13-0411

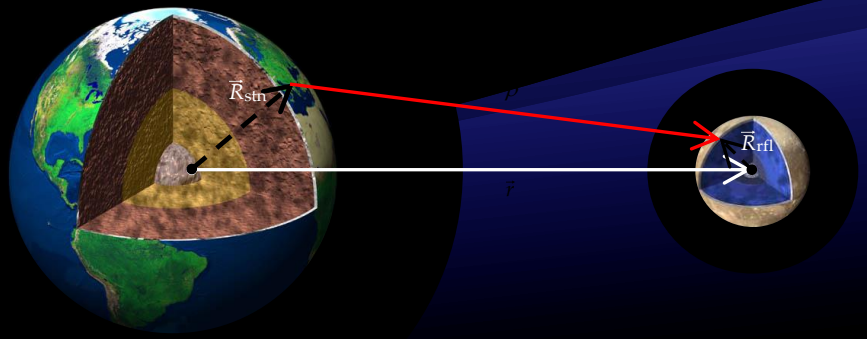
Development of the retro-reflector on the Moon for the future Lunar laser ranging

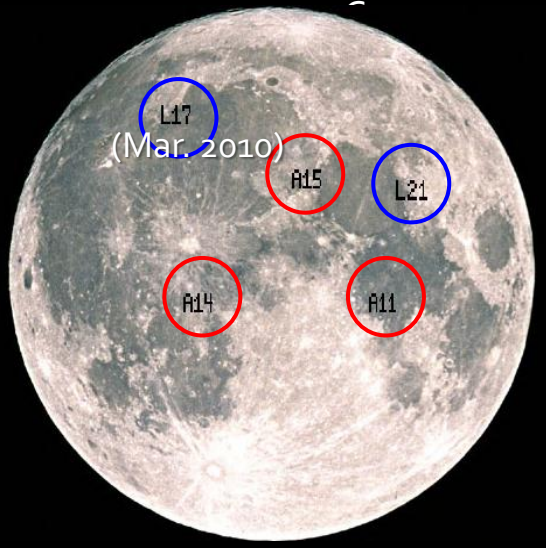
H. Araki[1)], S. Kashima[1)], H. Noda[1)], H. Kunimori[2)], H. Mashiko[3)], T. Otsubo[4)], M. Utsunomiya[5)], and Y. Matsumoto[6)]

[1)] NAOJ (RISE), [2)] NICT , [3)] Iwate Univ., [4)] Hitotsubashi Univ., [5)] JAXA, [6)] PLANET INC.

Historical Accuracy of LLR

Gusev 2010 modified





Appendix B. Measurement Residual Plots

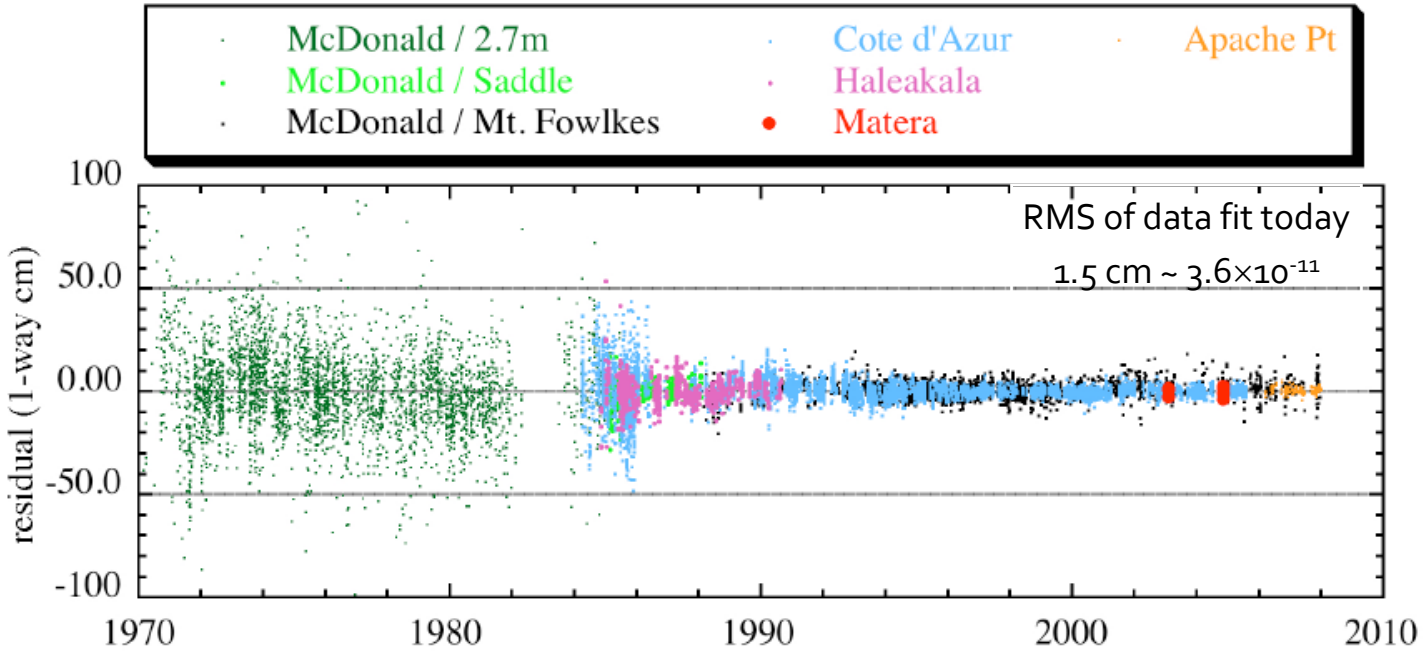


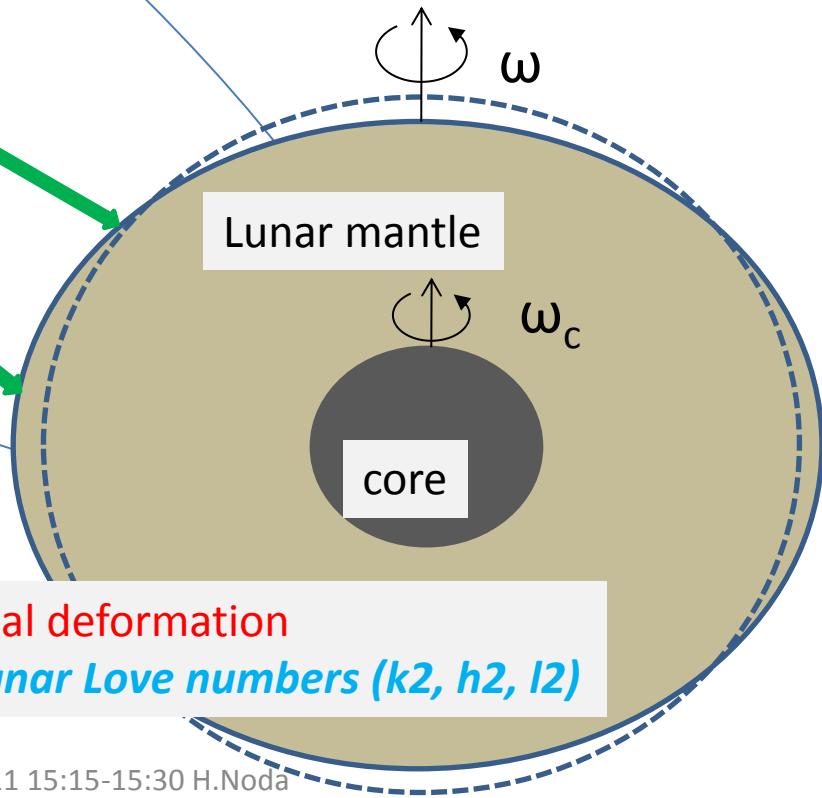
Figure B-1: Lunar laser ranging residuals.

