JGW-G1402435

Mitigation of Stray-Light Noise in KAGRA with Commercial Optical Simulators

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GWADW 2014, Takayama, Hida (May 28, 2014)

Contents

- Stray light noise and commercial software
- Simulation for KAGRA
- Summary

Stray-light noise *A stubborn show stopper*

An example scheme:

(1) Consider a stray light generated by a mirror of the interferometer hits at a secondary scatterer, say, an inner surface of a vacuum chamber, that is fluctuated by a seismic motion or acoustic vibration.

(2) The stray light is again scattered there with its phase fluctuated, and shower on the interferometer optics.

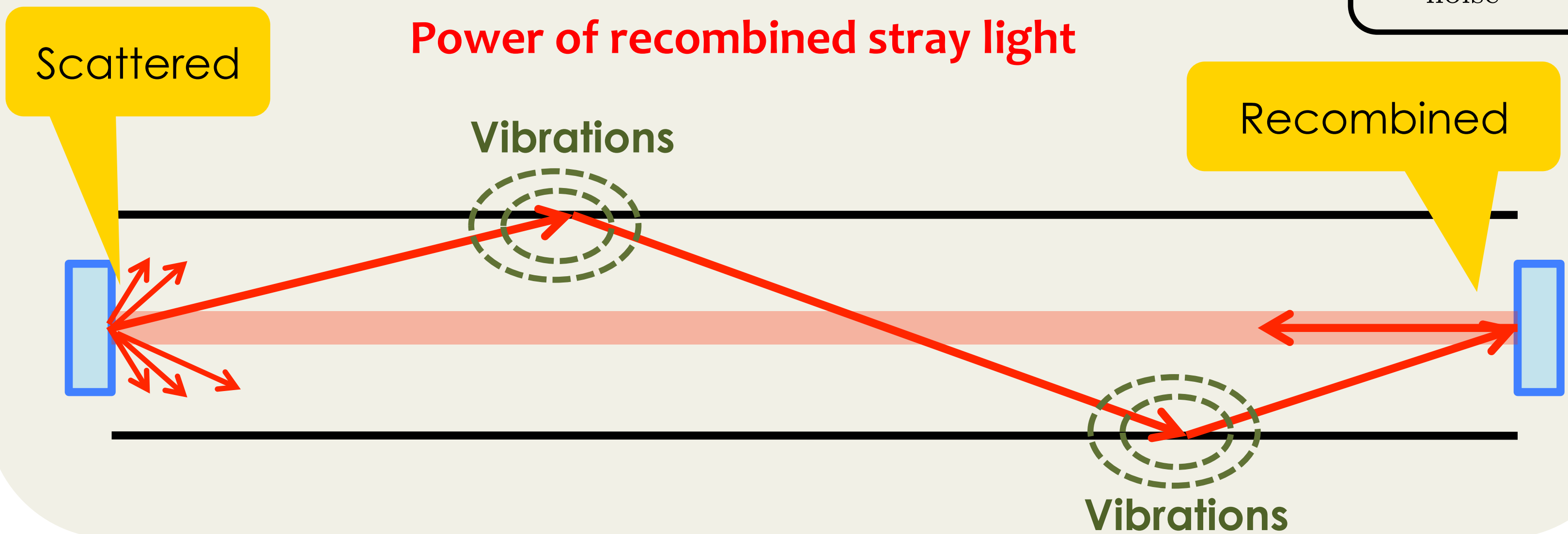
(3) In the end, a fraction of the stray light would recombine into the main optical beam mode. The recombined stray photons can cause ***fake signals*** in the interferometer output --- stray light noise.

Phase fluctuation by scatterer

Stray light noise: $$h_{\rm noise} \propto \sqrt{P_{\rm s}}\,\sin\phi_{\rm s}$$

Power of recombined stray light

When $|\phi_{\rm s}| \ll 1$,
$$h_{\rm noise} \propto \sqrt{P_{\rm s}}\,\phi_{\rm s}$$



Note: unwanted light on photo-detectors is also another kind of stray-light issues.

Back to 10 years ago

PHYSICAL REVIEW D, VOLUME 70, 062003

Direct measurement of the scattered light effect on the sensitivity in TAMA300

Ryutaro Takahashi,* Koji Arai, and Seiji Kawamura
National Astronomical Observatory, Mitaka, Tokyo 181-8588, Japan

Michael R. Smith
California Institute of Technology, M/S 51-33, Pasadena, California 91125, USA
(Received 28 June 2004; published 15 September 2004)

Laser interferometer gravitational wave detectors need vacuum tubes through which the laser beams pass. The light scattered from the arm cavity mirrors will make multiple reflections from the inside wall of the polished tube back onto the mirrors causing phase noise on the interferometer output beam. The TAMA300 has two 300 m length arms enclosed by vacuum tubes. By vibrating one of the tubes of the TAMA300, we directly observed the effect of the scattered light on the displacement sensitivity. It was found that a tube vibration amplitude of 5.6 μm at 776.5 Hz increased the mirror displacement noise by 1.2×10^{-17} m. This noise level is consistent with the calculated noise due to the scattered light effect.

PACS numbers: 04.80.Nn, 07.60.Ly

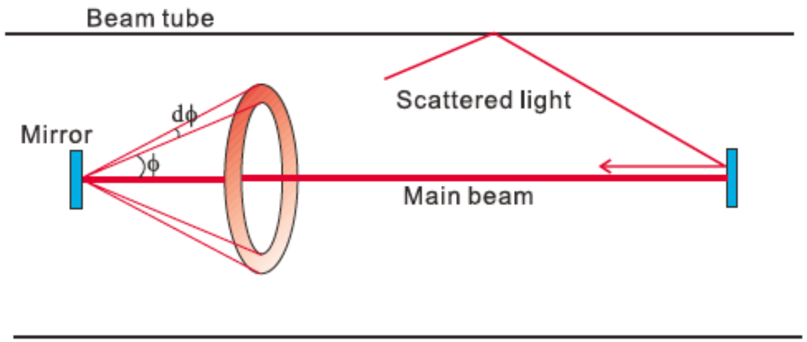
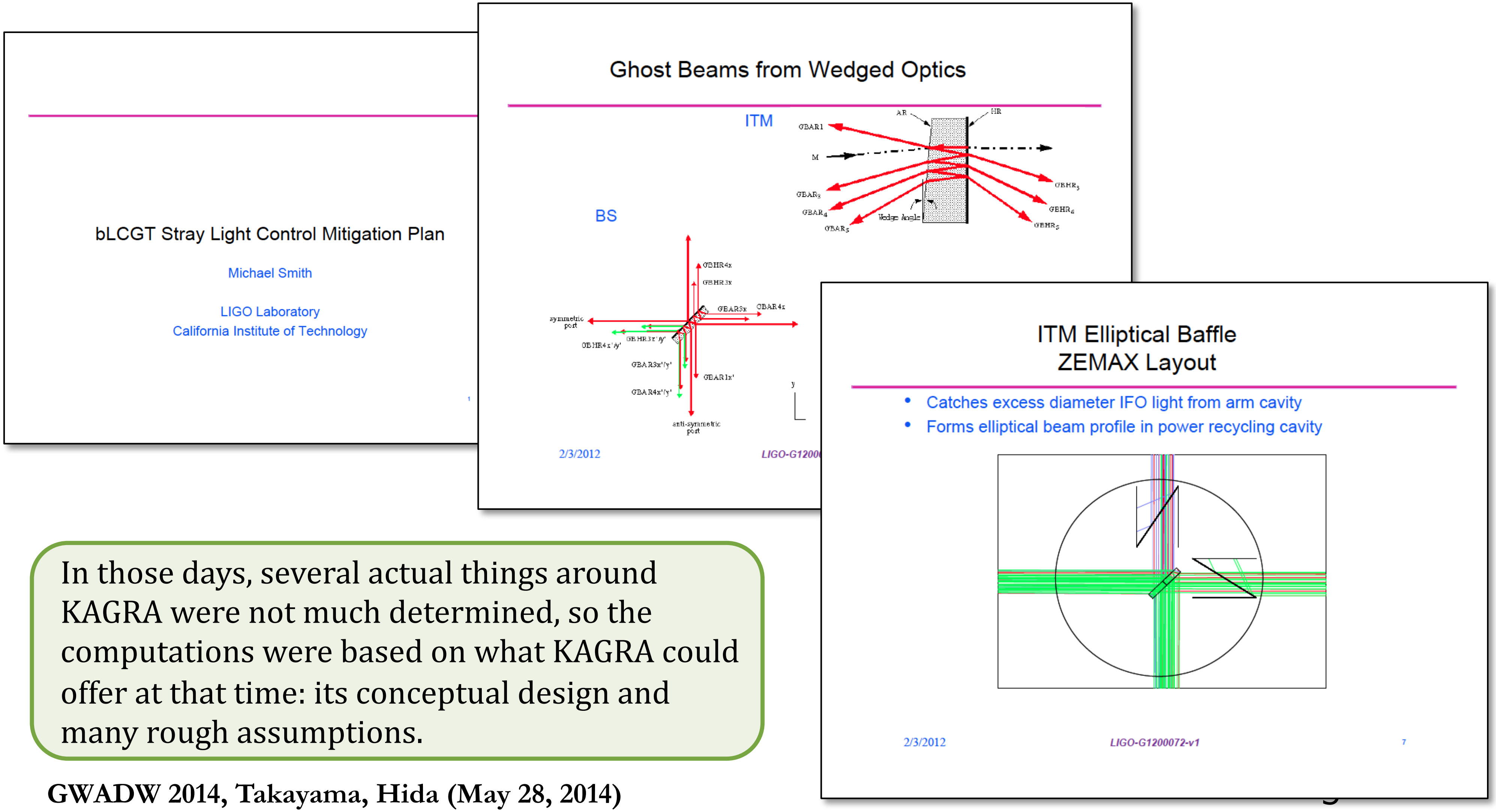


FIG. 1 (color online). Geometry of the scattered light path from the arm cavity mirrors. A part of the light reflected from the beam tube surface recombines to the main beam.

R. Takahashi, K. Arai, S. Kawamura, M. Smith, PRD 70, 062003 (2004)

Fall of 2011

- Evaluation of stray light noises in KAGRA
- Started with the help of M. Smith in LIGO (to 2012 spring)
- Using a commercial simulator: *Zemax* (non-sequential)



In those days, several actual things around KAGRA were not much determined, so the computations were based on what KAGRA could offer at that time: its conceptual design and many rough assumptions.

Which package is right for us?

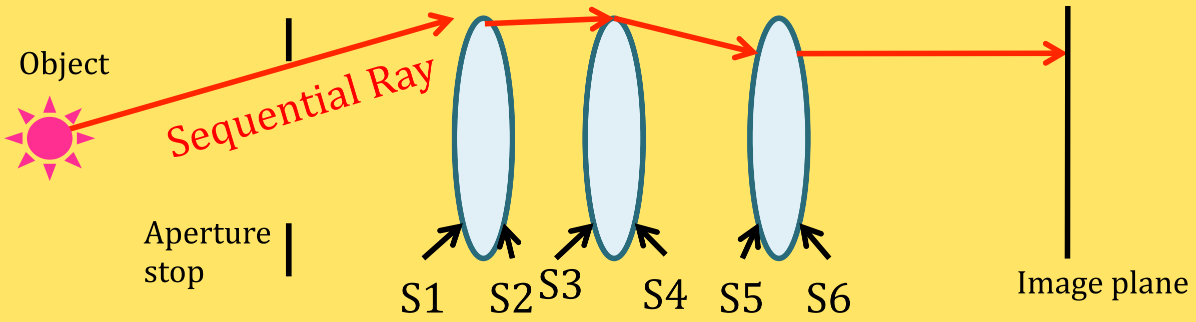
http://www.breault.com/knowledge-base/optical-software-which-program-right-me-opto-laser-europe-magazine

A selection of programs to consider

	Program	Company	Website
Sequential ray-tracing programs	Code V®	Optical Research Associates	www.opticalres.com
	Optalix®	Optenso	www.optenso.de
	OSLO®	Lambda Research Corporation	www.lambdares.com
	ZEMAX®	ZEMAX Development Corporation	www.zemax.com
Non-sequential ray-tracing programs	ASAP®	Breault Research Organization	www.breault.com
	FRED™	Photon Engineering	www.photonengr.com
	LightTools®	Optical Research Associates	www.opticalres.com
	SPEOS™	OPTIS	www.optis-world.com
	TracePro®	Lambda Research Corporation	www.lambdares.com
	ZEMAX®	ZEMAX Development Corporation	www.zemax.com
FDTD programs	FDTD Solutions™	Lumerical Solutions	www.lumerical.com
	FullWAVE™	RSoft Design Group	www.rsoftdesign.com
	JCMsuite™	JCMwave	www.jcmwave.com
	Omnisim™	Photon Design	www.photond.com
	OptiFDTD™	Optiwave Systems	www.optiwave.com

