Thermal and Structural Analysis of the ExoMars Navigation and Localization Cameras

Christopher Pye, Pierre-Luc Messier (Maya HTT)

Tim Elgin (Neptec Design Group)

Presented By
Christopher J. Pye

TFAWS
LaRC 2019

Thermal & Fluids Analysis Workshop
TFAWS 2019
August 26-30, 2019
NASA Langley Research Center
Hampton, VA

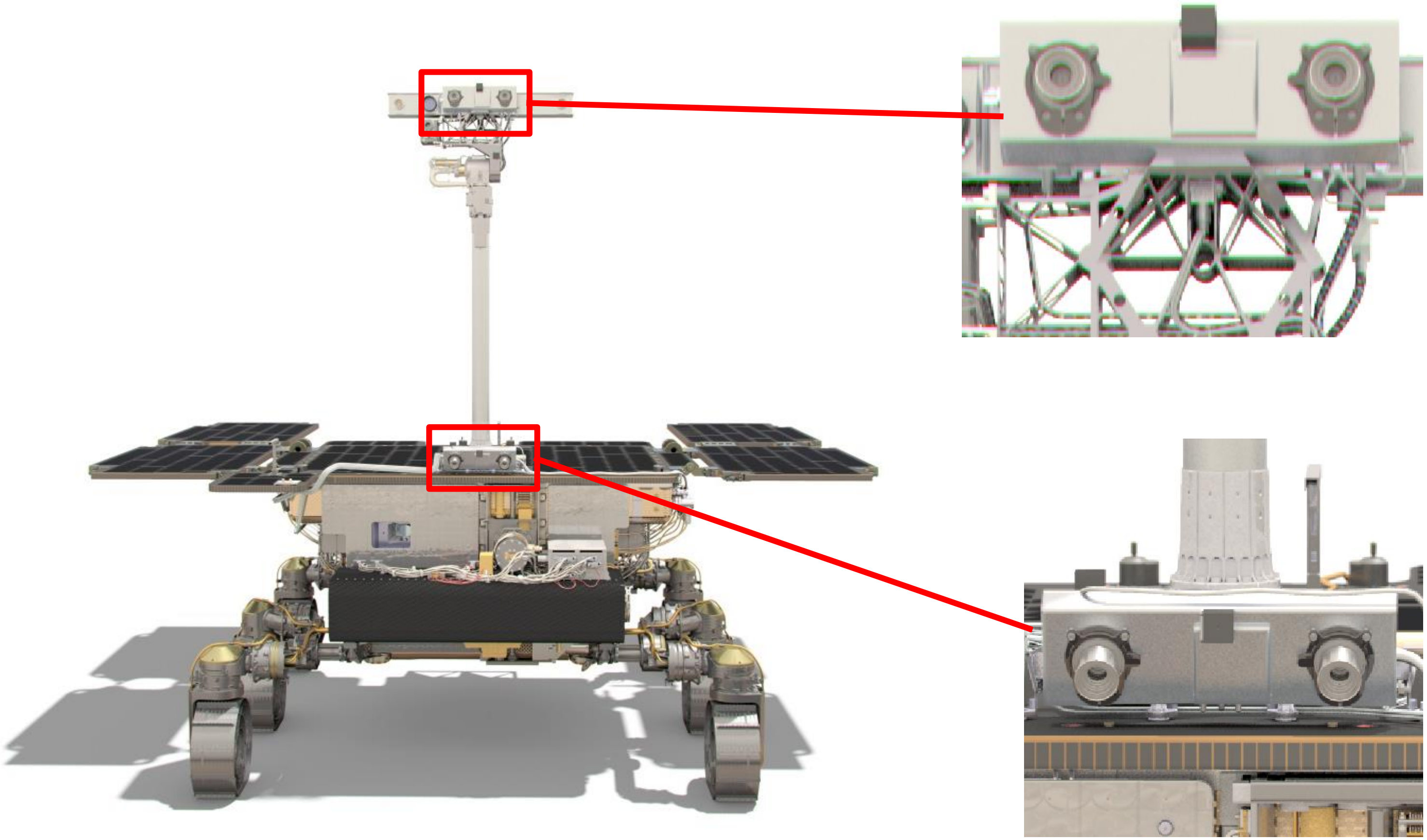
Agenda

- Introduction
- ExoMars Rover
- Thermal Modeling
- Thermal Results and Mapping Results to Structural Model
- Deformation Results and Optical Analysis

Introduction

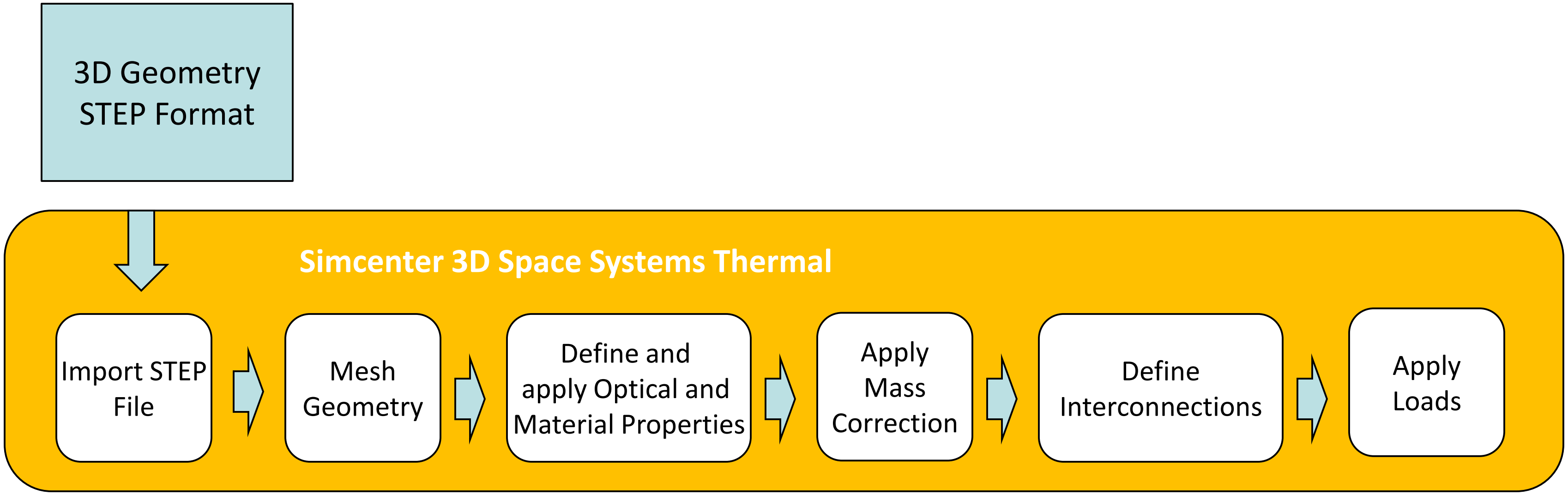
- The ESA ExoMars Rover provides key mission capabilities:
  - surface mobility,
  - subsurface drilling and automatic sample collection,
  - Sample processing, and distribution to instruments.
  - The instruments are dedicated to exobiology and geochemistry research: the Pasteur payload.
- Rover key features:
  - Solar panels to generate the required electrical power,
  - Designed to survive the cold Martian nights with the help of novel batteries and heater units.
  - Due to the infrequent communication opportunities, only 1 or 2 short sessions per sol (Martian day), the ExoMars Rover is highly autonomous.
  - Scientists on Earth will designate target destinations on the basis of compressed stereo images acquired by the cameras mounted on the Rover mast.
  - The Rover calculates navigation solutions by creating digital maps from navigation stereo cameras and computing a suitable trajectory. Close-up, collision avoidance cameras, are used to ensure safety. Travel is 100m per sol.
- This paper describes the thermal and structural analysis performed on the, identical, navigation (top of mast) and localization (base of mast) stereo cameras.
- The cameras were designed and built by Neptec Design Group, Maya HTT performed thermal and structural analysis.

