Thermal Balance Testing and Model Validation of CubeSat STIM

Presented By
Jesper Buch Jensen
jeje@gomspace.com

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Introduction

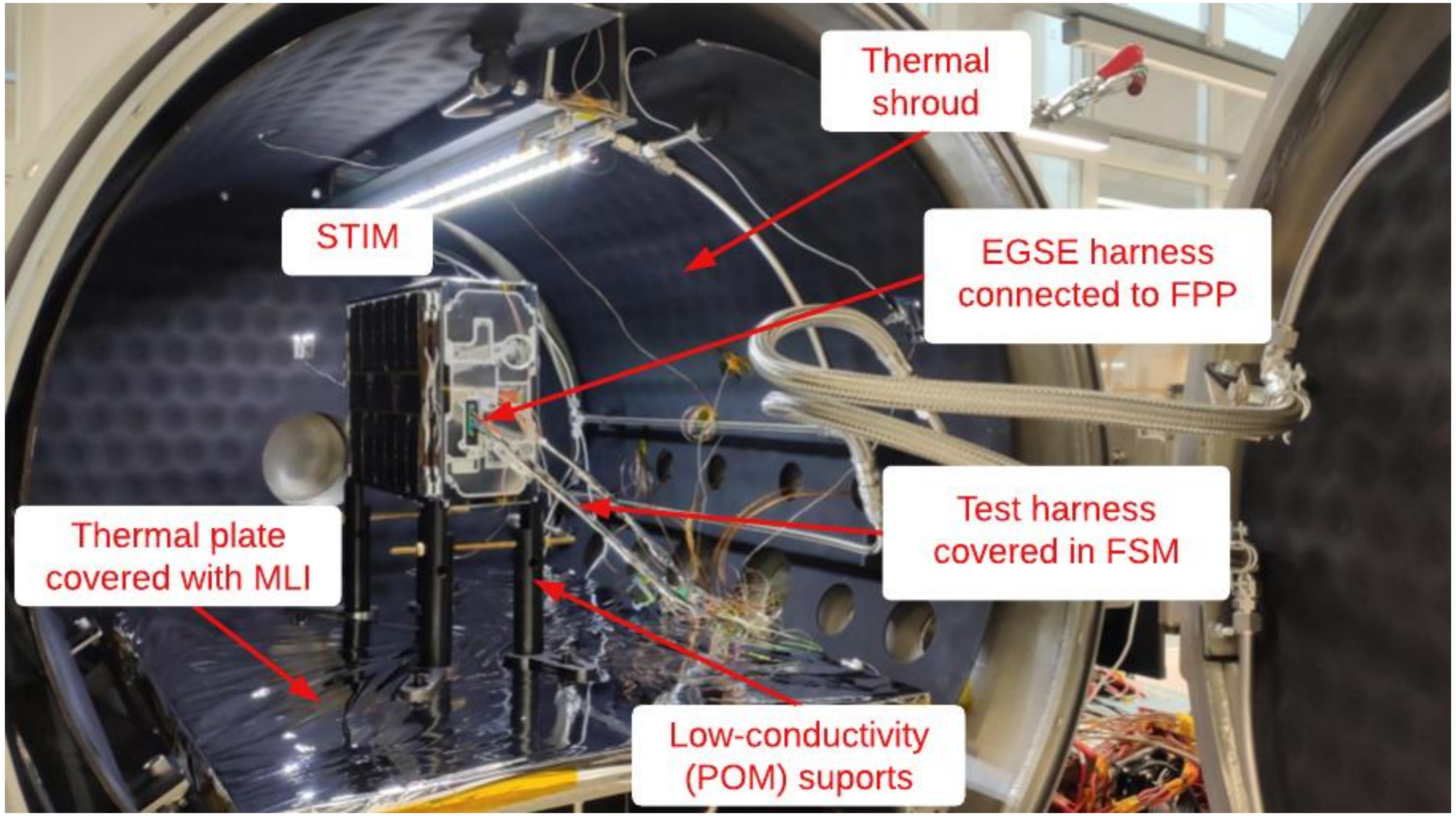
A Thermal Balance Test (TBT) has been done on a Structural Thermal Interface Model (STIM) of the Juventas CubeSat

- Mission
  - Deep space 6U CubeSat
  - Going to Didymos with Hera
  - Stowed for 2-4 years, operational for 0.5 years
  - No heritage with TBT or deep space missions

- Test
  - To validate Thermal Mathematical Model (TMM)
  - Estimate errors (reduce uncertainties)
  - Ensure the thermal control system is fit for purpose
  - Potential mitigations for Proto Flight Model (PFM)

Test Facility

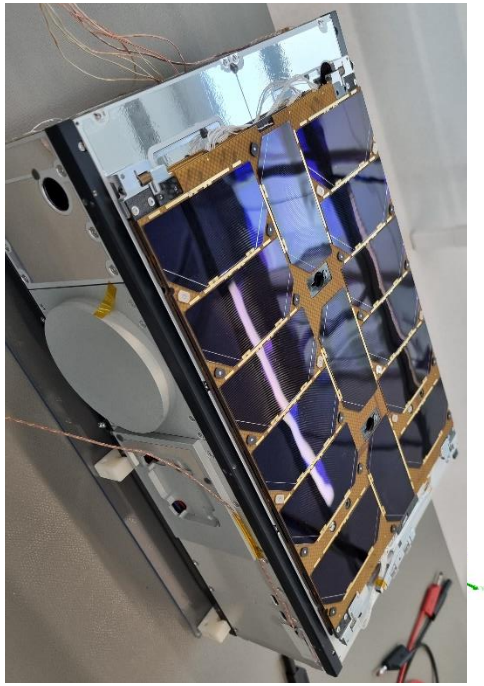
- TVAC chamber:
  - -55 C to +100 C
  - Not hot plate control
  - Solar Panels must be stowed
  - TVAC characterisation necessary
  - Can connect 16 external thermocouples (TCs)
  - 2 TCs for temperature control

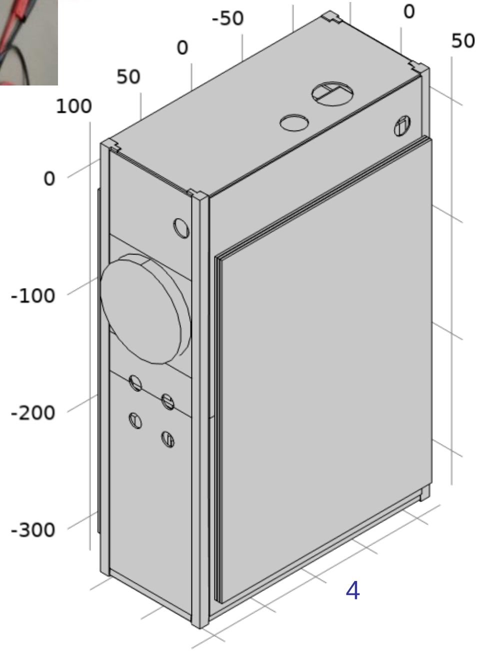


Device Under Test (DUT)

- Structural Thermal Interface Model (STIM)
  - Thermal mass dummies
    - Power dissipation using heaters
    - Interfaces are representative but not identical

- Instrumentation
  - 2 chamber TCs (data not saved)
  - 16 external TCs
  - 4 internal IC sensors (TS100s) (data retrieved after test)
  - 4 subsystem sensors (data retrieved after test)