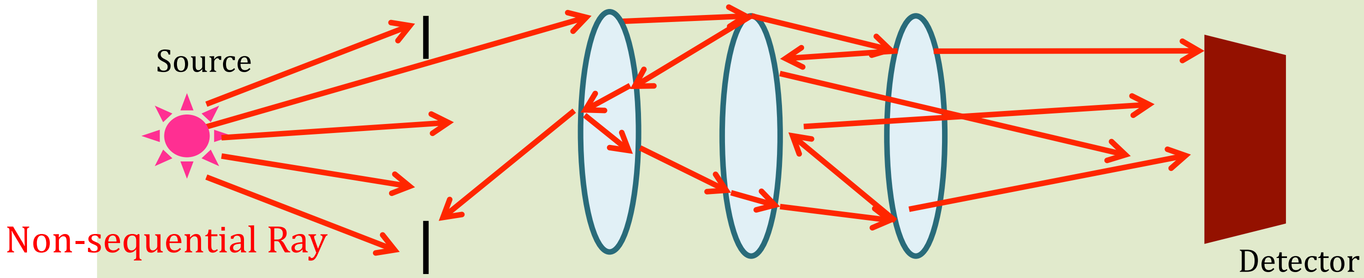
Sequential/Non-sequential

Sequential ray tracing



- A ray interacts with a surface only once in order (sequentially).
- Can design cameras, projectors... such imaging system
- Can design collimators for optical fibers with optimized coupling
- Can treat aberrations on the image plane.

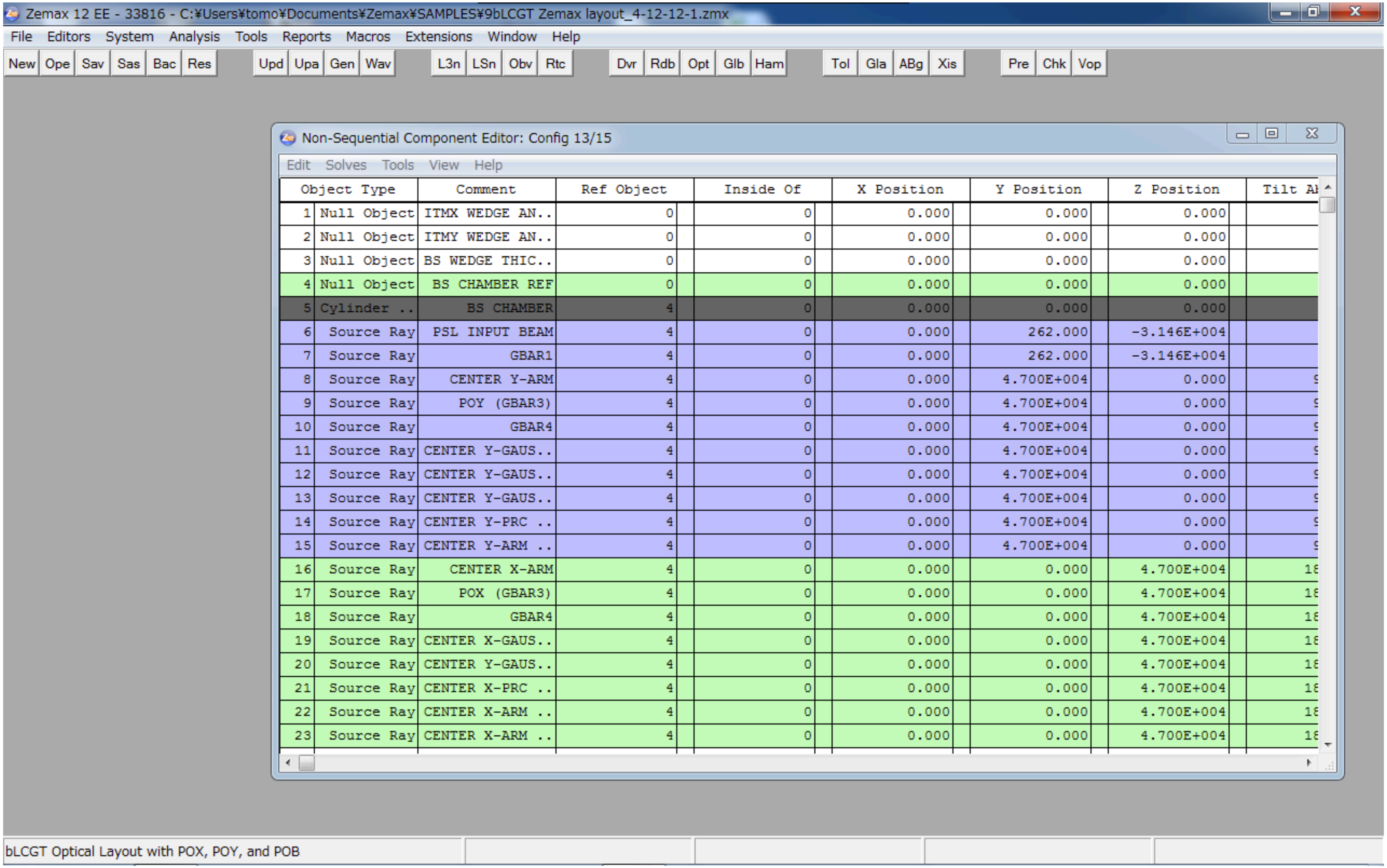
Non-sequential ray tracing



- A ray can interact with a surface several times out of order (non-sequentially).
- Can treat scatterings on each surface
- Can design an optimized uniform illumination with a LED array, or filament light source.
- Can evaluate ghost images for imaging system

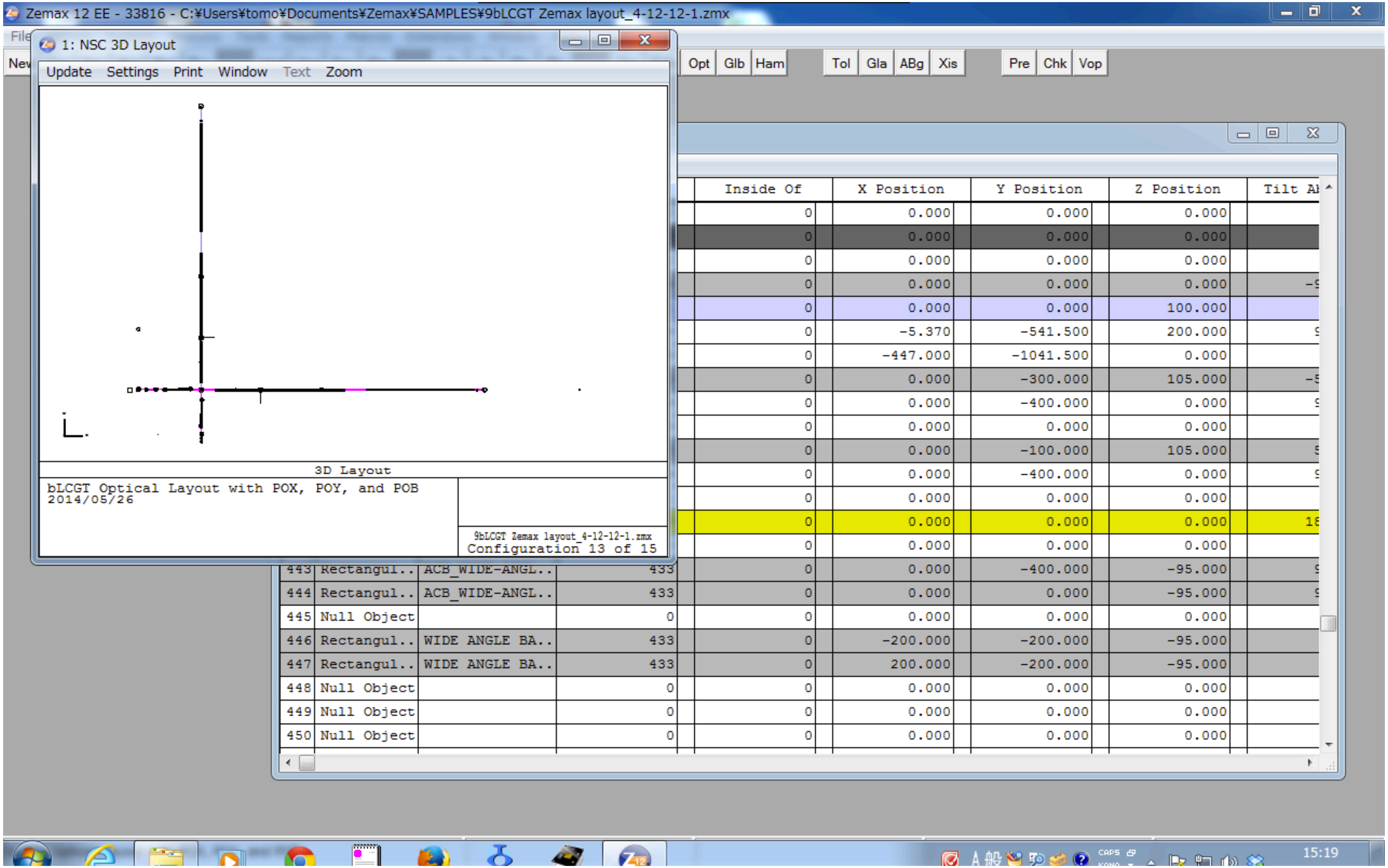
Zemax

国立天文台 NAOJ National Astronomical Observatory of Japan



	Object Type	Comment	Ref Object	Inside Of	X Position	Y Position	Z Position	Tilt Ab
1	Null Object	ITMX WEDGE AN..	0	0	0.000	0.000	0.000	
2	Null Object	ITMY WEDGE AN..	0	0	0.000	0.000	0.000	
3	Null Object	BS WEDGE THIC..	0	0	0.000	0.000	0.000	
4	Null Object	BS CHAMBER REF	0	0	0.000	0.000	0.000	
5	Cylinder ..	BS CHAMBER	4	0	0.000	0.000	0.000	
6	Source Ray	PSL INPUT BEAM	4	0	0.000	262.000	-3.146E+004	
7	Source Ray	GBAR1	4	0	0.000	262.000	-3.146E+004	
8	Source Ray	CENTER Y-ARM	4	0	0.000	4.700E+004	0.000	9
9	Source Ray	POY (GBAR3)	4	0	0.000	4.700E+004	0.000	9
10	Source Ray	GBAR4	4	0	0.000	4.700E+004	0.000	9
11	Source Ray	CENTER Y-GAUS..	4	0	0.000	4.700E+004	0.000	9
12	Source Ray	CENTER Y-GAUS..	4	0	0.000	4.700E+004	0.000	9
13	Source Ray	CENTER Y-GAUS..	4	0	0.000	4.700E+004	0.000	9
14	Source Ray	CENTER Y-PRC ..	4	0	0.000	4.700E+004	0.000	9
15	Source Ray	CENTER Y-ARM ..	4	0	0.000	4.700E+004	0.000	9
16	Source Ray	CENTER X-ARM	4	0	0.000	0.000	4.700E+004	18
17	Source Ray	POX (GBAR3)	4	0	0.000	0.000	4.700E+004	18
18	Source Ray	GBAR4	4	0	0.000	0.000	4.700E+004	18
19	Source Ray	CENTER X-GAUS..	4	0	0.000	0.000	4.700E+004	18
20	Source Ray	CENTER Y-GAUS..	4	0	0.000	0.000	4.700E+004	18
21	Source Ray	CENTER X-PRC ..	4	0	0.000	0.000	4.700E+004	18
22	Source Ray	CENTER X-ARM ..	4	0	0.000	0.000	4.700E+004	18
23	Source Ray	CENTER X-ARM ..	4	0	0.000	0.000	4.700E+004	18

