Effect of Solar Specularity and Ray-tracing Modeling in NX Thermal Solver on Thermal Analysis of SWOT Mission

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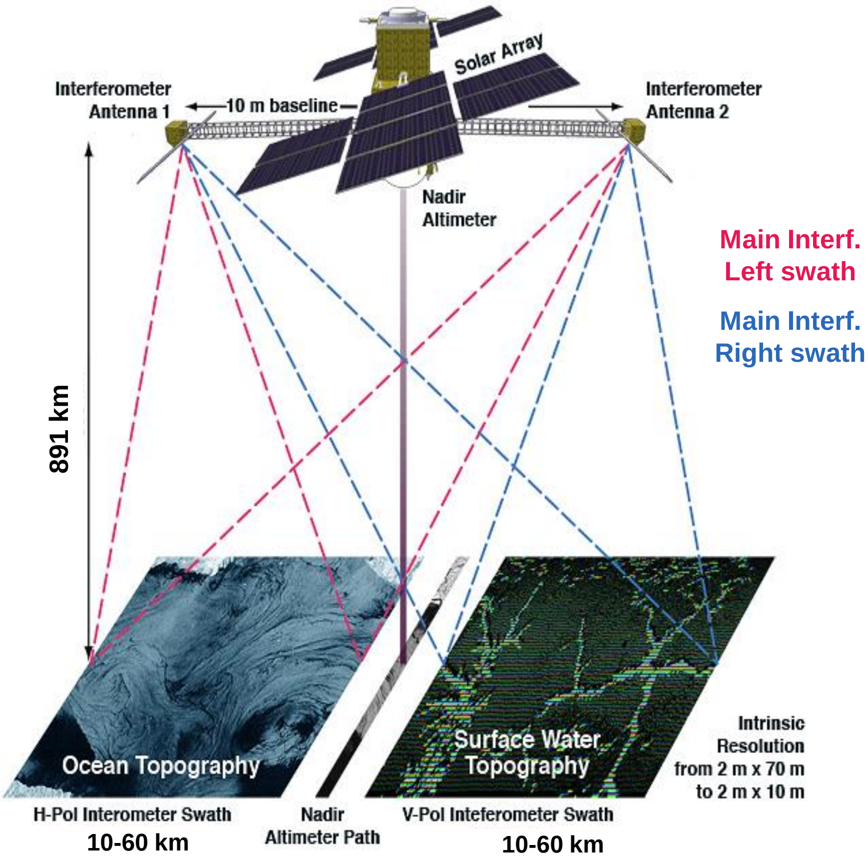
Objectives

- Investigate the impact of solar specularity of solar panels and spacecraft MLIs (multi-layer insulations) on SWOT (Surface Water and Ocean Topography) mission, particularly on reflectarray's temperatures and stability
- Two simple models were built to demonstrate similar effects seen in SWOT, and results of the simple models are presented

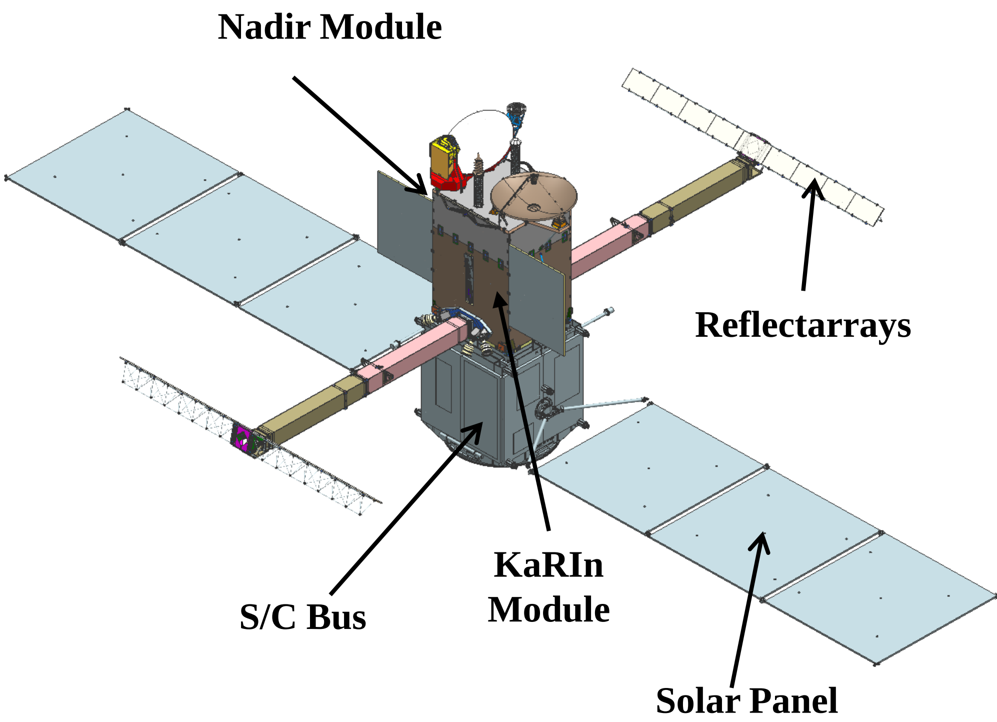
Surface Water and Ocean Topography (SWOT) Mission Overview

- JPL Partnered mission with CNES and CSA
- Mission Science
  - Oceanography: Characterize the ocean mesoscale and sub-mesoscale circulation at spatial resolutions of 15 km and greater.
  - Hydrology: To provide a global inventory of all terrestrial water bodies (lakes, reservoirs, wetlands and rivers)
- In conjunction with JPL, ATA provides thermal analysis support of SWOT mission



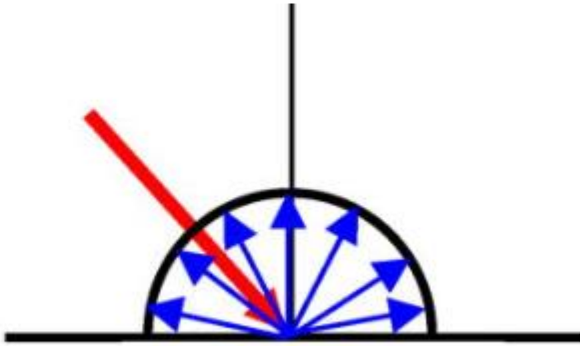
SWOT Thermal Driving Requirements

- Driving requirements fall into following categories
  - Allowed Flight Temperature (AFT) limits: driven by extreme environment
  - Temperature stabilities (dT/dt): KaRIn instrument requires tight temperature stabilities
  - Power constraints: Survival power limitation during post-launch, convergence phase and safe mode
  - Non-Science Modes: Wide range of S/C attitudes during convergence phase and orbit maneuvers are challenging both for cold and hot survival cases

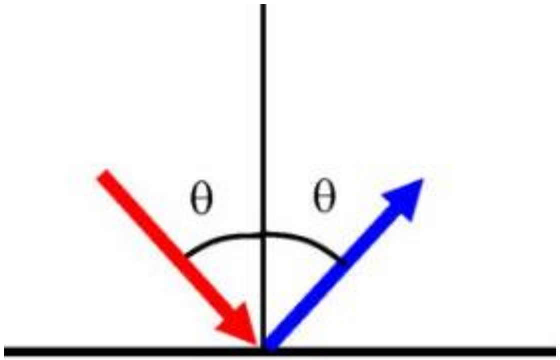


Diffuse and Specular Reflection*

- Three types of reflection phenomena may be observed when radiation strikes a surface
  - Diffuse – an incident beam is distributed uniformly in all directions after reflection
  - Specular – the angle of incidence is equal to the angle of reflection
  - Mixed – a combination of both, diffuse and specular modes



Diffuse Reflection



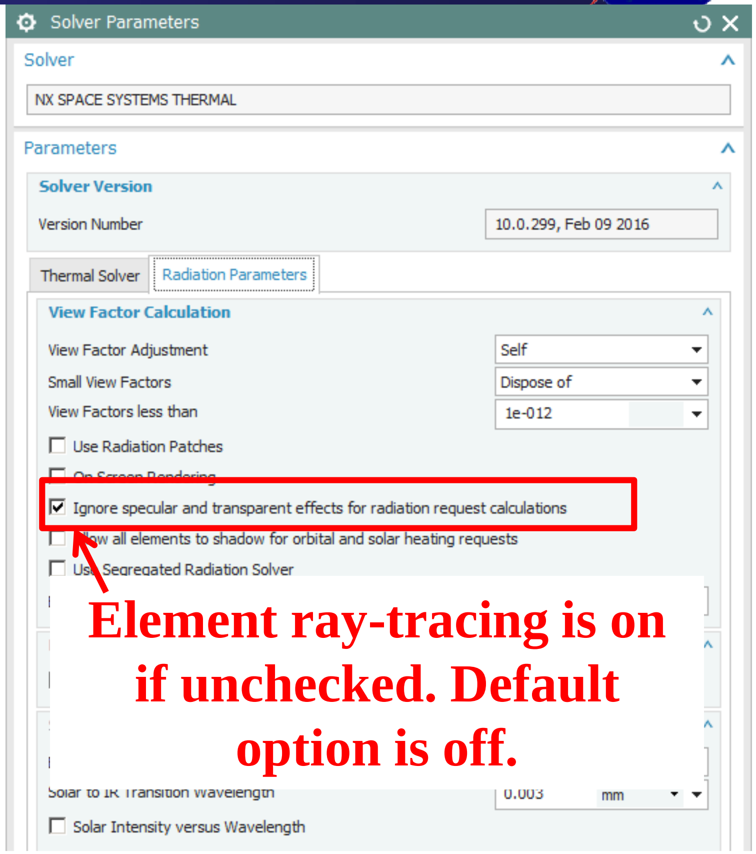
Specular Reflection

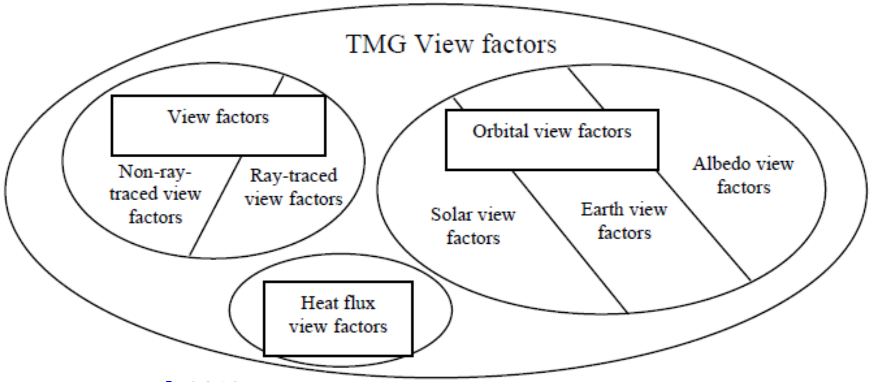
* Reference 1: Holman, J. P. *Heat Transfer*, McGraw-Hill, 1996. Print.

