LIGO LIVINGSTON
OBSERVATORY

FILTER CAVITY ANGULAR CONTROL SYSTEM FOR GREEN AUXILIARY BEAM

Tomris İlkim Doğan

CALTECH LIGO SURF
SUMMER 2025

Mentors: Adam Mullavey
Begüm Kabagöz

Middle East Technical University
Electrical and Electronics Engineering Department

LIGO-T2500287

TABLE OF CONTENTS

QUANTUM NOISE

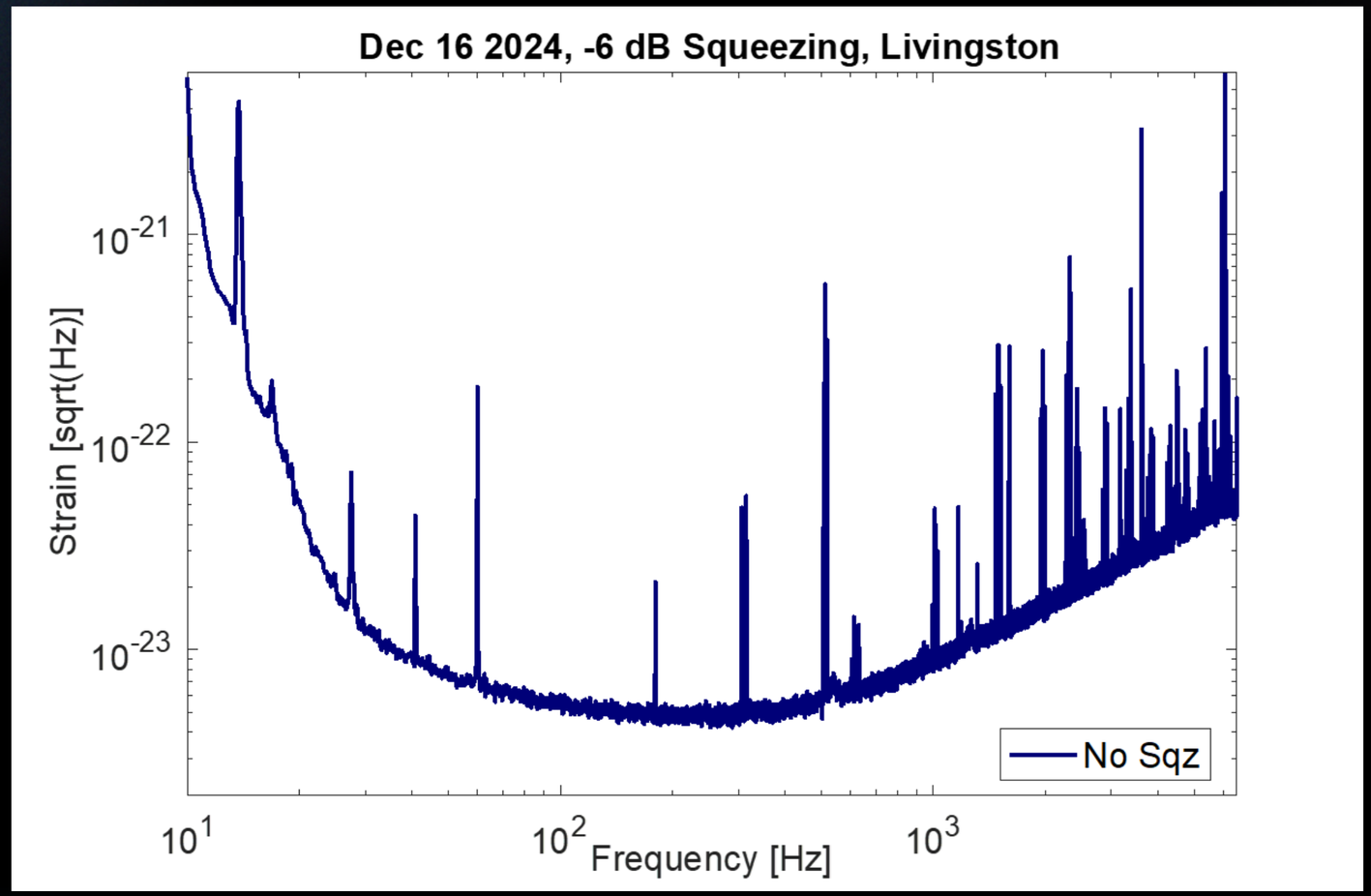
Quantum noise = fundamental measurement limit in LIGO

AMPLITUDE QUADRATURE

radiation pressure noise (dominant at low freq)

PHASE QUADRATURE

shot noise (dominant at high freq)

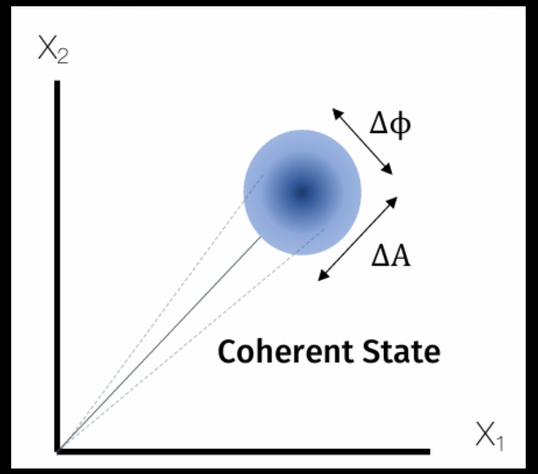


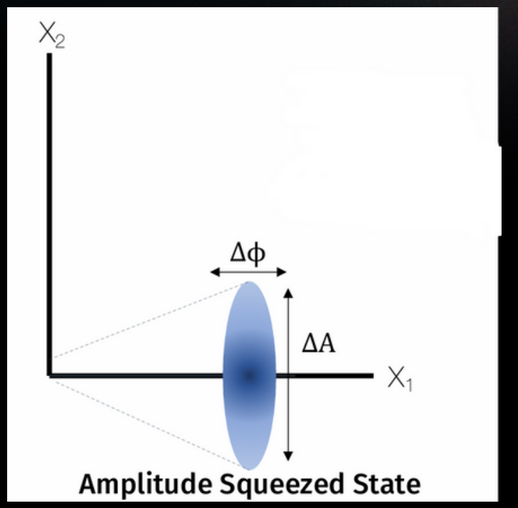
SQUEEZING

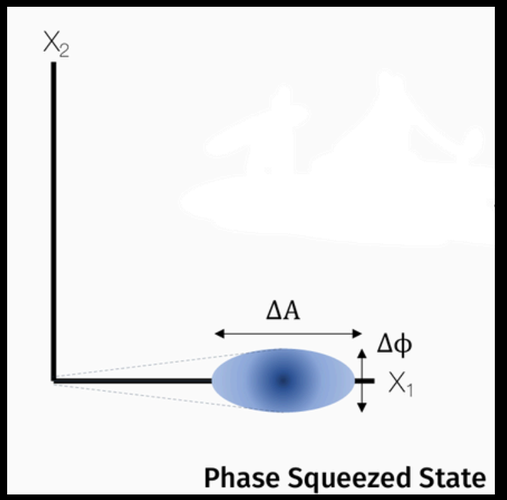
- Coherent state: equal uncertainty in both quadratures
- Squeezed state: reduce uncertainty in one quadrature at the cost of the other

$$E = \sin(\omega t + \phi) = \sin\phi\cos(\omega t) + \cos\phi\sin(\omega t)$$
$$= X_1\cos\phi + X_2\sin\phi$$

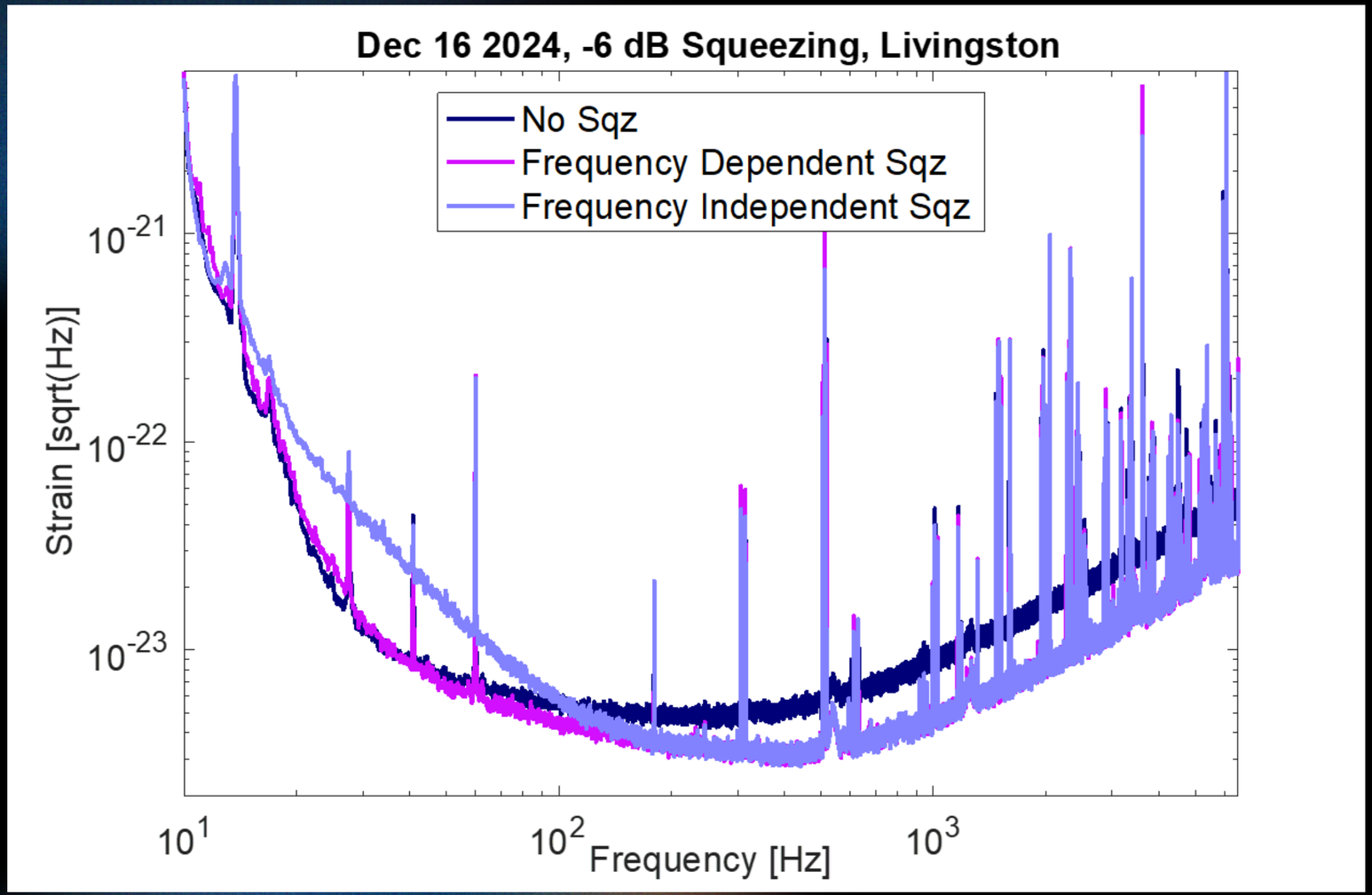
$$\Delta X_1 \, \Delta X_2 \geq \frac{1}{4}$$



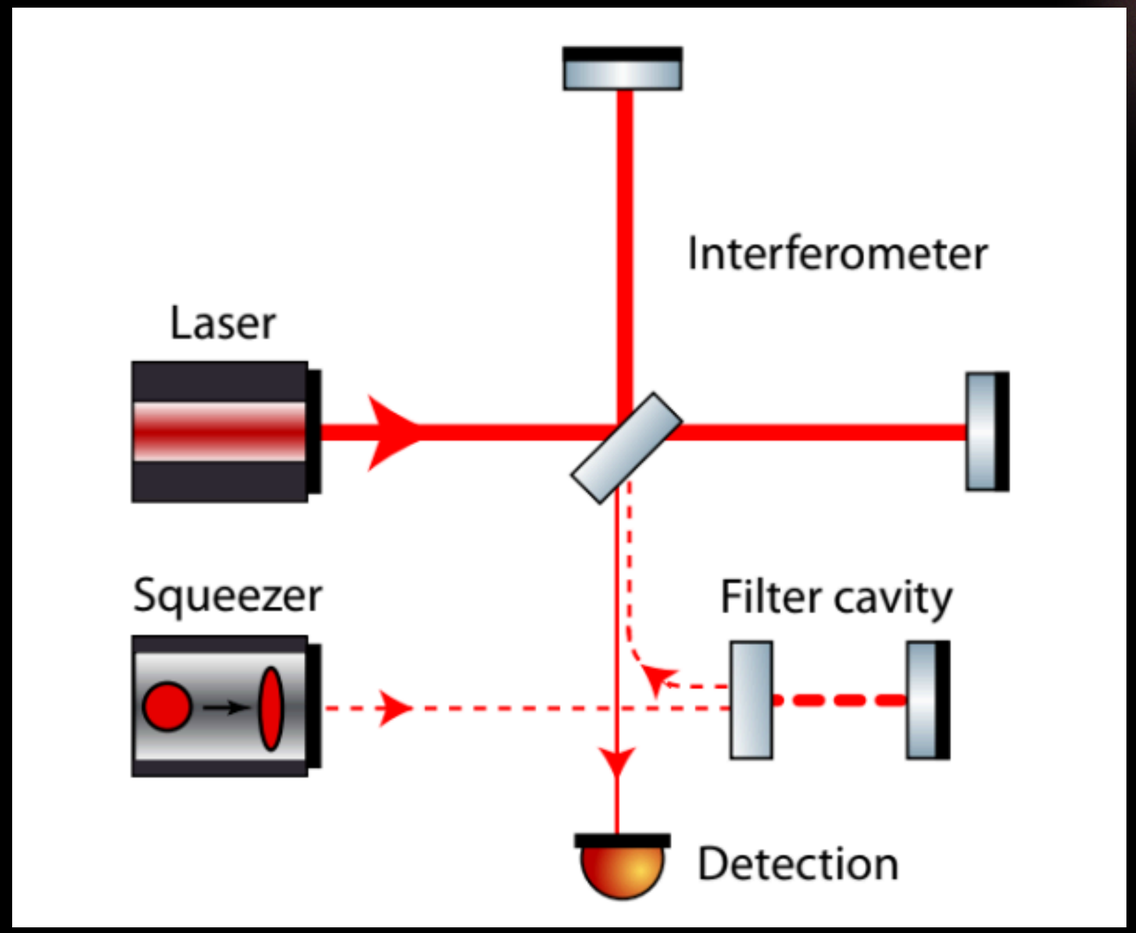




FREQUENCY DEPENDENT SQUEEZING



LIGO-T2500287



FILTER CAVITY

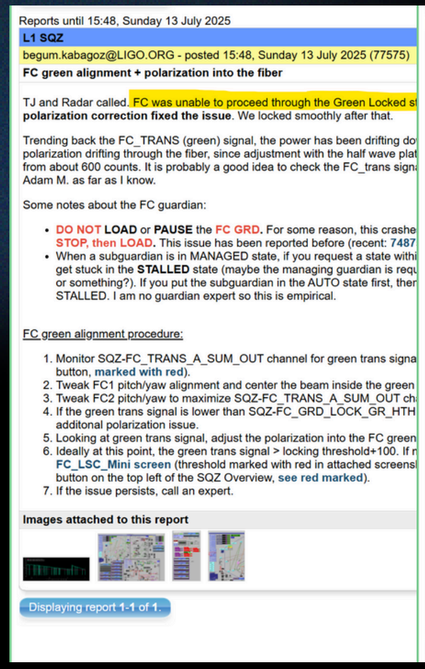
A long, high-finesse optical cavity that rotates the phase of squeezed vacuum light in a frequency-dependent way.