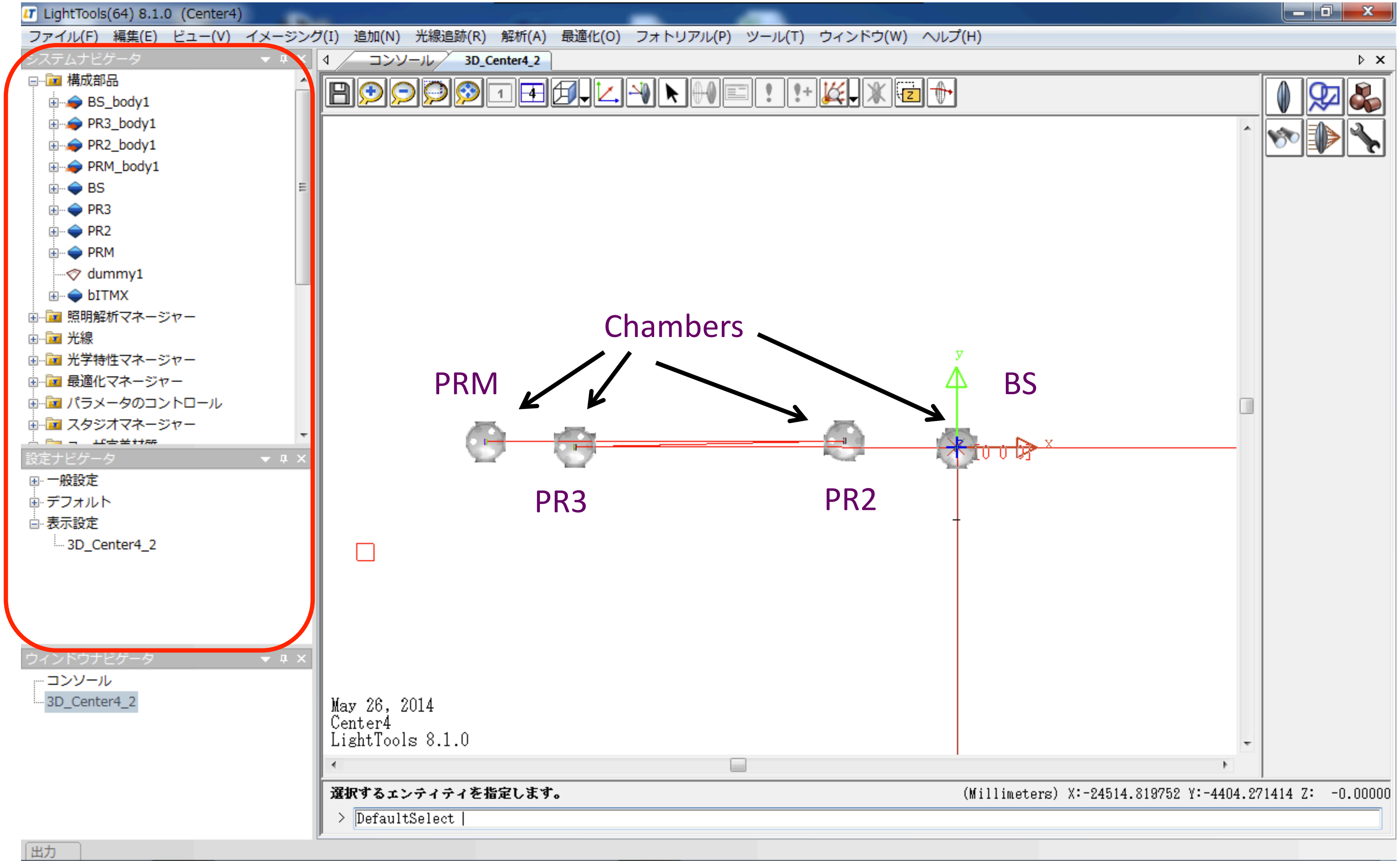
Zemax



Zemax 12 EE - 33816 - C:¥Users¥tomo¥Documents¥Zemax¥SAMPLES¥9bLCGT Zemax layout_4-12-12-1.zmx
1: NSC 3D Layout
Update Settings Print Window Text Zoom
Opt Glb Ham Tol Gla ABg Xis Pre Chk Vop
3D Layout
bLCGT Optical Layout with POX, POY, and POB
2014/05/26
9bLCGT Zemax layout_4-12-12-1.zmx
Configuration 13 of 15
Inside Of X Position Y Position Z Position Tilt A
443 Rectangul.. ACB_WIDE-ANGL.. 433 0 0.000 -400.000 -95.000
444 Rectangul.. ACB_WIDE-ANGL.. 433 0 0.000 0.000 -95.000
445 Null Object 0 0 0.000 0.000 0.000
446 Rectangul.. WIDE ANGLE BA.. 433 0 -200.000 -200.000 -95.000
447 Rectangul.. WIDE ANGLE BA.. 433 0 200.000 -200.000 -95.000
448 Null Object 0 0 0.000 0.000 0.000
449 Null Object 0 0 0.000 0.000 0.000
450 Null Object 0 0 0.000 0.000 0.000
15:19

LightTools

Several companies for optical engineering in Japan recommended to use it rather than Zemax.



Using commercial simulators

Anyway, whichever can be useful.

Merits:

- Off-the-shelf.
- Well checked by a lot of users in the world.
- Macros
- Easily involve new optical engineer.

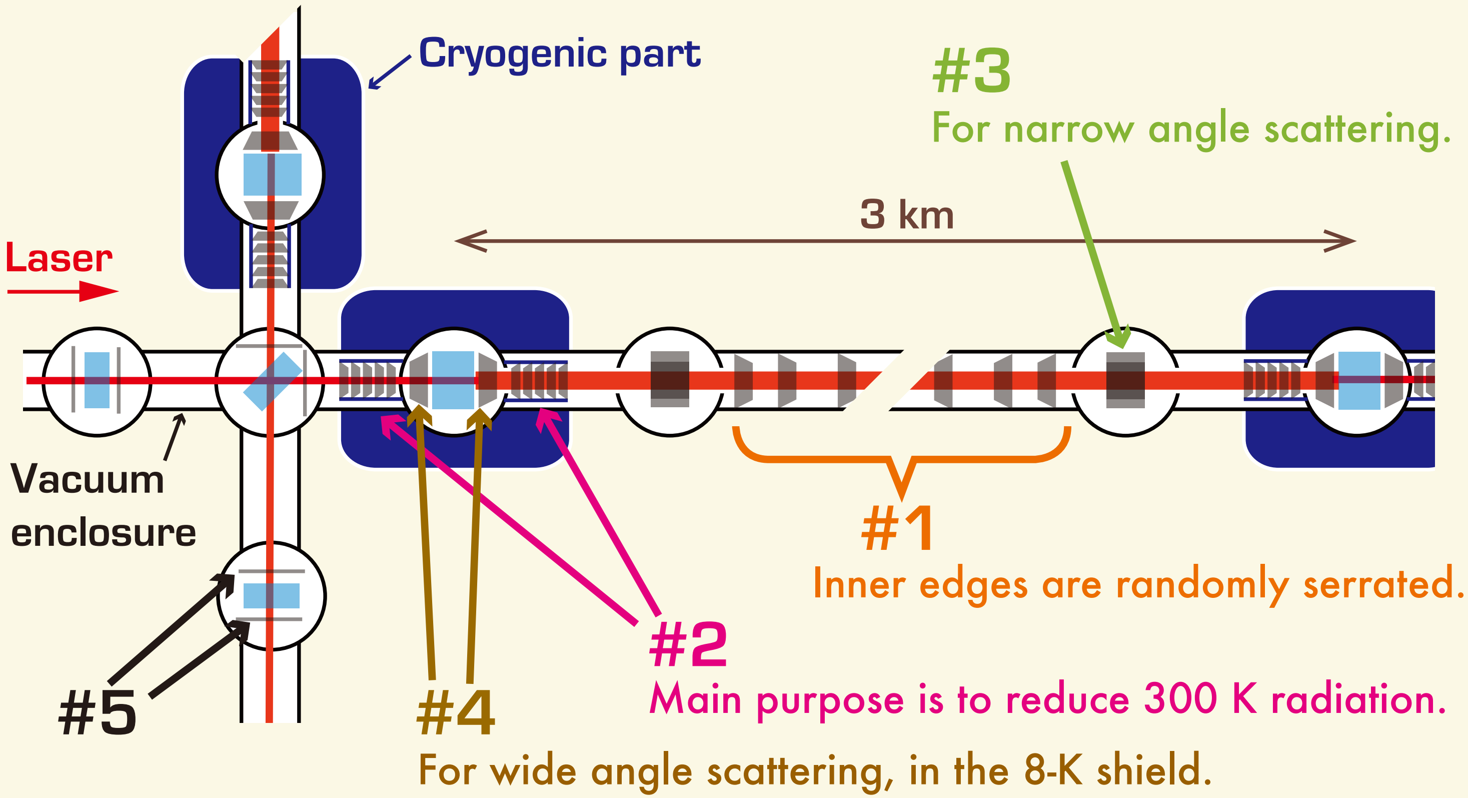
Demerits:

- Can’t hack it; the inside details are secret!
- Sometimes difficult to write desired macros
- Should pay.

- Stray light noise and commercial software
- Simulation for KAGRA
- Summary

Baffle system for KAGRA

#1 Arm duct baffles – 125 baffles per each 3-km arm
#2 Cryo-duct shield – 5 m long, cooled down to about 80 K
#3 Narrow-angle baffles
#4 Wide-angle baffles – cooled down to about 8 K
#5 Others



Schematic view of the main interferometer of KAGRA and its baffles

Black coating on baffle surface

The black coating on the baffles/beam dumps is critical.

Common requirements:

- Vacuum compatibility: < 10^{-7} Pa
- As low reflectivity as possible at 1064 nm
- Industrial applicability for large areas up to φ800 mm

For cryoduct shields (#2):

- Cryogenic compatibility: < 80 K
- As low reflectivity as possible for 300 K radiation (10 um)
- Applicability to aluminum

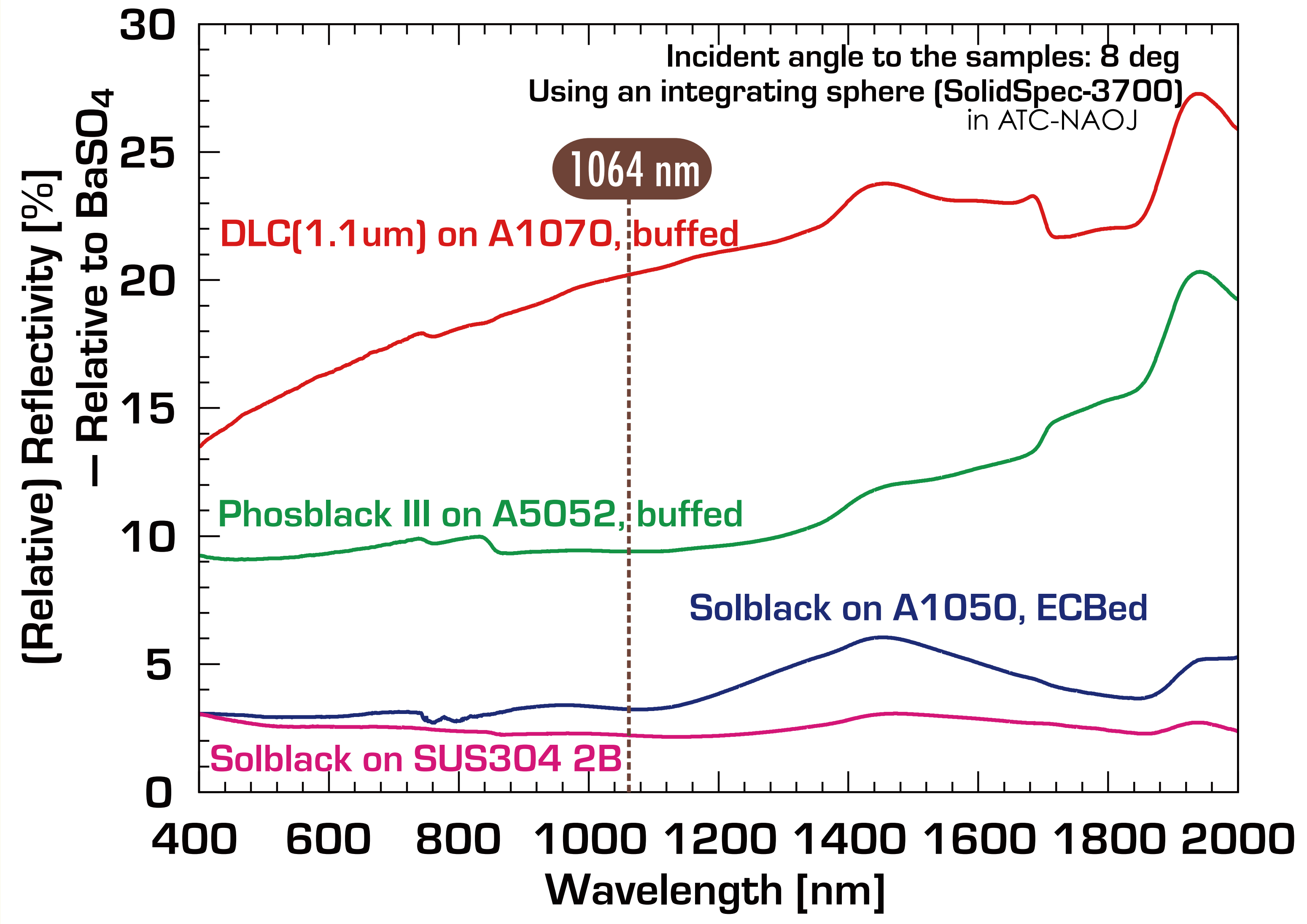
For wide-angle baffles (#4):

- More cryogenic compatibility: < 8 K

Getting stringent!