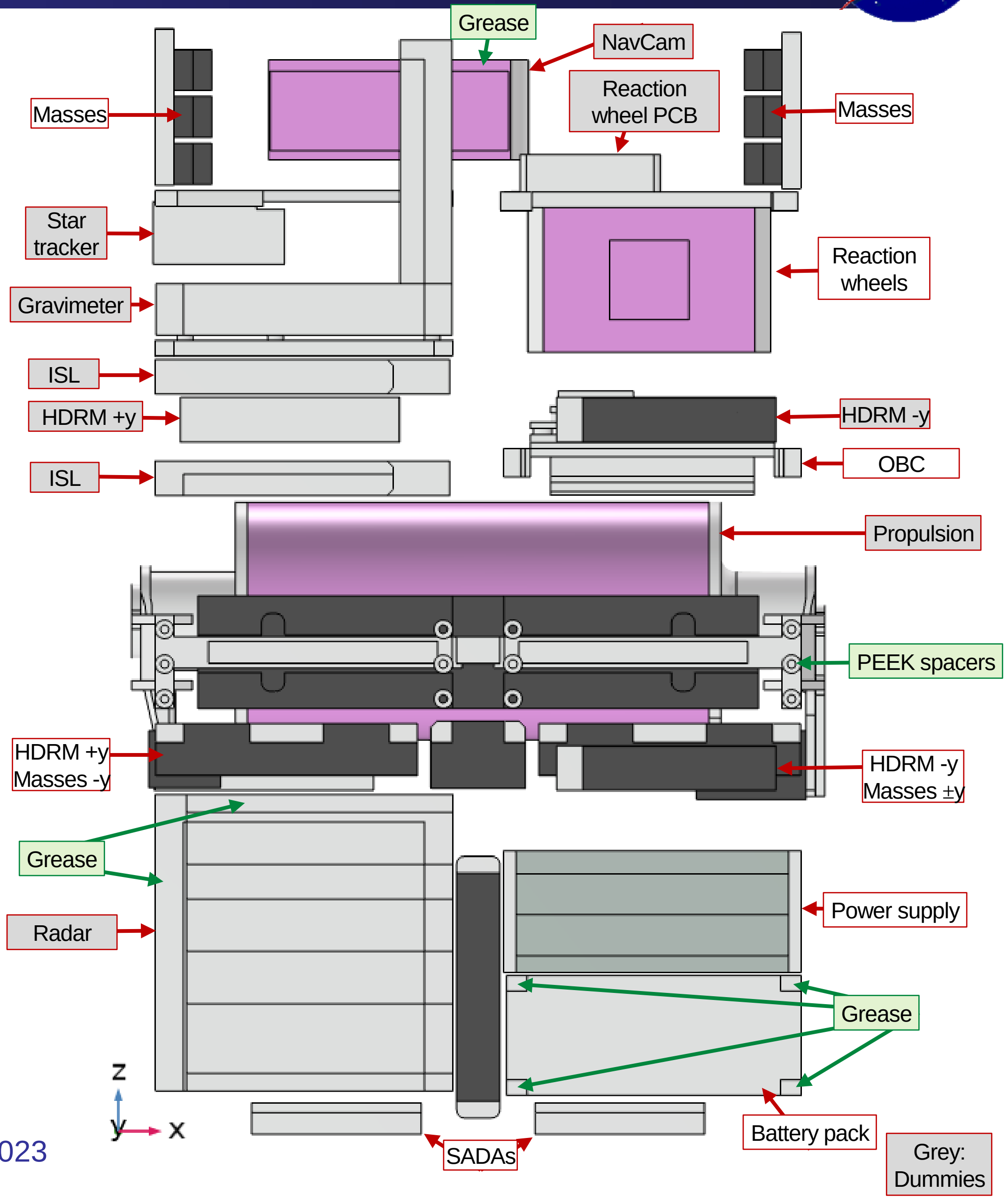




Device Under Test (DUT)

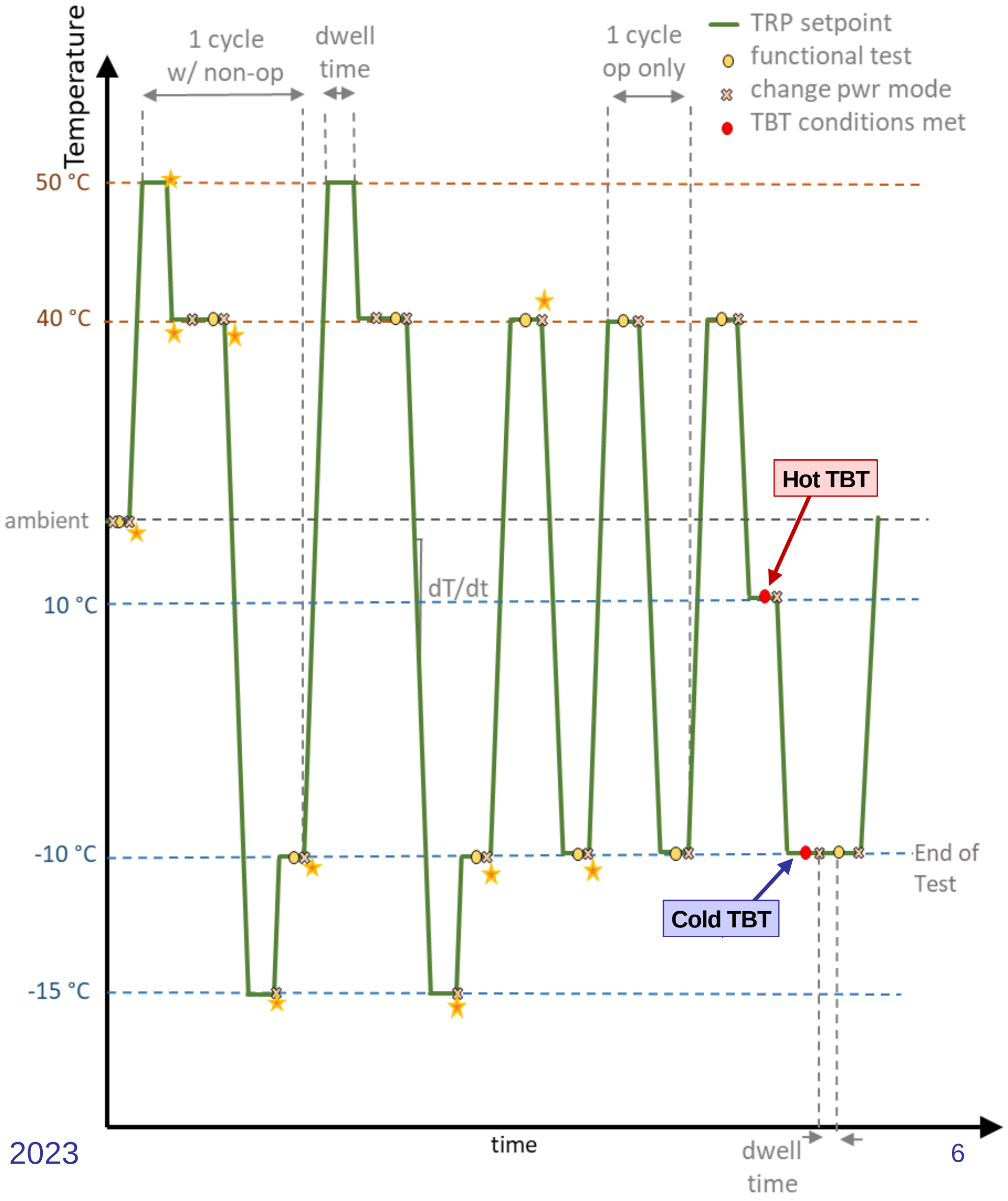
- Payload instruments
  - JuRa: Radar
  - GRASS: Gravimeter
  - NavCam: Navigation Camera

- Thermal features
  - Thermal grease on interfaces for NavCam, JuRa and BP8
  - PEEK spacers on propulsion
  - Rubber seal on propulsion



Test Sequence

- The test was run as a combined Thermal Cycling Test (TCT) and TBT
- Two TBTs were run at different temperatures near the end of the combined sequence



Test Cases

Temperature controlled on shroud:

- Hot TBT shroud setpoint: +10 C
- Cold TBT shroud setpoint: –10 C

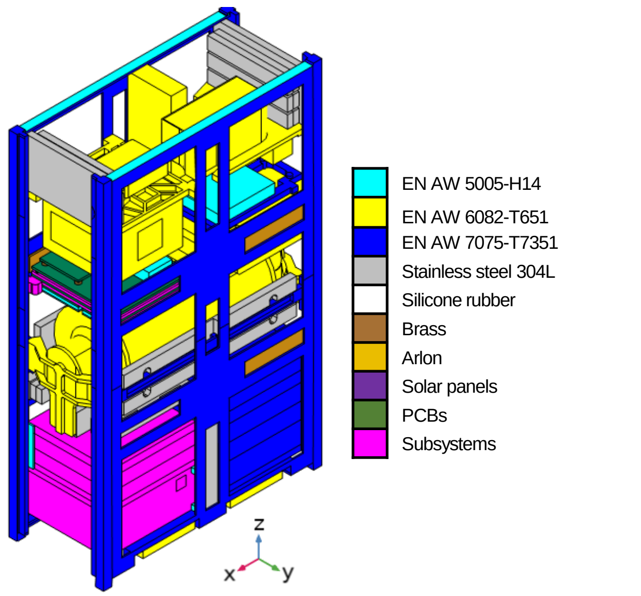
“Hot” and “cold” refer to the shroud temperature setpoint. Due to the higher power dissipation in the “cold” TBT, some temperatures are higher (e.g. for the propulsion).