- Enables frequency-dependent squeezing.

- Green beam (532 nm) pre-locks cavity length near IR (1064 nm) resonance.
- Squeezed light enters; cavity detuning controls quadrature rotation.

- Length ~300 m

ALOGS



Reports until 15:48, Sunday 13 July 2025

L1 SQZ

begum.kabagoz@LIGO.ORG - posted 15:48, Sunday 13 July 2025 (77575)

FC green alignment + polarization into the fiber

TJ and Radar called. FC was unable to proceed through the Green Locked st **polarization correction fixed the issue**. We locked smoothly after that.

Trending back the FC_TRANS (green) signal, the power has been drifting do polarization drifting through the fiber, since adjustment with the half wave plat from about 600 counts. It is probably a good idea to check the FC_trans signa Adam M. as far as I know.

Some notes about the FC guardian:

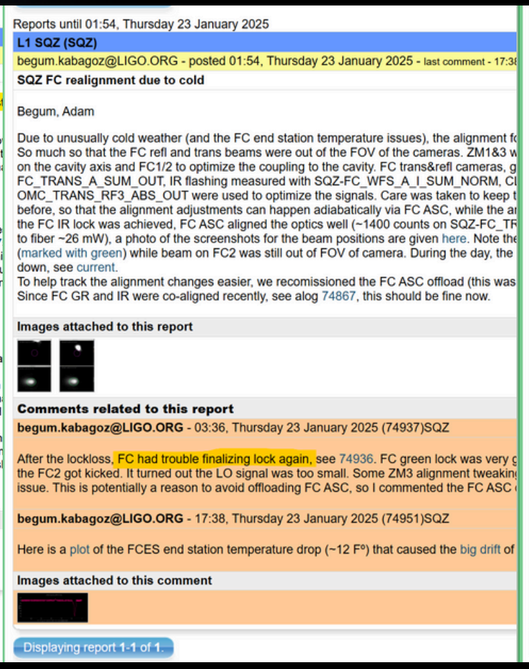
- **DO NOT LOAD** or **PAUSE** the **FC GRD**. For some reason, this crashe **STOP, then LOAD**. This issue has been reported before (recent: 7487
- When a subguardian is in MANAGED state, if you request a state withi get stuck in the **STALLED** state (maybe the managing guardian is requ or something?). If you put the subguardian in the AUTO state first, ther STALLED. I am no guardian expert so this is empirical.

FC green alignment procedure:

1. Monitor SQZ-FC_TRANS_A_SUM_OUT channel for green trans signa button, **marked with red**).
2. Tweak FC1 pitch/yaw alignment and center the beam inside the green
3. Tweak FC2 pitch/yaw to maximize SQZ-FC_TRANS_A_SUM_OUT ch
4. If the green trans signal is lower than SQZ-FC_GRD_LOCK_GR_HTH additonal polarization issue.
5. Looking at green trans signal, adjust the polarization into the FC green
6. Ideally at this point, the green trans signal > locking threshold+100. If r **FC_LSC_Mini screen** (threshold marked with red in attached screensl button on the top left of the SQZ Overview, **see red marked**).
7. If the issue persists, call an expert.

Images attached to this report

Displaying report 1-1 of 1.



Reports until 01:54, Thursday 23 January 2025

L1 SQZ (SQZ)

begum.kabagoz@LIGO.ORG - posted 01:54, Thursday 23 January 2025 - last comment - 17:3

SQZ FC realignment due to cold

Begum, Adam

Due to unusually cold weather (and the FC end station temperature issues), the alignment fo So much so that the FC refl and trans beams were out of the FOV of the cameras. ZM1&3 w on the cavity axis and FC1/2 to optimize the coupling to the cavity. FC trans&refl cameras, g FC_TRANS_A_SUM_OUT, IR flashing measured with SQZ-FC_WFS_A_I_SUM_NORM, CI OMC_TRANS_RF3_ABS_OUT were used to optimize the signals. Care was taken to keep t before, so that the alignment adjustments can happen adiabatically via FC ASC, while the ar the FC IR lock was achieved, FC ASC aligned the optics well (~1400 counts on SQZ-FC_TR to fiber ~26 mW), a photo of the screenshots for the beam positions are given here. Note the (marked with green) while beam on FC2 was still out of FOV of camera. During the day, the down, see current.
To help track the alignment changes easier, we recomissioned the FC ASC offload (this was Since FC GR and IR were co-aligned recently, see alog 74867, this should be fine now.

Images attached to this report

Comments related to this report

begum.kabagoz@LIGO.ORG - 03:36, Thursday 23 January 2025 (74937)SQZ

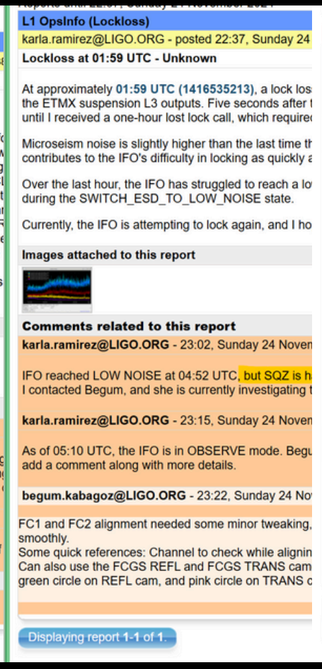
After the lockloss, FC had trouble finalizing lock again, see 74936. FC green lock was very g the FC2 got kicked. It turned out the LO signal was too small. Some ZM3 alignment tweakin issue. This is potentially a reason to avoid offloading FC ASC, so I commented the FC ASC

begum.kabagoz@LIGO.ORG - 17:38, Thursday 23 January 2025 (74951)SQZ

Here is a plot of the FCES end station temperature drop (~12 F°) that caused the big drift of

Images attached to this comment

Displaying report 1-1 of 1.



L1 OpsInfo (Lockloss)

karla.ramirez@LIGO.ORG - posted 22:37, Sunday 24

Lockloss at 01:59 UTC - Unknown

At approximately 01:59 UTC (1416535213), a lock los the ETMX suspension L3 outputs. Five seconds after t until I received a one-hour lost lock call, which require

Microseism noise is slightly higher than the last time th contributes to the IFO's difficulty in locking as quickly a

Over the last hour, the IFO has struggled to reach a lo during the SWITCH_ESD_TO_LOW_NOISE state.

Currently, the IFO is attempting to lock again, and I ho

Images attached to this report

Comments related to this report

karla.ramirez@LIGO.ORG - 23:02, Sunday 24 Noven

IFO reached LOW NOISE at 04:52 UTC, but SQZ is h I contacted Begum, and she is currently investigating t

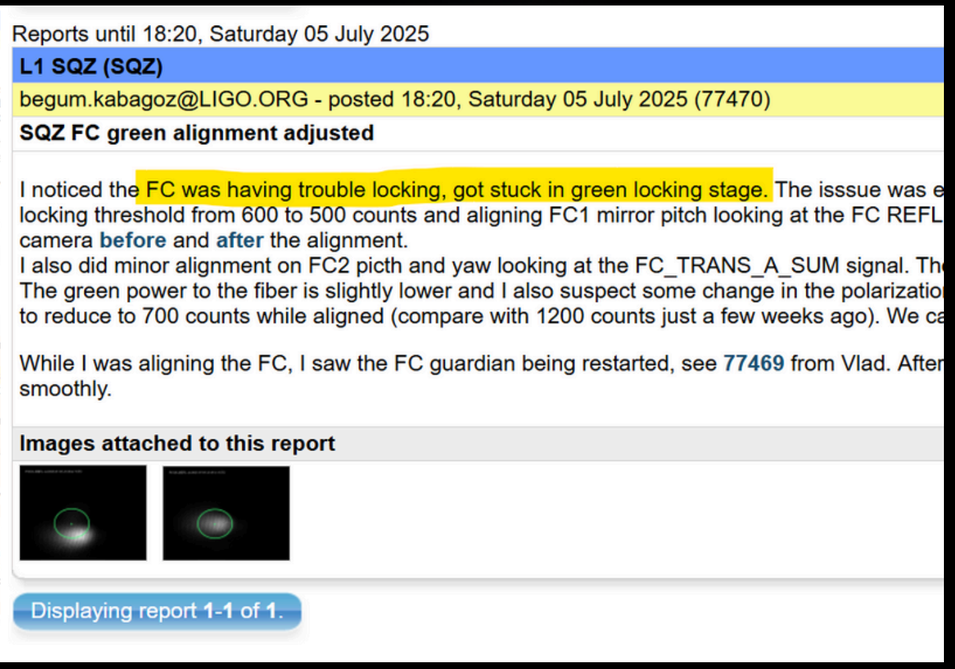
karla.ramirez@LIGO.ORG - 23:15, Sunday 24 Noven

As of 05:10 UTC, the IFO is in OBSERVE mode. Begu add a comment along with more details.

begum.kabagoz@LIGO.ORG - 23:22, Sunday 24 No

FC1 and FC2 alignment needed some minor tweaking, smoothly.
Some quick references: Channel to check while alignin Can also use the FCGS REFL and FCGS TRANS cam green circle on REFL cam, and pink circle on TRANS c

Displaying report 1-1 of 1.



Reports until 18:20, Saturday 05 July 2025

L1 SQZ (SQZ)

begum.kabagoz@LIGO.ORG - posted 18:20, Saturday 05 July 2025 (77470)

SQZ FC green alignment adjusted

I noticed the FC was having trouble locking, got stuck in green locking stage. The isssue was e locking threshold from 600 to 500 counts and aligning FC1 mirror pitch looking at the FC REFL camera **before** and **after** the alignment.
I also did minor alignment on FC2 picth and yaw looking at the FC_TRANS_A_SUM signal. The The green power to the fiber is slightly lower and I also suspect some change in the polarizatio to reduce to 700 counts while aligned (compare with 1200 counts just a few weeks ago). We ca

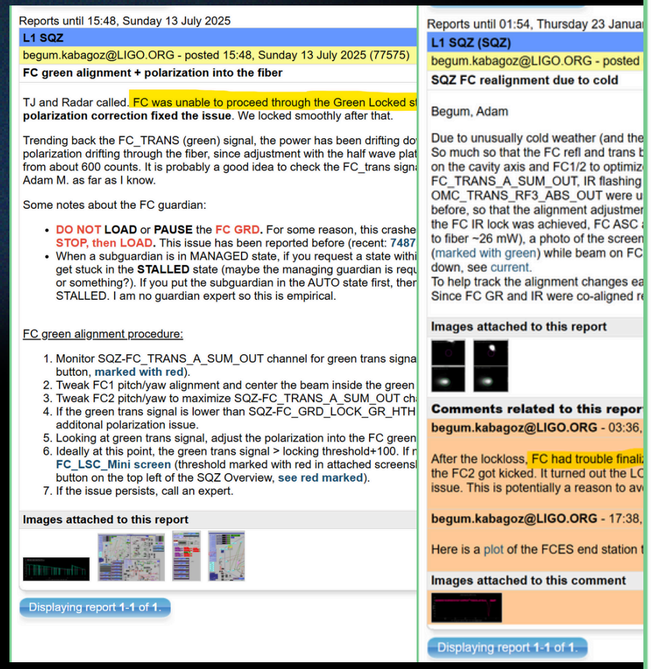
While I was aligning the FC, I saw the FC guardian being restarted, see **77469** from Vlad. After smoothly.

Images attached to this report

Displaying report 1-1 of 1.

01 77575 02 74935 03 74190 04 77470

ALOGS



Reports until 15:48, Sunday 13 July 2025

L1 SQZ

begum.kabagoz@LIGO.ORG - posted 15:48, Sunday 13 July 2025 (77575)

FC green alignment + polarization into the fiber

TJ and Radar called. FC was unable to proceed through the Green Locked st
polarization correction fixed the issue. We locked smoothly after that.

Trending back the FC_TRANS (green) signal, the power has been drifting do
polarization drifting through the fiber, since adjustment with the half wave plat
from about 600 counts. It is probably a good idea to check the FC_trans signa
Adam M. as far as I know.

Some notes about the FC guardian:

- **DO NOT LOAD** or **PAUSE** the **FC GRD**. For some reason, this crashe
  STOP, then LOAD. This issue has been reported before (recent: **7487**
- When a subguardian is in MANAGED state, if you request a state withi
  get stuck in the **STALLED** state (maybe the managing guardian is requ
  or something?). If you put the subguardian in the AUTO state first, ther
  STALLED. I am no guardian expert so this is empirical.

FC green alignment procedure:

1. Monitor SQZ-FC_TRANS_A_SUM_OUT channel for green trans signa
   button, **marked with red**).
2. Tweak FC1 pitch/yaw alignment and center the beam inside the green
3. Tweak FC2 pitch/yaw to maximize SQZ-FC_TRANS_A_SUM_OUT ch
4. If the green trans signal is lower than SQZ-FC_GRD_LOCK_GR_HTH
   additonal polarization issue.
5. Looking at green trans signal, adjust the polarization into the FC green
6. Ideally at this point, the green trans signal > locking threshold+100. If r
   FC_LSC_Mini screen (threshold marked with red in attached screensl
   button on the top left of the SQZ Overview, **see red marked**).
7. If the issue persists, call an expert.

Images attached to this report

Displaying report 1-1 of 1.

