Simposio de Tecnología Aeroespacial y Nuclear

Organizado por X-Plan S.R.L. y Siemens Digital Industries Software

SATELLOGIC THERMAL DESIGN FLOW, IN ORBIT VERIFICATION AND VALIDATION STRATEGY USING SPACE SYSTEMS THERMAL AND TMG CORRELATION TOOL

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Satellogic, Buenos Aires, Argentina

SATELLOGIC®

X-Plan Ingeniería Colaborativa

Expert Partner Digital Industries Software

SIEMENS

Simposio de Tecnología Aeroespacial y Nuclear 2022 | 2022-10-05

Agenda

1. Corporate Presentation
2. Satellogic Thermal Design Flow based on the use of Space Systems Thermal
3. In Orbit Verification & Validation Strategy
4. Space Systems Thermal CAD, FEM and SIM files flow
5. Thermal Model Correlation using Maya TMG Correlation Tool

Corporate Presentation

COMPANY OVERVIEW

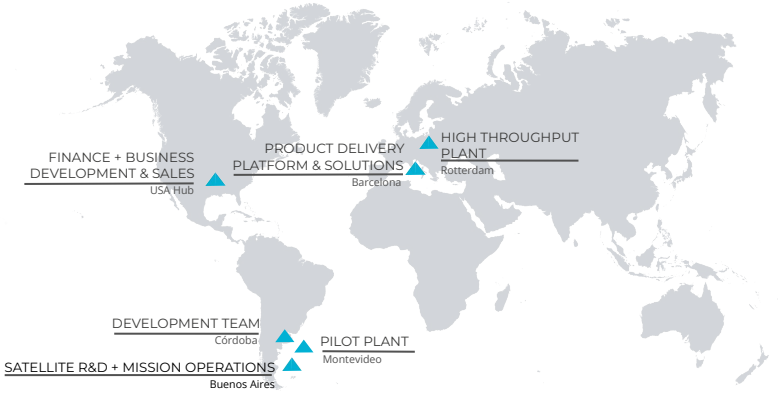
PROVEN LEADERSHIP

25+ years developing technology and tech companies, including Core Security Technologies, Garage Lab, and Aconcagua Ventures as well as consulting for corporations and government agencies.

25+ years leading technology labs and research teams, co-founding tech firms as well as consulting for enterprise tech and governments agencies

GLOBAL FOOTPRINT

- **Founded in 2010**
- **400+ member distributed team across 10+ countries**



CONSTELLATION DEPLOYMENT

34
Satellites Launched
(3 early prototypes + 31 NewSats)

26
Operational satellites in orbit

4
Satellites under integration process

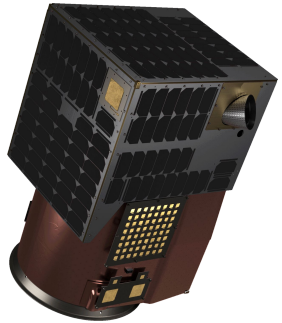
INTELLECTUAL PROPERTY

23
Granted patents

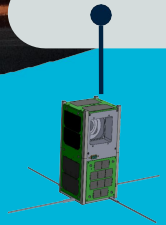
46
Pending applications

20+
Inventions in pipeline

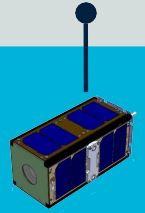
OUR FLEET



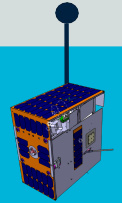
- 34 **satellites** launched
  26 **operational satellites** in orbit
- 100% **satellite deployment** success rate



CubeBug-1
Capitán Beto
April 2013



CubeBug-2
Manolito
November 2013



BugSat-1
Tita
June 2014

3 prototypes launched and tested successfully

A history of success and technological evolution

May 2016
Fresco & Batata
NewSat 1&2
Mark I

Jun 2017
MilaneSat
NewSat 3
Mark II

Feb 2018
Ada & Maryam
NewSat 4&5
Mark III

Jan 2020
Sophie & Marie
NewSat 7&8
Mark IV-A/B

Sep 2020
Hypatia
NewSat 6
Mark IV-A

Nov 2020
Alice, Caroline, Cora, Dorothy, Emmy, Hedy, Katherine, Lise, Mary & Vera
NewSat 9-18
Mark IV-B/C

Jun 2021
Rosalind, Grace, Elisa & Sofya
NewSat 19-22
Mark IV-E

Apr 2022
Annie Mauder, Kalpana Chawla, Mária Telkes, Mary Sommerville, Sally Ride
NewSat 23-27
Mark IV and Mark V

May 2022
Alice Lee
Edith Clarke
Margherita Hack
Ruby Payne-Scott
NewSat 28-31
Mark IV

SATELLOGIC

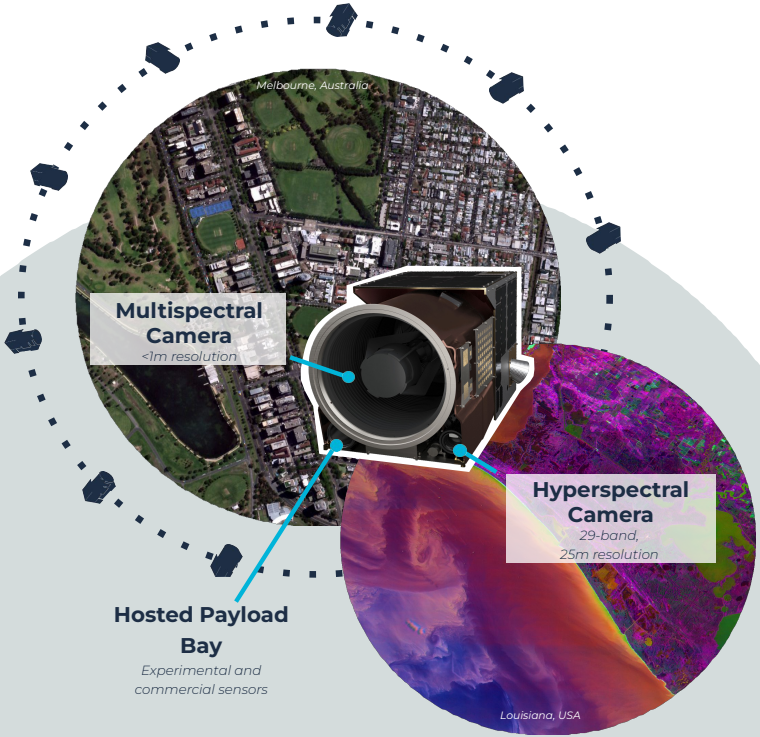
ASSEMBLY, INTEGRATION & TESTING

OUR PILOT PLANT

- Located in Zonamerica, the first Free Trade Zone in **Uruguay**
- **833 sq mt** manufacturing plant **Class**
- **100,000 / ISO 8** cleanroom **Lean**
- **Manufacturing** Methodology

By Q3-2023*

OUR SATELLITES

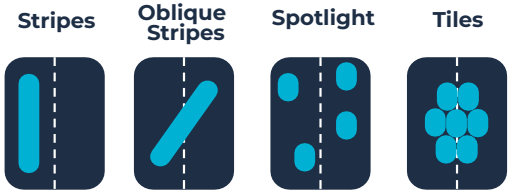


NewSat Design: MASS: **~40 kg** | LEO SSO: **~475 km** | LIFETIME: **3-4 YEARS**

We reinvented the satellite from the ground up to create a smaller, lighter, and more cost-effective system that can be produced at scale without compromising image quality. Our constellation delivers diverse, rich geospatial data at unmatched frequency, resolution, and cost.

- **Multispectral** and **Hyperspectral** cameras
- **Full-Motion Video** capability
- **Off-nadir** capturing with +/-25° angles
- **100x more cost-efficient than traditional satellites**

CAPTURE MODES



SATELLOGIC

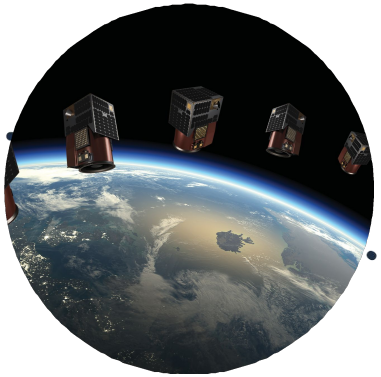
OFFERING PORTFOLIO

IMAGERY

High-resolution global captures

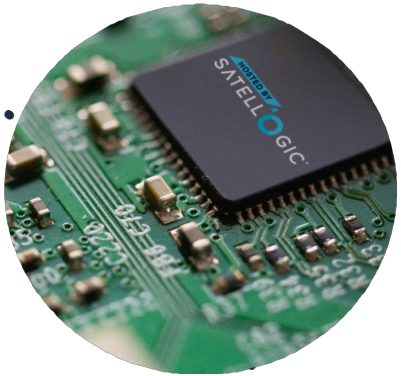
AI LAYERS

Planetary-scale insights



DEDICATED SATELLITE CONSTELLATIONS

Satellite-as-a-service



HOSTED PAYLOAD

Third-party sensor and hardware testing

TECHNOLOGY AND PRODUCT ROADMAP

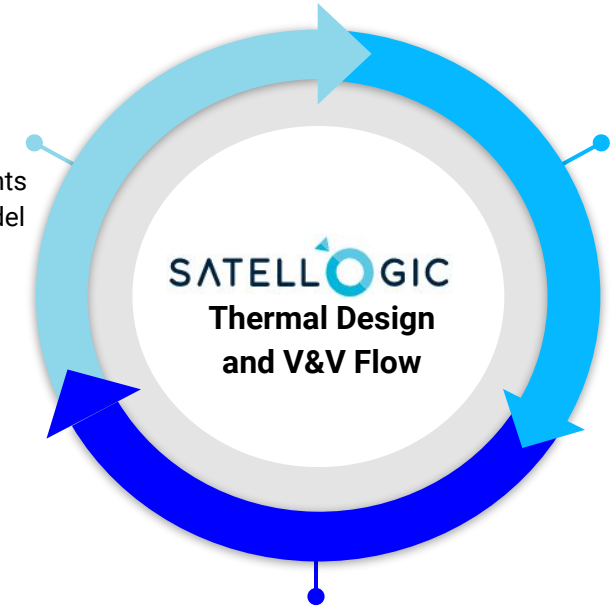
We plan to leverage our cost advantage for continuous capacity growth beyond weekly remaps

	2021	2022	2023	2024	2025+
SATELLITES IN ORBIT	17	34	63	139	202
SATELLITE CHARACTERISTICS (GSD RESOLUTION)	0.99m at 470 km	0.70m at 470 km		0.40m at 440 km	0.30m at 330 km
DAILY REVISITS OF POINTS OF INTEREST	4	7	13	28	40
PRODUCT LAUNCHES	DSC	Data Platform	Weekly World Remaps		Daily World Remaps

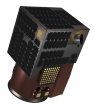
Thermal Design Flow based on the use of a Space System Thermal

Thermal Design Flow

REQUIREMENTS
Thermal Requirements
Analysis Cases Requirements
Thermal Mathematical Model Requirements



ANALYSIS VERIFICATION
Simcenter 3D

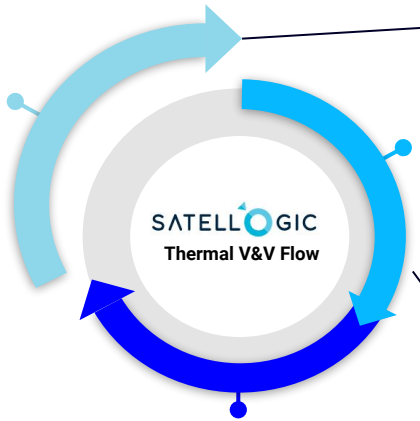


IN ORBIT VALIDATION
We **replace** the concept of **Thermal Model (TM)** by the **Flight Thermal Model Concept (FTM)**
Constant Telemetry Feedback

