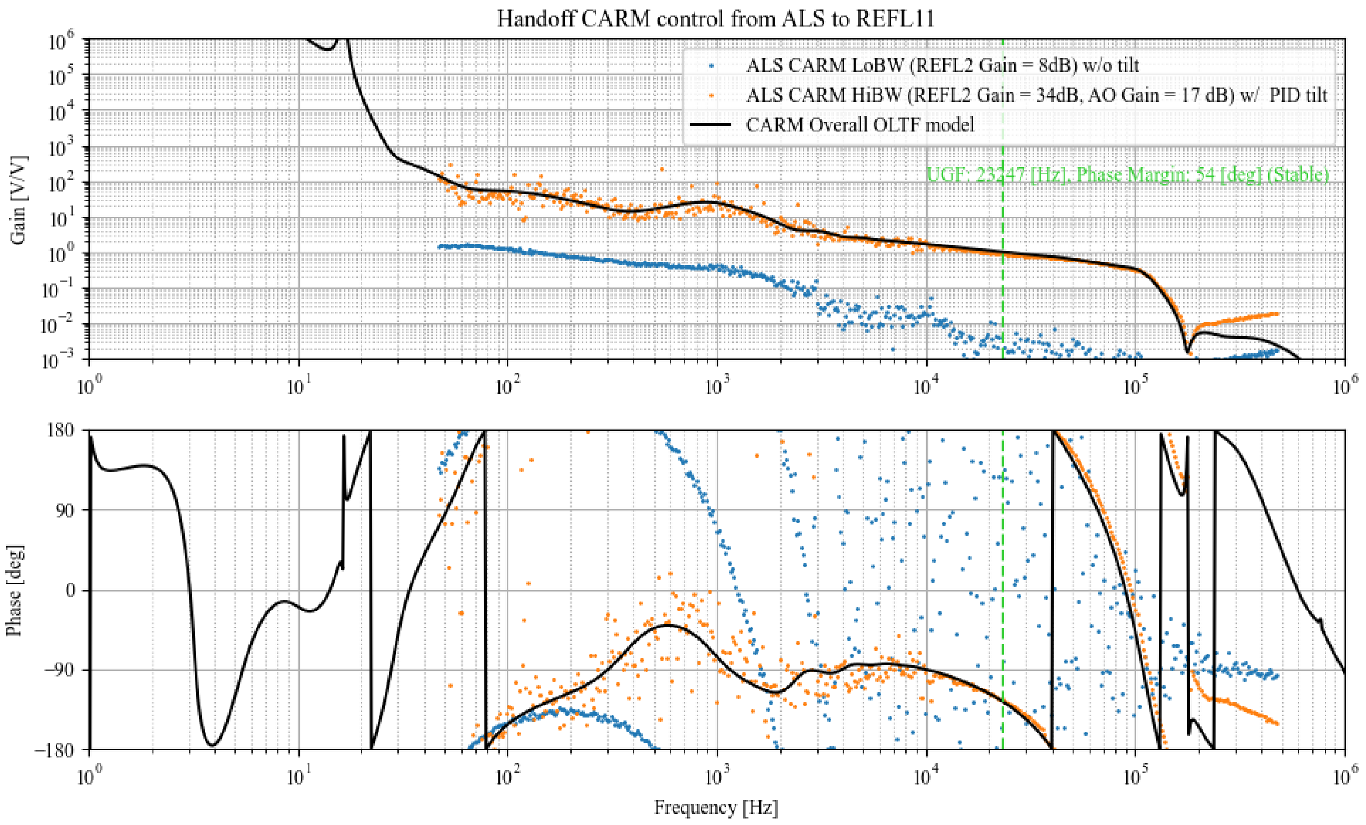
- Low frequency (< 100 Hz): IMC length is actuated, which gives us large dynamic range
- High frequency (>100 Hz): PSL frequency is actuated, which gives us fast control

Right graph shows open-loop transfer function of ALS CARM control

Blue : Low bandwidth (150 Hz)

