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Loss map measurement at Caltech 40 m lab

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Abstract

In order to know how dirty the test mass had got and well characterize 40 m interferometer, I measured round trip loss of both arms with the beam position on ETM shifted and the beam position on ITM fixed via ASS. I did this measurement at 5x5 points of the beam position for each arm. The result was that the round trip losses were ~480 ppm for X arm and ~230 ppm for Y arm, and the loss did not vary significantly depending on the beam position on ETM. In principle, the same measurement can be done for ITM but it was difficult to perform due to ASS issue and it has not been done yet.

Motivation

-- To characterize the interferometer well

According to the cavity scan experiment performed just before, arm loss was estimated to be ~2000 ppm, which is inconsistent with measured power recycling gain of ~ 7.0. We had to know what amount of loss there really exist.

-- To help make a plan about cleaning test masses at the next vent

Locally dirty or uniformly dirty ?

Method

Outline of the measurement:

1. Lock an arm with POX/POY
2. Align mirrors with ASS
3. Measure POX/POY DC level
4. Misalign ETM
5. Measure POX/POY DC level

1 sequence.
This sequence was done for each beam position on ETM.

-- I wrote scripts for this measurement (usage: see Appendix).

-- From the ratio of two kinds of POX/POY DC level, round trip loss of the arm can be obtained. => Next slides

Method:

How to obtain loss

Power of reflected light

When the arm is locked:

$$P_L = P_0 \left[1 - (1-\alpha) \frac{4T_{\mathrm{ITM}}}{T_{\mathrm{tot}}^2} T_{\mathrm{loss}} \right]$$

$1-\alpha$: power ratio of mode matching carrier field

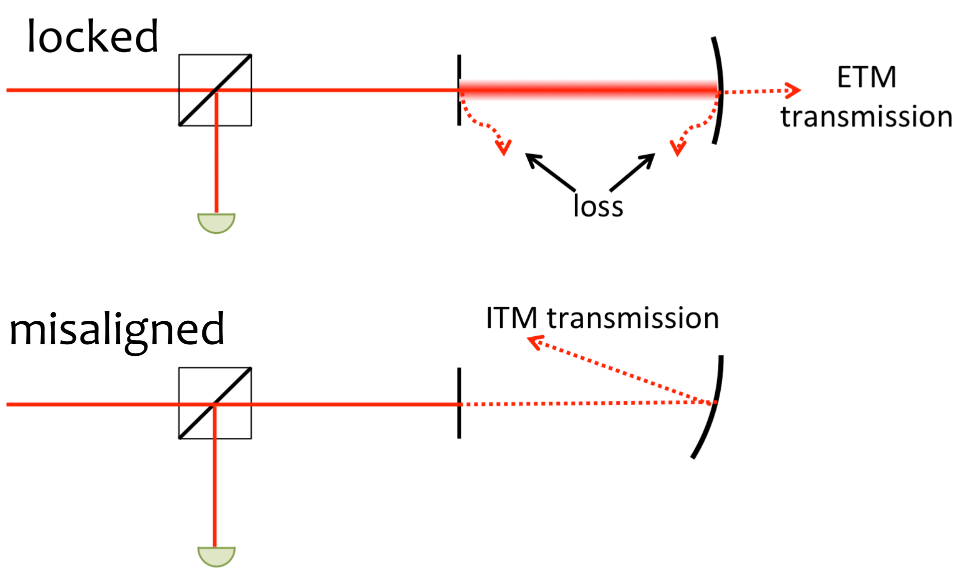
T_{ITM} : T of ITM, $T_{\mathrm{tot}} = T_{\mathrm{ITM}} + T_{\mathrm{loss}}$

T_{loss} : sum of loss and T of ETM

$(1-\alpha)P_0 \dfrac{4T_{\mathrm{ITM}}}{T_{\mathrm{tot}}^2}$: intracavity power

When ETM is misaligned:

$$P_M = P_0(1 - T_{\mathrm{ITM}})$$



Method:

How to obtain loss

$$\begin{cases} P_L = P_0\left[1-(1-\alpha)\dfrac{4T_{\rm ITM}}{T_{\rm tot}^2}T_{\rm loss}\right] \\ P_M = P_0(1-T_{\rm ITM}) \end{cases}$$

=> $$(1-\alpha)T_{\rm loss} = \frac{T_{\rm ITM}}{4}(1-P_L/P_M+T_{\rm ITM})$$

-- Roughly, loss is obtained as a product of $1-P_L/P_M$ (what is measured) and $T_{\rm ITM}$

-- In contrast, with other methods including ring down, cavity scan, and so on that measure finesse of the cavity, loss is obtained by $T_{\rm tot}-T_{\rm ITM}$, which is subtraction of two close numbers in many cases.

=> **This method is LESS sensitive to errors of measured value and $T_{\rm ITM}$.**

Method:

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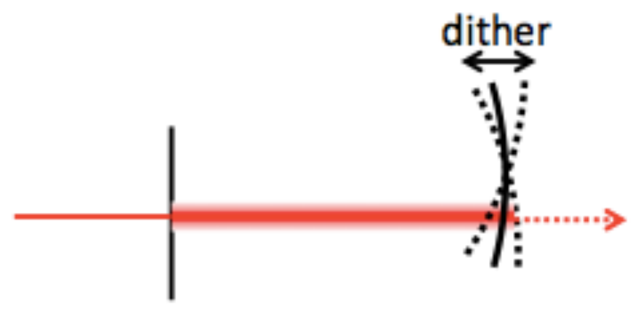
How to shift beam position



ASS (dithering)

-- beam centering

Mirrors dither at 4 different frequencies

(4 DoFs, ETM PIT/YAW, ITM PIT/YAW).

If the beam position is not centered on a certain mirror, cavity length will change at the frequency where the mirror dithers. Demodulate the length signal with this frequency and we get error signals of miscentering (4 DoFs).

-- mode matching

If incident beam and cavity axis do not match well, arm transmission power will vary at the dithering frequencies and so demodulation will give us the error signal of mode mismatch (4 DoFs).

Method:

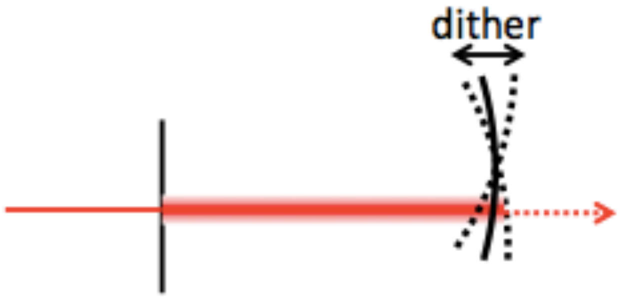
How to shift beam position

ASS for Y arm (BS-transmitted arm)

8 DoFs are controlled via these 8 angular DoFs:

ETMY PIT/YAW, ITMY PIT/YAW, TT1/2 PIT/YAW.

ASS for Xarm (BS-reflected arm)



8 DoFs are controlled via these 6 angular DoFs:

ETMX PIT/YAW, ITMX PIT/YAW, BS PIT/YAW.

