THERMAL/OPTICAL ANALYSIS OF CUBE CORNER RETROREFLECTORS FOR THE LUNAR ENVIRONMENT

Giovanni O. Delle Monache[1], Douglas Currie[2],
Simone Dell' Agnello[1], Bradfor Bher[2]

1 INFN-LNF Frascati Italy 2 UMD College Park MD

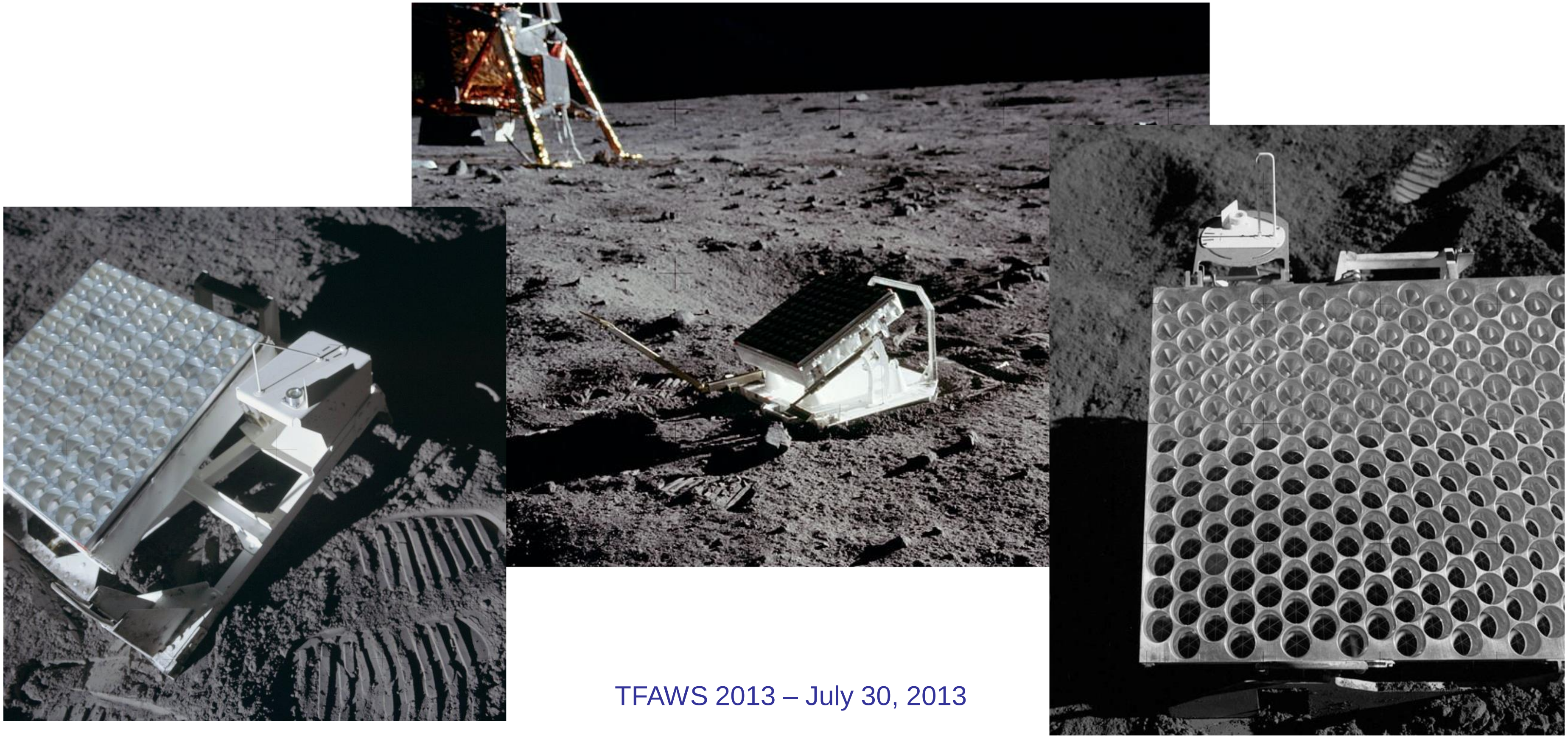
Presented By
Prof. Douglas Currie

OUTLINE

- Background and overwiev of LLR
- Thermal issues of CCR in Space environment
- 1-D model for Lunar Regolith simulation from HFE data
- Design and model of Moonlight experiment
- Preliminary thermal optical test description

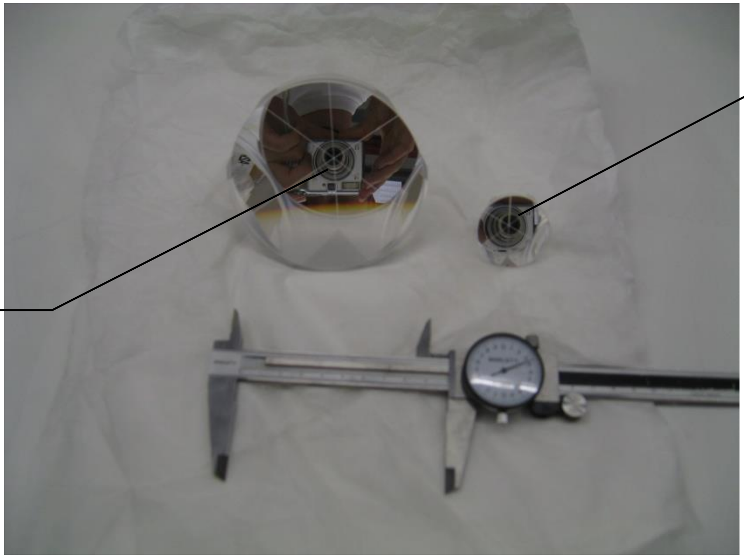
Background

- Laser Ranging is a technique which allows satellite tracking with the highest accuracy
- Apollo 11, 14 and 15 deployed LLRA which are the only Apollo ERA experiments still producing data



A new experiment: pro & cons

- GSE technology has improved by a factor of more than 100, such that the Apollo lunar arrays now contribute a significant portion of the ranging errors due to lunar librations (± 6 deg).
- Optical performance depend on the refraction index, which is T dependent. The CCR must be as “isothermal” as possible

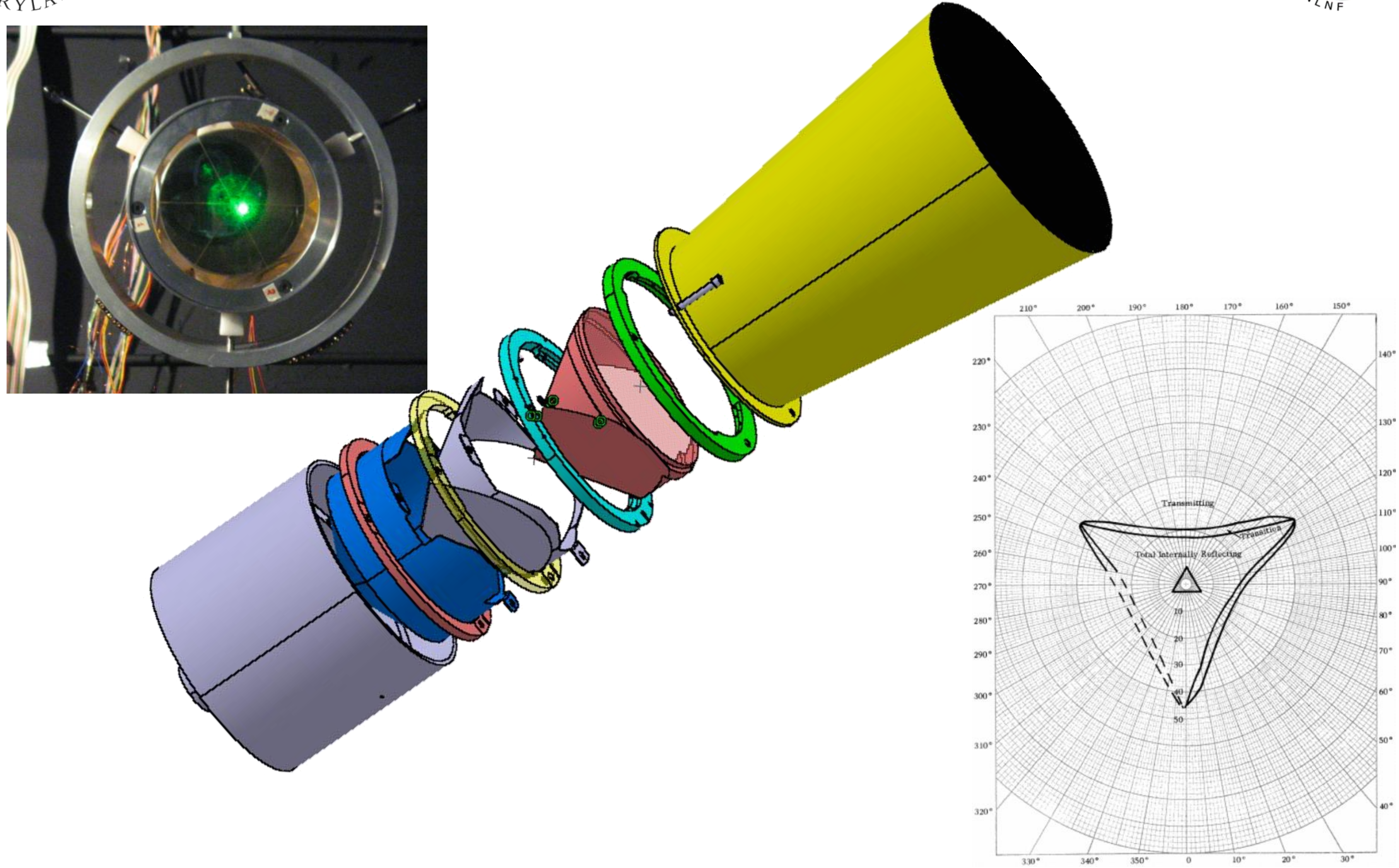


oonlight CCR:
ce Ø=100 mm

Apollo CCR:
Face Ø=38 mm

Signal return strengt ≈ (Face ø)^4

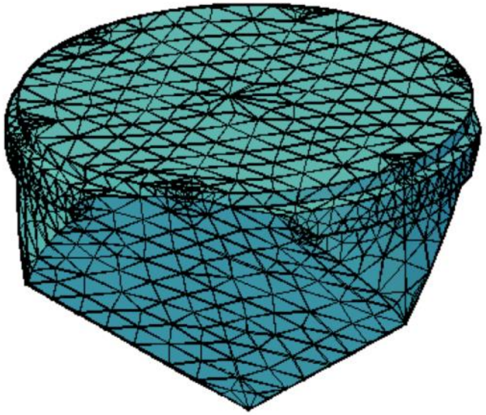
Moonlight experiment layout



Thermal Model Issue I

- One of the biggest issue of the CCR thermal model is the reproduction of the volumetric absorption in the FS
- A proprietary sw has been developed by UMD to calculate the heat absorbed by the CCR all around the lunar orbit accounting for different shades
- The thermal model mesh is interpolated in the optical mesh for which the Wien – Beer law is applied along the sun spectrum for several orbital positions.
- The heat loads evaluated are interpolated back in the thermal mesh and loaded in Sinda