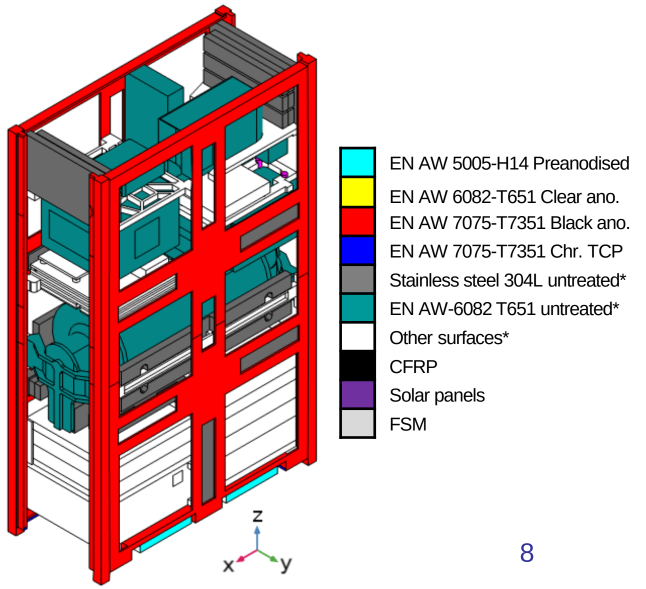
Consumer/heater	Power dissipation [W]
P80 PMU	0.14
P80 PDU	0.49
OBC	4.46
NavCam	2.72
Reaction Wheels	3.24
Total	**11.04**

Consumer/heater	Power dissipation [W]
P80 PMU	0.15
P80 PDU	0.49
OBC	4.44
Propulsion Distr 1	4.82
NavCam	2.72
JuRa dummy	6.09
Propulsion main	2.35
Reaction Wheels	3.24
Total	**24.28**

Thermal Mathematical Model (TMM)

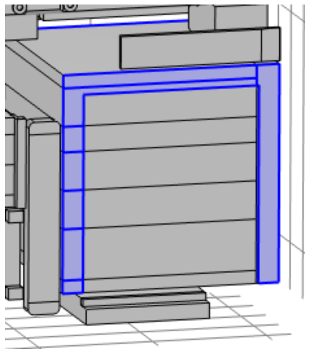
- A TMM was made specifically for the test
- Based on the mission TMM but with the following differences:
  - Shroud instead of space
  - No sun (chamber too small)
  - Dummies instead of actual subsystems where applicable
  - Different tape configuration on cover plates (SSMT)
- FEM with simplified but fairly complex geometry (~130000 elements)

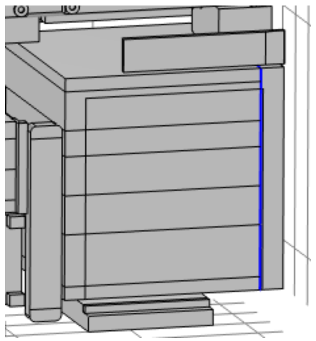


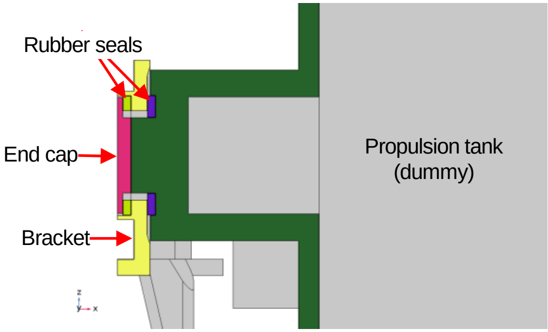


- Conductance values are generally based on internal standard assumptions, combined with estimation
- The JuRa (internal) and rubber seal values are adjusted (fudged) to match data (no initial assumptions were available)

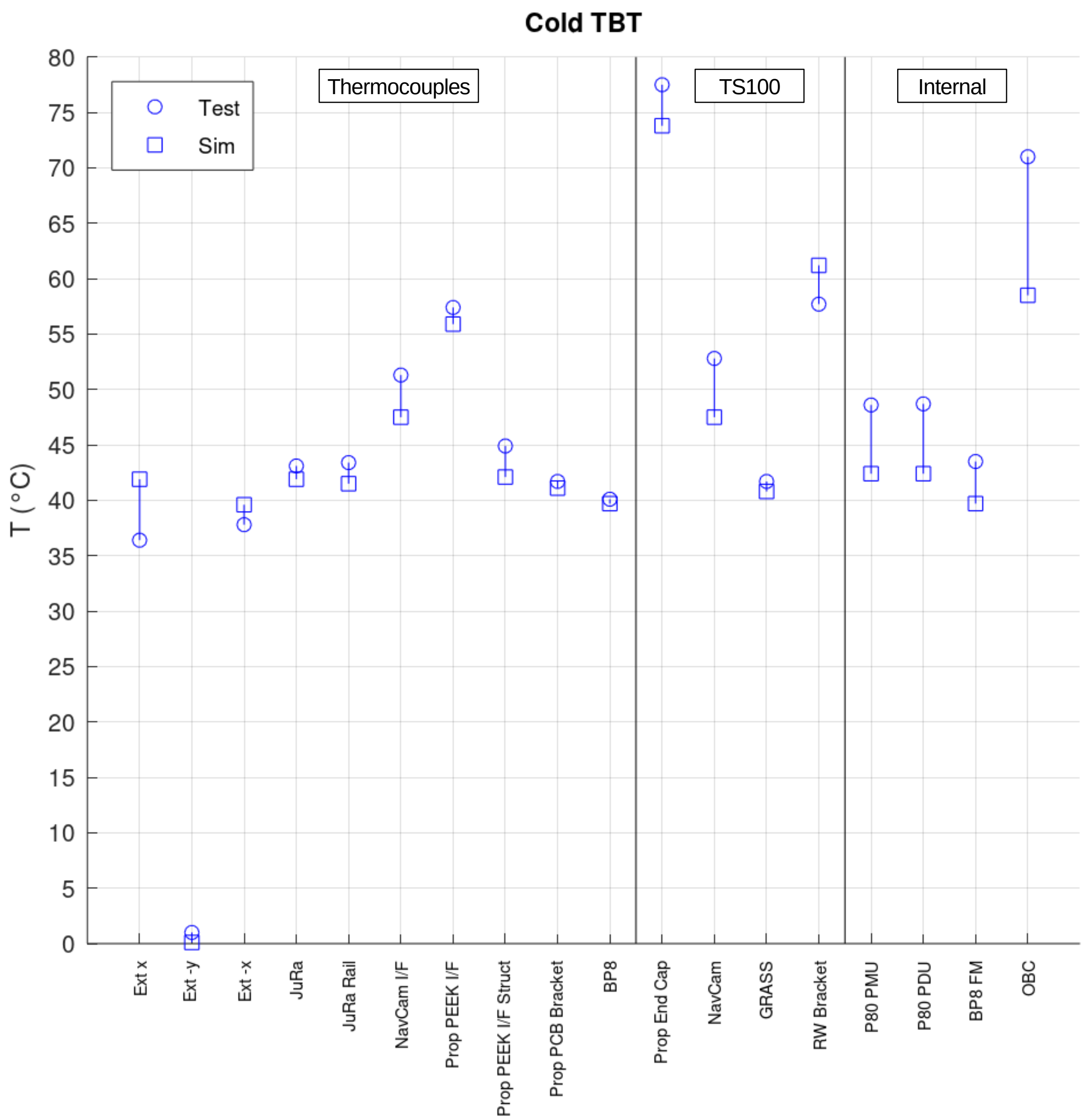
Interfaces	Conductance W/K/m²	Notes
Cover plates (x)	1000	
Cover plates (y)	263	Calculated from no of screws
Cover plates (z)	1000	
Masses	5000	
SADA (cover plate)	0	No contact
SADA (structure)	5000	
JuRa (structure)	12000	Thermal grease
JuRa (internal)	500	Estimated from test data
BP8	12000	Thermal grease
P80	8000	
Propulsion PEEK spacers	1000	
Prop rubber seal	500	Estimated from test data
Prop other internal	5000	
OBC	10000	
ISL	10000	
Reaction wheels (structure)	1000	
Reaction wheels (internal)	1000	
GRASS	5000	
VTT	12000	Thermal grease
Startracker bracket	5000	
Propulsion PCB	5000	