ExoMars Rover



- Cameras are attached to rover with three fasteners.

Creating Camera Thermal Model



Component	Initial FE Mass (gm)	CAD Mass (gm)	Final FE Mass (gm)
Rear Housing	85.1	95.8	95.8
Front Housing plus fasteners	163.0	203.0	204.5
PWB’s	38.0	219.8	220.0

Adjusting for additional material:	Adjust density
Adjusting for irregular thickness:	Adjust thickness

Meshing Methods

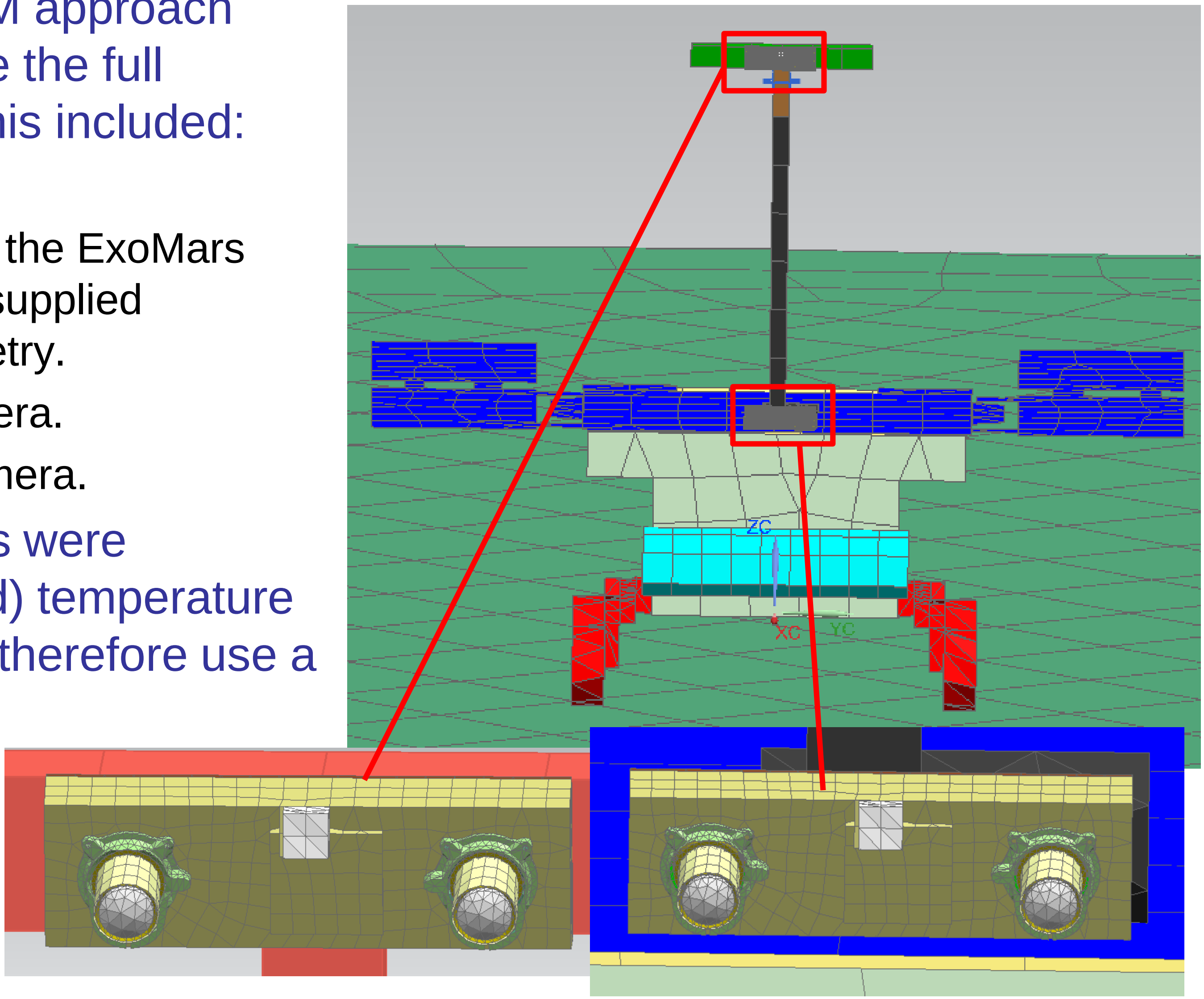
Part	Mesh Type	Comments
Front and back Housing	Shell	• A separate mesh was used for the inner surface of the front and rear housing near PWB components. • Provides the correct gap between component and housing for the atmospheric conduction modeling. • The inner surface was non- conducting and connected to the outer surface mesh to represent through thickness conduction. • All in plane-conduction was handled by the outer surface mesh.
PWBs	Shell	• Separate meshes were used for each face of the PWB's. • Each mesh assigned the PWB material and half the PWB thickness. • The faces were then thermally coupled to represent through thickness conduction, by creating a Conductive Thermal Coupling, selecting each surface and specifying the thermal conductivity.
Components	Shell	• Components with assigned dissipation were each modeled as a single shell element. • The element was connected to the PWB with a resistance representing Resistance from junction to case and resistance from case to board in series.
Lens Glass	Solid	• Tetrahedral elements. • The outer glass surface was meshed with shell elements for radiation modeling. This is not necessary but simplifies selection for exterior radiation.
Lens Clamp	Solid	
Optics housings	Shell	• The two (per lens) that the optical glass is mounted in were each modeled with shell elements. • The thickness was set such that the modeled mass of each part was correct.

Assembly FEM

- SC3D-SST supports the concept of Assembly FEM's. These work much the same way as part assemblies which contain instances of parts that are defined separately. The advantages of the assembly FEM approach are:
  - Each part or subassembly can be modeled independently and the model can be tested to ensure validity before being added to the Assembly FEM. The model would typically include the mesh, thermal couplings, heat loads and internal radiation.
  - If there are multiple instances of the same assembly then the same model can be instanced multiple times.
  - The task of creating the thermal model can be distributed amongst the thermal team. Each team member can focus on one component or sub-assembly then create and test a thermal model.
  - Changes to a part FEM is applied to all instances used in the Assembly FEM.

Assembly FEM

- The assembly FEM approach was used to create the full thermal model. This included:
  - Martian Surface.
  - Simple model of the ExoMars rover based on supplied simplified geometry.
  - Navigation Camera.
  - Localization Camera.
- Rover components were assigned (supplied) temperature profiles and could therefore use a coarse mesh.



Interconnections

Physical Phenomenon	Methodology
Air gap conduction	Applied internally. Surface geometry is accurately defined and a conductive gap coupling used. The thermal conductivity set to a temperature dependent relationship appropriate for the Martian atmosphere.
Bolted joints	Total conductance per joint calculated as (number of bolts x conductance per bolt). Values taken from handbooks.
Semiconductor mounting	Use supplied q_{jc}, q_{jb}.
Adhesive joint or thermal filler.	Calculate equivalent heat transfer coefficient and apply.

Environment

- Direct Solar Radiation
  - Used SC SST Diurnal heeting. Supports time varying solar flux, supplied values include atmospheric absorption, optical depth correction not required.
- Diffuse Sky Radiation
  - Created dome of shell elements around model that were used as diffuse flux source but not included in radiation conductance calculations.
  - Now included and as feature in SC3D-SST.
- Atmospheric Temperature
  - Temperature profile assigned to diffuse sky dome. Picked up by convection calculation code.
- Ground Temperature
  - Created 60m diameter disc to represent Martian surface

Convection

- Convection was modelled using Fortran code that is linked into the SC3D-SST temperature solver. The routine has access to the required geometry information, such as element area and all temperatures and heat loads.
- The routine used the algorithm supplied to the camera team to compute a heat transfer coefficient, h, from air properties and wind speed. The heat transfer is then used to calculate the convection heat loss, Qc, from:

$$Qc = h\ A\ (T_{elem} - T_{air})$$

- Heat transfer coefficients were supplied for different geometric configurations. Convecting elements were placed in one of four element groups corresponding to each configuration:
  - vertical surfaces
  - horizontal surfaces with air below
  - horizontal surfaces with air above
  - horizontal cylinders
- Characteristic lengths required for calculating heat transfer coefficients were hard coded.