Science with LLR

Observable
•Ranges between Earth/lunar surface

Rotation
•Total moment of inertia(MOI)
•core MOI/mantle MOI
•Dissipation by core-mantle coupling & oblate fluid core

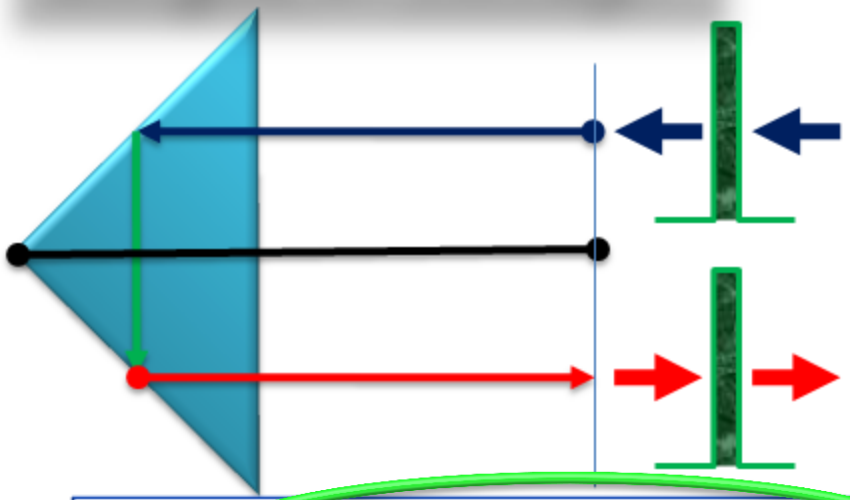
Lunar orbit
•Lunar GM
•Ġ/G
•Gravitational physics

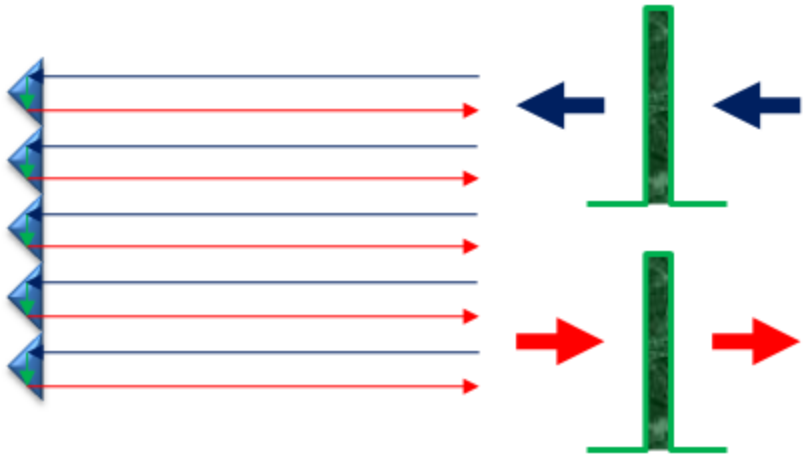


Tidal deformation
•Lunar Love numbers (k2, h2, l2)

Final goals:
•radius and state of the lunar core
•bulk composition of the Moon

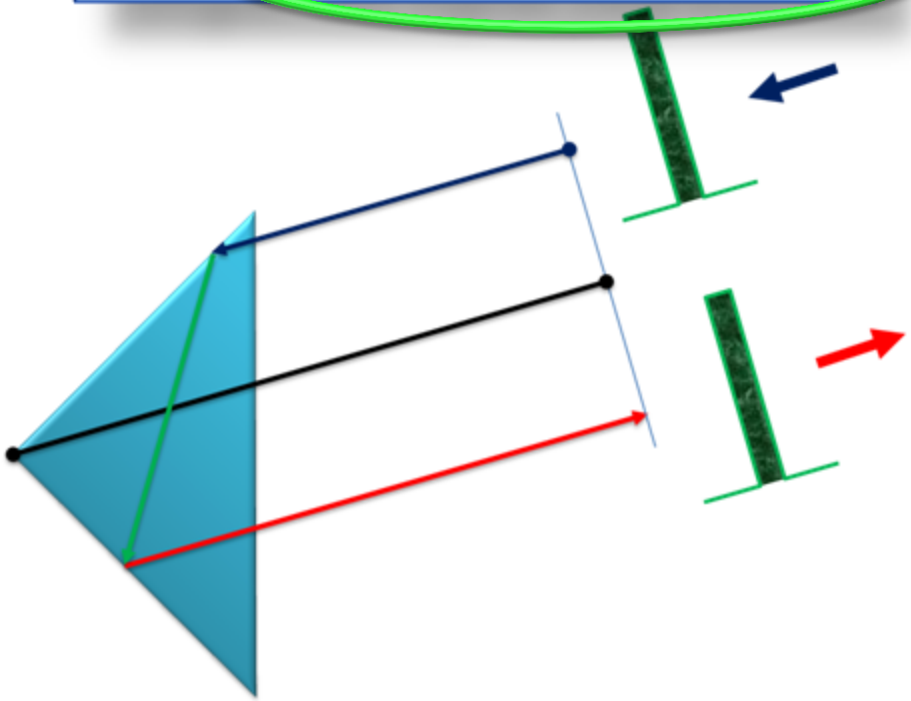
Single or Array?

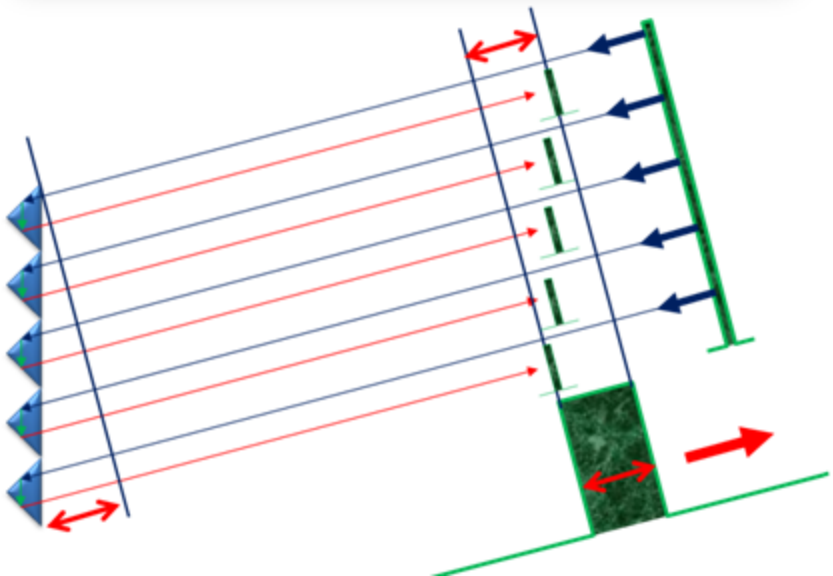




Single: No signal degradation

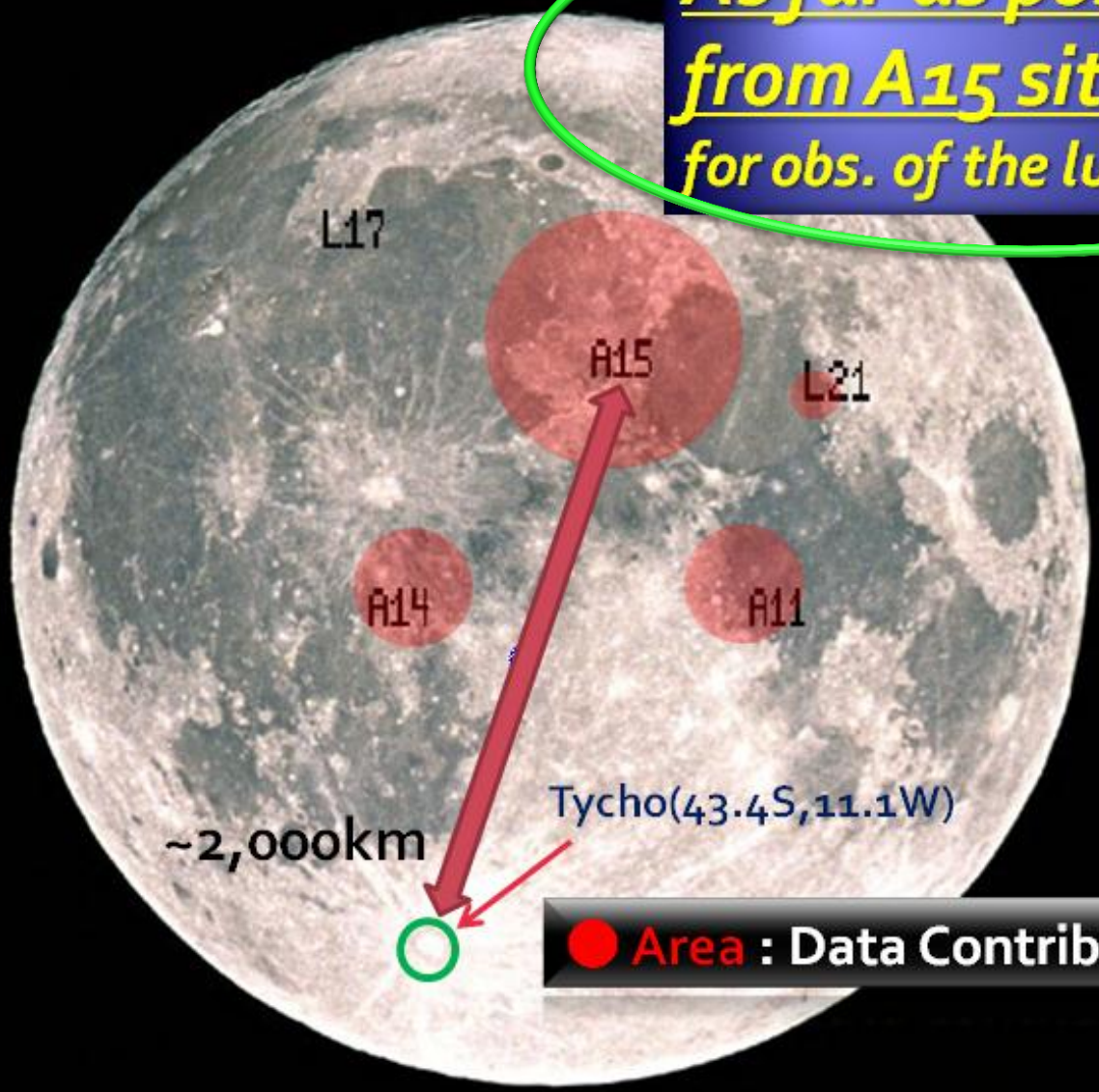
Array: Signal degradation for oblique incidence





Where on the Moon?