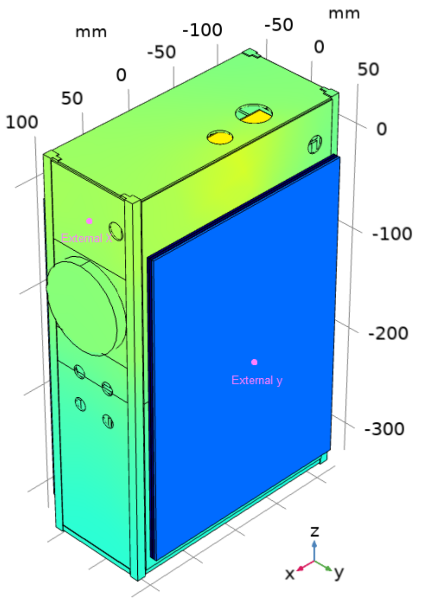


Results

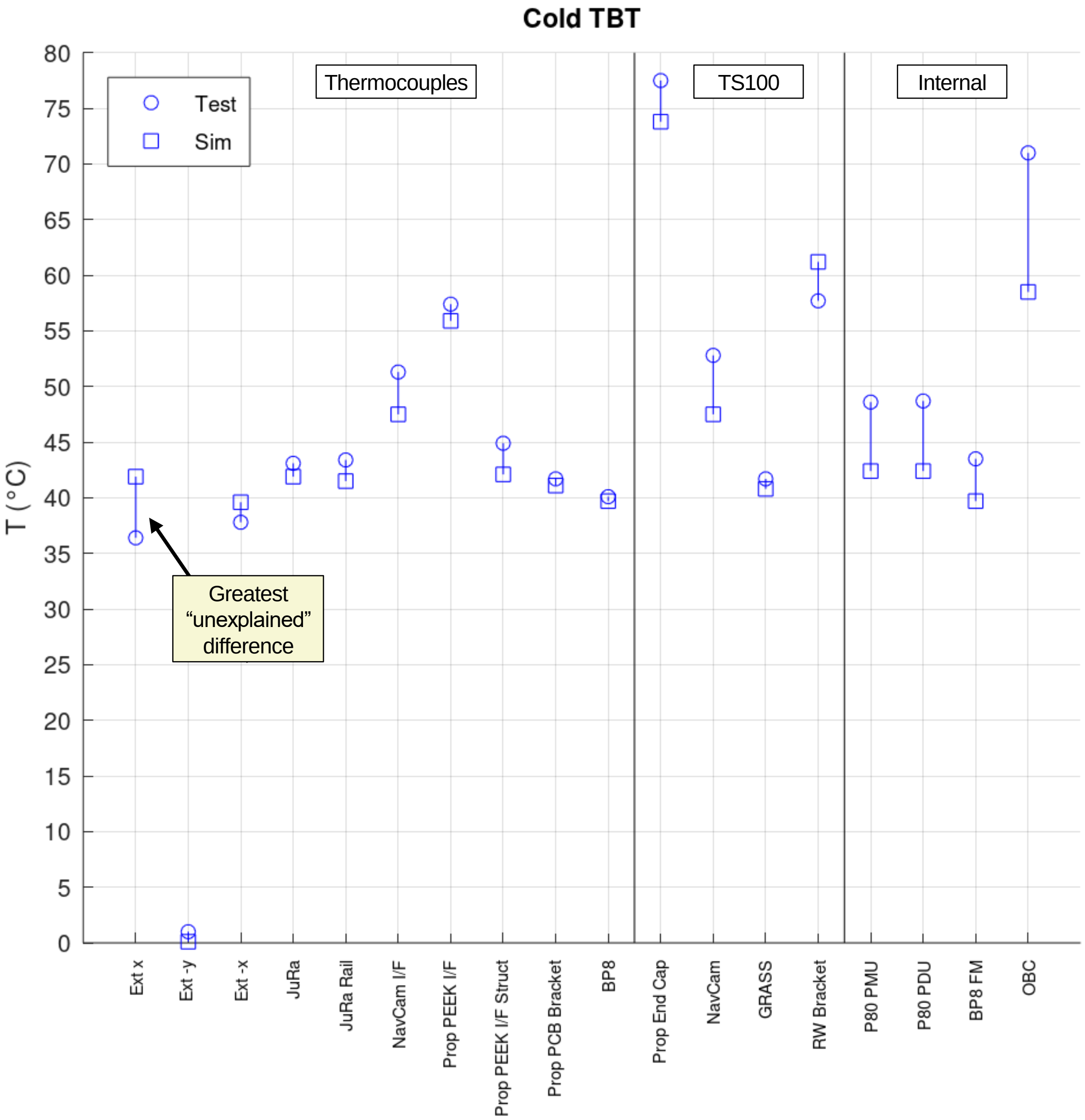


Cold TBT
T (°C)
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
Test
Sim
Thermocouples
TS100
Internal
Ext x
Ext -y
Ext -x
JuRa
JuRa Rail
NavCam I/F
Prop PEEK I/F
Prop PEEK I/F Struct
Prop PCB Bracket
BP8
Prop End Cap
NavCam
GRASS
RW Bracket
P80 PMU
P80 PDU
BP8 FM
OBC

Results

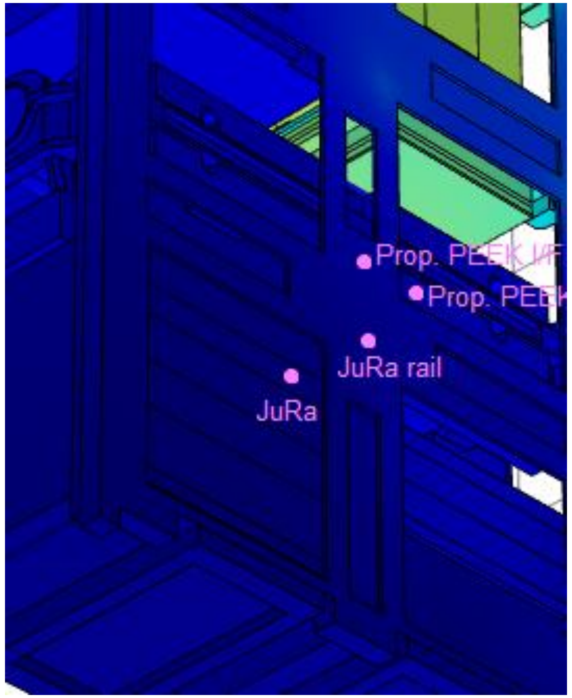


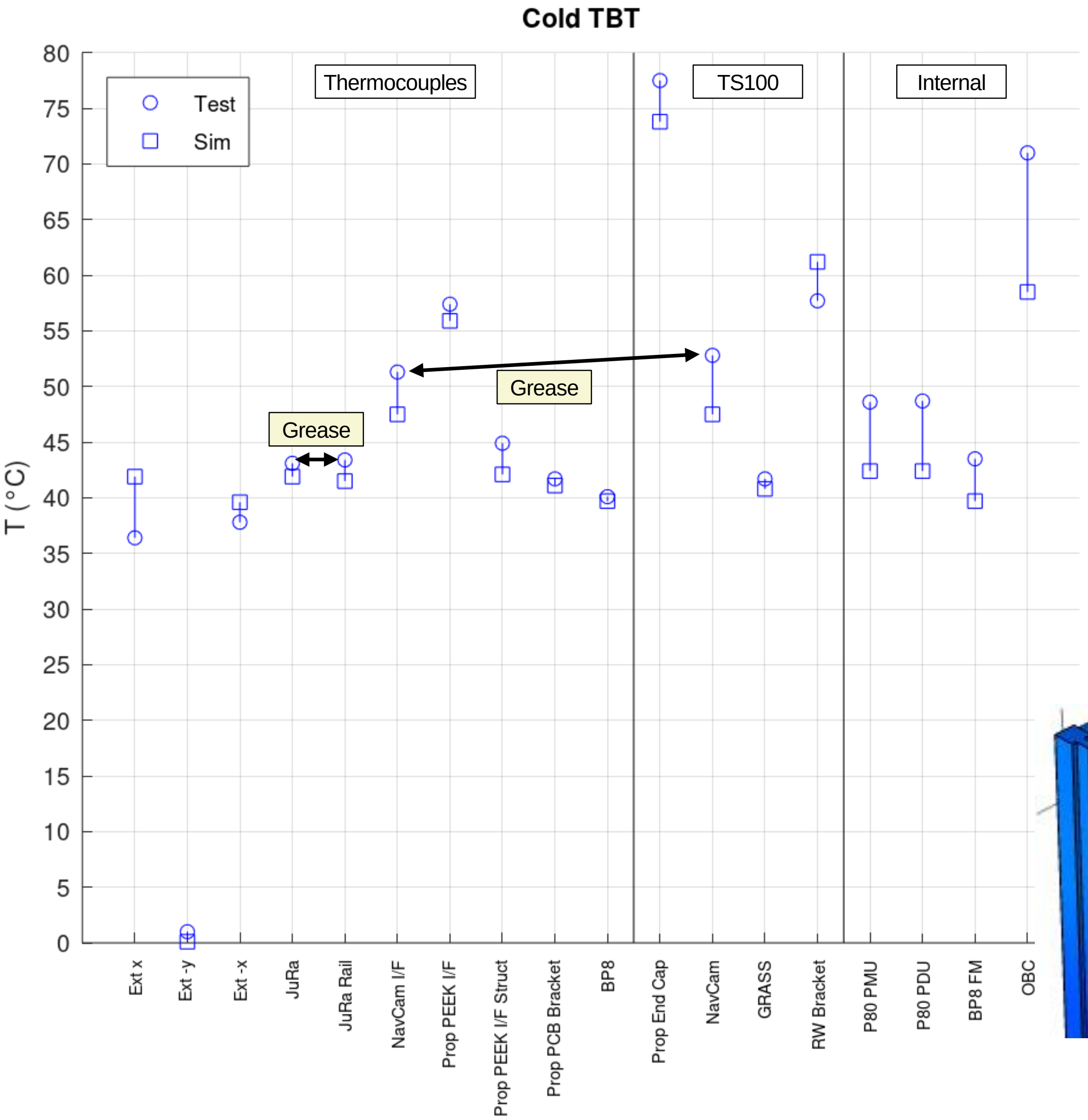
mm
-100
-50
mm
-50
0
0
50
50
100
0
-100
-200
-300
External x
External y
z
x
y