1733 nodes



Thermal Model Issue II

- The experiment must be considered for different missions configuration and deployment: manned, rover and lander
- For this reason the lunar regolith behavior must be considered in the thermal model so it can account for (self)shadowing effect
- Data from Apollo HFE and subsequent papers have been used to model the regolith thermo physical behaviour down to 3 m depth

Apollo Mission	Status
15	Probe 2 was not inserted to full depth because of problems with the Apollo lunar surface drill. Probe 2 still provides useful data to estimate heat flow in the lunar subsurface. Drill bore stems were redesigned for Apollo 16 and 17 missions.
16	Electrical cable was severed during initial deployment by crew. Contingency repair plan proposed was denied because of higher mission priorities. Cable strain-relief provisions were implemented on all cables
17	Nominal deployment and full experiment operation

Data for HFE from Keihm et. al

Many papers written by M. G. Langseth (PI) S. J. Keihm and J. L. Shute (and many models).

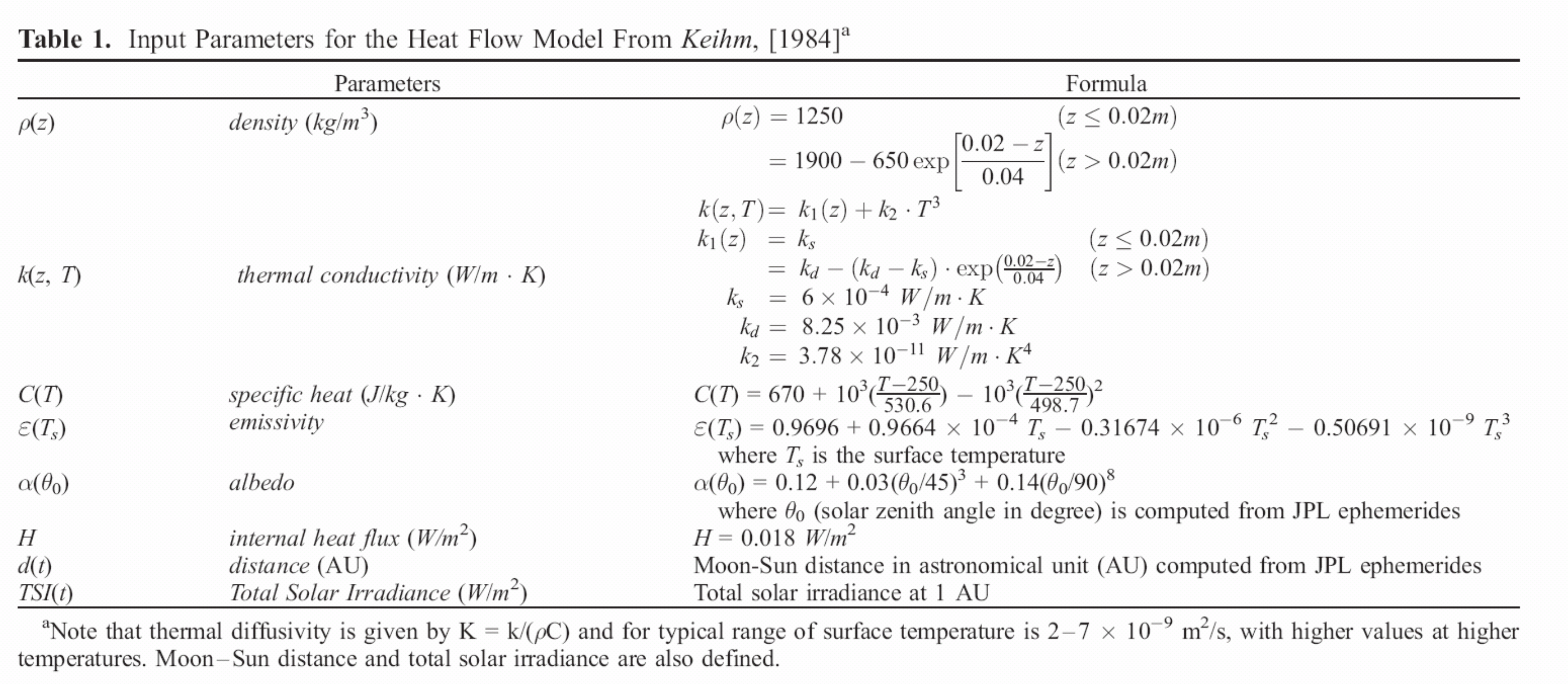


Table 1. Input Parameters for the Heat Flow Model From *Keihm*, [1984][a]

Parameters		Formula
$\rho(z)$	*density* (kg/m^3)	$\rho(z) = 1250 \quad (z \le 0.02m)$ $= 1900 - 650 \exp\left[\frac{0.02 - z}{0.04}\right] \quad (z > 0.02m)$
$k(z,\ T)$	*thermal conductivity* ($W/m \cdot K$)	$k(z,T) = k_1(z) + k_2 \cdot T^3$ $k_1(z) = k_s \quad (z \le 0.02m)$ $= k_d - (k_d - k_s) \cdot \exp(\frac{0.02-z}{0.04}) \quad (z > 0.02m)$ $k_s = 6 \times 10^{-4}\ W/m \cdot K$ $k_d = 8.25 \times 10^{-3}\ W/m \cdot K$ $k_2 = 3.78 \times 10^{-11}\ W/m \cdot K^4$
$C(T)$	*specific heat* ($J/kg \cdot K$)	$C(T) = 670 + 10^3(\frac{T-250}{530.6}) - 10^3(\frac{T-250}{498.7})^2$
$\varepsilon(T_s)$	*emissivity*	$\varepsilon(T_s) = 0.9696 + 0.9664 \times 10^{-4}\ T_s - 0.31674 \times 10^{-6}\ T_s^2 - 0.50691 \times 10^{-9}\ T_s^3$ where T_s is the surface temperature
$\alpha(\theta_0)$	*albedo*	$\alpha(\theta_0) = 0.12 + 0.03(\theta_0/45)^3 + 0.14(\theta_0/90)^8$ where θ_0 (solar zenith angle in degree) is computed from JPL ephemerides
H	*internal heat flux* (W/m^2)	$H = 0.018\ W/m^2$
$d(t)$	*distance* (AU)	Moon-Sun distance in astronomical unit (AU) computed from JPL ephemerides
$TSI(t)$	*Total Solar Irradiance* (W/m^2)	Total solar irradiance at 1 AU

[a] Note that thermal diffusivity is given by K = k/(ρC) and for typical range of surface temperature is 2–7 × 10^{-9} m^2/s, with higher values at higher temperatures. Moon–Sun distance and total solar irradiance are also defined.

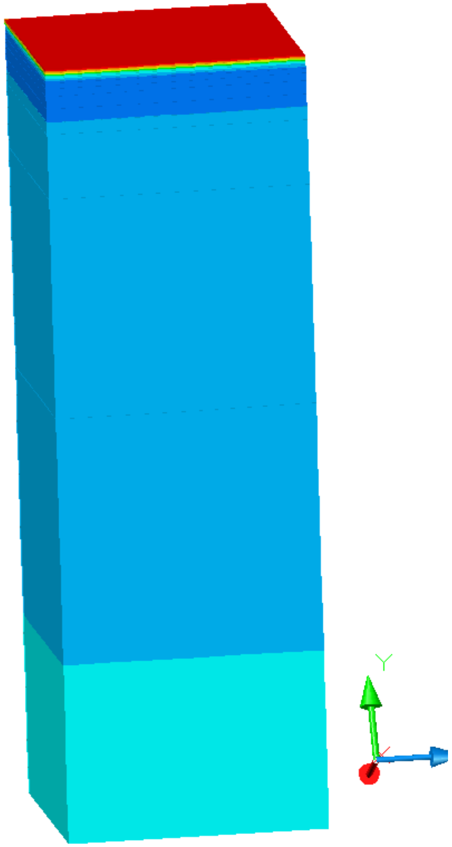
Some approximation have been made and not all parameters have been defined according to this table, exceptions are:
ε=0.93; $\alpha(\Theta0)$=12%; d(t)=1.00014 - 0.01671 cos g - 0.000 14 cos 2g
where in degrees g = 357.528 + 0.9856003 N