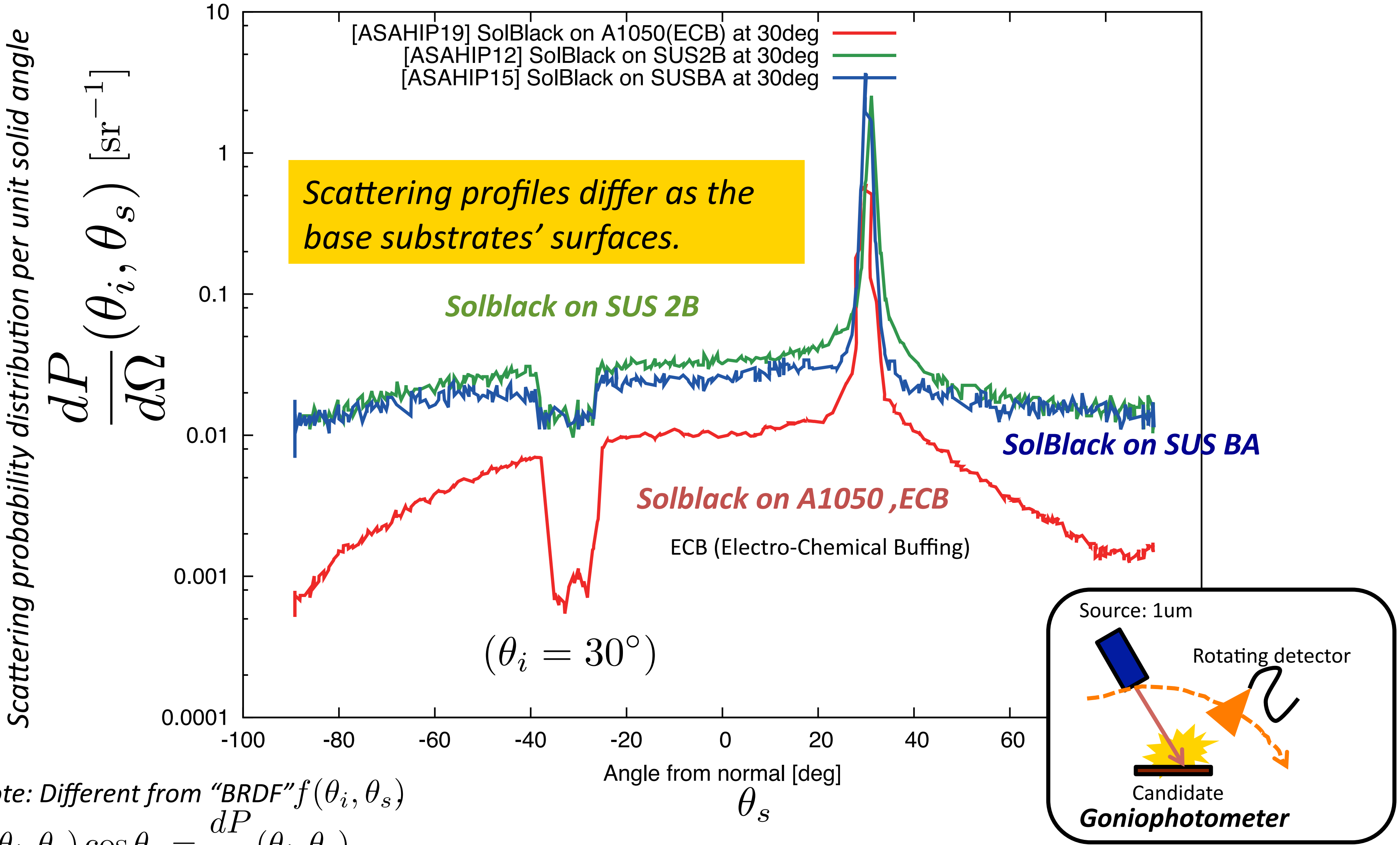
Unique to KAGRA

Reflectivity of candidates



Total integrated reflectivity (specular + scattering) of candidates

Scattering distributions (meas.)



Note: Different from "BRDF" $f(\theta_i, \theta_s)$

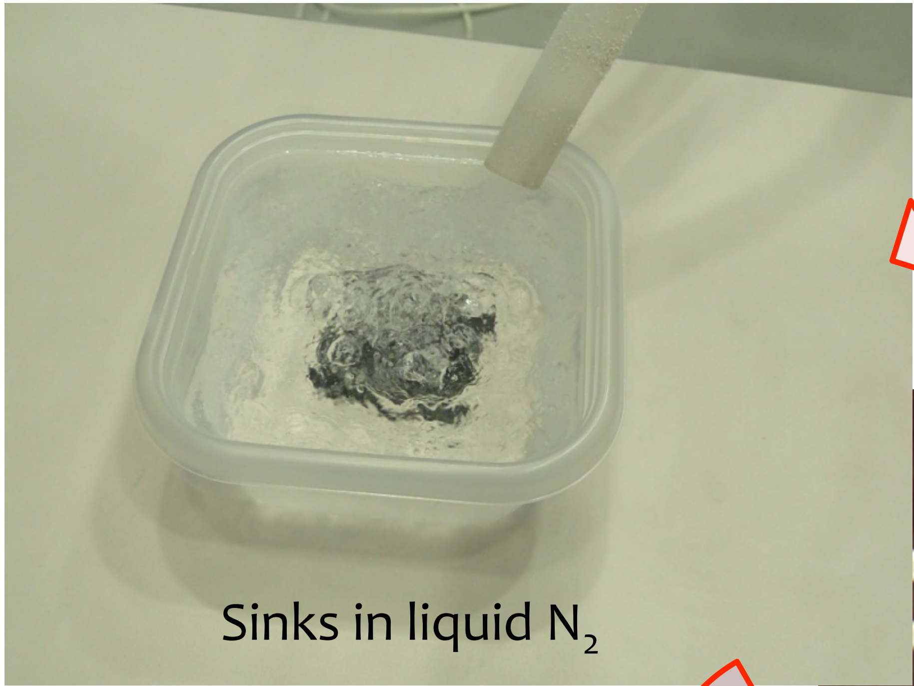
$$f(\theta_i, \theta_s)\cos\theta_s = \frac{dP}{d\Omega}(\theta_i, \theta_s)$$

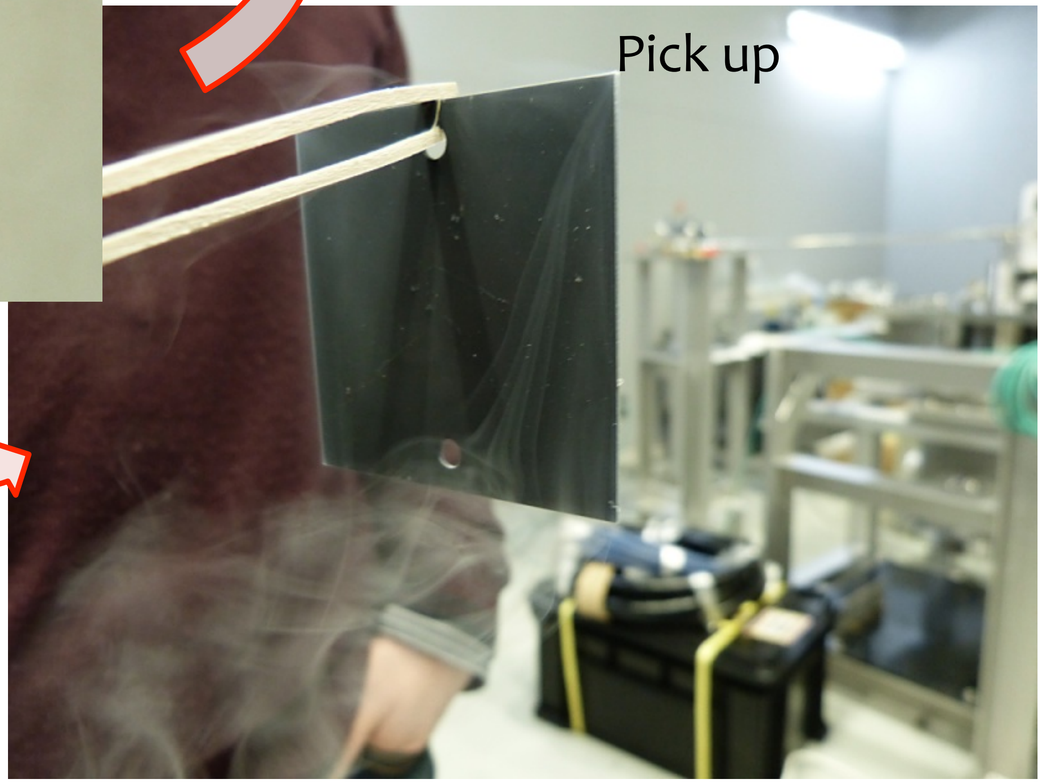
Measurement by Y. Niwa in JASMINE Project, NAOJ
Measurement system also belongs to their project.

Other tests

An example.

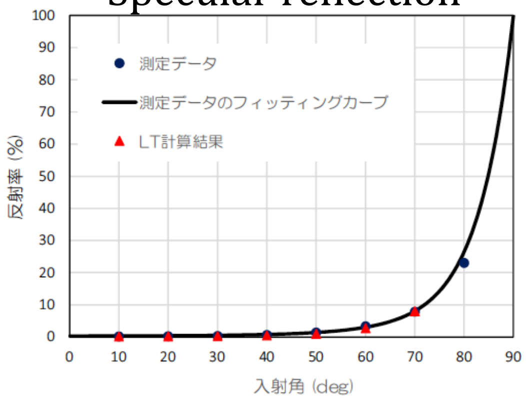
Not directly related to the simulator.