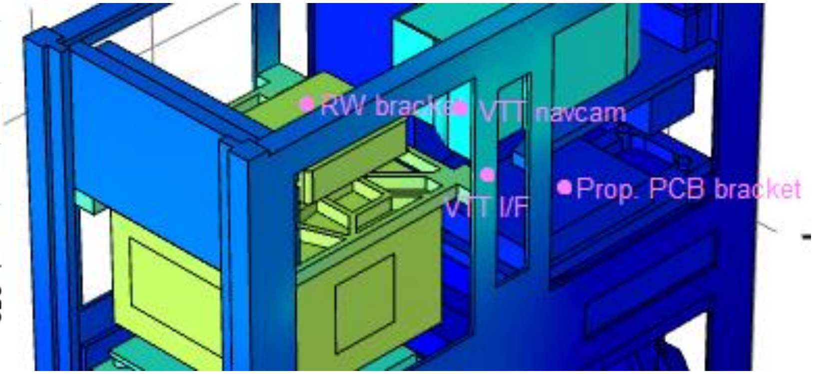


Cold TBT
Test
Sim
Thermocouples
TS100
Internal
Greatest "unexplained" difference
T (°C)
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
Ext x
Ext -y
Ext -x
JuRa
JuRa Rail
NavCam I/F
Prop PEEK I/F
Prop PEEK I/F Struct
Prop PCB Bracket
BP8
Prop End Cap
NavCam
GRASS
RW Bracket
P80 PMU
P80 PDU
BP8 FM
OBC

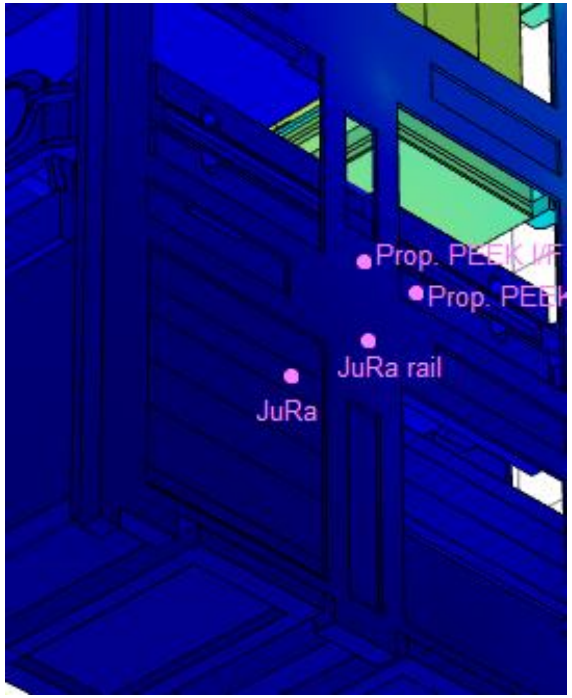
Results

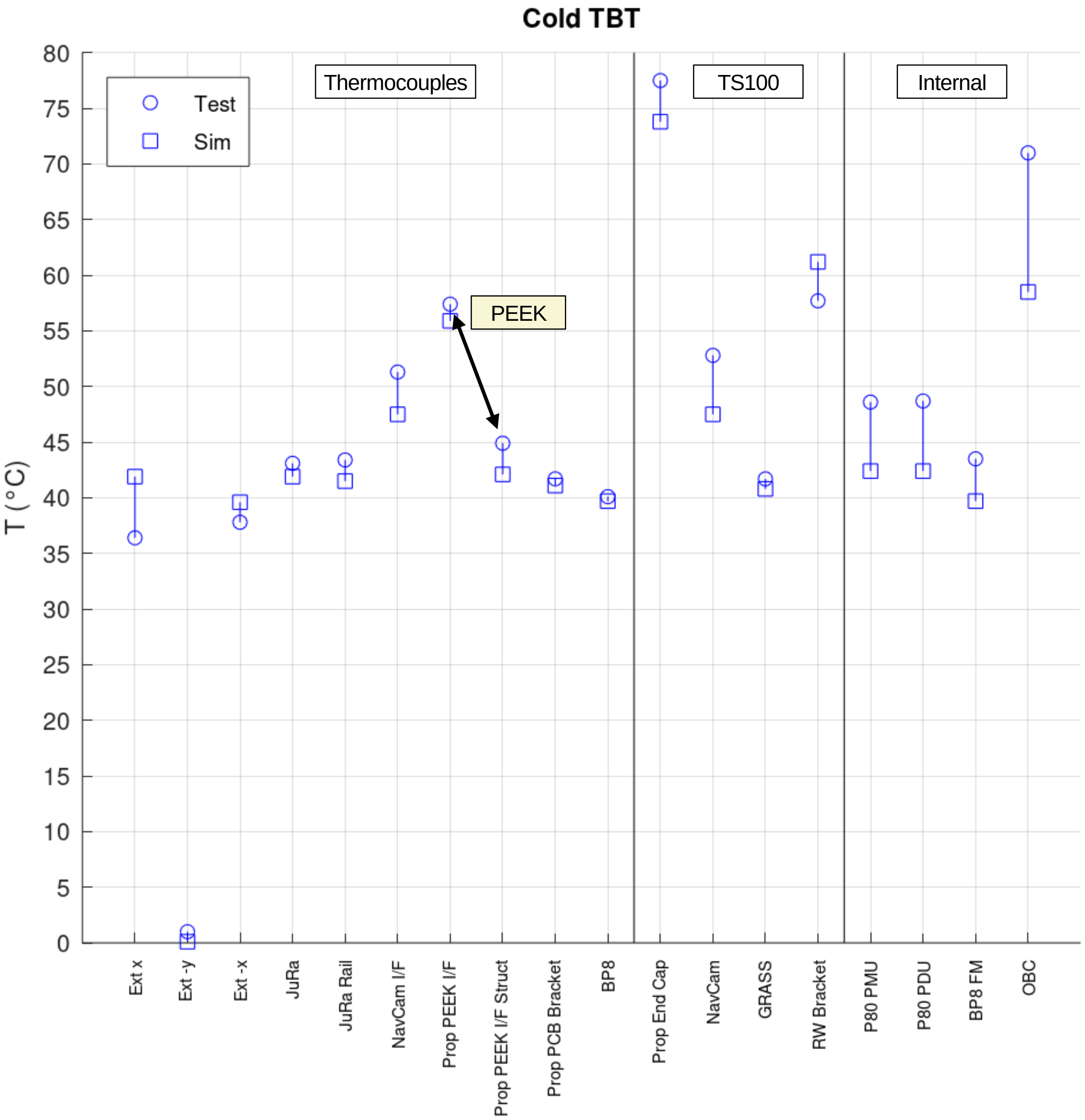

Prop. PEEK I/F
Prop. PEEK
JuRa rail
JuRa


Cold TBT
T (° C)
Test
Sim
Thermocouples
TS100
Internal
Grease
Grease
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
Ext x
Ext -y
Ext -x
JuRa
JuRa Rail
NavCam I/F
Prop PEEK I/F
Prop PEEK I/F Struct
Prop PCB Bracket
BP8
Prop End Cap
NavCam
GRASS
RW Bracket
P80 PMU
P80 PDU
BP8 FM
OBC