As far as possible from A15 site
for obs. of the lunar libration



● Area : Data Contribution (A15: ~77%)

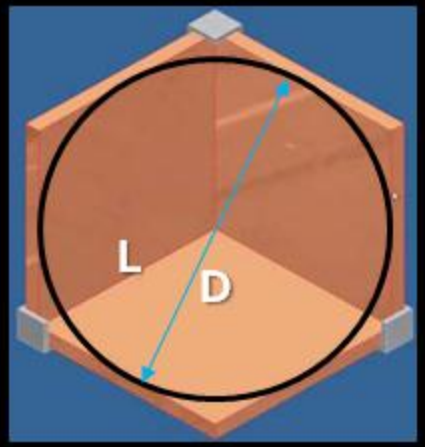
How large ? - More efficient than A11 CCR -

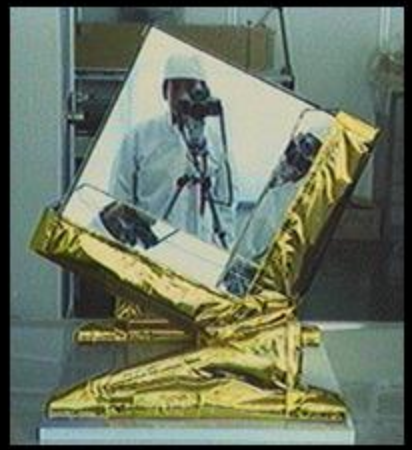
- Optical Cross Section:

σ_{cc} : Optical Cross Section
ρ : Reflectivity
D_{cc} : CCR Aperture Area
λ : Wavelength
n : ~3 (taking into account Earth-Moon vel. "aberration" with DAO)
4 (relative velocity = 0)

$$\sigma_{CC} = \frac{4\pi\rho\, D_{cc}^{\,n}}{\lambda^{2}}$$

- CCR Diameter Equivalent to…
- A11 array : D=17.64cm
  (L=12.5 cm)
  100 · σ_{cc}(D=3.8cm) = σ_{cc}(D=17.64cm)
- A15 array : D=25.44cm
  (L=18.0 cm)
  300 · σ_{cc}(D=3.8cm) = σ_{cc}(D=25.44cm)



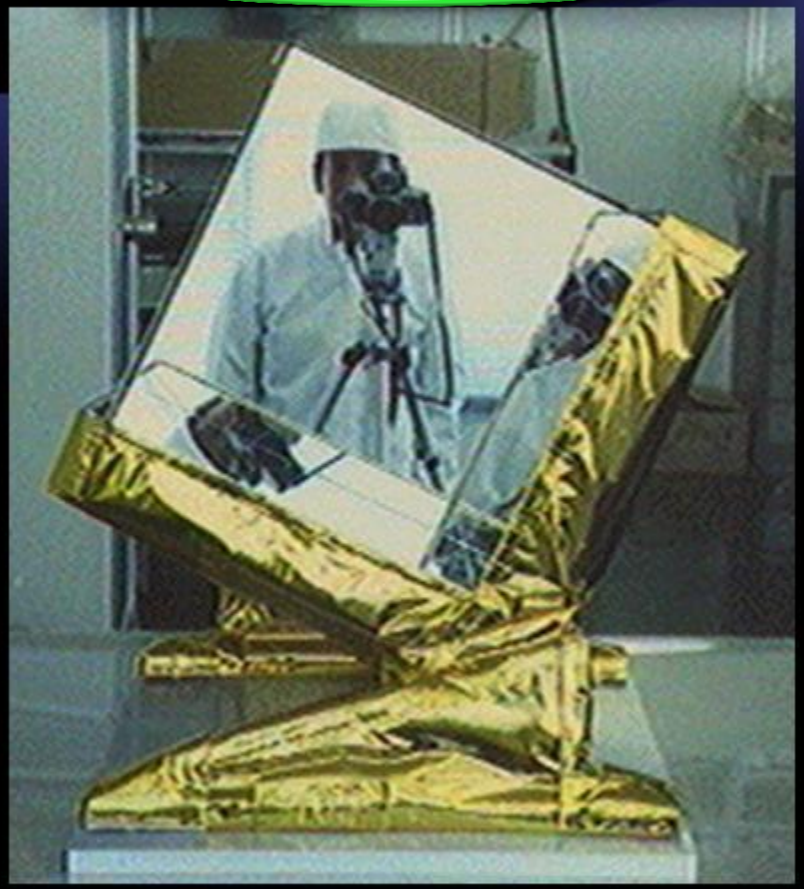


MIDORI, JAXA

Aperture: ~20 cm or more

Hollow or Prism?

Hollow type (CCM)



Prism type (CCP)

(photo by Currie et al., 2011)

10cm prism type (CCP)

higher accuracy but aperture may be up to 10 cm due to material homogenity and/or weight budget

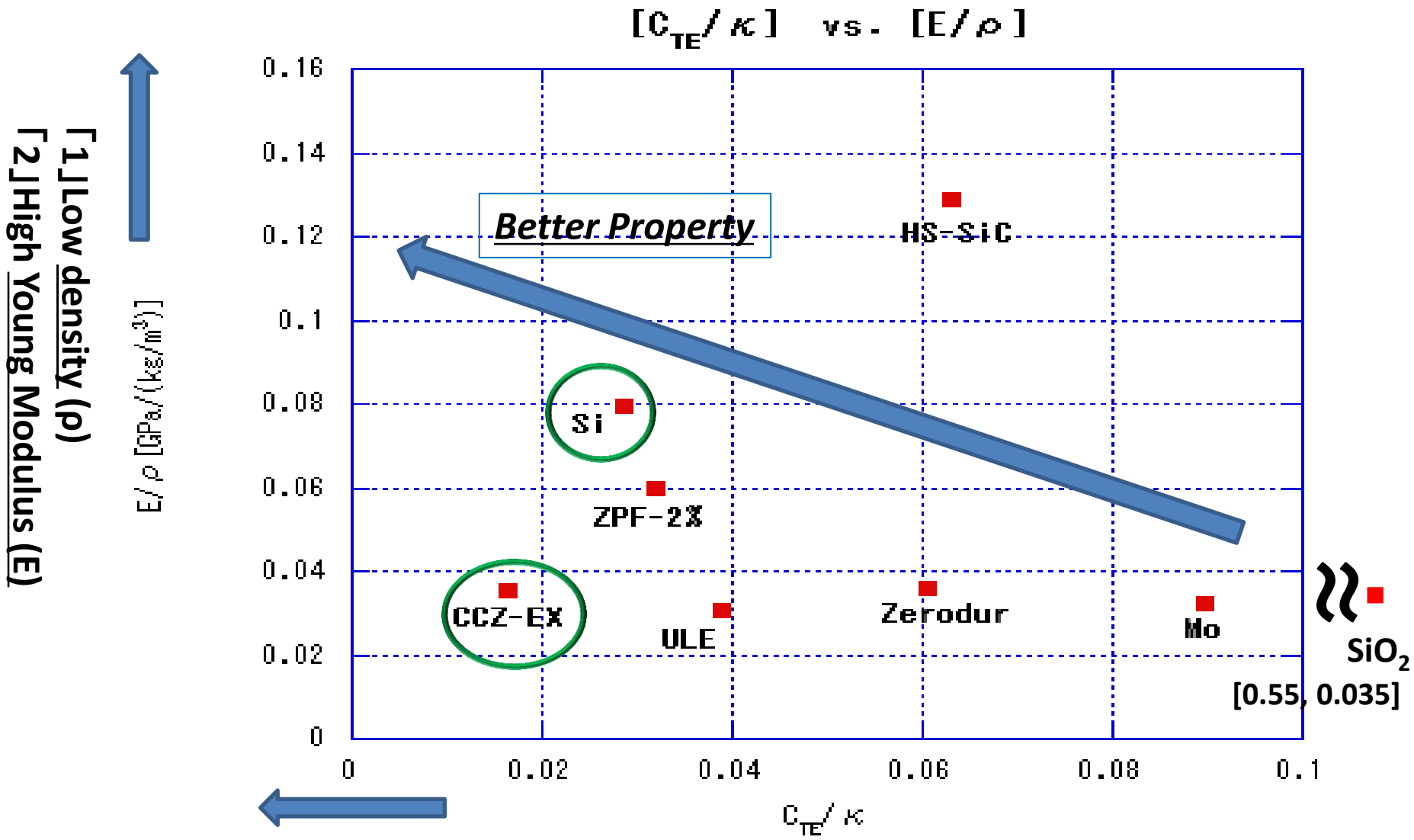
ADEOS / RIS (1994); ***50cm hollow type (CCM)***

Higher accuracy and relatively large aperture are allowed.

- To improve the sensitivity and accuracy of LLR data especially for lunar **physical libration and tide…**

- New **C**orner **C**ube **R**eflector 【Concept】
  1) Single Aperture
  2) As far as from A15 and High latitude region.
  3) Diameter ≧ 20cm [more effective than A11]
  4) Hollow Type → CCM (Corner Cube Mirror).

