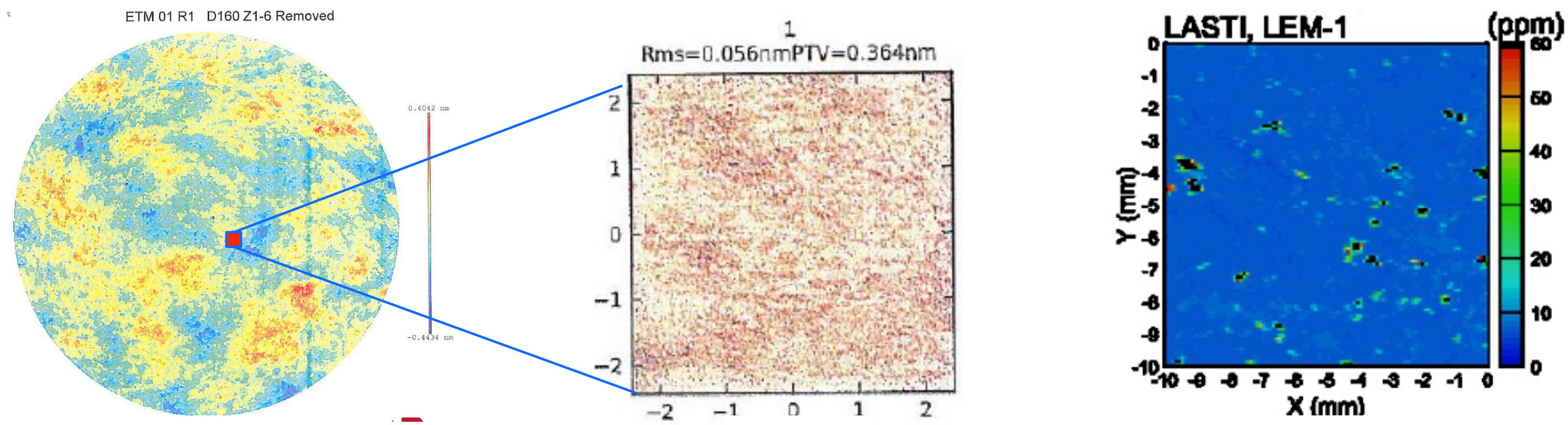
Optics, Cavity and Loss : What we learned in aLIGO

Hiro Yamamoto / LIGO Lab @ Caltech

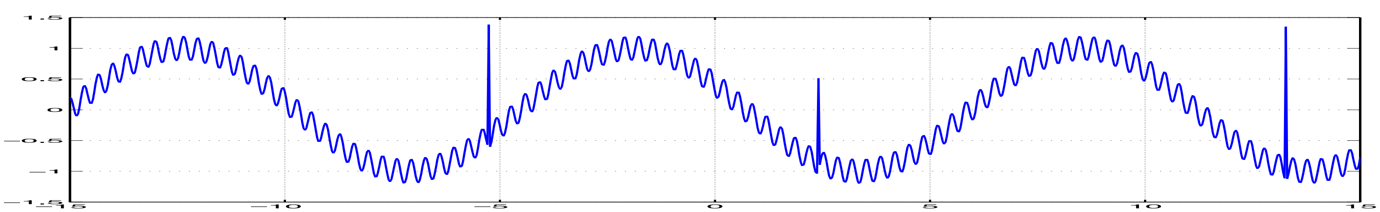
- Optics, Cavity and Loss
  - » Mirror surface aberration and scattering
  - » Scattering Loss in a Cavity
- Real world optics
  - » Past and present findings
  - » A quick look at aLIGO Optics
- Modeling and Simulation
  - » SIS, Stationary Interferometer Simulation
  - » Details of cavity and optics
  - » Tools to help to understand what is going on

Surface structure with different spatial distribution



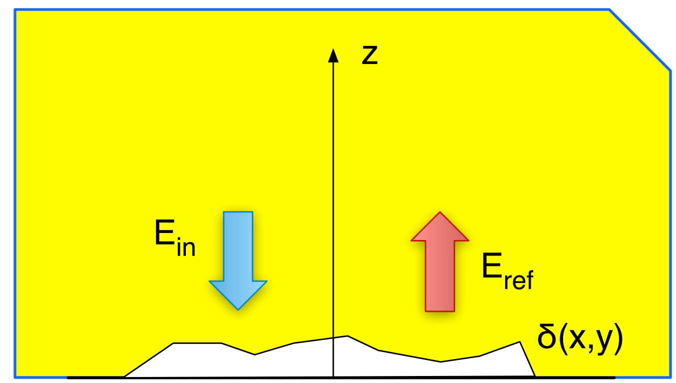
160mm | 5mm | 10mm

Fizeau IFO | Phase Measuring Microscope | Integrating Sphere



Scattering by aberration

$$E_{ref} = E^0_{ref} \cdot \exp(i2k\delta(x,y))$$
$$= E^0_{ref} \cdot (1 + i2k\delta - 2(k\delta)^2)$$
$$= E^0_{ref} \cdot (1 - 2(k\delta)^2) + E^0_{ref} \cdot i2k\delta$$



$$dP = \iint dx\,dy \left|E^0_{ref}\right|^2 4k^2\delta(x,y)^2$$
$$= P^0_{ref}\left(\frac{4\pi\sigma}{\lambda}\right)^2 S$$
$$\sigma^2 \equiv \iint dx\,dy\,\delta(x,y)^2 / S$$
$$= \int df\, PSD_{1D}(f)$$

Scattering by point source

Far field Fraunhofer approximation : $x^2/L\lambda \ll 1$

$$dE(x,y,L) \sim \frac{1}{L}\exp(-ik\frac{x^2+y^2}{2L})\iint dx_0\, dy_0 \delta(x_0,y_0)\exp(ik\frac{x\cdot x_0 + y\cdot y_0}{L})$$

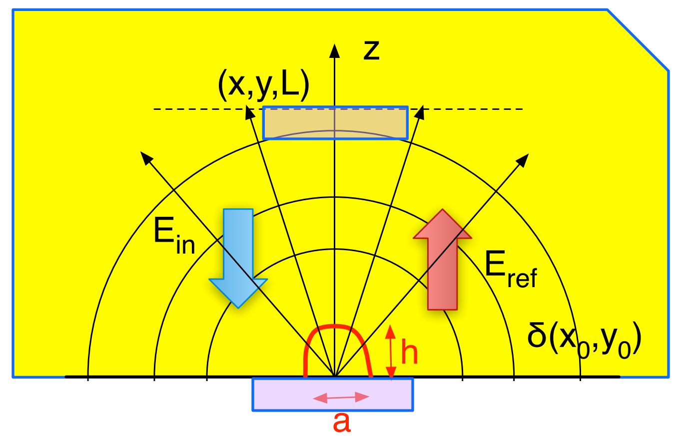
Point source : spherical wave from the point source and mostly lost out of cavity

$$dE(x,y,L) \sim \frac{1}{L}\exp(-ik\frac{r^2}{L})$$

Fractional loss for gaussian beam input

$$loss = 32\pi(\frac{a}{w_0})^2(\frac{h}{\lambda})^2$$

$= 4e^{-5}$ppm for a=2μm, h=20nm, w_0=6cm



Total loss = 0.22xN(1/mm^2) ppm
for randomly distributed point scattering with density N (1/mm^2)

Scattering by periodic source

Far field Fraunhofer approximation : $x^2/L\lambda << 1$

$$dE(x,y,L) \sim \frac{1}{L}\exp(-ik\frac{x^2+y^2}{2L})\iint dx_0\, dy_0 \delta(x_0,y_0)\exp(ik\frac{x\cdot x_0 + y\cdot y_0}{L})$$