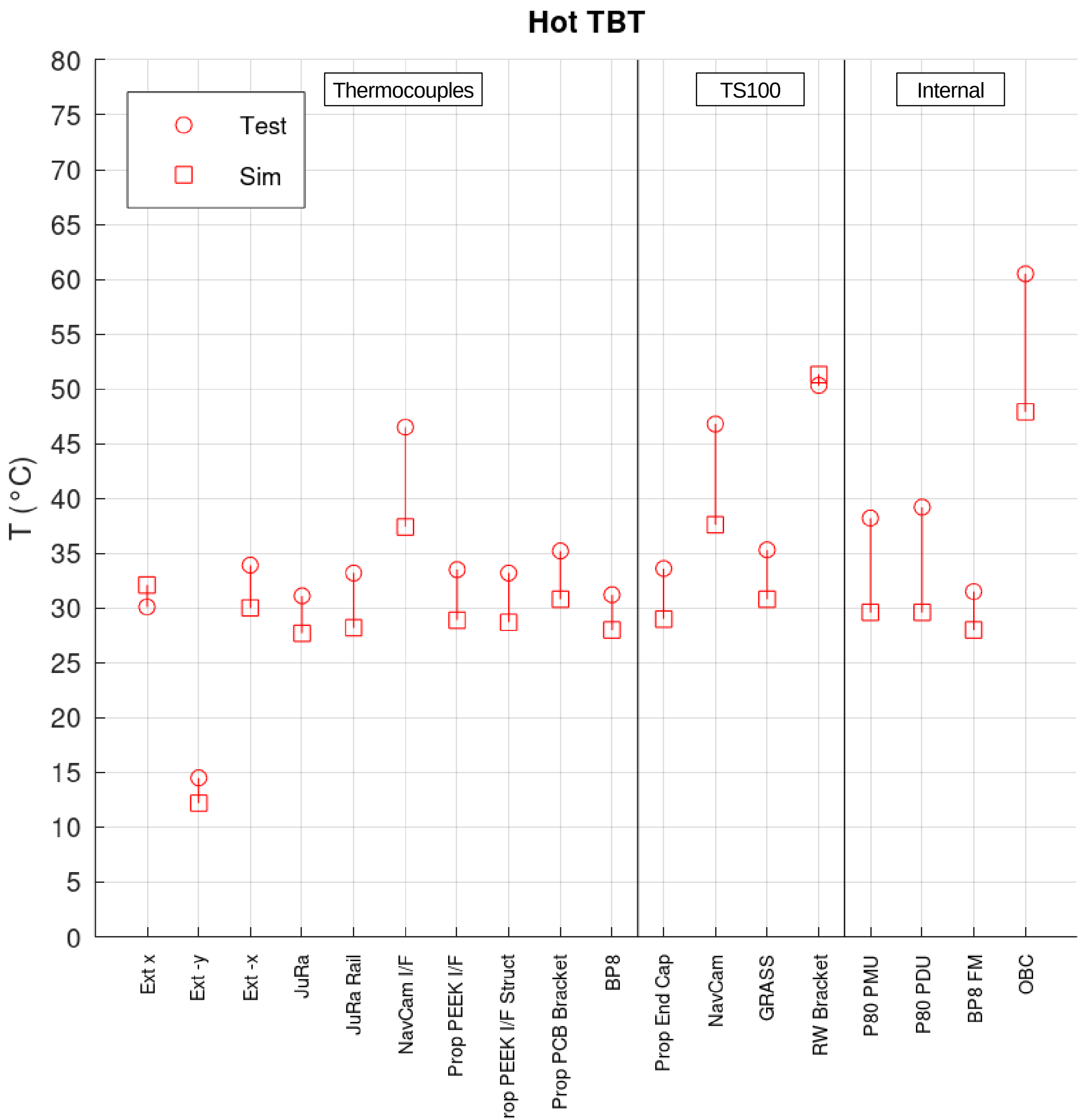

VTT navcam
VTT I/F
Prop. PCB bracket

Results


Prop. PEEK I/F
Prop. PEEK
JuRa rail
JuRa

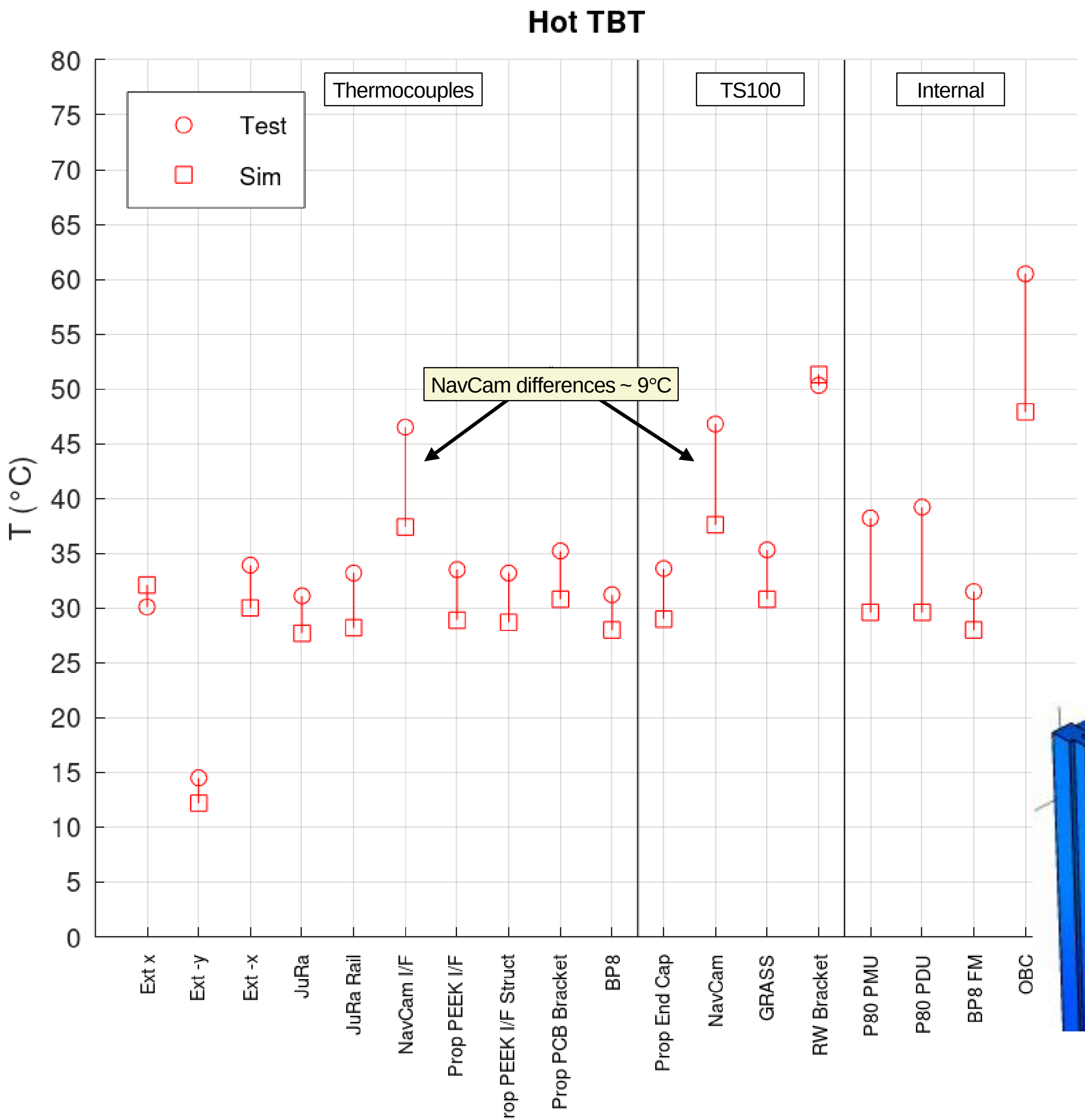

Cold TBT
T (°C)
Test
Sim
Thermocouples
TS100
Internal
PEEK
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
Ext x
Ext -y
Ext -x
JuRa
JuRa Rail
NavCam I/F
Prop PEEK I/F
Prop PEEK I/F Struct
Prop PCB Bracket
BP8
Prop End Cap
NavCam
GRASS
RW Bracket
P80 PMU
P80 PDU
BP8 FM
OBC

Results

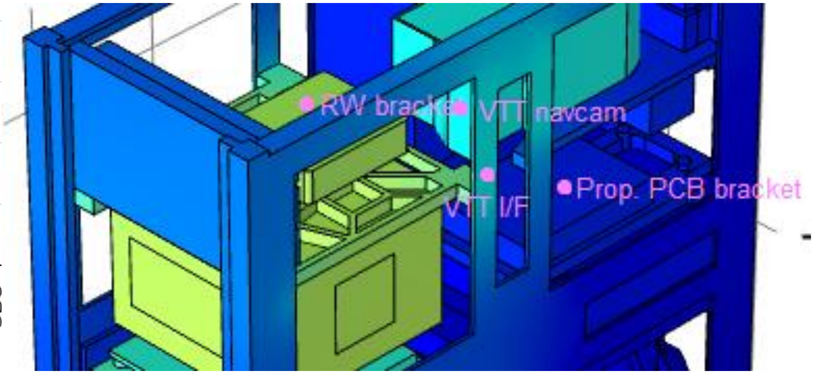


Hot TBT
Test
Sim
Thermocouples
TS100
Internal
T (°C)
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
Ext x
Ext -y
Ext -x
JuRa
JuRa Rail
NavCam I/F
Prop PEEK I/F
rop PEEK I/F Struct
Prop PCB Bracket
BP8
Prop End Cap
NavCam
GRASS
RW Bracket
P80 PMU
P80 PDU
BP8 FM
OBC

Results

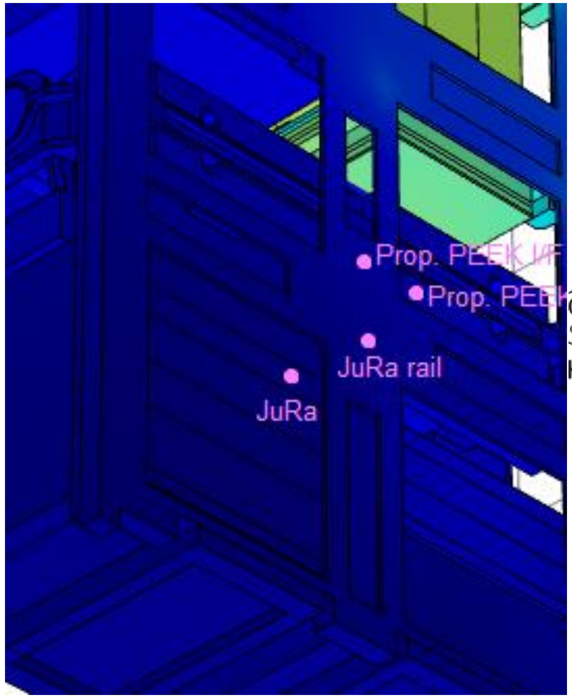


Hot TBT
T (°C)
Test
Sim
Thermocouples
TS100
Internal
NavCam differences ~ 9°C
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
Ext x
Ext -y
Ext -x
JuRa
JuRa Rail
NavCam I/F
Prop PEEK I/F
rop PEEK I/F Struct
Prop PCB Bracket
BP8
Prop End Cap
NavCam
GRASS
RW Bracket
P80 PMU
P80 PDU
BP8 FM
OBC