Reports until 01:54, Thursday 23 Janua

L1 SQZ (SQZ)

begum.kabagoz@LIGO.ORG - posted

SQZ FC realignment due to cold

Begum, Adam

Due to unusually cold weather (and the
So much so that the FC refl and trans b
on the cavity axis and FC1/2 to optimiz
FC_TRANS_A_SUM_OUT, IR flashing
OMC_TRANS_RF3_ABS_OUT were u
before, so that the alignment adjustmer
the FC IR lock was achieved, FC ASC
to fiber ~26 mW), a photo of the screen
(marked with green) while beam on FC
down, see current.
To help track the alignment changes ea
Since FC GR and IR were co-aligned r

Images attached to this report

Comments related to this repor

begum.kabagoz@LIGO.ORG - 03:36,

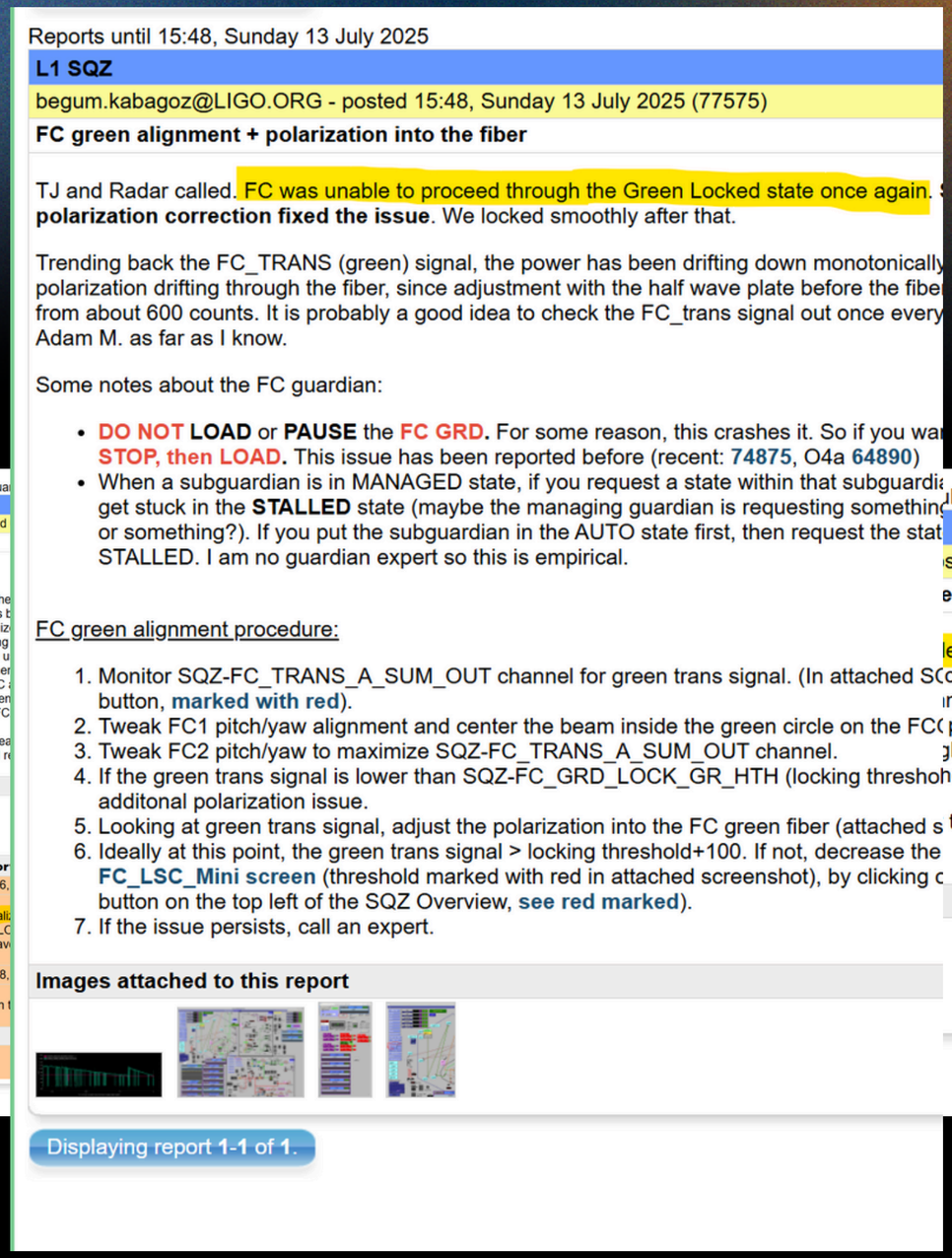
After the lockloss, FC had trouble finali
the FC2 got kicked. It turned out the LO
issue. This is potentially a reason to av

begum.kabagoz@LIGO.ORG - 17:38,

Here is a plot of the FCES end station t

Images attached to this comment

Displaying report 1-1 of 1.



Reports until 15:48, Sunday 13 July 2025

L1 SQZ

begum.kabagoz@LIGO.ORG - posted 15:48, Sunday 13 July 2025 (77575)

FC green alignment + polarization into the fiber

TJ and Radar called. FC was unable to proceed through the Green Locked state once again.
polarization correction fixed the issue. We locked smoothly after that.

Trending back the FC_TRANS (green) signal, the power has been drifting down monotonically
polarization drifting through the fiber, since adjustment with the half wave plate before the fiber
from about 600 counts. It is probably a good idea to check the FC_trans signal out once every
Adam M. as far as I know.

Some notes about the FC guardian:

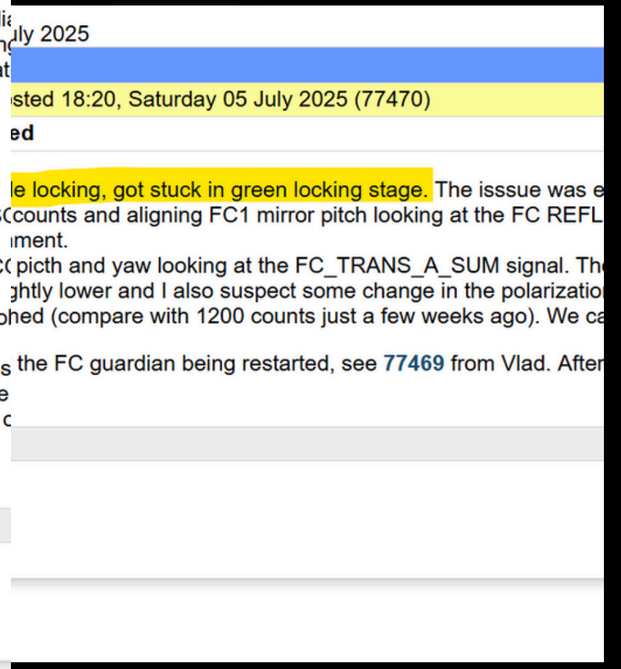
- **DO NOT LOAD** or **PAUSE** the **FC GRD**. For some reason, this crashes it. So if you wa
  STOP, then LOAD. This issue has been reported before (recent: **74875**, O4a **64890**)
- When a subguardian is in MANAGED state, if you request a state within that subguardia
  get stuck in the **STALLED** state (maybe the managing guardian is requesting somethin
  or something?). If you put the subguardian in the AUTO state first, then request the stat
  STALLED. I am no guardian expert so this is empirical.

FC green alignment procedure:

1. Monitor SQZ-FC_TRANS_A_SUM_OUT channel for green trans signal. (In attached SC
   button, **marked with red**).
2. Tweak FC1 pitch/yaw alignment and center the beam inside the green circle on the FC
3. Tweak FC2 pitch/yaw to maximize SQZ-FC_TRANS_A_SUM_OUT channel.
4. If the green trans signal is lower than SQZ-FC_GRD_LOCK_GR_HTH (locking thresho
   additonal polarization issue.
5. Looking at green trans signal, adjust the polarization into the FC green fiber (attached s
6. Ideally at this point, the green trans signal > locking threshold+100. If not, decrease the
   FC_LSC_Mini screen (threshold marked with red in attached screenshot), by clicking c
   button on the top left of the SQZ Overview, **see red marked**).
7. If the issue persists, call an expert.

Images attached to this report

Displaying report 1-1 of 1.



ly 2025

sted 18:20, Saturday 05 July 2025 (77470)

ed

le locking, got stuck in green locking stage. The isssue was e
counts and aligning FC1 mirror pitch looking at the FC REFL
ment.
picth and yaw looking at the FC_TRANS_A_SUM signal. The
ghtly lower and I also suspect some change in the polarizatio
hed (compare with 1200 counts just a few weeks ago). We ca

the FC guardian being restarted, see **77469** from Vlad. After

01 77575

04 77470

ALOGS

Reports until 15:48, Sunday 13 July 2025

L1 SQZ

begum.kabagoz@LIGO.ORG - posted 15:48, Sunday 13 July 2025 (77575)

FC green alignment + polarization into the fiber

TJ and Radar called. FC was unable to proceed through the Green Locked st **polarization correction fixed the issue**. We locked smoothly after that.

Trending back the FC_TRANS (green) signal, the power has been drifting do polarization drifting through the fiber, since adjustment with the half wave plat from about 600 counts. It is probably a good idea to check the FC_trans signa Adam M. as far as I know.

Some notes about the FC guardian:

- **DO NOT LOAD** or **PAUSE** the **FC GRD**. For some reason, this crashe **STOP, then LOAD**. This issue has been reported before (recent: 7487
- When a subguardian is in MANAGED state, if you request a state withi get stuck in the **STALLED** state (maybe the managing guardian is requ or something?). If you put the subguardian in the AUTO state first, ther STALLED. I am no guardian expert so this is empirical.

FC green alignment procedure:

1. Monitor SQZ-FC_TRANS_A_SUM_OUT channel for green trans signa button, **marked with red**).
2. Tweak FC1 pitch/yaw alignment and center the beam inside the green
3. Tweak FC2 pitch/yaw to maximize SQZ-FC_TRANS_A_SUM_OUT ch
4. If the green trans signal is lower than SQZ-FC_GRD_LOCK_GR_HTH additonal polarization issue.
5. Looking at green trans signal, adjust the polarization into the FC green
6. Ideally at this point, the green trans signal > locking threshold+100. If r **FC_LSC_Mini screen** (threshold marked with red in attached screensi button on the top left of the SQZ Overview, **see red marked**).
7. If the issue persists, call an expert.

Images attached to this report

Displaying report 1-1 of 1.

01 77575

Reports until 01:54, Thursday 23 January 2025

L1 SQZ (SQZ)

begum.kabagoz@LIGO.ORG - posted 01:54, Thursday 23 January 2025 - last comment - 17:38, Thursday 23 January

SQZ FC realignment due to cold

Begum, Adam

Due to unusually cold weather (and the FC end station temperature issues), the alignment for the filter cavity wa
So much so that the FC refl and trans beams were out of the FOV of the cameras. ZM1&3 were used to correct
on the cavity axis and FC1/2 to optimize the coupling to the cavity. FC trans&refl cameras, green power measur
FC_TRANS_A_SUM_OUT, IR flashing measured with SQZ-FC_WFS_A_I_SUM_NORM, CLF power through O
OMC_TRANS_RF3_ABS_OUT were used to optimize the signals. Care was taken to keep the IR resonance off
before, so that the alignment adjustments can happen adiabatically via FC ASC, while the ambient temperature
the FC IR lock was achieved, FC ASC aligned the optics well (~1400 counts on SQZ-FC_TRANS_A_SUM_OUT
to fiber ~26 mW), a photo of the screenshots for the beam positions are given here. Note the beam on FC1 is ba
(marked with green) while beam on FC2 was still out of FOV of camera. During the day, the beam on FC trans c
down, see current.
To help track the alignment changes easier, we recomissioned the FC ASC offload (this was commented out bef
Since FC GR and IR were co-aligned recently, see alog 74867, this should be fine now.

Images attached to this report

Comments related to this report

begum.kabagoz@LIGO.ORG - 03:36, Thursday 23 January 2025 (74937)SQZ

After the lockloss, FC had trouble finalizing lock again, see 74936. FC green lock was very good, but every time
the FC2 got kicked. It turned out the LO signal was too small. Some ZM3 alignment tweaking while looking at OI
issue. This is potentially a reason to avoid offloading FC ASC, so I commented the FC ASC offload once again.

begum.kabagoz@LIGO.ORG - 17:38, Thursday 23 January 2025 (74951)SQZ

Here is a plot of the FCES end station temperature drop (~12 F°) that caused the big drift of the FC2 optic.

Images attached to this comment

Displaying report 1-1 of 1.

aturday 05 July 2025 (77470)

stuck in green locking stage. The isssue was e
ligning FC1 mirror pitch looking at the FC REFL

v looking at the FC_TRANS_A_SUM signal. The
d I also suspect some change in the polarizatio
with 1200 counts just a few weeks ago). We ca

dian being restarted, see **77469** from Vlad. After

77470

ALOGS

Reports until 15:48, Sunday 13 July 2025

L1 SQZ

begum.kabagoz@LIGO.ORG - posted 15:48, Sunday 13 July 2025 (77575)

FC green alignment + polarization into the fiber

TJ and Radar called. FC was unable to proceed through the Green Locked st **polarization correction fixed the issue**. We locked smoothly after that.

Trending back the FC_TRANS (green) signal, the power has been drifting do polarization drifting through the fiber, since adjustment with the half wave plat from about 600 counts. It is probably a good idea to check the FC_trans signa Adam M. as far as I know.

Some notes about the FC guardian:

- DO NOT **LOAD** or **PAUSE** the FC GRD. For some reason, this crashe STOP, then LOAD. This issue has been reported before (recent: 7487
- When a subguardian is in MANAGED state, if you request a state withi get stuck in the **STALLED** state (maybe the managing guardian is requ or something?). If you put the subguardian in the AUTO state first, ther STALLED. I am no guardian expert so this is empirical.

FC green alignment procedure:

1. Monitor SQZ-FC_TRANS_A_SUM_OUT channel for green trans signa button, marked with red).
2. Tweak FC1 pitch/yaw alignment and center the beam inside the green
3. Tweak FC2 pitch/yaw to maximize SQZ-FC_TRANS_A_SUM_OUT ch
4. If the green trans signal is lower than SQZ-FC_GRD_LOCK_GR_HTH additonal polarization issue.
5. Looking at green trans signal, adjust the polarization into the FC green
6. Ideally at this point, the green trans signal > locking threshold+100. If r **FC_LSC_Mini screen** (threshold marked with red in attached screensi button on the top left of the SQZ Overview, see red marked).
7. If the issue persists, call an expert.

Images attached to this report

Displaying report 1-1 of 1.

Reports until 01:54, Thursday 23

L1 SQZ (SQZ)

begum.kabagoz@LIGO.ORG -

SQZ FC realignment due to c

Begum, Adam

Due to unusually cold weather (So much so that the FC refl and on the cavity axis and FC1/2 to FC_TRANS_A_SUM_OUT, IR f OMC_TRANS_RF3_ABS_OUT before, so that the alignment ad the FC IR lock was achieved, F to fiber ~26 mW), a photo of the (marked with green) while beam down, see current.
To help track the alignment cha Since FC GR and IR were co-al

Images attached to this repor

Comments related to this

begum.kabagoz@LIGO.ORG

After the lockloss, FC had troub the FC2 got kicked. It turned ou issue. This is potentially a reasc

begum.kabagoz@LIGO.ORG

Here is a plot of the FCES end

Images attached to this comm

Displaying report 1-1 of 1.

01 [77575](#)

L1 OpsInfo (Lockloss)

karla.ramirez@LIGO.ORG - posted 22:37, Sunday 24 November 2024 - last comment - 23:22, Sunday 24 November 20

Lockloss at 01:59 UTC - Unknown

At approximately **01:59 UTC (1416535213)**, a lock loss occurred. The cause is unclear, but the lock loss page in the ETMX suspension L3 outputs. Five seconds after the lock loss, the MC2 suspension watchdog tripped and r until I received a one-hour lost lock call, which required human intervention.

Microseism noise is slightly higher than the last time the interferometer (IFO) lost lock and subsequently relocke contributes to the IFO's difficulty in locking as quickly as before. Please refer to the attached document for more

Over the last hour, the IFO has struggled to reach a low noise state. It lost lock twice during the TURN_ON_DHA during the SWITCH_ESD_TO_LOW_NOISE state.

Currently, the IFO is attempting to lock again, and I hope it will succeed this time.

Images attached to this report

Comments related to this report

karla.ramirez@LIGO.ORG - 23:02, Sunday 24 November 2024 (74188)

IFO reached LOW NOISE at 04:52 UTC, but SQZ is having difficulty locking FC.
I contacted Begum, and she is currently investigating this issue.

karla.ramirez@LIGO.ORG - 23:15, Sunday 24 November 2024 (74189)

As of 05:10 UTC, the IFO is in OBSERVE mode. Begum mentioned tweaking the alignment a little bit, and then add a comment along with more details.

begum.kabagoz@LIGO.ORG - 23:22, Sunday 24 November 2024 (74190)SQZ

FC1 and FC2 alignment needed some minor tweaking, using the procedure outlined in the SQZ Wiki. After that t smoothly.
Some quick references: Channel to check while aligning is SQZ-FC_TRANS_A_SUM_OUT.
Can also use the FCGS REFL and FCGS TRANS cameras while aligning, a good beam position for green lockin green circle on REFL cam, and pink circle on TRANS cam.

Displaying report 1-1 of 1.

