Appendix Q

Thermal Correlation of BepiColombo MOSIF 10 Solar Constants Simulation Test

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Abstract

BepiColombo is the first European mission directed so close to the Sun and will provide the greatest advance in understanding Mercury. It is an international cooperation coordinated by the European Space Agency (ESA) with the participation of the Japan Aerospace Exploration Agency (JAXA).
The mission is composed of four spacecraft, the most important of which are the Mercury Planetary Orbiter (MPO), which will map and study the planet surface and interior from a low orbit, and the Mercury Magnetospheric Orbiter (MMO), whose main goal is to investigate the magnetosphere of the planet closer to the Sun.
One of the most complex and demanding activities related to the BepiColombo thermal control concerns the design of the MOSIF, the solar shield which will protect the Japanese module (MMO) during the journey from the Earth to Mercury. BepiColombo will be exposed to an ever increasing solar heat flux along the whole cruise: up to ten times higher, once orbiting around Mercury, than when launched from the Earth.
A Thermal Balance Test (TBT) of MOSIF was held in ESA/ESTEC in November 2010. This presentation compares two different methods for correlating the test data with the TMM analysis results.
The first part is focused on a brief description of the activities related to the correlation of MOSIF TMM; this work has been carried out by applying the rules specified by a TAS-I internal procedure. The second part reports the process followed to achieve the same correlation level in a different way, which consists in implementing a stochastic approach by means of iSight^{TM}. Eventually, advantages and disadvantages in using these two different methods are highlighted.

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THERMAL CORRELATION OF BEPICOLOMBO MOSIF 10 SOLAR CONSTANTS SIMULATION TEST

Written by: *Tiziano Malosti, Gianluca Filiddani*

Presented by: *Savino De Palo*

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INTRODUCTION

2

- MOSIF ⇨ BepiColombo solar shield which shades the MMO (the Japanese orbital module) during the cruise mission phase

- Two different approaches for the correlation of MOSIF TMM with 10 solar constants Thermal Balance Test (TBT) held in ESA/ESTEC in November 2010 :

  1. Standard / classical method
  2. Optimization / DoE approach using iSight™

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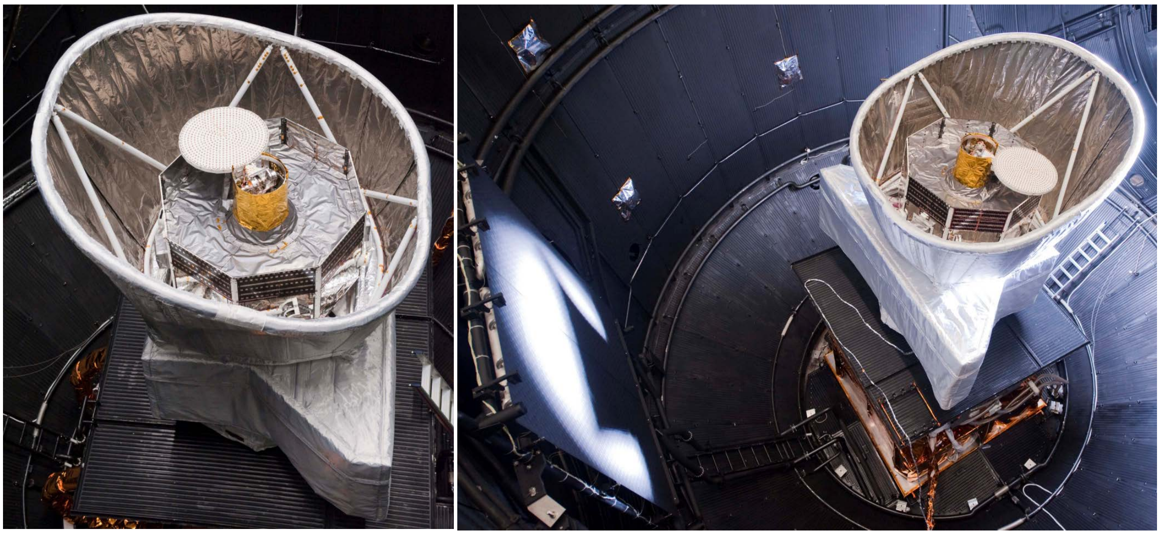
3