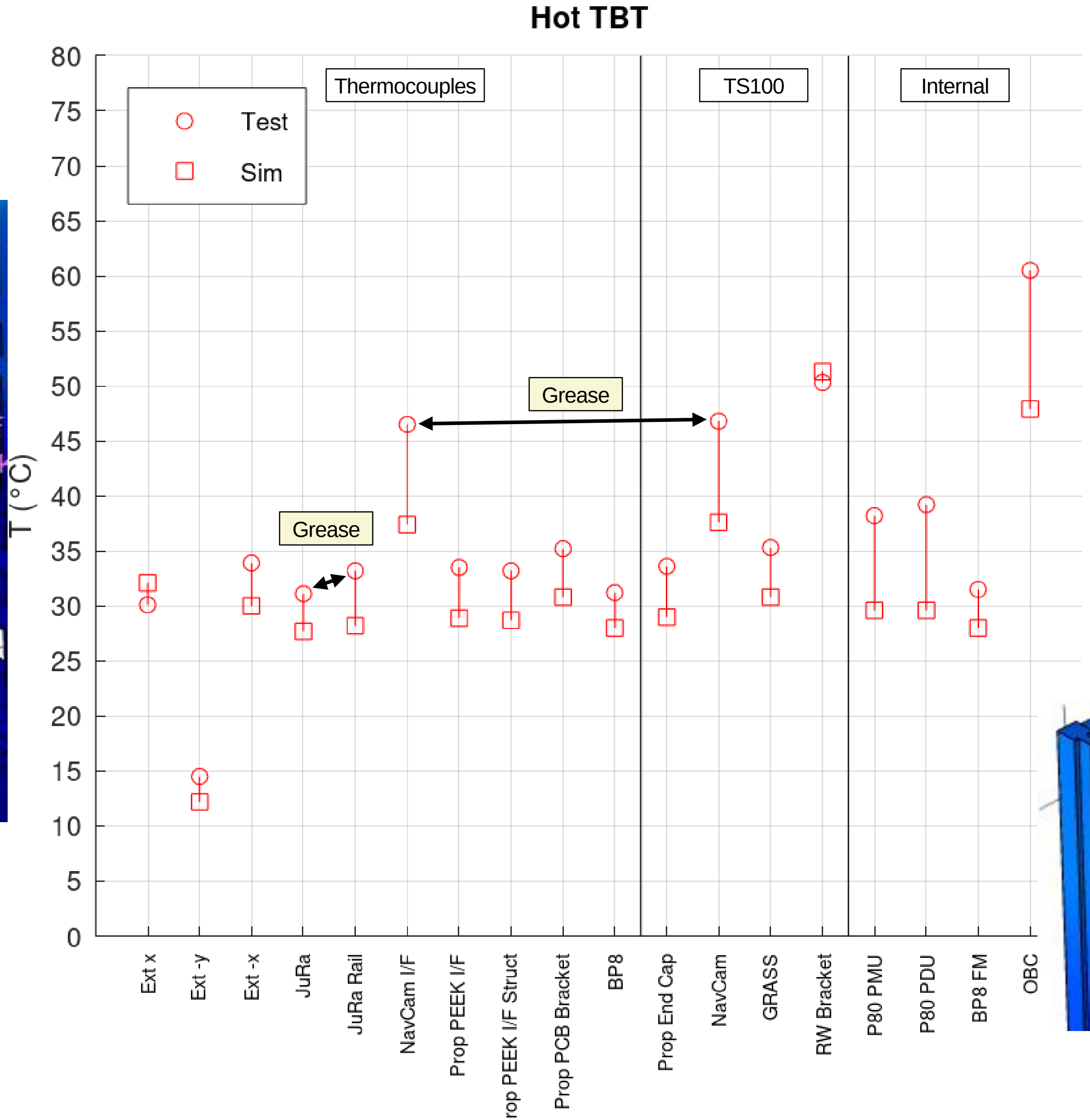


RW bracket
VTT navcam
VTT I/F
Prop. PCB bracket

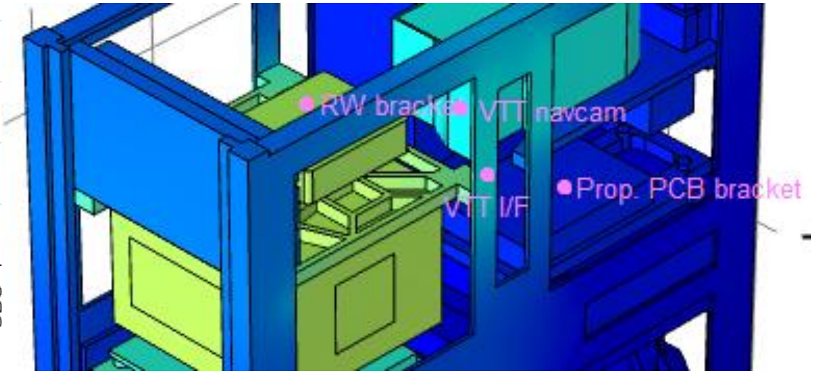
Results



Prop. PEEK I/F
Prop. PEEK
JuRa rail
JuRa

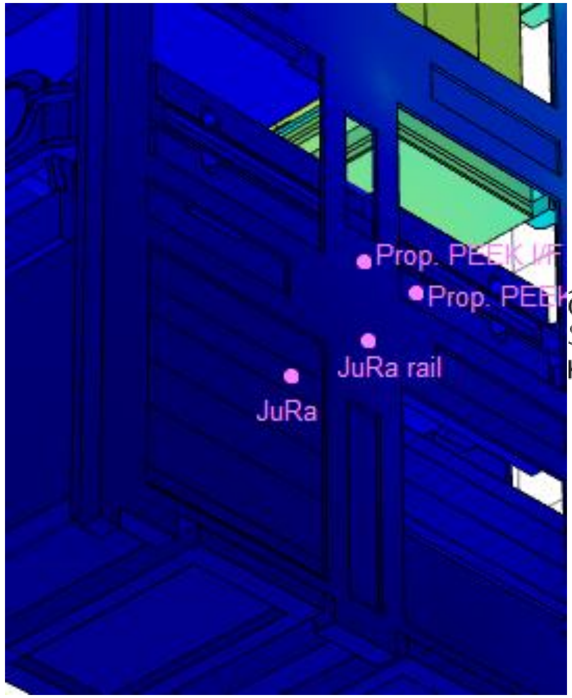


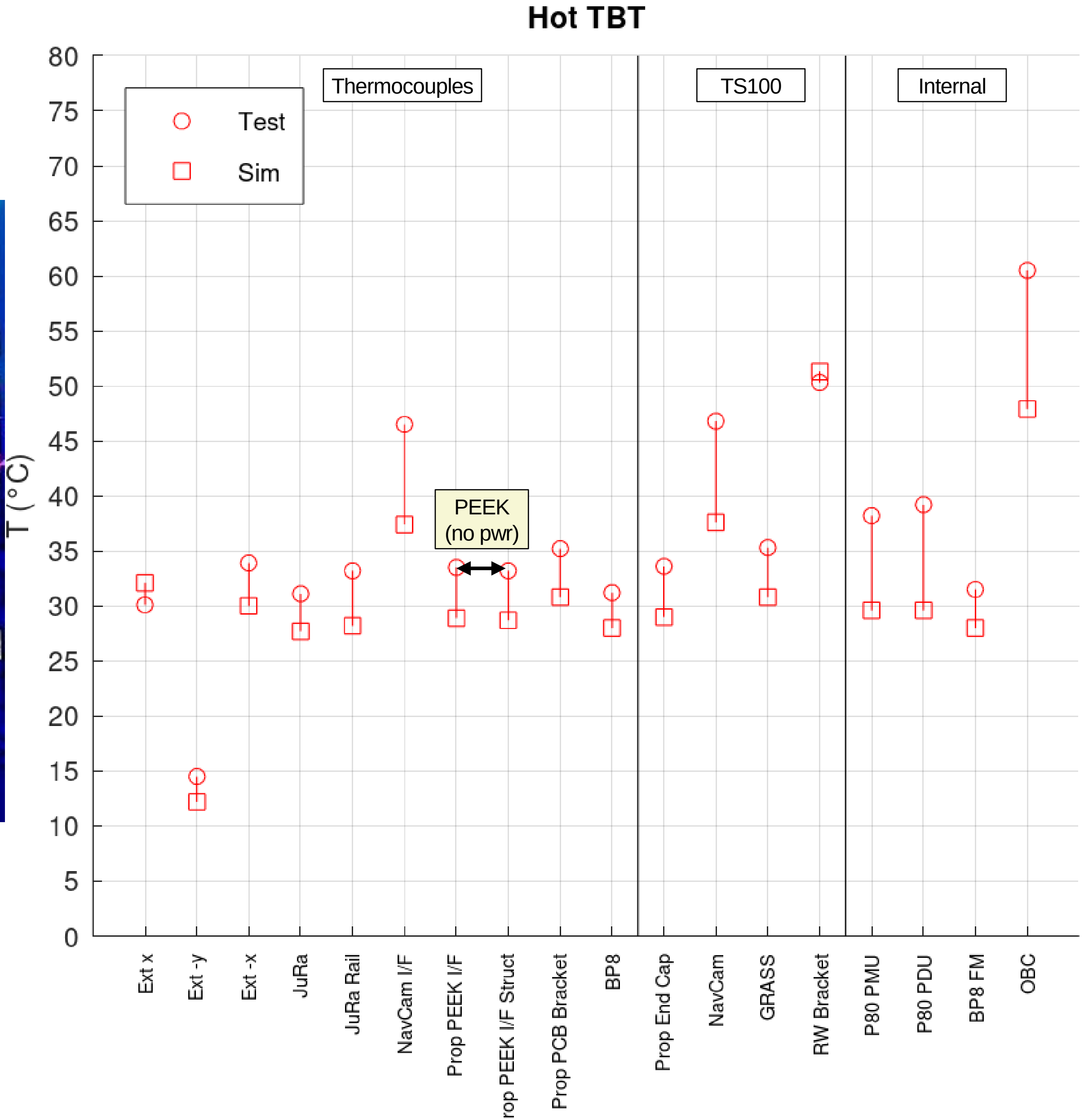
Hot TBT
Test
Sim
Thermocouples
TS100
Internal
Grease
Grease
T (°C)
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
Ext x
Ext -y
Ext -x
JuRa
JuRa Rail
NavCam I/F
Prop PEEK I/F
rop PEEK I/F Struct
Prop PCB Bracket
BP8
Prop End Cap
NavCam
GRASS
RW Bracket
P80 PMU
P80 PDU
BP8 FM
OBC



RW bracket
VTT navcam
VTT I/F
Prop. PCB bracket

Results


Prop. PEEK I/F
Prop. PEEK
JuRa rail
JuRa


Hot TBT
Test
Sim
Thermocouples
TS100
Internal
PEEK
(no pwr)
T (°C)
Ext x
Ext -y
Ext -x
JuRa
JuRa Rail
NavCam I/F
Prop PEEK I/F
Prop PEEK I/F Struct
Prop PCB Bracket
BP8
Prop End Cap
NavCam
GRASS
RW Bracket
P80 PMU
P80 PDU
BP8 FM
OBC

Results

Hot TBT

	Sensor	Test	TMM	Diff
Thermocouples	External x	30.1	32.1	-2.0
	External -y	14.5	12.2	2.3
	External -x	33.9	30.0	3.9
	JuRa Electronics Box	31.1	27.7	3.4
	JuRa Electronics Box Rail	33.2	28.2	5.0
	NavCam interface	46.5	37.4	9.1
	Propulsion PEEK interface	33.5	28.9	4.6
	Prop Peak I/F Prim Struct	33.2	28.7	4.5
	Propulsion PCB Bracket	35.2	30.8	4.4
	BP8	31.2	28.0	3.2
TS100s	Propulsion End Cap	33.6	29.0	4.6
	NavCam	46.8	37.6	9.2
	GRASS	35.3	30.8	4.5
	RW Bracket	50.3	51.3	-1.0
Internal	P80 PMU	38.2	29.6	8.6
	P80 PDU	39.2	29.6	9.6
	BP8 FM	31.5	28.0	3.5
	OBC	60.5	47.9	12.6

Cold TBT

	Sensor	Test	TMM	Diff
Thermocouples	External x	36.4	41.9	-5.5
	External -y	1.0	0.1	0.9
	External -x	37.8	39.6	-1.8
	JuRa Electronics Box	43.1	41.9	1.2
	JuRa Electronics Box Rail	43.4	41.5	1.9
	NavCam interface	51.3	47.5	3.8
	Propulsion PEEK interface	57.4	55.9	1.5
	Prop Peak I/F Prim Struct	44.9	42.1	2.8
	Propulsion PCB Bracket	41.7	41.1	0.6
	BP8	40.1	39.7	0.4
TS100s	Propulsion End Cap	77.5	73.8	3.7
	NavCam	52.8	47.5	5.3
	GRASS	41.7	40.8	0.9
	RW Bracket	57.7	61.2	-3.5
Internal	P80 PMU	48.6	42.4	6.2
	P80 PDU	48.7	42.4	6.3
	BP8 FM	43.5	39.7	3.8
	OBC	71.0	58.5	12.5

Results

Modifications made to TMM after test:

- Implementation errors
- Conductance between $\pm$y cover plates and structures
- Inclusion of rails in external radiation (~12 % of $\dot{q}$)
- Propulsion rubber seal modelled in more detail
- (Minor) adjustment of FSMT surface assumption
- (Internal radiation must include all surfaces)

What Can We Validate

- Yes:
  - ✓ Conductive heat paths
  - ✓ Interface conductances
  - ✓ External radiation boundaries (IR)
  - ✓ Conductivities

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  - ✓ Conductive heat paths
  - ✓ Interface conductances
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  - ✓ Conductivities
- Maybe:
  - ? Power supply dissipation
  - ? Internal radiation
  - ? Degree of steady state achieved in test

What Can We Validate

- Yes:
  - ✓ Conductive heat paths