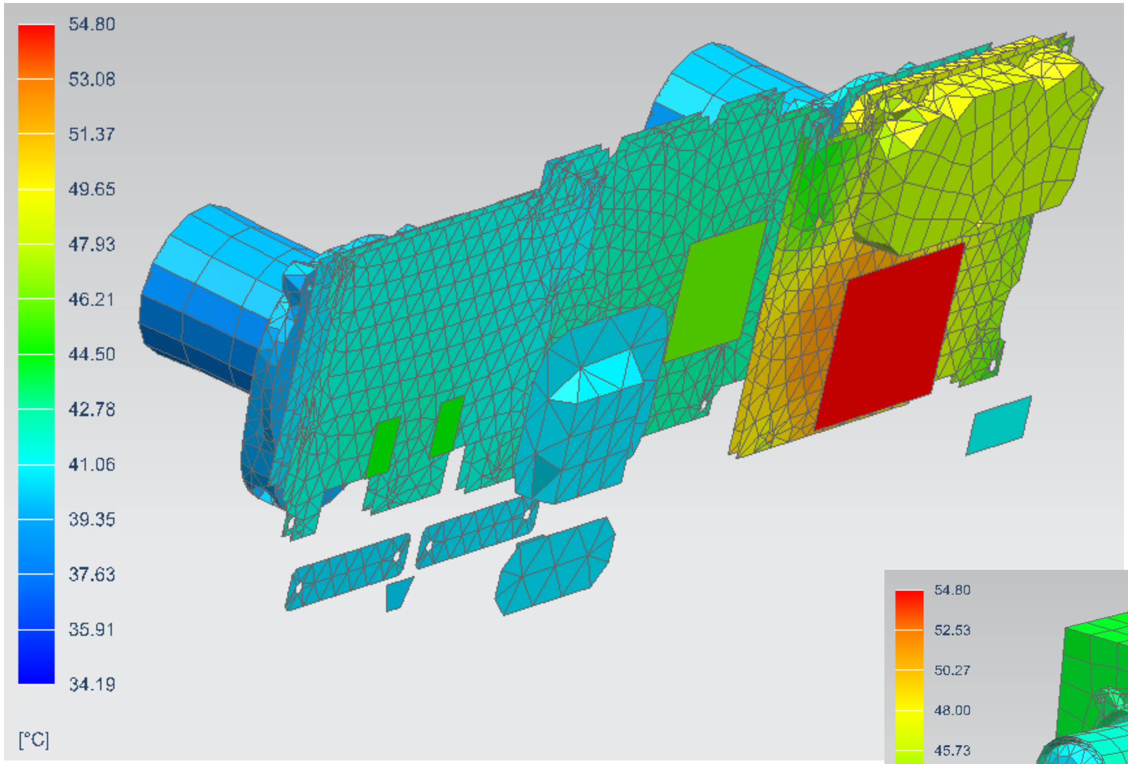
Solution Cases

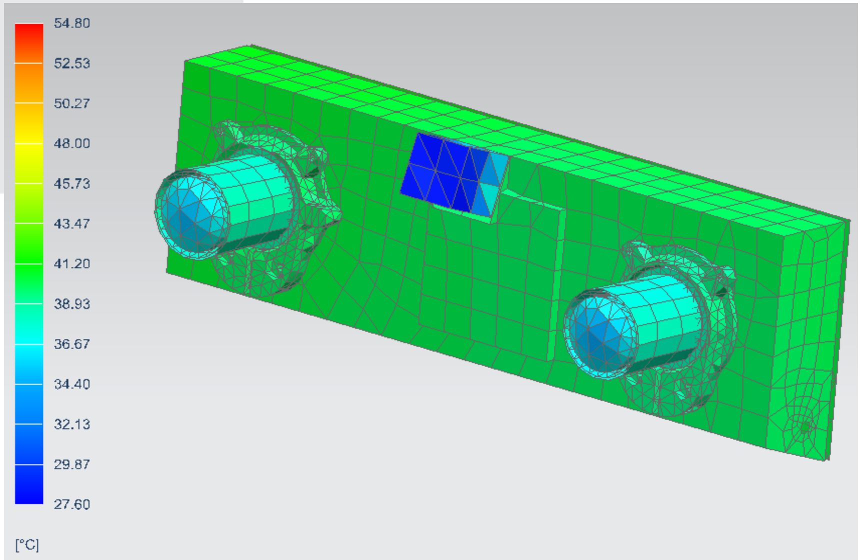
- The thermal load cases used represented 25 different combinations of the following:
  - Environment: seven environments were defined by parameters such as season, latitude, optical depth, atmospheric pressure and wind speed.
  - Power dissipations: three power dissipation cases were defined, minimum, typical, and maximum. With total power of the typical case defined as 100% the other two cases were 93% and 136%. Component power dissipations did not all change by the same percentage. Note that power dissipation is zero at night because the camera is off and no local keep alive power is present.
  - Presence of absence of dust: the presence of dust was modeled as changes in surface optical properties and transmissibility of the atmosphere. The values used were validated experimentally.
- The thermal solver provides the option to run the radiation calculations and the temperature solution in parallel, either locally or using multiple machines .
  - Parallel processing was used when a single case was run.
  - When running multiple cases greater efficiency is achieved by running each case on a single core and running the cases simultaneously.