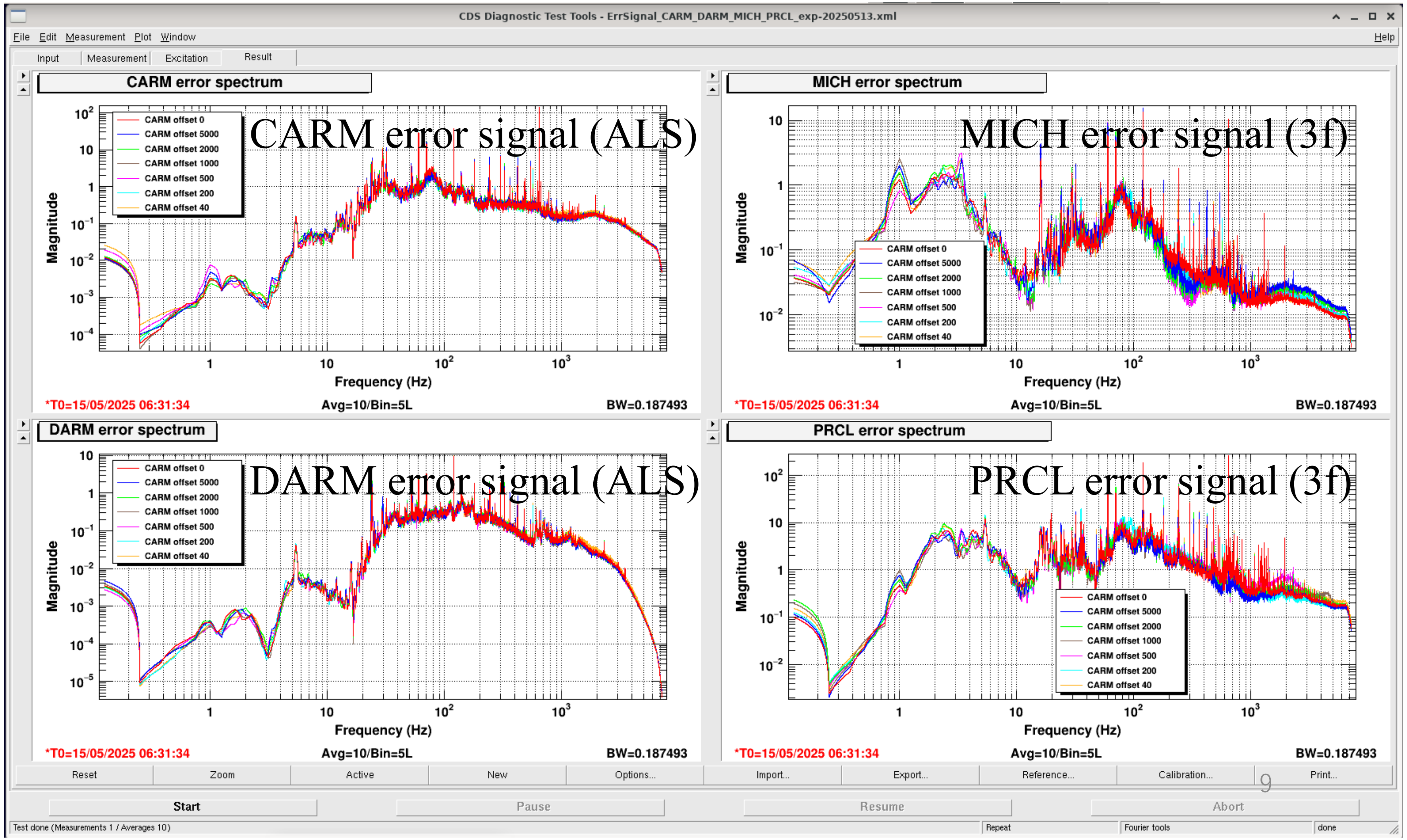
Orange : High bandwidth (23 kHz)

Black : High bandwidth, Fit



Stable CARM offset reduction with ALS CARM High bandwidth control

After the improvement of the CARM control high bandwidth from 150 Hz to 20 kHz, the PRCL and MICH error signal contamination is suppressed !