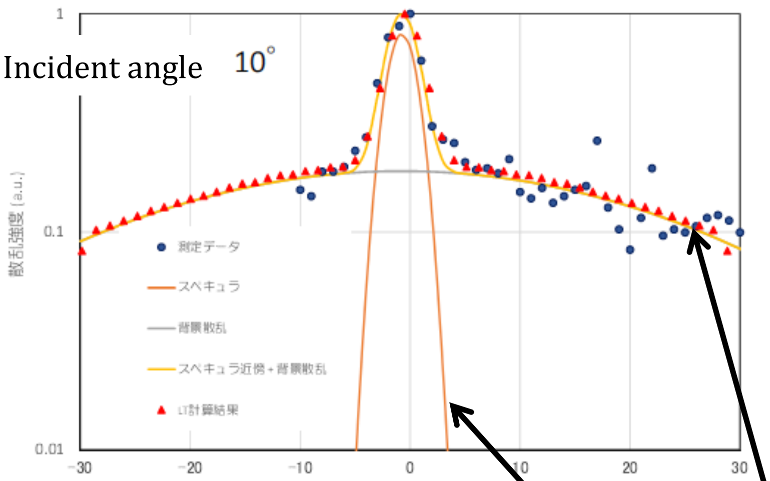


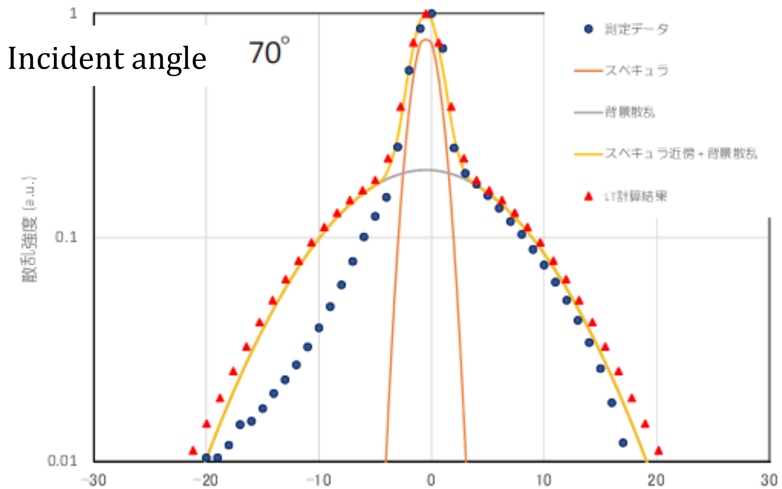
Scattering distribution model

Specular reflection



- Model the surface of baffles (and the inner surface of duct) with the measured the scattering distributions.
- Very simple: double Gaussian model





Uniform scattering component

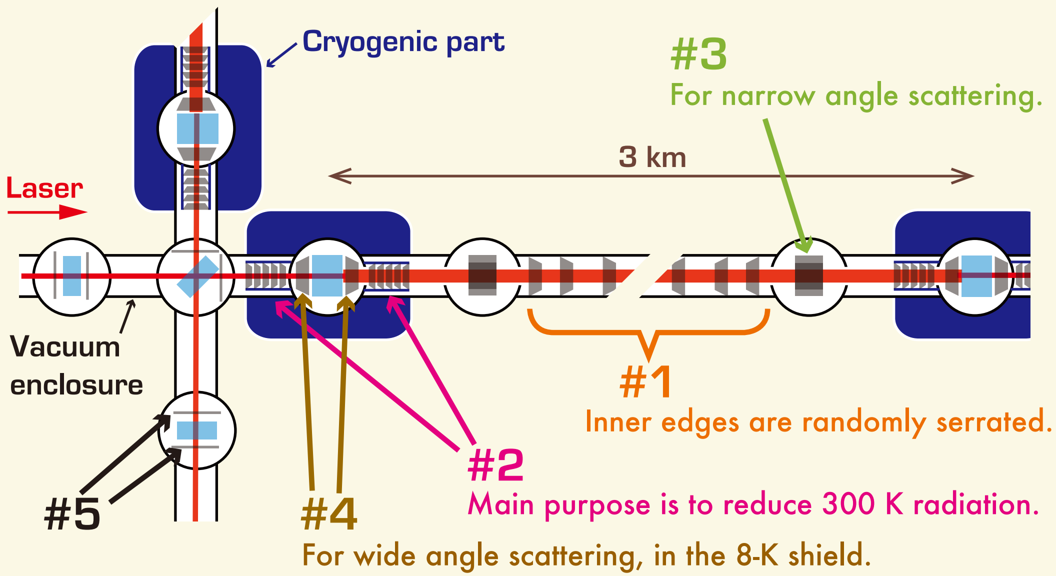
Specular reflection

Simulations

- Case1: with #1 (3-km arm baffles) only
- Case2: w/ #1, #2, and #3 baffles.
- Case3: w/ #4 baffles only

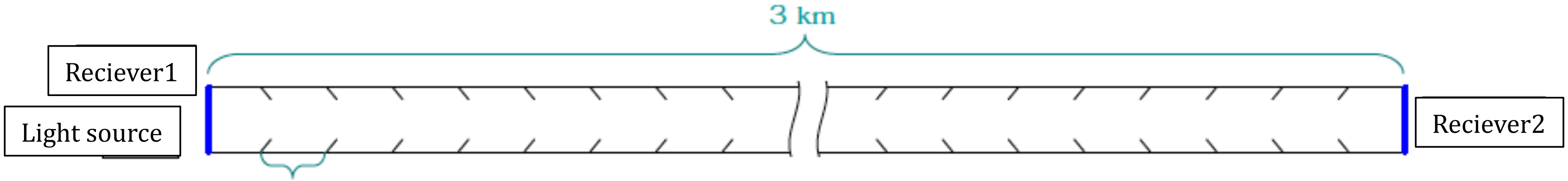
This talk

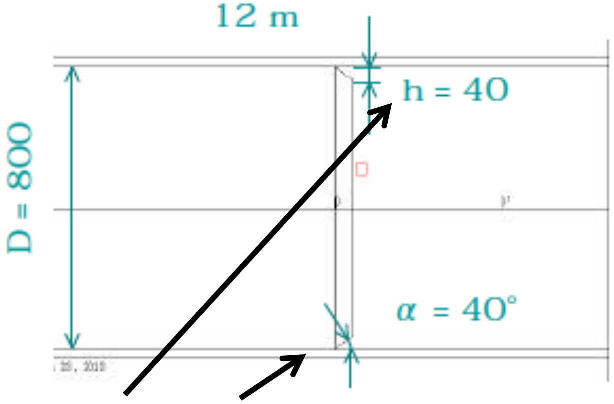
#1 Arm duct baffles – 125 baffles per each 3-km arm
#2 Cryo-duct shield – 5 m long, cooled down to about 80 K
#3 Narrow-angle baffles
#4 Wide-angle baffles – cooled down to about 8 K
#5 Others



Schematic view of the main interferometer of KAGRA and its baffles

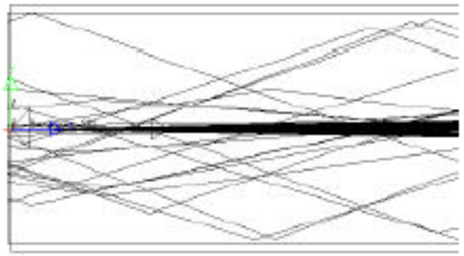
Case 1





Parameters

Preview w/ a point light source



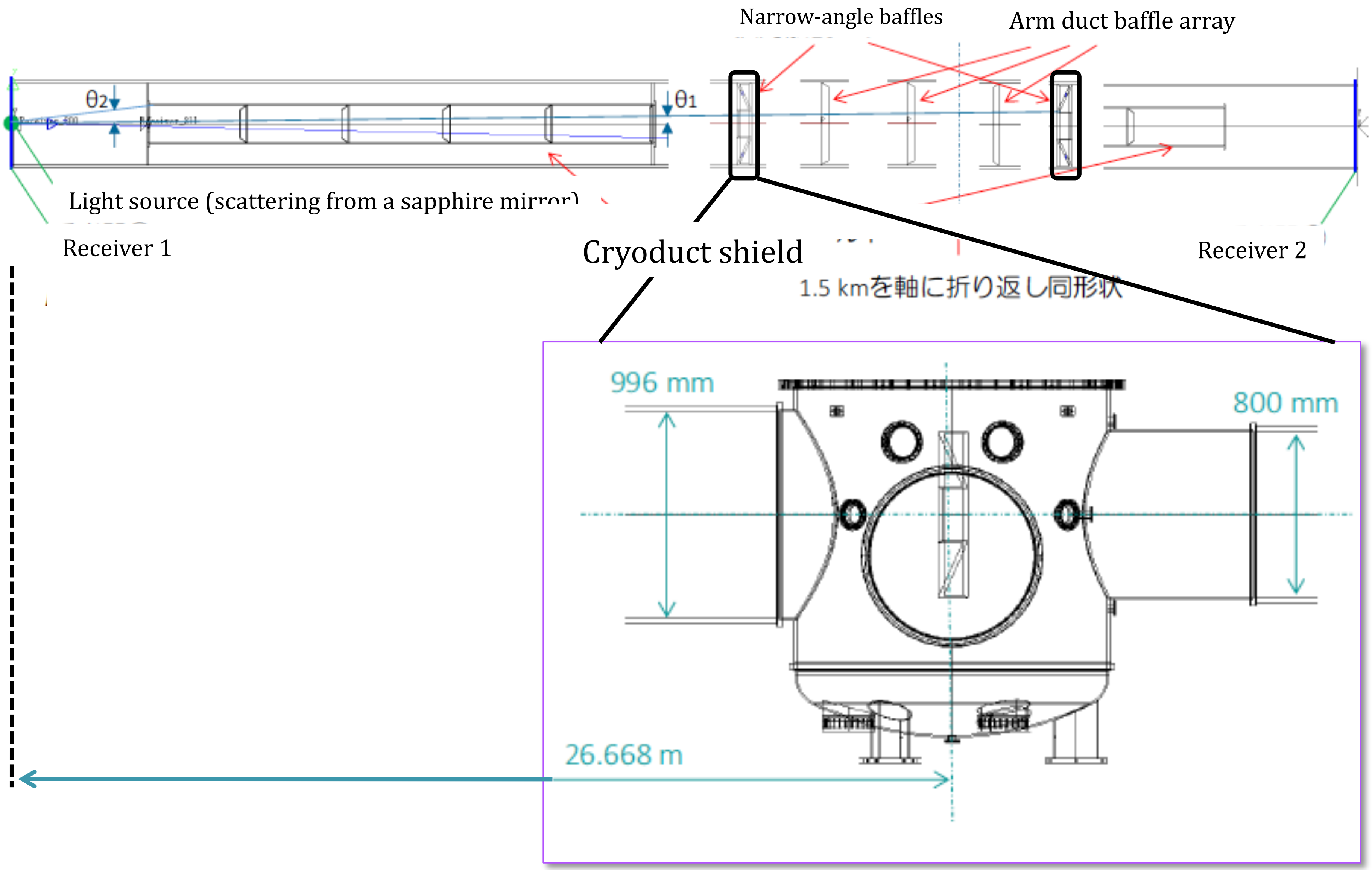
Preview w/ area light source

※ 一部、戻り光も描画されている

$$d_n = \left(1 + \alpha \frac{h}{R-h}\right)^{n-1} d_1 \qquad (35)$$

... And the installable positions for arm-duct baffles are at every 12 m (connection point of each duct).

Case 2



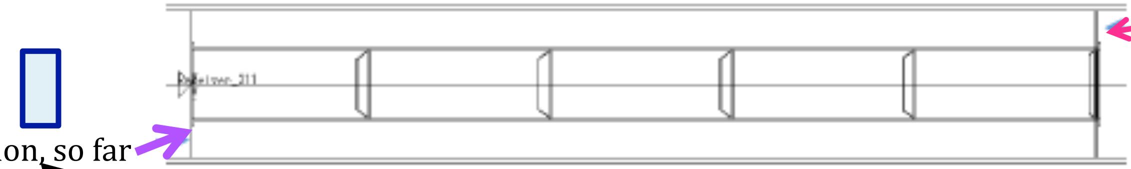
Narrow-angle baffles
Arm duct baffle array
θ2
θ1
Light source (scattering from a sapphire mirror)
Receiver 1
Cryoduct shield
Receiver 2
1.5 kmを軸に折り返し同形状
996 mm
800 mm
26.668 m

Close-up of cryo-duct shield

A cryo-duct shield will be wrapped by thermal insulator → it would be shining!