Results

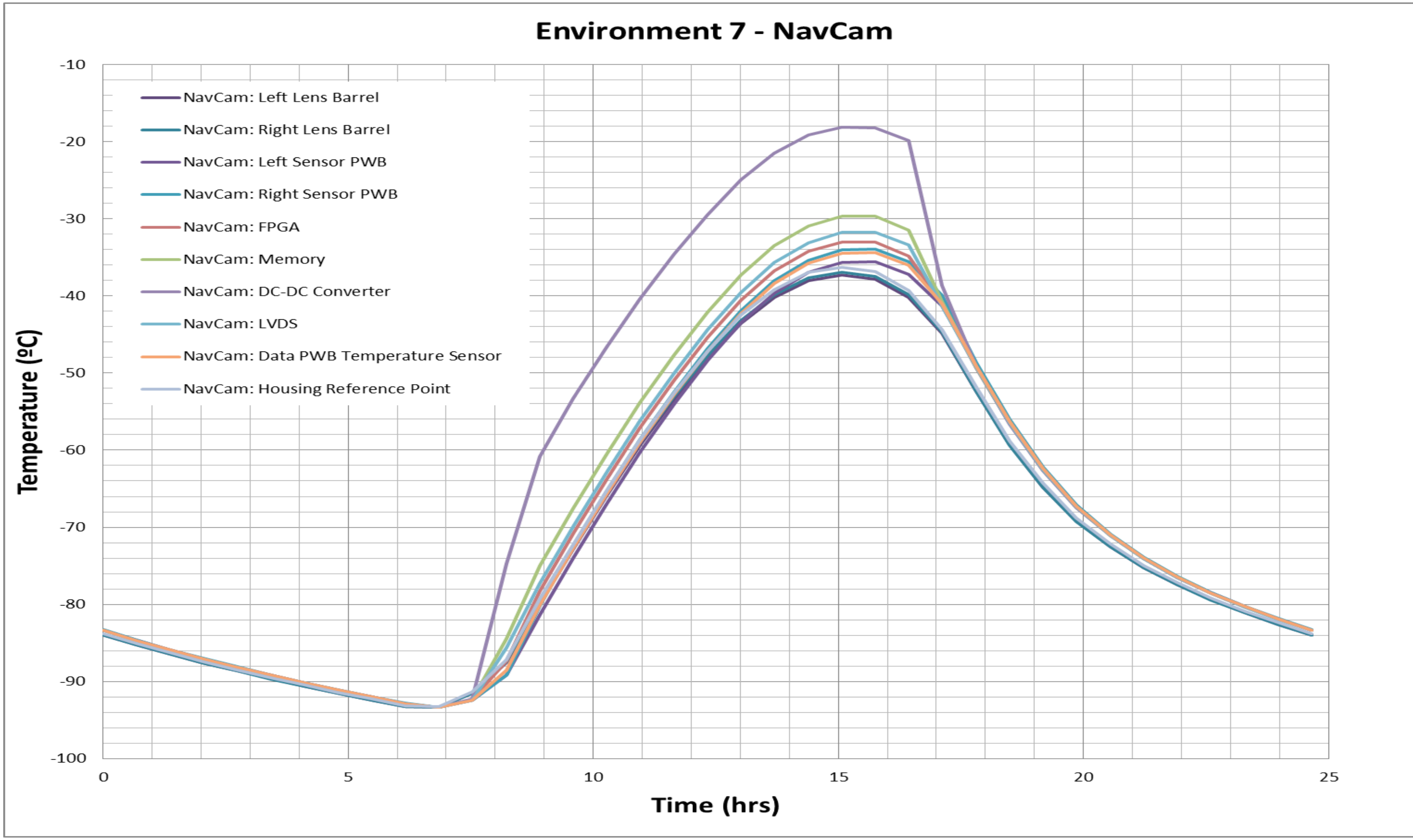
- One of the key points on the camera is the Temperature Reference Point (TRP), which is used by the vehicle for determining when the cameras may be safely powered on (or should they need to be, turned off during nominal operation).
- The TRP is located on the camera housing and is the primary temperature monitored during operation on Mars.

Hot Case Temperature Maps (NavCam)