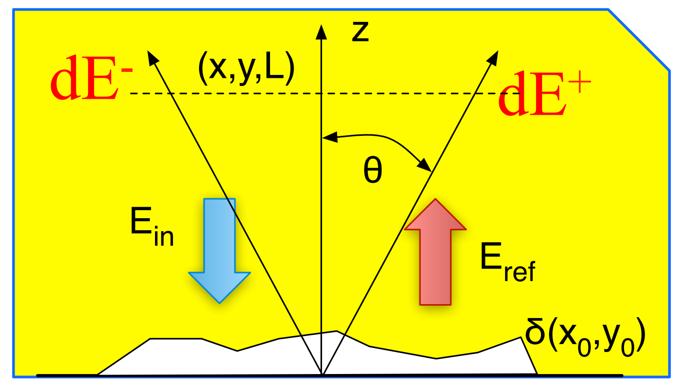
Periodic source characterized by spatial frequency

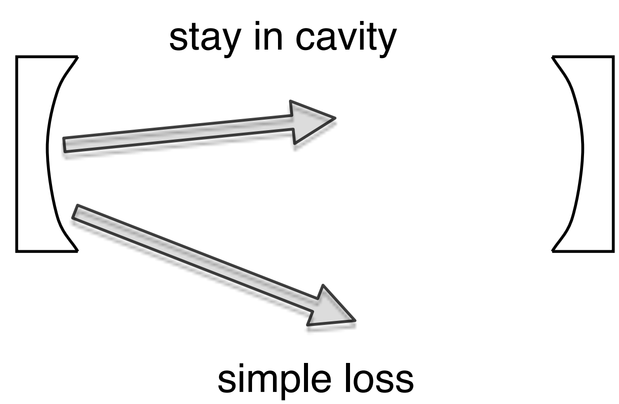
$$\delta(x,y) = \iint df_x df_y D(f_x,f_y)\exp(-i2\pi(x\cdot f_x + y\cdot f_y))$$

$$dE(x,y,L) \sim D(f_x,f_y) \text{ where } f_{x,y} = \frac{x,y}{L\cdot\lambda_{laser}} = \theta / \lambda_{laser}$$

$$\theta = \lambda_{laser}\cdot f_{spatial} = \lambda_{laser}/\lambda_{spatial}$$

$$\begin{aligned} loss &\sim \sigma^2(f_{cut}) \\ &= \int_{f_{cut}} PSD_{1D}(f) \\ &= \int lossFunction(f)\cdot PSD_{1D}(f) \end{aligned}$$

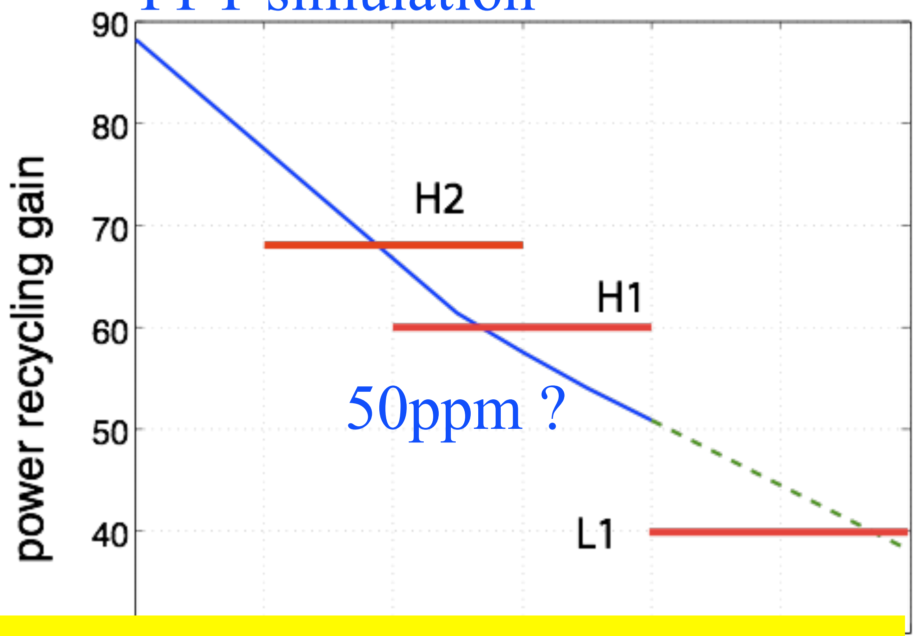




What we learned from iLIGO

- Recycling gain, visibility, etc are consistent with 140 ppm loss per arm
- known loss per arm
  - » surface figure (λ>0.5m) : 10 ppm / mirror x 2
  - » ETM transmission : 7 ppm
  - » absorption : 4ppm / mirror x 2
  - » diffractive loss : 2ppm
- 140ppm total loss - known loss = 100 ppm / arm or 50 ppm / mirror