Specular Reflection

Ray-tracing Option in NX TMG Solver Parameters*

- Ray-tracing increases accuracy of radiative couplings between elements and diffusely reflected component of incident solar radiation
- When specular surfaces are encountered, ray-tracing is performed automatically for directly incident component of solar radiation, regardless ray-tracing (VFTRACE) option is enabled or not
- For element view factors to be ray-traced, VFTRACE option must be turned on

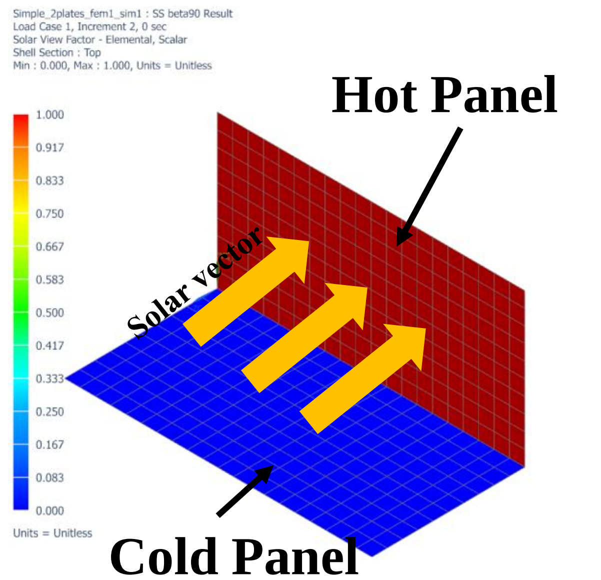


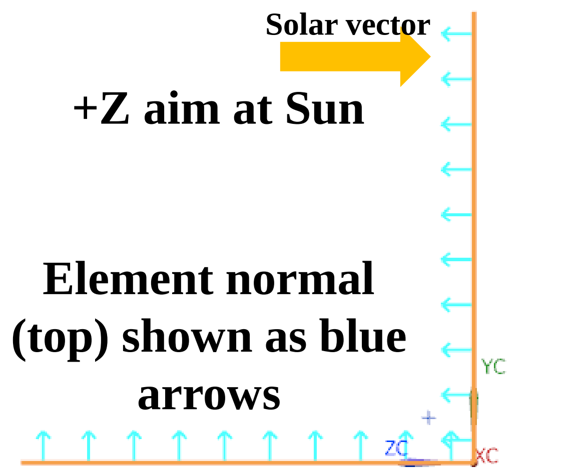


*Reference 2: Maya Heat Transfer Technologies Ltd. NX 9 Thermal Solver TMG Reference Manual, 2013.

Simple Model 1: Solar Specularity Effects On Two Perpendicular Identical Plates

- Plate top optical property: (no bottom property)
  - Emissivity: e=0.7
  - Solar absorptivity: a=0.3
  - (if any) Solar Specularity = 0.8
- No thermal conduction between plates, no sharing nodes
- Solar Flux = 1414 W/m², no earth IR and albedo, steady-state solution
- Model built and analyzed in NX 11.0



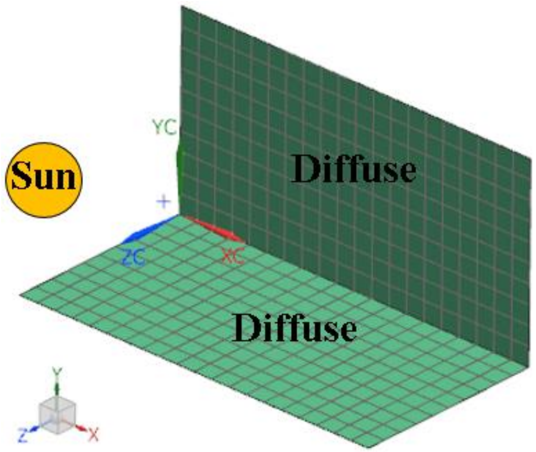


Simple Model 1: Steady State Cases

- Case 1: Baseline, No Specularity
- Case 2: Both Panels Have Solar Specularity, Ray Tracing Option (VFTRACE) Off
- Case 3: Both Panels Have Solar Specularity, Ray Tracing Option (VFTRACE) On

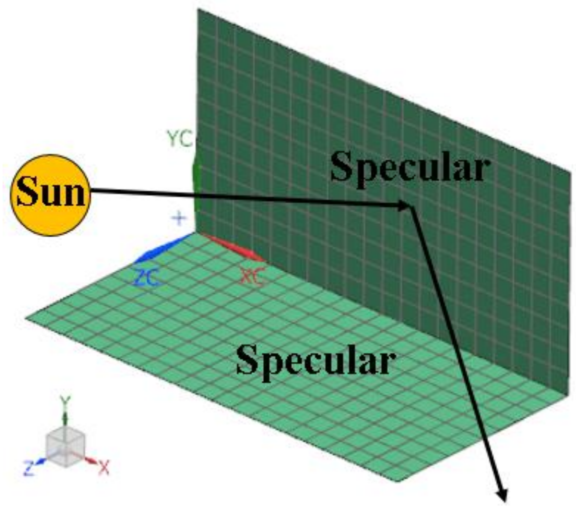
How Ray-tracing Works in 3 Cases

Case 1: No Specularity



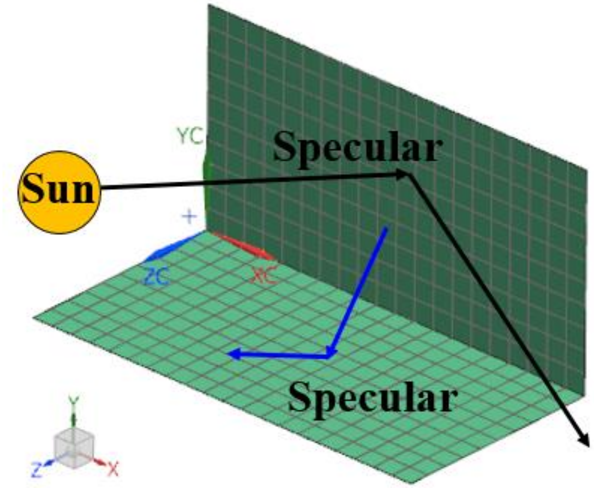
No rays launched at all

Case 2: Specularity = 0.8



Ray-tracing performed for solar view factors

Case 3: Specularity = 0.8, VFTRACE On

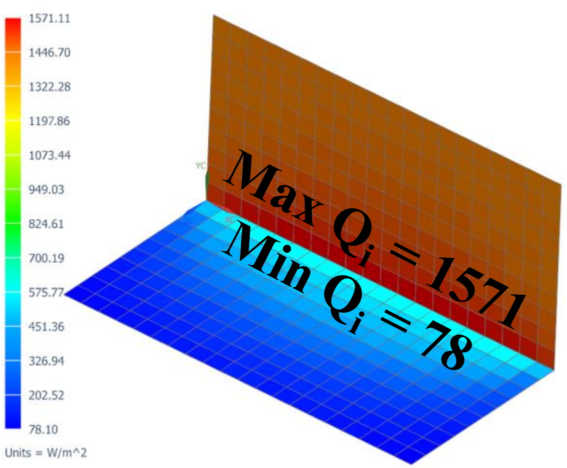


Ray-tracing performed for solar and element view factors

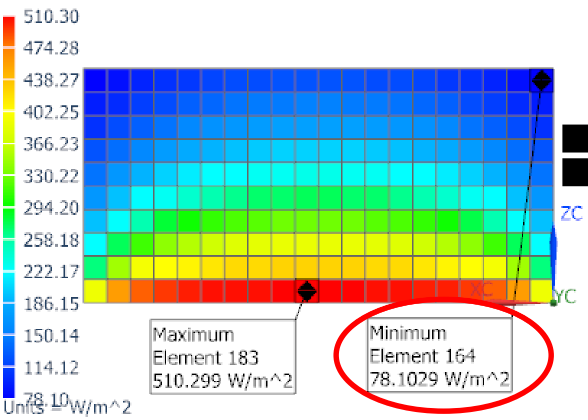
Case 1: Baseline, No Specularity, Cold Panel Solar Radiative Flux Balance

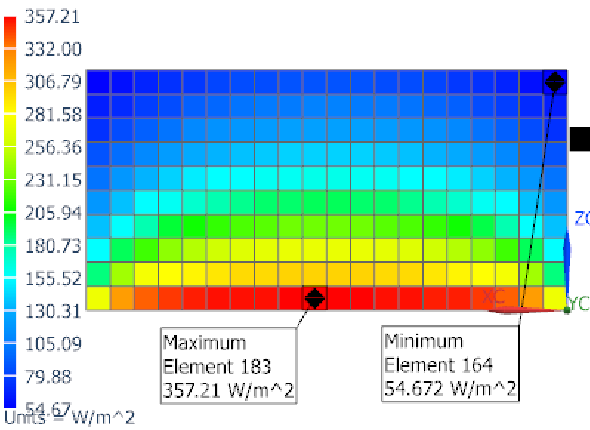
- For each element, solar flux balance:
  - Incident = Reflected + Absorbed
    - Absorbed Flux = 0.3*Incident Flux (α = 0.3)
    - Reflected Flux = 0.7*Incident Flux
- Cold panel incident solar flux comes only from diffusely reflected solar flux from hot panel, because cold panel has zero solar view factor