Thermal Requirements

REQUIREMENTS

Thermal Requirements
Analysis Cases Requirements
Thermal Mathematical Model Requirements



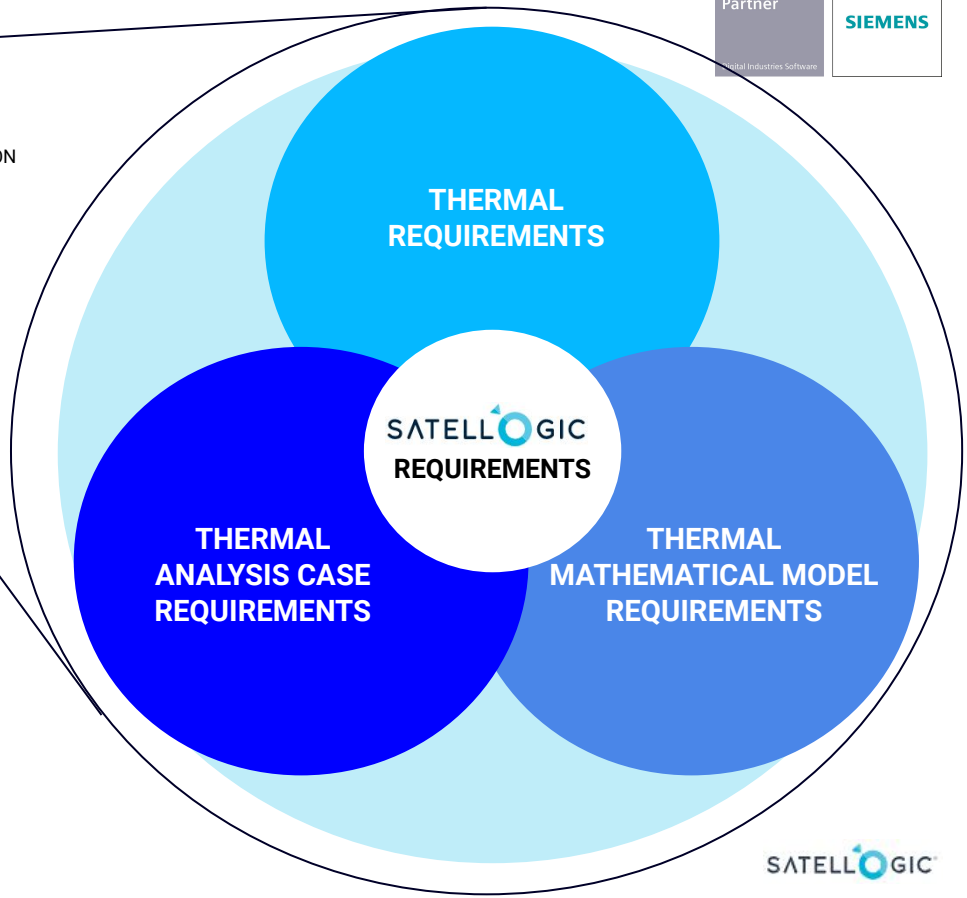
ANALYSIS VERIFICATION

Simcenter 3D

IN ORBIT VERIFICATION
Flight Thermal Model Concept (FTM)
Constant Telemetry Feedback

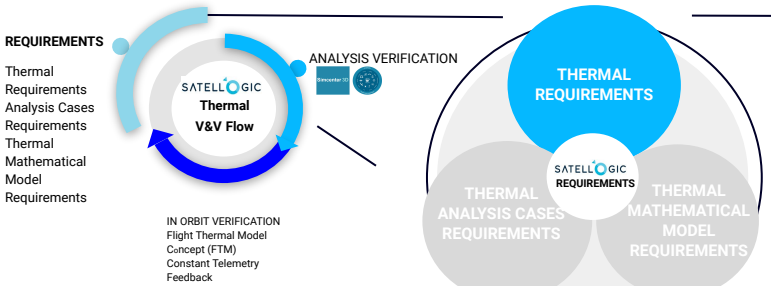
Expert Partner

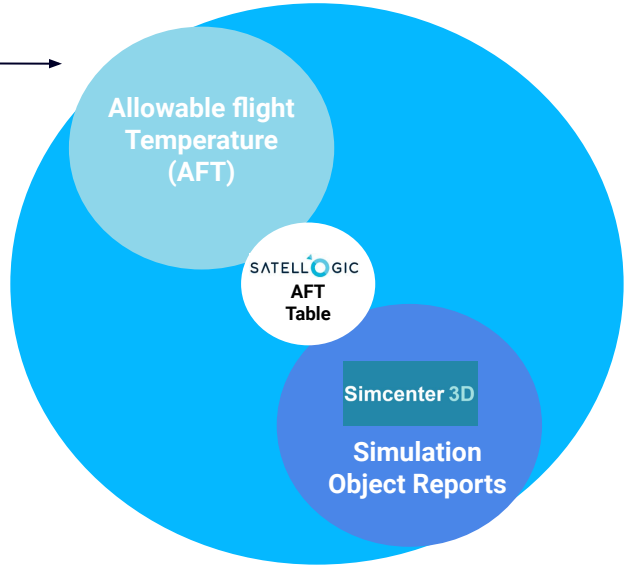
SIEMENS



SATELLOGIC

Thermal Requirements





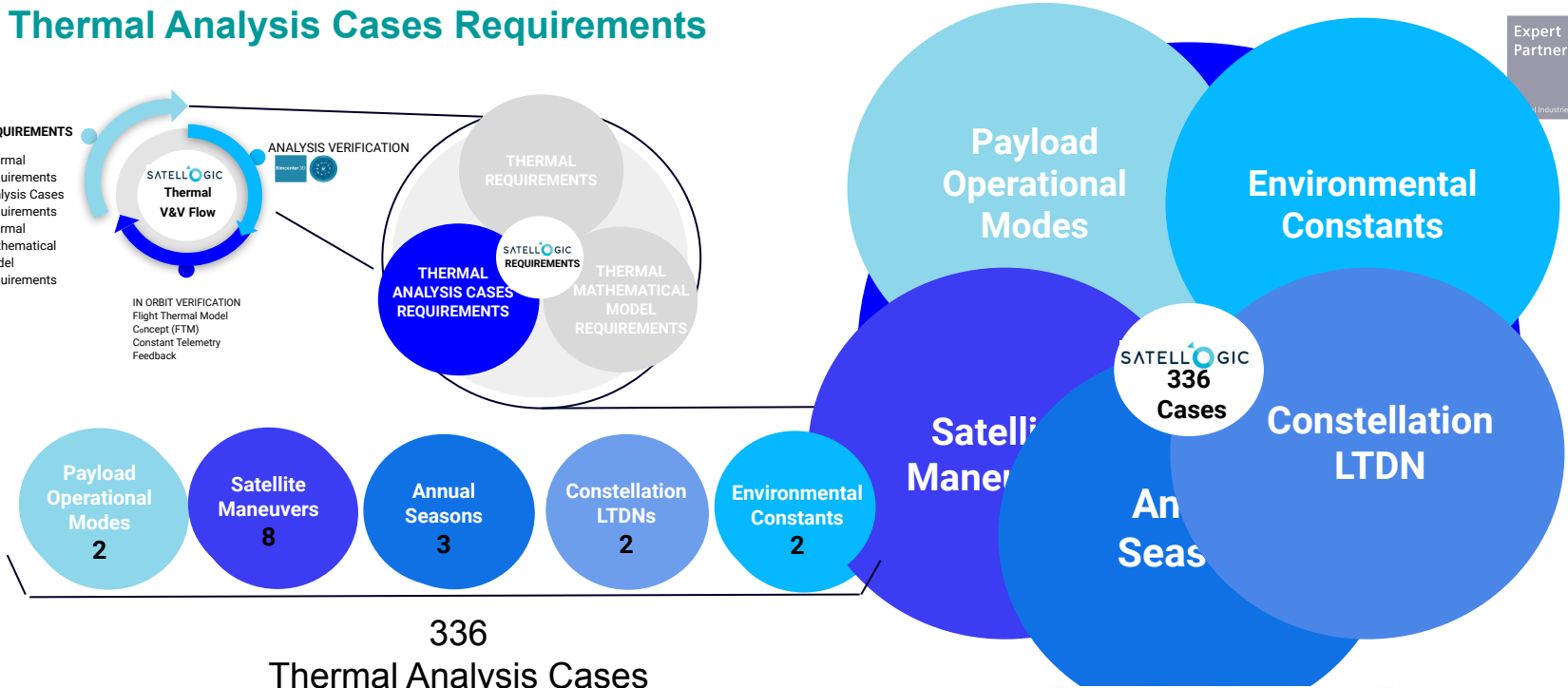
Expert Partner
Digital Industries Software
SIEMENS

Case	Device	Group Report Name Simcenter 3D	Time Cold	Time Hot	AFT min	AFT max	Min Temp	Max Temp	Design Margin Cold	Design Margin Hot	Pass Cold	Pass Hot
700012_m1Yp_0930_JS_034	Ramon	TRP_Comms_Ramon	1027	3565	0	66.2	-34.2	-27.7	-34.2	93.9	FAIL	ok!

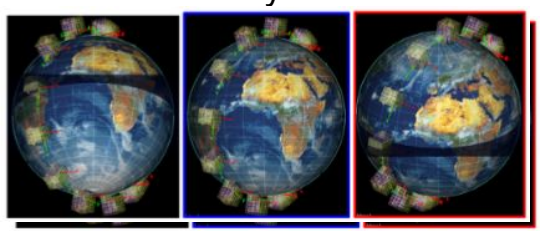
The AFT Table will be used to verify the requirements by analysis comparing the simulation object report temperature Simcenter 3D Vs. the AFT Table automatically