To the closest sapphire mirror

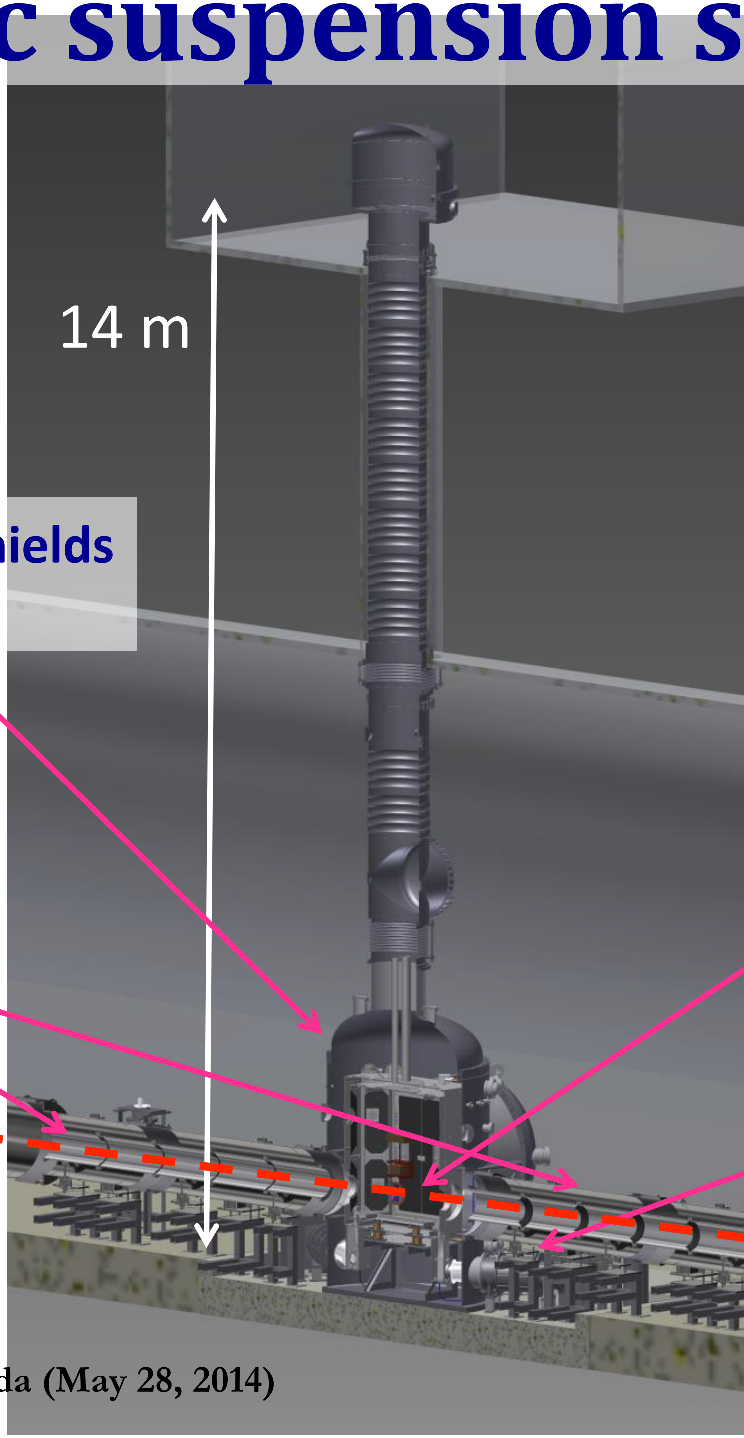
Lambert scattering (R=100%)



100% absorption, so far

The design around here is still unclear. So far leave it black.

Cryogenic suspension system



2nd floor

Base of the suspension

Cryostat (double inner shields and an outer chamber)

Sapphire Mirror

Cryo-duct shield

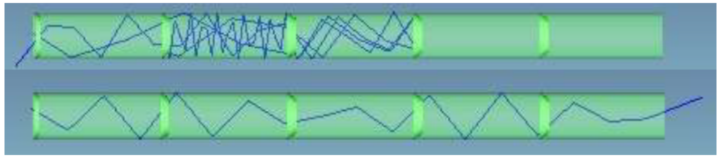
Interferometer beam line

4 Coolers per 1 cryostat

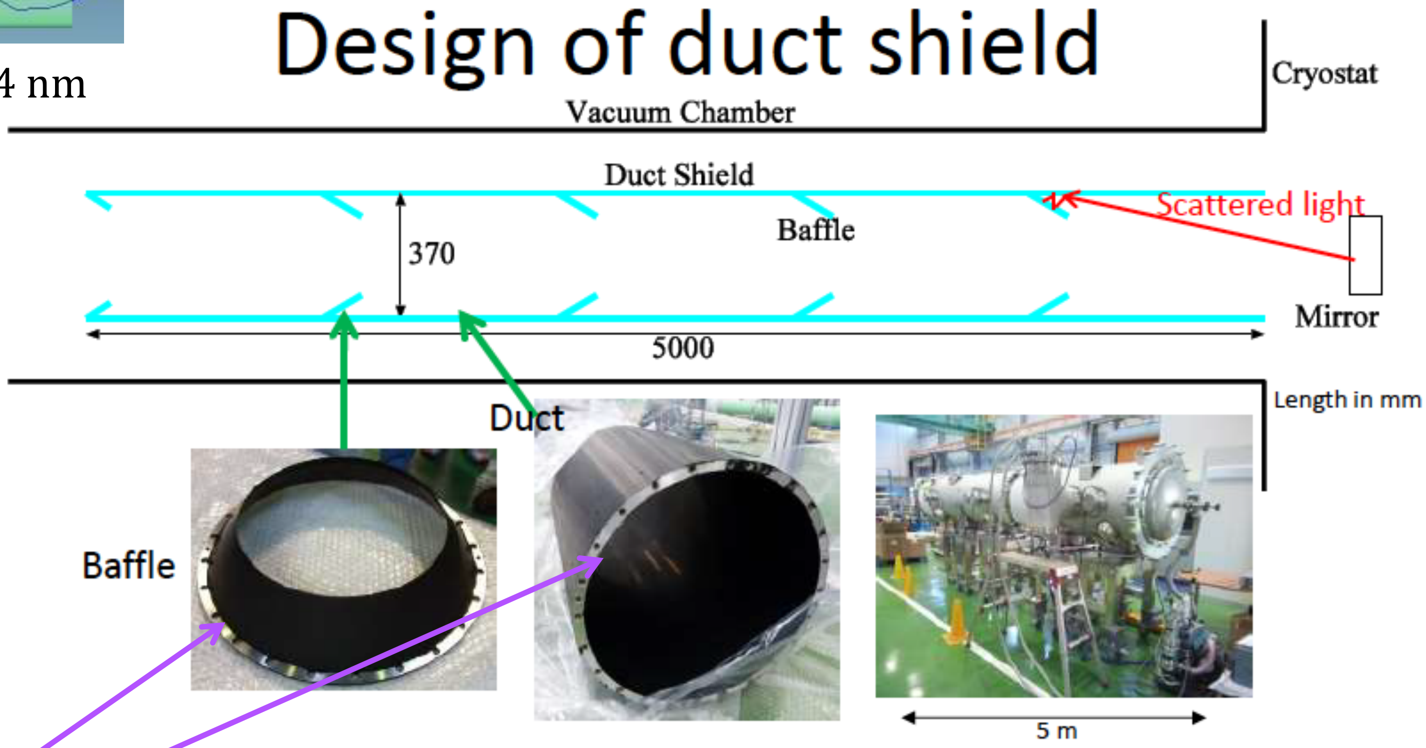
1st floor

Ground

Cryo-duct shields



Simulation: scattering of 1064 nm and 300K radiation.



“Solblack” (black plating)

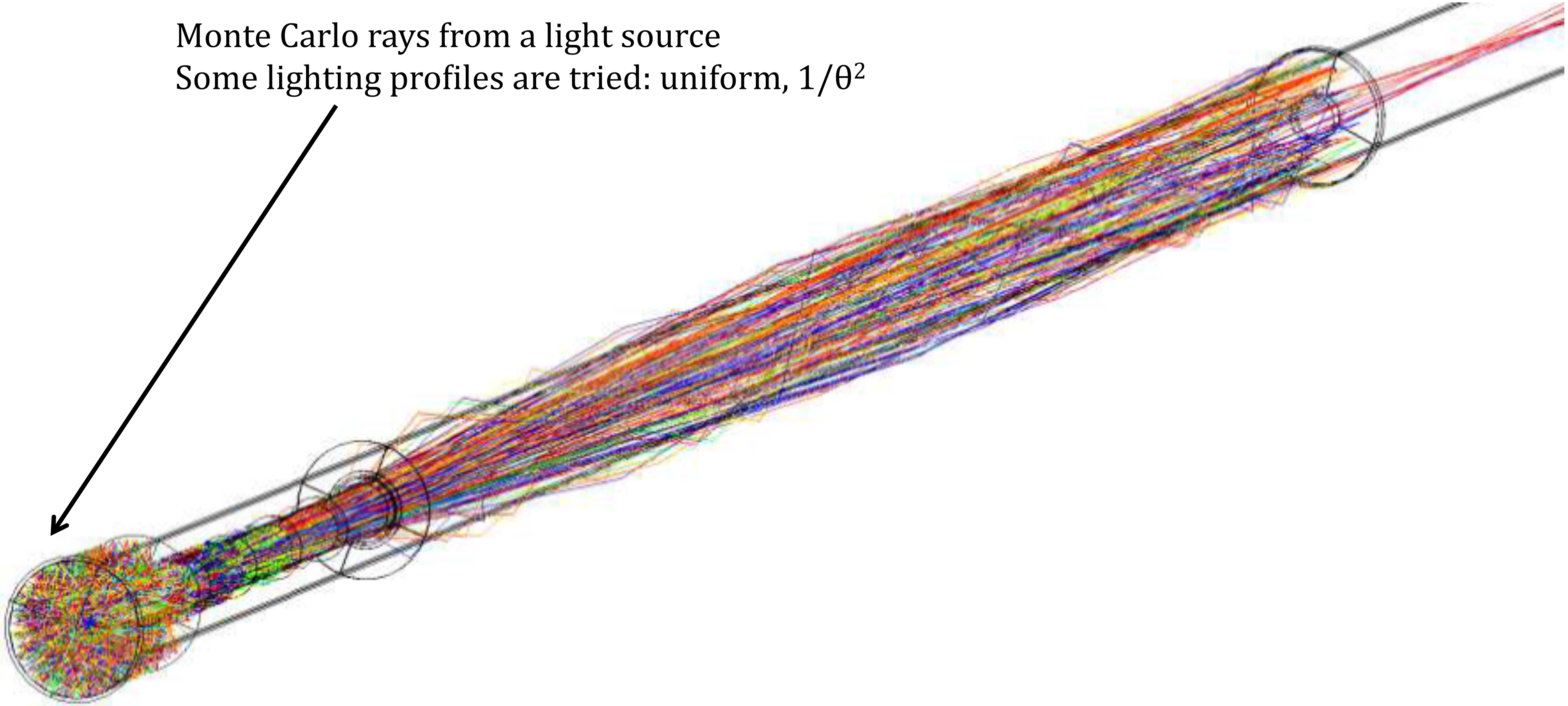
Figs by Y. Sakakibara

Cryo-duct shield (face-on)

Close-up view with LED illumination

Run

Monte Carlo rays from a light source
Some lighting profiles are tried: uniform, $1/\theta^2$

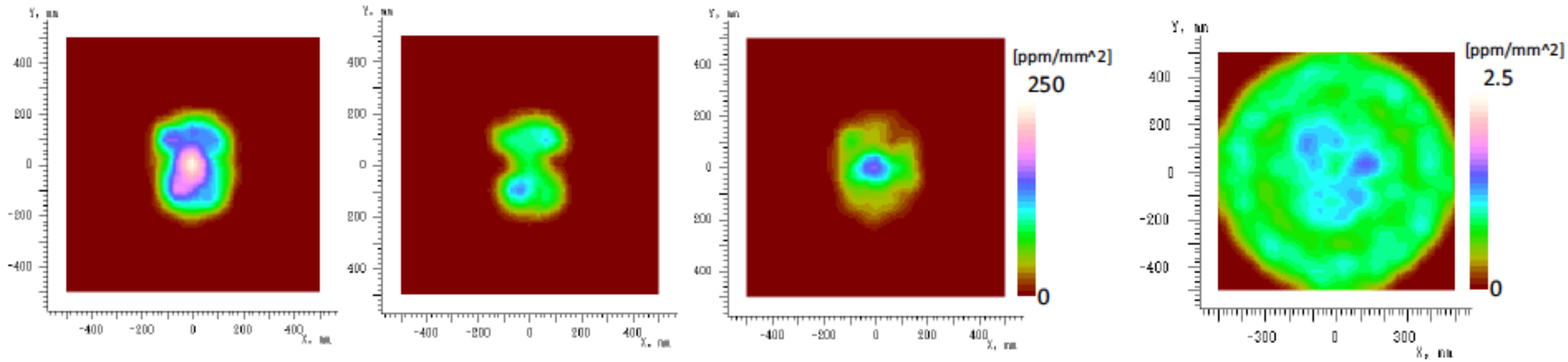


Irradiance maps

One of the results.

Receiver 1 irradiance map (reflected back stray light)

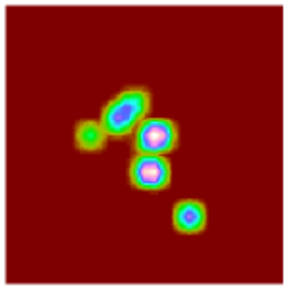
All | From the viewports | From the chamber | Other components



Total power 13.15 ppm | 6.68 ppm | 5.78 ppm | 0.69 ppm

Note: the incident power to this model is assumed to total power of 1.