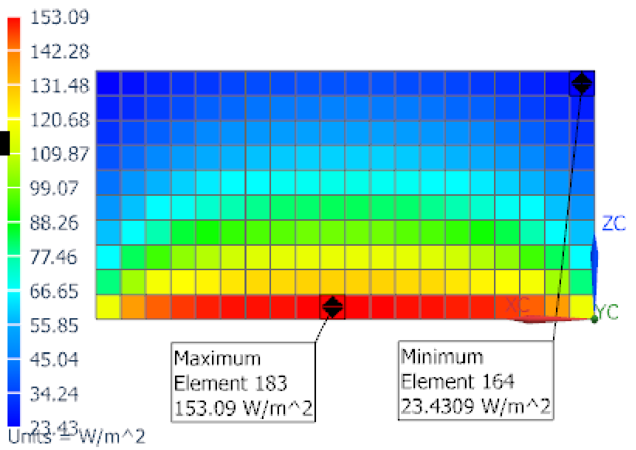
Incident Solar Radiative Flux



Incident Solar Radiative Flux = **Reflected Solar Radiative Flux** + **Absorbed Solar Radiative Flux**



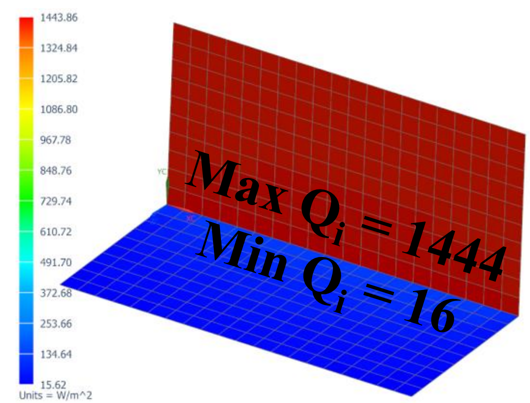




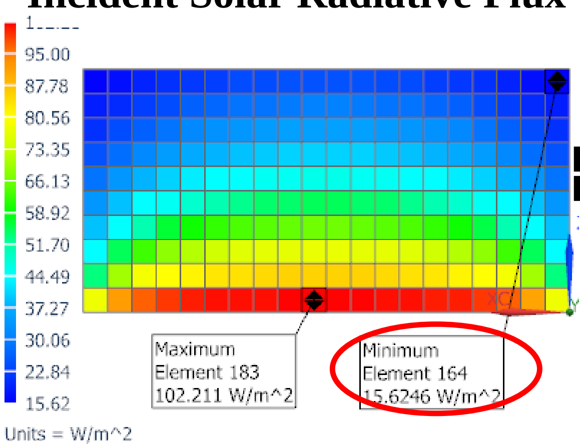
Case 2: Solar Specularity = 0.8, Cold Panel Receives Much Less Solar Flux

- Cold panel incident solar flux is much less than that in case 1
  - Hot panel's solar specularity is 0.8, which means 80% of solar flux is specularly reflected to space, and only 20% is diffusely reflected. Therefore, cold panel receives only 20% of diffusely reflected solar energy in case 1.
  - For element 164 (upper right corner): incident radiative flux = 78.1*20% = 15.6 W/m²

Incident Solar Radiative Flux



Incident Solar Radiative Flux



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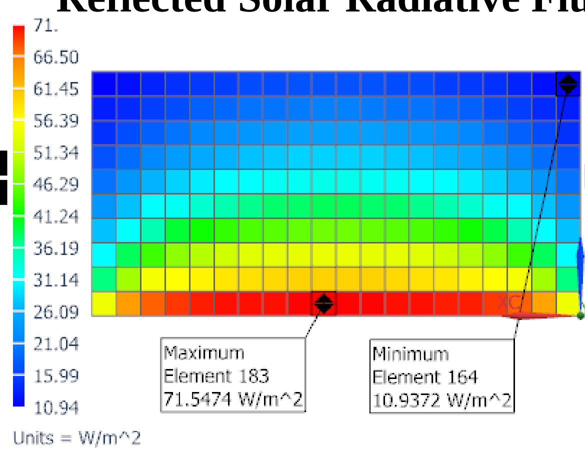
Reflected Solar Radiative Flux



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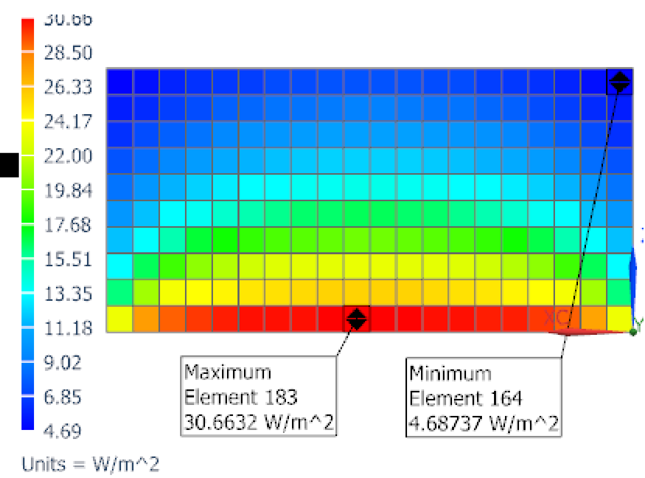
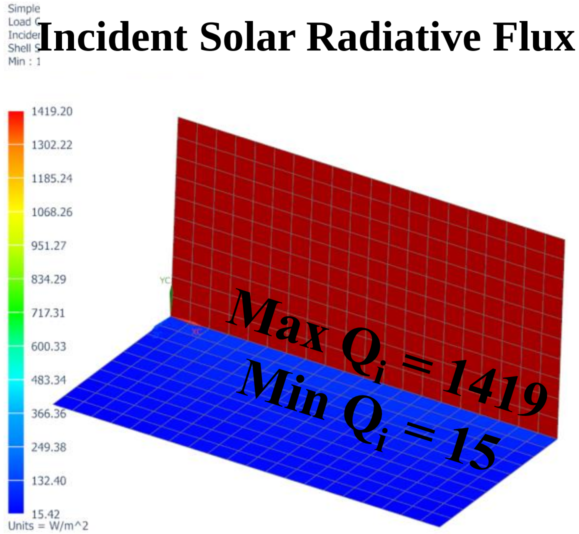
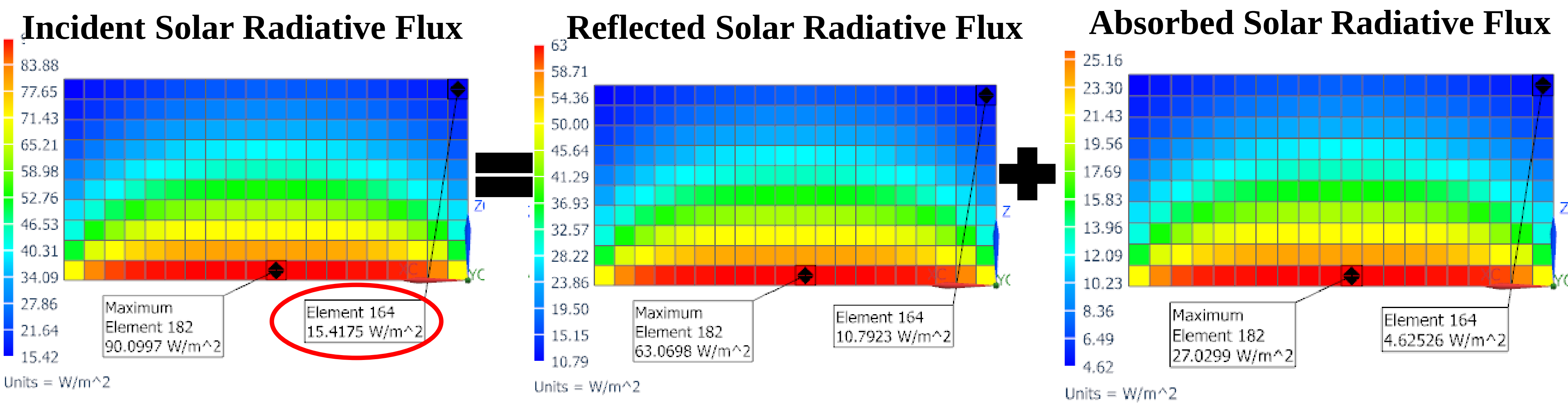
Absorbed Solar Radiative Flux



Case 3: Solar Specularity = 0.8, VFTRACE Option Makes Small Difference

- Case 3 with VFTRACE on shows small difference in solar radiative flux from case 2
  - For element 164 (upper right corner): incident radiative flux = 15.6 W/m² (vs. 15.4 in case 2)