MOSIF TEST ARTICLE INTO ESTEC LARGE SPACE SIMULATOR (LSS)



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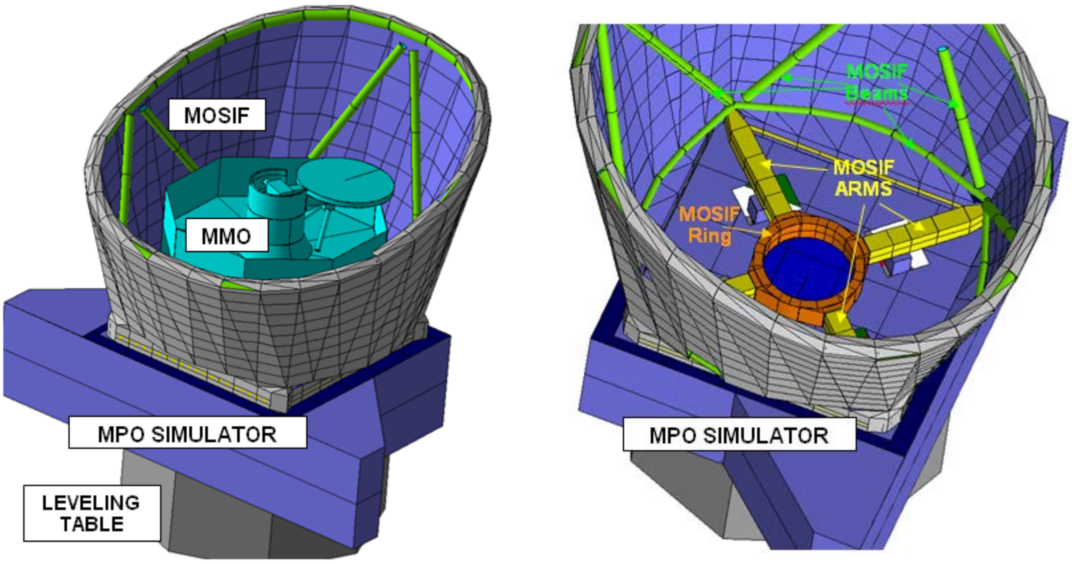
ESARAD GMM OF MOSIF TEST ARTICLE



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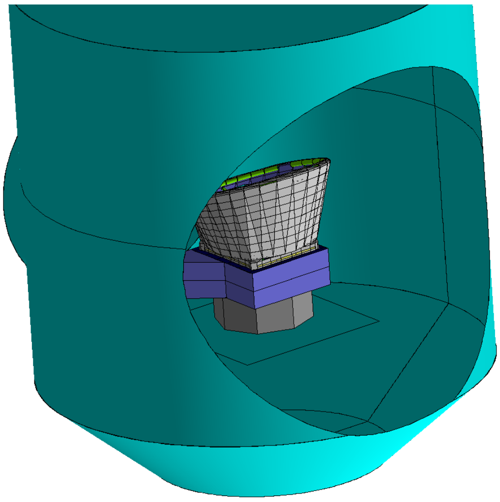
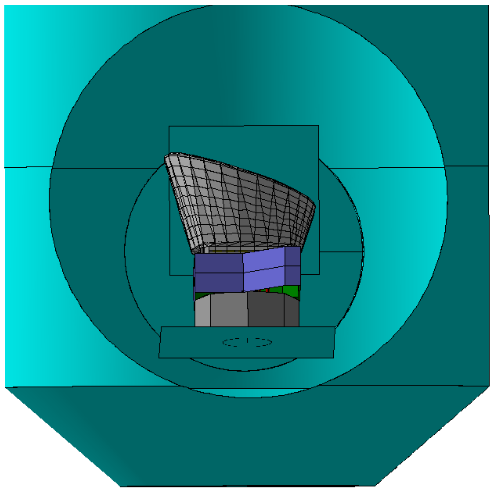
MOSIF TEST ARTICLE INTO LSS – ESARAD MODEL



NOMINAL POSITION



SURVIVAL POSITION

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STANDARD CORRELATION

6

STANDARD CORRELATION MAIN RESULTS

1. GMM Replacement

   - Original MOSIF Sunshade GMM provided by manufacturer did not reproduce the concavity on +Y side (see next chart) of the test item