Recycling gain as a function of extra loss per mirror in FFT simulation

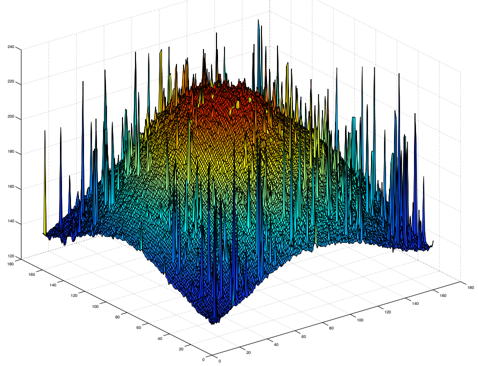


cause unclear, possibly cleaning procedure, point scattering

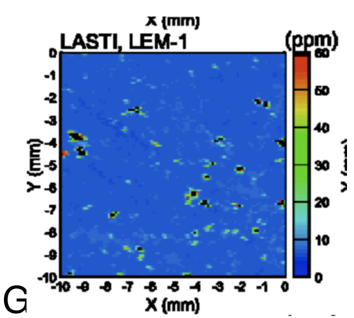
Peeking at LIGO mirror profile

LASTI LEM-1
With LMA coating

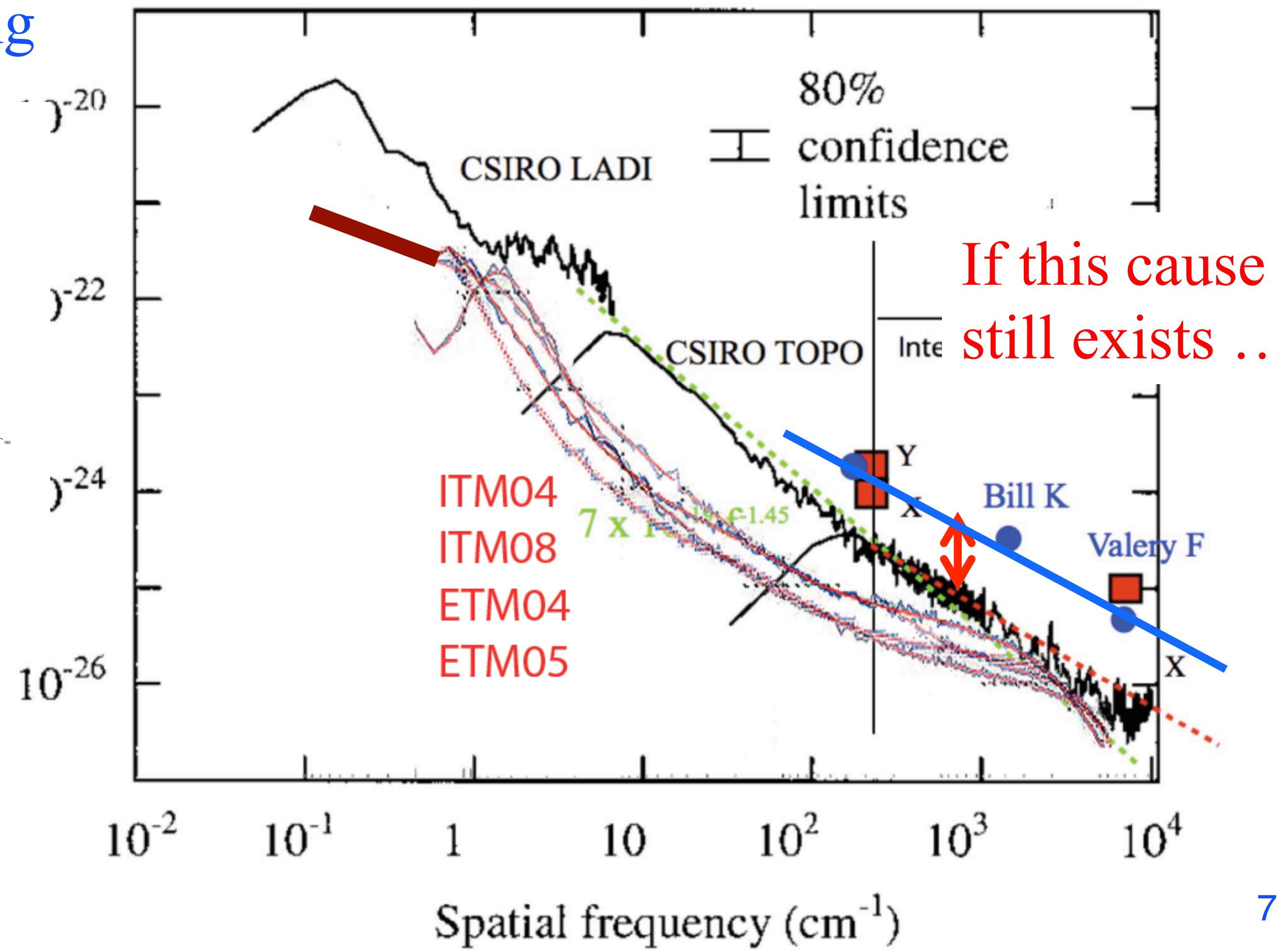
AR reflection



HR point scatter



iLIGO vs aLIGO PSD



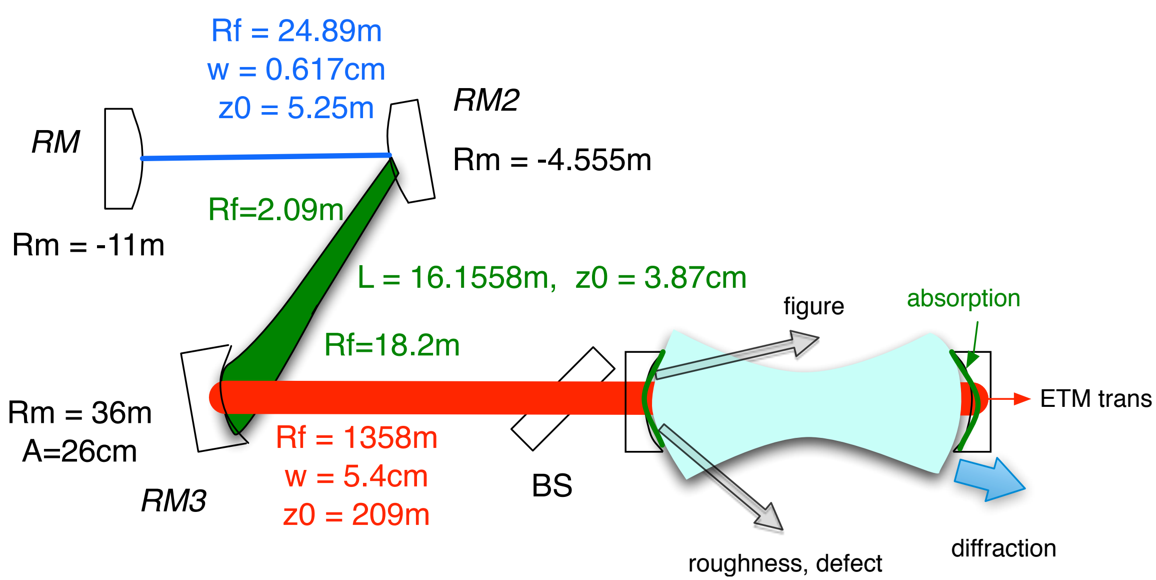
Advanced LIGO Optics

what we need

Arm loss budget (ppm)

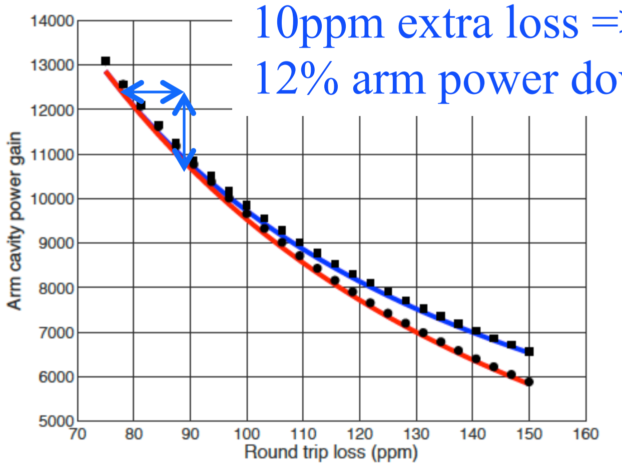
diffraction	Roughness (HSF)	Defect	absorption	Figure (LSF)	ETM transmission	Total
0.6	10 x 2	4 (?) x 2	0.5 x 2	20 x 2	5	75

Recycling cavity round trip loss ~ 1000ppm
or net loss ~ a few %



Coupled Cavity mess

(1) Round trip loss in Arm vs power gain

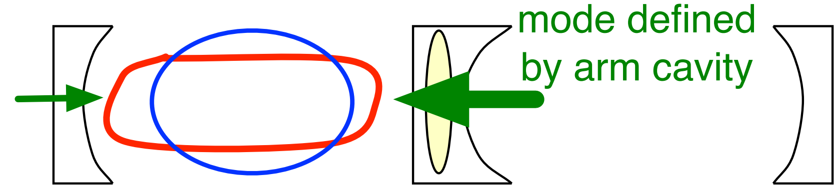


$$\frac{Power(loss)}{Power(no\,loss)} = \frac{1}{(1+\frac{4Loss}{T_{RM}T_{ITM}})^2}$$

(2) Round trip loss in RC vs total loss

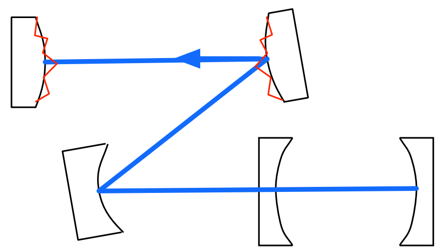
Depends on finesse, resonant condition, etc etc.