=> DoFs are lacking!!

--> Beam position at ITMX is not controlled.

(ITMX is close to BS compared to ETMY, so usually it's not a big deal.)

Method:

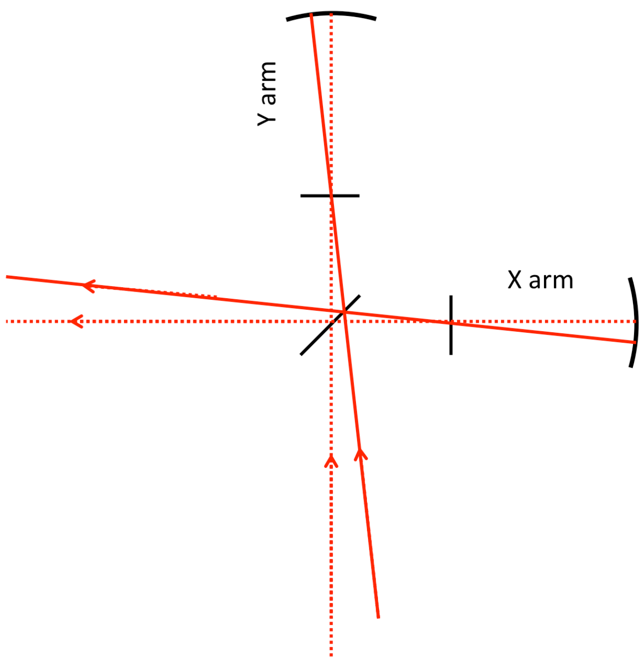
How to shift beam position

Beam position shift for Y arm (BS-transmitted arm)

Just add offset to the error signals of miscentering.

Beam position shift for X arm (BS-reflected arm)

Just adding offset to the error signals of miscentering on ETMX will shift slightly the position on ITMX and adding offset to the error signals of miscentering on ITMX will do nothing.
Then, I added offset to Y arm ASS as well as X arm ASS so that beam centering on ITMX is ensured by Y arm ASS, thanks to the symmetry between X and Y arm.



Method:

How to shift beam position

Calibration from the offsets to the shift of beam position

-- I did the calibration for the shift on ETMY and ETMX.

-- How I calibrated:

- got linear relation between offsets added just after the demodulation and angle of ETM and ITM measured with oplevs.

(Calibration method: see Appendix)

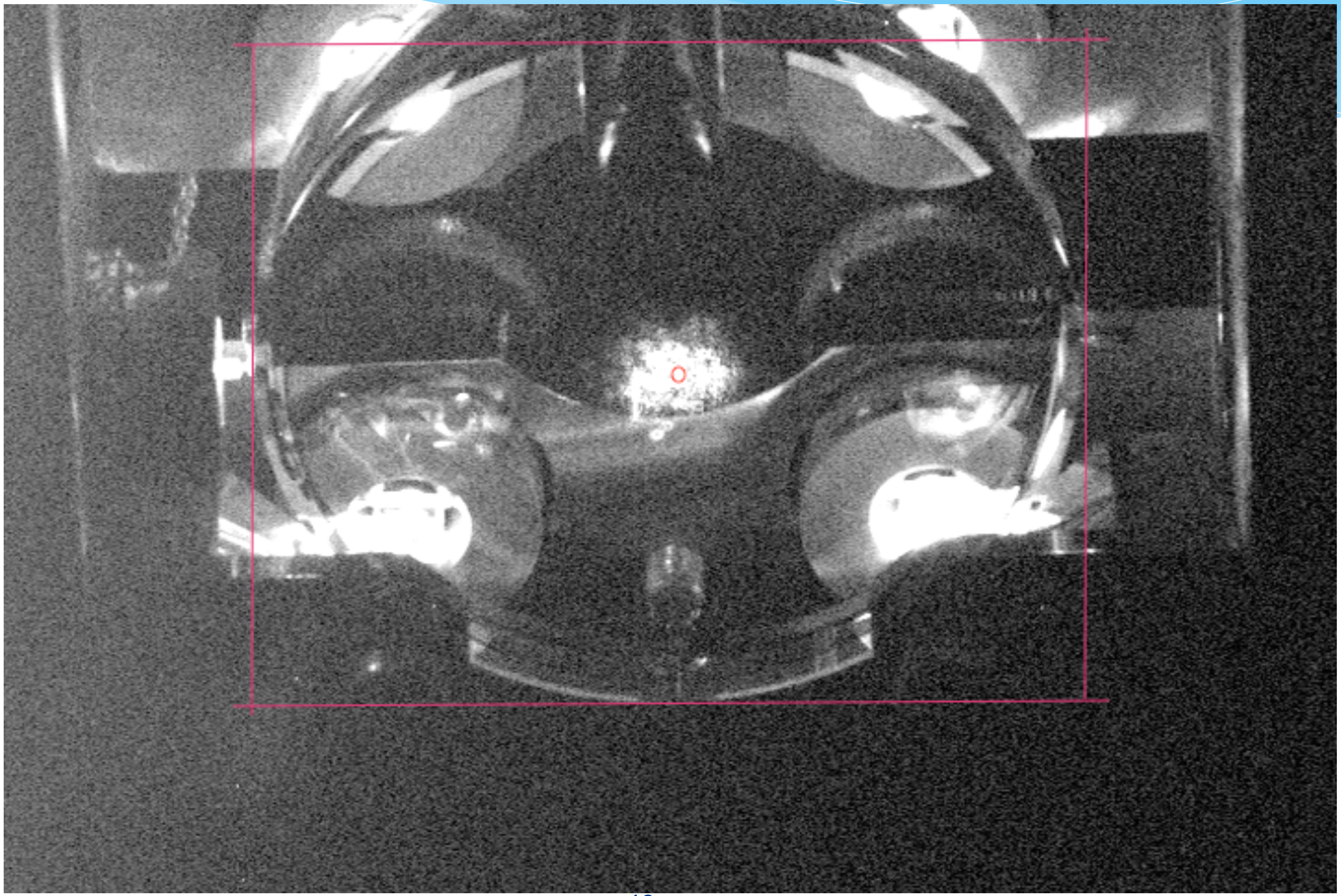
- For Y arm, I calibrated with captured images of ETMY using the diameter of the mirror as a standard of length.

(images are on the next slides).

--> The results of two calibration coincided.