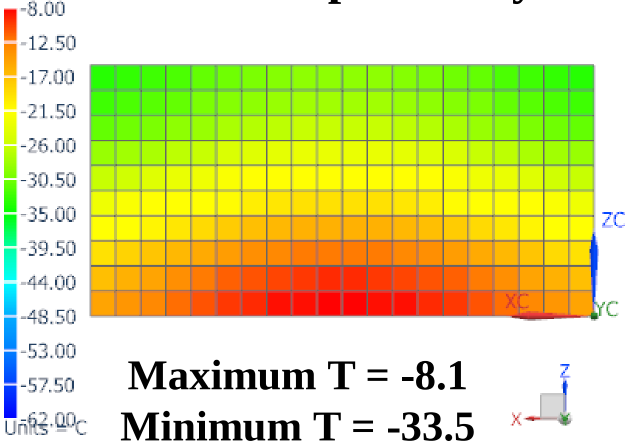




Temperature Comparison of Cold Panels

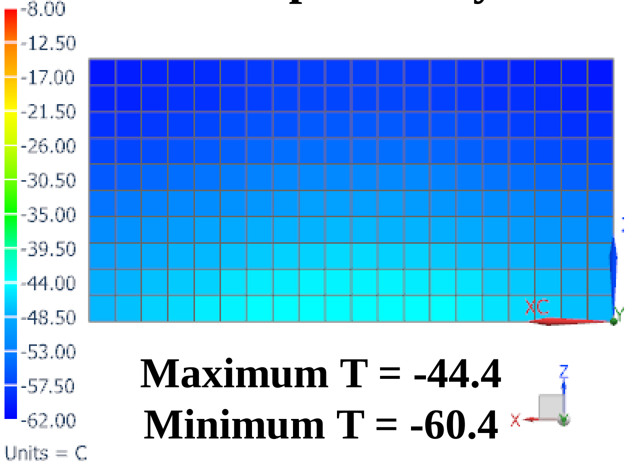
- Cold panels in case 2 & 3 with specularity show significant temperature reduction from case 1 without specularity because cold panel receives much less reflected solar flux from hot panels in case 2 and 3.
- Turning on VFTRACE option, maximum temperature change is no more than 2° C
  - In some instances, if mesh fidelity or MESH parameter is not sufficiently high, ray-tracing may results in bad view factor sum, and predicted temperatures may not be accurate
  - VFTRACE is computationally expensive (30 sec in Case 2 to 5 min in Case 3)

Case 1: No Specularity



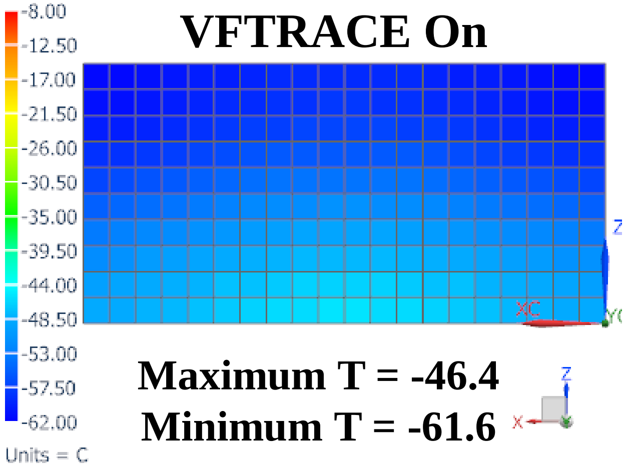
Maximum T = -8.1
Minimum T = -33.5

Case 2: Specularity = 0.8



Maximum T = -44.4
Minimum T = -60.4

Case 3: Specularity = 0.8, VFTRACE On

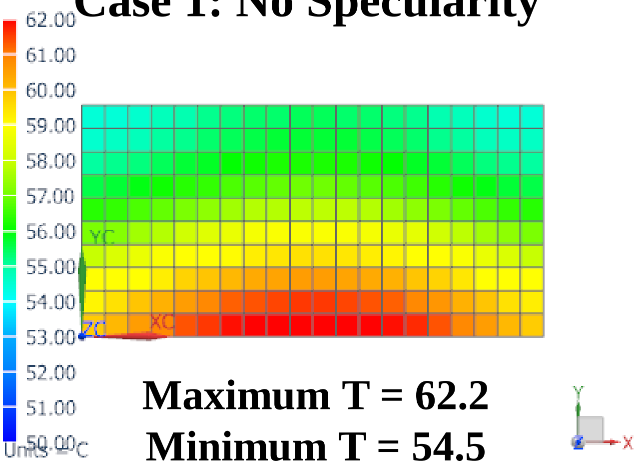


Maximum T = -46.4
Minimum T = -61.6

Temperature Comparison of Hot Panels

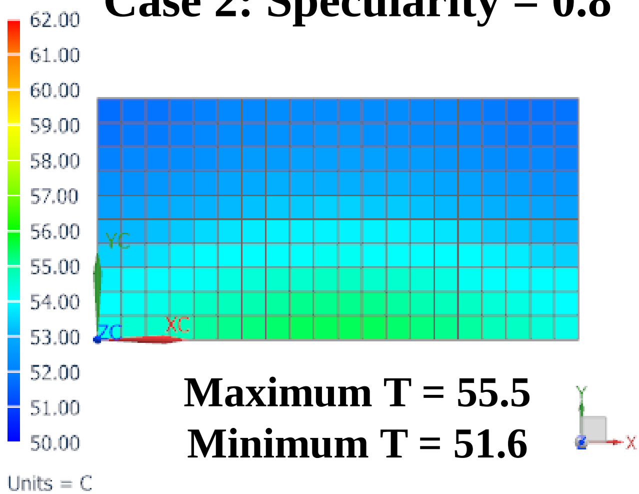
- Hot panels in case 2 and 3 with specularity show moderate temperature reduction from case 1, because hot panel receives less reflected solar flux from cold panel
- Turning on VFTRACE option, maximum temperature change is less than 2° C

Case 1: No Specularity



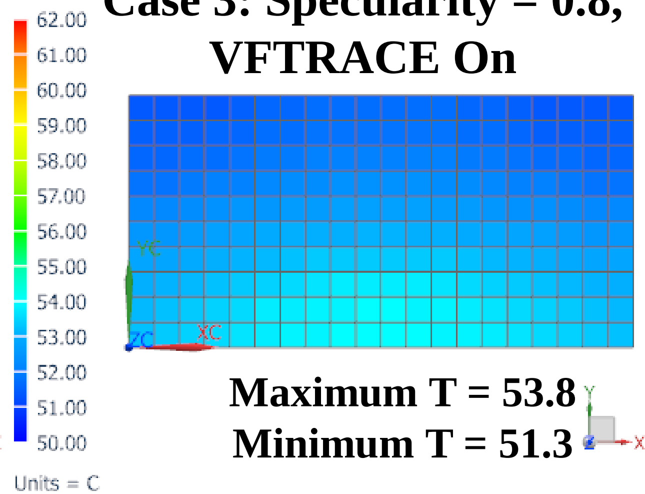
Maximum T = 62.2
Minimum T = 54.5

Case 2: Specularity = 0.8



Maximum T = 55.5
Minimum T = 51.6

Case 3: Specularity = 0.8, VFTRACE On



Maximum T = 53.8
Minimum T = 51.3

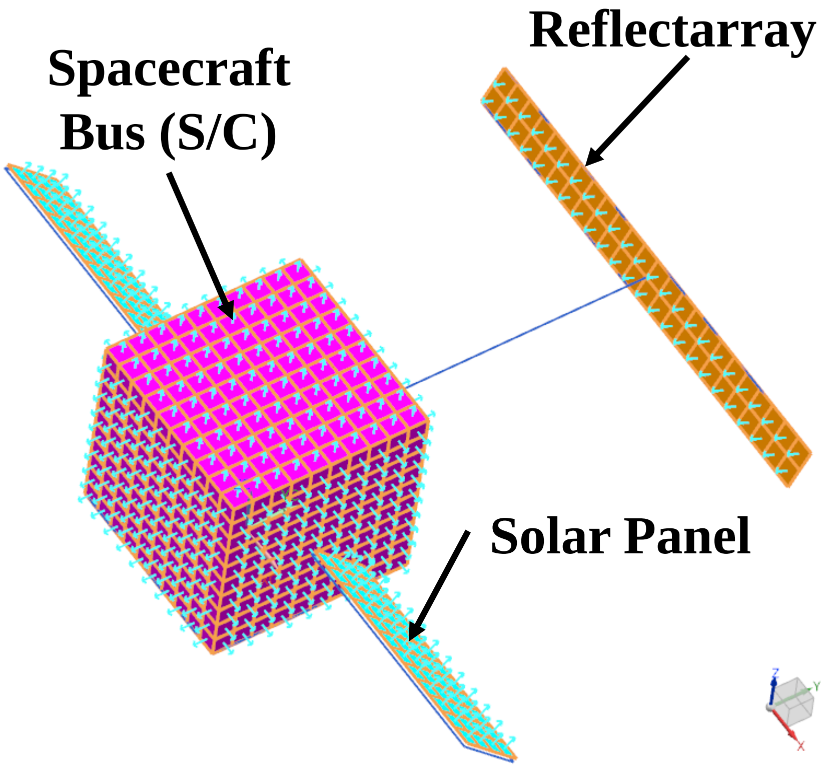
Simple Model 1: Summary

- Both panels in case 2 & 3 with specularity show moderate to large temperature change from case 1
- Ray-tracing option has small effect on both panels' temperatures, and is computationally expensive

Component	Description	Case 1	Case 2	Case 3
		No Specularity	With Specularity	With Specularity, VFTRACE On
Hot Panel	Max Temperature (°C)	62.2	55.5	53.8
	Min Temperature (°C)	54.5	51.6	51.3
Cold Panel	Max Temperature (°C)	-8.1	-44.4	-46.4
	Min Temperature (°C)	-33.5	-60.4	-61.6
Component	**Description**	**Case 1**	**Case 2**	**Case 3**
		No Specularity	**With Specularity**	**With Specularity, VFTRACE On**
Both Panels	Max Incident Solar Radiative Flux (W/m^2)	1571	1444	1419
	Min Incident Solar Radiative Flux (W/m^2)	78	16	15
Both Panels	Max Reflected Solar Radiative Flux (W/m^2)	1100	1011	993
	Min Reflected Solar Radiative Flux (W/m^2)	55	11	11
Both Panels	Max Absorbed Solar Radiative Flux (W/m^2)	471	433	426
	Min Absorbed Solar Radiative Flux (W/m^2)	23	5	5

Simple Model 2: Transient On-orbit Analysis

- A simple spacecraft model to represent SWOT
  - Interested in reflectarray's temperatures and stability
  - All properties are representative values
- On-orbit transient analysis
- Case 1t: baseline, no specularity for all components
- Case 2t: Solar panel and S/C solar specularity = 1, ray-tracing option (VFTRACE) Off
- Only radiation heat transfer
- Only solar heat load (1414 W/m²) and ignore earth IR and albedo to easily track energy source