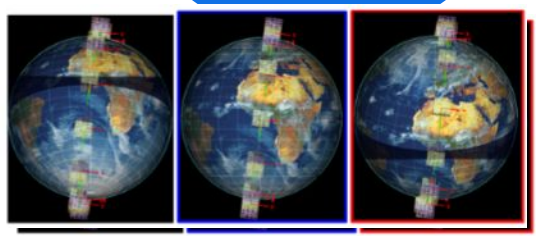
SATELLOGIC

Thermal Analysis Cases Requirements

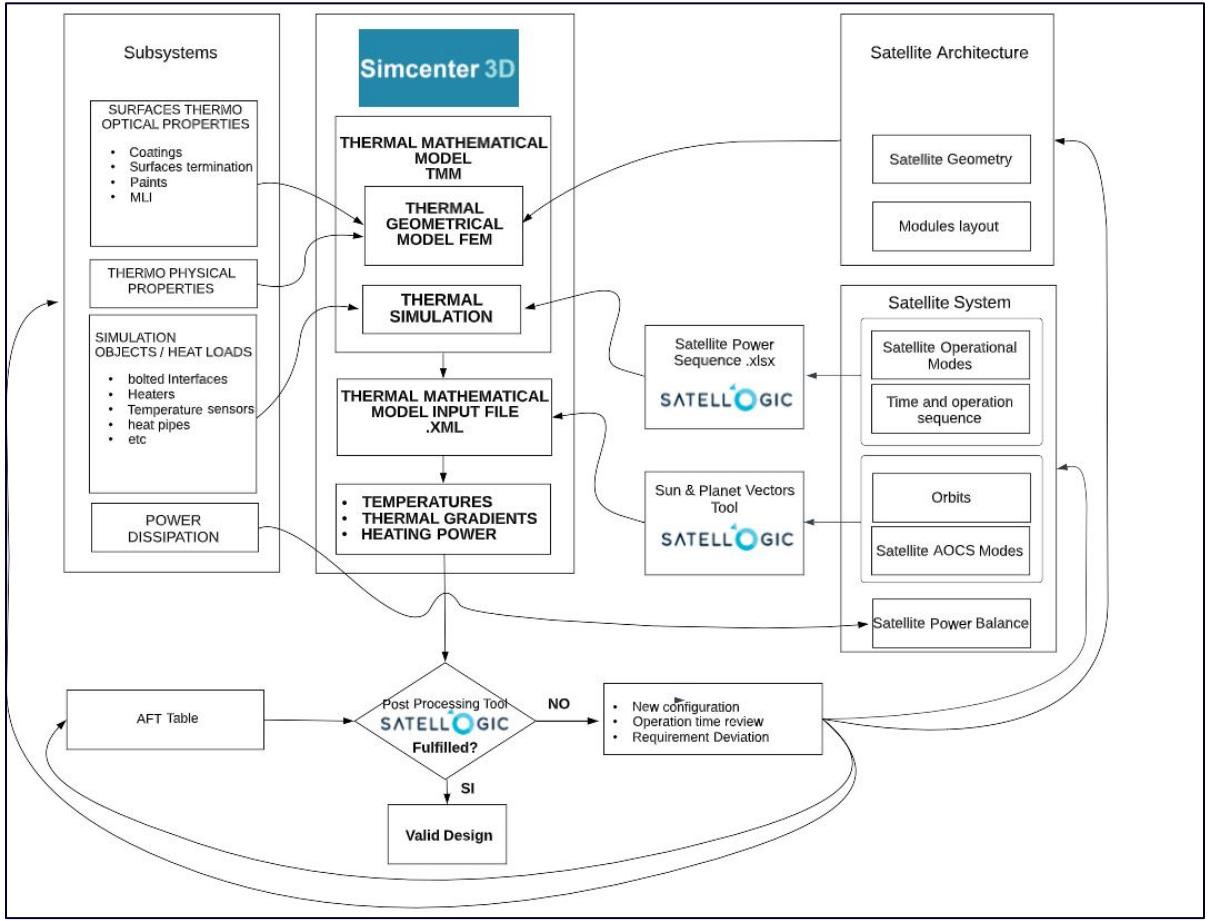


336
Thermal Analysis Cases





Thermal Model Requirements



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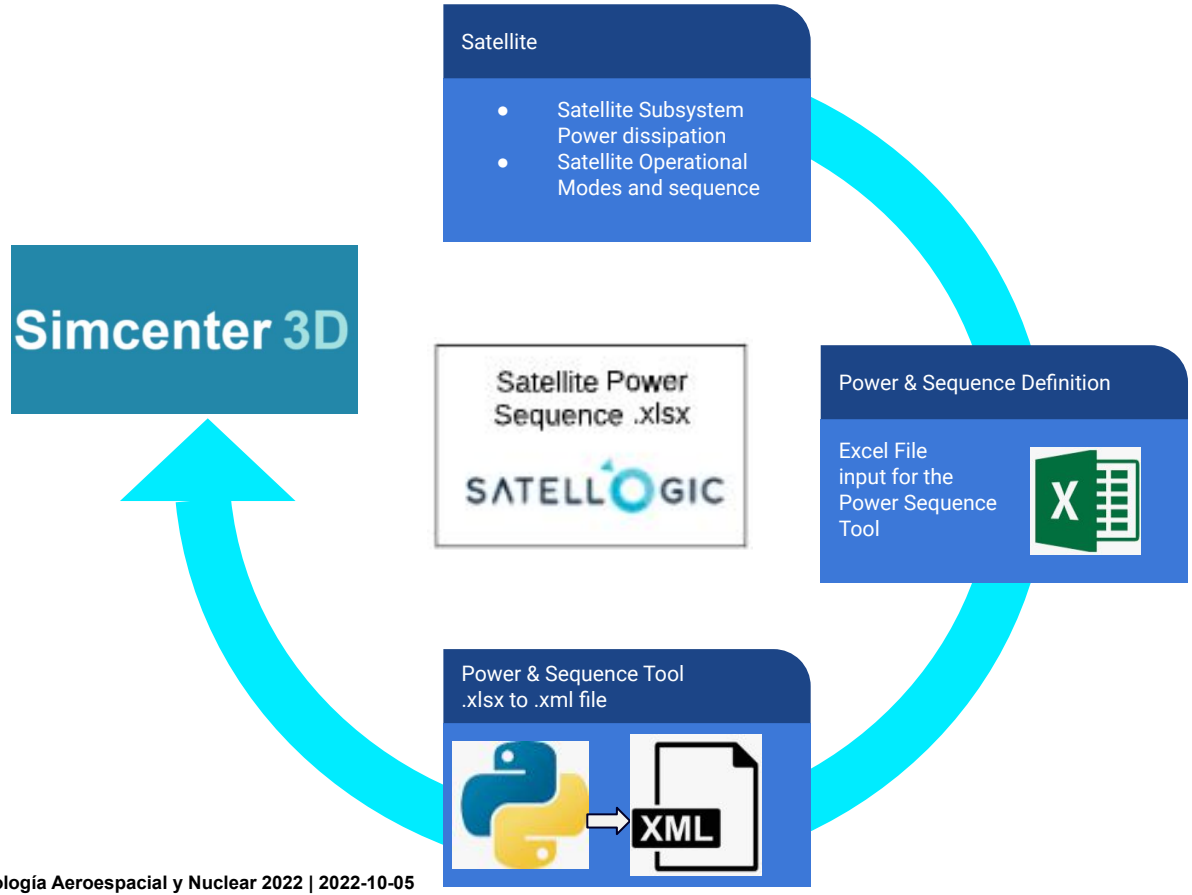
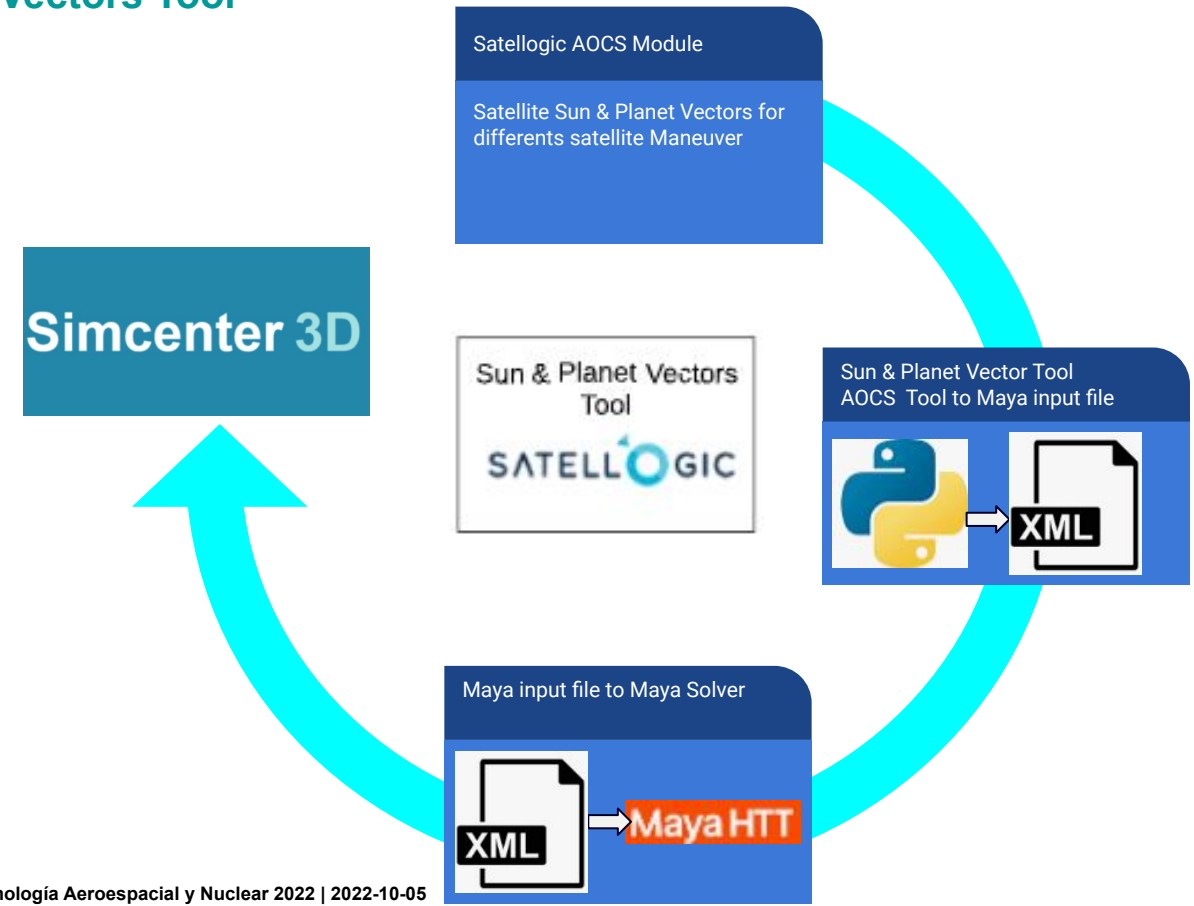
SATELLOGIC

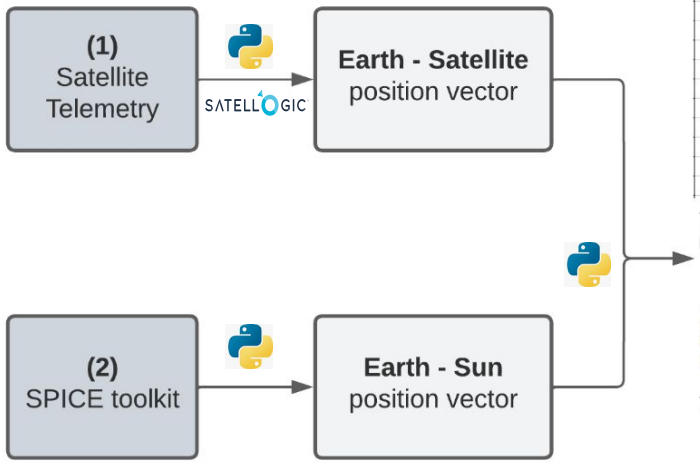
Power Sequence Tool



Sun & Panet Vectors Tool



Orbit Telemetry to Space System Thermal Tool

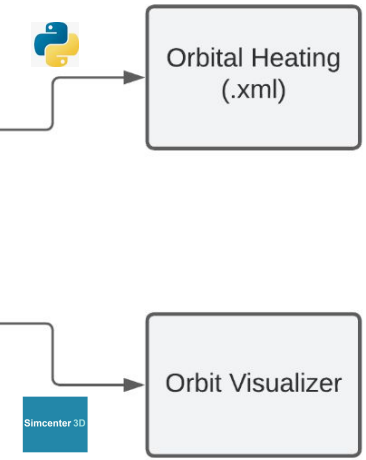


time (sec)	Sun-X (mm) *	Sun-Y (mm) *	Sun-Z (mm) *	Planet-X (mm) *	Planet-Y (mm) *	Planet-Z (mm) *	Altitude (mm)
0	3.60E+10	-1.30E+11	7.20E+10	-6.19E+06	9.52E+07	6.88E+09	5.27E+05
60	3.60E+10	-1.26E+11	8.05E+10	-6.94E+06	1.81E+08	6.88E+09	5.26E+05
120	3.60E+10	-1.20E+11	8.87E+10	-8.96E+06	1.81E+08	6.88E+09	5.26E+05
180	3.60E+10	-1.15E+11	9.65E+10	-8.21E+06	1.82E+08	6.88E+09	5.25E+05
240	3.60E+10	-1.09E+11	1.04E+11	-1.14E+07	1.81E+08	6.88E+09	5.25E+05
300	3.60E+10	-1.02E+11	1.11E+11	-1.24E+07	1.80E+08	6.88E+09	5.24E+05
360	3.60E+10	-9.47E+10	1.17E+11	-1.33E+07	1.85E+08	6.88E+09	5.23E+05
420	3.60E+10	-8.71E+10	1.24E+11	-1.53E+07	1.86E+08	6.88E+09	5.22E+05
480	3.60E+10	-7.92E+10	1.29E+11	-1.55E+07	1.86E+08	6.89E+09	5.21E+05
540	3.60E+10	-7.10E+10	1.34E+11	-1.73E+07	1.86E+08	6.89E+09	5.20E+05
600	3.60E+10	-6.24E+10	1.38E+11	-1.77E+07	1.86E+08	6.89E+09	5.18E+05