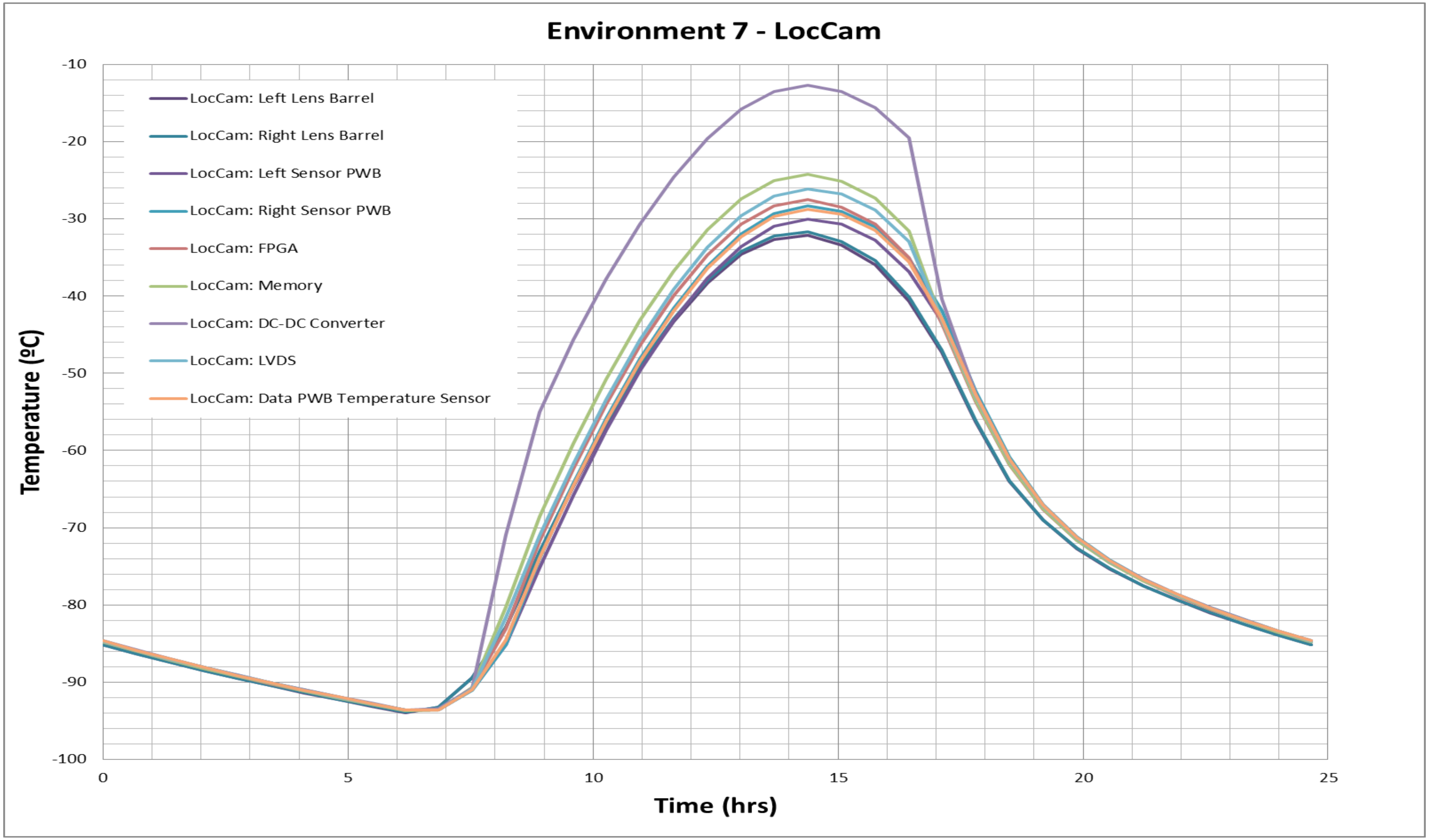




Cold Case Temperature Profile - NavCam

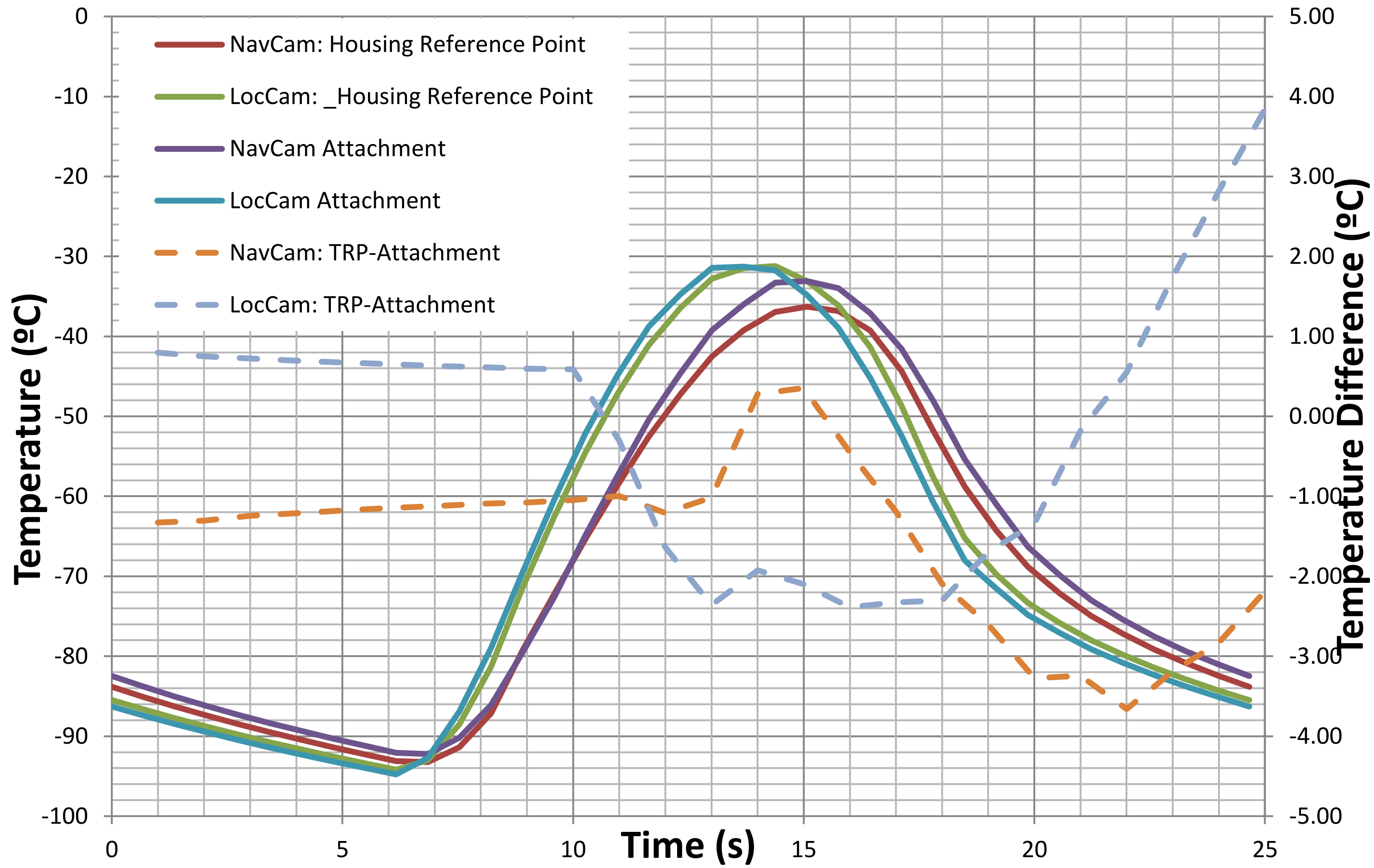


Cold Case Temperature Profile - LocCam



Env7- TRP and Attachment Temps

Dashed lines use Secondary Y Axis



Modified Mounting Conductance

- As expected, temperatures are driven mostly by the temperature of the mounting point in the rover.
- Model was run with the mounting conductance set to half its nominal value.

Modified Mounting Conductance	Temperature Change			
	Hot		Cold	
	No Dust		Dust	
	Maximum Power		Minimum Power	
	Min	Max	Min	Max
NavCam FPGA	-4.60	6.84	-0.57	-2.06
NavCam LVDS	-4.57	6.82	-0.55	-6.20
NavCam DC-DC Converter	-4.56	6.47	-0.53	-1.52
NavCam Memory	-4.60	6.82	-0.56	-2.15
NavCam Left Lens Barrel	-4.55	6.50	-0.50	-1.53
NavCam Right Lens Barrel	-4.54	6.48	-0.49	-1.46
NavCam Left Sensor PWB	-4.59	6.84	-0.56	-2.04
NavCam Right Sensor PWB	-4.59	6.80	-0.55	-1.75
NavCam Power Wire	-4.58	6.57	-0.52	-1.48
NavCam Data PWB Temperature Sensor	-4.58	6.83	-0.55	-3.49
NavCam Housing Reference Point	-4.73	7.18	-0.61	-1.79
LocCam FPGA	0.11	1.01	0.07	-0.70
LocCam LVDS	0.12	0.98	0.05	-4.92
LocCam DC-DC Converter	0.12	0.95	0.07	-0.30
LocCam Memory	0.11	1.01	0.07	-0.82
LocCam Left Lens Barrel	0.10	0.79	0.07	-0.30
LocCam Right Lens Barrel	0.11	0.78	0.06	-0.25
LocCam Left Sensor PWB	0.11	0.97	0.07	-0.73
LocCam Right Sensor PWB	0.11	0.97	0.06	-0.46
LocCam Power Wire	0.11	0.94	0.07	-0.31
LocCam Data PWB Temperature Sensor	0.11	0.97	0.01	-2.20
LocCam Housing Reference Point	0.10	0.89	0.07	-0.22

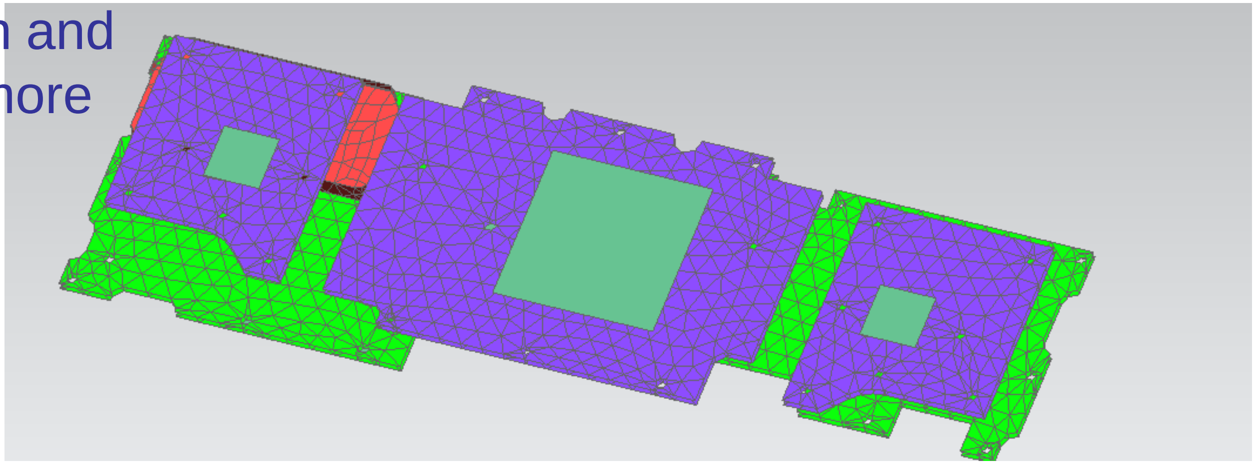
Effect of Dust

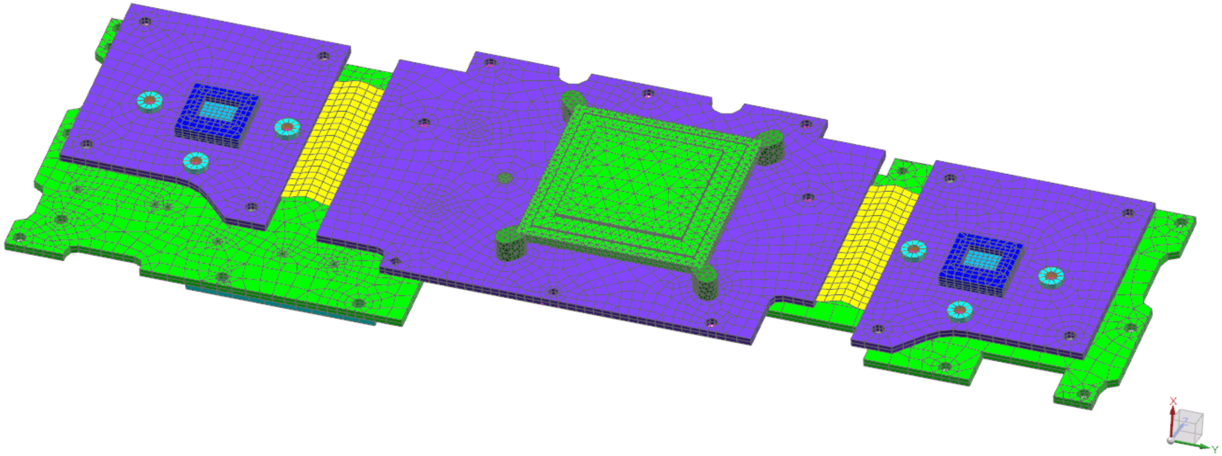
- For cold case with dust, mounting points are colder.
- Table shows temperature changes, adjusted for change in mounting point temperature.