Material for CCM



「1」Low thermal expansion (C_{TE})

「2」High thermal diffusivity (κ)

Selectionof CCM material

-Optical Evaluation and Comparison-

Temperature Distribution

by Matsumoto

PLANET INC., ***ThermalDesktop***

[Si] vs. [CCZ-EX]

Surface Deformation

by Mashiko, Chiba;

Iwate Univ., ***ANSYS***

Optical Evaluation

by Araki, Kashima;

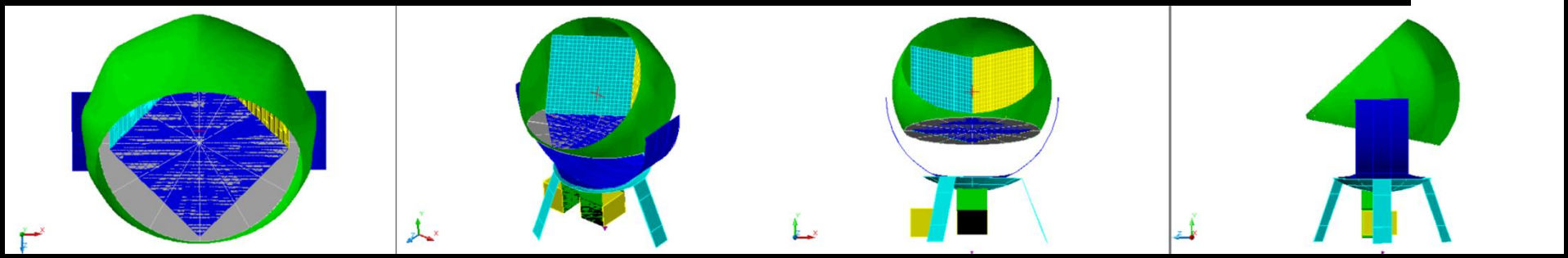
NAOJ (RISE), ***Code V***

Simulation Setting

[Si] vs. [CCZ-EX]

- Aperture of CCM is 20cm
- Silver coating (Ag; α=0.04, ε=0.02)
- Set inside Tycho crater (lat. 43°)
- The optical axis is in the mean Earth direction
- Temperature is calculated when the solar elevation is maximum taking into account self-shadowing in the gimbal model.

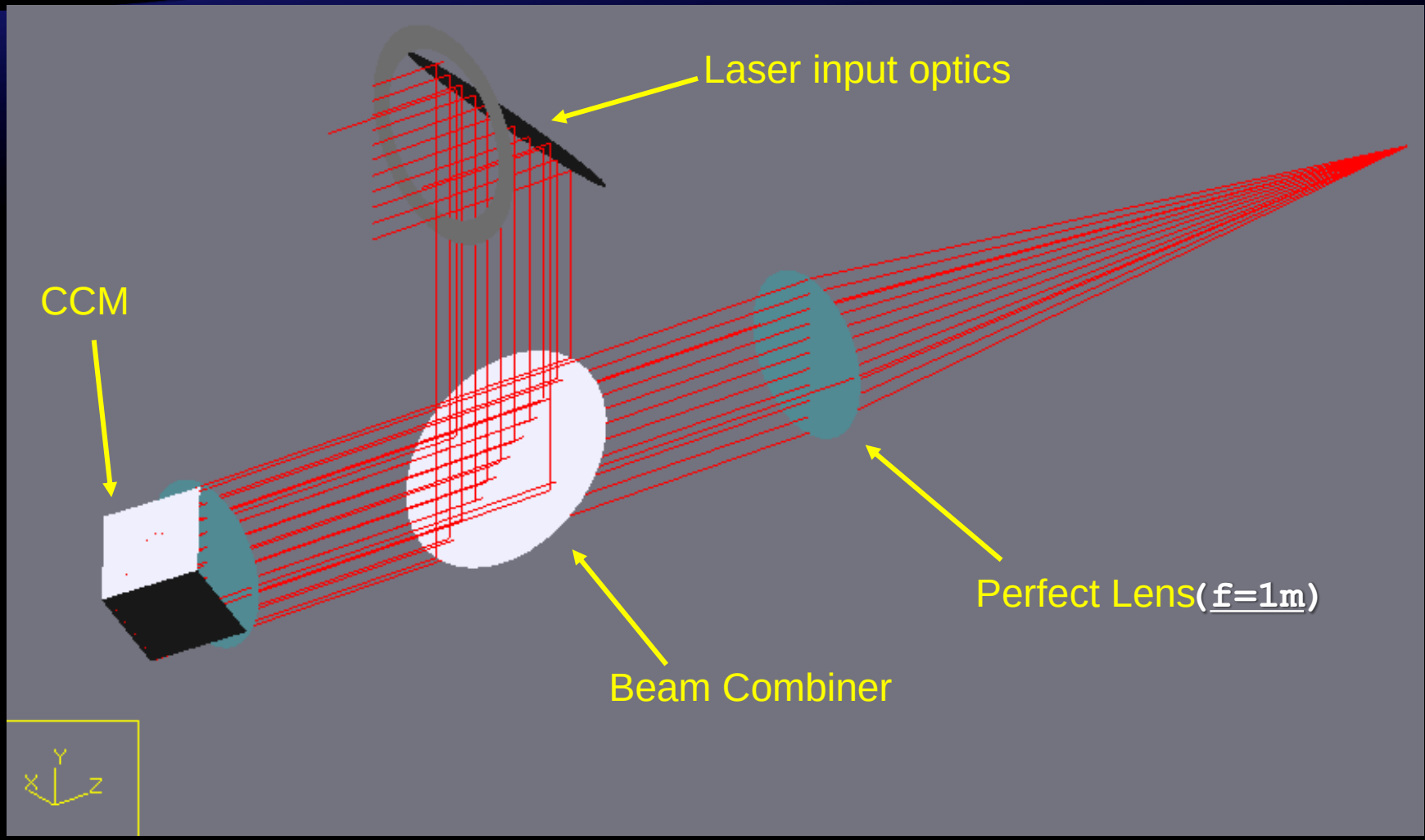
Planet



CCM optical response evaluation model –CodeV –

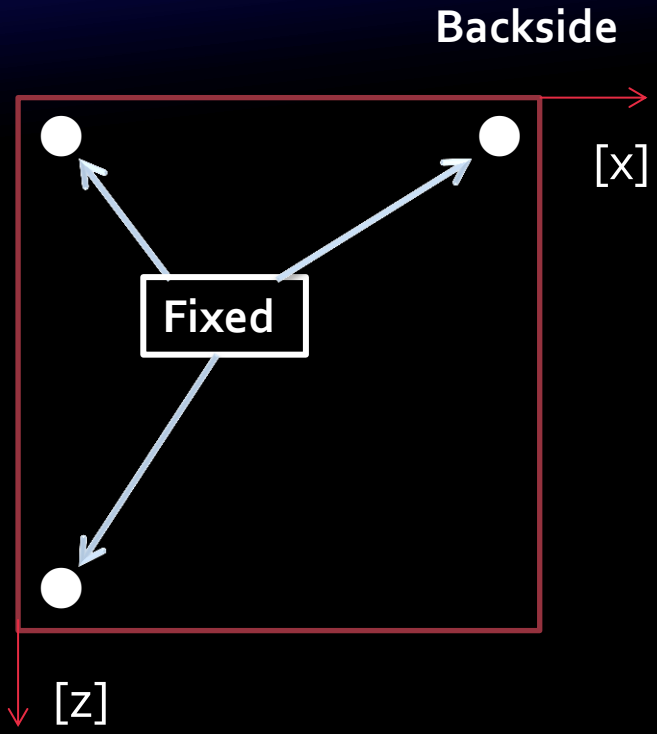
Airy disk diameter: 2.44(λ/D)=1.339″ (D=20cm, λ=532nm)

Criteria: More than 50% of energy reflected by CCM is converged within a circle whose diameter is 6.49004μm (=1.339″*1m).