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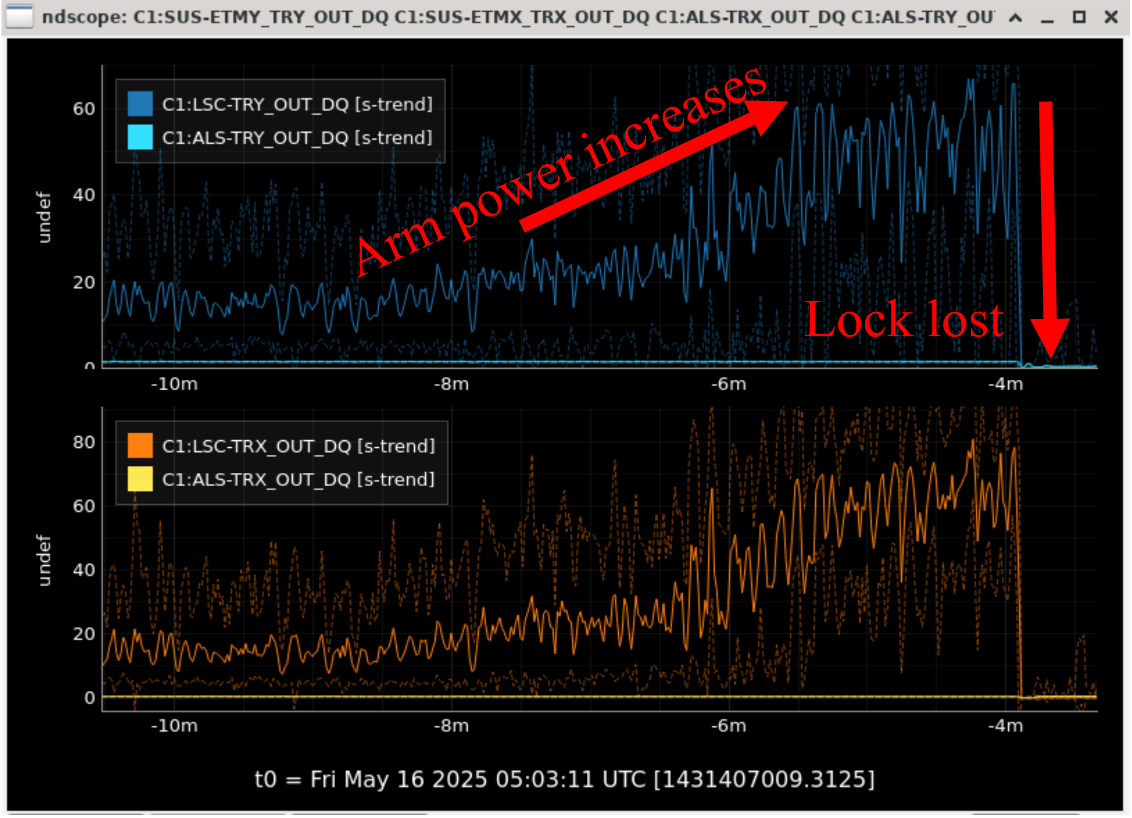
Problem in the handing off CARM control to RF from ALS

- Current problem for locking acquisition of PRFPMI in 40m is
  - Cannot hand off the CARM control from ALS to RF
  - In this handoff, the intracavity power increases and the plant response changes (The cutoff frequency changes from "Arm pole" (~ 4 kHz) to "CARM-couple cavity pole" (~100 Hz))

- If the RMS of the residual noise is more than CARM pole frequency, we do not see a significant power build up and we see the fast power up-and-down as shown in the right figure

- This wild intracavity power fast fluctuation causes to change the optical gain response wildly 👎 (Arm pole↔CARM pole)



Arm transmission power build-up during CARM control handoff (Top: Y-ARM, Bottom: X-ARM)