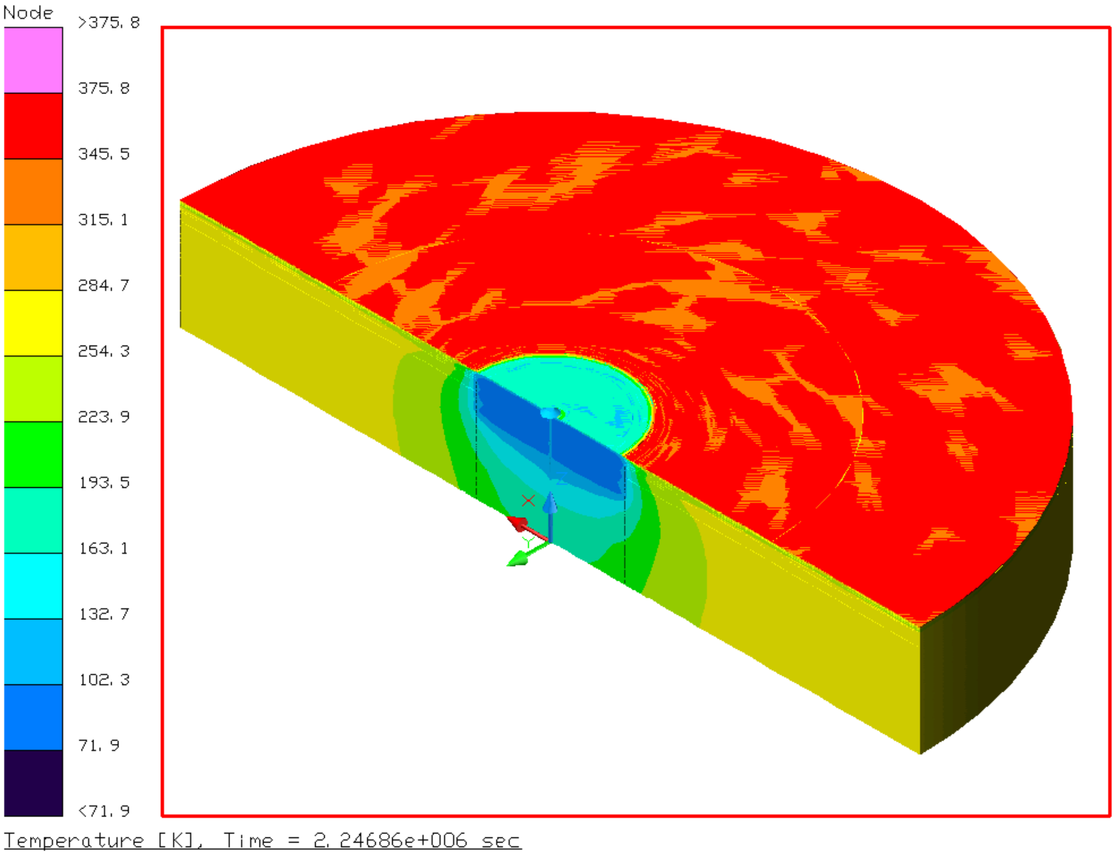
1-D Regolith Model

Block H=3 m Surface 1 X 1 m^2 - 40 nodes

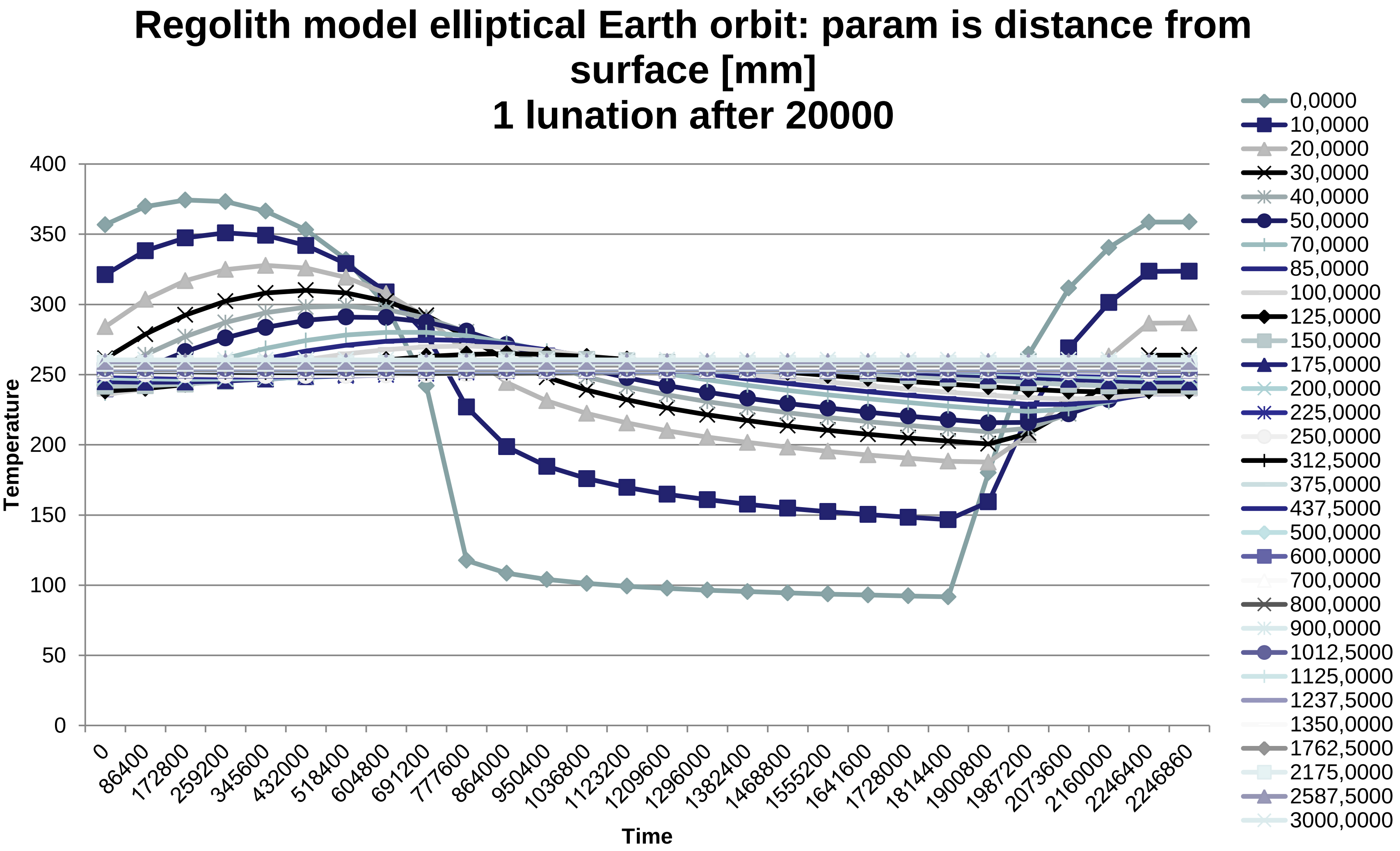
The vertical elements subdision will be used for the 3-D model

The block has been rotated to consider for Apollo 15 26° latitude



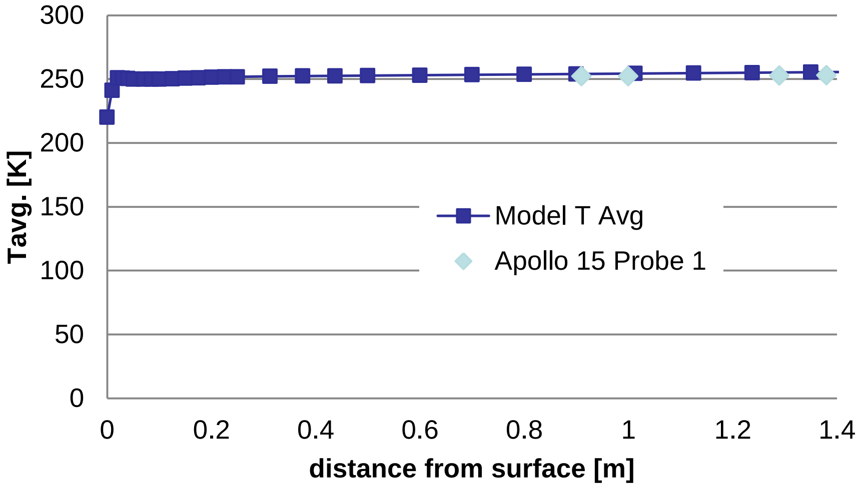


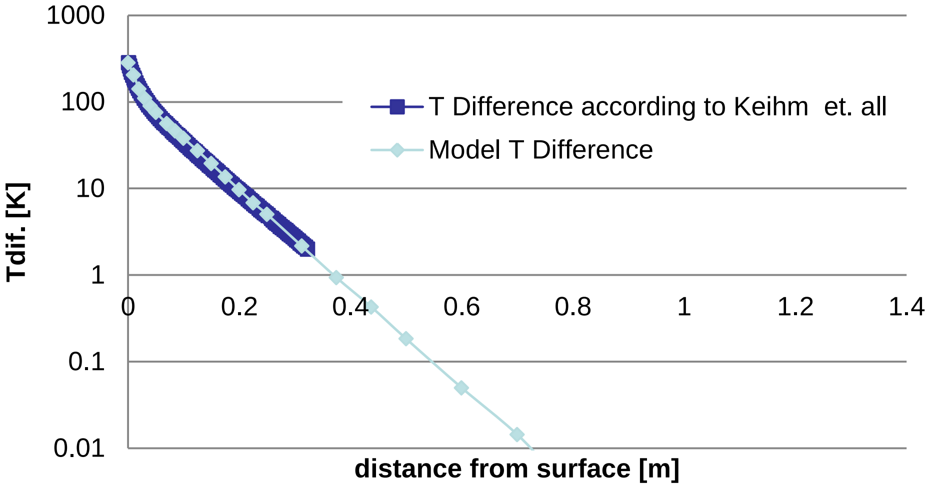
Regolith model T


Regolith model elliptical Earth orbit: param is distance from surface [mm]
1 lunation after 20000