05 July 2025 (77470)

n green locking stage. The isssue was e FC1 mirror pitch looking at the FC REFL

g at the FC_TRANS_A_SUM signal. Th suspect some change in the polarizatio 200 counts just a few weeks ago). We ca

ng restarted, see 77469 from Vlad. After

[470](#)

ALOGS

L1 OpsInfo (Lockloss)

karla.ramirez@LIGO.ORG - posted 22:37, Sunday 24 November 2024 - last comment - 23:22, Sunday 24 November 20

Lockloss at 01:59 UTC - Unknown

At approximately **01:59 UTC (1416535213)**, a lock loss occurred. The cause is unclear, but the lock loss page in
the ETMX suspension L3 outputs. Five seconds after the lock loss, the MC2 suspension watchdog tripped and r
until I received a one-hour lost lock call, which required human intervention.

Reports until 18:20, Saturday 05 July 2025

L1 SQZ (SQZ)

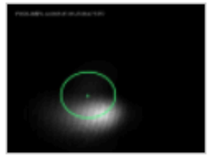
begum.kabagoz@LIGO.ORG - posted 18:20, Saturday 05 July 2025 (77470)

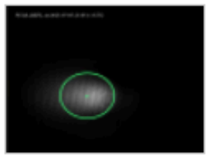
SQZ FC green alignment adjusted

I noticed the FC was having trouble locking, got stuck in green locking stage. The isssue was e
locking threshold from 600 to 500 counts and aligning FC1 mirror pitch looking at the FC REFL
camera **before** and **after** the alignment.
I also did minor alignment on FC2 picth and yaw looking at the FC_TRANS_A_SUM signal. Th
The green power to the fiber is slightly lower and I also suspect some change in the polarizatio
to reduce to 700 counts while aligned (compare with 1200 counts just a few weeks ago). We ca

While I was aligning the FC, I saw the FC guardian being restarted, see **77469** from Vlad. After
smoothly.

Images attached to this report





Displaying report **1-1** of **1**.

Reports until 15:48, Sunday 13 July 2025

L1 SQZ

begum.kabagoz@LIGO.ORG - posted 15:48, Sunday 13 July 2025

FC green alignment + polarization into the fiber

TJ and Radar called. FC was unable to proceed through the Green
polarization correction fixed the issue. We locked smoothly after

Trending back the FC_TRANS (green) signal, the power has been d
polarization drifting through the fiber, since adjustment with the half
from about 600 counts. It is probably a good idea to check the FC_t
Adam M. as far as I know.

Some notes about the FC guardian:

- **DO NOT LOAD** or **PAUSE** the **FC GRD**. For some reason, th
  STOP, then LOAD. This issue has been reported before (rec
- When a subguardian is in MANAGED state, if you request a s
  get stuck in the **STALLED** state (maybe the managing guardi
  or something?). If you put the subguardian in the AUTO state
  STALLED. I am no guardian expert so this is empirical.

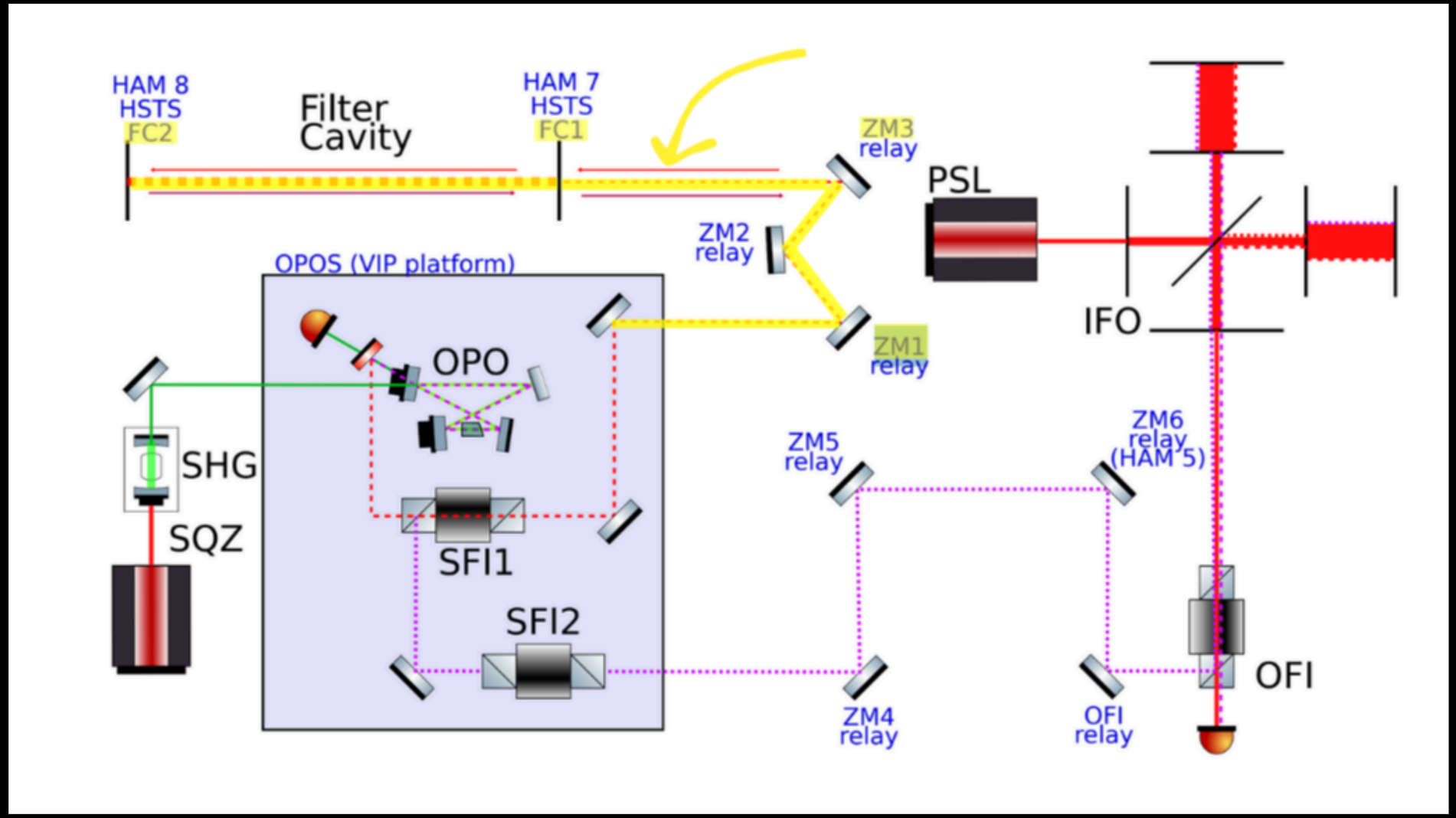
FC green alignment procedure:

1. Monitor SQZ-FC_TRANS_A_SUM_OUT channel for green tra
   button, **marked with red**).
2. Tweak FC1 pitch/yaw alignment and center the beam inside t
3. Tweak FC2 pitch/yaw to maximize SQZ-FC_TRANS_A_SUM
4. If the green trans signal is lower than SQZ-FC_GRD_LOCK_
   additonal polarization issue.
5. Looking at green trans signal, adjust the polarization into the
6. Ideally at this point, the green trans signal > locking threshold
   FC_LSC_Mini screen (threshold marked with red in attachec
   button on the top left of the SQZ Overview, **see red marked**).
7. If the issue persists, call an expert.

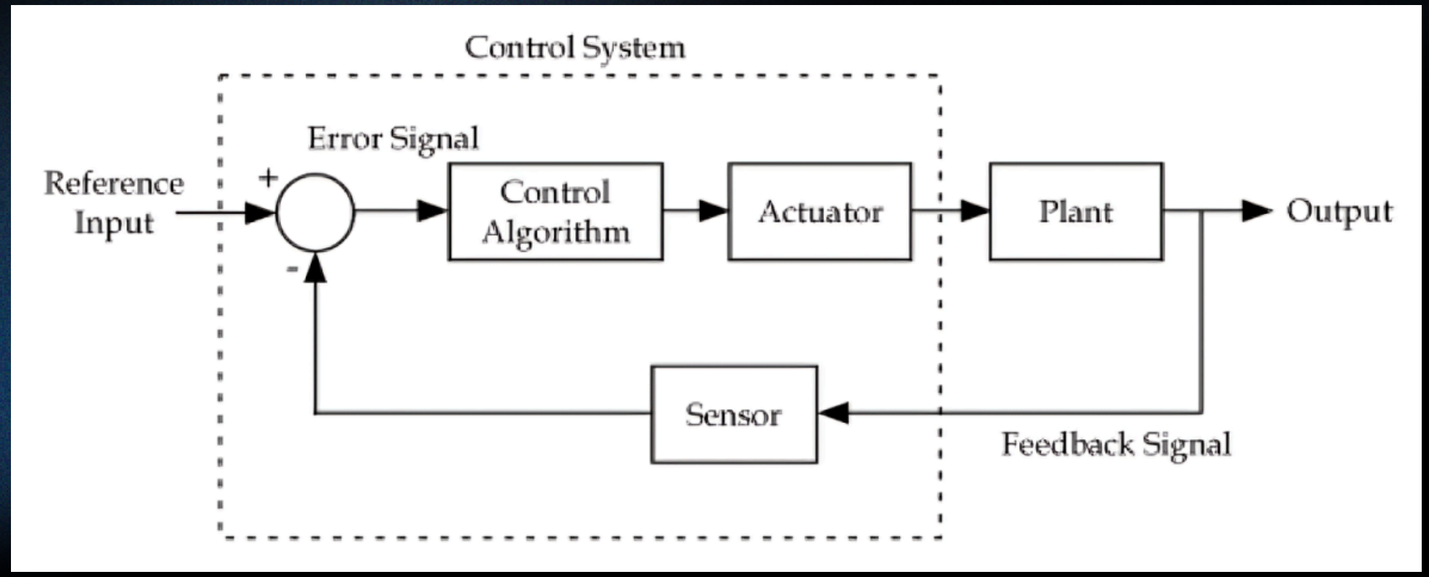
Images attached to this report

Displaying report 1-1 of 1.

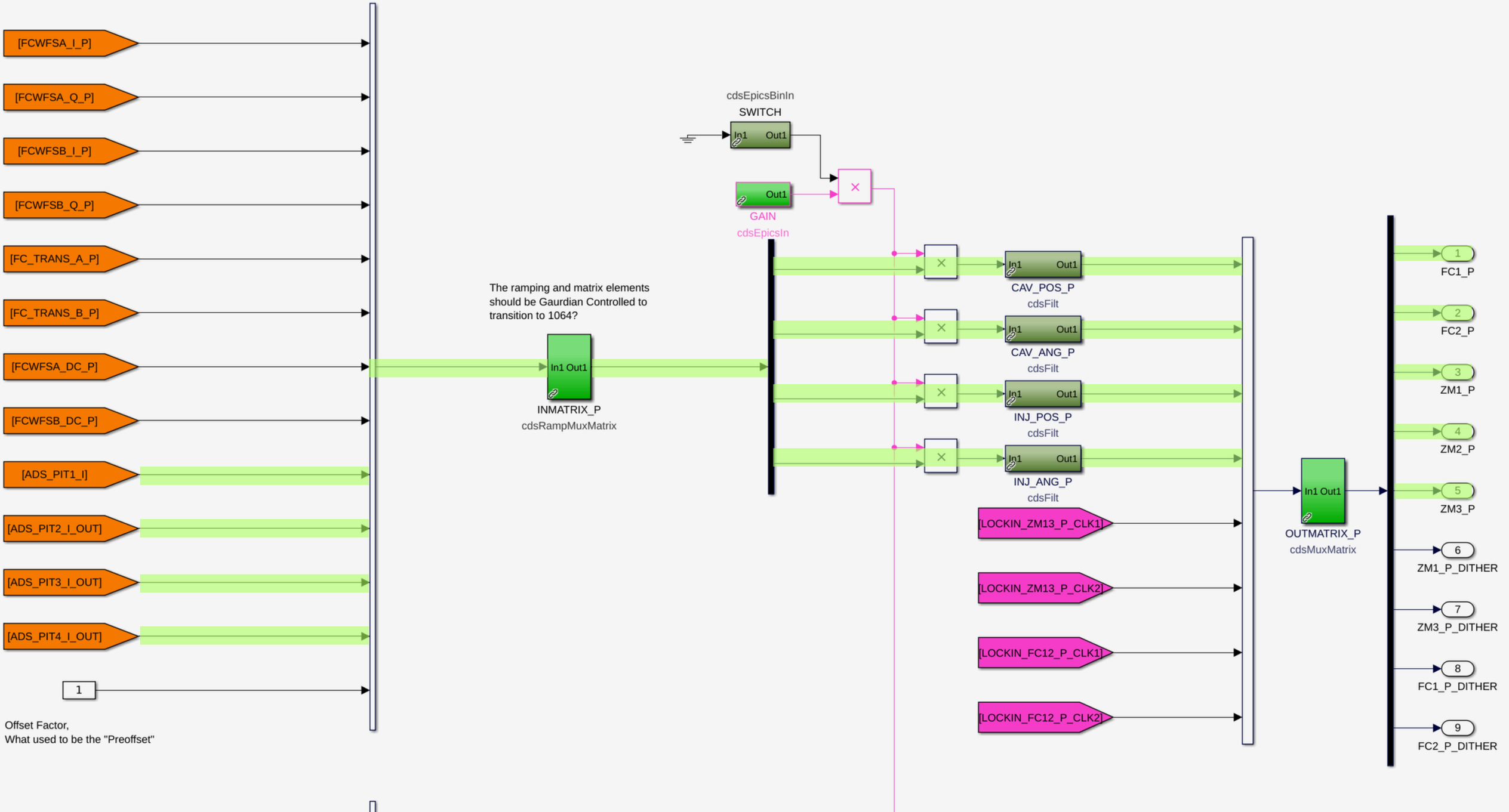
01 77575


HAM 8
HSTS
FC2
Filter
Cavity
HAM 7
HSTS
FC1
ZM3
relay
PSL
ZM2
relay
OPOS (VIP platform)
IFO
OPO
ZM1
relay
SHG
ZM5
relay
ZM6
relay
(HAM 5)
SQZ
SFI1
SFI2
OFI
ZM4
relay
OFI
relay

ALIGNMENT CONTROL LOOP



Sensor	Controller	Actuator
Filter Cavity Transmitted Green Signal	Filter Bank	Electro-Magnetic actuator on ZM mirrors
Filter Cavity Length Control Signal	Filter Bank	Electro-Magnetic actuator on FC mirrors


[FCWFSA_I_P]
[FCWFSA_Q_P]
[FCWFSB_I_P]
[FCWFSB_Q_P]
[FC_TRANS_A_P]
[FC_TRANS_B_P]
[FCWFSA_DC_P]
[FCWFSB_DC_P]
[ADS_PIT1_I]
[ADS_PIT2_I_OUT]
[ADS_PIT3_I_OUT]
[ADS_PIT4_I_OUT]
1
Offset Factor,
What used to be the "Preoffset"
The ramping and matrix elements should be Gaurdian Controlled to transition to 1064?
In1 Out1
INMATRIX_P
cdsRampMuxMatrix
cdsEpicsBinIn
SWITCH
In1 Out1
Out1
GAIN
cdsEpicsIn
In1 Out1
CAV_POS_P
cdsFilt
In1 Out1
CAV_ANG_P
cdsFilt
In1 Out1
INJ_POS_P
cdsFilt
In1 Out1
INJ_ANG_P
cdsFilt
[LOCKIN_ZM13_P_CLK1]
[LOCKIN_ZM13_P_CLK2]
[LOCKIN_FC12_P_CLK1]
[LOCKIN_FC12_P_CLK2]
In1 Out1
OUTMATRIX_P
cdsMuxMatrix
1
FC1_P
2
FC2_P
3
ZM1_P
4
ZM2_P
5
ZM3_P
6
ZM1_P_DITHER
7
ZM3_P_DITHER
8
FC1_P_DITHER
9
FC2_P_DITHER

DITHER & DEMODULATION

Dithering

- Apply small sinusoidal excitation (mirror pitch/yaw) at a known frequency.
- This creates a controlled oscillation in a chosen readout signal.