Finesse simulation for the optical gain frequency response

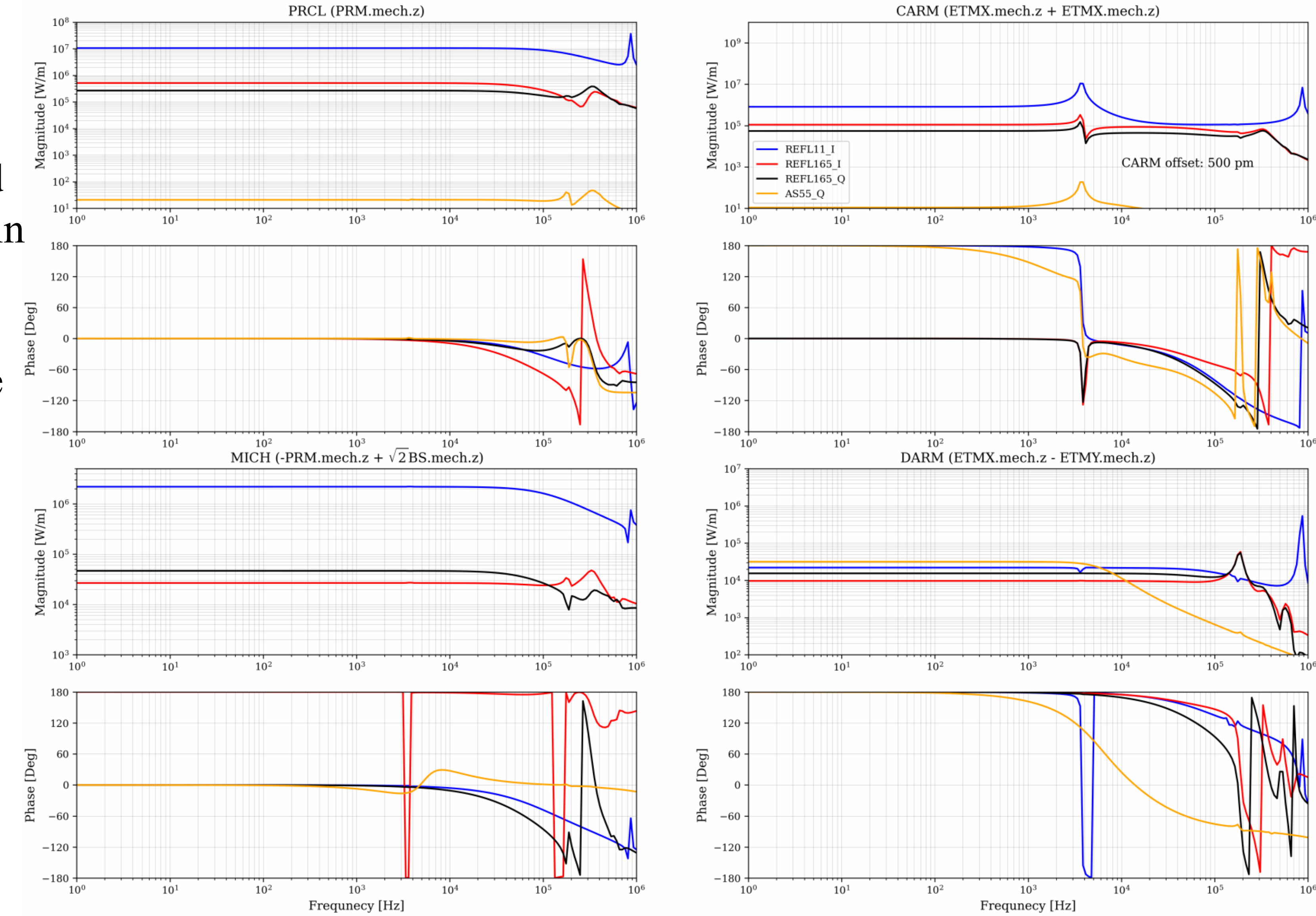
Finesse 3

Using Finesse, I **numerically simulated** the frequency response of the optical gain for 4 sensors.

The right figure has 16 plots to show the frequency response of 4 sensors listed below to the 4 DoF excitations

Blue : REFL11_I (CARM signal)
Red : REFL165_I (PRCL signal)
Black : REFL165_Q (MICH signal)
Yellow: AS55_Q (DARM signal)

The animation shows **the CARM offset reduction (500 [pm] → 0 [pm])**



Arm cavity pole (~4 kHz) to CARM-coupled cavity pole (~100 Hz)

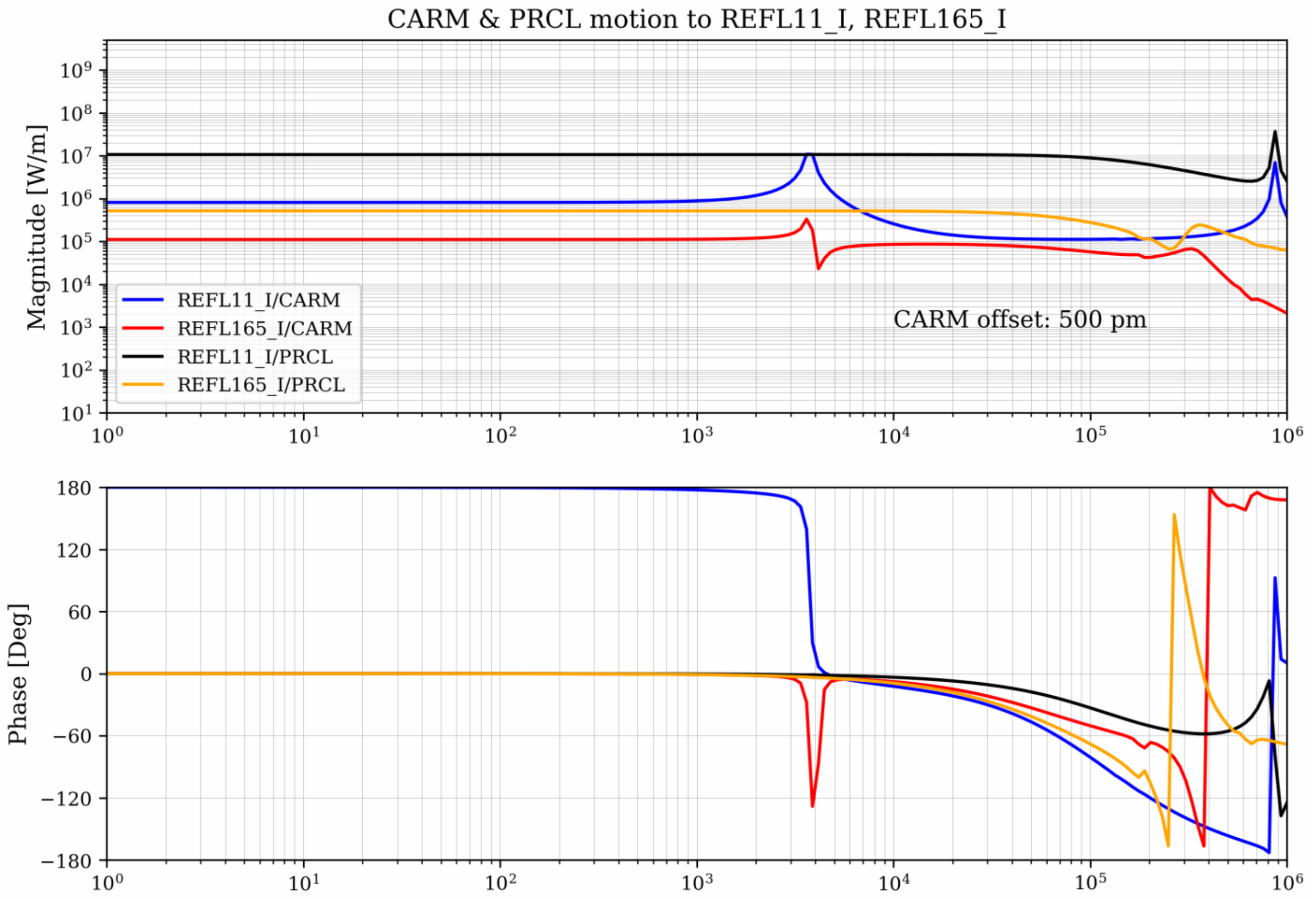
Focusing on the common mode (CARM and PRCL)