Receiver 2 irradiance map (transmitted stray light)



"Less than 0.001 ppm"

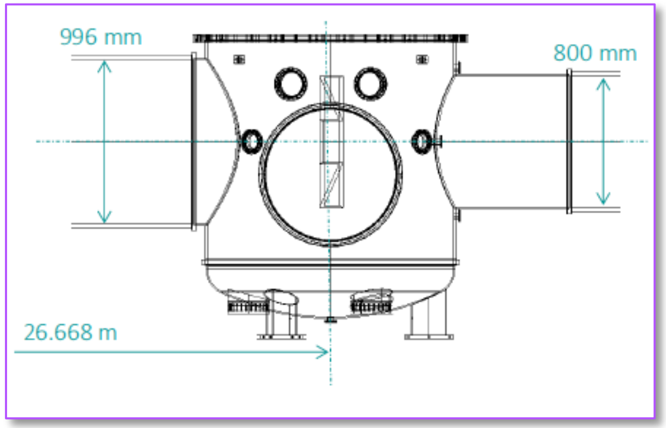


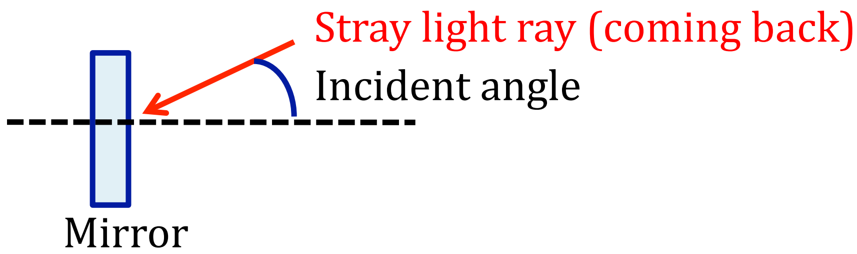
Table of irradiance

Incident angle width （θ1 < θ <θ2）

Number of bounces of stray light

θ1	0	0.3	0.3212	0.3456	0.3741	0.4076	0.4478	0.4967	0.5576	0.6356	0.7389	0.8824	1.0949	1.4423	2.1127	3.9474	30
θ2	0.3	0.3212	0.3456	0.3741	0.4076	0.4478	0.4967	0.5576	0.6356	0.7389	0.8824	1.0949	1.4423	2.1127	3.9474	30	90
1回	0	0	0	0	0	0	0	1.50502E-07	5.31531E-08	0	3.5729E-08	3.65937E-08	4.45439E-08	7.64008E-08	4.91709E-07	1.03381E-06	0
2回	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	0	1.32442E-08	5.02045E-05	0.000142374	5.96981E-05	6.57337E-07	1.1196E-06	0
3回	0	0	0	6.16E-06	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3.88226E-05	1.99782E-07	2.46021E-07	0
4回	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0
5回	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0
6回	0	0	0	0	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0
8回	0	0	0	0	0	0	0	0	0	0	0	1.06364E-07	[illegible]	[illegible]	[illegible]	[illegible]	0
9回	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.10094E-06	0
10回	0	0	0	0	0	0	0	0	0	0	2.49482E-06	0	0	0	0	3.26557E-07	0
11回	0	0	0	0	0	0	0	0	0	0	0	0	1.91722E-06	0	0	0	0
12回	0	0	0	0	0	0	0	0	0	0	0	1.0528E-06	0	0	0	0	0
13回	0	0	0	0	0	0	0	0	0	0	0	0	7.42294E-06	0	0	0	0
14回	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.75653E-08	0
16回	0	0	0	0	0	0	0	0	0	0	0	1.57658E-07	0	0	0	1.50E-08	0
39回	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.787E-08	0

Preliminary



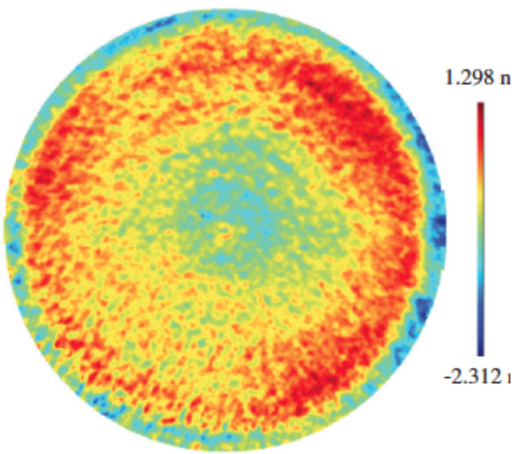
Recombine probability

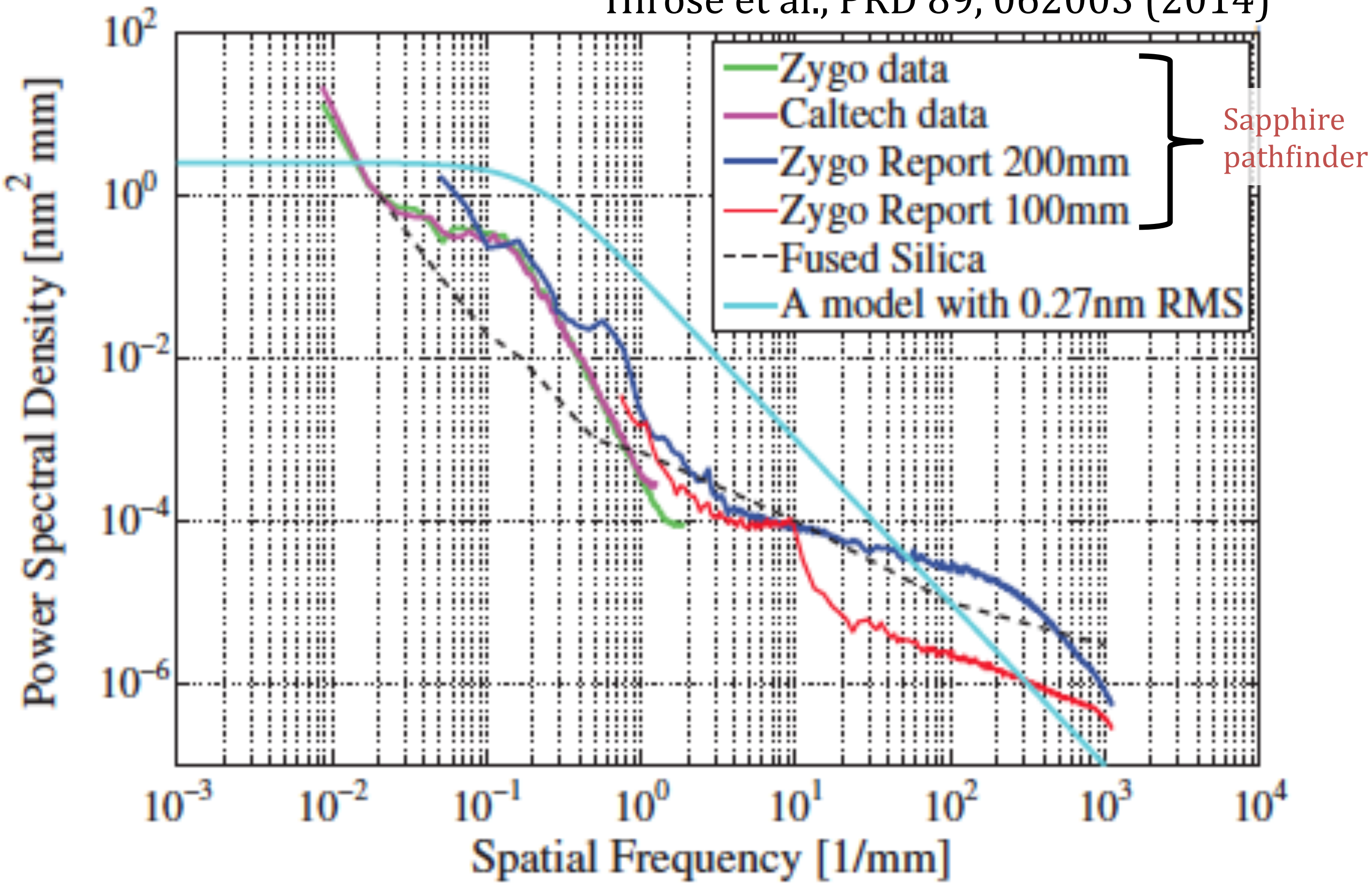
At a sapphire mirror

- Based on ‘reciprocal theorem’: scattering probability distribution is a kind of bi-directional.
- Requires a mirror’s roughness in terms of spatial power spectrum (vs spatial frequency) .

→ Just use a result of polish of a sapphire pathfinder

Hirose et al., PRD 89, 062003 (2014)



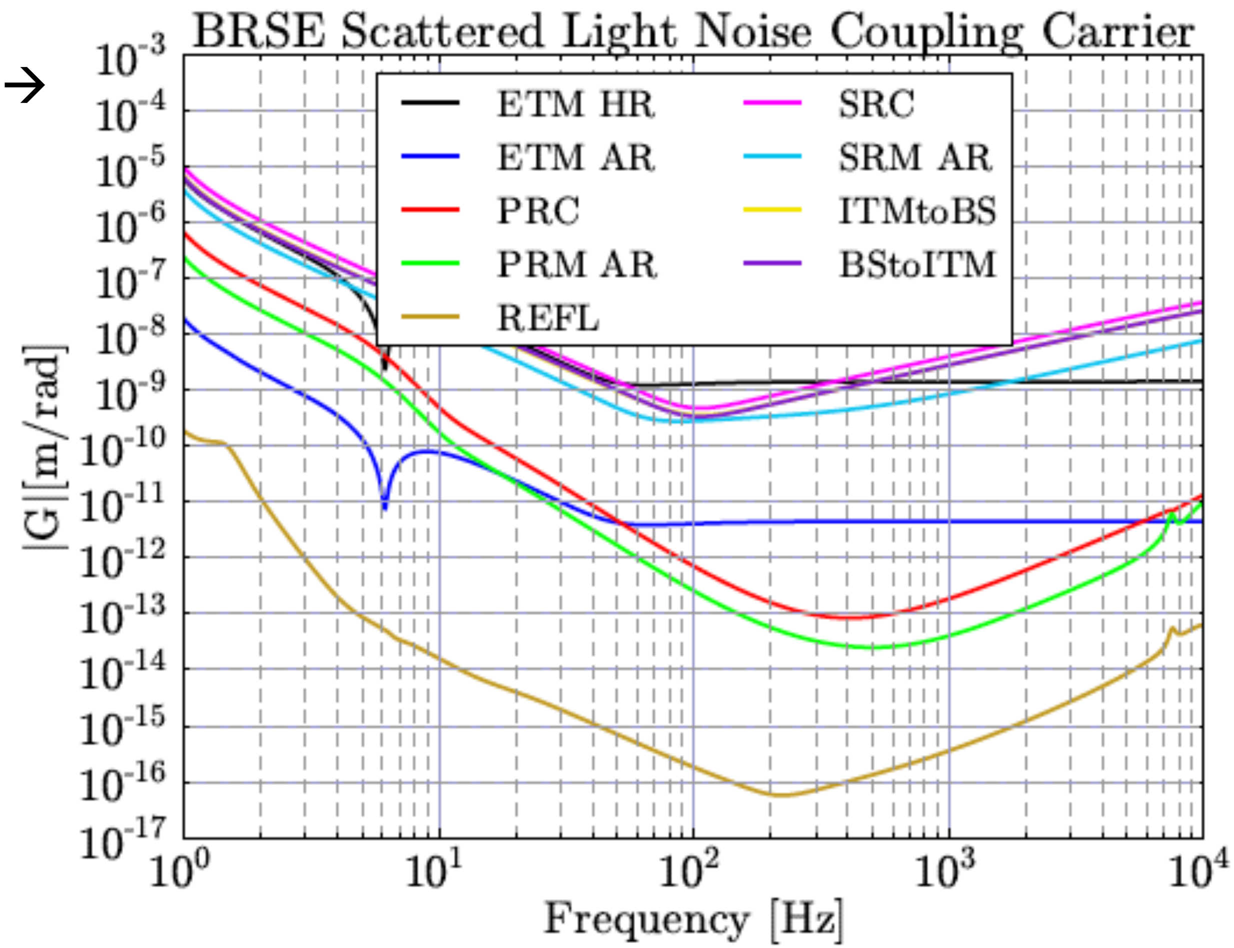


Note: determining ray distribution from a light source also needs this spectrum.