   - Original GMM replaced with a new one derived from CATIA model, meshed with HyperMesh tool and exported to ESATAN-TMS via NASTRAN .bdf import capability

2. MLI parameters refinement

   - MLI thermo-physical parameters (equivalent emissivities used in radiative conductor calculation) were updated to obtain a proper simulation of MLI performances

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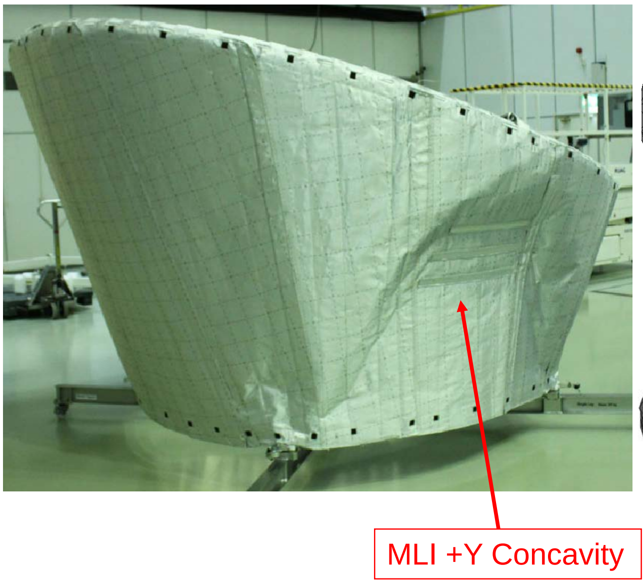
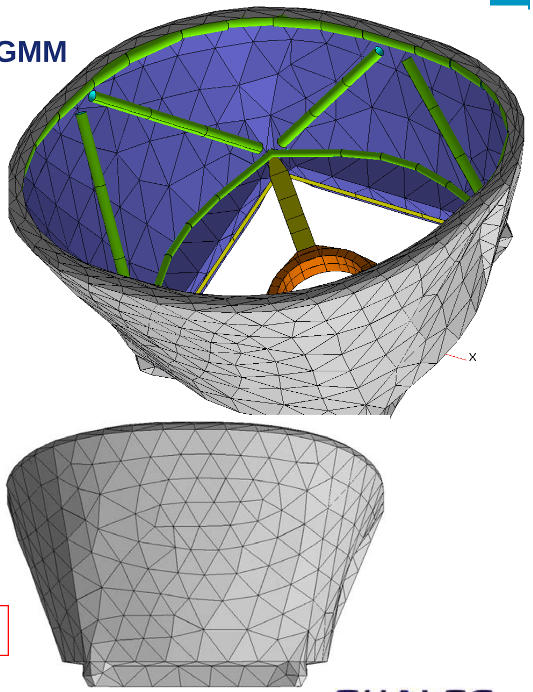
STANDARD CORRELATION

7

MOSIF SUNSHADE +Y CONCAVITY & NEW GMM





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STANDARD CORRELATION

8

- MOSIF Sunshade TMM was correlated with TBT results, obtaining **fully acceptable values of Delta-T and standard deviation (σ) for all cases** as showed by table in the following slide
- **The correlated values of MLI** thermo-physical parameters are reported in the table here below

Thermo-Physical Parameter	Test article items	Old Value	Updated value
Equivalent emissivity in the radiative conductor	External 1st layer (Nextel) → MLI ext 2nd layer	*0.140*	**0.140**
Equivalent emissivity in the radiative conductor	MLI ext 2nd layer → MLI inner layer Titanium **(APPLIED IN THE +X HGA CONCAVITY)**	*0.019*	**0.023**
Equivalent emissivity in the radiative conductor	MLI ext 2nd layer → MLI inner layer Titanium **(APPLIED IN THE MLI GAP)**	*0.019*	**0.024**
Equivalent emissivity in the radiative conductor	MLI ext 2nd layer → MLI inner layer Titanium **(ALL THE OTHER SUNSHADE ZONES)**	*0.019*	**0.019**