Element normal (top) direction shown as blue arrows

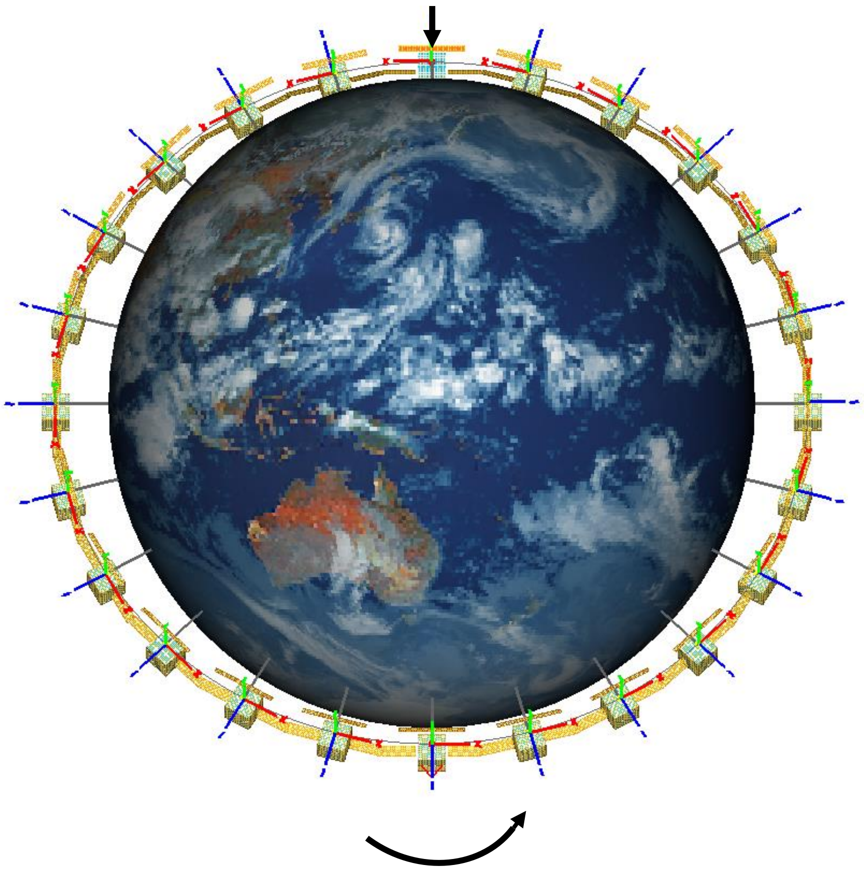
	IR Emissivity ε	Solar Absorptivity α	Mass (kg)
Reflectarray	0.7	0.3	13
S/C	0.6	0.4	163
Solar Panel	0.8	0.2	26

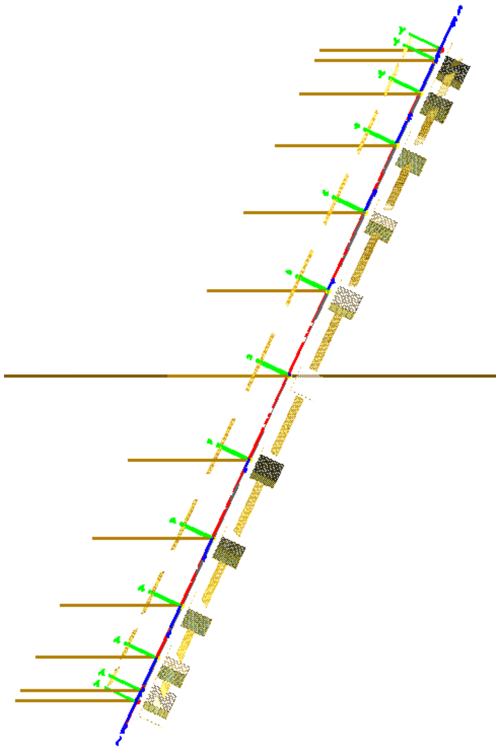
Beta = 65° Orbit

Orbit starts at local midnight, counter clock-wise

Analyzed with 24 orbital positions

S/C orientation:
-Z aim at Nadir;
+X align with velocity
Orbit altitude: 1000 km
Orbit period: 6300 seconds
Beta = 65° (no eclipse)

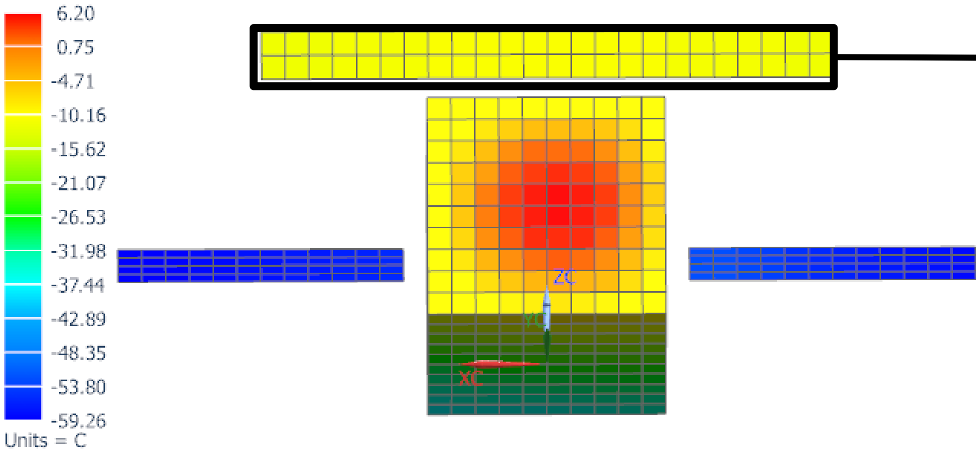


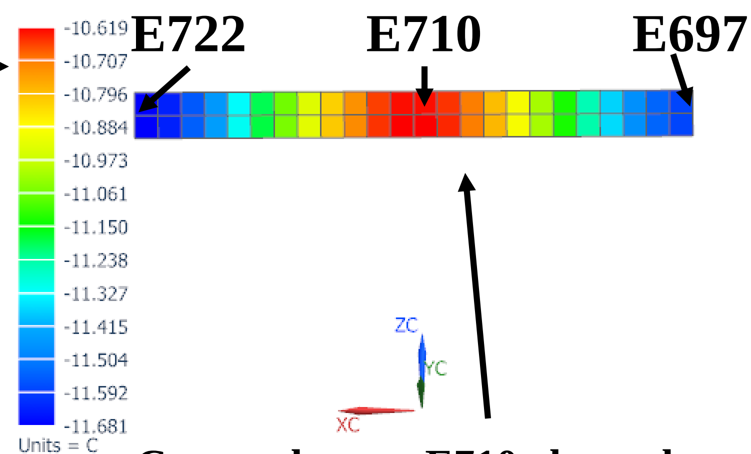


View from Sun

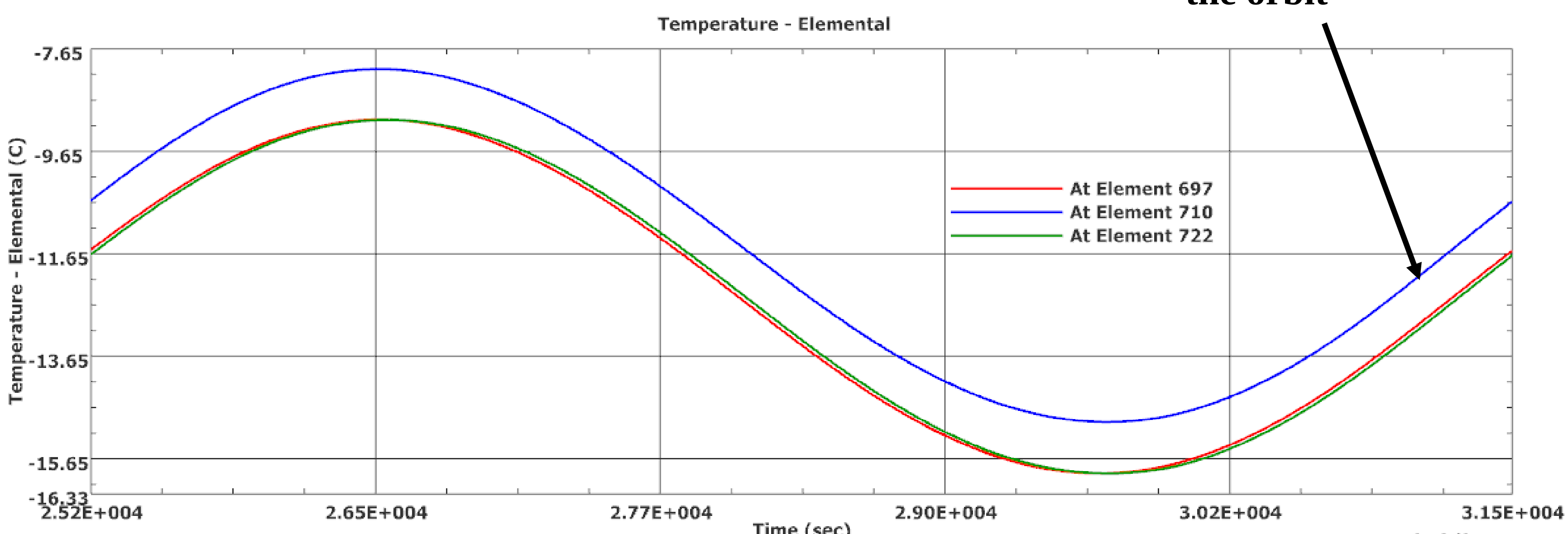
Case 1t Baseline: Reflectarray Temperature