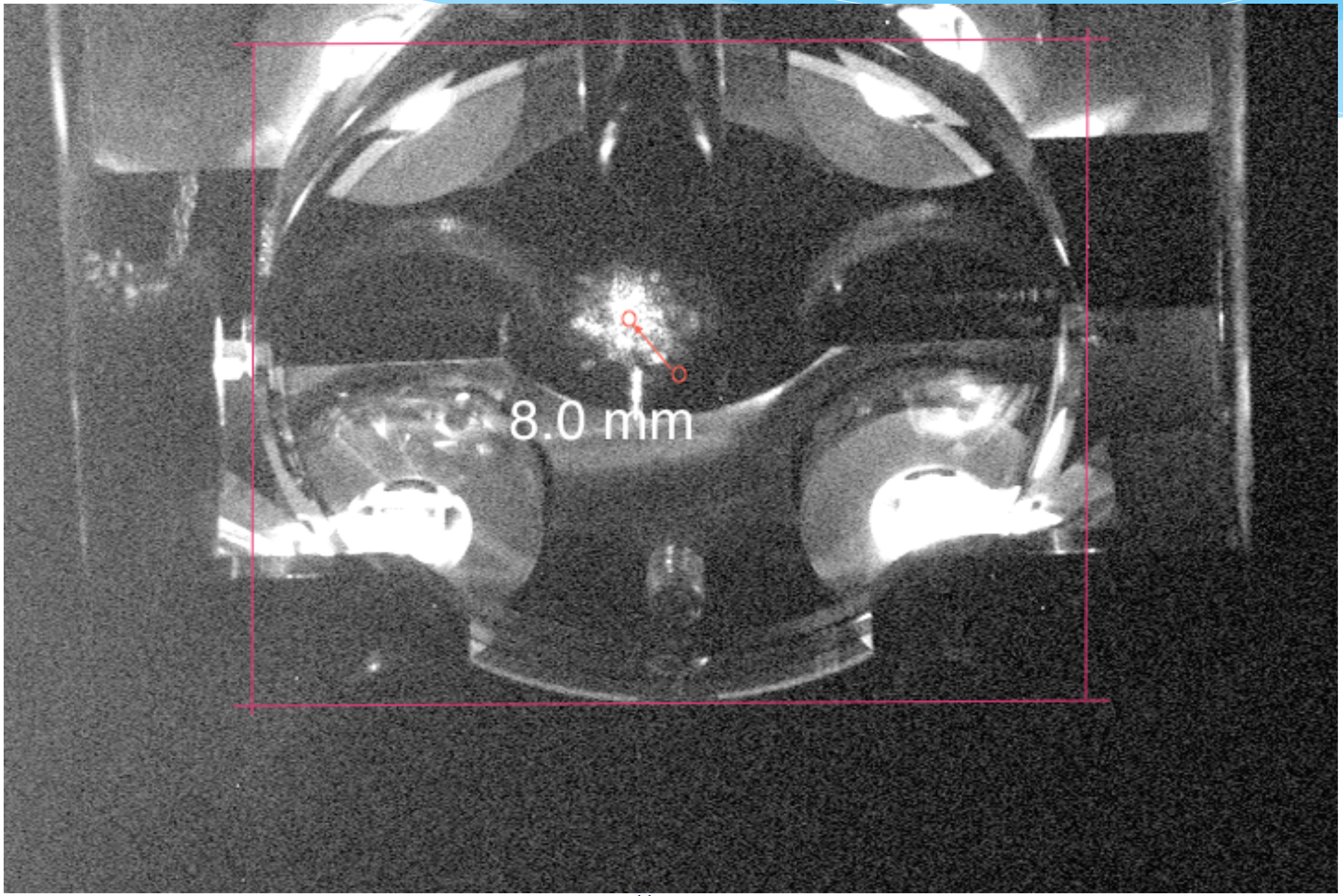
Method:

How to shift beam position



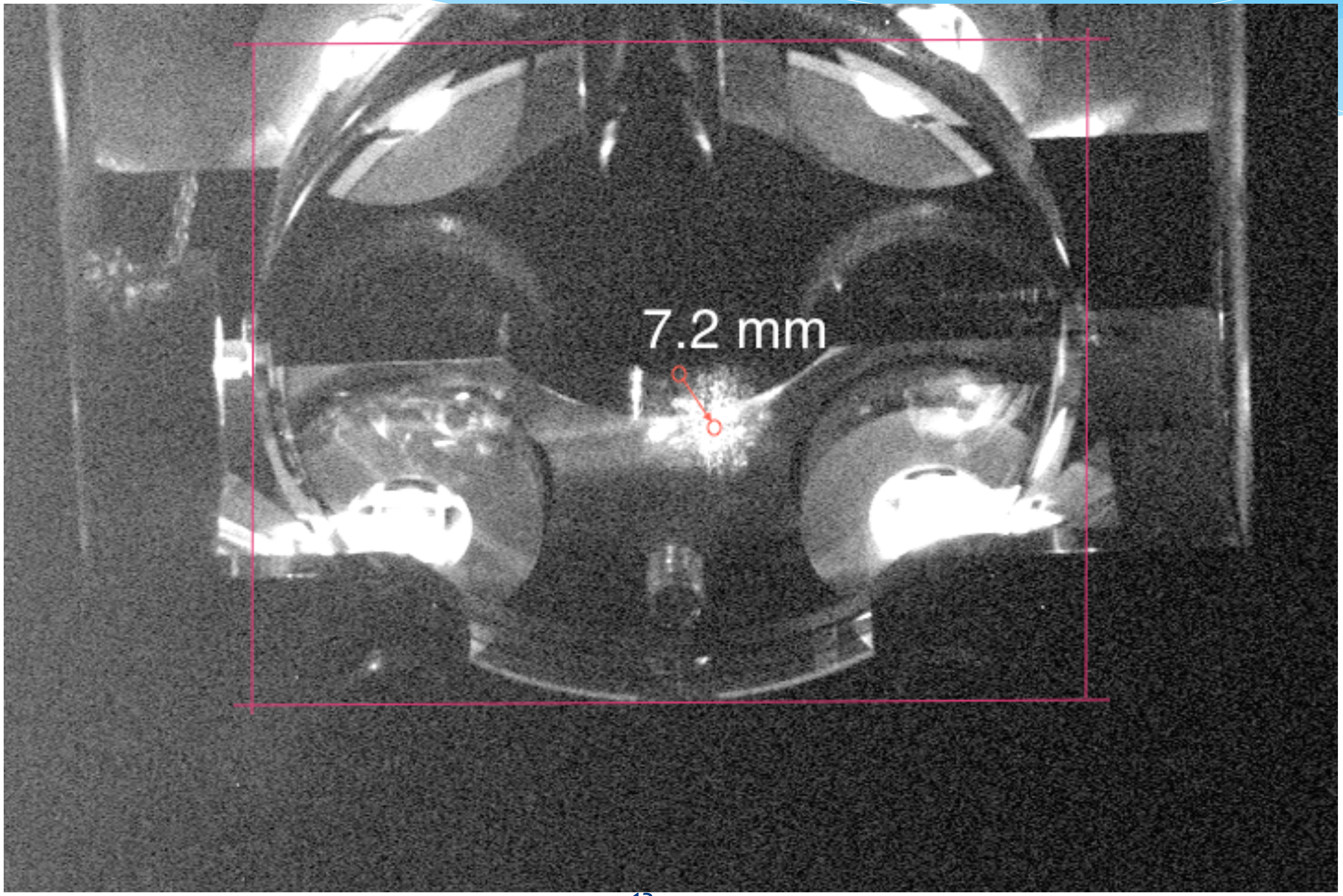
Method:

How to shift beam position



Method:

How to shift beam position



Results

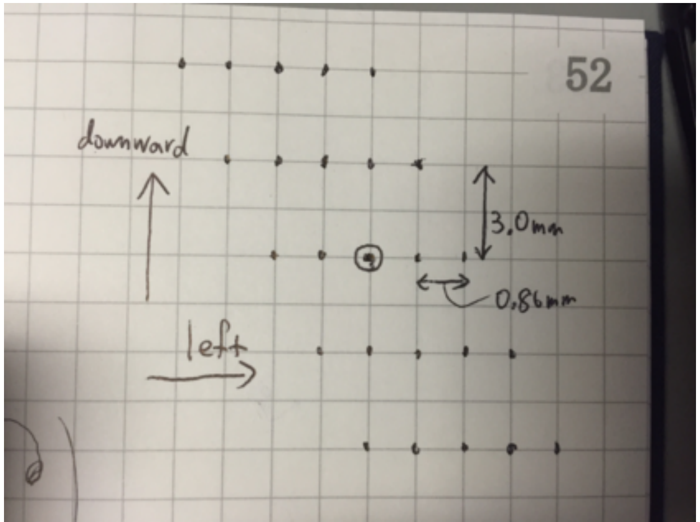
Loss map for ETMY

(unit: ppm)

494.9 +/- 7.6	356.8 +/- 6.0	253.9 +/- 7.9	250.3 +/- 8.2	290.6 +/- 5.1
215.7 +/- 4.8	225.6 +/- 5.7	235.1 +/- 7.0	284.4 +/- 5.4	294.7 +/- 4.5
205.2 +/- 6.0	227.9 +/- 5.8	229.4 +/- 7.2	280.5 +/- 6.3	320.9 +/- 4.3
227.9 +/- 5.7	230.5 +/- 5.5	262.1 +/- 5.9	315.3 +/- 4.7	346.8 +/- 4.2
239.7 +/- 4.5	260.7 +/- 5.3	281.2 +/- 5.8	333.7 +/- 5.0	373.8 +/- 4.9

Correspondence between each value of loss shown above and the amount of beam position shift. The shown directions correspond to the directions seen via ETMYF camera.

-->



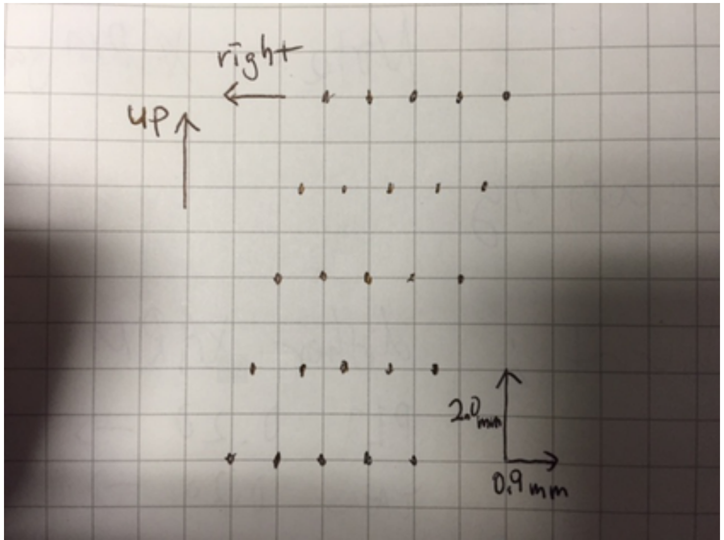
Results

Loss map for ETMX

(unit: ppm)

455.4 +/- 21.1	437.1 +/- 21.8	482.3 +/- 21.8	461.6 +/- 22.5	507.9 +/- 20.1
448.4 +/- 20.7	457.3 +/- 21.2	495.6 +/- 20.2	483.1 +/- 20.8	472.2 +/- 19.8
436.9 +/- 19.3	444.6 +/- 19.7	483.0 +/- 19.5	474.9 +/- 20.9	498.3 +/- 18.7
454.4 +/- 18.7	474.4 +/- 20.6	487.7 +/- 21.4	482.6 +/- 20.7	487.0 +/- 19.9
443.7 +/- 18.6	469.9 +/- 20.2	482.8 +/- 18.7	480.9 +/- 19.5	486.1 +/- 19.2

Correspondence between each value of loss shown above and the amount of beam position shift. The shown directions correspond to the directions seen via ETMXF camera. -->



Discussions

Consistency with measured power recycling gain (PRG)

-- In principle, PRG is determined by power transmittivity of PRM $T_{\rm PRM}$, amplitude reflectivity of PRM $r_{\rm PRM}$ and amplitude reflectivity of arm cavities $r_{\rm FP}$.

-- Then, with the results of arm loss measurement, PRG can be estimated as follows:

$$\mathrm{PRG} = \frac{T_{\rm PRM}}{(1 - r_{\rm PRM} r_{\rm FPMI})^2}$$

$$r_{\rm FP} = \sqrt{1 - \frac{4 T_{\rm ITM} T_{\rm loss}}{T_{\rm tot}^2}}$$

$$r_{\rm FPMI} = \frac{1}{2}(r_{\rm FP,X} + r_{\rm FP,Y})$$

I assumed: $T_{\rm ITM} \simeq T_{\rm tot} = \frac{2\pi}{401} = 0.01566$

$T_{\rm PRM} = 0.05637$ $r_{\rm PRM} = \sqrt{1 - T_{\rm PRM}}$

(finesse=401 and $T_{\rm PRM}$ are known.)

Discussions

Consistency with measured power recycling gain (PRG)

-- Estimated PRG is: **PRG = 9.8 +/- 0.8**

-- Mesured PRG is: PRG ~ 7.0

This estimate should be regarded as an upper bound.

☹ No other sources of loss are taken into account: for example mismatch between arm cavity mode and PRC mode, imperfect contrast of FPMI, and AR reflection of PR2 and PR3 (PR2 and PR3 are flipped because it otherwise makes PRC unstable).

- loss due to AR reflection of PR3 is ~ 4x0.5 % = 2 % according to specification. => **PRG = 7.8**

Discussions

Maximum offsets that can be added

-- When some amount of offset is added, arm transmission power starts degrading bacause ASS starts not working well.

=> This problem determined the maximum offsets now.

-- Shift in YAW suffers more from this problem than PIT; the maximum beam position shift in YAW is smaller than that of PIT.

-- Shift on ITM suffers more from this problem than ETM.

We have to find out why this problem occurs, to do loss map measurement for ITMs with the same method.