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STANDARD CORRELATION

9

MOSIF SUNSHADE MLI	Phase 3 - Cold calibration			Phase 4 - Hot Final Cruise			Phase 6 - Survival Sun from +X			Phase 7 - Intermediate Cruise			Phase 8 - Initial Cruise		
	Post Correlation results	TEST DATA 02/12/2010 18.51.00	Δ T (Test-Analysis)	Post Correlation results	TEST DATA 04/12/2010 13.07.00	Δ T (Test-Analysis)	Post Correlation results	TEST DATA 05/12/2010 14.46.00	Δ T (Test-Analysis)	Post Correlation results	TEST DATA 07/12/2010 10.42.00	Δ T (Test-Analysis)	Post Correlation results	TEST DATA 08/12/2010 16.21.00	Δ T (Test-Analysis)
+Y UPPER (Outer Ti layer)	-148.0	-138.6	9.4	44.7	79.1	34.4	-79.8	-52.6	27.2	-24.7	-0.7	24.0	-82.4	-61.2	21.2
+Y UPPER (Ti layer behind nextel)	-176.2	-133.2	43.0	268.7	313.6	44.9	-8.8	-16.3	-7.5	146.1	180.4	34.4	37.9	68.0	30.1
+Y MEDIUM (Outer Ti layer)	-131.3	-135.3	-4.0	48.7	77.2	28.5	-60.8	-14.6	46.2	-20.1	-0.2	19.9	-75.3	-60.0	15.3
+Y MEDIUM (Ti layer behind nextel)	-173.2	-132.6	40.6	272.3	303.0	30.7	32.8	118.1	85.3	148.9	172.5	23.6	40.0	61.5	21.5
+Y LOWER (Outer Ti layer)	-112.6	-125.4	-12.8	56.3	98.3	42.0	-49.9	6.9	56.8	-12.2	15.1	27.2	-64.7	-49.5	15.2
+Y LOWER (Ti layer behind nextel)	-168.8	-127.8	41.0	274.1	332.8	58.7	27.6	147.4	119.8	150.3	193.3	43.0	41.2	76.1	34.9
+Y+X UPPER (Outer Ti layer)	-148.1	-148.3	-0.3	-3.5	17.6	21.1	43.9	92.2	48.3	-60.3	-36.2	24.1	-105.1	-81.5	23.6
+Y+X UPPER (Ti layer behind nextel)	-176.1	-150.1	26.0	172.5	166.2	-6.3	264.7	283.2	18.5	71.9	65.2	-6.7	-16.6	-26.9	-10.3
+Y+X MEDIUM (Outer Ti layer)	-130.2	-143.8	-13.6	2.5	22.7	20.2	47.9	110.7	62.8	-53.2	-29.5	23.7	-94.7	-74.6	20.1
+Y+X MEDIUM (Ti layer behind nextel)	-172.8	-150.7	22.1	174.6	173.6	-1.0	269.8	346.8	77.0	73.5	78.1	4.6	-15.3	-16.0	-0.7
+Y+X LOWER (Outer Ti layer)	-106.3	-138.2	-31.9	4.4	6.2	1.8	56.1	118.4	62.3	-46.4	-39.5	6.9	-80.3	-78.1	2.2
+Y+X LOWER (Ti layer behind nextel)	-166.7	-147.1	19.6	161.5	56.6	-104.9	271.1	344.9	73.8	63.5	-4.3	-67.9	-22.3	-63.3	-41.1
-Y UPPER (Outer Ti layer)	-125.2	-134.0	-8.8	-93.8	-85.0	8.8	-52.5	-28.7	23.8	-111.3	-109.7	1.5	-119.3	-123.7	-4.4
-Y UPPER (Ti layer behind nextel)	-171.7	-150.5	21.2	-141.4	-115.9	25.5	39.7	40.9	1.2	-157.8	-133.6	24.2	-166.5	-143.4	23.1
-Y LOWER (Outer Ti layer)	-110.8	-122.7	-11.9	-83.1	-83.2	-0.1	-47.5	-18.1	29.4	-98.5	-103.7	-5.2	-105.1	-114.3	-9.2
-Y LOWER (Ti layer behind nextel)	-168.2	-142.8	25.4	-141.6	-114.1	27.5	34.6	80.1	45.5	-156.2	-129.1	27.1	-163.6	-136.9	26.7
MOSIF SUNSHADE MLI AVERAGE DELTA T	*10.3*			*14.5*			*48.2*			*12.8*			*10.5*		
MOSIF SUNSHADE MLI STD DEVIATION	*22.8*			*36.7*			*32.7*			*25.7*			*19.7*		