1-D Model vs. Apollo 15 P1

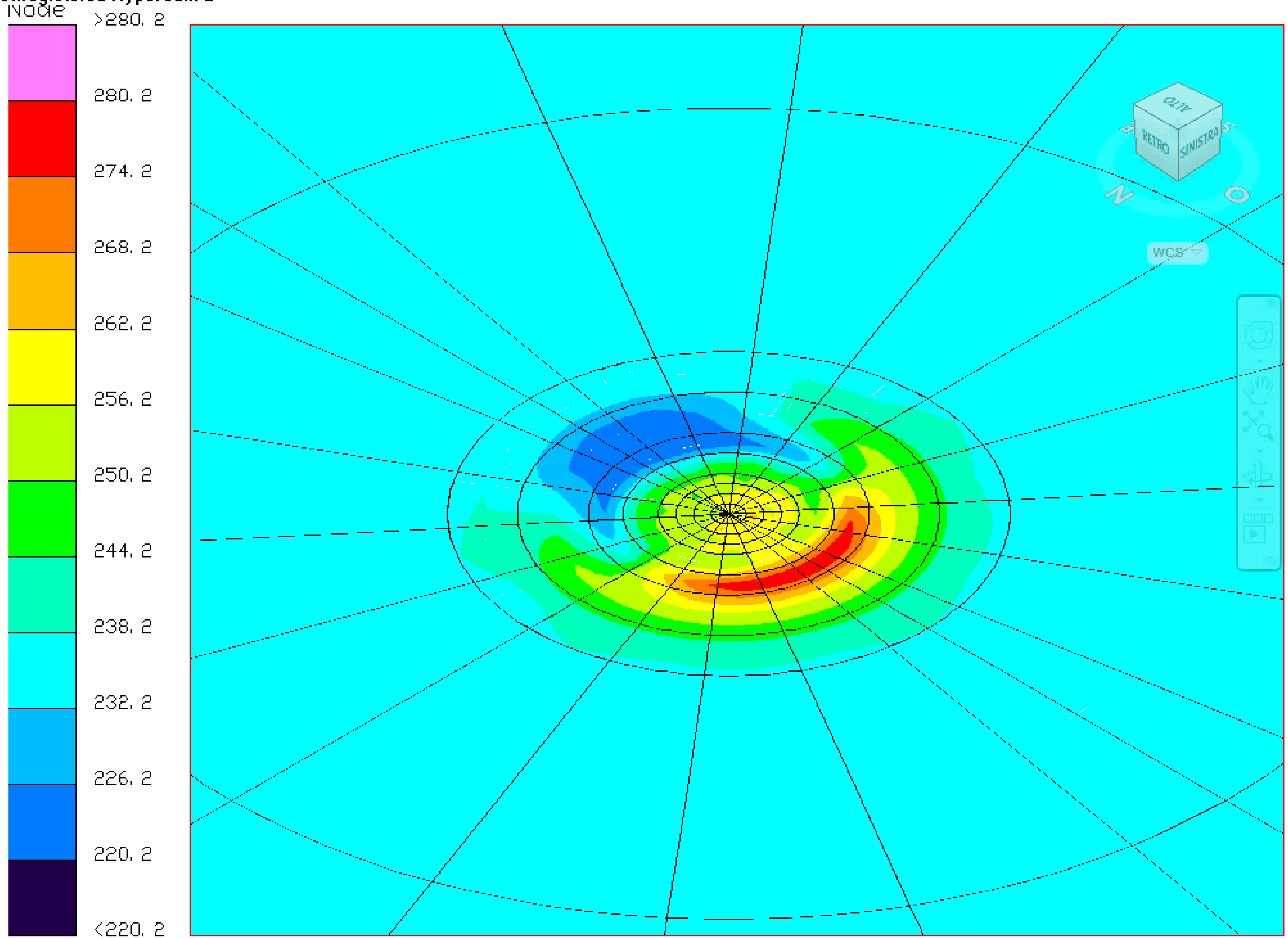
- Difference between the 1D model and the Apollo 15 data varies between 0.9% and 1.3%. Match can be improved by raising Regolith density (detrimental effect on difference plot)





1 lunation after 20000

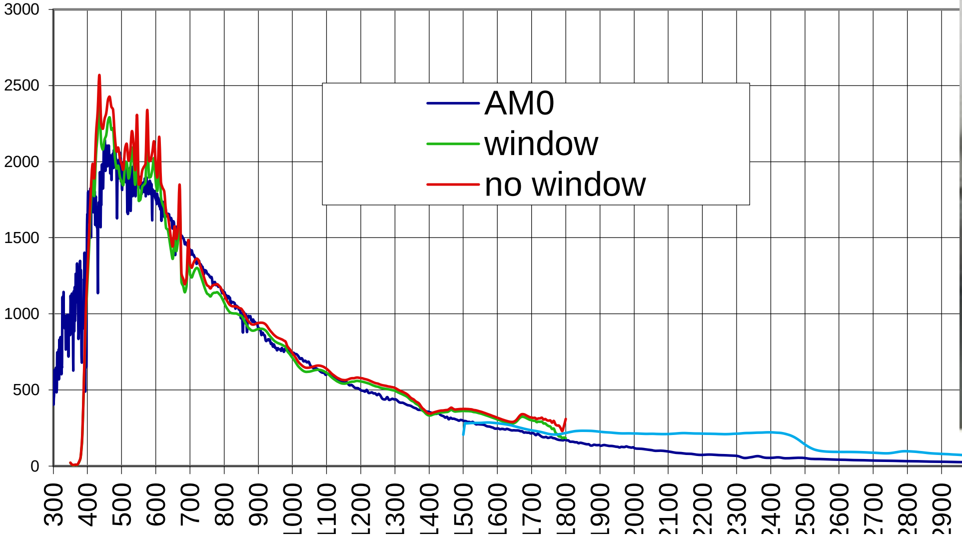
2nd surface FEP/AL 2 m blanket



Temperature [K], Time = 0 sec

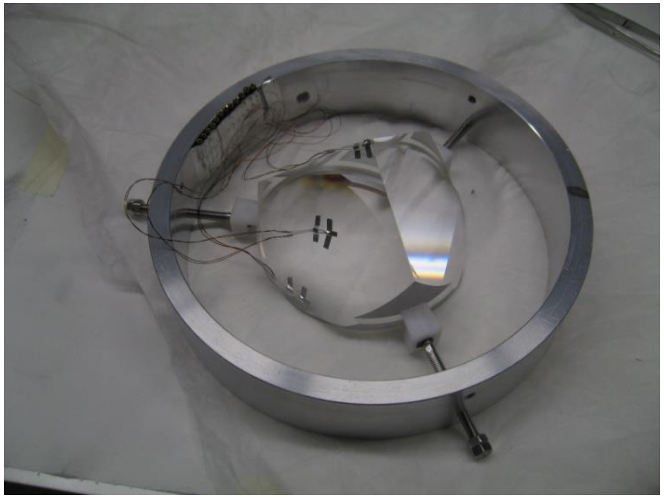
Frascati SCF_LAB

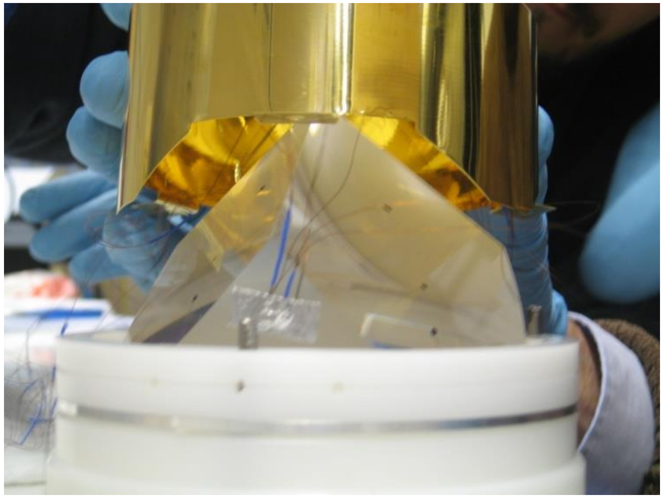
The SCF (Satellite lunar laser ranging Characterization Facility) is a set of specialized instruments, which make possible the recreation of a realistic space environment around the tested CCRs and the concurrent monitoring of temperature variations of the tested payloads and of optical performance, in terms of FFDP and wavefront Interferogram



Some critical issues

- CCR works on TIR effect. To fix a thermometer on the reflecting faces is extremely invasive (for the thermometer)
- T measurent cannot be made while the CCR is exposed to the Sun simulator but we can take advantage of the much much bigger τ of the reflector with respect to the thermometer.

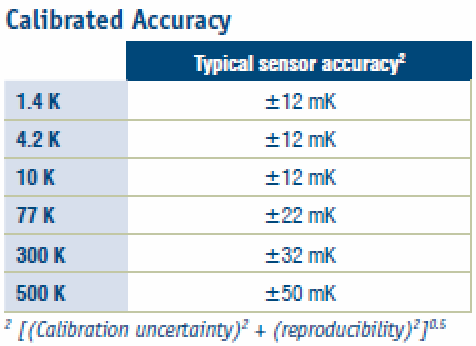




Giovanni O. Delle Monache et. al

Thermometers environment

- Nominal heat flux absorbed by the thermometer due to TIR loss is ≅ 1.5 x 10-3 W (Al or Ag coating spot?)
- Nominal heat flux radiated by the thermometer due to TIR loss is ≅ 0.7 x 10-4 W (360 K vs. 300 K); coating of the dome could be advantageous and cheap (TIR loss)
- 4W Manganine 36 AWG
- Thermal interface conductance≅ 0.1 W/K (Hp: Stycast thickness =0.001 mm - contact factor 0.1)



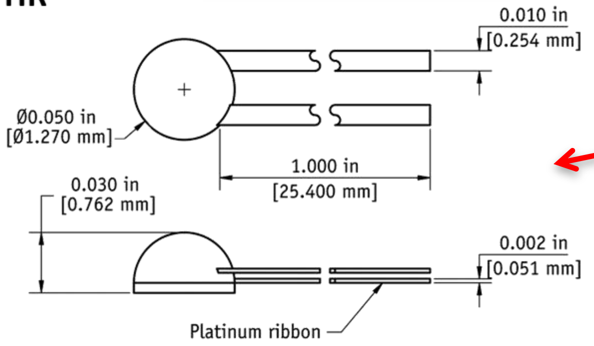
Calibrated Accuracy

	Typical sensor accuracy[2]
1.4 K	±12 mK
4.2 K	±12 mK
10 K	±12 mK
77 K	±22 mK
300 K	±32 mK
500 K	±50 mK