Effect of Dust	Normalized Temperature Change (ºC)			
	Dust - No Dust			
	Hot		Cold	
	Typical Power		Typical Power	
	Min	Max	Min	Max
NavCam FPGA	-0.20	-0.75	0.17	0.19
NavCam LVDS	-0.26	-0.99	0.29	0.50
NavCam DC-DC Converter	-0.23	-0.50	0.33	0.37
NavCam Memory	-0.21	-0.77	0.17	0.22
NavCam Left Lens Barrel	-0.52	-2.56	-0.09	0.80
NavCam Right Lens Barrel	-0.53	-2.64	-0.05	0.41
NavCam Left Sensor PWB	-0.27	-0.96	0.24	0.31
NavCam Right Sensor PWB	-0.27	-0.94	0.26	0.29
NavCam Power Wire	-0.21	-0.61	0.37	0.47
NavCam Data PWB Temperature Sensor	-0.26	-0.97	0.27	0.48
NavCam Housing Reference Point	0.00	0.00	0.00	0.00
LocCam FPGA	-0.06	-0.95	-0.05	-0.60
LocCam LVDS	-0.09	-1.33	-0.08	-0.79
LocCam DC-DC Converter	-0.09	-1.19	-0.08	-0.64
LocCam Memory	-0.06	-0.97	-0.05	-0.61
LocCam Left Lens Barrel	-0.15	-2.59	-0.13	-1.32
LocCam Right Lens Barrel	-0.16	-2.70	-0.14	-1.34
LocCam Left Sensor PWB	-0.08	-1.19	-0.07	-0.65
LocCam Right Sensor PWB	-0.08	-1.26	-0.06	-0.69
LocCam Power Wire	-0.10	-1.23	-0.08	-0.66
LocCam Data PWB Temperature Sensor	-0.09	-1.29	-0.07	-0.78
LocCam Housing Reference Point	0.00	0.00	0.00	0.00

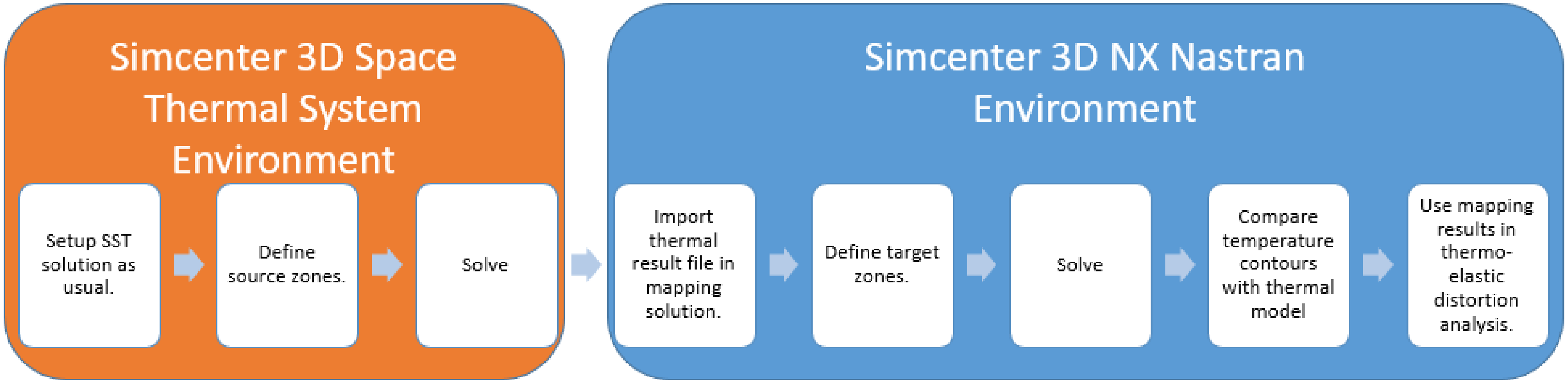
Structural Model

- Structural model uses more refined mesh and explicitly models more components.