APPENDICES

Appendix:

Usage of the scripts

I wrote python scripts for this loss map measurement and put them in **/opt/rtcds/caltech/c1/scripts/lossmap_scripts**. You can copy this directory anywhere in controls if you want. The should work. In this directory, there are 7 scripts:

- lossmap.py	wrapper script
- lossmapx.py	do measurement and save data for X
- lossmapy.py	do measurement and save data for Y
- lossmapx_resume.py	restart measurement for X
- lossmapy_resume.py	restart measurement for Y
- lossmap_convert.py	convert data into round trip loss
- make.py	show results

Appendix:

Usage of the scripts

Usage of the wrapper script (1)

-- To start measurement from the beginning

Run the following command in an arbitrary directory and you will get several text files including the result of loss map measurement:

$ python /opt/rtcds/caltech/c1/scripts/lossmap_scripts/lossmap.py [maximum shift in mm (PIT)] [maximum shift in mm (YAW)] [arm name (XorY)] [mirror name (E or I)]

Optionally, you can add "AUTO" at the end of the above command. Without "AUTO", you will be asked if the dithering has already settled down or not after each shift of the beam spot and you can let the scripts wait until the dithering settles down sufficiently. If you add "AUTO", it will be judged if the dithering has settled down or not according to some criteria, and the measurement will continue without your response to the terminal.

The files to be created in the current directory by the scripts are:

- lossmapETMX1-1.txt # [POX power (locked)] / [POX power (misaligned)]
- lossmapETMX1-2.txt # standard deviation of [POX power (locked)] / [POX power (misaligned)]
- lossmapETMX1-3.txt # TRX
- lossmapETMX1-1_converted.txt # round trip loss (ppm) calculated from lossmapETMX1-1.txt
- lossmapETMX1-1_converted_sigma.txt # standard deviation of round trip loss calculated from 1-1.txt and 1-2.txt
- lossmapETMX_result.txt # round trip loss and its error in a clear form.

The name of the files would be "lossmapITMY1-1.txt" etc. depending on which mirror you have chosen.

Appendix:

Usage of the scripts

Usage of the wrapper script (2)

-- To restart measurement from a certain point

Run the following command in a directory containing "lossmap(mirror name)1-1.txt", "lossmap(mirror name)1-2.txt" and "lossmap(mirrorname)1-3.txt" which are created by previous not-completed measurement:

$ python /opt/rtcds/caltech/c1/scripts/lossmap_scripts/lossmap.py [maximum shift in mm (PIT)] [maximum shift in mm (YAW)] [arm name (XorY)] [mirror name (E or I)] [restart point (PIT)] [restart point (YAW)]

You can also add "AUTO".

How to designate the restart point:

Matrix elements of output of this measurement procedure are characterized by a pair of two numbers as the following shows.

```
(-1,-1) ->  (-1,-0.5) ->   (-1,0) ->     (-1,0.5)  ->     ( -1,1)
                                                             v
(-0.5,1) <- (-0.5,0.5) <- (-0.5,0) <- (-0.5,-0.5) <- (0.5,-1)
  v
(0,-1) ->   (0,-0.5)  ->   (0,0)  ->    (0,0.5)  ->     (0,1)
                                                             v
(0.5,1)  <- (0.5,0.5)  <- (0.5,0)  <- (0.5,-0.5)  <-   (0.5,-1)
  v
(1,-1) ->   (1,-0.5) ->    (1,0)  ->    (1,0.5)   ->    (1,1)
```

Please write the numbers that correspond to the matrix element you want to restart at. Arrows show the order of sequence of measurement. About the correspondence between the matrix elements and real position on the ETMY and ETMX, see elog 11818 and 11857, respectively.

This script will overwrite the files (~1-1.txt etc.) so it is safer to make backup of the files before you run this script.

Appendix:

Usage of the scripts

Some notes on the scripts and measurement

- Calibration has been done only for ETMs, i.e. for ITMs unit of [maximum shift] is not mm, but the values written in [maximum shift] equal to the maximum offsets added just after demodulation of ASS loop (ex. C1:ASS-YARM_ITM_PIT_L_DEMOD_I_OFFSET).

- It should be checked before doing measurement if the following parameters are correct or not.

POXzero (L47 in lossmapx.py and L52 in lossmapx_resume.py: the value of C1:LSC-POXDC_OUTPUT when no light injects into POXPD.)

POYzero (L45 in lossmapy.py and L50 in lossmapy_resume.py: the value of C1:LSC-POYDC_OUTPUT when no light injects into POYPD.)

mmr (L11 in lossmap_convert.py: (mode matching carrier power)/(total power))

Tf (L12 in lossmap_convert.py; transmittivity of ITM)

Tetm (L13 in lossmap_convert.py: transmittivity of ETM in ppm)

- Changing **n** (L50 in lossmap.py) from 5 to 3, the grid points will be 3x3 changed from the default value of 5x5. If 3x3, the matrix elements are characterized by

```
(-1,-1) -> (-1,0) -> (-1,1)
                        v
(0,1)  <-  (0,0) <-  (0,-1)
  v
(1,-1) ->  (1,0) ->  (1,1)
```

similarly to the case of 5x5.

- You can copy the directory lossmap_scripts anywhere in controls and use it. These scripts will work as long as all the 7 scripts exist in a same directory.

Appendix:

Calibration of oplevs

I calibrated oplevs for ETMs and ITMs using the following method.

-- lock an arm cavity

-- run dither and freeze dither

-- tilt one mirror of the cavity intentionally, and measure oplev output and the power of transmission of the arm.

How this method work:

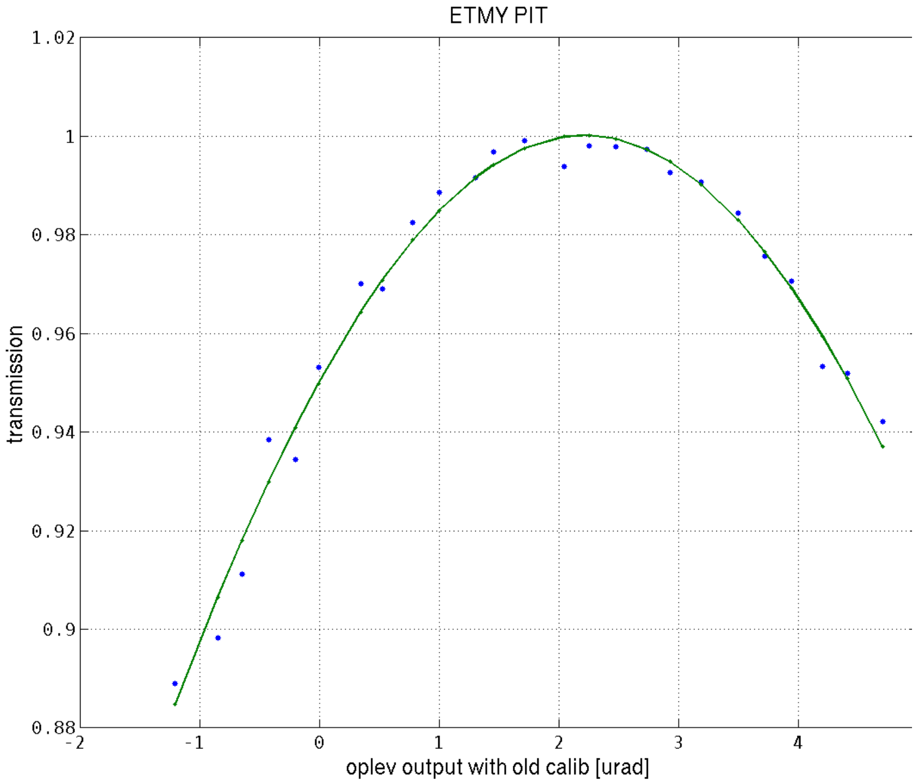
The transmission power degrades quadratically to the tilt angle, how the power degrades depends only on cavity length and RoC of ETM/ITM, which are known. Therefore calibrated angle can be obtained with this quadratic plot.