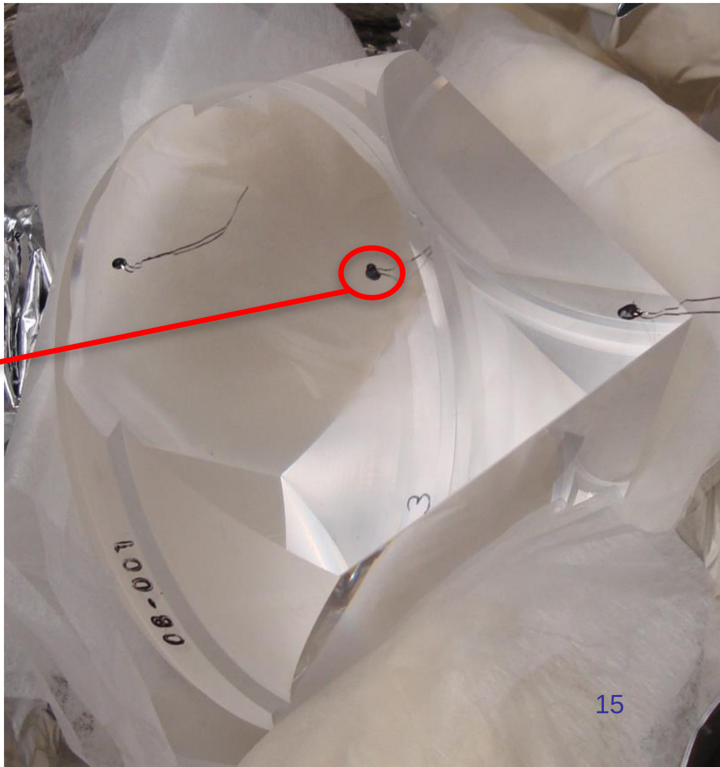
[2] $[(\text{Calibration uncertainty})^2 + (\text{reproducibility})^2]^{0.5}$

m = 23 mg

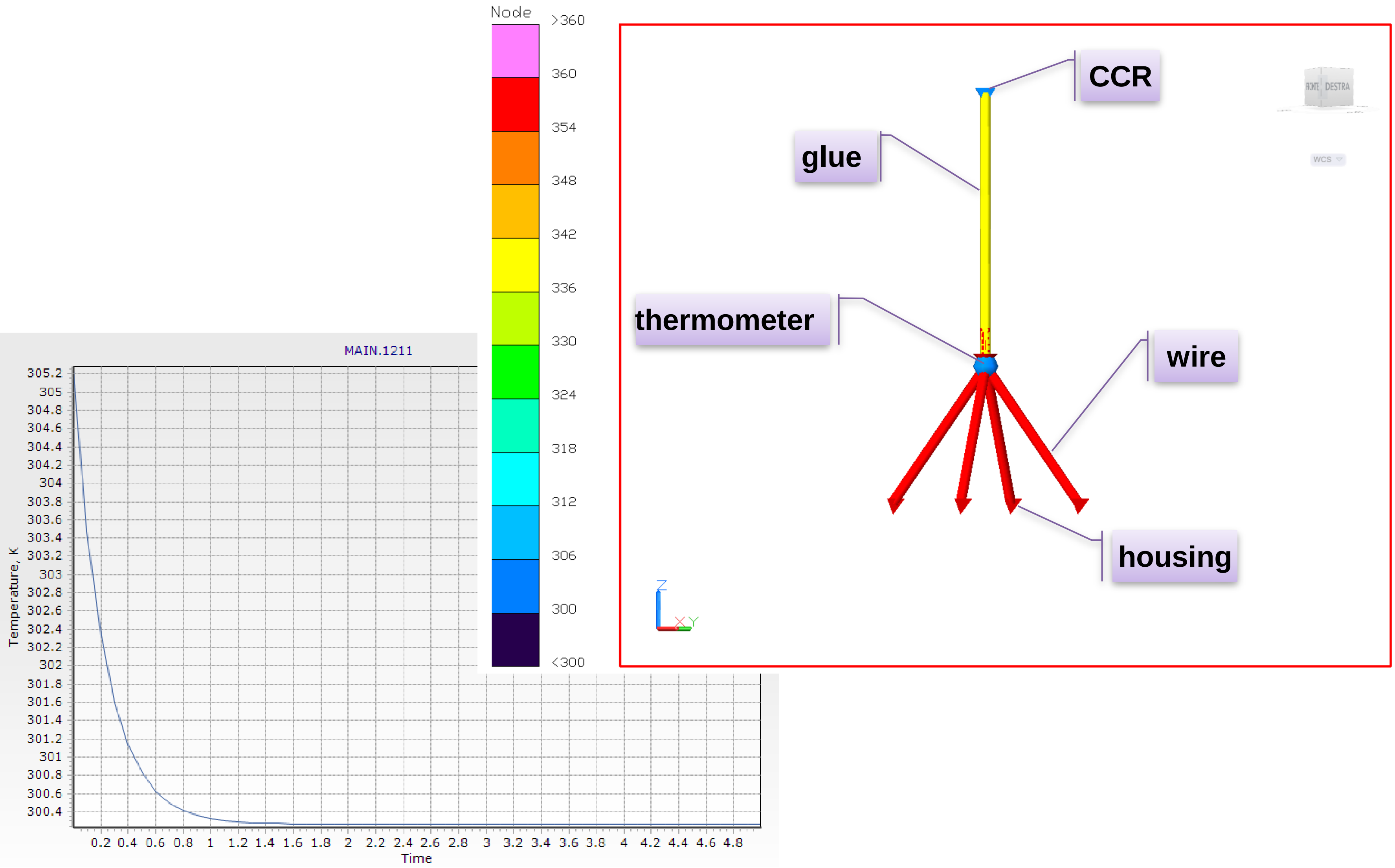
HR



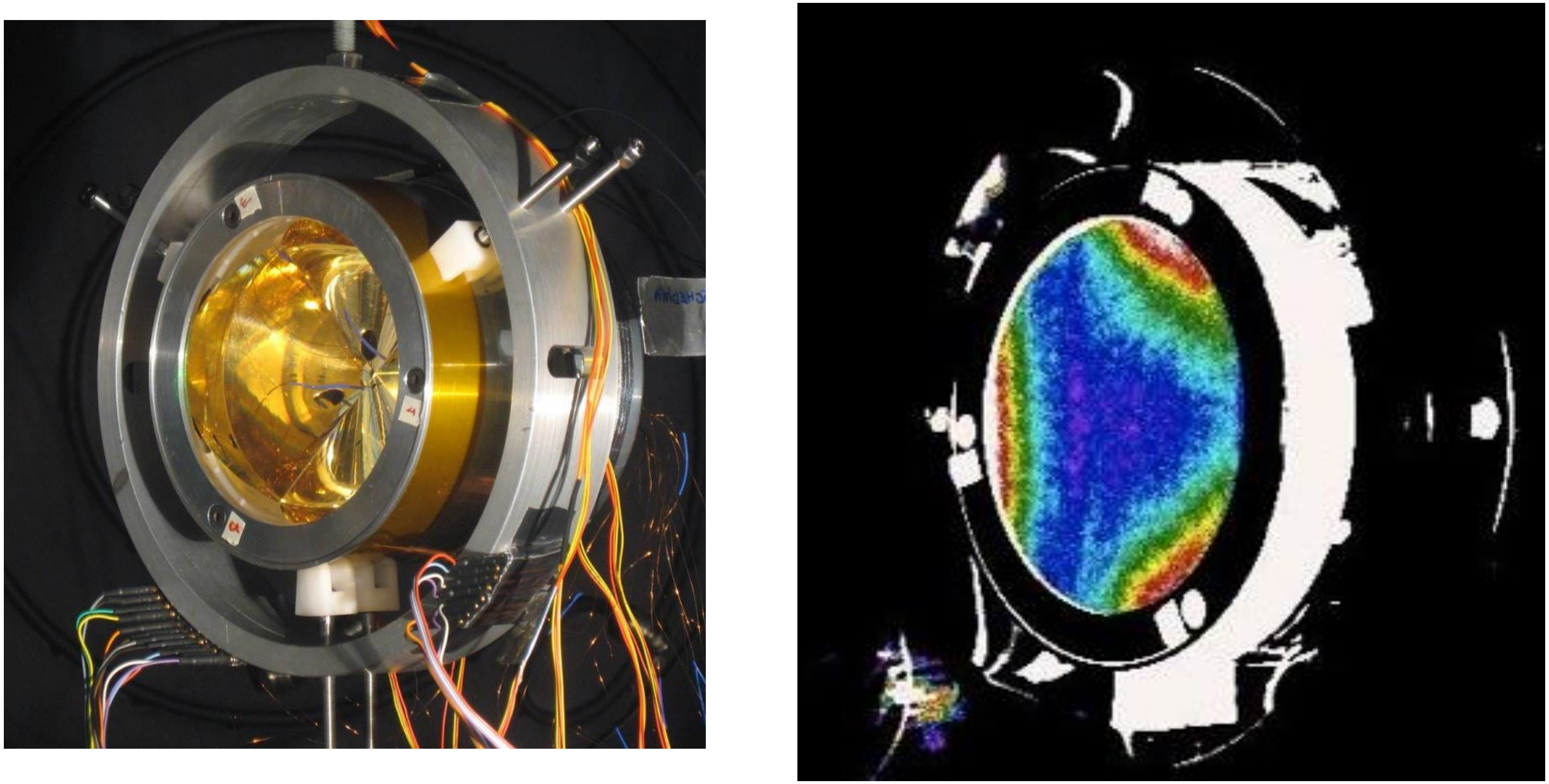
General tolerance of ±0.005 in [±0.127 mm] unless otherwise noted