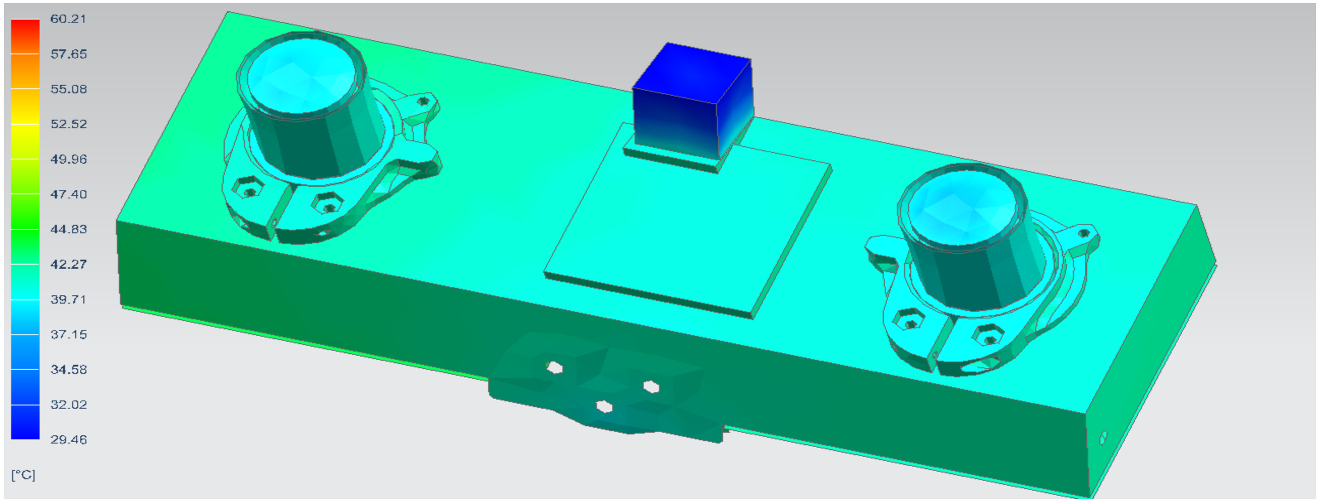
Temperature Mapping Process



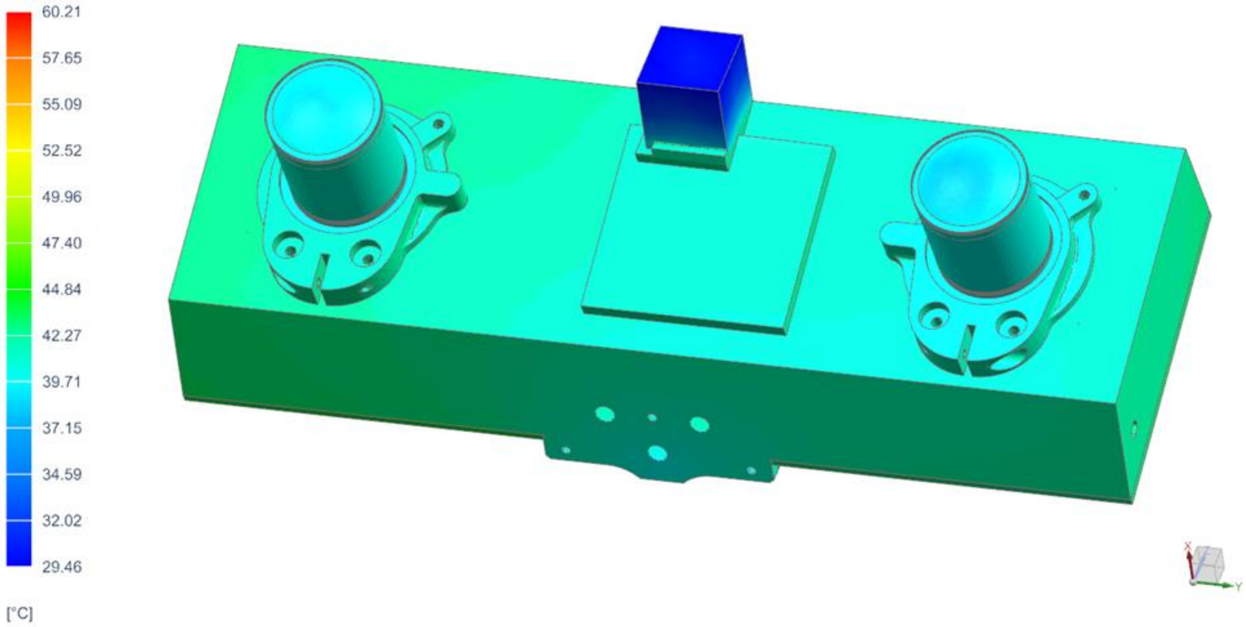
- Source zones contain element, target zones contain nodes.
- Two types of mapping zones were used:
  - Thermal Association Zone:
    - for parts modeled with a single layer of shell elements or solid elements.
    - Node temperature calculated from single element.
  - Transverse Gradient Zone:
    - For parts modeled with two layers of shell elements (e.g. housing and PWBs')
    - Node mid-plane temperature and through thickness gradient determined from two element temperatures.

Mapped Temperatures - Exterior

Thermal

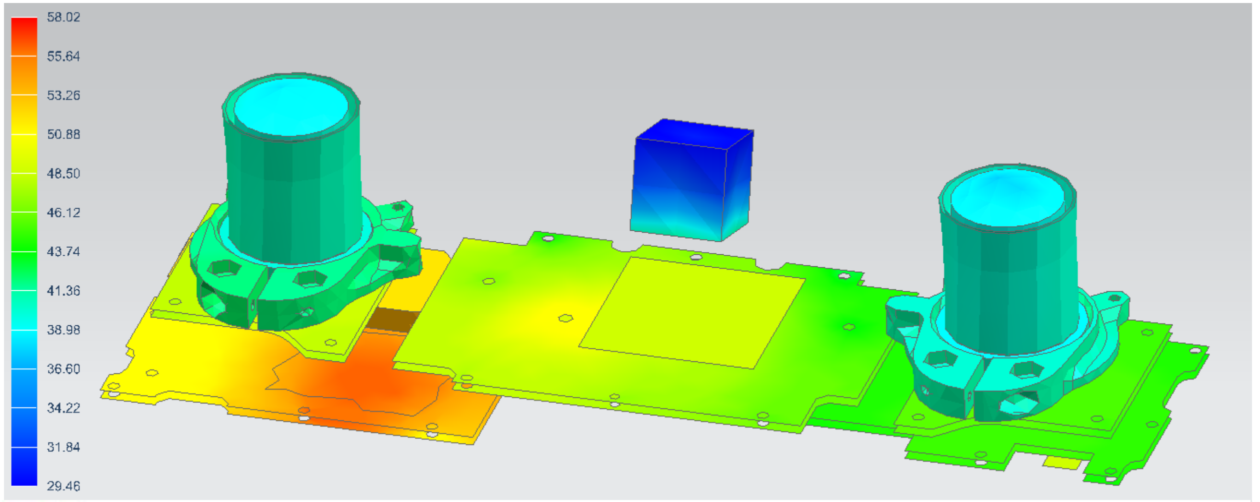


Structural

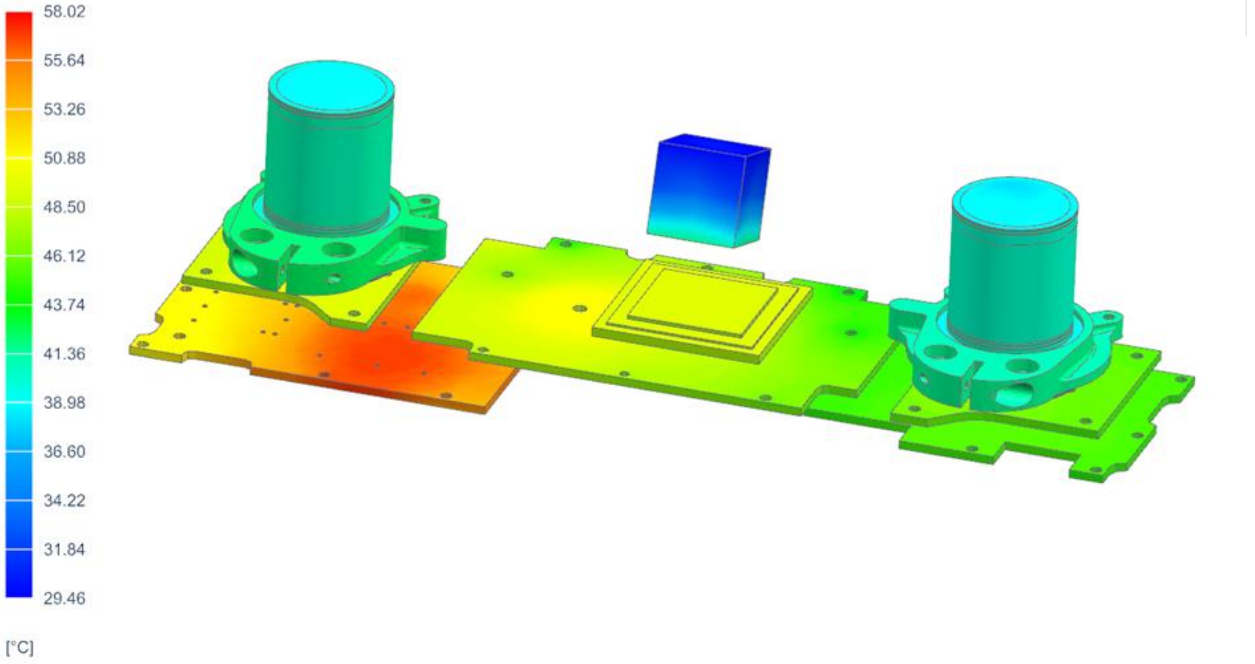


Mapped Temperatures - Interior

Thermal



Structural



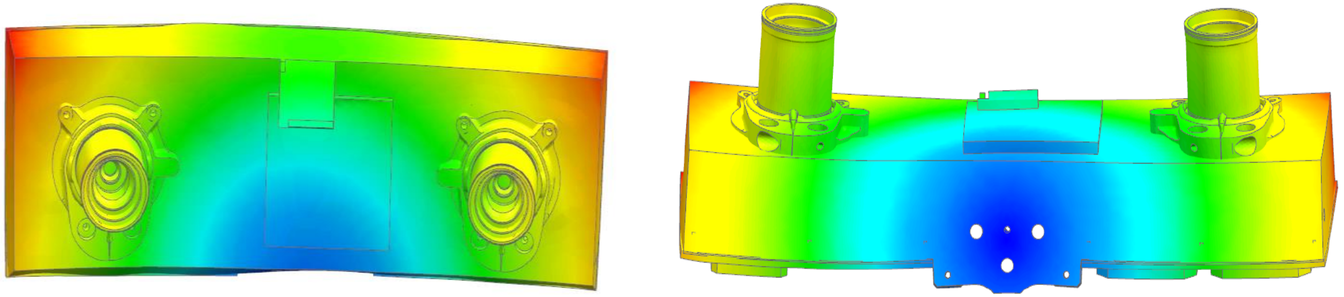
Thermal Distortion Case Criteria

- Hot –
  - the instant where the Temperature Reference Point (TRP) was hottest, i.e. closest to +50° C.
    - Note that the resulting temperature of the TRP is lower than the maximum qualification temperature of +50° C.
- Cold – Only when operating.
  - The instant where the Temperature Reference Point (TRP) was -60° C (coldest qualification temperature) and the air temperature was coldest.
  - Since the temperature fell below -60° C at night for a number of load cases, the second criteria of coldest air temperature was needed to select a single test case.