Blue : REFL11_I response to CARM excitation
Red : REFL165_I response to CARM excitation
Black : REFL11_I response to PRCL excitation
Yellow: REFL165_I response to PRCL excitation

One can find

- **Pole frequency moves to the lower** as reducing CARM offset (see the blue curve)
- **REFL165 I is robust to the CARM offset changing**, which is the reason why we use 3f locking in the lock acquisition

This plant response changing happens < 10 kHz.
In order to minimize negative effect, our strategy (Increasing the control bandwidth of CARM ALS to >10 kHz from 150 Hz) works, and UGF is set on robust area.



Judgement of the stability of the system (Open loop and Closed loop)

If the SISO (Single Input Single Output) case, it is enough to see the phase margin at the unity gain frequency of open-loop transfer function as we all know well. (See the Right of the graph, Bode plot)

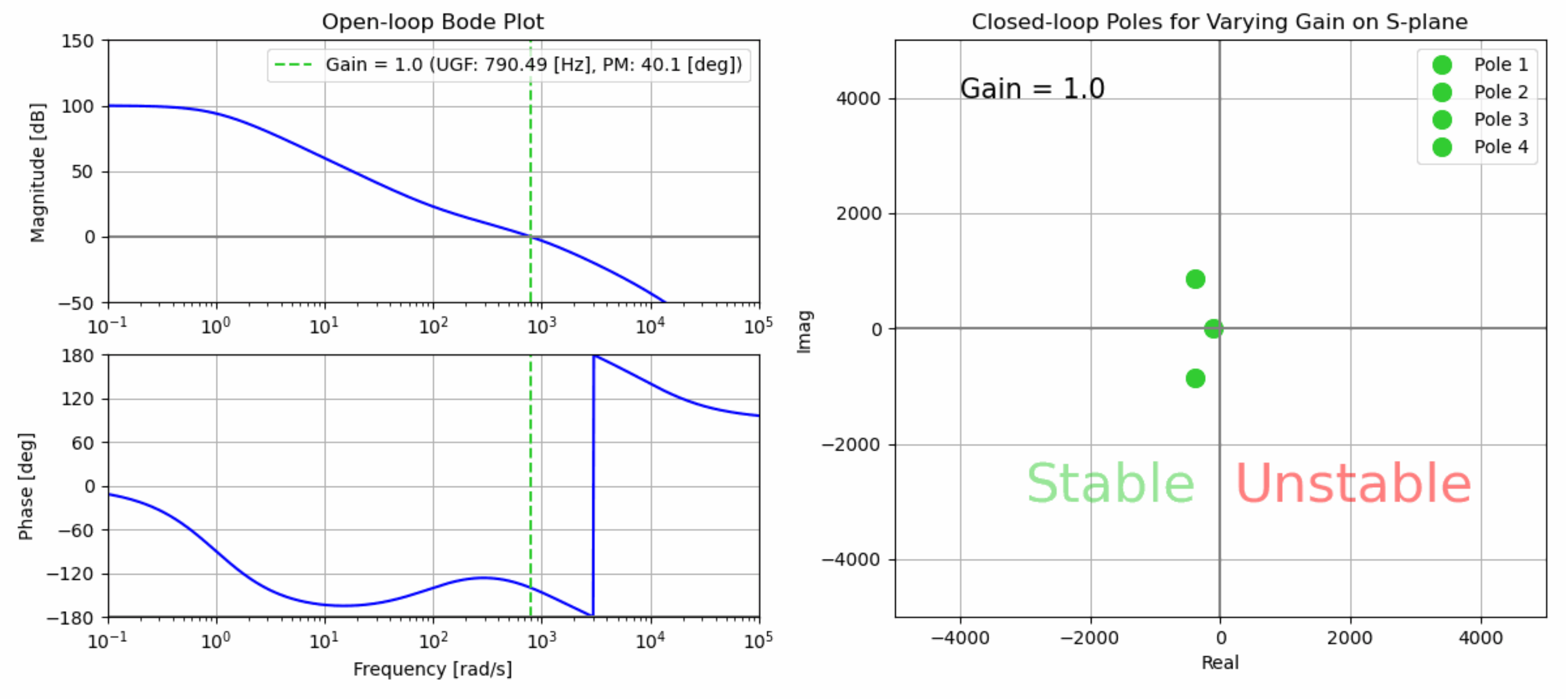
However, in the MIMO case such that it has cross-coupling, **<u>we need to see the closed-loop transfer function</u>** and make the servo so that all poles of CLTF is on the left-hand side of the S-plane. (See the left of the graph, S-plane)