(3) Mode in the RC

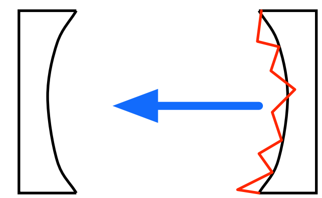


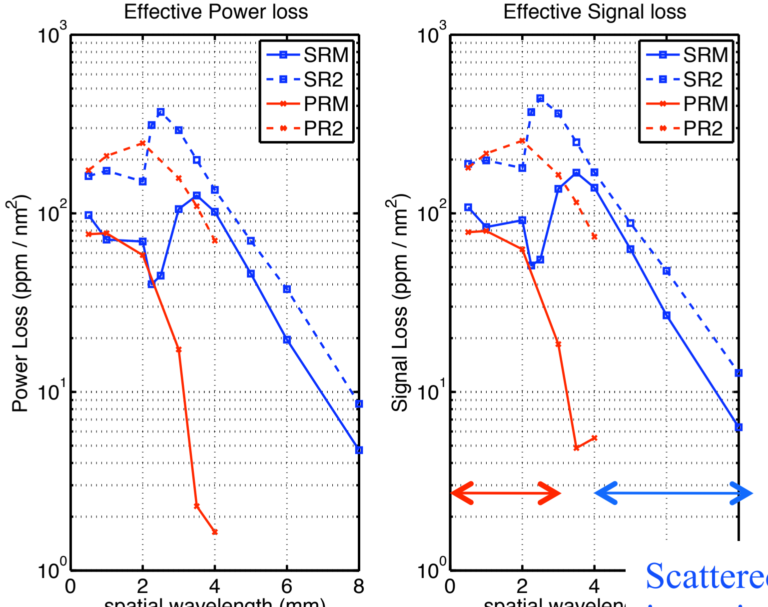
Total loss is a *complex convolution of* PSD and loss function

$$1-\frac{P(a\ \sin(2\pi\cdot f\cdot r))}{P(no\ aberration)}$$



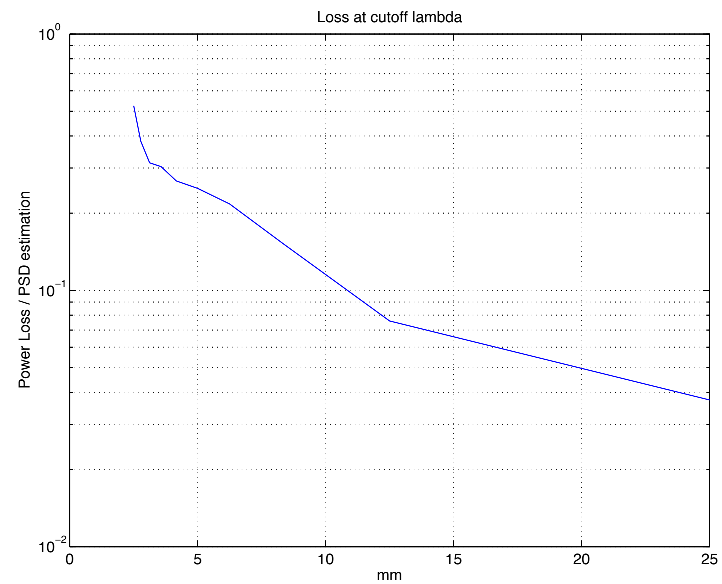
$$\frac{\int_{f}^{f_{max}} CavityPower(f)}{\int_{f}^{f_{max}} PSD(f)}$$





Scattered field lost out of cavity

Scattered field stay in cavity and reused



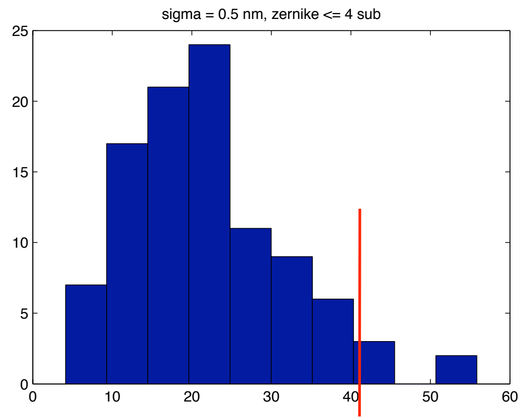
From specification to acceptance

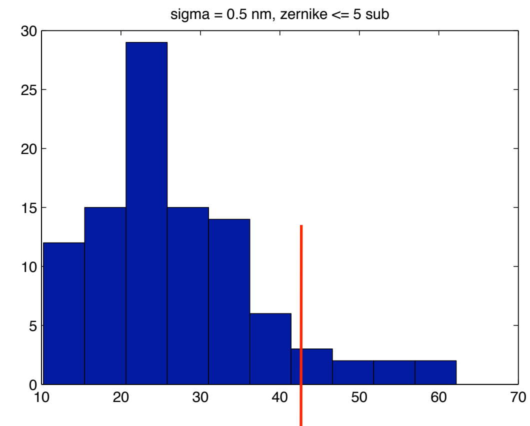
- Use simulation to define the specification
  - » RMS (see next page as example)
  - » Loss function as a function of frequency
  - » Astigmatism treated separately
- When delivered, evaluate if it is acceptable
  - » There are signatures specific to the production process which cannot be characterized by the specification
  - » Unexpected defects
- Work with the vendor to improve the quality
  - » When time and money allows