Diode thermalization on CCR

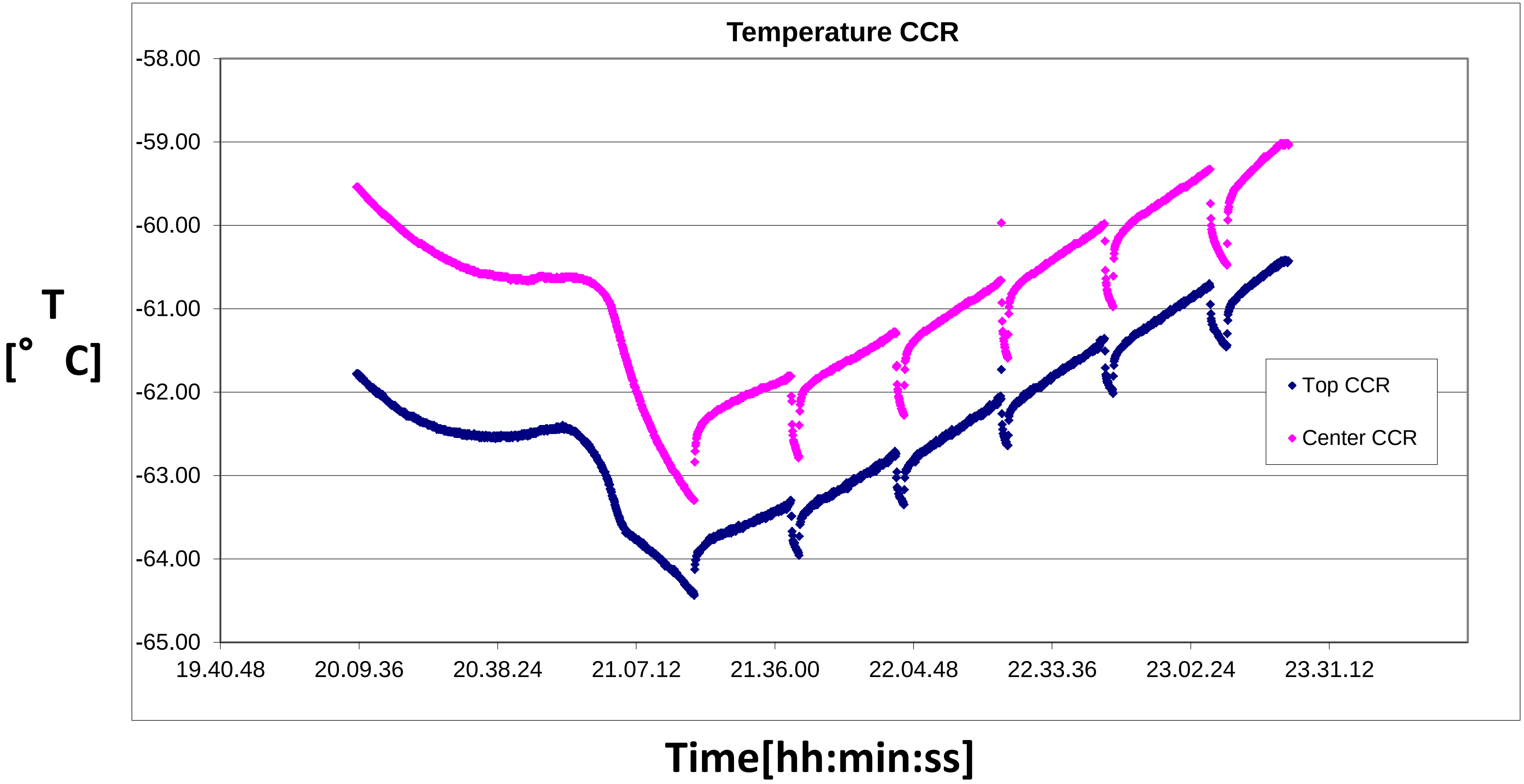


Moonlight In the SCF

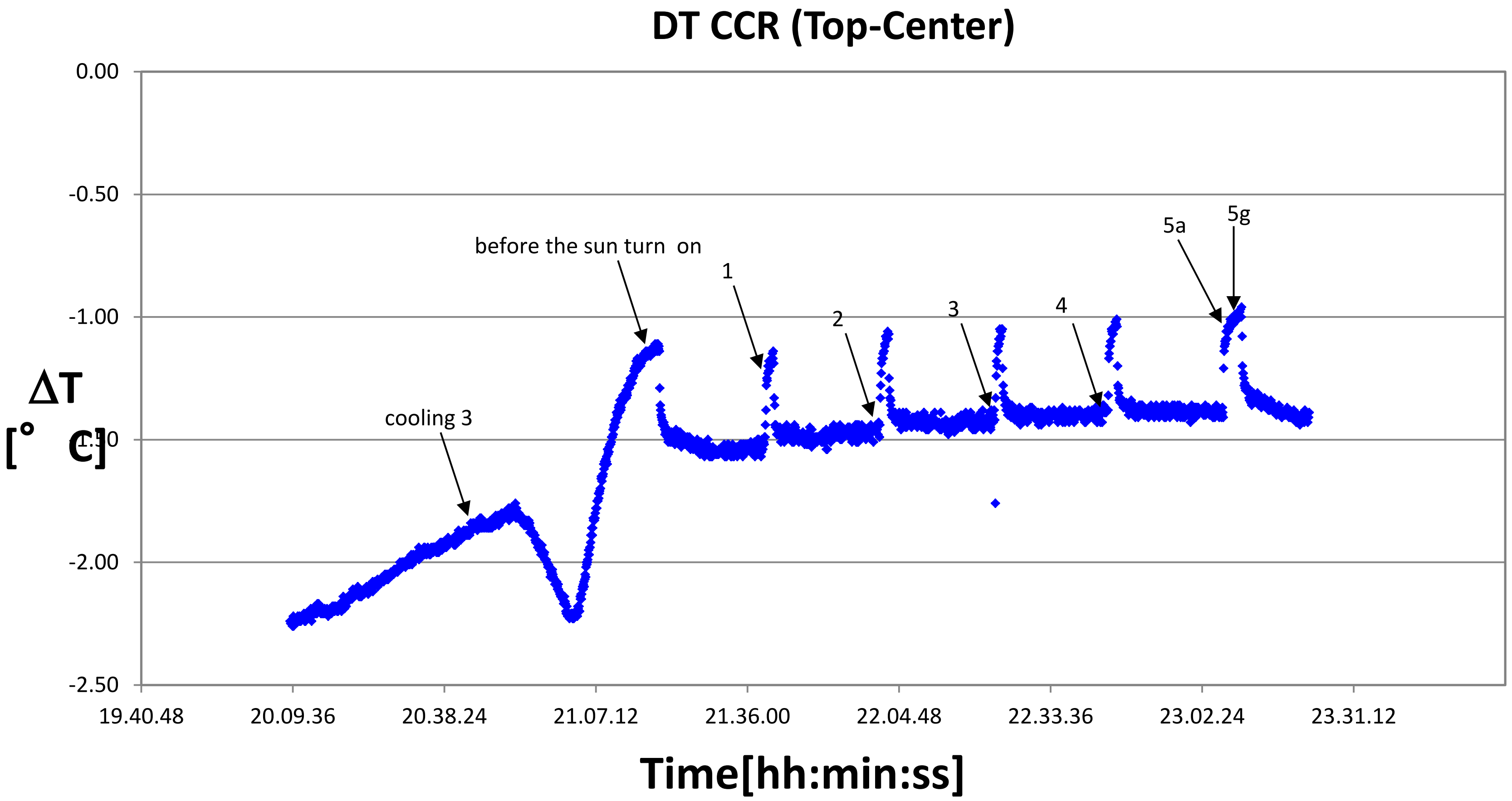


SCF Thermo-optical test

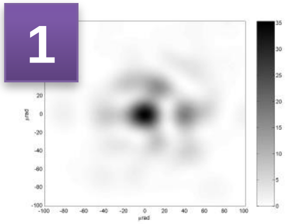
Run from cold to hot case SS expected to last 2 weeks!!



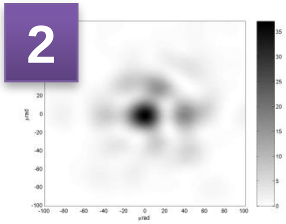
SCF Thermo-optical test


DT CCR (Top-Center)