Open-loop transfer function:

$$\mathbf{G} = \mathbf{C} \cdot \mathbf{P}$$

Closed-loop transfer function:

$$\mathbf{T} = (\mathbf{I} + \mathbf{G})^{-1}$$



OLTF(Left) and CLTF (Right) with a simple loop example

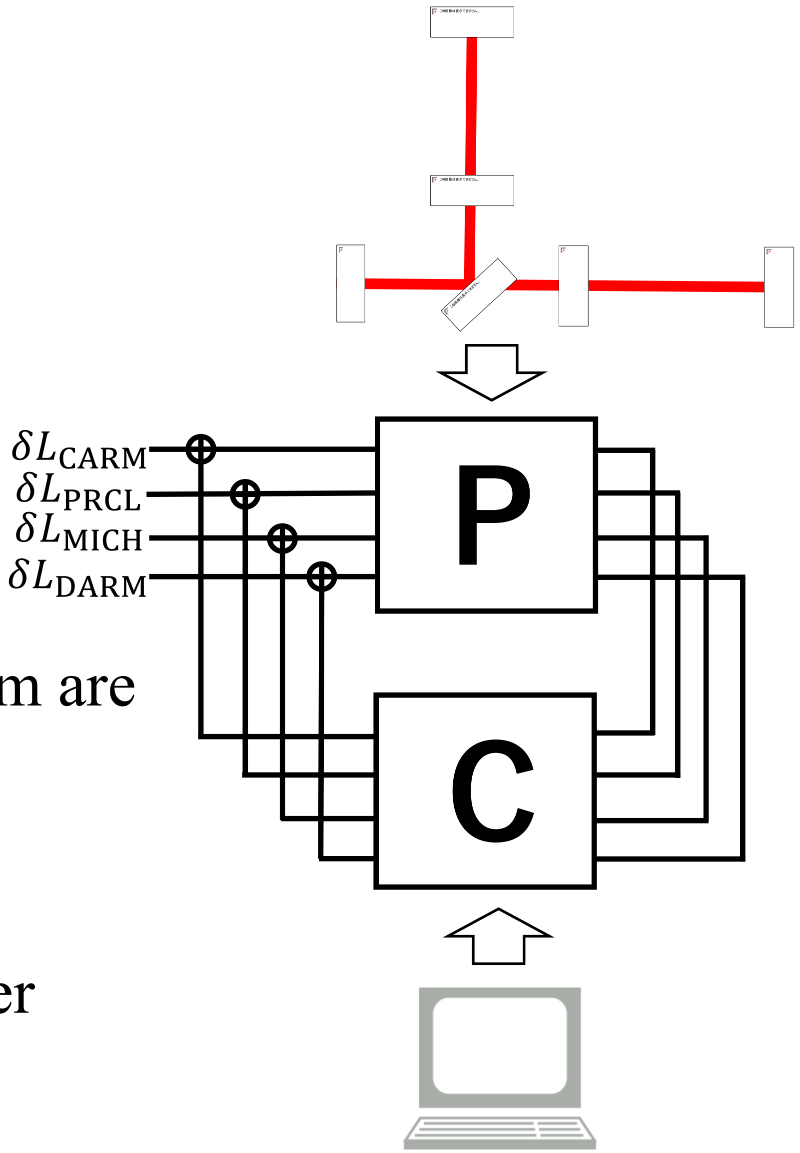
Diagram for MIMO system

- P: Plant (PRFPMI's sensor)
  - REFL11_I
  - REFL165_I
  - REFL165_Q
  - AS55_Q
- C: Controller (CDS, Moku, Analog Circuit)