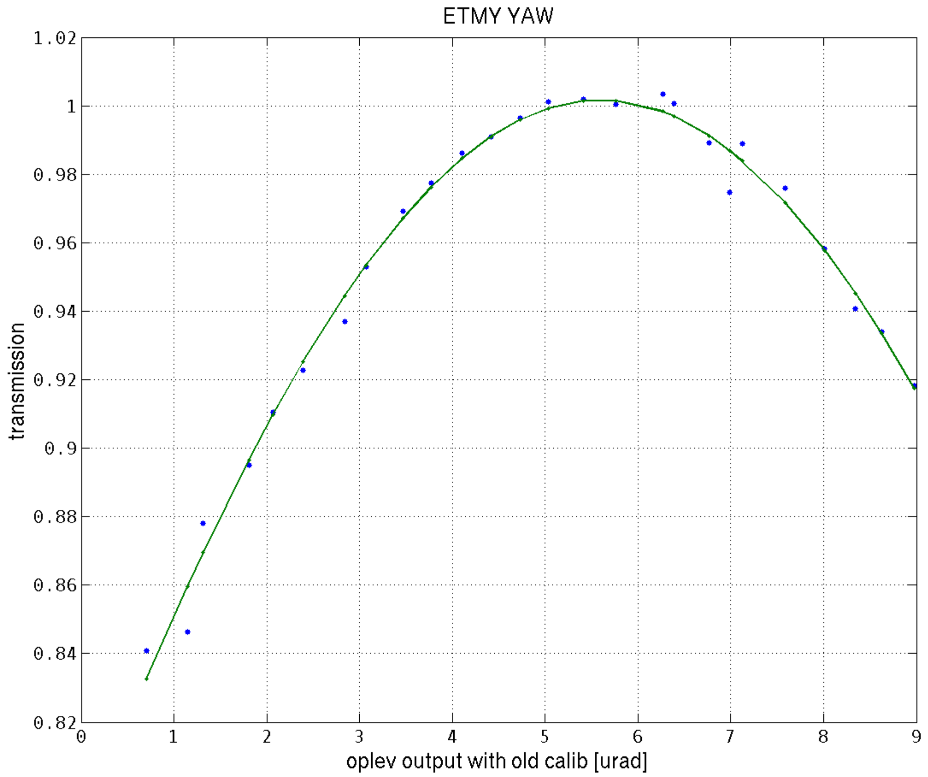
I used Kakeru's Matlab script to derive the calibration factor from the data (oplev output vs. transmission). See 40 m elog 1434 for more detail.

Appendix:

Calibration of oplevs

Results of calibration (ETMY)





Appendix:

Calibration of oplevs

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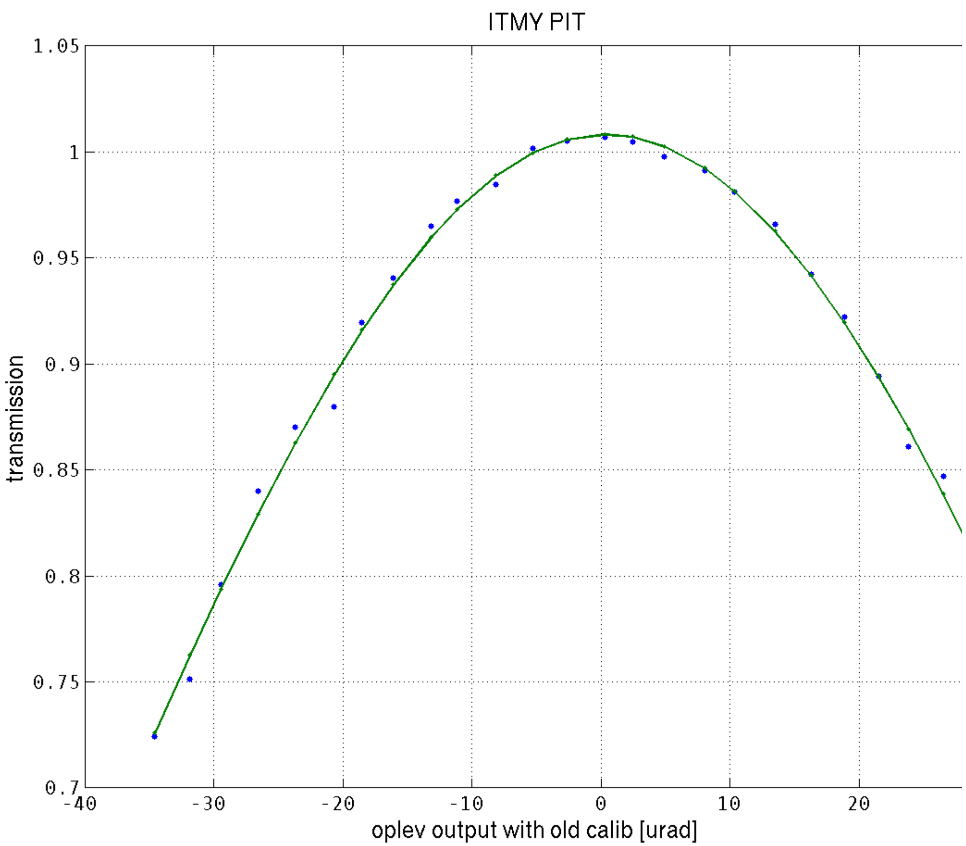
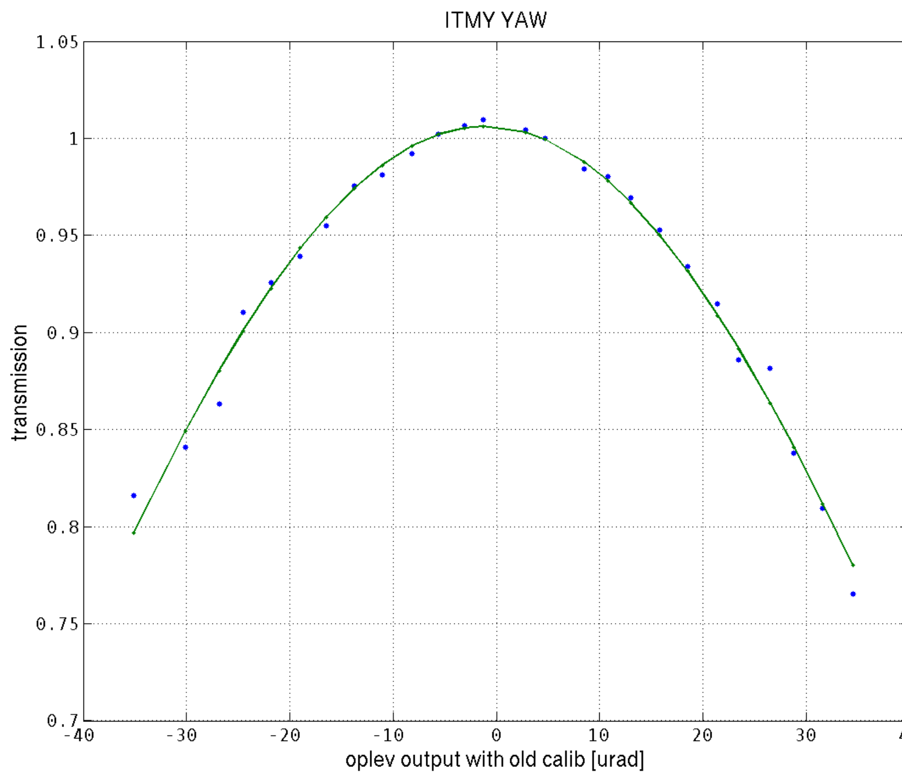
Results of calibration (ITMY)