  - ✓ Interface conductances
  - ✓ External radiation boundaries (IR)
  - ✓ Conductivities
- Maybe:
  - ? Power supply dissipation
  - ? Internal radiation
  - ? Degree of steady state achieved in test
- No:
  - × Wavelength-dependent optical properties (SSMT)
  - × External radiation boundaries (solar radiation)
  - × Solar panel operation
  - × Battery operation
  - × Orientation and shading effects
  - × Transient thermal behaviour (heat capacities)

Conclusions

- Planned validations successful
- Thermal grease works
- PEEK spacers work
- Can ignore:
  - Harness
  - Solar panel conductive links
  - Non-essential conductances (for steady state)
- Internal subsystem temperature resolution not sufficient to compare with measurements
- Accurate conductance estimates should be calculated for interfaces with large areas
- Local variations in conductance to cover plates can be significant

Backup slides

Lessons Learned

- Steady state criteria should be <0.5 C/4h (instead of <0.5 C/1h for 2 hrs)
- Make a TMM before test:
  - Plan power profiles
  - Make test procedure
  - Predict internal sensor measurements
- Stick to the plan: minimise revisions of test procedure after test has begun
- Minimise manual interaction during test
- Large interfaces need careful estimation of conductance, may need to be split into regions
- Internal radiation needs to be calculated for all internal surfaces
- Start TBT from cold and let it settle (should give a transient profile)

Error Estimates

Overall error estimates

	Location	Negative °C	Positive °C
Thermocouples	External x	-5.5	0
	External -y	0	2.3
	External -x	-1.8	3.9
	JuRa Electronics Box	0	3.4
	JuRa Electronics Box Rail	0	5.0
	NavCam interface	0	9.1
	Propulsion PEEK interface	0	4.6
	Prop Peak I/F Prim Struct	0	4.5
	Propulsion PCB Bracket	0	4.4
	BP8	0	3.2
TS100s	Propulsion End Cap	0	4.6
	NavCam	0	9.2
	GRASS	0	4.5
	RW Bracket	-3.5	0

Observations:

- NavCam errors possibly due to local conductance variations
- External x: max error -5.5 C,
  ECSS recommendations are less than:
  ± 10 C externally
  ± 5 C internally

Sensitivities

- A simple sensitivity check was made for:
  - Emissivity of each external surface material (7 × 2 runs)
  - Conductivity of: each type of Aluminium, PEEK, silicone rubber, stainless steel, solar panels (7 × 2 runs)
  - Conductance of all interfaces in the following groups: Each power dissipating subsystem, cover plates: each of ±x, ±y and ±z, all masses, all ignored interfaces (18 × 2 runs)
  - Internal radiation (on/off)
- Observations:
  - External emissivities most significant
  - Conductance and PEEK spacers have significant effect on the propulsion system
  - Reaction wheel conductance fairly sensitive
  - Conductivity only significant for propulsion and to a lesser degree reaction wheels (due to long heat paths)
  - Internal radiation: ± ~1 C. If not using all surfaces, up to: ± ~10 C