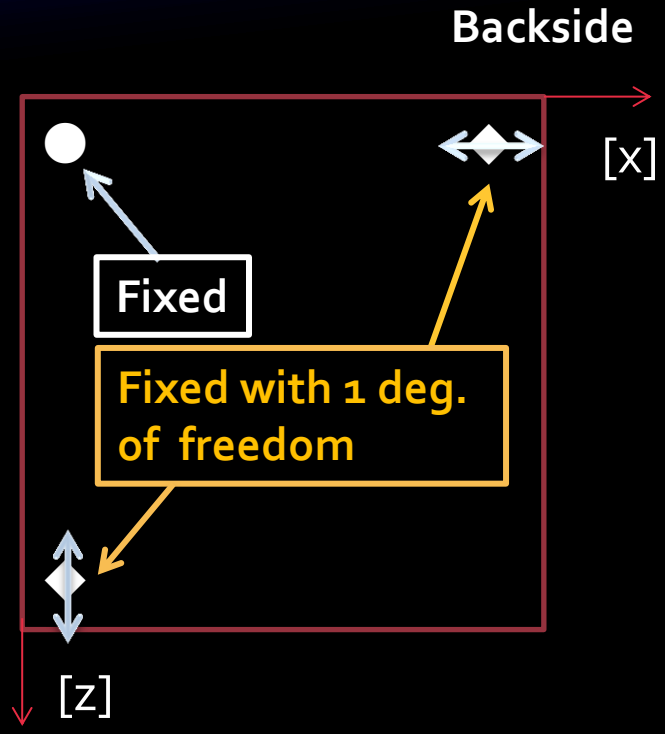


Deformation Analysis by ANSYS
–Boundary Condition–

Fixation:
Type [0,0,0]



Fixation:
Type [0,1,1]

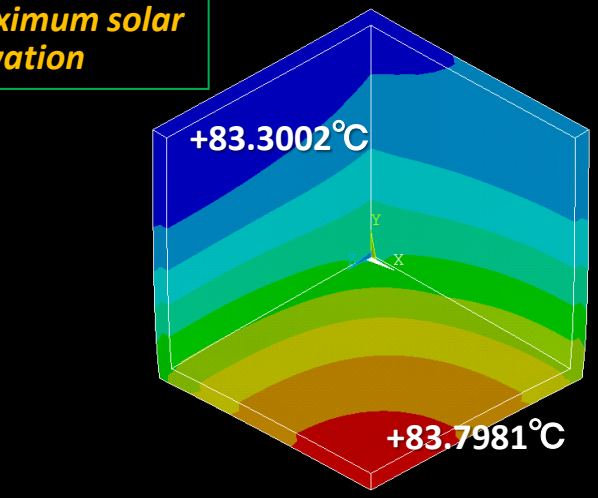


Heterogeneity of elasticity is taken into account.

Si : Temperature Distribution

ANSYS Noncommercial use only

Maximum solar elevation

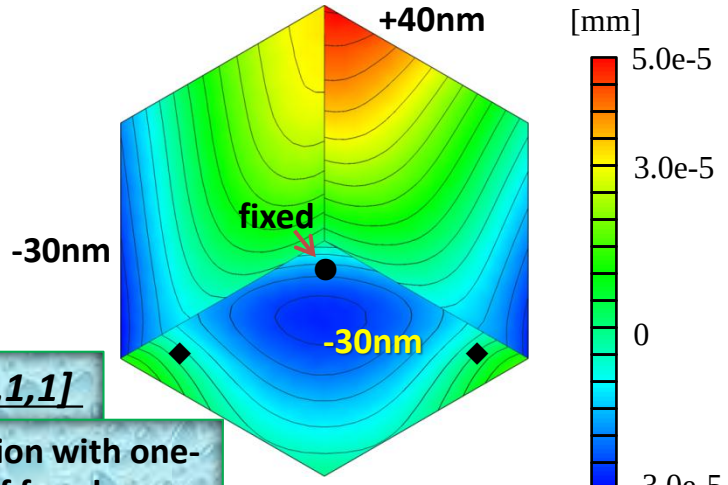


Si: Surface Deformation

ANSYS Noncommercial use only

Normal Component

No deformation @25℃

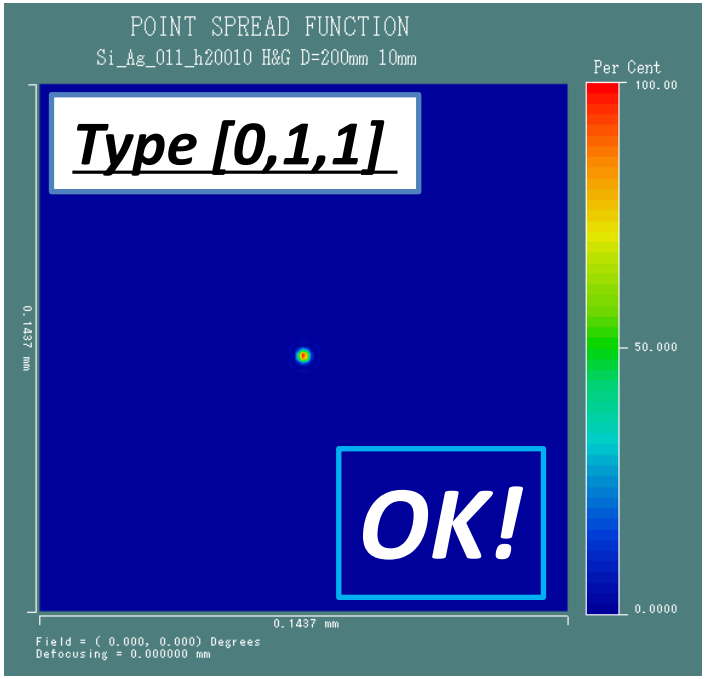


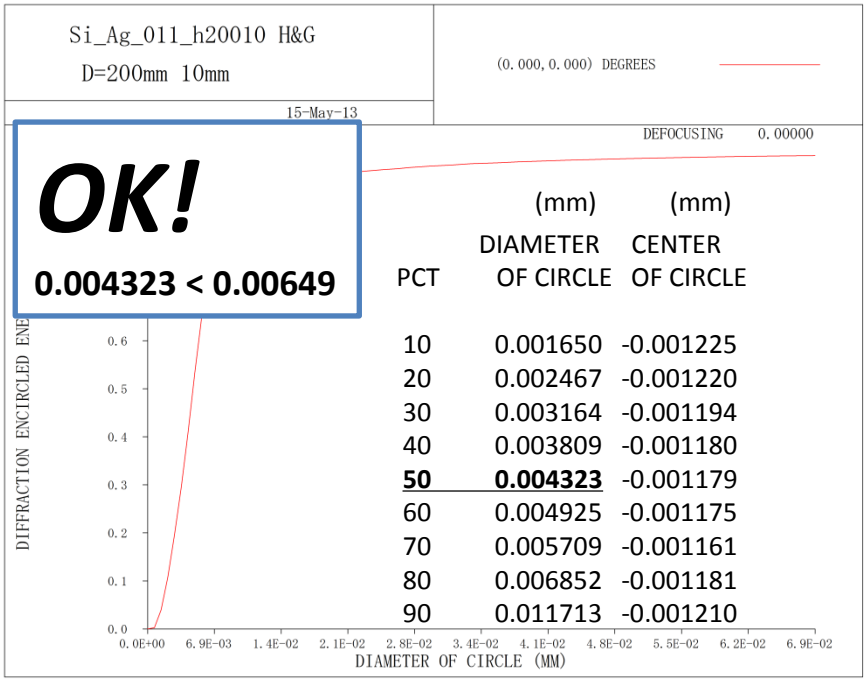
Type [0,1,1]

◆ : Fixation with one-degree of freedom

Si

Optical Test





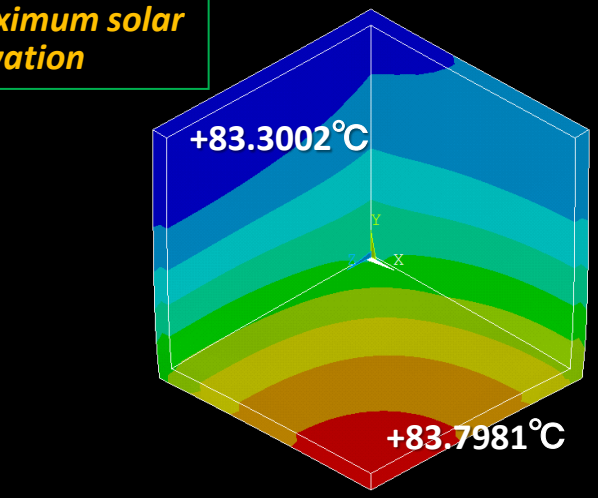
OK!

0.004323 < 0.00649

PCT	(mm) DIAMETER OF CIRCLE	(mm) CENTER OF CIRCLE
10	0.001650	-0.001225
20	0.002467	-0.001220
30	0.003164	-0.001194
40	0.003809	-0.001180
50	**0.004323**	-0.001179
60	0.004925	-0.001175
70	0.005709	-0.001161
80	0.006852	-0.001181
90	0.011713	-0.001210