mirror rms requirement

Zernike <=4 subtracted | Zernike <=5 subtracted

rms = 0.5nm

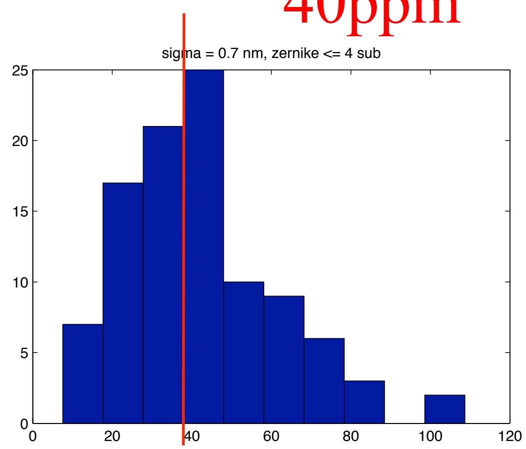


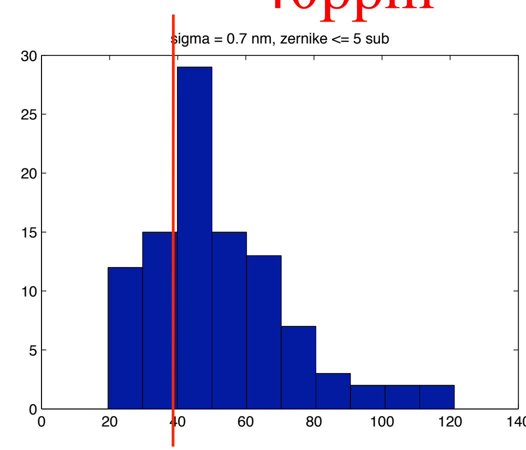


40ppm

40ppm

rms = 0.7nm





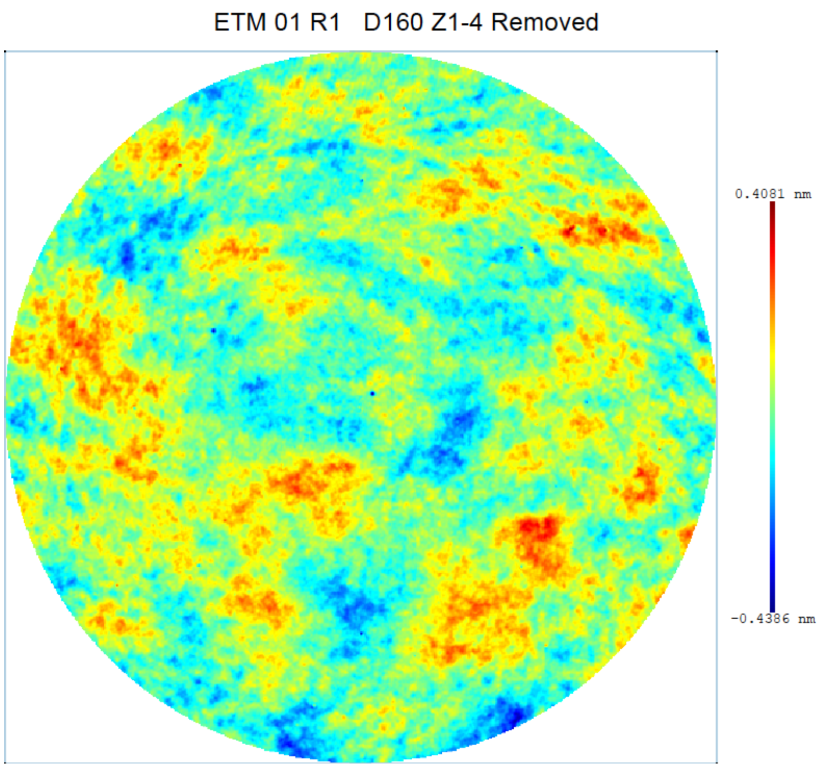
40ppm

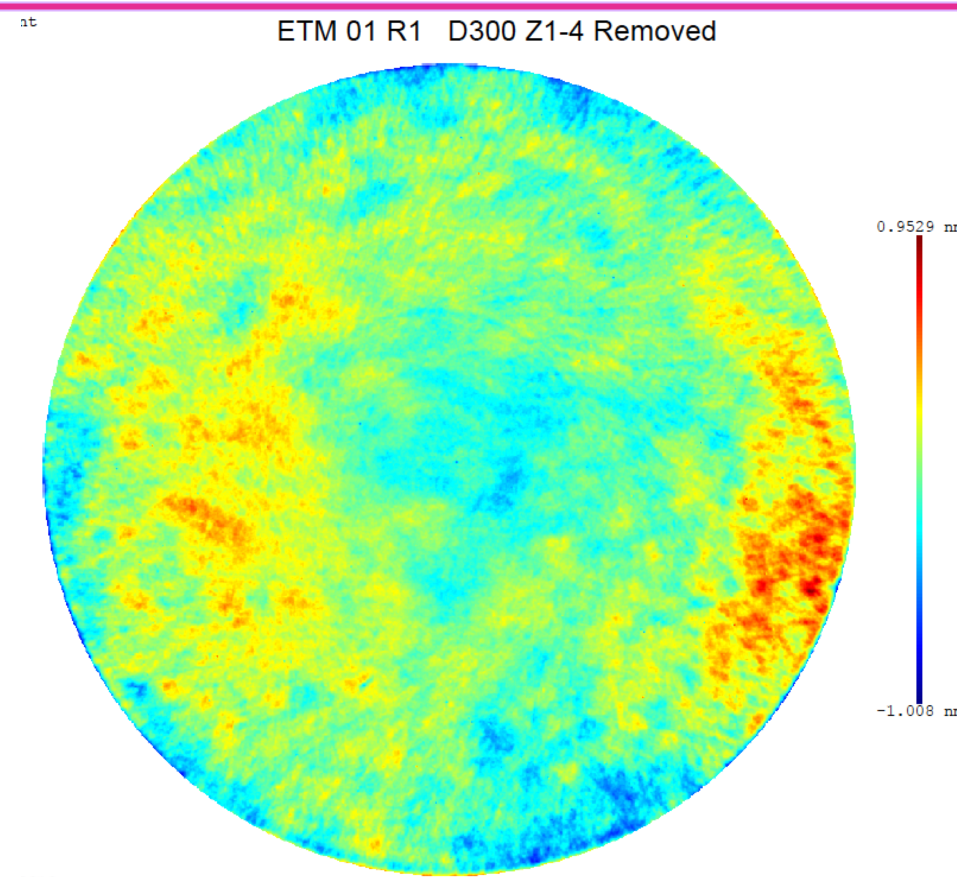
40ppm

Surface Figure: better than we thought possible

(Subcontractor L3 Tinsley)

By G.Billingsley at March 2011 LSC meeting





Φ 160 mm 0.0966 nm rms

Φ 300mm 0.17 nm rms

Requirement and result ITM04

Surface	Specification Parameter	Location	Specification Value	Actual Value	Pass/Fail
1	Spherical, CC, RoC	Central 160 mm	1934 m - 5m/+15m	1938.61 m	PASS
	Radius Difference from all ITMs	Central 160 mm	1938.53 m ± 3 m	0.08 m	PASS
	Astigmatism Amplitude ($Z_{2,2}$)	Central 160 mm	$\sigma_{RMS} < 3$ nm	0.12 nm	PASS
	Figure Error (LSF) $<1mm^{-1}$	Central 300 mm	$\sigma_{RMS} < 2.5$ nm	0.37 nm	PASS
	$Z_{0,0} \cdot Z_{1,1} \cdot Z_{2,0} \cdot Z_{2,2}$ Fit	Central 160mm	$\sigma_{RMS} < 0.3$ nm	0.15 nm	PASS
	Error (HSF) $1\text{-}750mm^{-1}$	Center, Ø60 mm, Ø120 mm	$\sigma_{RMS} \leq 0.16$ nm	0.137 nm	PASS

Requirement by simulation — Actually delivered

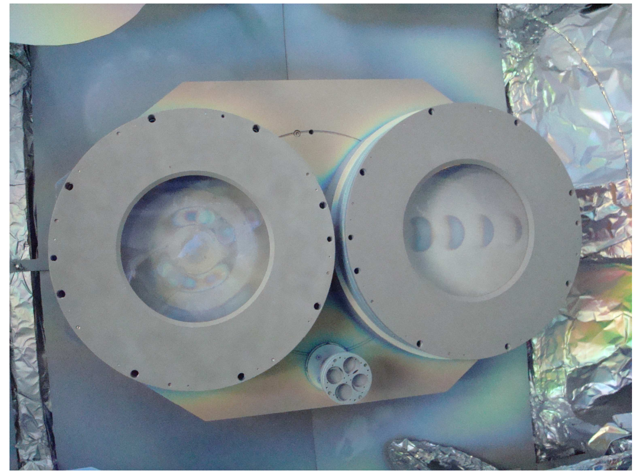
LSF(>2mm) : σ < 0.5nm for loss < 20ppm, σ = 0.15nm -> 2ppm

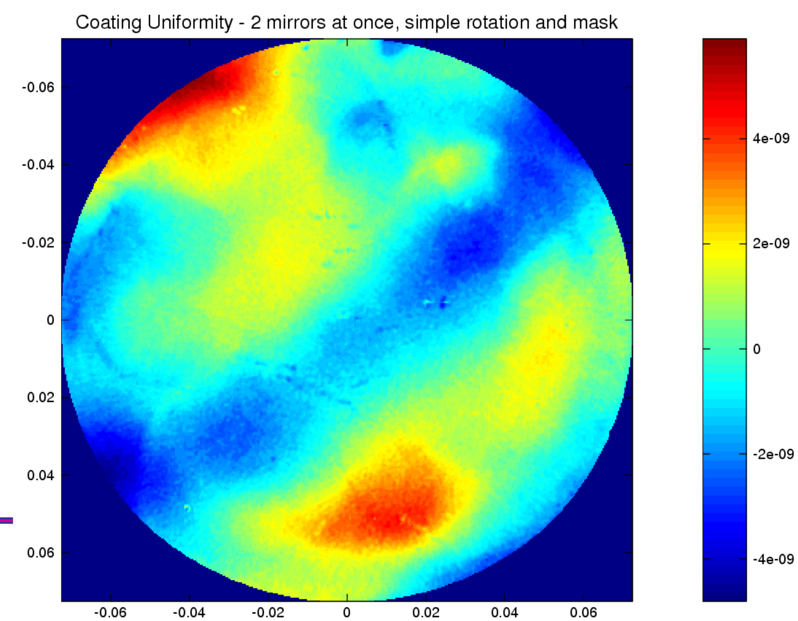
HSF(<1mm) : σ = 0.137nm -> ~3ppm (< 1mm), <6ppm (<2mm)