Demodulation

- Take the readout signal (contains oscillation at dither frequency).
- Multiply by reference sine at same frequency and low-pass filter.
- Output is an error signal

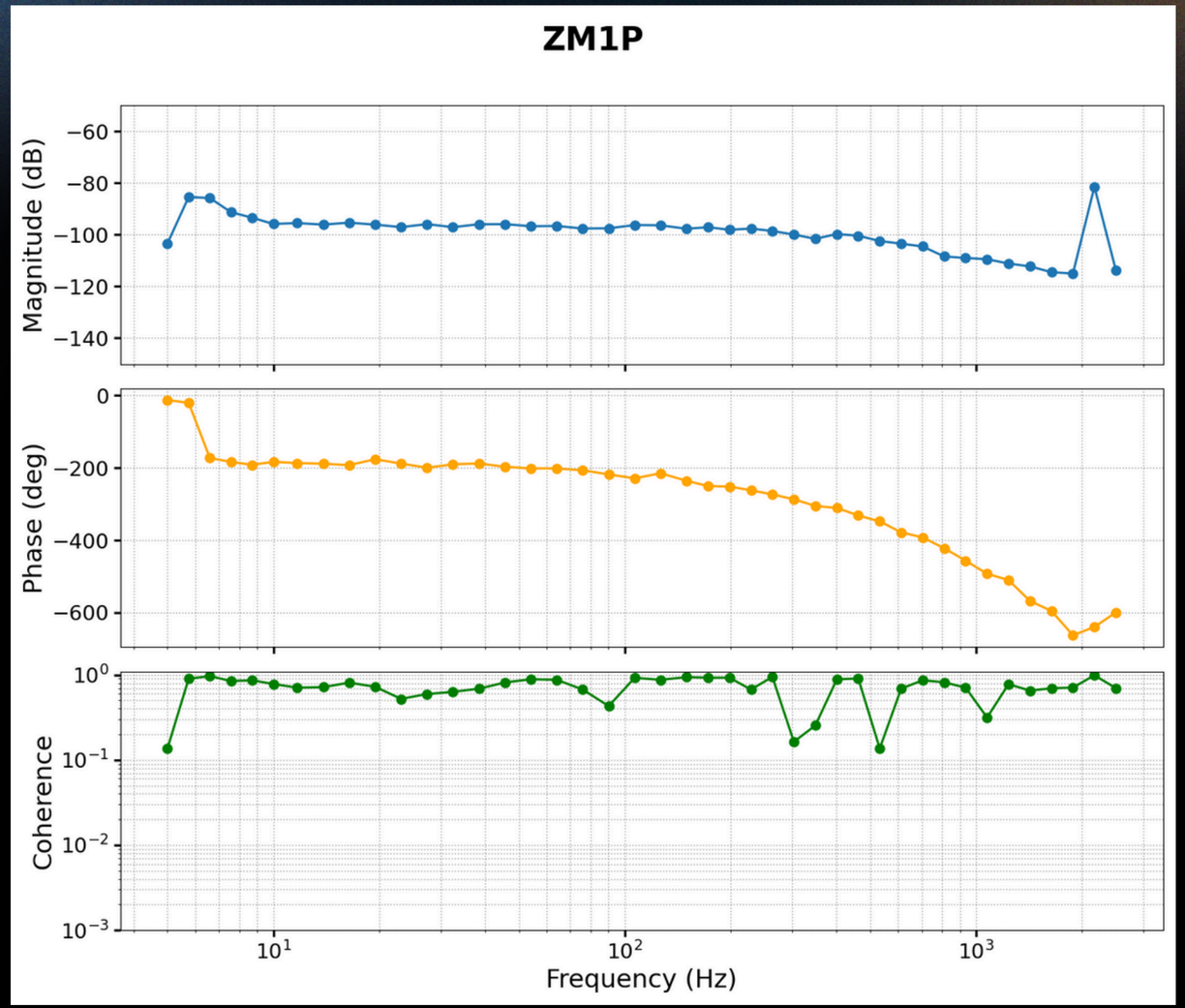
- ZM mirrors → green transmission signal.
- FC mirrors → cavity length control signal

PART 1

TRANSFER FUNCTIONS OF ZM'S

ZM1 PITCH TF

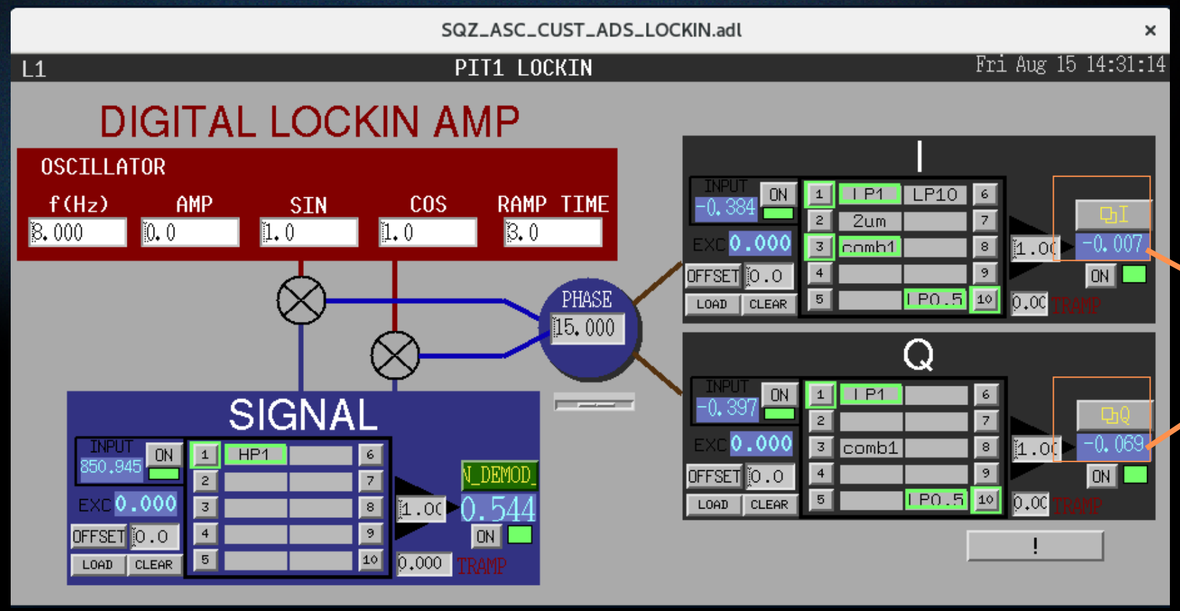
- Dither frequency selection requires actuator TFs
- Measured ZM1 & ZM3 bottom-stage (M2) transfer functions
- Applied swept sine: 5–2500 Hz
- Signal: excitation → 'L1:SUS-{ZM1,ZM3}_M2_DITHER_{P,Y}_OUT'
- Readout: transmitted green → 'L1:SQZ-FC_TRANS_A_SUM_OUT'
- Cavity DoFs deliberately misaligned to enhance sensitivity

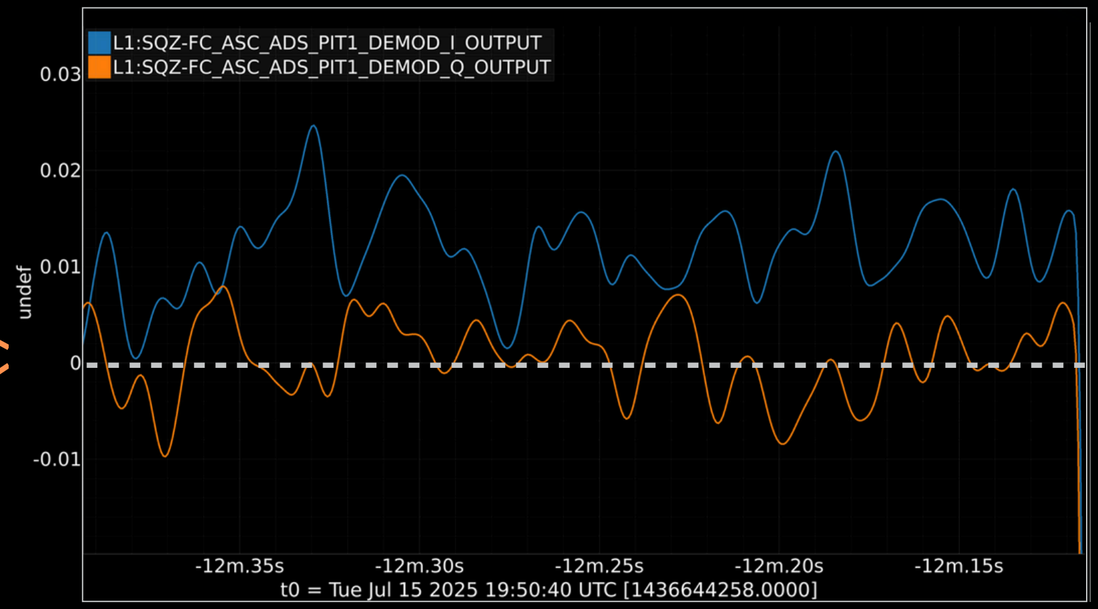


PART 2

ZM DITHER / DEMODULATION

DITHER PHASE





Excitation (dither):

- Small sinusoidal modulation applied to ZM1/ZM3 DoFs..

Error signal (sensing):

- Demodulated TRANS_A_SUM photodiode signal at each dither frequency.
- Output is proportional to misalignment in pitch/yaw.

Servo filter (controller):

- Error signal is processed (gain, phase compensation, filtering).
- Converts raw error into a stable control signal.

Control signal (output):

- Sent to angular actuation channels:
- INJ_POS_P / INJ_POS_Y → ZM1 pitch & yaw
- INJ_ANG_P / INJ_ANG_Y → ZM3 pitch & yaw

Actuators (plant):

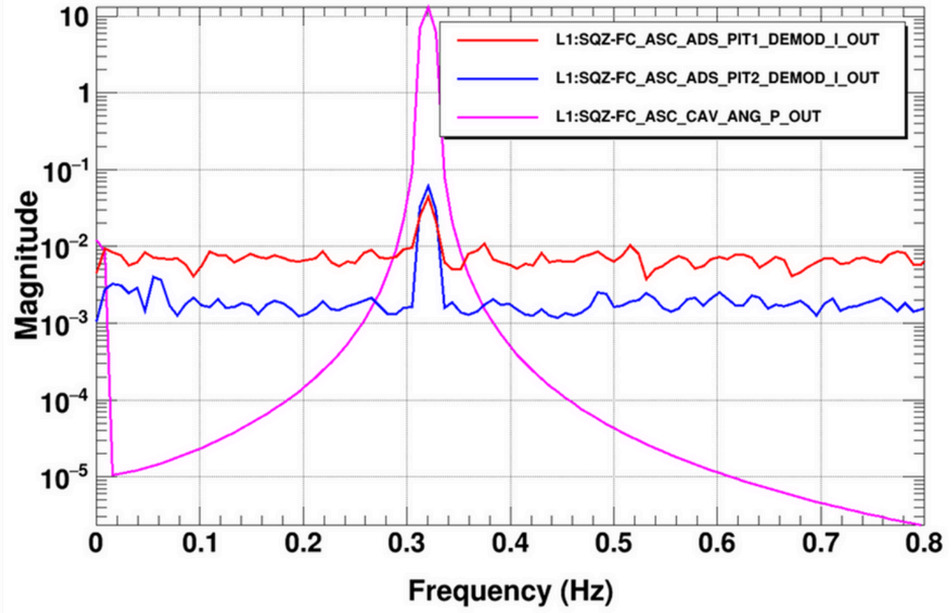
- Electromagnetic coil actuators at mirror suspensions
- Adjust mirror angles → correct cavity alignment

DoF	Frequency (Hz)	Gain	Phase (°)
ZM1 Pitch	101.1	2000	−40
ZM1 Yaw	126.1	2000	+140
ZM3 Pitch	151.1	200	+120
ZM3 Yaw	176.1	200	+105

PART 3

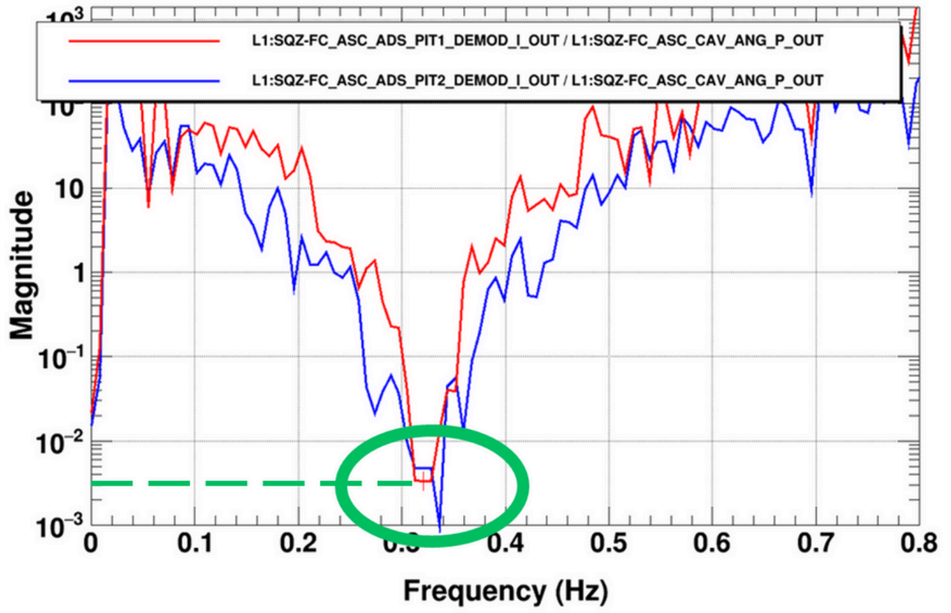
ZM INPUT MATRIX DETECTION

Power spectrum



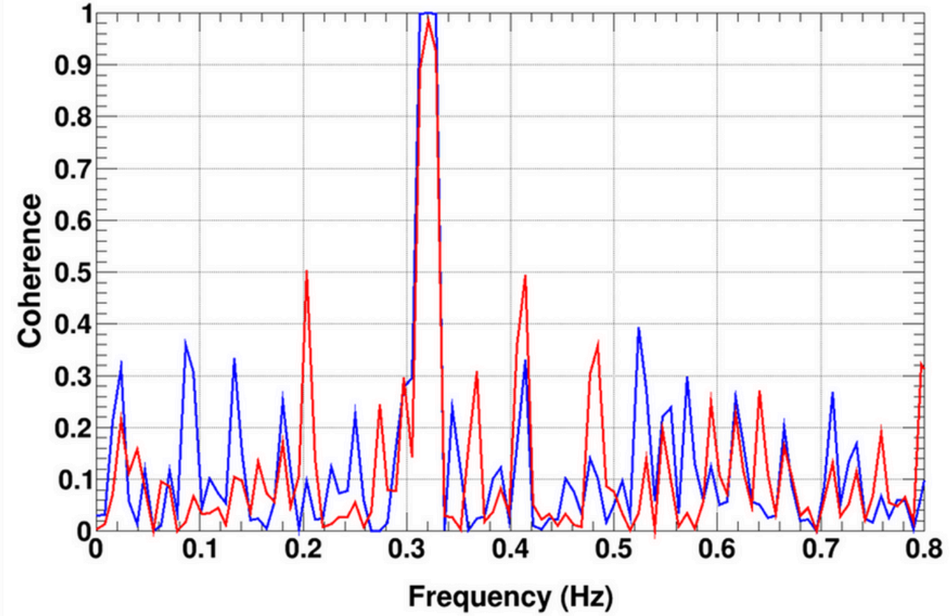
T0=14/08/2025 18:18:57 Avg=10 BW=0.0117178