- PRFPMI is coupled cavity system, so all degrees of freedom are coupled, and no sensor cannot sense only one DoF, which makes non-zero off-diagonal components of "P" matrix

- For designing servo, we need all zpk of Plant and Controller

$$\mathbf{P} = \begin{pmatrix} P_{11} & P_{12} & P_{13} & P_{14} \\ P_{21} & P_{22} & P_{23} & P_{24} \\ P_{31} & P_{32} & P_{33} & P_{34} \\ P_{41} & P_{42} & P_{43} & P_{44} \end{pmatrix} \quad \mathbf{C} = \begin{pmatrix} C_{11} & 0 & 0 & 0 \\ 0 & C_{22} & 0 & 0 \\ 0 & 0 & C_{33} & 0 \\ 0 & 0 & 0 & C_{44} \end{pmatrix}$$

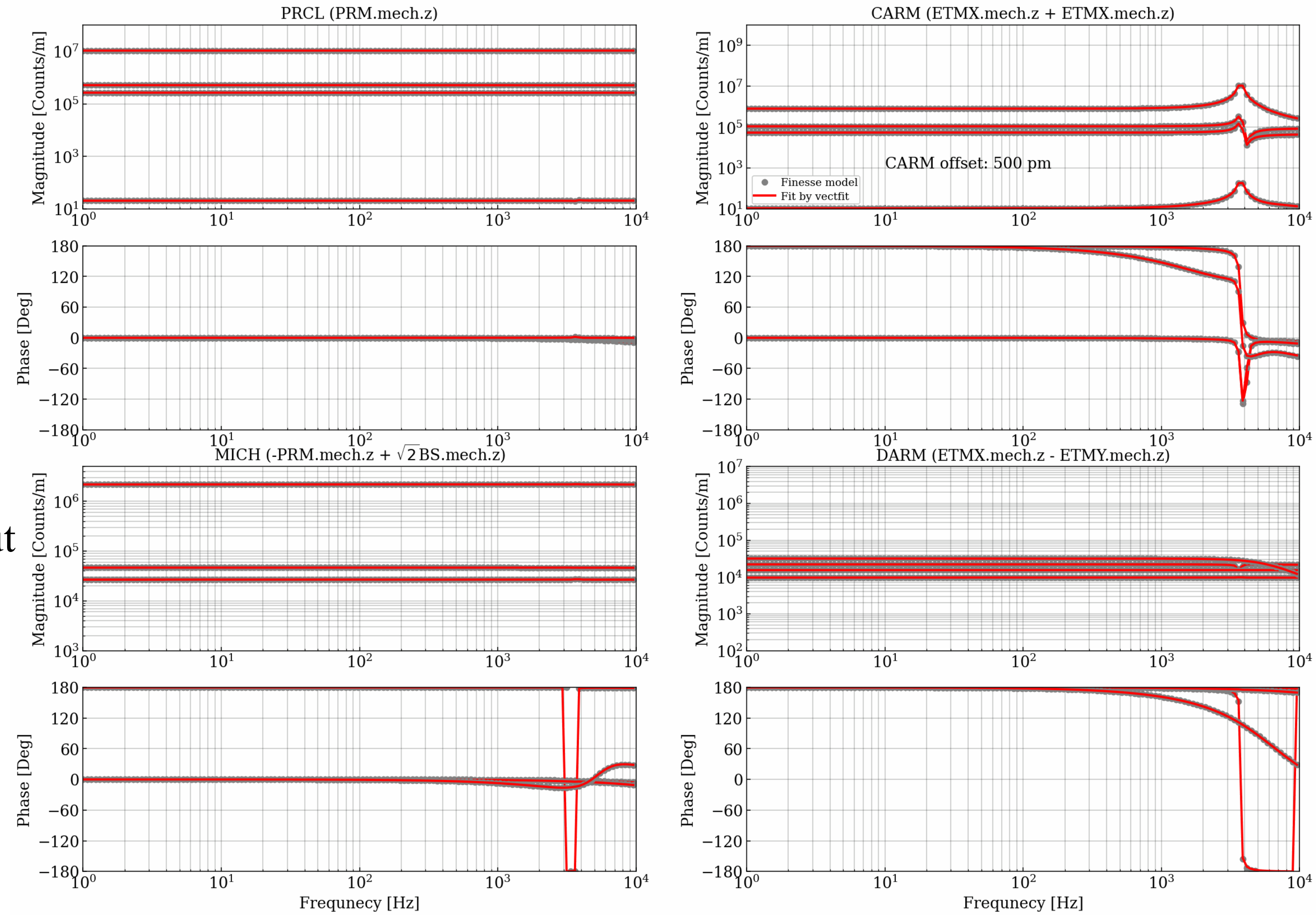


Vector fitting (for getting zpk from numerically modeled TFs)