Contour at End of Orbit



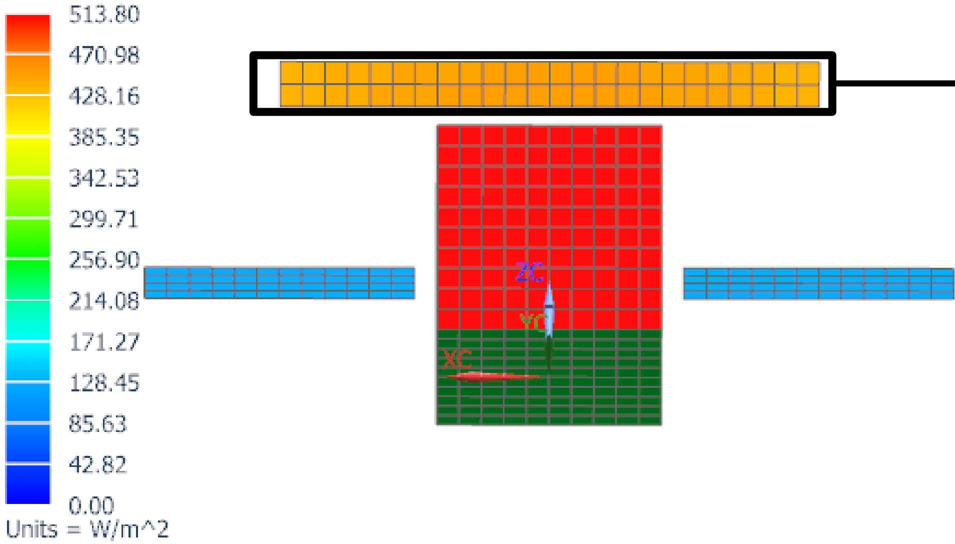


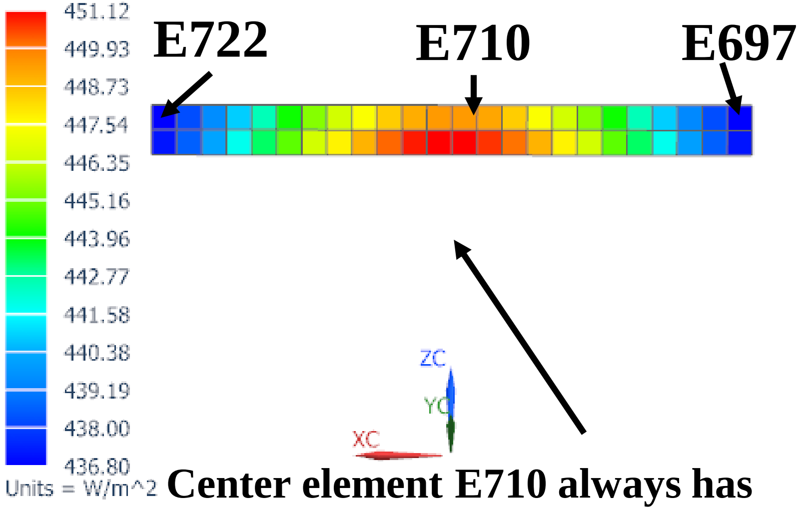
Center element E710 always has highest temperature throughout the orbit



Case 1t Baseline: Reflectarray Total Heat Flux

Contour at End of Orbit





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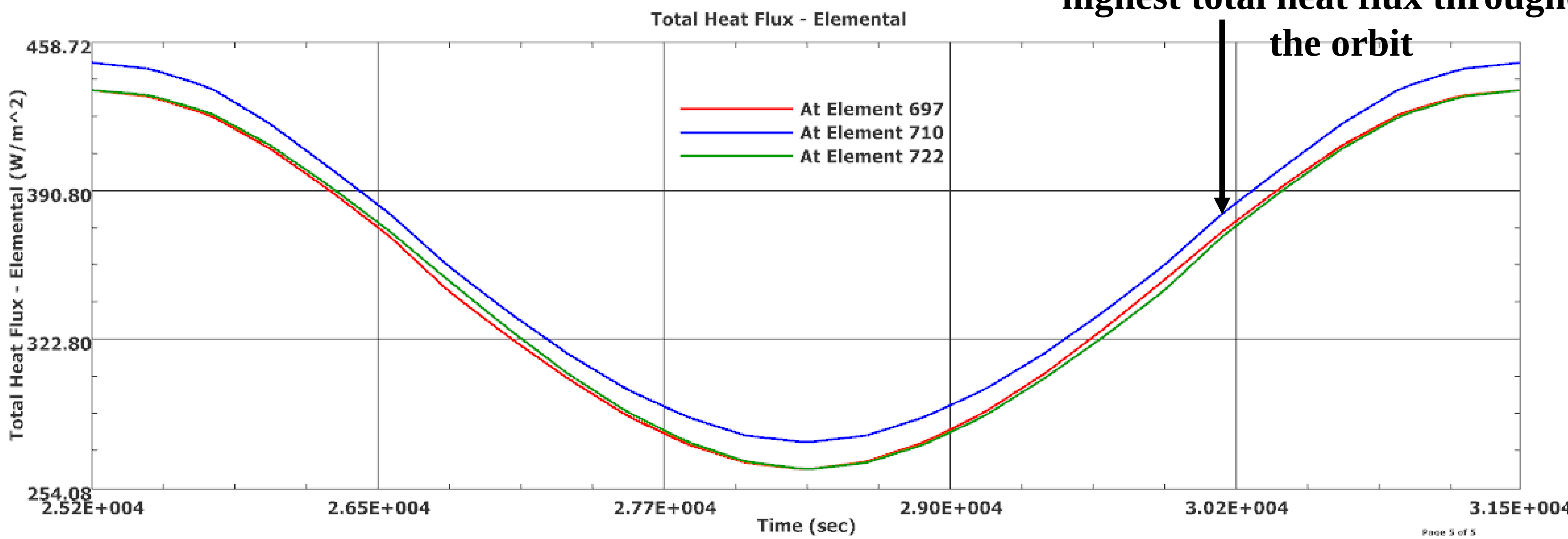
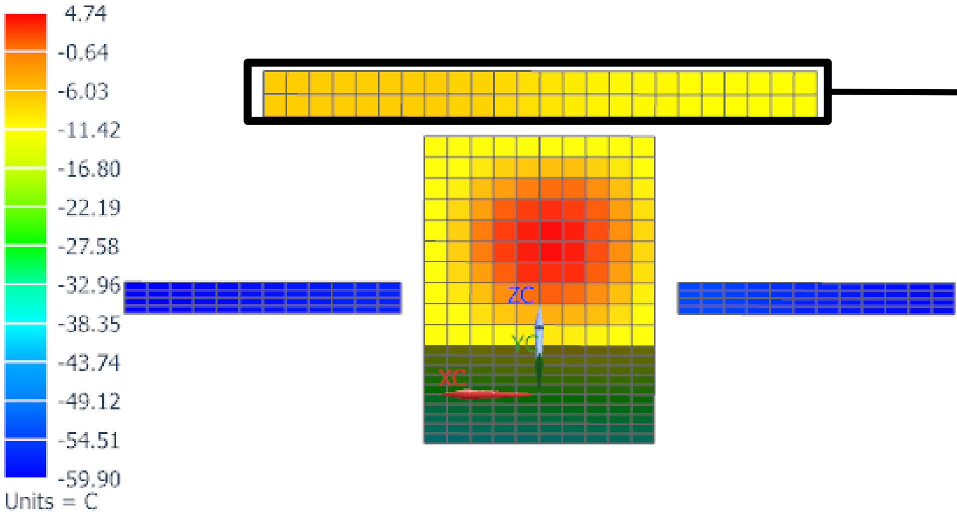
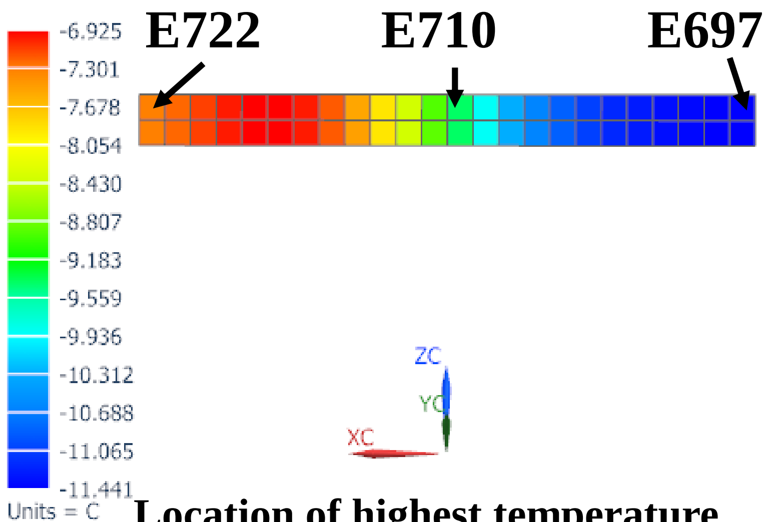