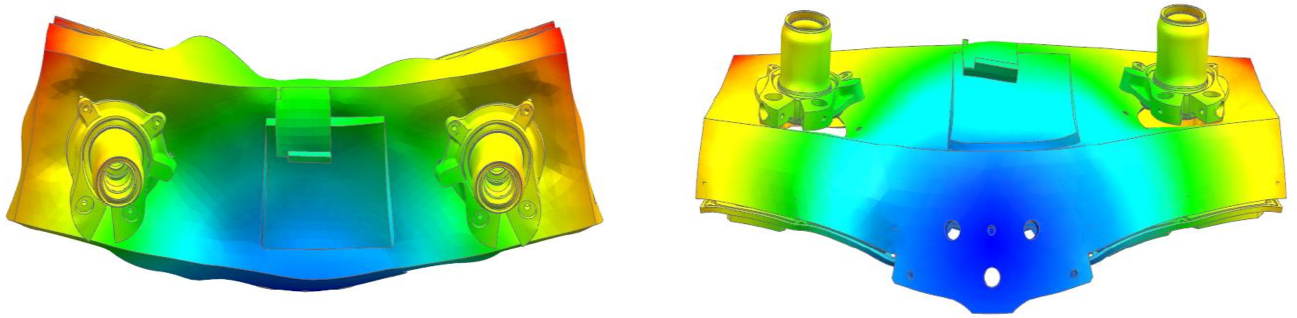
Case	Camera	Environment	Dust?	Power	Time (hr)	TRP Temp. (ºC)	Atmos. Temp. (ºC)
Hot	NavCam	1	No	Max.	15.75	42.6	-3.74
Cold	LocCam	5	No	Typ.	8.22	-62.2	-86.4

Exaggerated Thermo-elastic Distortions

Hot



Cold



Optical Analysis

- The intent of the thermal distortion analysis is to give an indication of the magnitude of change when at different temperatures.
- A full ray tracing of the displaced optics to find the new optical center is beyond the scope of what was intended with this analysis. As such, a simplified approach was used to determine linear and angular changes in the optics.
- The linear change in optical alignment was defined as:
  - the change in position of a point at the base of the optics located on the center of the bottom face of the filter element.
- The angular pointing direction of the optics was defined as:
  - the vector starting from the center of the bottom face of the filter element and going to the top face of the top lens.
- The position of the detector was determined from averaging the position of 3 points on the imaging plane.
- Angular changes in detector position are not evaluated, nor is change in focal length or optical distortion models. These effects were measured in test for each camera.

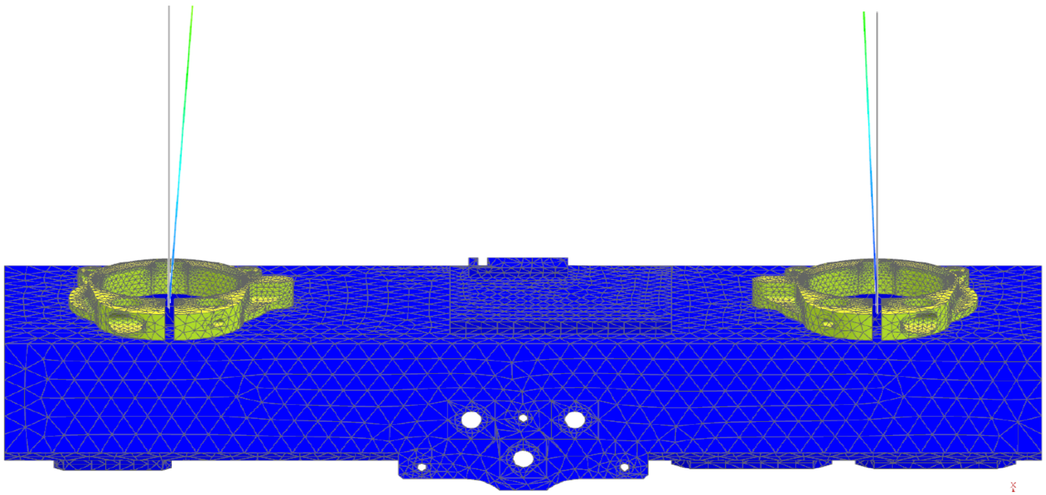
Thermal Distortion Results

Load Case	Temperature	Item	dX (µm)	dY (µm)	dZ (µm)	Total Linear (µm)	Total Angular (Arc Sec)
1	Coldest	Optics to Optics	1.10	-283.3	-0.901	283.3	11.6*
1	Coldest	Detector to Detector	1.09	-283.6	-1.27	283.6	n/a
2	Hottest	Optics to Optics	-0.554	76.2	-3.09	76.26	18.9*
2	Hottest	Detector to Detector	-0.2718	76.48	-3.38	76.56	n/a

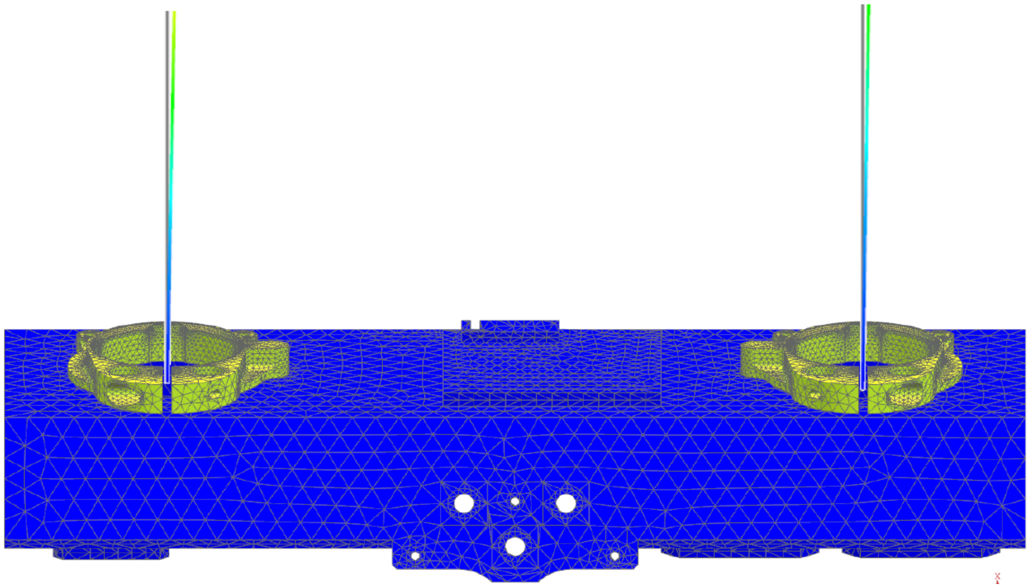
**calculated based on best fitting plane at split clamp to front enclosure interface*

Lens Pointing Changes

Hot



Cold



Summary

- A detailed thermal analysis of the ExoMars navigational and location cameras was performed to predict the temperature range experienced by each component in a number of different Martian environments.
- The hottest and coldest operational cases were then used to perform a thermo-elastic deformation analysis.
- Temperatures from the thermal model were mapped onto the SC3D Nastran structural model used to perform the thermo-elastic analysis.
- All analysis was performed in the Simcenter 3D environment.
- The displacements from the thermo-elastic analysis were then used to determine relative displacement of lenses and sensor to evaluate impact on camera performance.

Questions?

Maya HTT Better thinking Better future®

neptec

Chris Pye

C.pye@mayahtt.com