Gray marker: Numerical simulation
Red curve　: Fitting result

Vector fitting enable us to **extract (complex conjugate) zpk from numerically modeled transfer function**

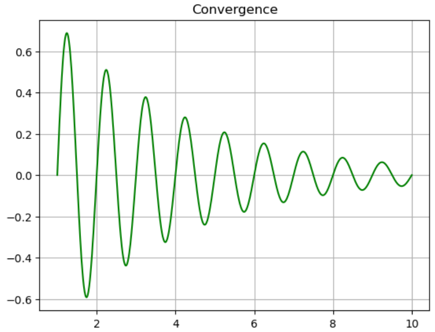
LISO developed by G.H. have been used for long time. It runs in Matlab but I used python this time.

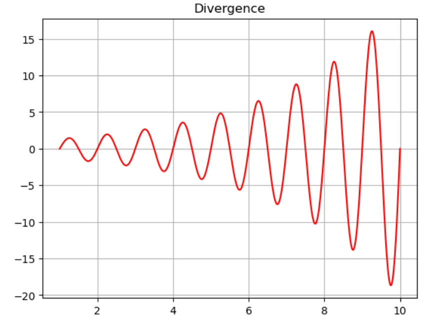


Currently designing servo...

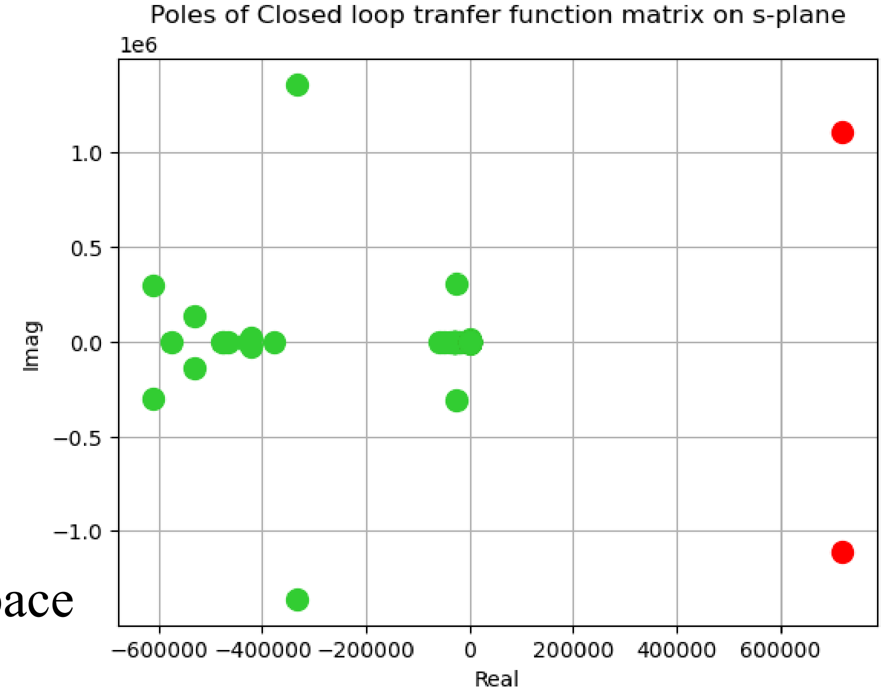
- Finesse simulation and vector fitting gave the zpk of the plant (P matrix)
- We can get all zpk of controllers (C matrix) from out device
- I found that there are 188 poles in our system (Right graph)
- All poles needs to be on left side of the S-plane for stable system
  - For that purpose, I am designing the servo now.
- To be able to show human interpretable values, I will convert the TFs to time domain (Inverse Laplace Transform) and see the divergence and convergence

Time domain





Laplace transform



State space

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Summary

- Reported recent experimental works
- Two problems are introduced. One is solved. The other is not yet
  - PRCL and MICH were contaminated when reduced CARM offset, but it was suppressed by increasing the CARM control bandwidth
  - Failing to hand off CARM control from ALS to RF
    - All 4 degrees of freedom are coupled, so for modeling the servo, it is necessary to see the closed-loop transfer function
    - Currently designing the CARM servo so that all poles are on left-side in state space

End