Transfer function



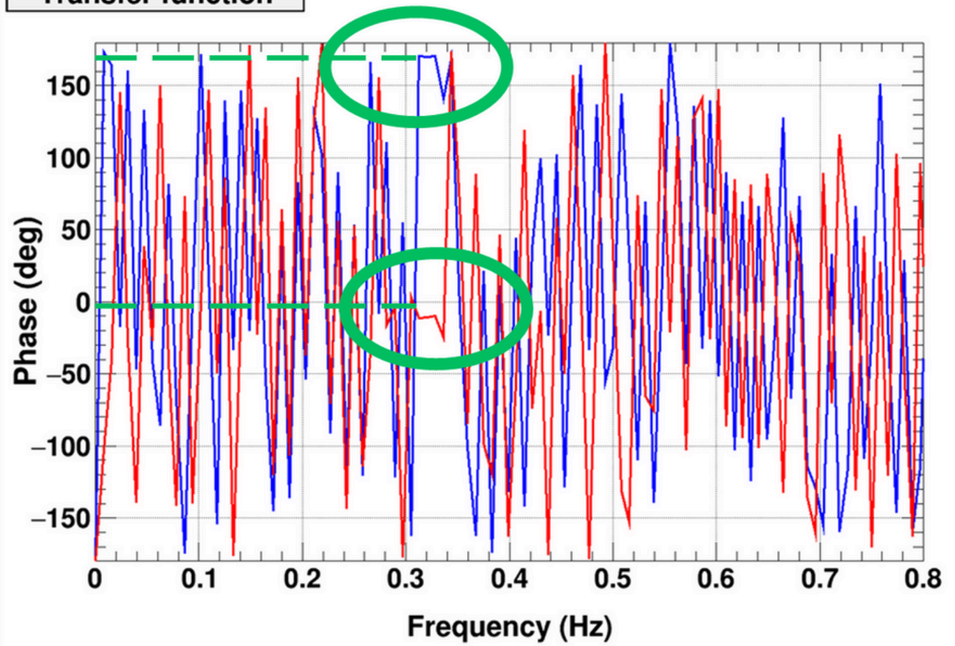
T0=14/08/2025 18:18:57 Avg=10 BW=0.0117178

Coherence



T0=14/08/2025 18:18:57 Avg=10 BW=0.0117178

Transfer function



T0=14/08/2025 18:18:57 Avg=10 BW=0.0117178

$$\begin{bmatrix} \mathrm{ZM1}_{\mathrm{Pitch}} \\ \mathrm{ZM3}_{\mathrm{Pitch}} \end{bmatrix} = \begin{bmatrix} -0.004 & 0.003 \\ 0.003 & -0.004 \end{bmatrix} \begin{bmatrix} X_{\mathrm{FC1}} \\ X_{\mathrm{FC2}} \end{bmatrix} \rightarrow \begin{bmatrix} -571.4 & -428.6 \\ -428.6 & -571.4 \end{bmatrix}$$

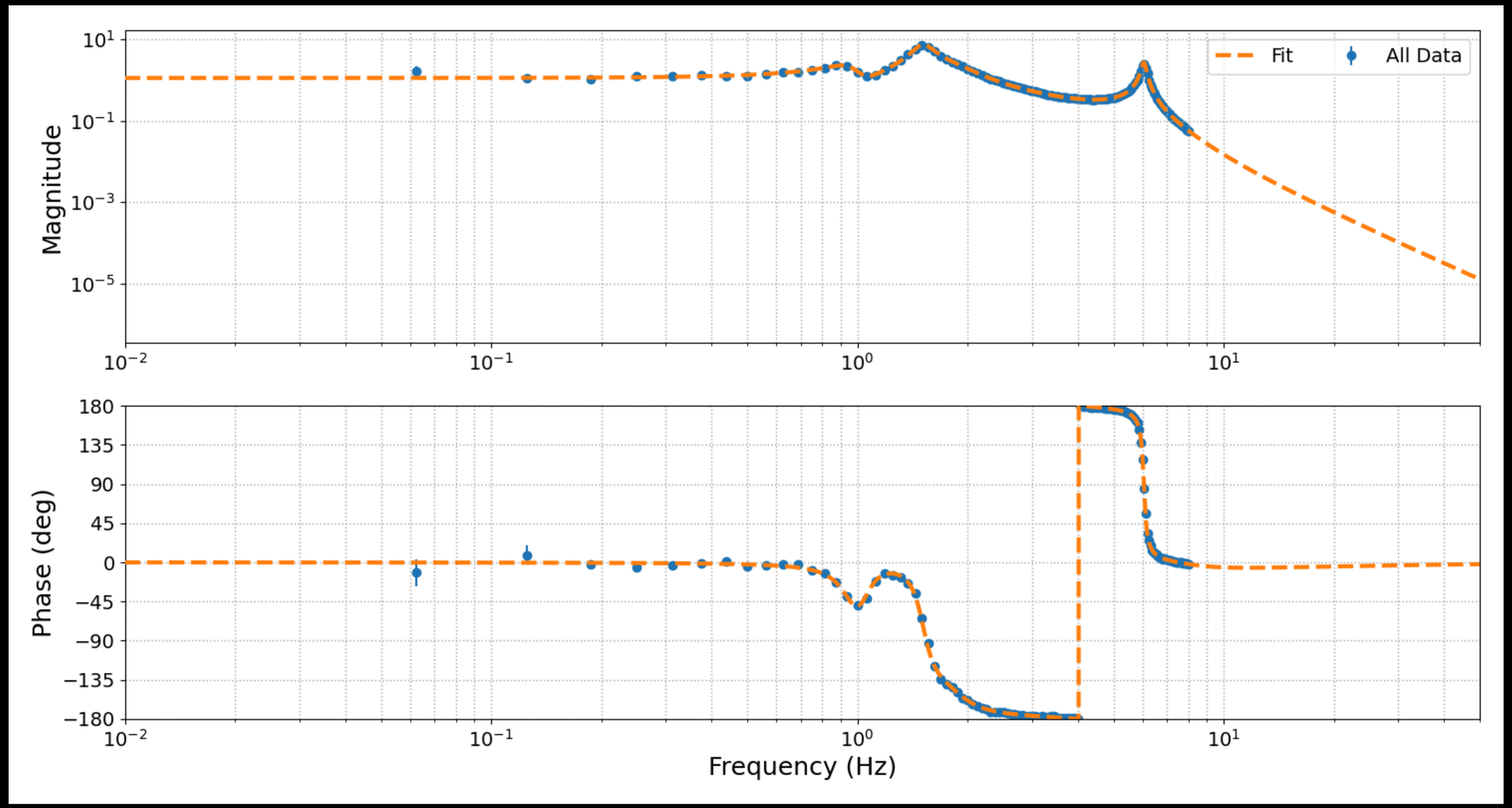
$$\begin{bmatrix} \mathrm{ZM1}_{\mathrm{Yaw}} \\ \mathrm{ZM3}_{\mathrm{Yaw}} \end{bmatrix} = \begin{bmatrix} 0.005 & -0.004 \\ 0.003 & -0.004 \end{bmatrix} \begin{bmatrix} X_{\mathrm{FC1}} \\ X_{\mathrm{FC2}} \end{bmatrix} \rightarrow \begin{bmatrix} 500.0 & -500.0 \\ 375.0 & -625.0 \end{bmatrix}$$

ZM’S – PART 4

PLANT FILTERS FOR ZM'S

LIGO-T2500287

ZM1 PITCH Fitting Plot



LIGO-T2500287

https://git.ligo.org/vladimir.bossilkov/chebychef

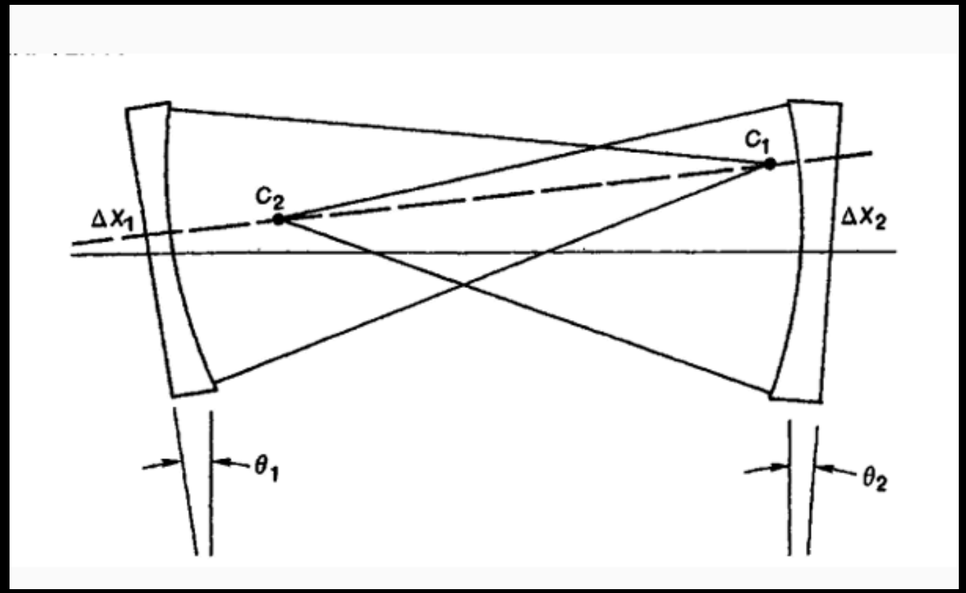
PART 5

FC LOOPS

BEAM SPOT POSITION

$$\begin{bmatrix} x_1 \\ \\ x_2 \end{bmatrix} = \frac{L}{1 - g_1 g_2} \begin{bmatrix} g_2 & 1 \\ \\ 1 & g_1 \end{bmatrix} \begin{bmatrix} \theta_1 \\ \\ \theta_2 \end{bmatrix}$$

$$g_i = 1 - \frac{L}{R_i}, \quad i = 1, 2$$



$$\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \frac{L}{1 - g_1 g_2} \begin{bmatrix} g_2 & 1 \\ 1 & g_1 \end{bmatrix} \begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix}$$

$$L = 300,$$

$$g_1 = 1,$$

$$g_2 = \frac{231}{531}$$

Substitute L, g1 and g2

$$\begin{bmatrix} X_{\mathrm{FC1}} \\ X_{\mathrm{FC2}} \end{bmatrix} = \begin{bmatrix} 231 & 531 \\ 531 & 531 \end{bmatrix} \begin{bmatrix} \theta_{\mathrm{FC1}} \\ \theta_{\mathrm{FC2}} \end{bmatrix}$$

Invert the Matrix

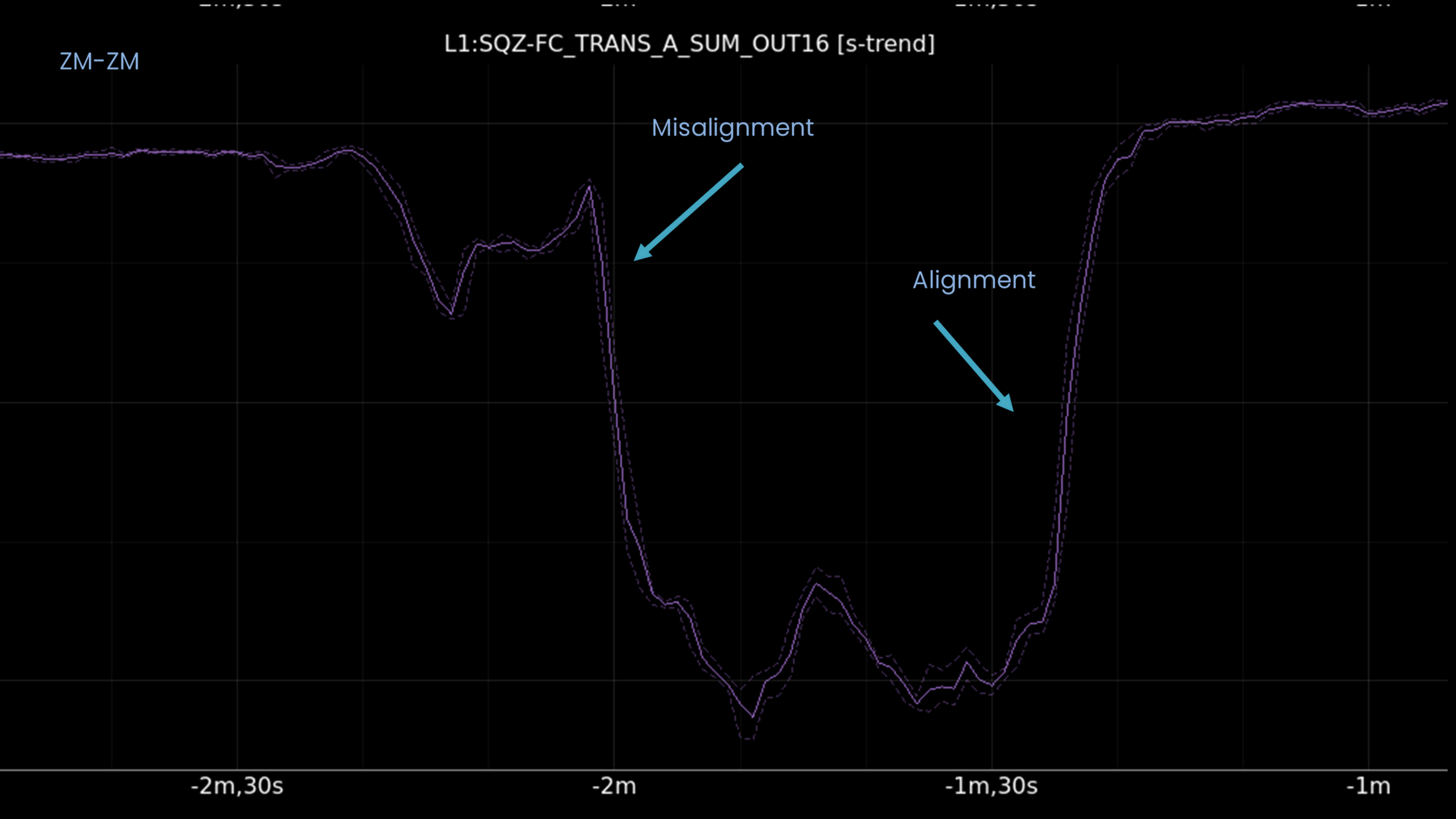
$$\begin{bmatrix} \theta_{\mathrm{FC1}} \\ \theta_{\mathrm{FC2}} \end{bmatrix} = \begin{bmatrix} -3 & 3 \\ 3 & -1 \end{bmatrix} \begin{bmatrix} X_{\mathrm{FC1}} \\ X_{\mathrm{FC2}} \end{bmatrix}$$