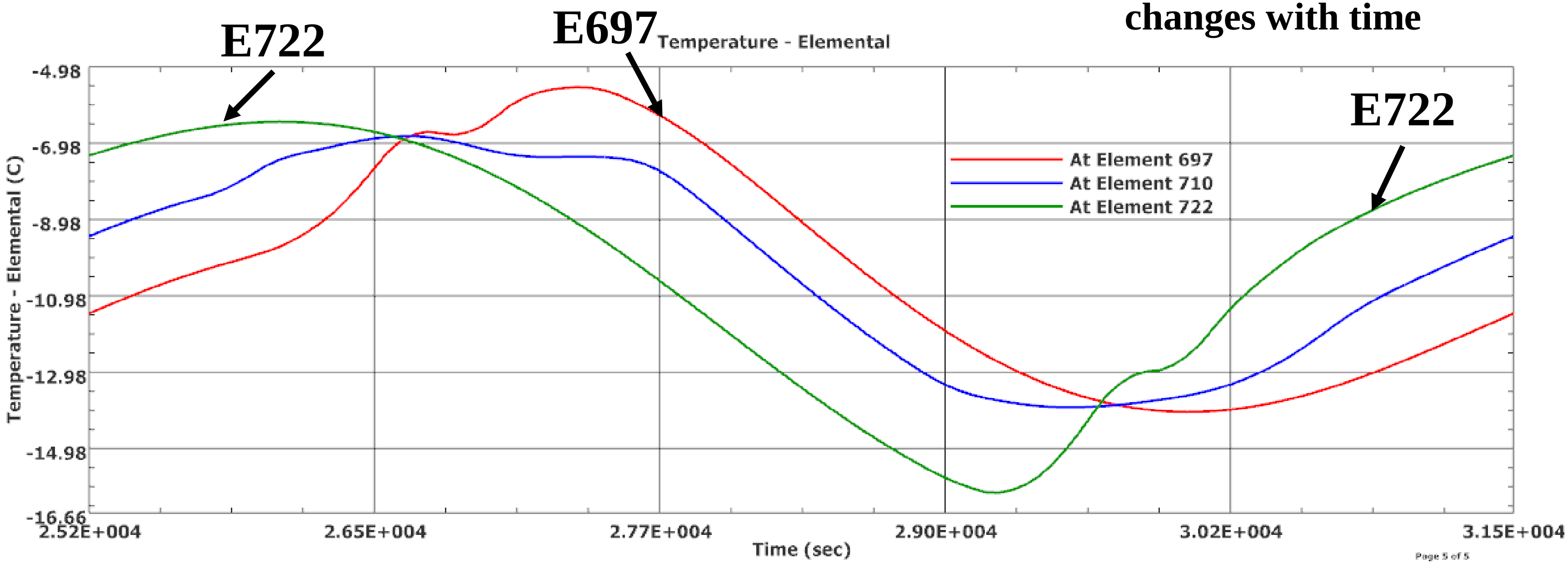
Case 2t w/ Specularity: Reflectarray Temperature

Contour at End of Orbit



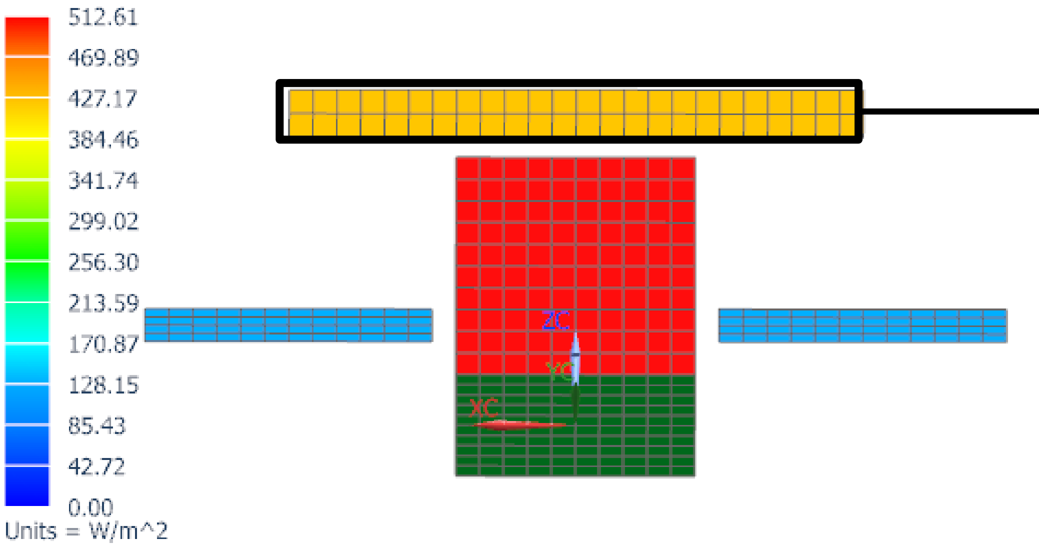


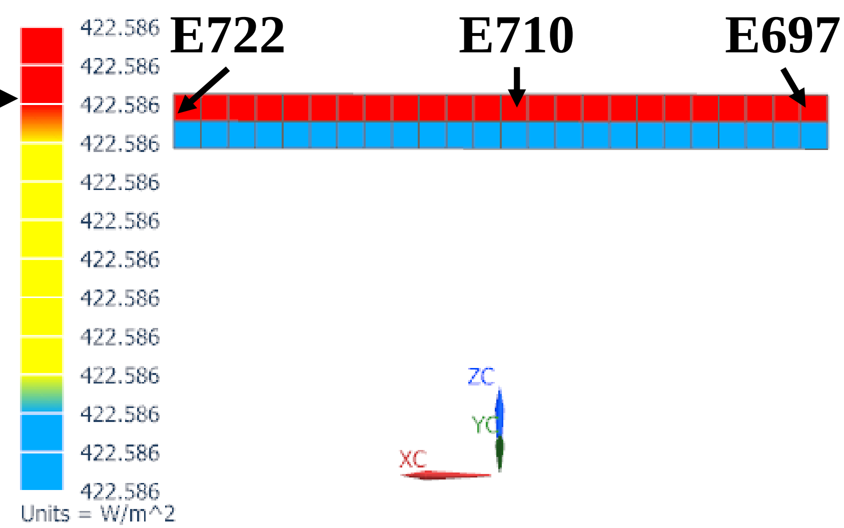
Location of highest temperature changes with time