Post Test Predictions vs TBT

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STANDARD CORRELATION

10

MOSIF SUNSHADE MLI	Phase 3 - Cold calibration			Phase 4 - Hot Final Cruise			Phase 6 - Survival Sun from +X			Phase 7 - Intermediate Cruise			Phase 8 - Initial Cruise		
	Post Correlation results	TEST DATA 02/12/2010 18.51.00	Δ T (Test-Analysis)	Post Correlation results	TEST DATA 04/12/2010 13.07.00	Δ T (Test-Analysis)	Post Correlation results	TEST DATA 05/12/2010 14.46.00	Δ T (Test-Analysis)	Post Correlation results	TEST DATA 07/12/2010 10.42.00	Δ T (Test-Analysis)	Post Correlation results	TEST DATA 08/12/2010 16.21.00	Δ T (Test-Analysis)
+Y UPPER (Outer Ti layer)	-152.7	-138.6	14.1	81.3	79.1	-2.2	-59.4	-52.6	6.8	2.6	-0.7	-3.3	-64.5	-61.2	3.3
+Y UPPER (Ti layer behind nextel)	-174.5	-133.2	41.3	294.4	313.6	19.2	-9.6	-16.3	-6.7	165.9	180.4	14.5	52.6	68.0	15.4
+Y MEDIUM (Outer Ti layer)	-145.0	-135.3	9.7	84.3	77.2	-7.1	-13.5	-14.6	-1.1	5.4	-0.2	-5.6	-61.4	-60.0	1.4
+Y MEDIUM (Ti layer behind nextel)	-172.3	-132.6	39.7	297.3	303.0	5.7	110.9	118.1	7.2	168.2	172.5	4.3	54.3	61.5	7.2
+Y LOWER (Outer Ti layer)	-119.3	-125.4	-6.1	92.3	98.3	6.0	1.8	6.9	5.1	13.4	15.1	1.7	-50.8	-49.5	1.3
+Y LOWER (Ti layer behind nextel)	-163.7	-127.8	35.9	302.6	332.8	30.2	134.3	147.4	13.1	172.4	193.3	20.9	57.6	76.1	18.5
+Y+X UPPER (Outer Ti layer)	-153.1	-148.3	4.8	12.1	17.6	5.5	86.6	92.2	5.6	-49.5	-36.2	13.2	-99.7	-81.5	18.2
+Y+X UPPER (Ti layer behind nextel)	-174.5	-150.1	24.4	169.6	166.2	-3.4	301.4	283.2	-18.2	69.6	65.2	-4.5	-18.2	-26.9	-8.7
+Y+X MEDIUM (Outer Ti layer)	-143.2	-143.8	-0.6	28.4	22.7	-5.7	100.6	110.7	10.1	-36.3	-29.5	6.8	-88.7	-74.6	14.1
+Y+X MEDIUM (Ti layer behind nextel)	-170.5	-150.7	19.8	177.8	173.6	-4.2	303.4	346.8	43.4	76.0	78.1	2.1	-13.3	-16.0	-2.7
+Y+X LOWER (Outer Ti layer)	-122.6	-138.2	-15.6	-10.8	6.2	17.0	111.7	118.4	6.8	-60.7	-39.5	21.2	-95.3	-78.1	17.2
+Y+X LOWER (Ti layer behind nextel)	-163.0	-147.1	15.9	87.9	56.6	-31.3	314.0	344.9	31.0	7.2	-4.3	-11.5	-62.5	-63.3	-0.8
-Y UPPER (Outer Ti layer)	-129.0	-134.0	-5.0	-83.8	-85.0	-1.2	-29.0	-28.7	0.3	-107.6	-109.7	-2.1	-120.2	-123.7	-3.6
-Y UPPER (Ti layer behind nextel)	-167.3	-150.5	16.8	-126.4	-115.9	10.5	53.0	40.9	-12.1	-147.5	-133.6	14.0	-159.6	-143.4	16.2
-Y LOWER (Outer Ti layer)	-111.8	-122.7	-10.9	-78.8	-83.2	-4.4	-27.3	-18.1	9.2	-97.0	-103.7	-6.7	-105.3	-114.3	-9.0
-Y LOWER (Ti layer behind nextel)	-160.7	-142.8	17.9	-129.7	-114.1	15.6	60.6	80.1	19.5	-146.5	-129.1	17.4	-155.1	-136.9	18.2
MOSIF SUNSHADE MLI AVERAGE DELTA T	*12.6*			*3.1*			*7.5*			*5.1*			*6.6*		
MOSIF SUNSHADE MLI STD DEVIATION	*17.5*			*14.1*			*15.1*			*10.5*			*10.1*		