Table 1: Sun & Planet Vectors defined with Cartesian coordinates in the satellite local reference system

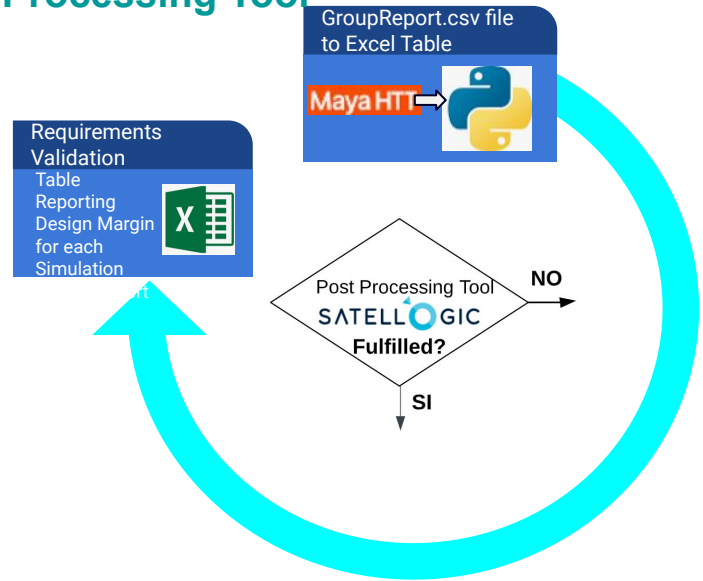
Time (UTCG)	Latitude (deg)	Longitude (deg)	J2000-x (km)	J2000-y (km)	J2000-z (km)
20 Mar 2020 12:00:00.000	0.000000	157.500000	-6360.974874	2869.188618	12.301381
20 Mar 2020 12:01:00.000	3.706901	156.745111	-6321.520082	2919.006468	460.631178
20 Mar 2020 12:02:00.000	7.413134	155.986019	-6255.446903	2956.533849	907.021295

Table 2: Epoch, latitude, longitude, and satellite position in J2000 ECI



https://naif.jpl.nasa.gov/naif/

Requirements Validation Processing Tool



Case	Device	Group Report Name Simcenter 3D	Time Cold	Time Hot	AFT min	AFT max	Min Temp	Max Temp	Design Margin Cold	Design Margin Hot	Pass Cold	Pass Hot
700012_m1Yp_0930_JS_034	Ramon	TRP_Comms_Ramon	1027	3565	0	66.2	-34.2	-27.7	-34.2	93.9	FAIL	ok!

The AFT Table will be used to verify the requirements by analysis comparing the simulation object report temperature Simcenter 3D Vs. the AFT Table automatically

In Orbit Verification & Validation Strategy

In Orbit Verification & Validation Philosophy

Expert Partner
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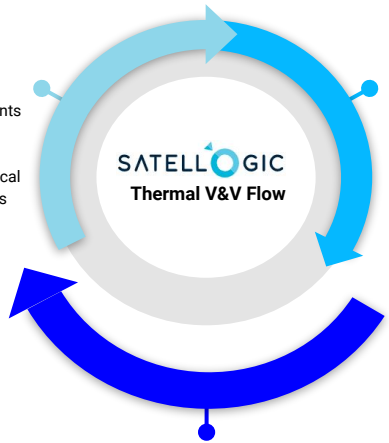
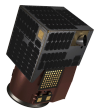
REQUIREMENTS

Thermal Requirements
Analysis Cases
Requirements
Thermal Mathematical
Model Requirements



ANALYSIS VERIFICATION

Simcenter 3D



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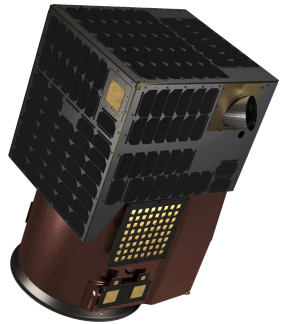
We **replace** the concept of **Thermal Model (TM)** by the **Flight Thermal Model Concept (FTM)**
Constant Telemetry Feedback

26 Operational satellites



FTM Flight thermal Model

SATELLOGIC

In Orbit Verification & Validation Philosophy

REQUIREMENTS

Thermal Requirements
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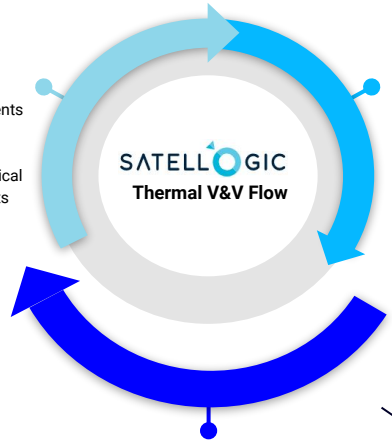
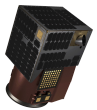


ANALYSIS VERIFICATION

Simcenter 3D



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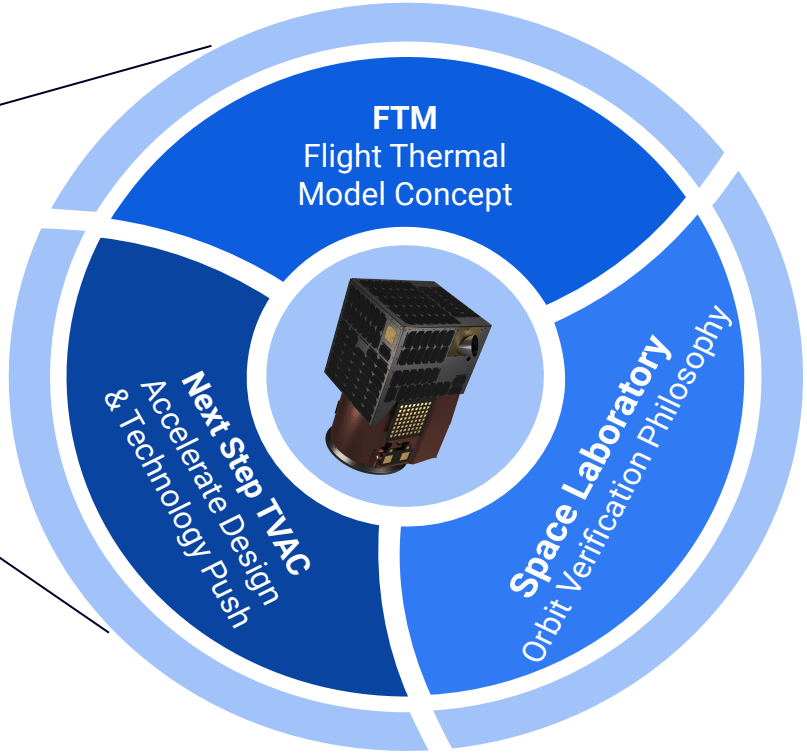


In Orbit Verification & Validation Philosophy

Expert Partner — Digital Industries Software — SIEMENS

Maximum Technology Push

Space Laboratory - No TVAC Test in the AIT Flow → **Space Laboratory - FTM Flight Thermal Model Concept**

No TVAC Test in the AIT Flow allows us:

- **Decreasing the cost per Satellite**
- **Increasing the velocity of production**
- **Cheaper FTM**

Using the Space as a Laboratory allows:

- **Fast Design interaction with Flight**
- **Increasing the Technology Push**
- **Strong TMM models and Thermal Engineering**
- **Test New Thermal HW**
- **Constant Research**

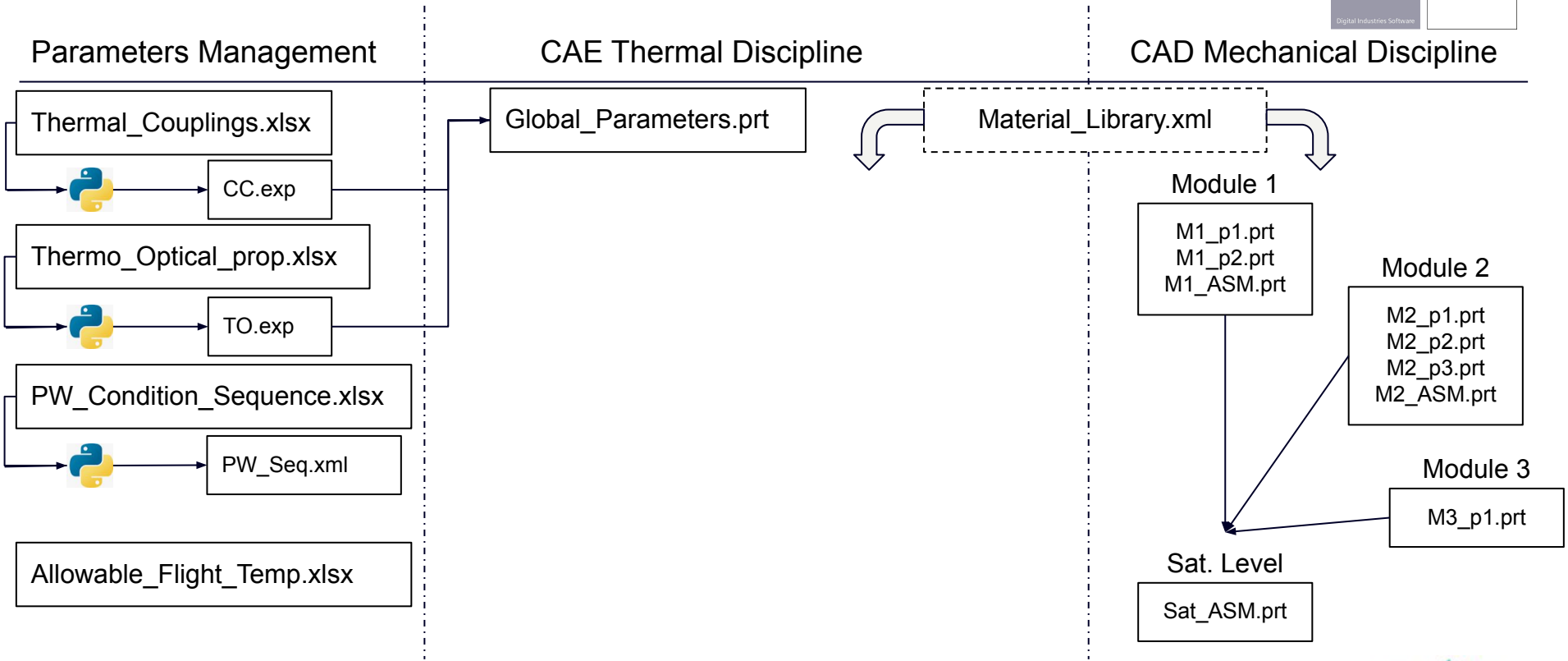
Next Step

Experimental TVAC between Launches

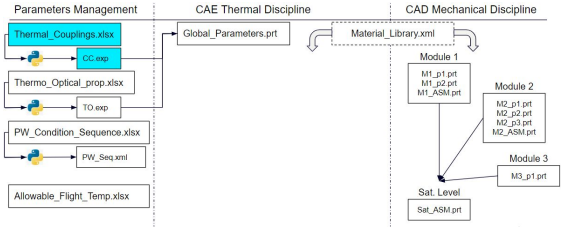
SATELLOGIC

Space Systems Thermal CAD, FEM and SIM files flow

Thermal Model Requirements Implementation. Files and procedure. *Introduction*



Thermal Model Requirements Implementation. Thermal Couplings.