Si : Temperature Distribution

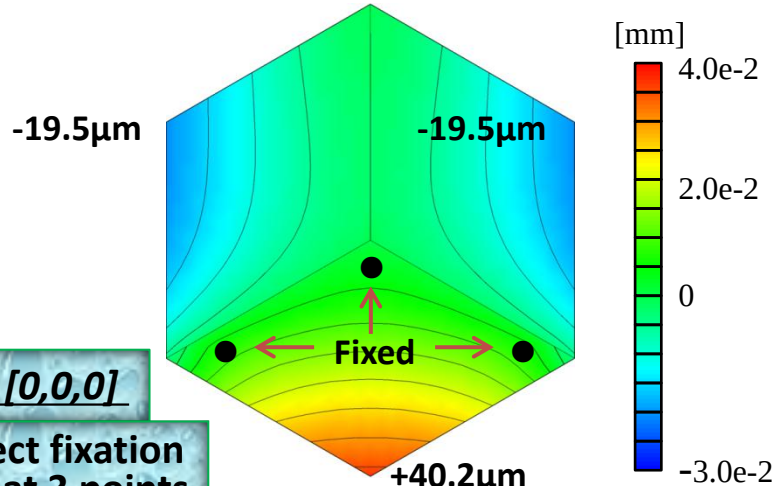
Maximum solar elevation



Si: Surface Deformation

Normal Component

No deformation @25℃

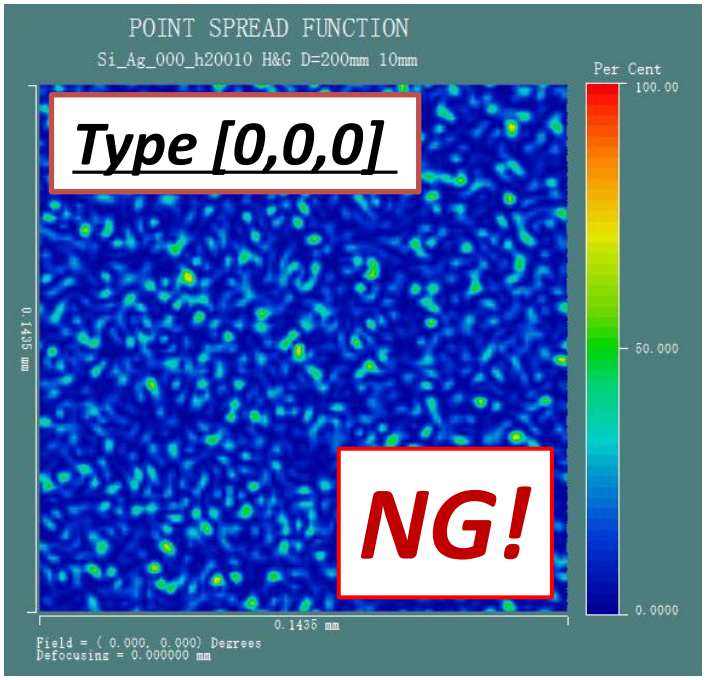


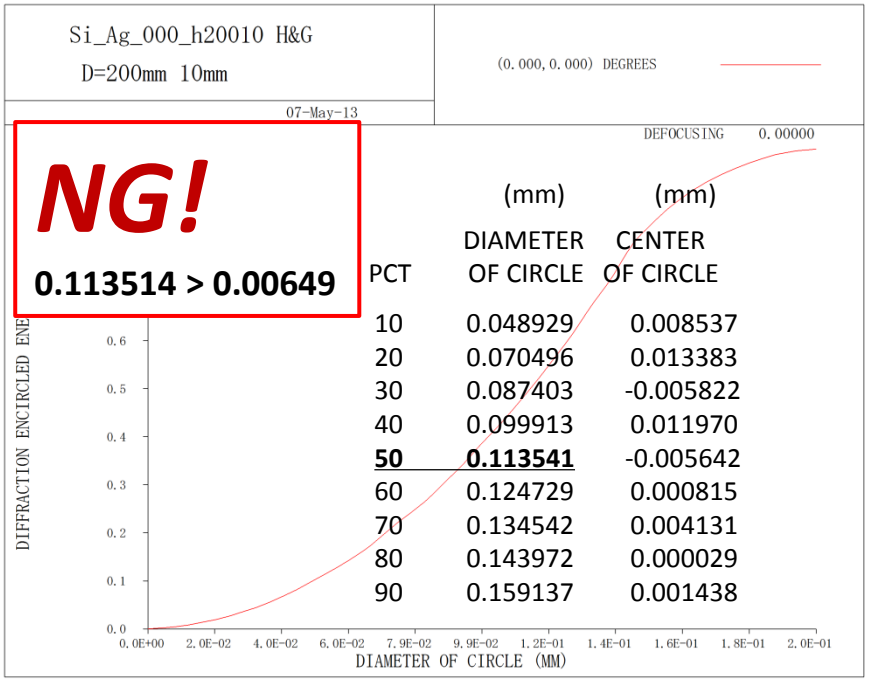
Type [0,0,0]

Perfect fixation at 3 points

Si

Optical Test



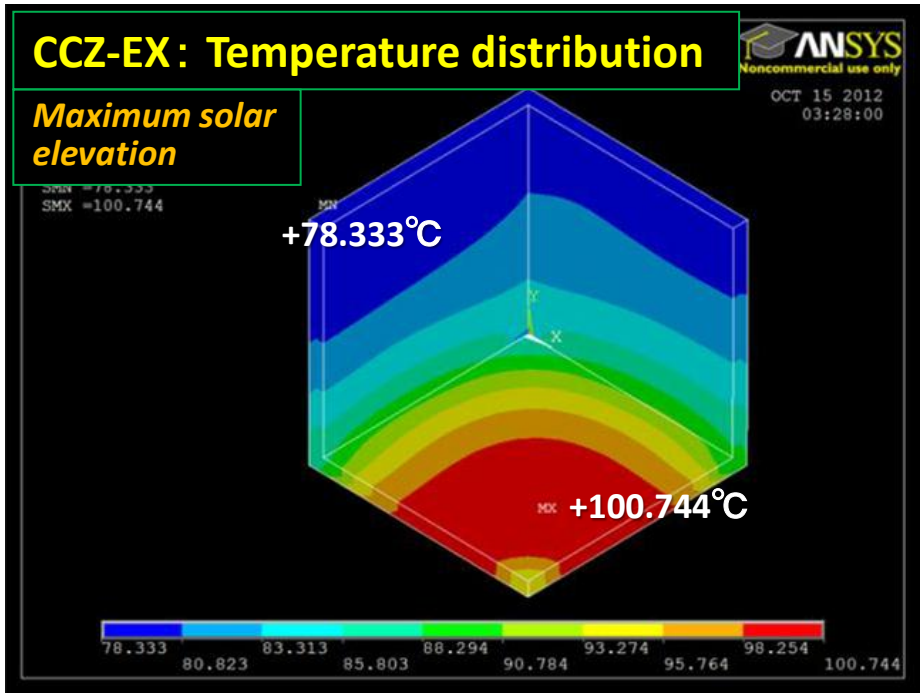


NG!

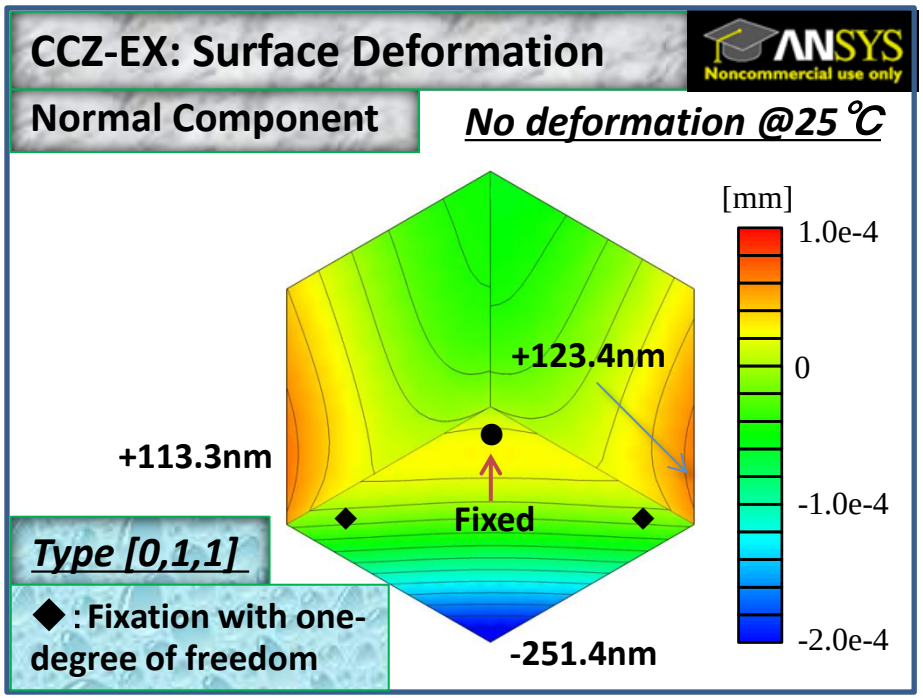
0.113514 > 0.00649

PCT	(mm) DIAMETER OF CIRCLE	(mm) CENTER OF CIRCLE
10	0.048929	0.008537
20	0.070496	0.013383
30	0.087403	-0.005822
40	0.099913	0.011970
50	**0.113541**	-0.005642
60	0.124729	0.000815
70	0.134542	0.004131
80	0.143972	0.000029
90	0.159137	0.001438