Appendix:

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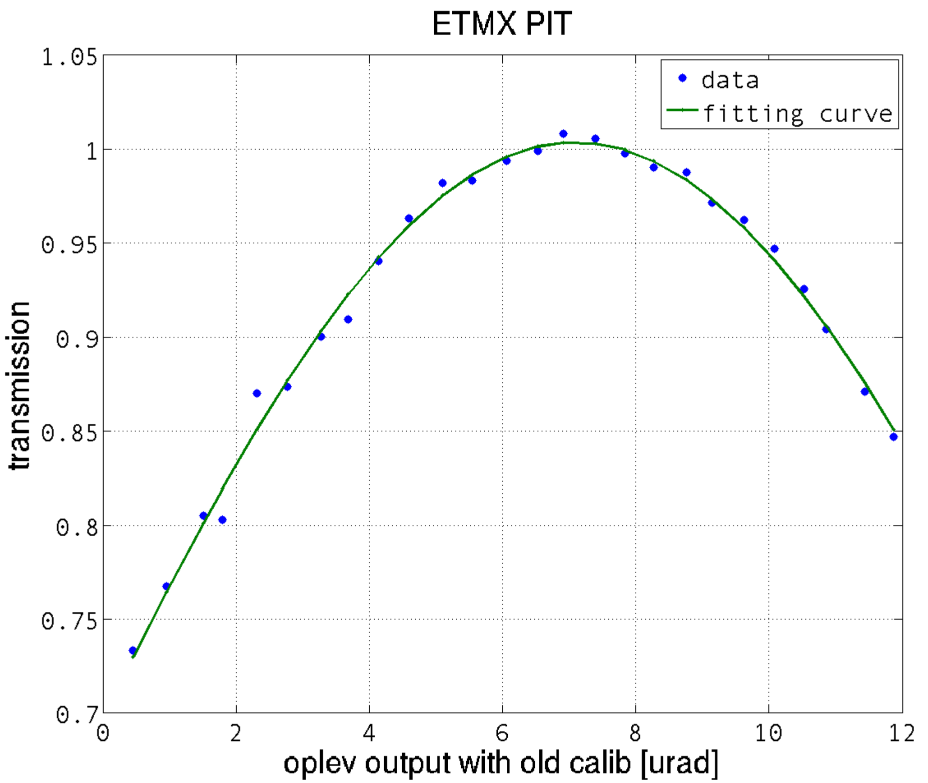
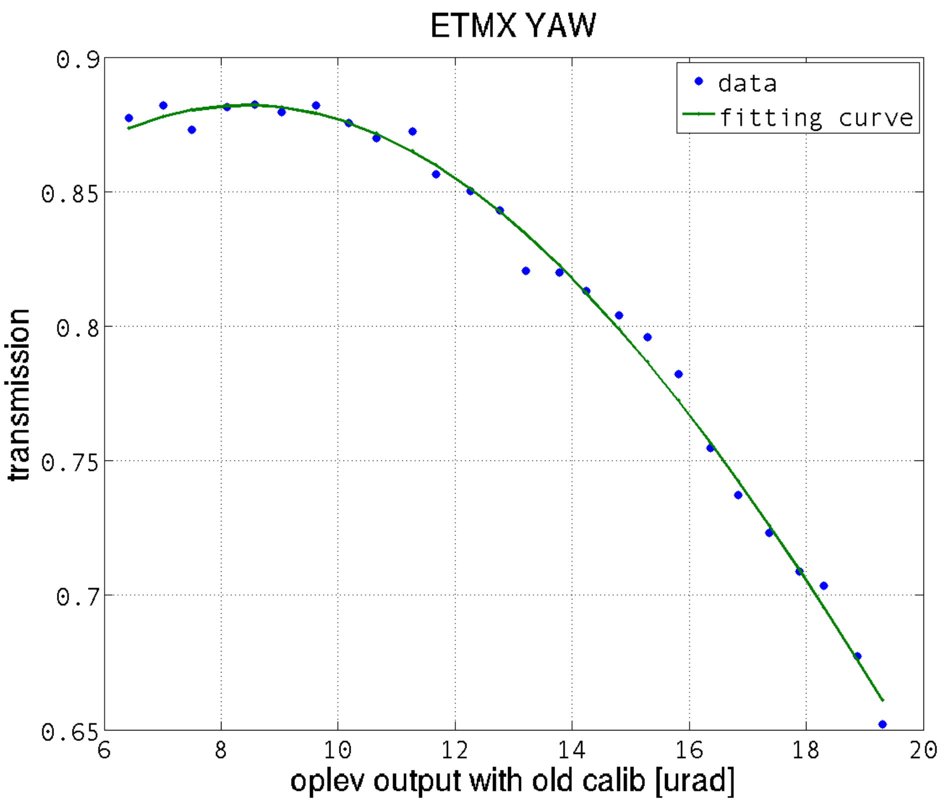
Calibration of oplevs

Results of calibration (ETMX)