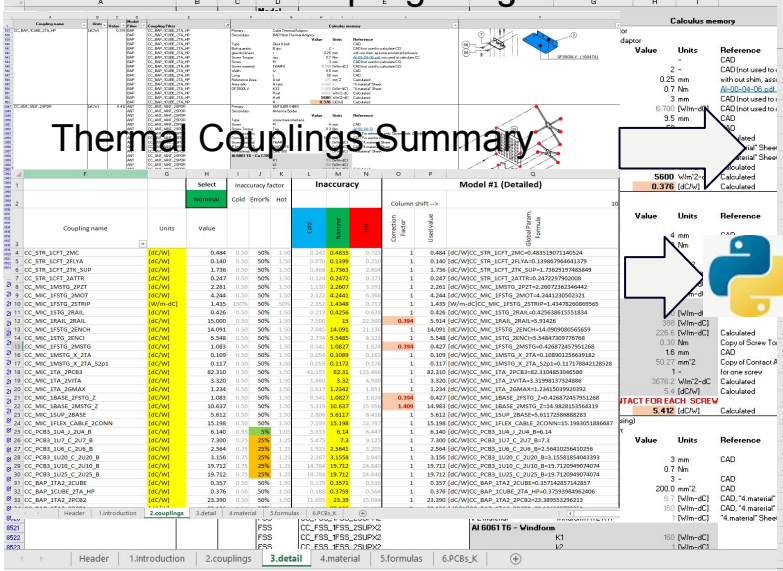
Thermal Couplings Log

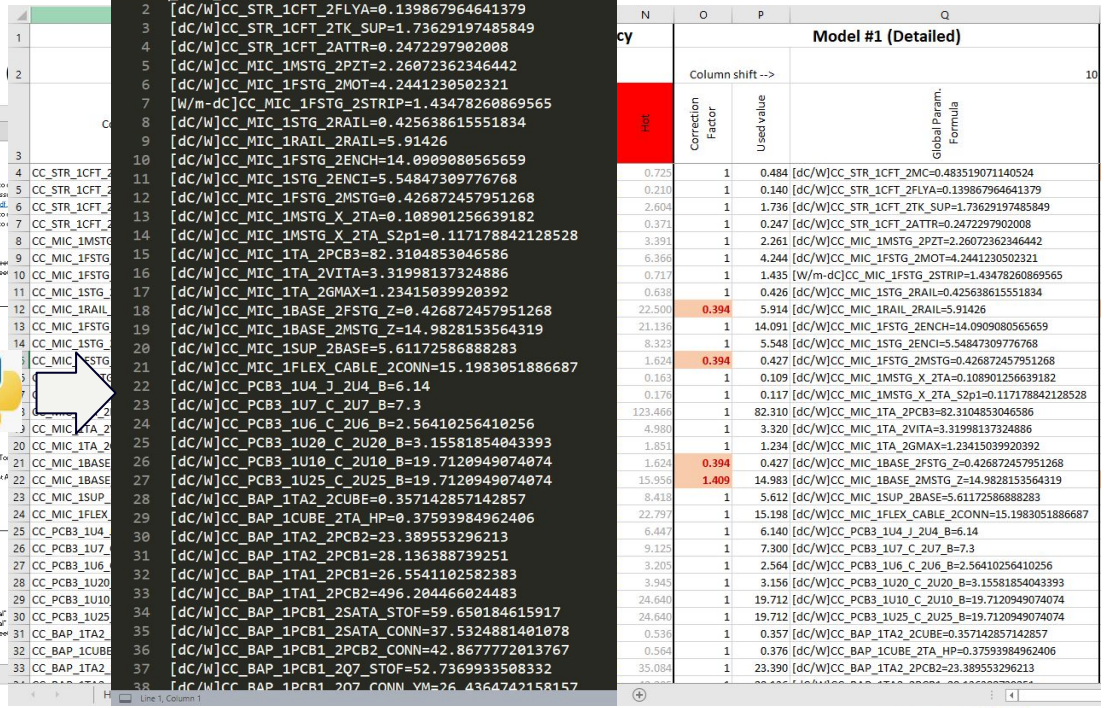
Thermal Couplings Summary

CC.exp file

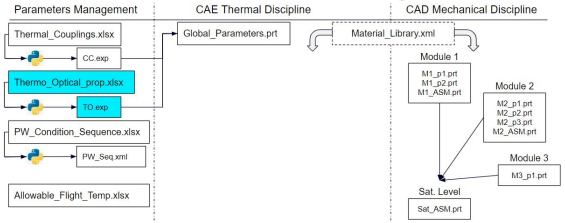
Thermal

s Summary

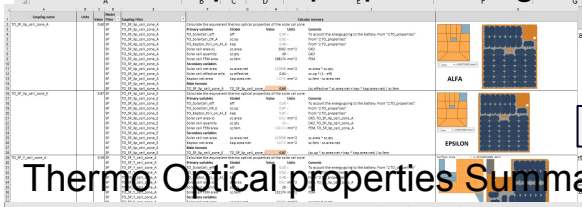




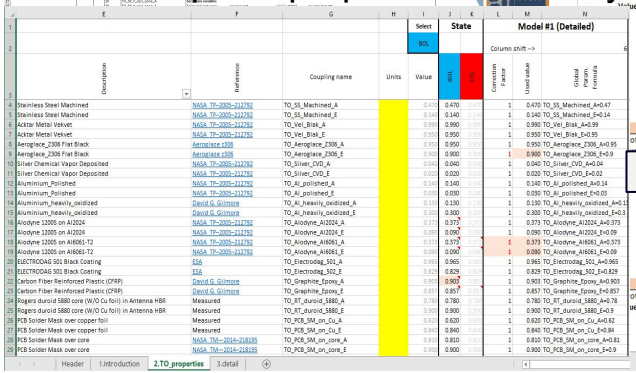
Thermal Model Requirements Implementation. Thermo Optical Properties.