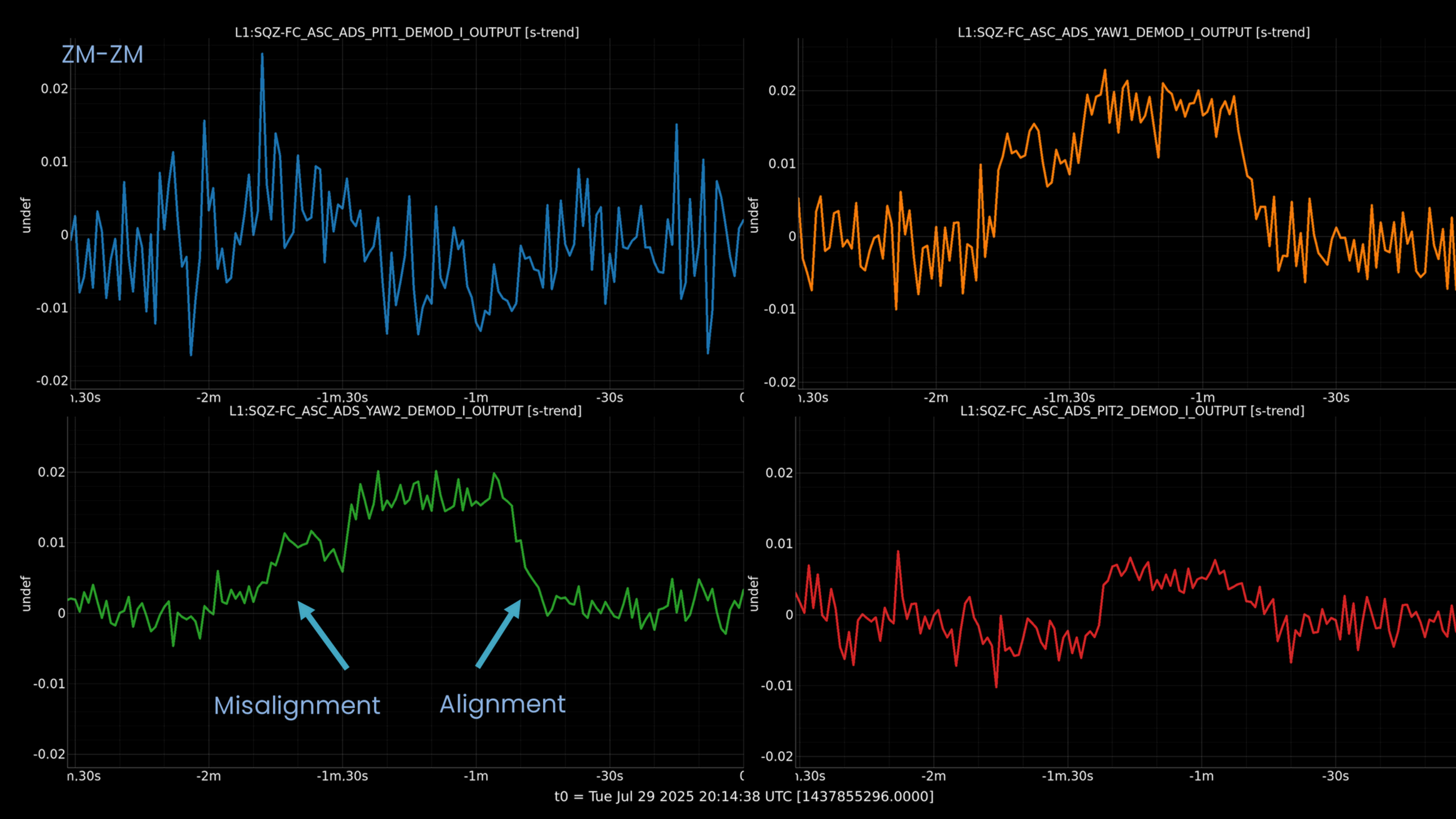
Pitch

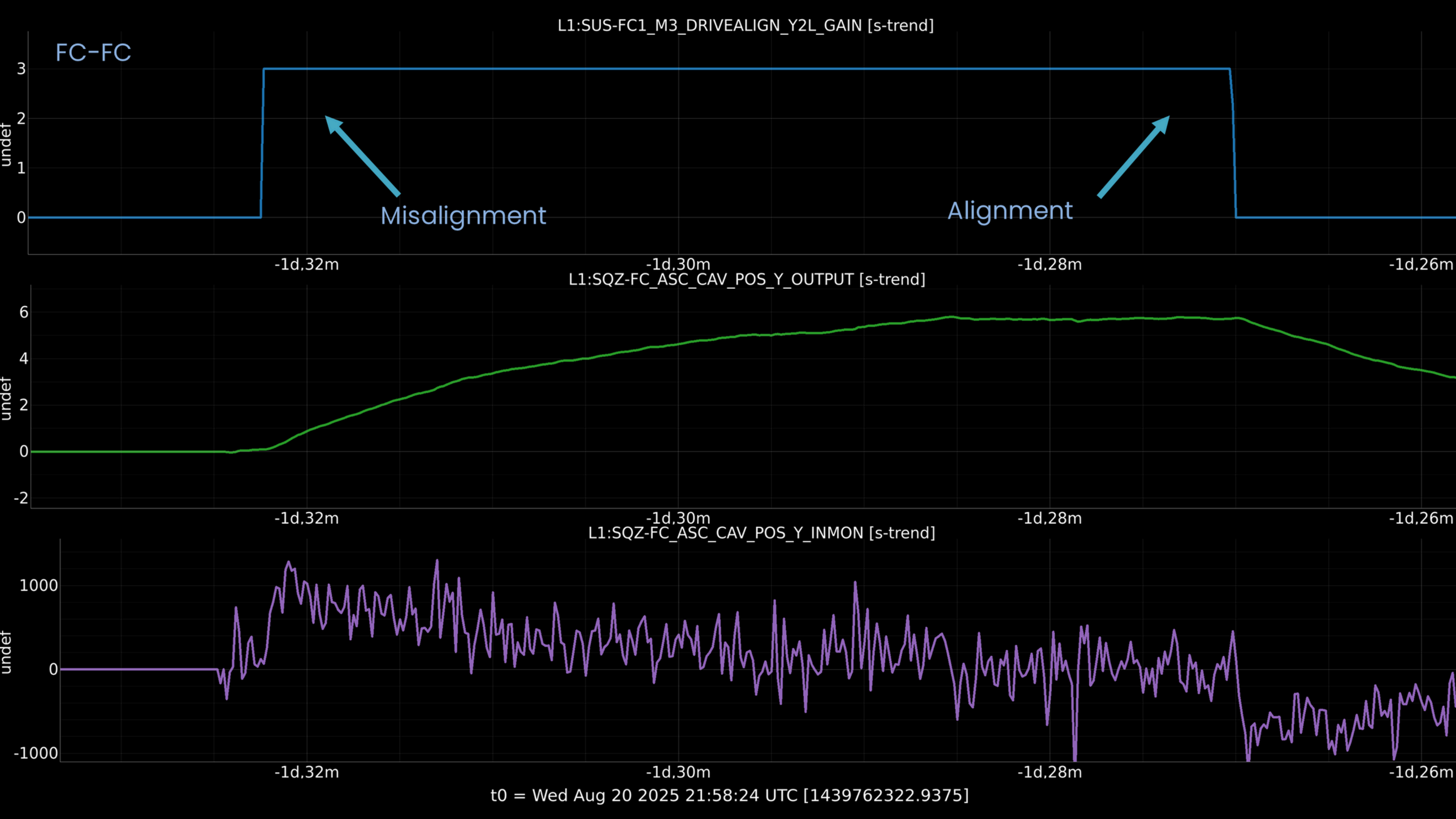
$$\begin{bmatrix} \theta_{\mathrm{FC1}} \\ \theta_{\mathrm{FC2}} \end{bmatrix} = \begin{bmatrix} -3 & 3 \\ -3 & 1 \end{bmatrix} \begin{bmatrix} X_{\mathrm{FC1}} \\ X_{\mathrm{FC2}} \end{bmatrix}$$