CCZ-EX : Temperature distribution

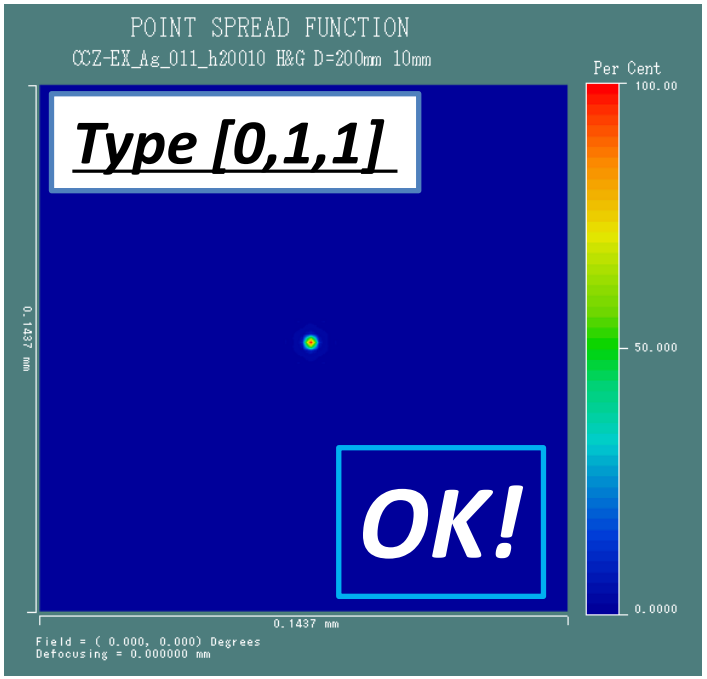


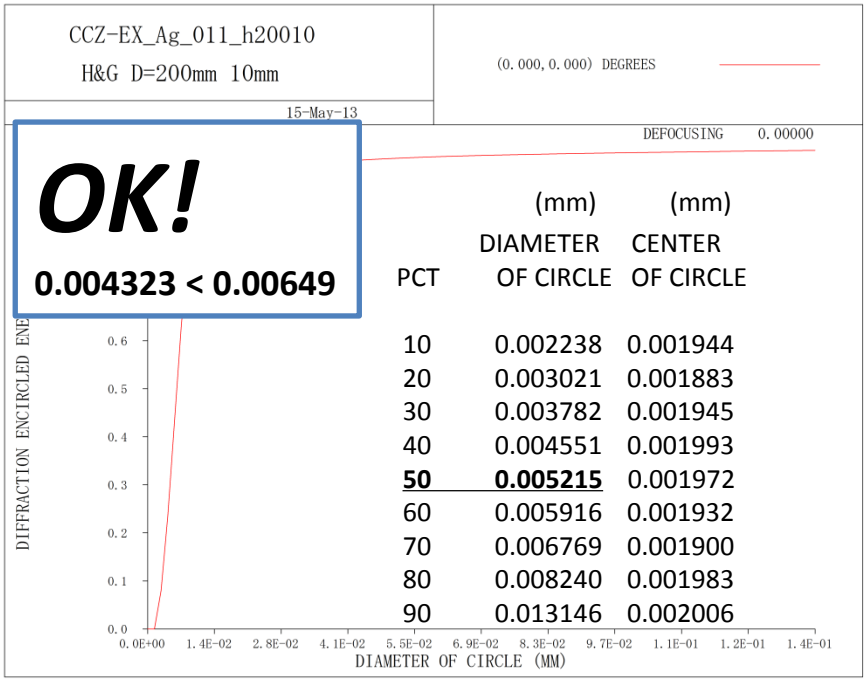
CCZ-EX: Surface Deformation



CCZ-EX

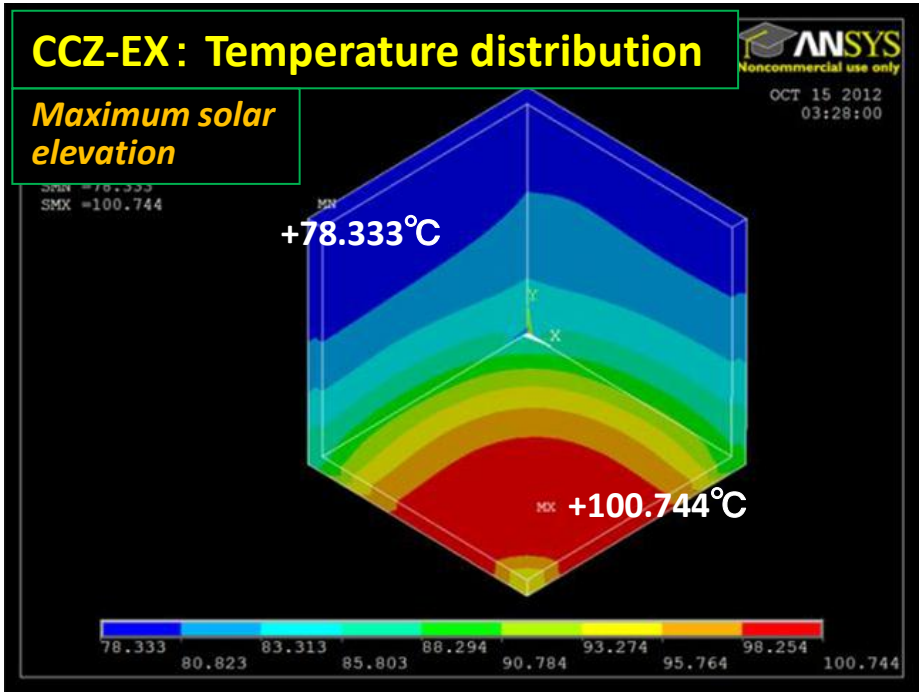
Optical Test





PCT	(mm) DIAMETER OF CIRCLE	(mm) CENTER OF CIRCLE
10	0.002238	0.001944
20	0.003021	0.001883
30	0.003782	0.001945
40	0.004551	0.001993
50	**0.005215**	0.001972
60	0.005916	0.001932
70	0.006769	0.001900
80	0.008240	0.001983
90	0.013146	0.002006

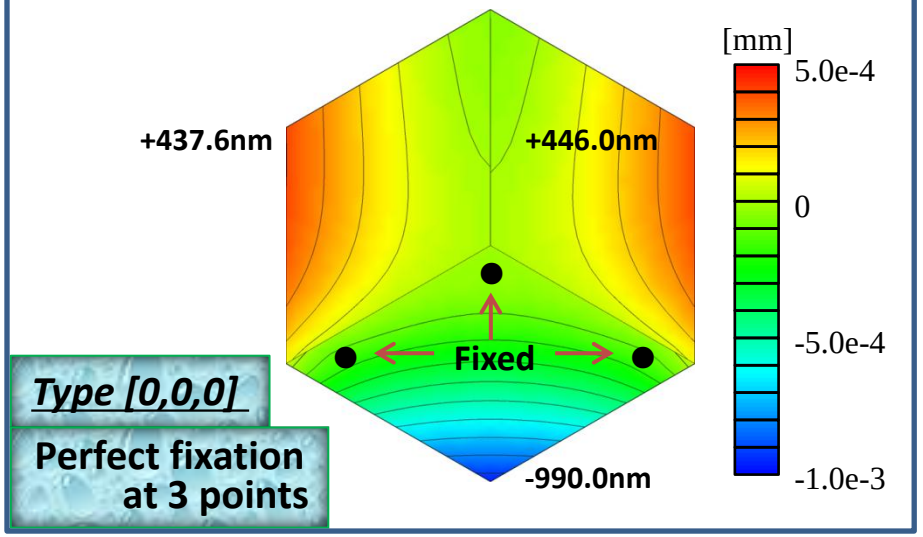
CCZ-EX : Temperature distribution



CCZ-EX: Surface Deformation

Normal Component

No deformation @25℃

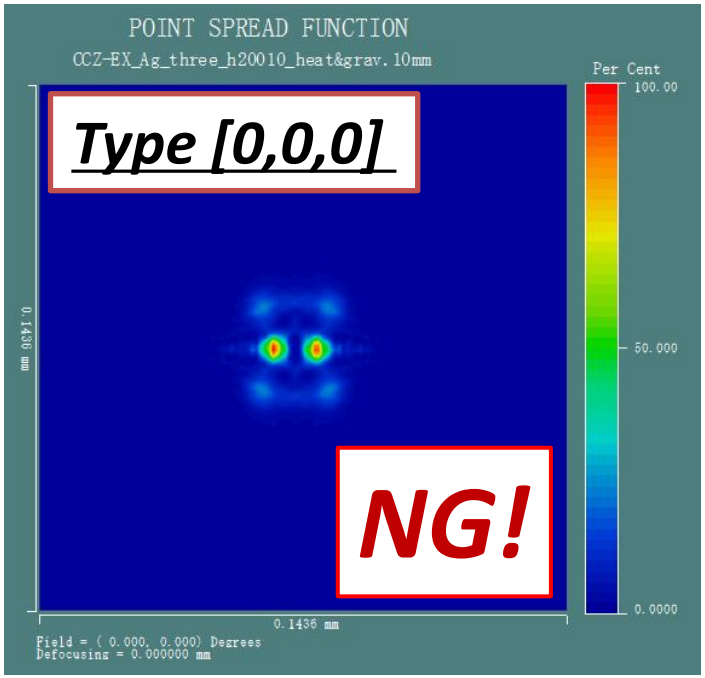


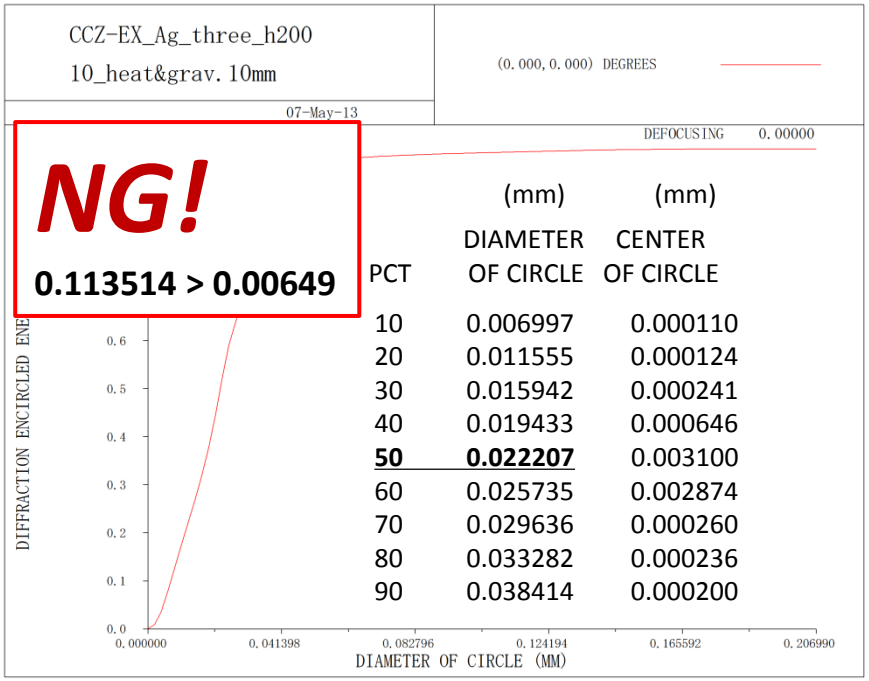
Type [0,0,0]