Transfer functions

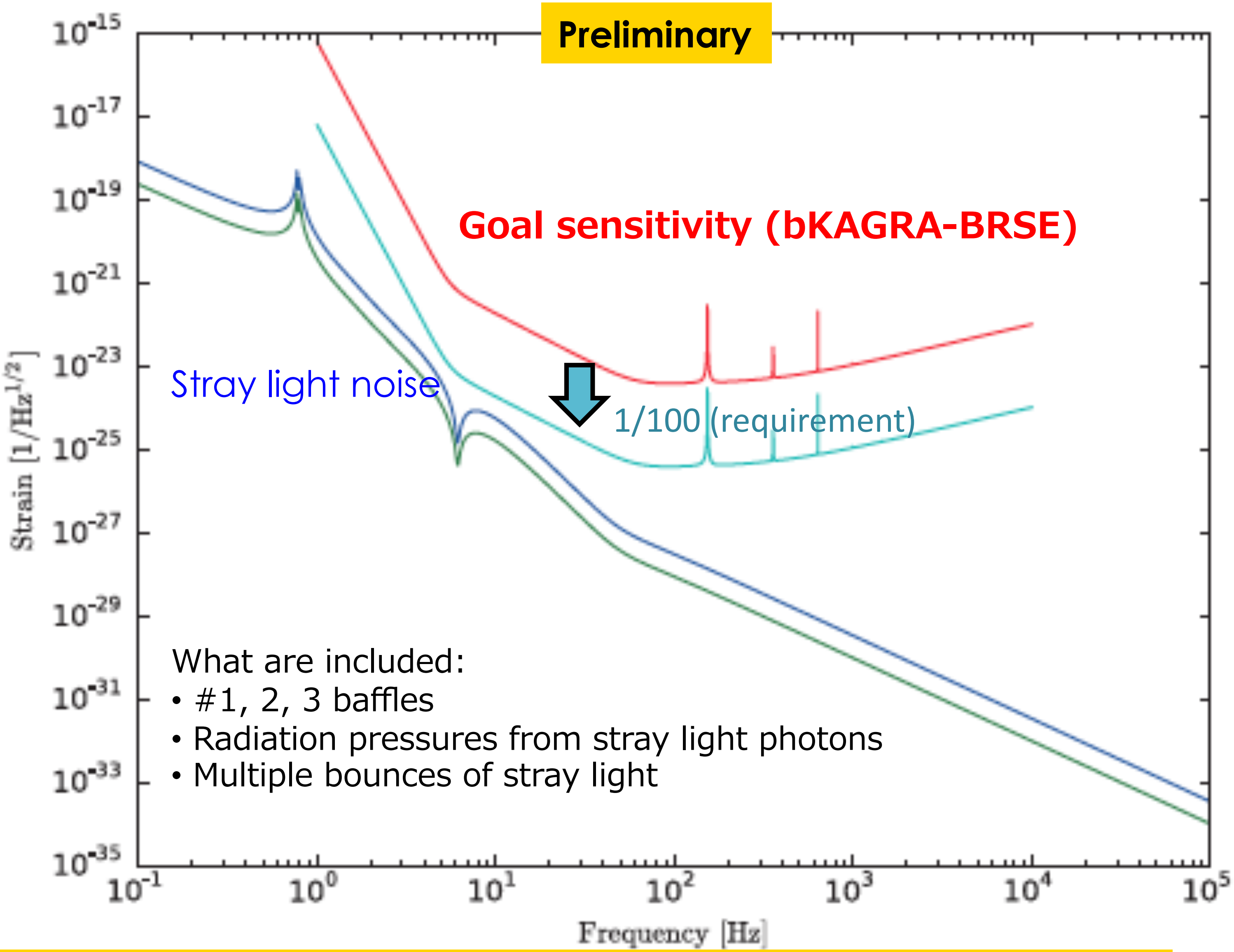
Estimated with Optickle by Y. Aso

JGW-T1200913 →



With this transfer function, scattered light power, power spectrum of scatterer's vibrations, recombination probability →

Stray-light noises



What are not included:

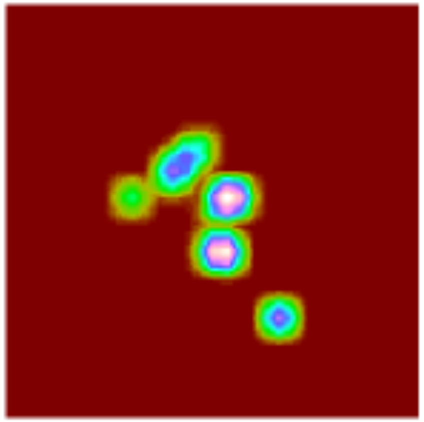
• Actual seismic or acoustic noise level by air flow or cryo-cooler actuation or...

Concerns on the ray trace

- Non-sequential ray tracing with a monte carlo light source is a *statistics*.
- Needs sufficient counts of rays on a receiver; what we want to know is actually a number density of rays (illuminance or irradiance [W/m^2]) there.

Opposite!

We want to make system less scattered lightened, or zero counts of rays on a receiver.



- Future work: ***reverse ray tracing*** or other algorithms?

Note: tracing thermal photons can be done if one know only the total number of rays (like yesterday's Y. Sakakibara's talk), and in that case, the number density of rays wouldn't be so important.

Memos

Share information with others subsystem!!

- The optical simulator should be "interactive" or "*lively* linked" with mechanical CADs (like SolidWorks or Inventor)

  Hope changes by the each subsystem should be immediately reflected to the master CAD in an organized manner.

  Today most of the simulators can deal general 3D file formats (by adding modules for that), but sometime the information on the original geometry would get lost unless the live-link is used.

- Needs cares to ghost beams.

  Non-sequential ray trace with monte-carlo light source is applied for evaluating scattered light, but not ghost beams (and both are 'stray light'). Hope new function that can easily treat both scattering and ghost beams.

- Do flexible works!

  Some parts are already made while other parts don't!

Another example: sequential ray trace

An *old* design of a transmission monitor (beam reduce telescope) for KAGRA

New design would be with lenses rather than reflective system (to be determined, needing certain cares for back-scattering).

Algorithm to be used: Gaussian beam decomposition, or Gaussian beam summation.

Not FFT-like. Divides a beam to tiny fractional Gaussian beamlets, and traces them as 'complex rays', and then sums up them coherently at each (dummy) surface of an optical element. Gaussian beam propagation with aberration can be taken into account as well.

Ref: B. Stone and T. Bruegge, "Practical considerations for simulating beam propagation: A comparison of three approaches"

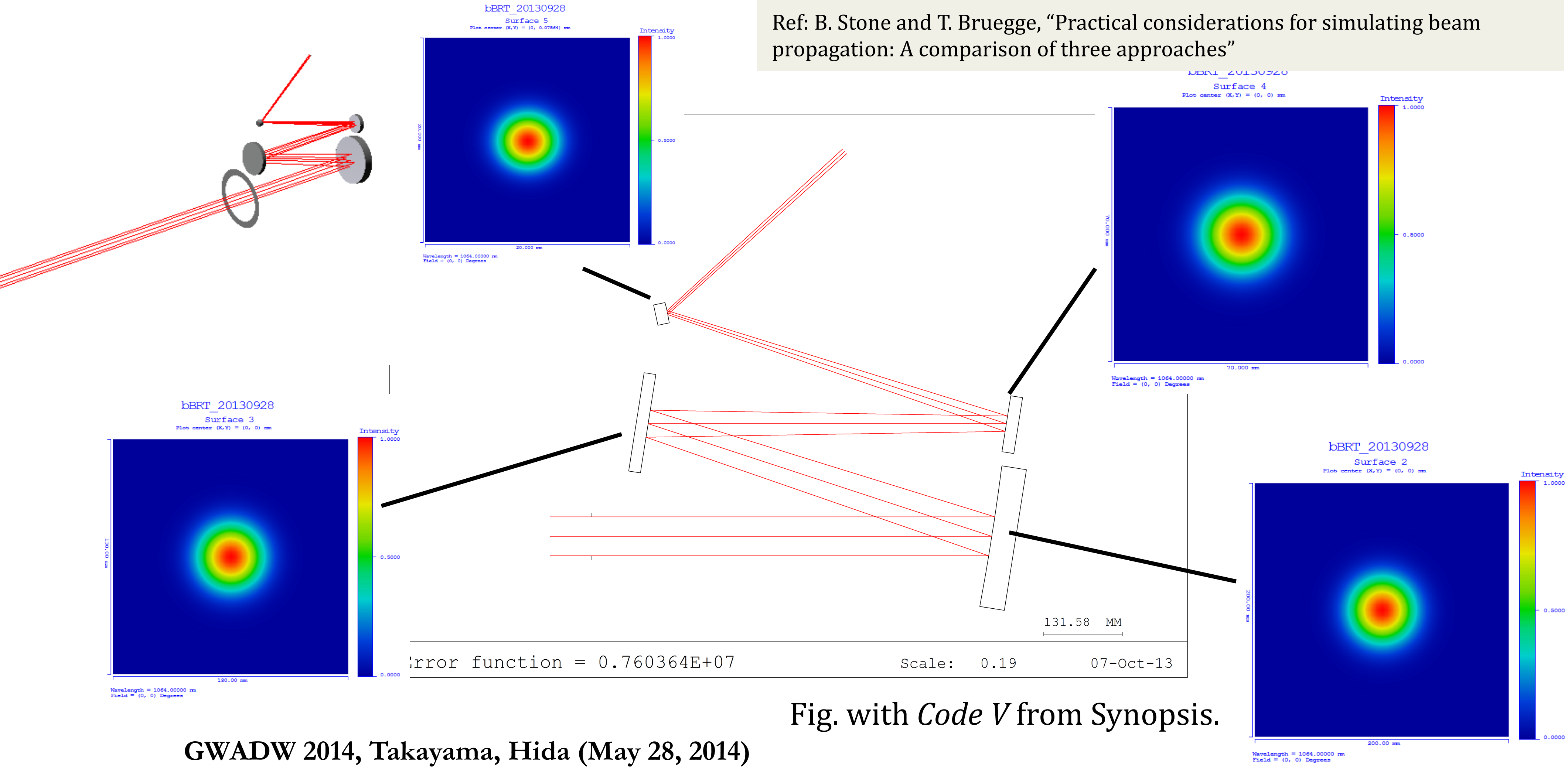
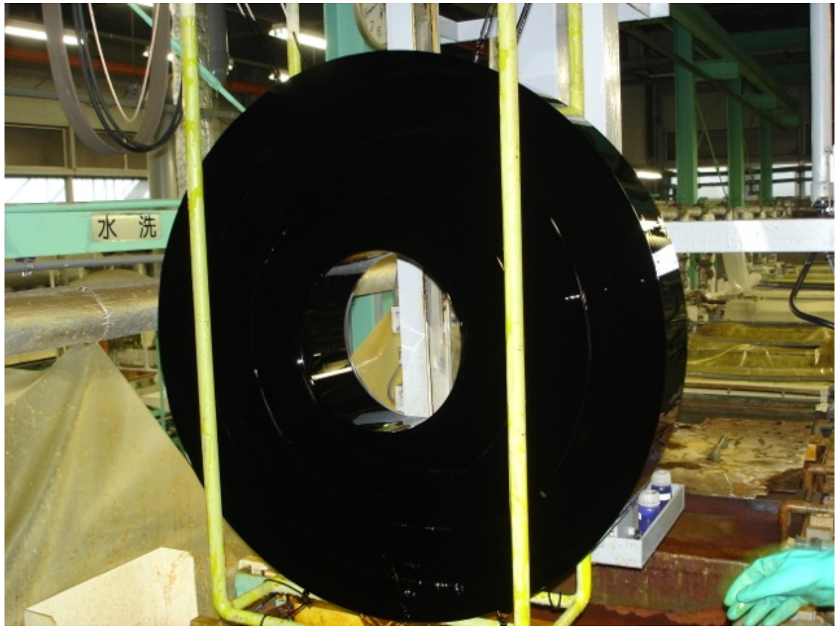


Fig. with *Code V* from Synopsis.

Summary

- Reviewed commercial optical simulators.
- Non-sequential ray tracing is useful for calculating stray rays.
- Estimated stray-light noise in KAGRA, around 3-km arms.
- Needs more measurements for some parameters to make the estimation more realistic.



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