Thermo Optical properties log



Thermo Optical properties Summary



TO.exp file

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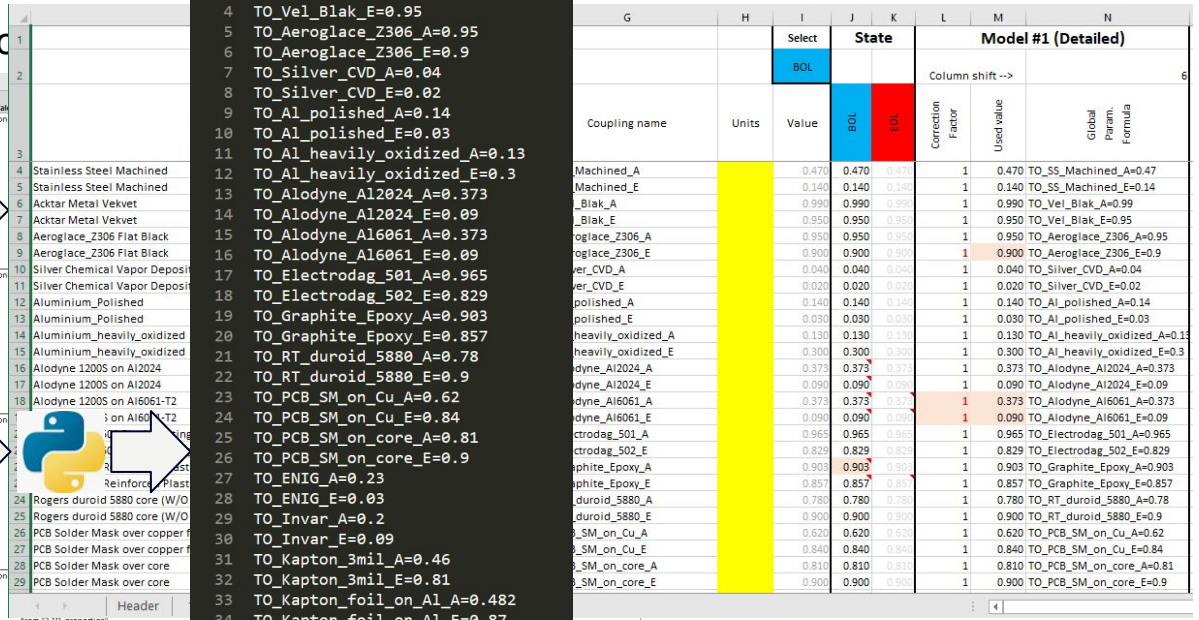
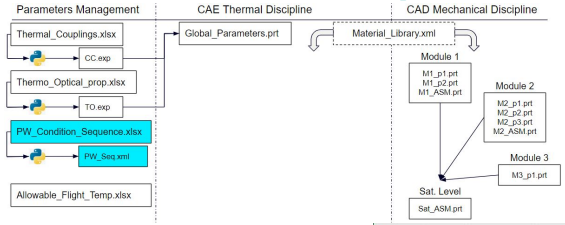
1  TO_SS_Machined_A=0.47
2  TO_SS_Machined_E=0.14
3  TO_Vel_Blak_A=0.99
4  TO_Vel_Blak_E=0.95
5  TO_Aeroglace_Z306_A=0.95
6  TO_Aeroglace_Z306_E=0.9
7  TO_Silver_CVD_A=0.04
8  TO_Silver_CVD_E=0.02
9  TO_Al_polished_A=0.14
10 TO_Al_polished_E=0.03
11 TO_Al_heavily_oxidized_A=0.13
12 TO_Al_heavily_oxidized_E=0.3
13 TO_Alodyne_Al2024_A=0.373
14 TO_Alodyne_Al2024_E=0.09
15 TO_Alodyne_Al6061_A=0.373
16 TO_Alodyne_Al6061_E=0.09
17 TO_Electrodag_501_A=0.965
18 TO_Electrodag_502_E=0.829
19 TO_Graphite_Epoxy_A=0.903
20 TO_Graphite_Epoxy_E=0.857
21 TO_RT_duroid_5880_A=0.78
22 TO_RT_duroid_5880_E=0.9
23 TO_PCB_SM_on_Cu_A=0.62
24 TO_PCB_SM_on_Cu_E=0.84
25 TO_PCB_SM_on_core_A=0.81
26 TO_PCB_SM_on_core_E=0.9
27 TO_ENIG_A=0.23
28 TO_ENIG_E=0.03
29 TO_Invar_A=0.2
30 TO_Invar_E=0.09
31 TO_Kapton_3mil_A=0.46
32 TO_Kapton_3mil_E=0.81
33 TO_Kapton_foil_on_Al_A=0.482
34 TO_Kapton_foil_on_Al_E=0.87
35 TO_Black_Anodized_A=0.86
36 TO_Black_Anodized_E=0.86
37 TO_MLI_eff_CFRP_E=0.01
38 TO_MLI_eff_SP_E=0.01
```

Thermo Optical properties Summary



Thermal Model Requirements Implementation. PW Conditions Sequence.

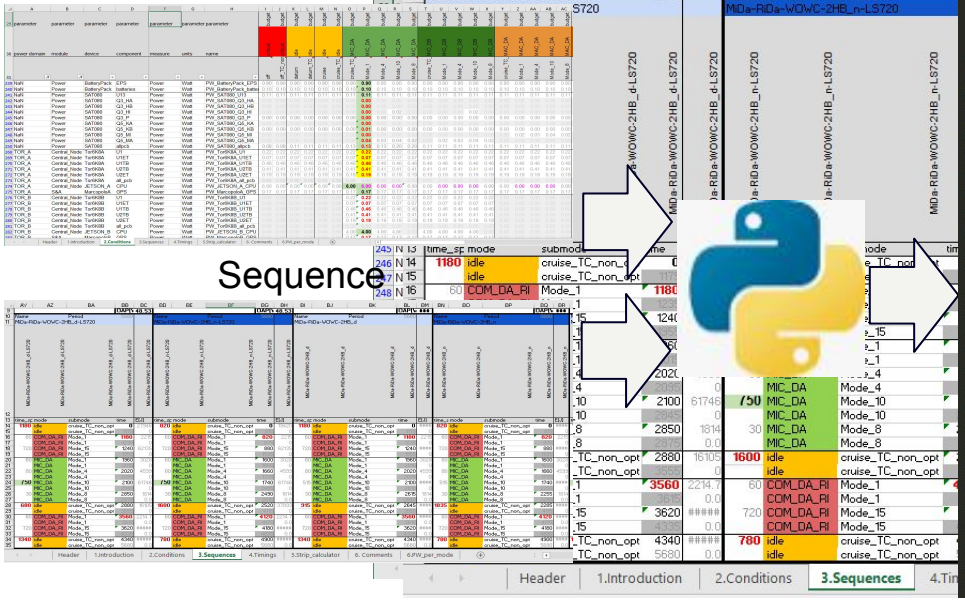


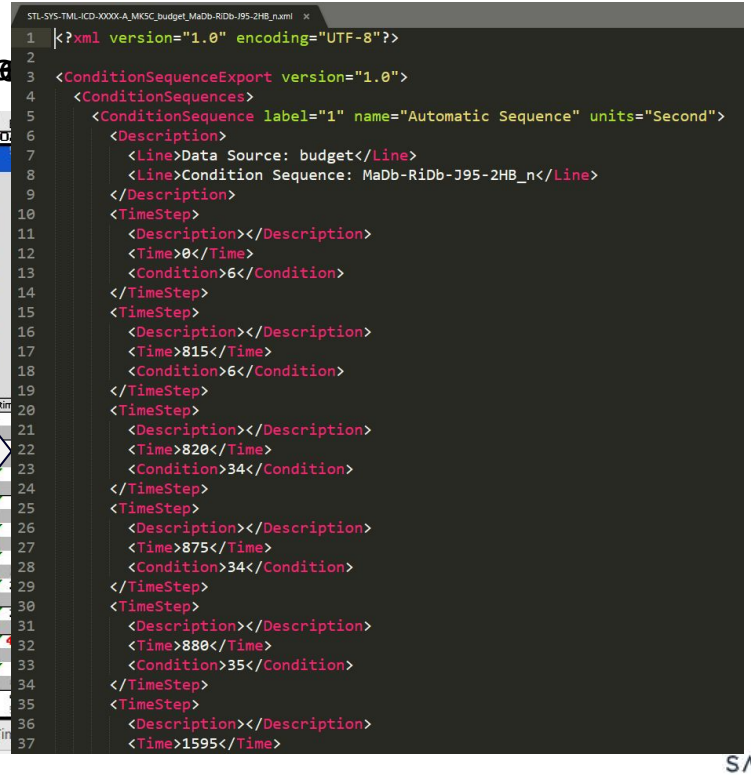
Conditions (Operational modes)

PW_Seq.xml

Conditions

Sequence





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        <Line>Data Source: budget</Line>
        <Line>Condition Sequence: MaDb-RiDb-J95-2HB_n</Line>
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        <Time>1595</Time>
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Thermal Model Requirements Implementation. Files and procedure.
Import Expression

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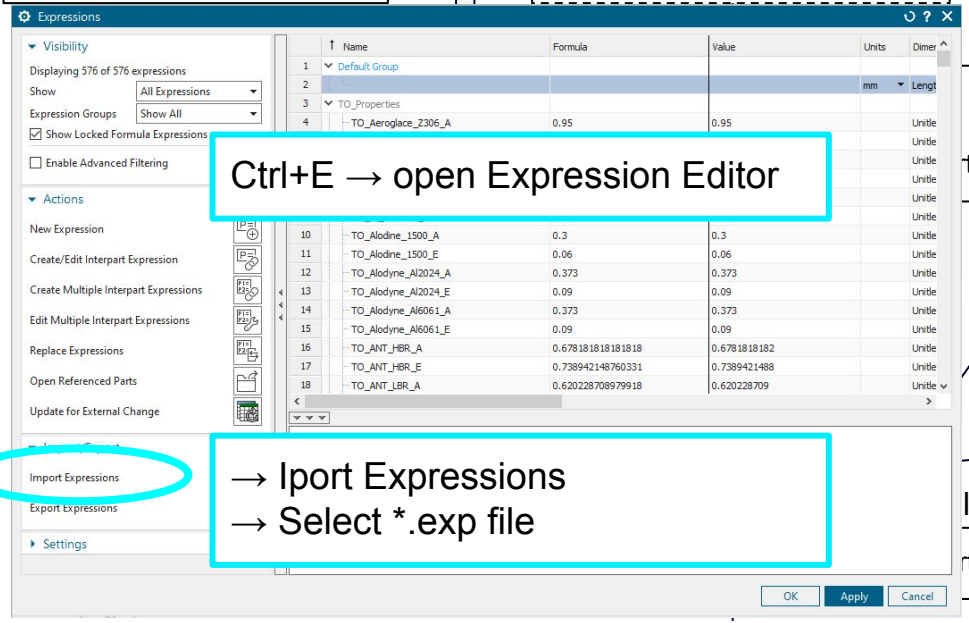
Parameters Management

- Thermal_Couplings.xlsx → CC.exp
- Thermo_Optical_prop.xlsx → TO.exp
- PW_Condition_Sequence.xlsx → PW_Seq.xml
- Allowable_Flight_Temp.xlsx

CAE Thermal Discipline

Global_Parameters.prt



Ctrl+E → open Expression Editor

→ Iport Expressions
→ Select *.exp file

CAD Mechanical Discipline

Material_Library.xml

Module 2
- M2_p1.prt
- M2_p2.prt
- M2_p3.prt
- M2_ASM.prt

Module 3
- M3_p1.prt

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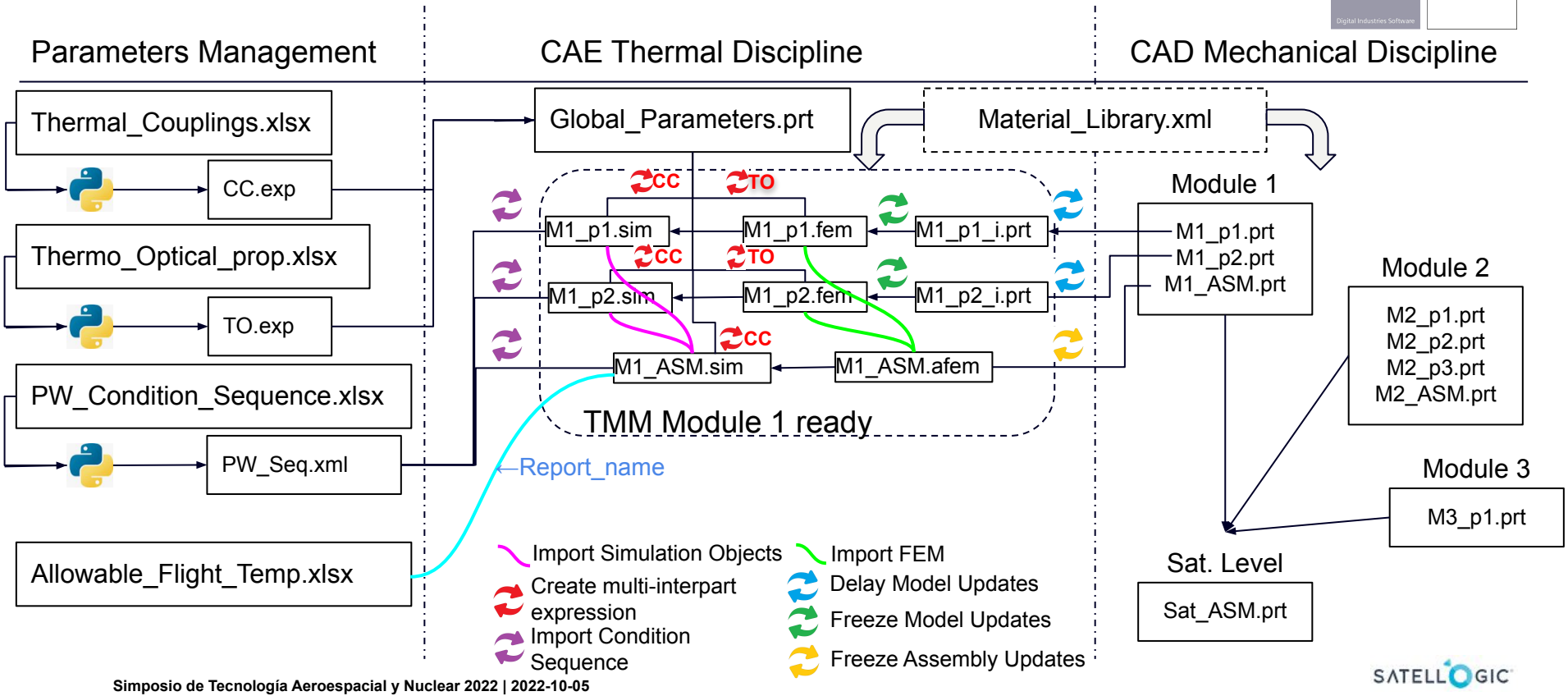
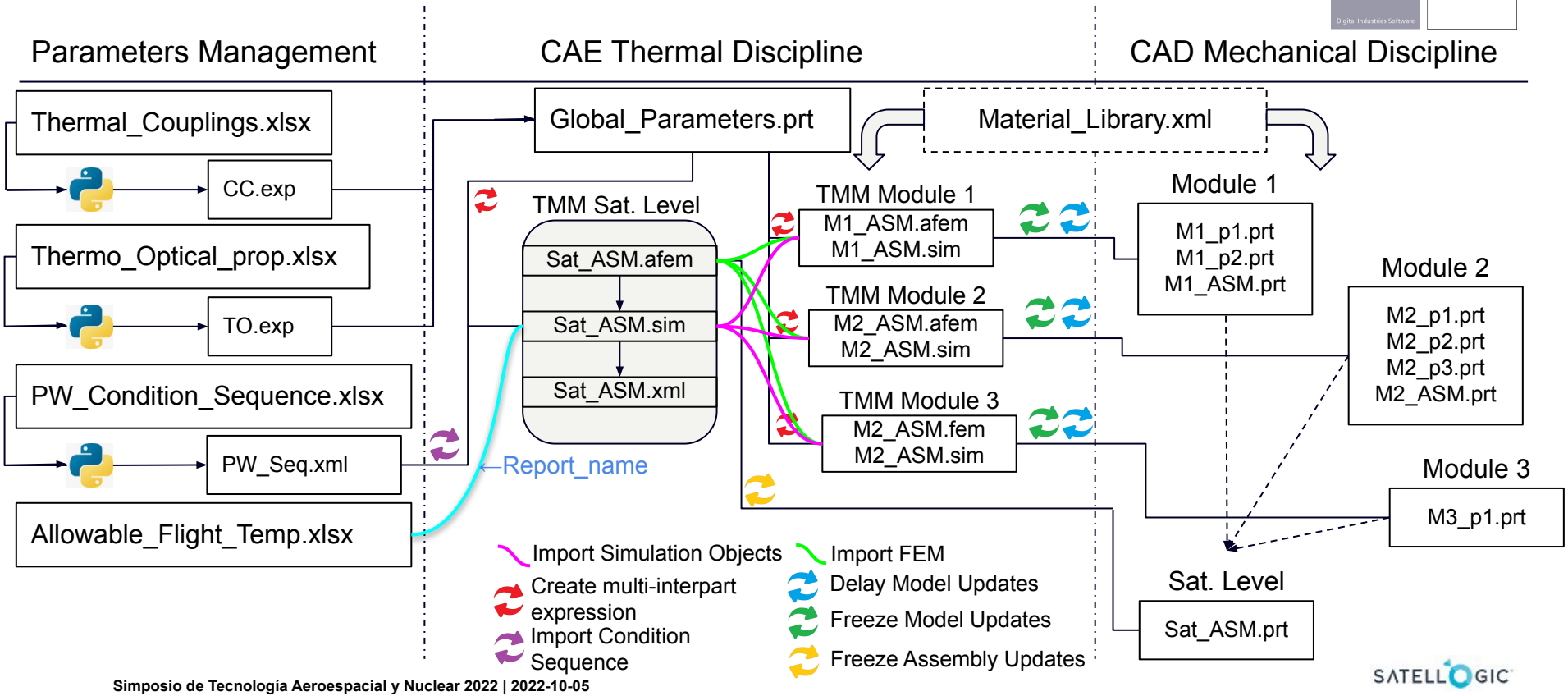
Thermal Model Requirements Implementation. Files and procedure. Procedure for one Module



Thermal Model Requirements Implementation. Files and procedure.