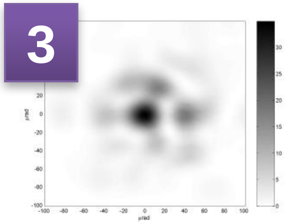
1



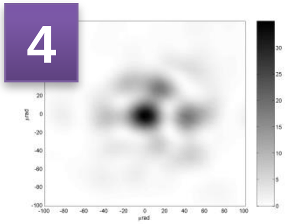
2



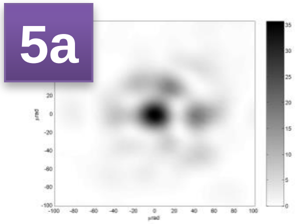
3



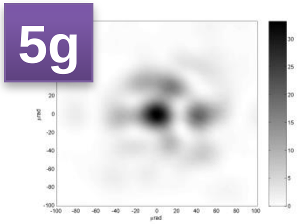
4



5a

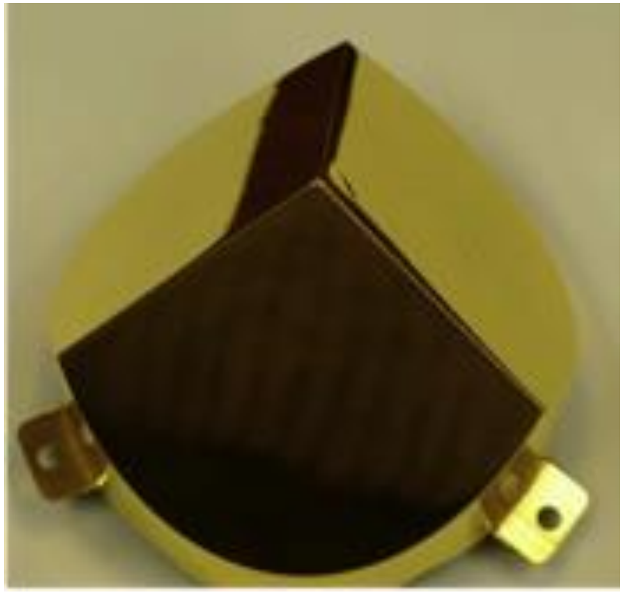


5g



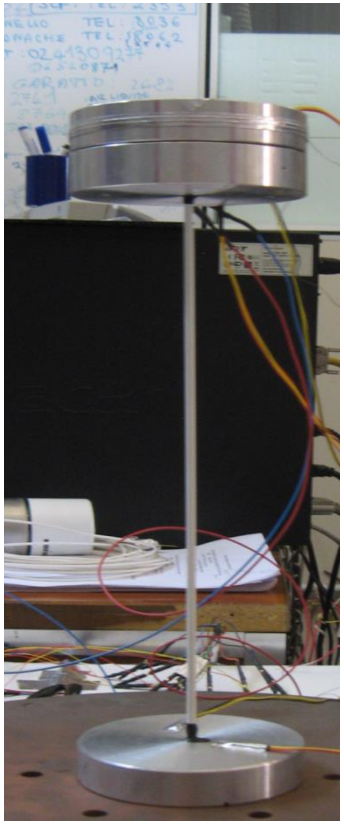
Hardware design for next test

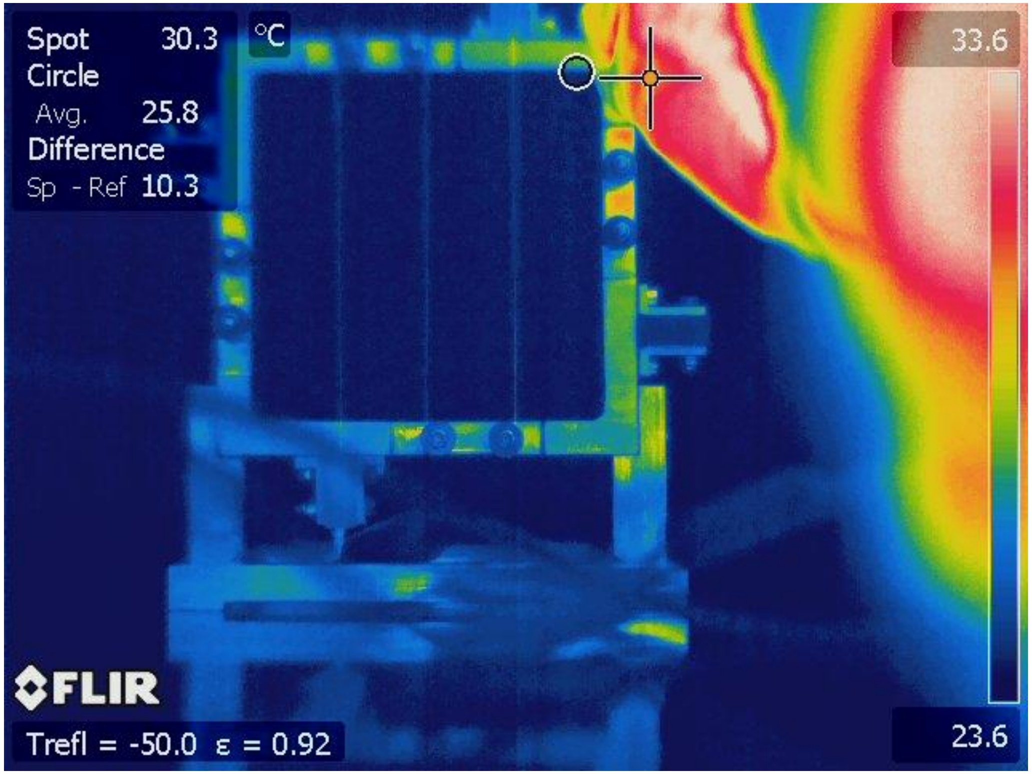
“Jigsaw” Sun shade: geometry and thermo optical properties optimized to reflect <u>back to space </u>as much Sun radiation as possible



Inner conformal shield: to limit green house thermal budget in the CCR cavity

Hardware design for next test





Breadbord for thermal interface study between CCR and mounting rings

New concept of IR simulator for CCRs

Conclusions

1. FFDPs measured in the preliminary test show encouraging performance of the CCR and the surrounding hardware
2. During the test the half gradient along the CCR approched 1 ° C despite external control coating was not applied to the external side of the payload
3. Silicon diode thermometers are good choice if we want to glue them on CCR reflecting faces
4. The regolith model is being used for science investigation about Apollo 11 LLRA performance degradation possibly due to dust deposition

Questions?

Thanks for your attention!

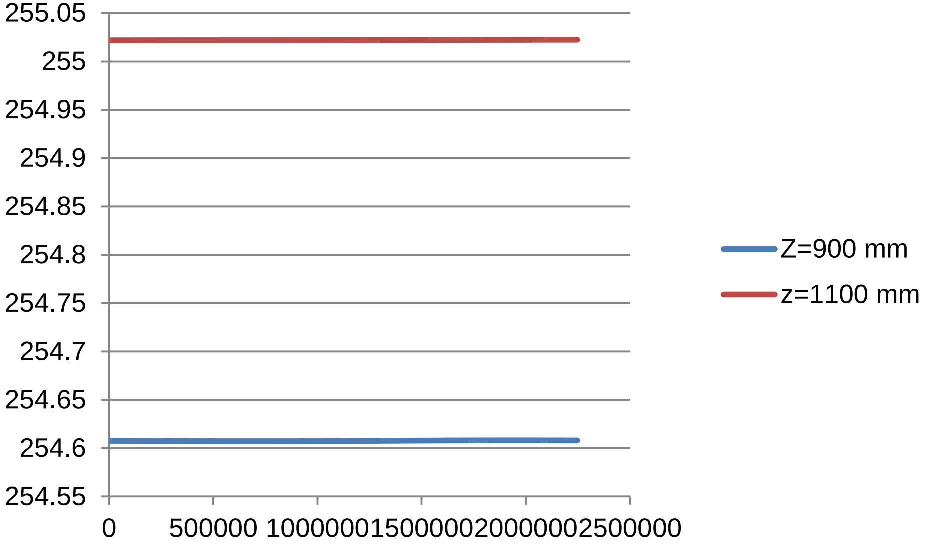
Giovanni O. Delle Monache INFN LNF

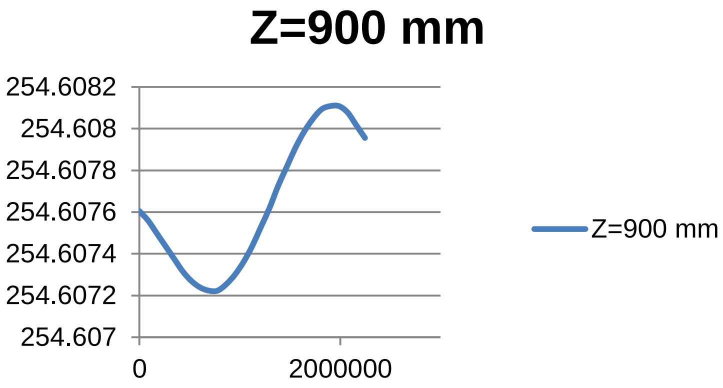
e-mail: dellemon@lnf.infn.it

Spares

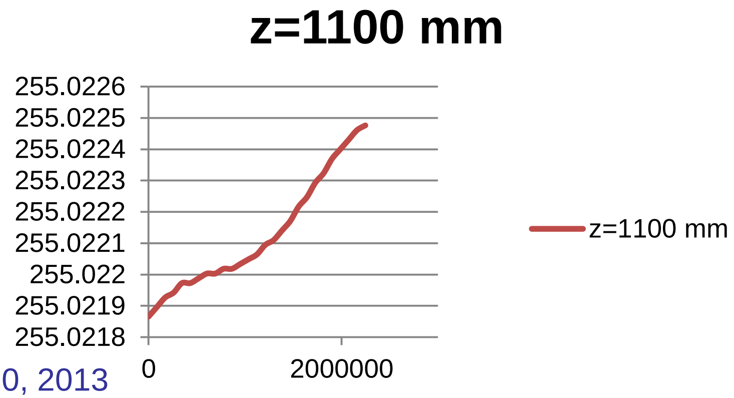
1D Model SS

- Are 20000 Lunations enough for the model to reach SS? Environment alteration due to Astronauts EVA effect on the area evaluated to last 7-8 years the Apollo 15 PSR
- We can consider T=T(t) during one Lunation at a depth such that we expect T=cost