By R.Flaminio at Amaldi 9, 2011

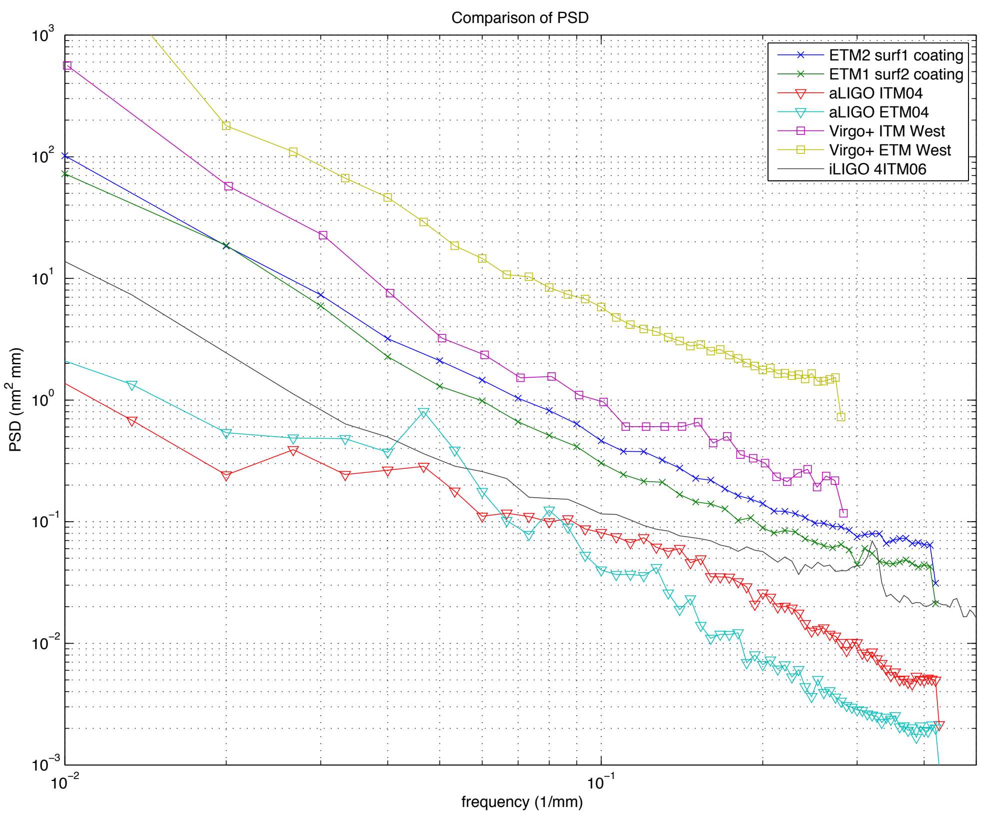
Uniformity with two mirrors

- Coating two mirrors at the same time allows minimizing the interferometer asymmetry
  - Masking technique needed
  - ΔR/R < 0.25% on ∅ 120 mm for Virgo+ input mirrors
- Coating uniformity becomes an issue
  - Masking technique becomes critical
- Best result so far
  - Good reflectivity asymmetry: ΔR/R ~ 1 % on ∅ 160 mm
  - Good absorption: 0.3 ppm
  - But insufficient uniformity: ~ 1.6 nm rms, 11 nm p-p
- Losses in the cavities would be too high
  - 100 - 200 ppm

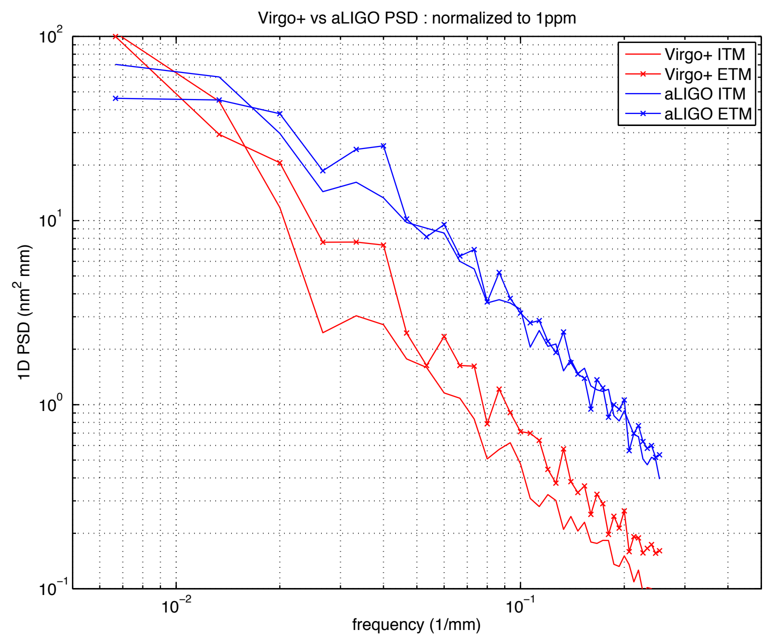




aLIGO optics, Virgo+ optics and coating



RMS is deceiving, careful to understand what it represents

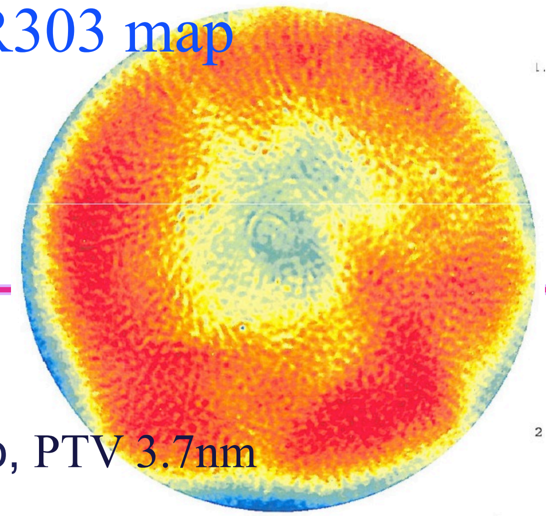


PR3 qualities

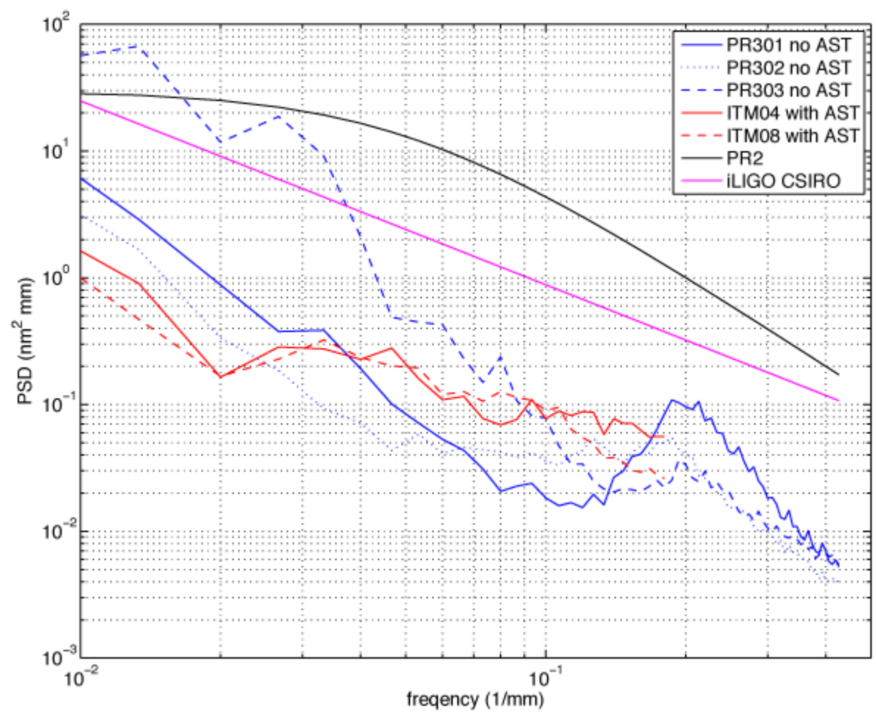
PR3	Loss of P00 on BS (ppm)	Z(2,2) amp
PR301 w/ast	167	~1nm
PR301 wo/ast	95	
PR302 w/ast	35	~1pm
PR302 wo/ast	0	
PR303 w/ast	676	~1nm
PR303 wo/ast	576	