Standard Correlation Results vs TBT

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OPTIMIZATION / DoE CORRELATION

11

- MOSIF Sunshade TMM correlation redone through an Optimization /DoE approach
- Main goals of this "exercise" were:
  - Confirm and refine results obtained with the standard method
  - Test the applicability of the software to the correlation task
- iSight™is a Dassault Système product sold under the Simulia™ brand is able to run multiple TMM cases through an automatic procedure which allows the variation of specified parameters within user-imposed ranges to perform DoE, Optimization, Stochastic analysis, Monte Carlo Simulation etc.

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OPTIMIZATION / DoE CORRELATION

12

- iSight™ provides a suite of visual tools to set up and manage computer software required to run simulation-based design processes:
  - commercial CAD/CAE software
  - internally developed programs
  - Matlab™, Excel™ spreadsheets, etc.
- Advantage of the tool:
  - Rapid integration of applications
  - Automatic run of calculation chain with significantly speed up the design/test space exploration
  - Advanced techniques for Optimization, DFSS (Design for Six Sigma), Approximations and DoE (Design of Experiment) available with the tool

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OPTIMIZATION / DoE CORRELATION

13

- Selection of significant parameters for the Optimization / DoE took advantage of the experience gained from the standard correlation: correct physical understanding of the TMM response to the changes of all the most significant thermal parameters

- 3 equivalent IR emissivities were selected for this scope

Thermo-Physical Parameter	Test article items	Parameter Name
Equivalent emissivity in the radiative conductor	External 1st layer (Nextel) → MLI ext 2nd layer	MOSIF_EPS_12
Equivalent emissivity in the radiative conductor	MLI ext 2nd layer → MLI inner layer Titanium	MOSIF_SS_EPS
Equivalent emissivity in the radiative conductor	MLI on GAP position	MOSIF_GAP_EPS

- Optimization/DoE goal: minimization of the temperature differences between TMM and TBT

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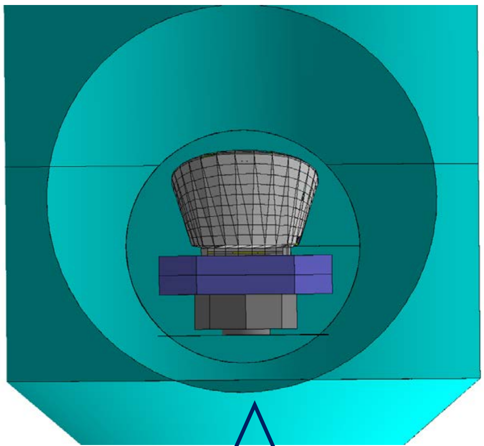
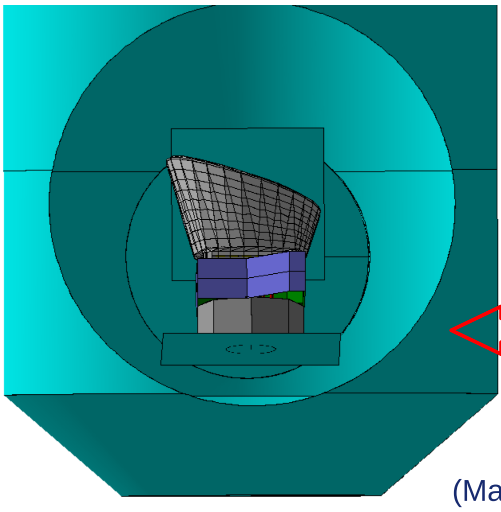
OPTIMIZATION / DoE CORRELATION

TARGETS of Correlation:
Delta temperatures Test – Analysis, calculated with an **Excel Spreadsheet**