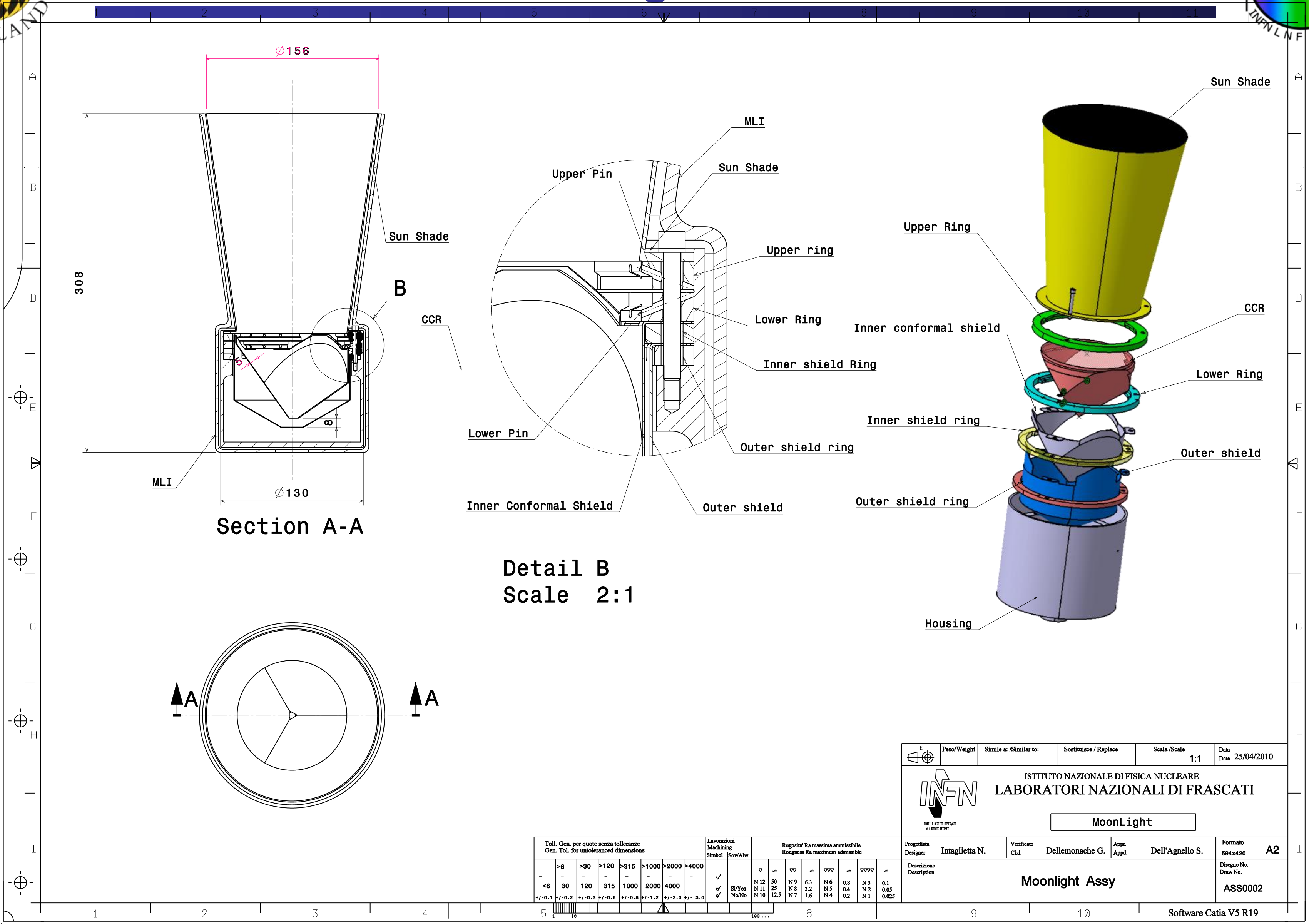




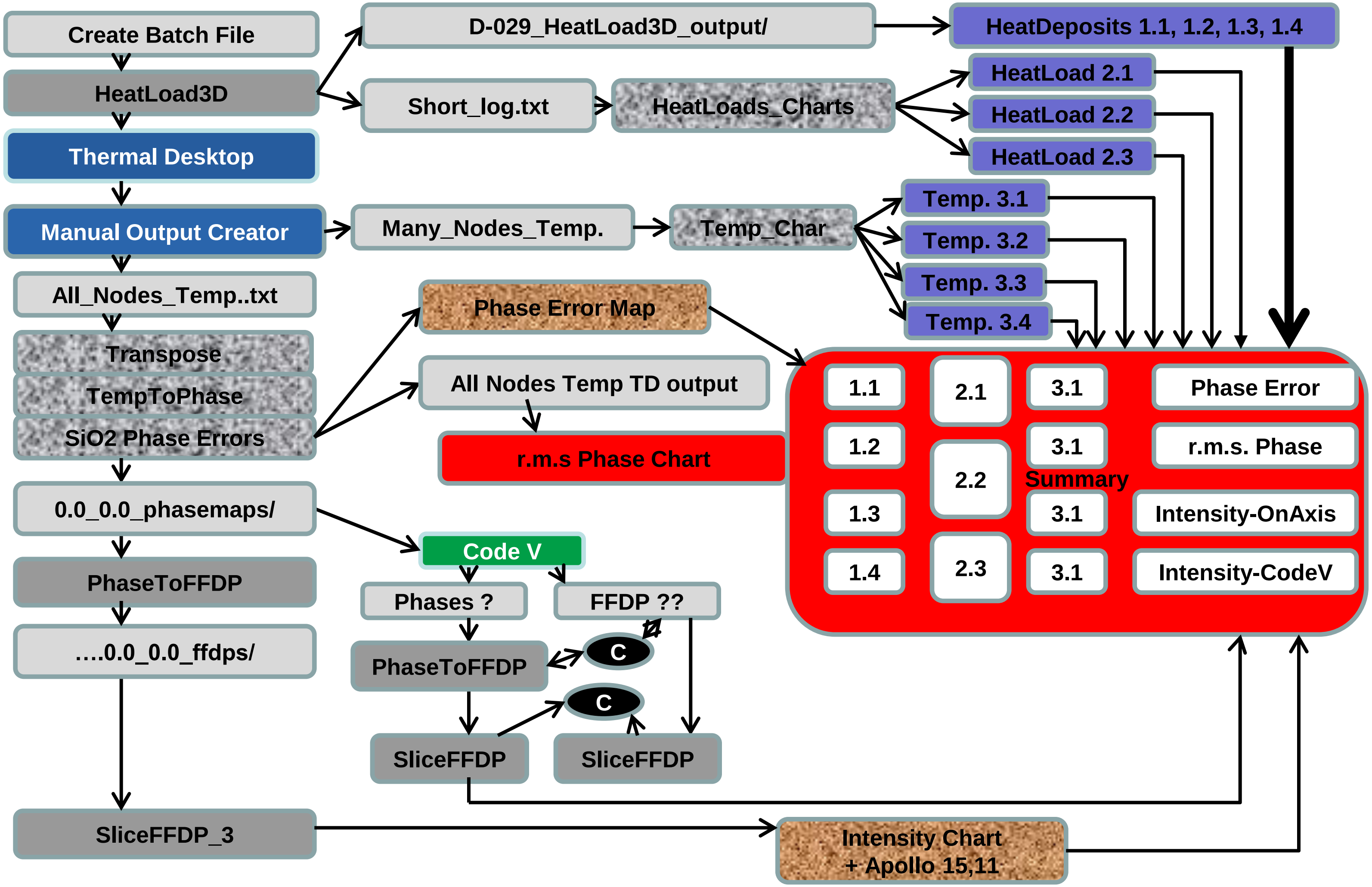
Further investigation required to understand if the 900 mm is just beautifully behaving computational noise

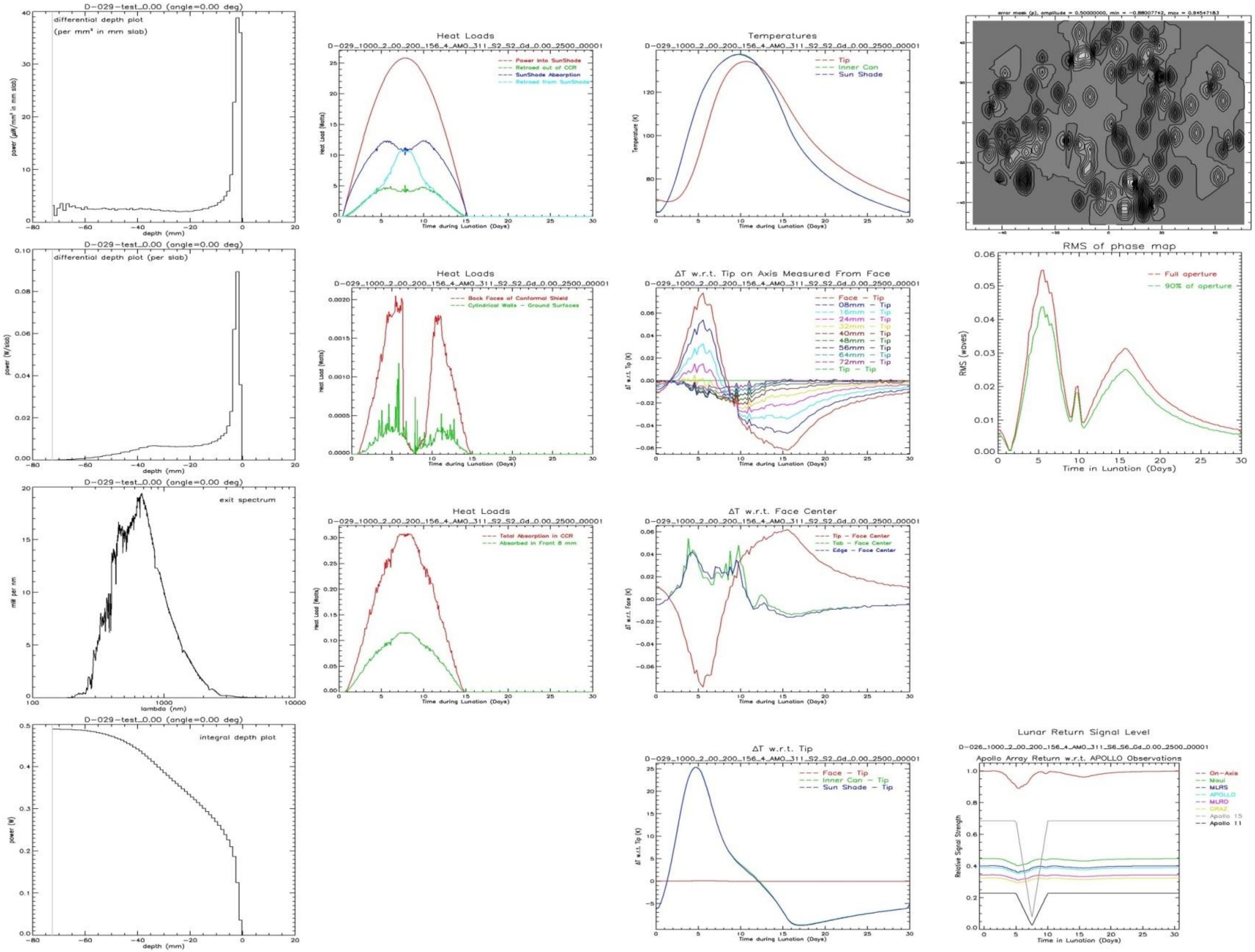


Hardware design for next test



LLRRA-21 Thermal/Optical Simulation




D−029−test_0.00 (angle=0.00 deg)
differential depth plot
(per mm³ in mm slab)
power (μW/mm³ in mm slab)
depth (mm)
D−029−test_0.00 (angle=0.00 deg)
differential depth plot (per slab)
power (W/slab)
depth (mm)
D−029−test_0.00 (angle=0.00 deg)
exit spectrum
milli per nm
lambda (nm)
D−029−test_0.00 (angle=0.00 deg)
integral depth plot
power (W)
depth (mm)
Heat Loads
D−029_1000_2_00_200_156_4_AM0_311_S2_S2_Gd_0.00_2500_00001
Power into SunShade
Retroed out of CCR
SunShade Absorption
Retroed from SunShade
Heat Load (Watts)
Time during Lunation (Days)
Heat Loads
D−029_1000_2_00_200_156_4_AM0_311_S2_S2_Gd_0.00_2500_00001
Back Faces of Conformal Shield
Cylindrical Walls − Ground Surfaces
Heat Load (Watts)
Time during Lunation (Days)
Heat Loads
D−029_1000_2_00_200_156_4_AM0_311_S2_S2_Gd_0.00_2500_00001
Total Absorption in CCR
Absorbed in Front 8 mm
Heat Load (Watts)
Time during Lunation (Days)
Temperatures
D−029_1000_2_00_200_156_4_AM0_311_S2_S2_Gd_0.00_2500_00001
Tip
Inner Can
Sun Shade
Temperature (K)
Time during Lunation (Days)
ΔT w.r.t. Tip on Axis Measured From Face
D−029_1000_2_00_200_156_4_AM0_311_S2_S2_Gd_0.00_2500_00001
Face − Tip
08mm − Tip
16mm − Tip
24mm − Tip
32mm − Tip
40mm − Tip
48mm − Tip
56mm − Tip
64mm − Tip
72mm − Tip
Tip − Tip
ΔT w.r.t. Tip (K)
Time during Lunation (Days)
ΔT w.r.t. Face Center
D−029_1000_2_00_200_156_4_AM0_311_S2_S2_Gd_0.00_2500_00001
Tip − Face Center
Tab − Face Center
Edge − Face Center
ΔT w.r.t. Face (K)
Time during Lunation (Days)
ΔT w.r.t. Tip
D−029_1000_2_00_200_156_4_AM0_311_S2_S2_Gd_0.00_2500_00001
Face − Tip
Inner Can − Tip
Sun Shade − Tip
ΔT w.r.t. Tip (K)
Time during Lunation (Days)
error mask (p), amplitude = 0.50000000, min = −0.88007742, max = 0.94547183
RMS of phase map
Full aperture
90% of aperture
RMS (waves)
Time in Lunation (Days)
Lunar Return Signal Level
D−026_1000_2_00_200_156_4_AM0_311_S6_S6_Gd_0.00_2500_00001
Apollo Array Return w.r.t. APOLLO Observations
On−Axis
Maui
MLRS
APOLLO
MLRO
GRAZ
Apollo 15
Apollo 11
Relative Signal Strength
Time in Lunation (Days)

Return Signal Strength