↓ repolished

PR303 map

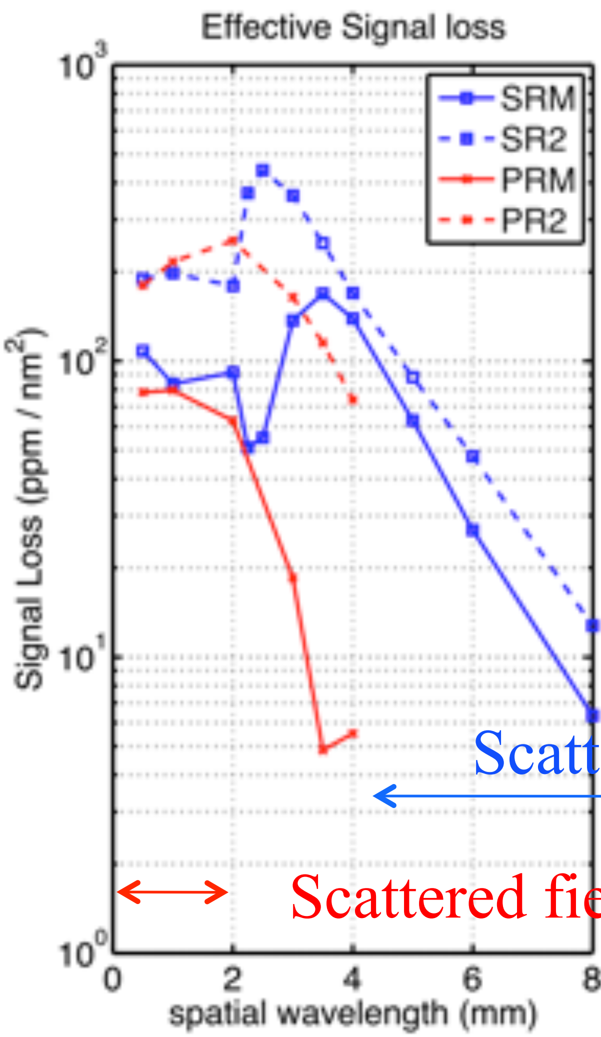


160mm ϕ, PTV 3.7nm



RM2
ROC(PRM2:-4.56m,SRM2:-6.43m)

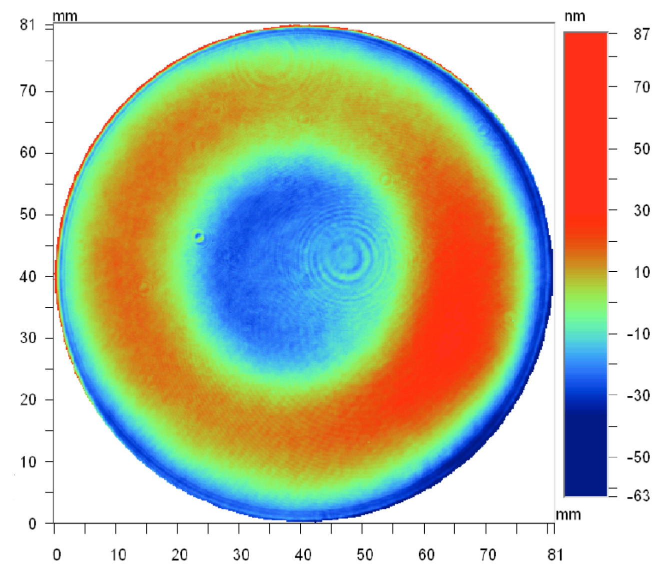
Loss calculated using SIS



Scattered field stay

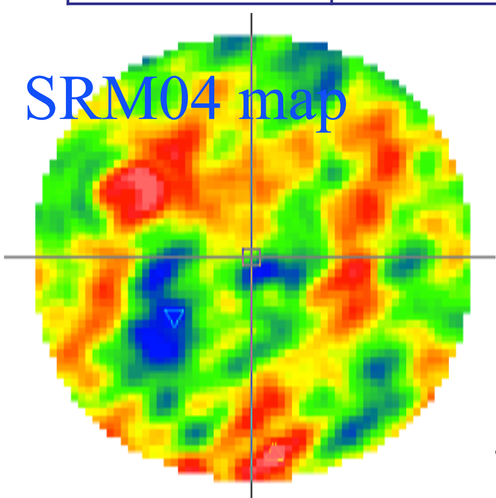
Scattered field lost out of cavity

- Loss by SRM2-4
  - 3000ppm by SIS
  - 800ppm by this loss function



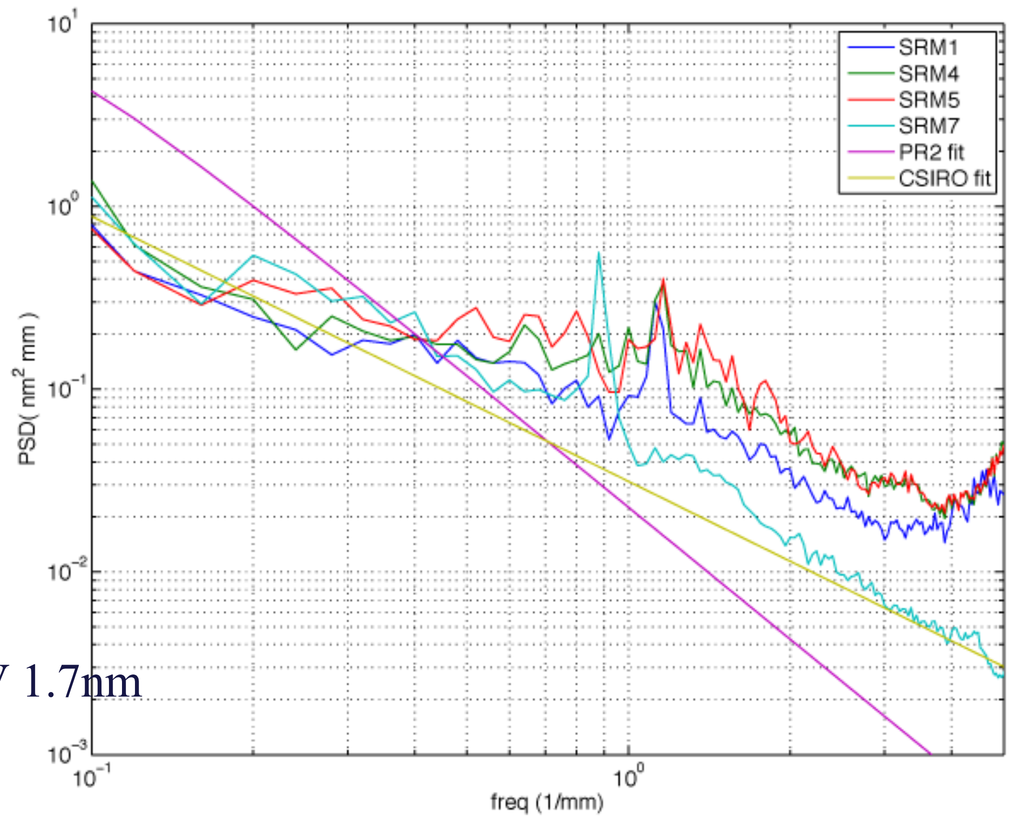
SRM
ROC(PRM:-11.0m,SRM:-5.67m)

SRM	Loss of CR (ppm)
01	650
04	1060
05	860
07	320



SRM04 map

30mm ϕ, PTV 1.7nm



1mm pattern real or not?