Thermal Model Correlation using Maya TMG Correlation Tool

Thermal Model Correlation using Maya TMG Correlation Tool

The Thermal model correlation is performed in three steps:

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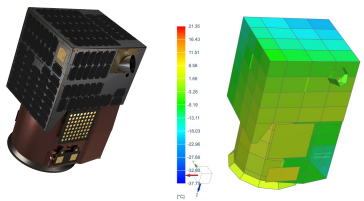
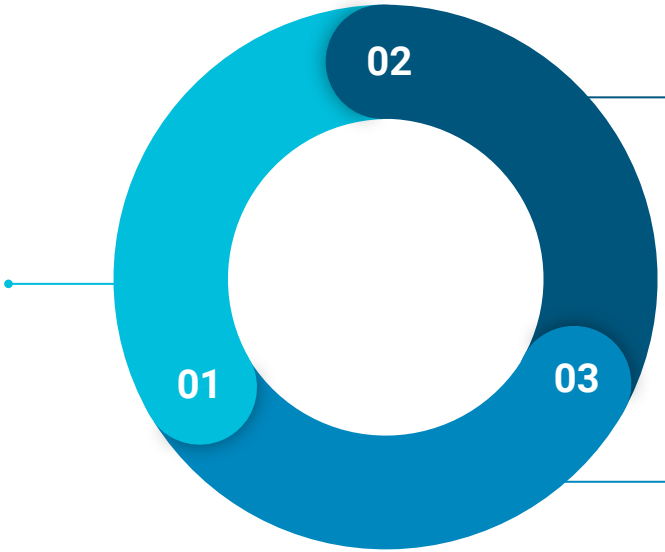
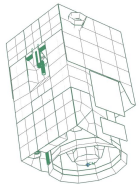
Not Correlated Model
versus
Orbit Telemetry





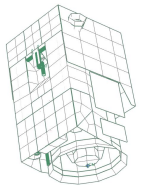
Radiation Correlation
α and ε



Simulation file .sim
hand correlated

Conductive Correlation Tool

Simulation file .sim
TMG Correlation Tool



Simcenter 3D
Maya HTT

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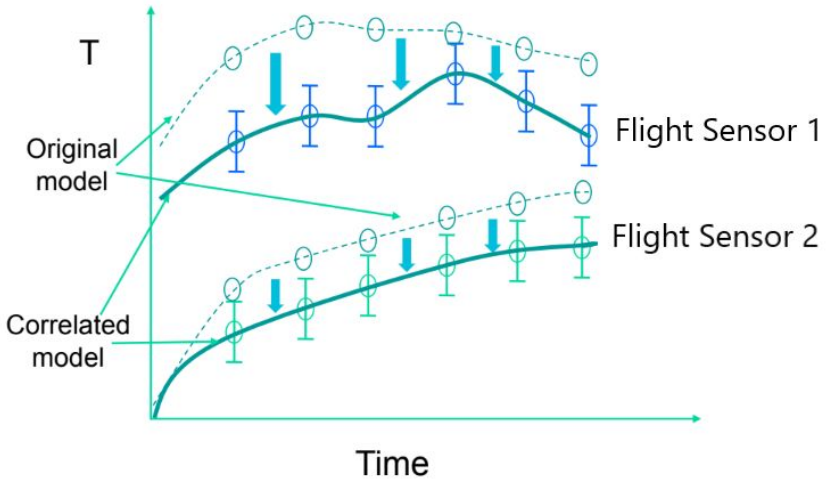
Thermal Model Correlation using Maya TMG Correlation Tool

For a set of **design variables D**, the error at each measurement point is expressed as

$$\epsilon_i = \underbrace{T_i^{model}(\vec{D})}_{\text{From TMG}} - T_i^{data}$$

A well correlated model minimizes the **functional**

$$f(\vec{D}) = \sum_{i=1}^{N_T} W_i {\epsilon_i}^2$$



Where NT is the total number of data points collected and Wi is some weighting factor.

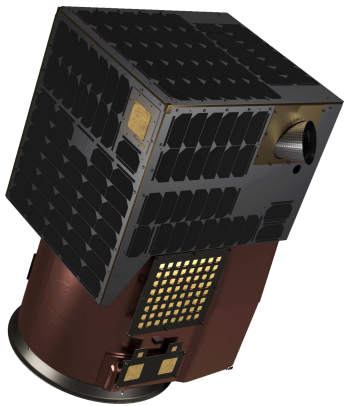
A gradient based method can be used to minimize the error function $f(\vec{D})$
Once the gradient $\vec{G}$ is calculated, the design variables are updated:

$$\vec{D}^{new} = \vec{D}^{old} - \alpha\vec{G}$$

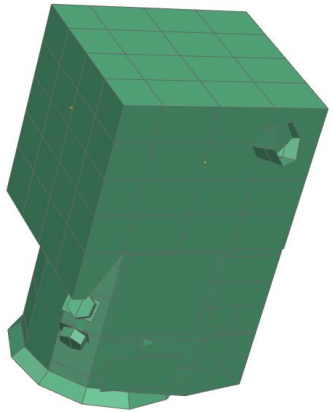
Thermal Model Correlation using Maya TMG Correlation Tool

- **33** Flight thermal sensors telemetry to correlate
- **50** conductive design variables to adjust
- Objective Function **0.5**
- **1316** nodes – conduction/radiation
- **Design Variable Multiplier Criteria.** **Multiplied Factor result = Min. 0.02 Max. 8.74**
- Correlation at **3** time steps, **1440s, 2820s, 4260s**
- TMG Correlation Tool perform the conductive correlation in **4 minutes**

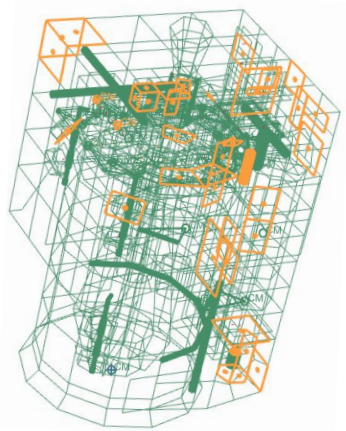
$$F = \sqrt{\frac{1}{N_{times} * N_{targets}} \times \sum_{times} \left(\sum_{target} \left(T - T_{target} \right)^2 \right)}$$



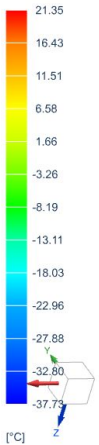
NewSat Satellite

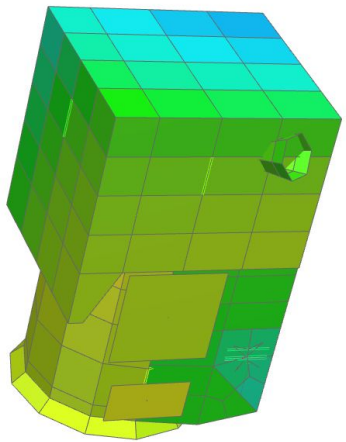


NewSat FEM



NewSat Sensors

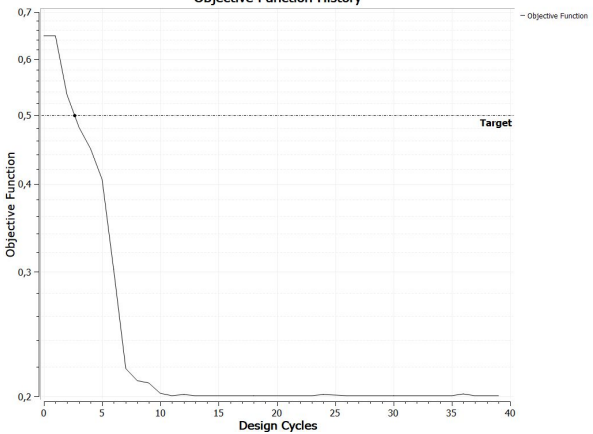




Thermal Model Correlation using Maya TMG Correlation Tool

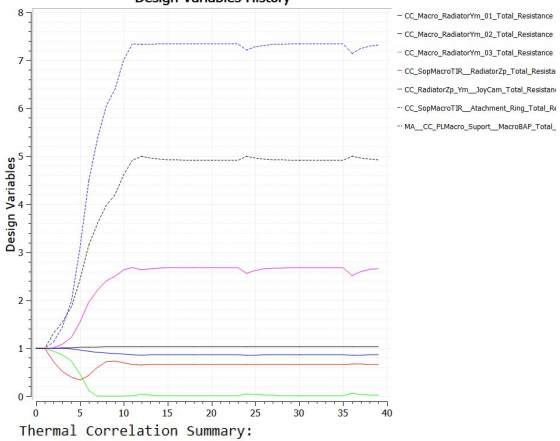
Objective Function and **Design Variables** Convergence example

$$F = \sqrt{\frac{1}{N_{times} * N_{targets}} \times \sum_{times} \left(\sum_{target} (T - T_{target})^2 \right)}$$



Thermal Correlation Sensors

Sensor Name	Temperature Difference	Temperature
"TC_2271"	0.4504E+00	-0.1245E+02
"TC_2269"	0.5685E+00	-0.1557E+02