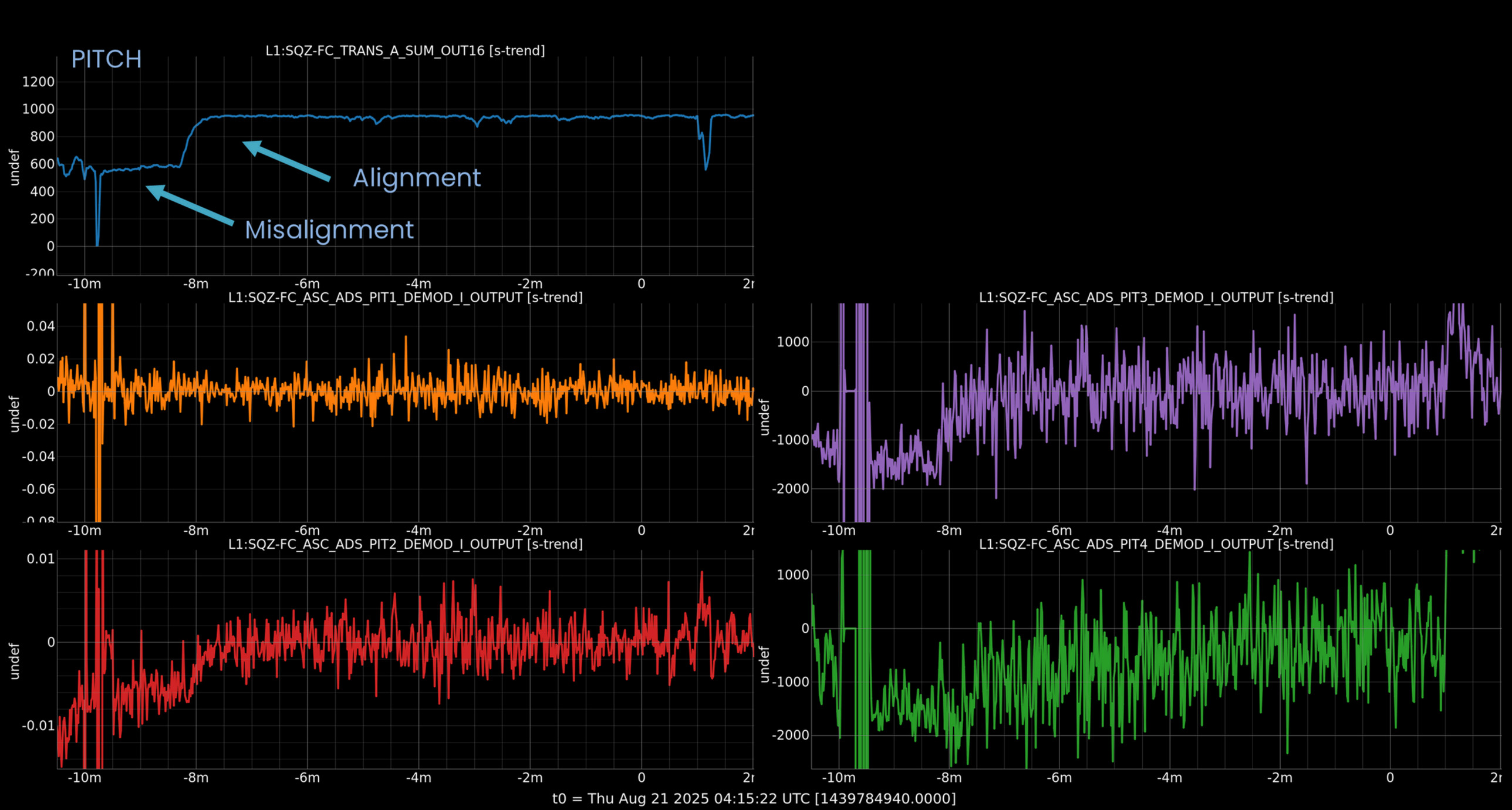
Yaw

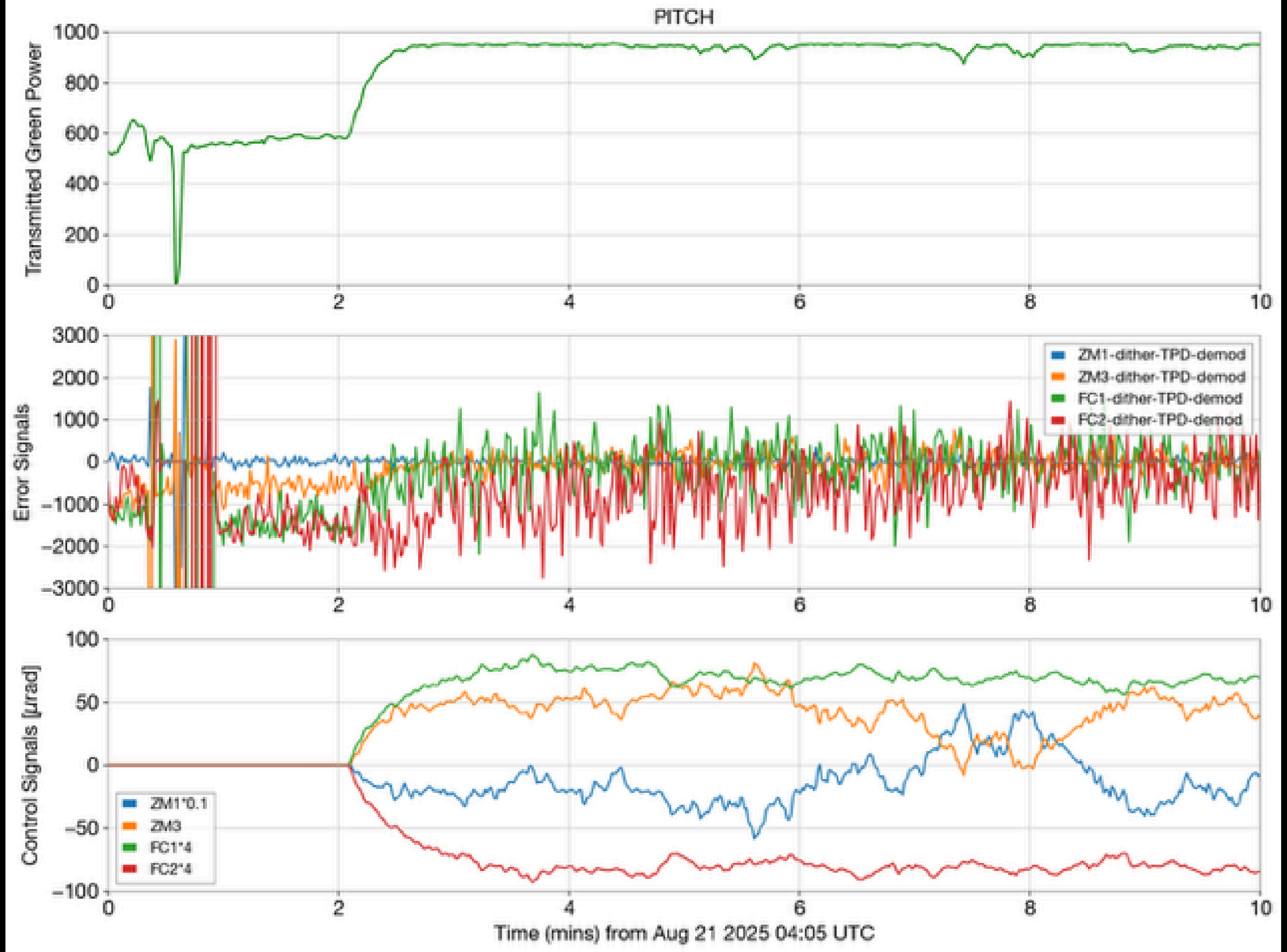
RESULTS

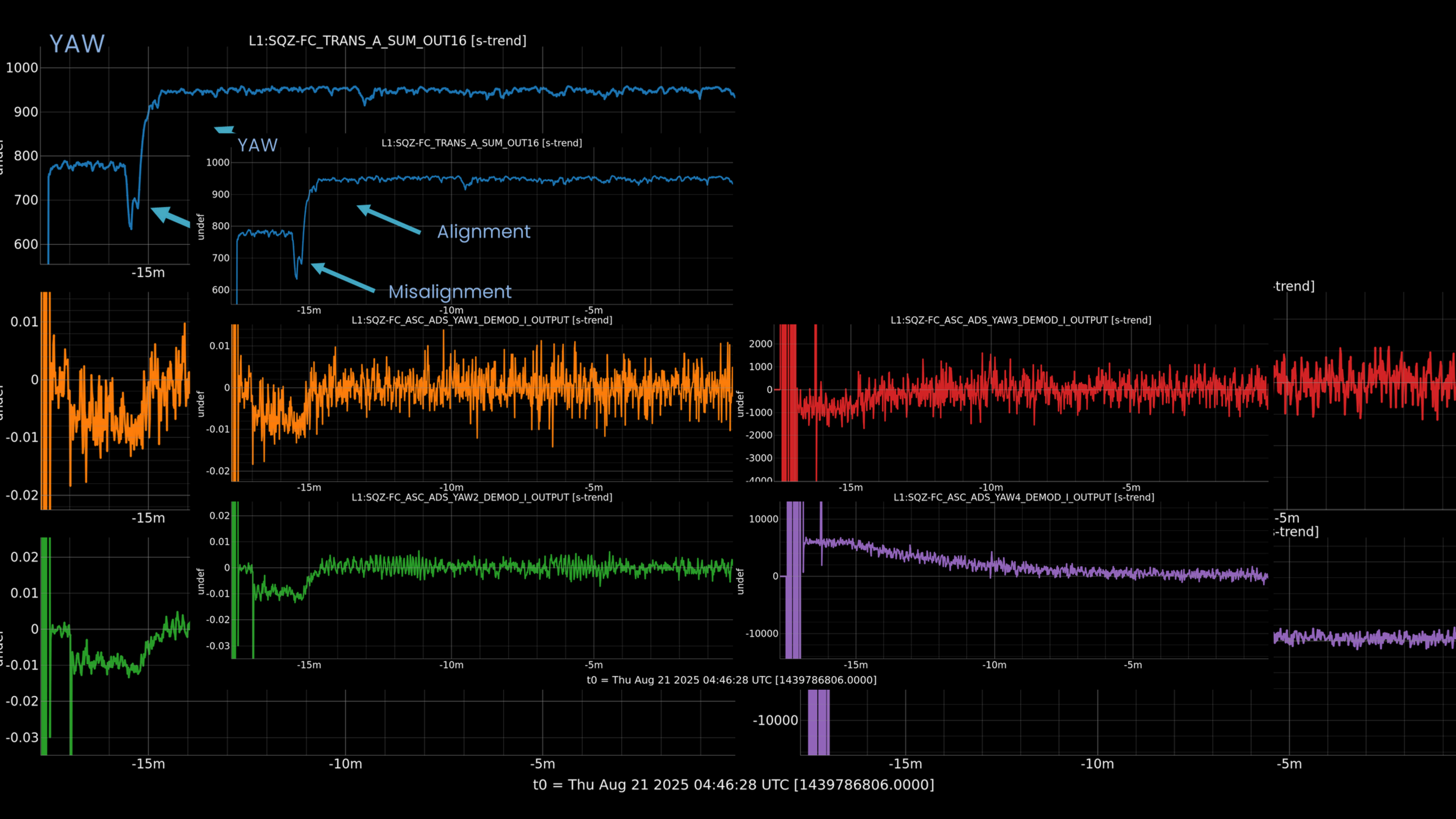

L1:SQZ-FC_TRANS_A_SUM_OUT16 [s-trend]
ZM-ZM
Misalignment
Alignment
-2m,30s
-2m
-1m,30s
-1m

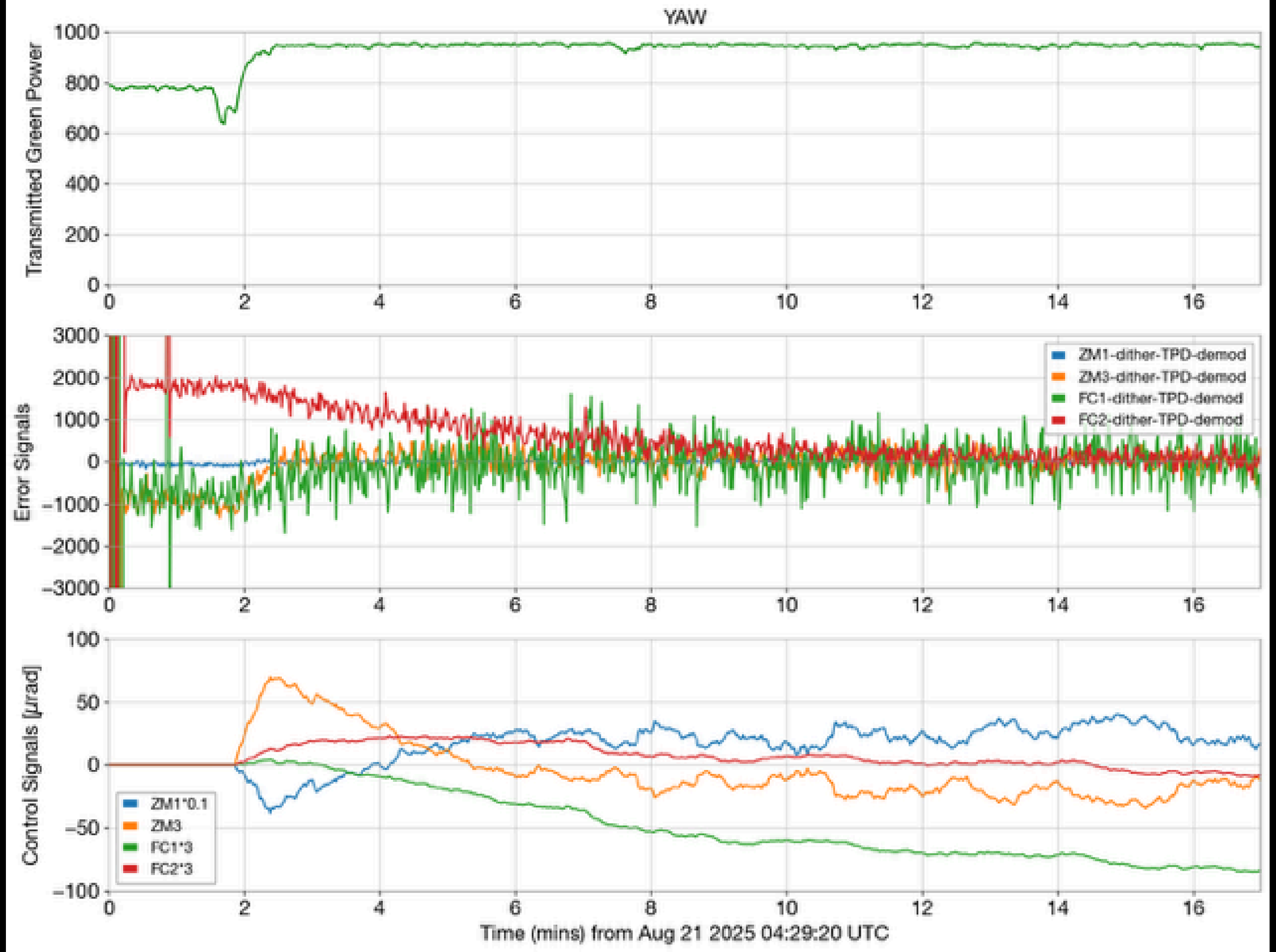

ZM−ZM
L1:SQZ-FC_ASC_ADS_PIT1_DEMOD_I_OUTPUT [s-trend]
L1:SQZ-FC_ASC_ADS_YAW1_DEMOD_I_OUTPUT [s-trend]
L1:SQZ-FC_ASC_ADS_YAW2_DEMOD_I_OUTPUT [s-trend]
L1:SQZ-FC_ASC_ADS_PIT2_DEMOD_I_OUTPUT [s-trend]
undef
0.02
0.01
0
-0.01
-0.02
-2m
-1m,30s
-1m
-30s
Misalignment
Alignment
t0 = Tue Jul 29 2025 20:14:38 UTC [1437855296.0000]


L1:SUS-FC1_M3_DRIVEALIGN_Y2L_GAIN [s-trend]
FC-FC
3
2
1
0
undef
Misalignment
Alignment
-1d,32m
-1d,30m
-1d,28m
-1d,26m
L1:SQZ-FC_ASC_CAV_POS_Y_OUTPUT [s-trend]
6
4
2
0
-2
undef
-1d,32m
-1d,30m
-1d,28m
-1d,26m
L1:SQZ-FC_ASC_CAV_POS_Y_INMON [s-trend]
1000
0
-1000
undef
-1d,32m
-1d,30m
-1d,28m
-1d,26m
t0 = Wed Aug 20 2025 21:58:24 UTC [1439762322.9375]


PITCH
L1:SQZ-FC_TRANS_A_SUM_OUT16 [s-trend]
1200
1000
800
600
400
200
0
-200
undef
Alignment
Misalignment
-10m
-8m
-6m
-4m
-2m
0
L1:SQZ-FC_ASC_ADS_PIT1_DEMOD_I_OUTPUT [s-trend]
0.04
0.02
0
-0.02
-0.04
-0.06
L1:SQZ-FC_ASC_ADS_PIT3_DEMOD_I_OUTPUT [s-trend]
1000
0
-1000
-2000
L1:SQZ-FC_ASC_ADS_PIT2_DEMOD_I_OUTPUT [s-trend]
0.01
0
-0.01
L1:SQZ-FC_ASC_ADS_PIT4_DEMOD_I_OUTPUT [s-trend]
t0 = Thu Aug 21 2025 04:15:22 UTC [1439784940.0000]


PITCH
Transmitted Green Power
1000
800
600
400
200
0
0
2
4
6
8
10
Error Signals
3000
2000
1000
0
−1000
−2000
−3000
ZM1-dither-TPD-demod
ZM3-dither-TPD-demod
FC1-dither-TPD-demod
FC2-dither-TPD-demod
Control Signals [µrad]
100
50
0
−50
−100
ZM1*0.1
ZM3
FC1*4
FC2*4
Time (mins) from Aug 21 2025 04:05 UTC


YAW
L1:SQZ-FC_TRANS_A_SUM_OUT16 [s-trend]
1000
900
800
700
600
undef
-15m
YAW
L1:SQZ-FC_TRANS_A_SUM_OUT16 [s-trend]
Alignment
Misalignment
-15m
-10m
-5m
L1:SQZ-FC_ASC_ADS_YAW1_DEMOD_I_OUTPUT [s-trend]
L1:SQZ-FC_ASC_ADS_YAW3_DEMOD_I_OUTPUT [s-trend]
L1:SQZ-FC_ASC_ADS_YAW2_DEMOD_I_OUTPUT [s-trend]
L1:SQZ-FC_ASC_ADS_YAW4_DEMOD_I_OUTPUT [s-trend]
t0 = Thu Aug 21 2025 04:46:28 UTC [1439786806.0000]


YAW
Transmitted Green Power
1000
800
600
400
200
0
0
2
4
6
8
10
12
14
16
Error Signals
3000
2000
1000
0
−1000
−2000
−3000
ZM1-dither-TPD-demod
ZM3-dither-TPD-demod
FC1-dither-TPD-demod
FC2-dither-TPD-demod
Control Signals [μrad]
100
50
0
−50
−100
ZM1*0.1
ZM3
FC1*3
FC2*3
Time (mins) from Aug 21 2025 04:29:20 UTC

CONCLUSION

FC GREEEN
ANGULAR
CONTROL LOOP
COMISSIONED

ZM TO ZM

ZM Loops
compensating
the ZM errors

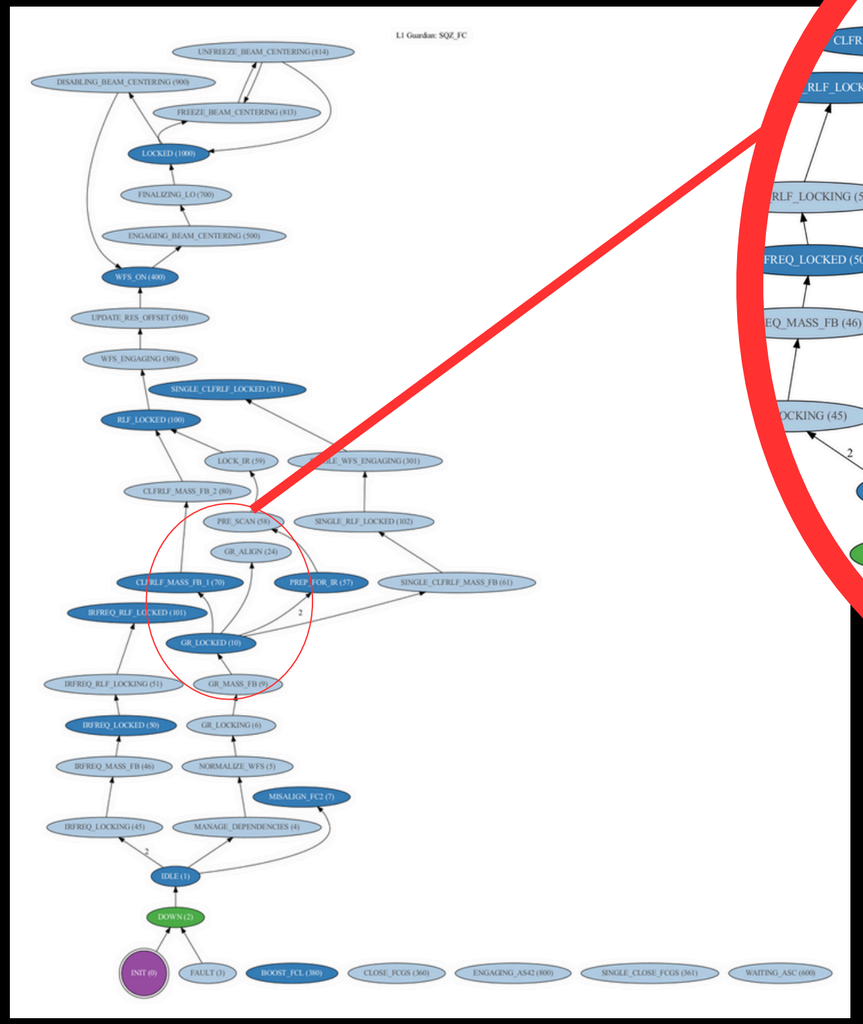
ZM TO FC

ZM Loops
compensating
the FC errors

FC TO FC

FC Loops
compensating
the FC errors

GUARD STATE “ GR_ALIGN “



LIGO-T2500287

/opt/rtcds/userapps/release/s1z/l1/guardian/SQZ_FC.py

FUTURE WORK

IMPLEMENTATION

Implementing the guardian state into filter cavity locking sequence

FINE-TUNING

Input, output matrix values

GRAD SCHOOL APPLICATION

Personal future outlook :)

ACKNOWLEDGES

CALTECH

NATIONAL SCIENCE FOUNDATION

LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

Thanks to my mentors Adam, Begum. and all the people in the Ligo Livingston Observatory. To the all the people that I met during this 10 weeks journey.

QUESTIONS

Phone
+1 225 224 56 58

Email
t.ilkim.dogan@gmail.com

Linkedin
linkedin.com/in/tomrisilkim