SIS : Stationary Interferometer Simulation
Motivation and usage

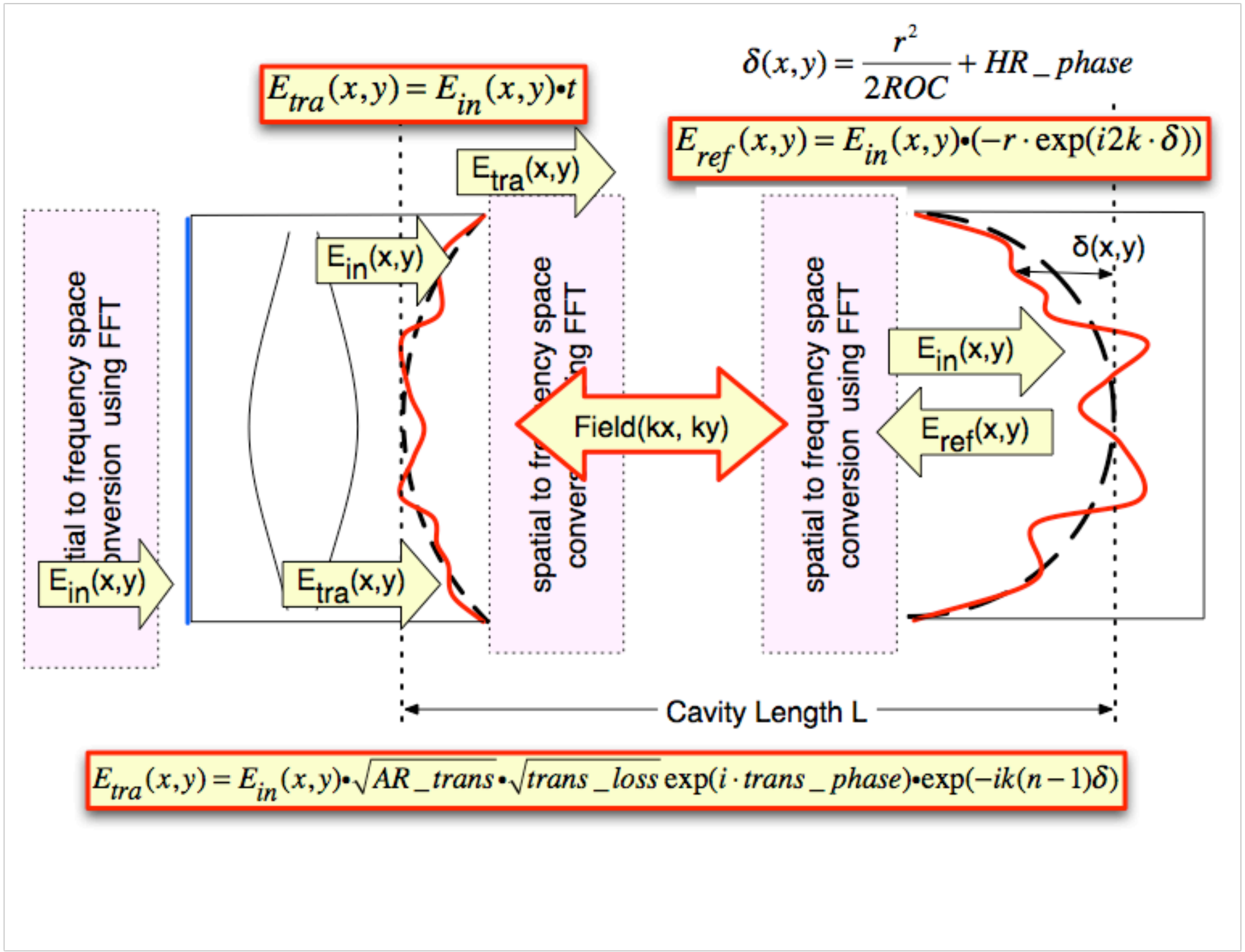
- aLIGO design tool
- Interferometer configuration trade study
  - » Demonstrated that the stable configuration is more immune to imperfection
- Effect of finite size optics
  - » RM3&BS, flat, wedge angle, baffle, etc
  - » Changed from symmetric arm design (6cm) to slightly asymmetric (5.3cm)
- Tolerance of radius of curvature of COC mirrors
- Surface aberration requirements and delivery check
  - » Test mass and recycling cavity mirrors
- Thermal lensing and surface deformation
  - » Quantitative estimation of diffractive loss and mode mismatching
- Parametric instability
  - » highly distorted field, hard to be expressed by simple functions

Try to answer these questions quantitatively, and more

SIS basics

- SIS as interferometer simulator
  - » FFT-based field calculation written in C++
  - » Details of optics can be easily included in the simulation
  - » FP and coupled cavity with BS
  - » Under construction : Full aLIGO dual recycled IFO
  - » Signal sideband generation
- SIS as analysis tool
  - » Mode expansion to understand the basic process
  - » Random surface specified by analytic form or by real surface map
    - – Looping for statistical analysis
  - » Thermal lensing : Hello-Vinet
  - » Calculation tools : PSD, zernike, etc
  - » Telescope to guide large beam to small detector

Simulating details of optics



- Specify details
  - Size, aberration, etc
- Basic interaction
  - Transmission and reflection
- Propagation
- Repeat until stationary
- Repeat until lock
- User interface
- Enough physics
- Speed

SIS User Interface

```
SIS>        lock            calcField       signalGen       timeTrace       telescope
SIS>        delL            modeAmp         saveField       mirrorInfo      storeMap
SIS>        summary         simSpec         loadSimSpec     runSpec         help
SIS>        exit
SIS>
SIS> Select 1 item(s)
SIS> Type "name" to choose item(s)  >> ?
SIS>
SIS>     lock         : Lock the cavity
SIS>     calcField    : Calculate stationary field
SIS>     signalGen    : Generate audio signal by sinusoidal motion of mirrors
SIS>     timeTrace    : Move mirror and save field evolution
SIS>     telescope    : calculate telescope outputs
SIS>     delL         : Print and set the cavity length
SIS>     modeAmp      : Decompose a field by LG or HG
SIS>     saveField    : Save field in a file
SIS>     mirrorInfo   : View mirror information
SIS>     storeMap     : Store mirror maps
SIS>     summary      : Print summary status
SIS>     simSpec      : Set simulation parameters
SIS>     loadSimSpec  : load simulation setup
SIS>     runSpec      : Set run conditions, like convergence criteria
SIS>     help         : main help
SIS>     exit         : Exit this process
```

Sample script specifying a FP

```
% ITM Specification
ITM.aperture = 0.34
ITM.opt.ROC = 1934
     % non uniform transmitance
ITM.opt.T = ( 1.34787 + 7.685e-2*x - 34.827e-2*y ) * 1e-2
     % loadin data file, calculate 2D PSD, generate mirror maps like that PSD
ITM.opt.HR_phase = RANDOMMAP( 12345, 0, "ITM4_W60cm_N512.dat", "SELF", {0} )

% ETM specification
     % yaw angle rotation
ETM.mech.tY = PI * 1e-8
     % Generate mirror maps with 1D PSD of
Ali = 2.5 * 1e-21; Bli = 0.05; Cli = 2
ETM.opt.HR_phase = RANDOM1D( 0, 0.3e-9, Ali, Bli, Cli, -5 )
     % calculate stationary state fields when ETM surface is oscillating
ETM.oscillation.amplitude = DATAFILE(“DrumModeMap.dat”,-3)

% Cavity specification
FPcav.L0 = 3994.5

% input beam specification
inputBeam.beamType = ”HG”; inputBeam.index1 = 0; inputBeam.index2 = 0
     % input beam parameters calculated automatically to best match to cavity
inputBeam.waistSize = 0; inputBeam.waistPosition = 0
```

$$\frac{A}{\left(1+(B*f)^2\right)^{C/2}}$$

Conclusion

- aLIGO is much more complex than iLIGO
- Not all are understood and predictable
- Understanding past observations and using modeling tool can take off a piece of uncertainty to make the life a little bit easier
- Modeling can give us some precaution so that we can save a few “OUCH”
- SIS is
  - » Free for LIGO, €4000+ for Virgo
  - » Endorsed by professors about its value and ease of use
  - » Supported only on Macintosh.