"TC_2149"	0.3409E+00	-0.1634E+02
"TC_17002"	0.4879E-01	-0.1505E+02
"TC_16001"	0.1887E+00	-0.1181E+02
"TC_16006"	0.7460E+00	-0.1725E+02
"TC_16009"	0.9536E-01	-0.1190E+02
"TC_2241"	0.1987E+00	-0.1980E+02

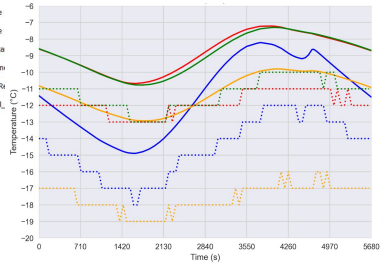


Thermal Correlation Summary:

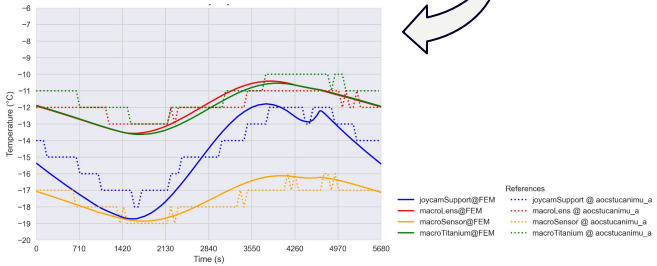
Final objective function	0.2004E+00
Number of design cycles	39

DESIGN VARIABLE NAME	VALUE
CC_Macro_RadiatorYm_01_Total_Resistan	0.1035E+01
CC_Macro_RadiatorYm_02_Total_Resistan	0.8608E+00
CC_Macro_RadiatorYm_03_Total_Resistan	0.1956E-01
CC_SopMacroTIR__RadiatorZp_Total_Resi	0.2658E+01
CC_RadiatorZp_Ym__JoyCam_Total_Resist	0.6654E+00
CC_SopMacroTIR__Atachment_Ring_Total_	0.4925E+01
MA__CC_PLMacro_Suport__MacroBAP_Total	0.7313E+01

Not correlated Model



Conduction Correlation Tool



Thermal Model Correlation using Maya TMG Thermal Correlation Tool

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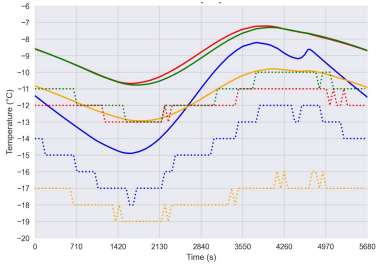
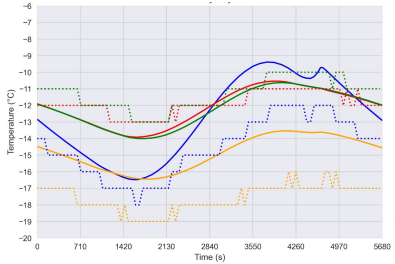
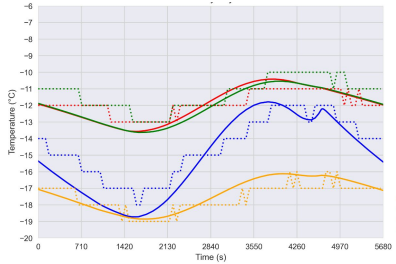
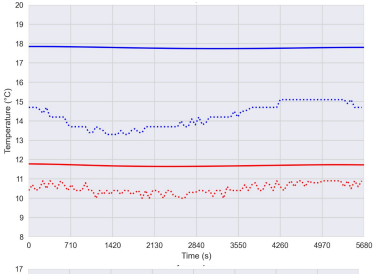
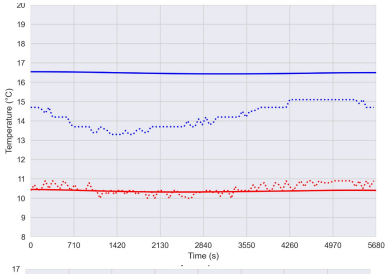
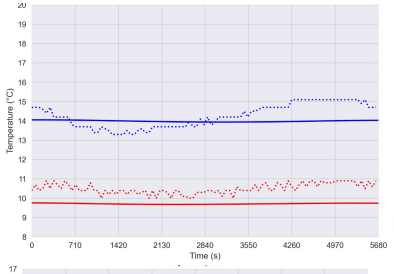
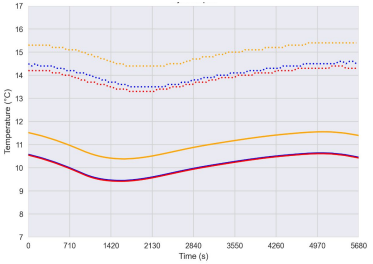
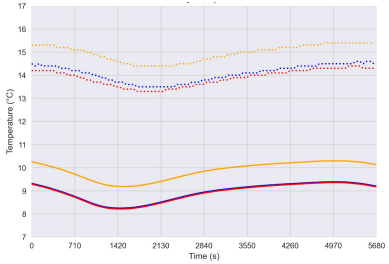
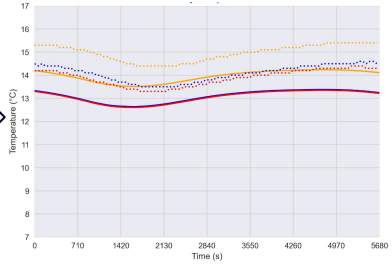
Thermal Model Not Correlated

Thermal Orbit Telemetry

	Not Correlated Model	Radiation Correlation	Conduction Correlation Tool
Secondary Payload			
Battery Pack			
Gyroscopes			

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Thermal Model Correlation using Maya TMG Thermal Correlation Tool

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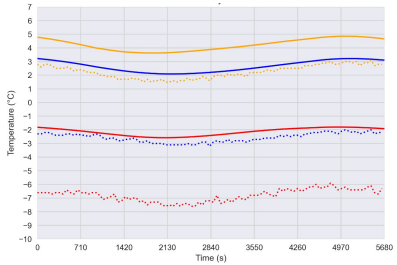
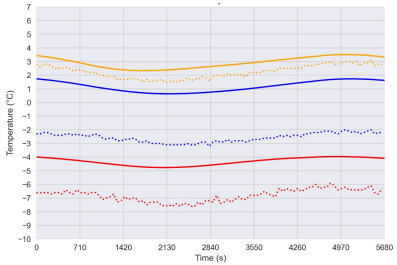
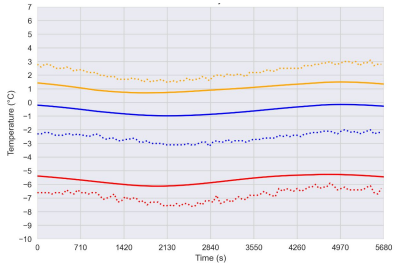
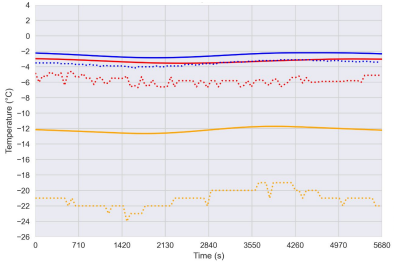
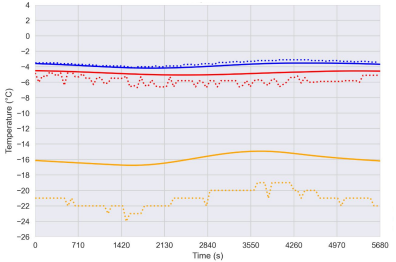
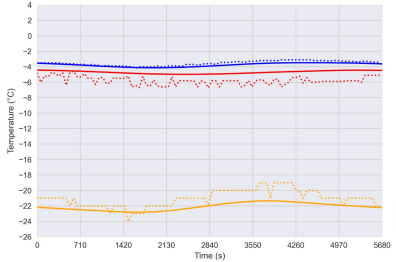
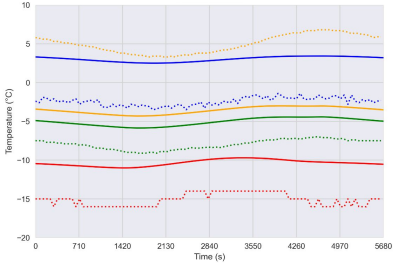
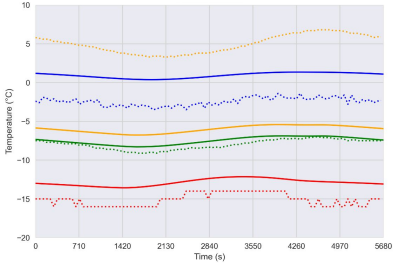
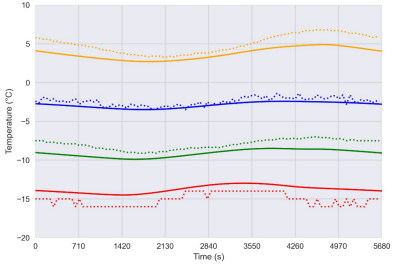
	Not Correlated Model	Radiation Correlation	Conduction Correlation Tool
Micro Payload			
Propulsion Set			
Electronic Rack			

Thermal Model Not Correlated

Thermal Orbit Telemetry

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Thermal Model Correlation using Maya TMG Thermal Correlation Tool

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Digital Industries Software

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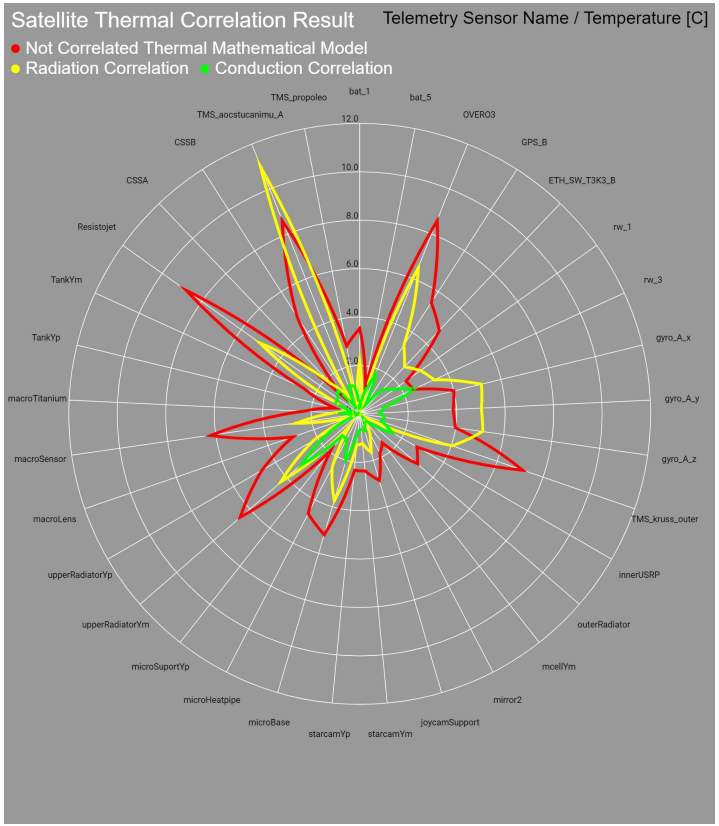
Satellite Thermal Correlation Final Temperature Error

- Not Correlated TMM
- Radiation Correlation
- Conduction Correlation Tool



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