Perfect fixation at 3 points

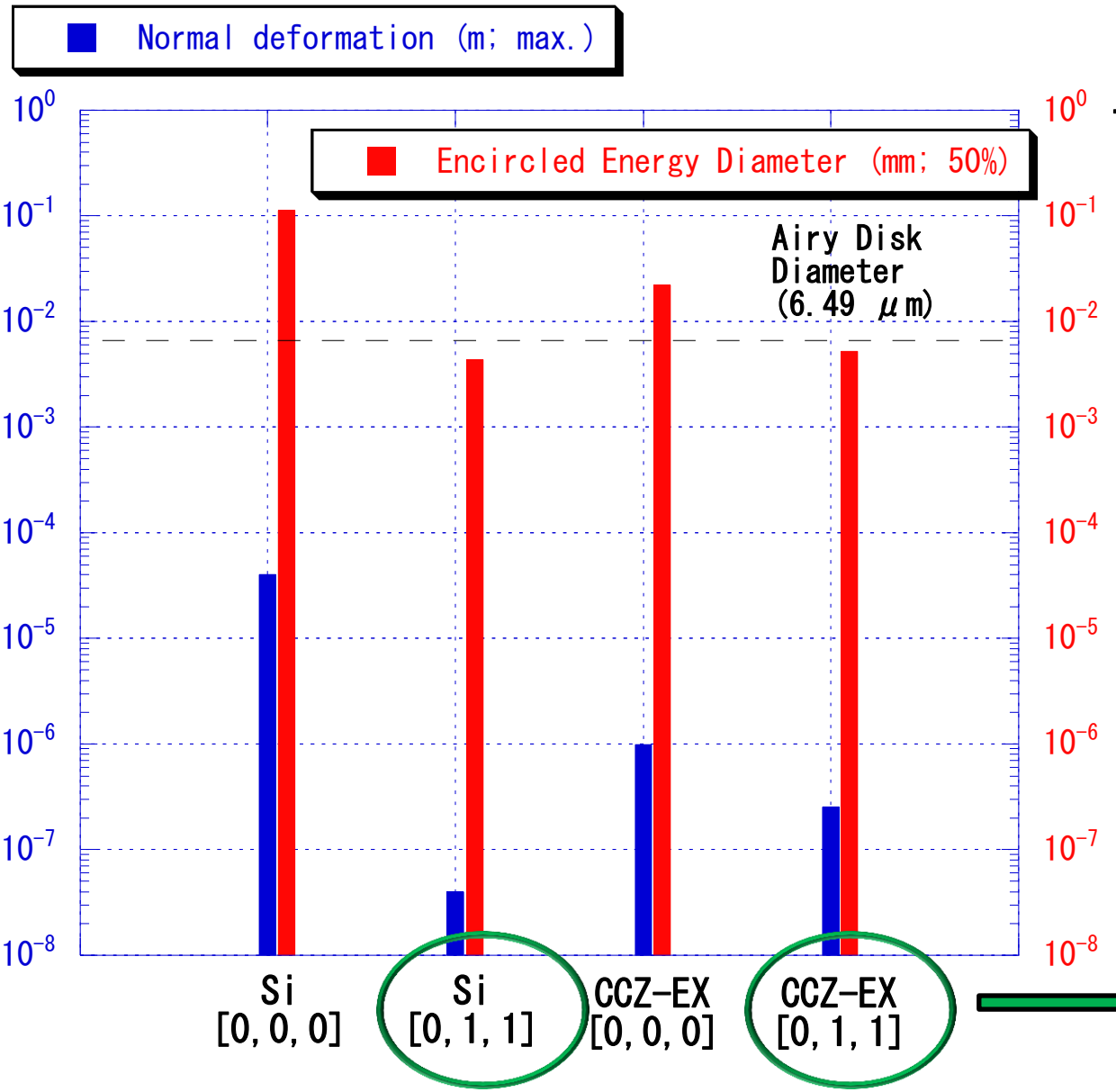
CCZ-EX

Optical Test





Summary of 4 cases



--- optical criteria

Si is better.

➢Conclusions

1. **Surfaces of CCM for any material is severely deformed if CCM is supported by fixed points on the base plate, which is caused by thermal expansion (C_{TE}) itself.**
2. **Both materials passed optical test for the case of [011] support. The difference of them is very small but "Si" shows better optical performance.**
3. **"Si" is also preferable from other sides such as weight, strength, and easiness of processing;**

- **Density〔2.329 g/cm^3(Si) vs. 2.5 g/cm^3(CCZ-EX)〕**
- **Young modulus〔130GPa(Si; 100 axis)#, 90GPa(CCZ-EX)〕**
- **Damage of "Si" surface during polishing is considered smaller than "CCZ-EX".**

#) http://www.ioffe.ru/SVA/NSM/Semicond/Si/

Future Themes

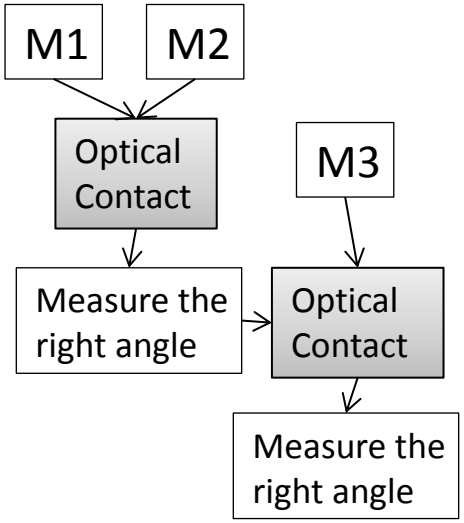
1. How to realize [011] fixation of CCM to the base plate with, for example, *kinematic mounts*
2. Thermal, mechanical, and optical modeling of CCM with its holder
3. To search for more environmental resistant coating materials than Silver
4. Radioactive affection on the Moon of the CCM surface properties such as reflectivity or deformation
5. How to fabricate CCM;

- Application of "Optical contact" with Okamoto Opt. Works Inc. Japan.
- Coring of the Si-block and finishing using IBF (Ion Beam Figuring) with Chiba Inst. Tech. and Tokyo Univ of Science, Japan.

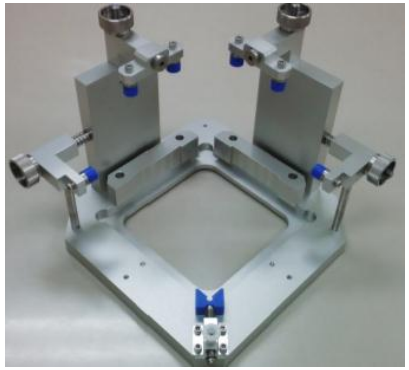
Corner Cube Mirror

OKAMOTO OPTICS WORKS, INC.

Test fabrication of single and large aperture CCM model for the future Lunar Laser Ranging

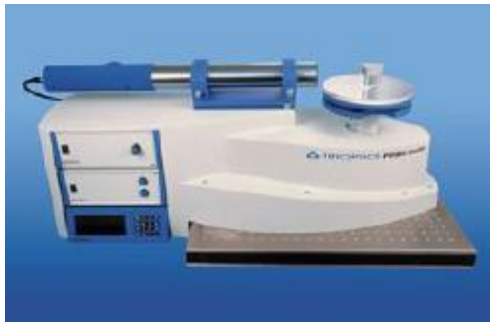


Zygo (12”) interferometer



Support tool for the optical contact

External Size: 175 × 175 × 175(mm)
Internal Size: 150 × 150 × 150(mm)
Material: Clear CeramZ-EX
[OHARA Co. Ltd.]
Thickness : 25 (mm)
Surface error : less than 1/10 λ (PV)
Fabrication : Optical Contact
Coating : Aluminum (tentative)
S/D : MIL20-10



Prism Master (Trioptics Japan)
for measurement of the right angle

NiCT

国立天文台 NAOJ National Astronomical Observatory of Japan

Thank you for your attention !