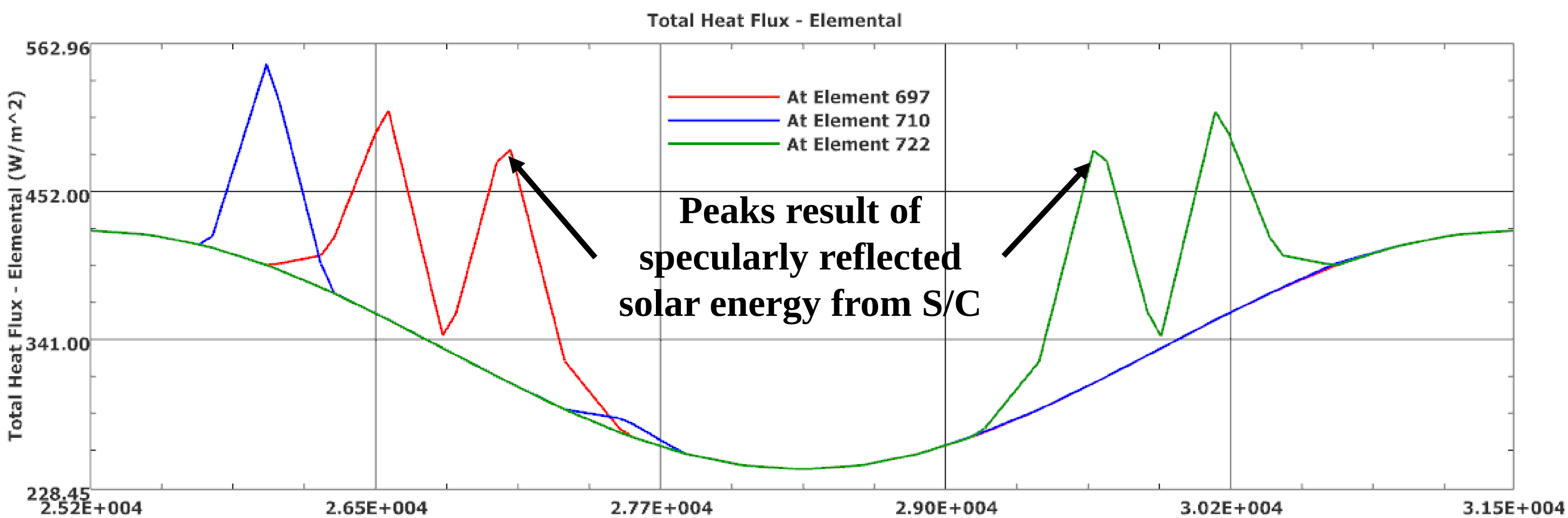


Case 2t w/ Specularity: Reflectarray Total Heat Flux

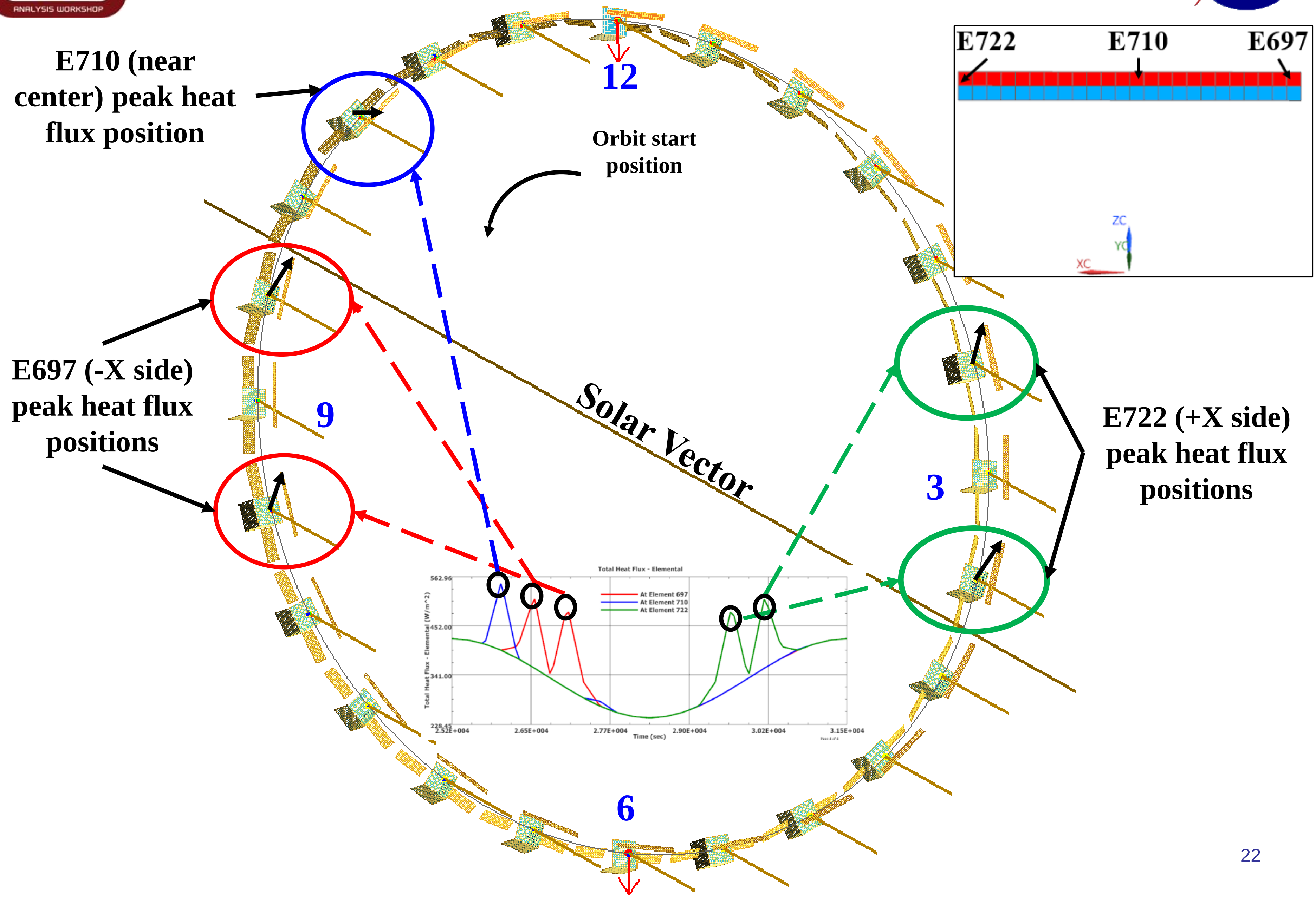
Contour at End of Orbit



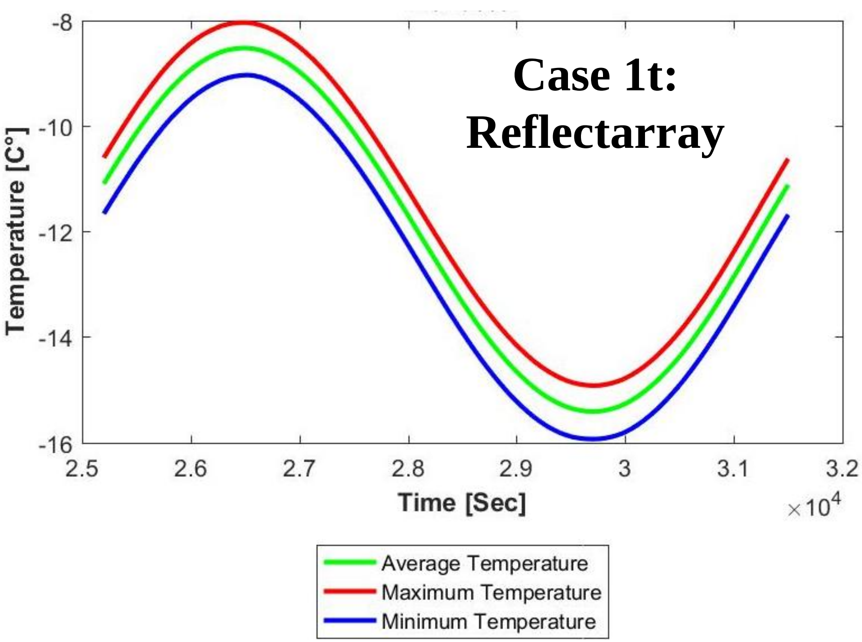




Case 2t: Orbital Positions Correspond to Peak Heat Flux

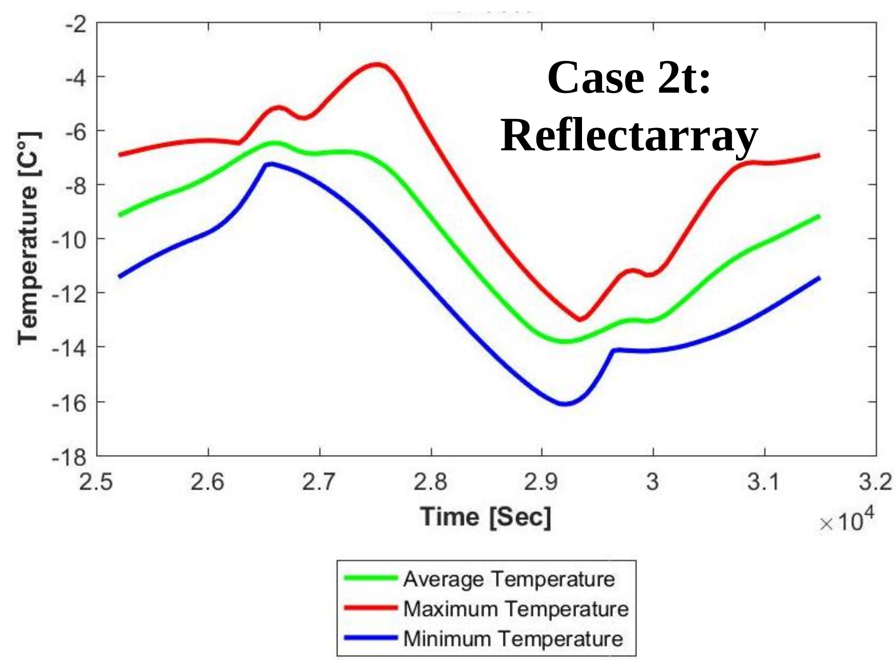


- Solar panel and S/C MLI's specularity affects reflectarry's maximum temperatures substantially (element-inconsistent transient plot)
  - Maximum temperature increases 4.4°C from Case 1t to Case 2t because of higher absorbed solar flux specularly reflected from spacecraft in Case 2t
  - Minimum temperatures in both cases are nearly the same



Case 1t (No Specularity)

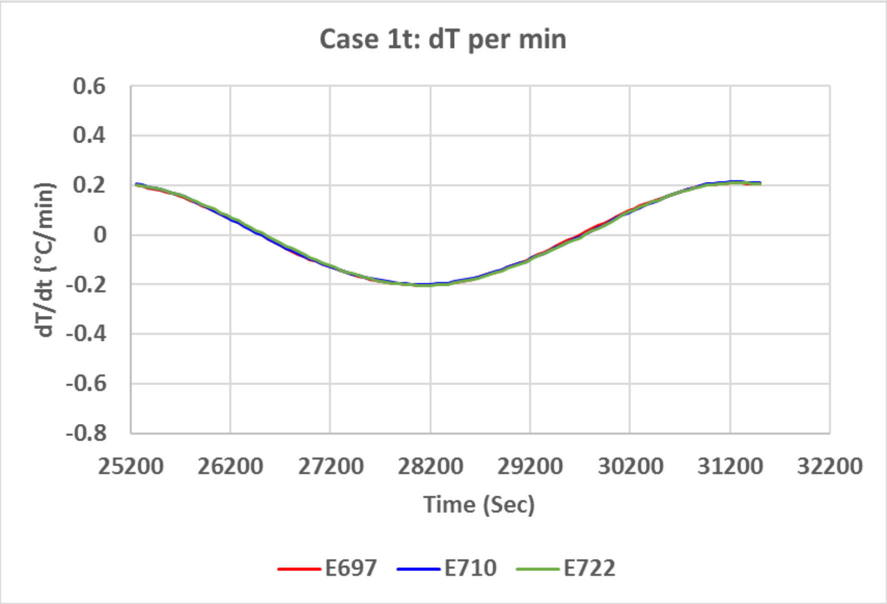
Max = -8.0°C, Min = -15.9°C



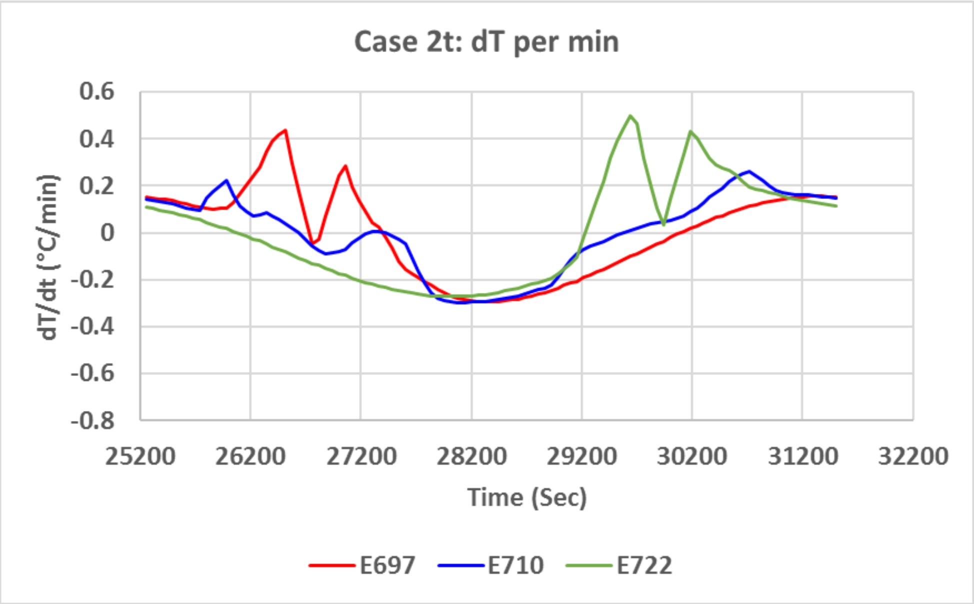
Case 2t (Specularity)

Max = -3.6°C, Min = -16.1°C

- Specularity also has large impact on reflectarray's temperature stability
  - Elemental temperature change per minute plotted for three elements on reflectarray for Case 1t and 2t below
  - Peaks in Case 2t are due to increased solar energy specularly reflected from spacecraft
  - Maximum temperature change per minute in Case 2t is 2.5 times higher than that in Case 1t.



Case 1t (No Specularity)
Max dT/dt = 0.2°C/min



Case 2t (Specularity)
Max dT/dt = 0.5°C/min

Conclusion

- Solar specularity has substantial impact on temperatures and thermal stability of surfaces that have direct view of the specular surfaces
- Element ray-tracing option in NX thermal solver is computationally expensive and has a small effect on the predicted temperatures