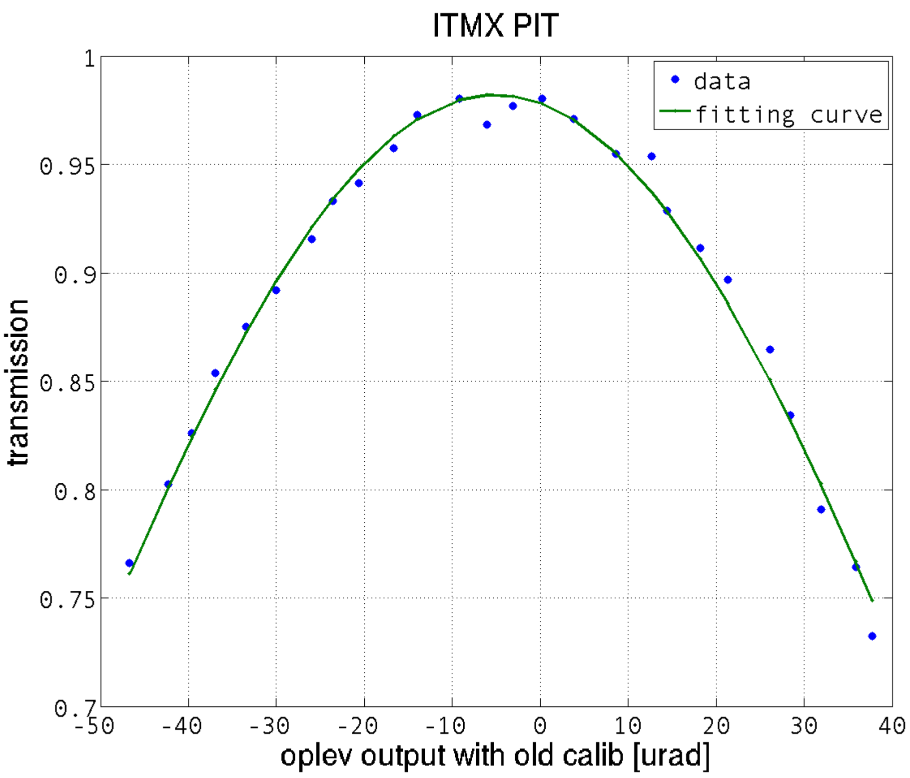


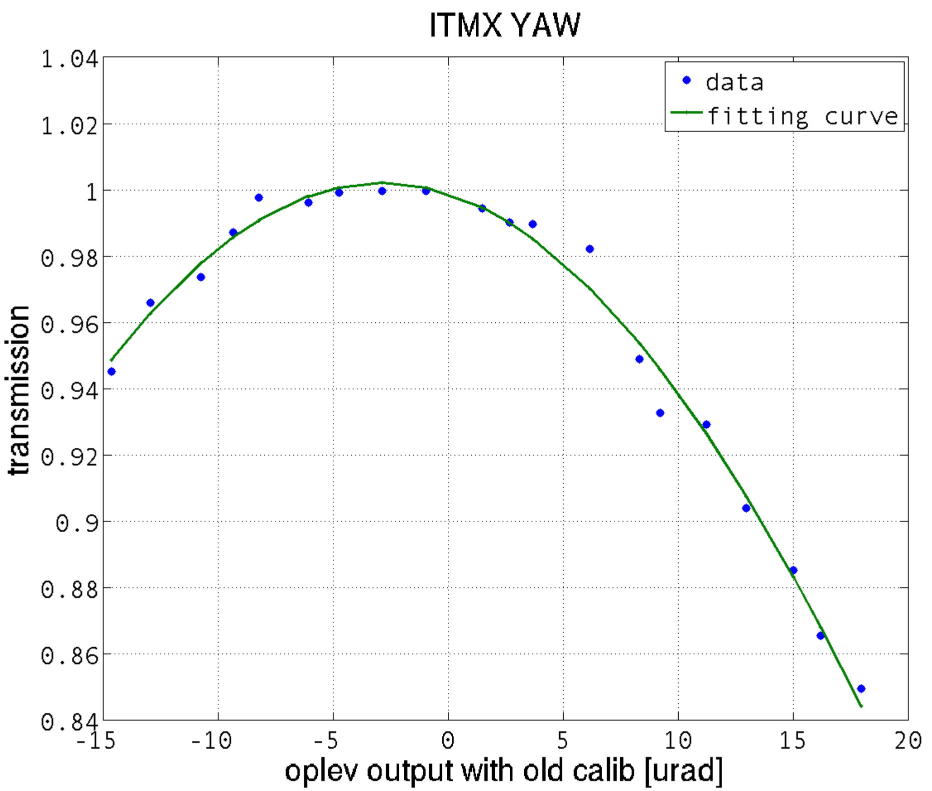
Appendix:

Dec 11, 2015

Calibration of oplevs

Results of calibration (ITMX)





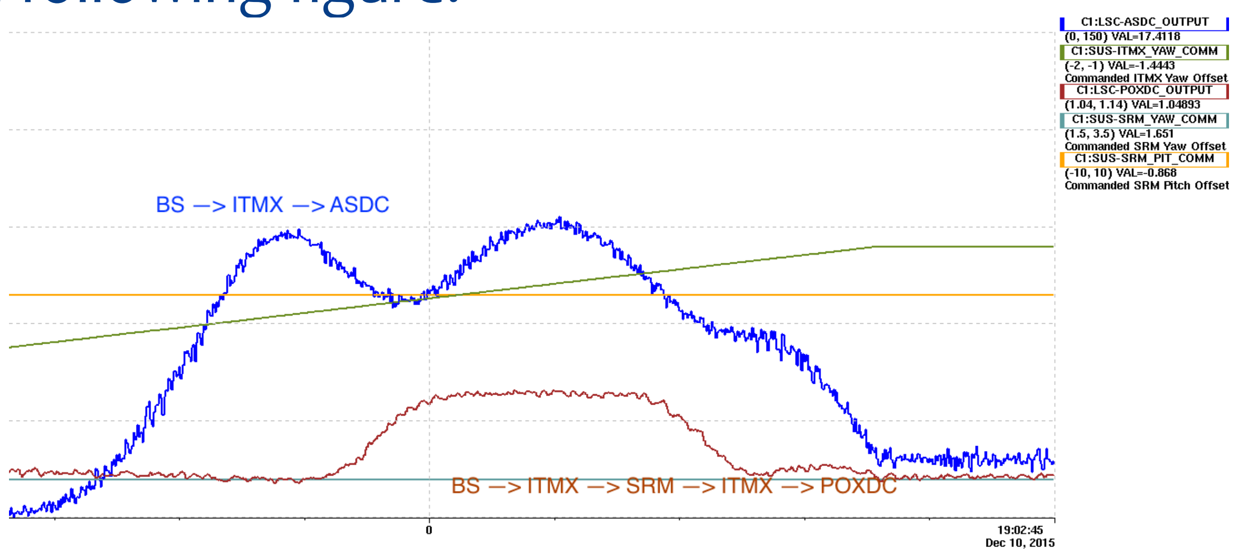
Appendix:

Practical issue

Strange behavior of ASDC

Considering noise level, it is better to use ASDC than POX/POY to measure the power of light reflected by an arm cavity. However, ASDC behaves strangely when the angle of the light coming into AS port, as shown in the following figure.

I confirmed that the cause of this behavior exists between AS table and SRM.



Appendix:

Practical issue

POX/POY often receives light reflected by PRM/SRM

The light that goes through the path:

MI -> PRM/SRM -> BS -> ITMX/ITMY -> POX/POY often gets into POX/POY PD.

So, DO misalign PRM/SRM completely!!

Just pushing the misalign button for PRM/SRM is not sufficient.

Misalign them using alignment sliders.