TEST CASES:
Phase 4 – *Hot Final Cruise*
Phase 6 – *Survival*

(Maximum) Solar Heat Flux =13000 W/m²

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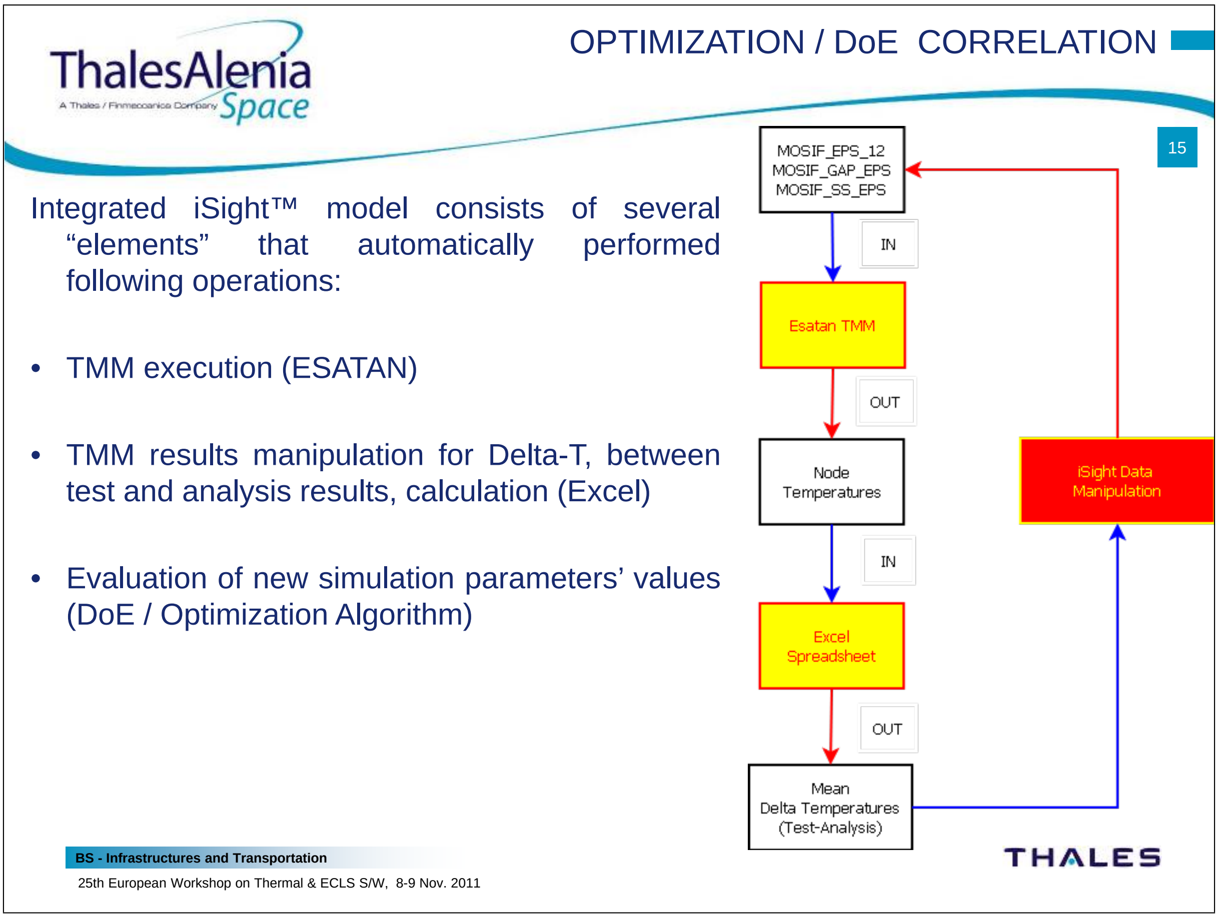
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OPTIMIZATION / DoE CORRELATION
15
Integrated iSight™ model consists of several "elements" that automatically performed following operations:
• TMM execution (ESATAN)
• TMM results manipulation for Delta-T, between test and analysis results, calculation (Excel)
• Evaluation of new simulation parameters' values (DoE / Optimization Algorithm)
MOSIF_EPS_12
MOSIF_GAP_EPS
MOSIF_SS_EPS
IN
Esatan TMM
OUT
Node Temperatures
IN
Excel Spreadsheet
OUT
Mean Delta Temperatures (Test-Analysis)
iSight Data Manipulation
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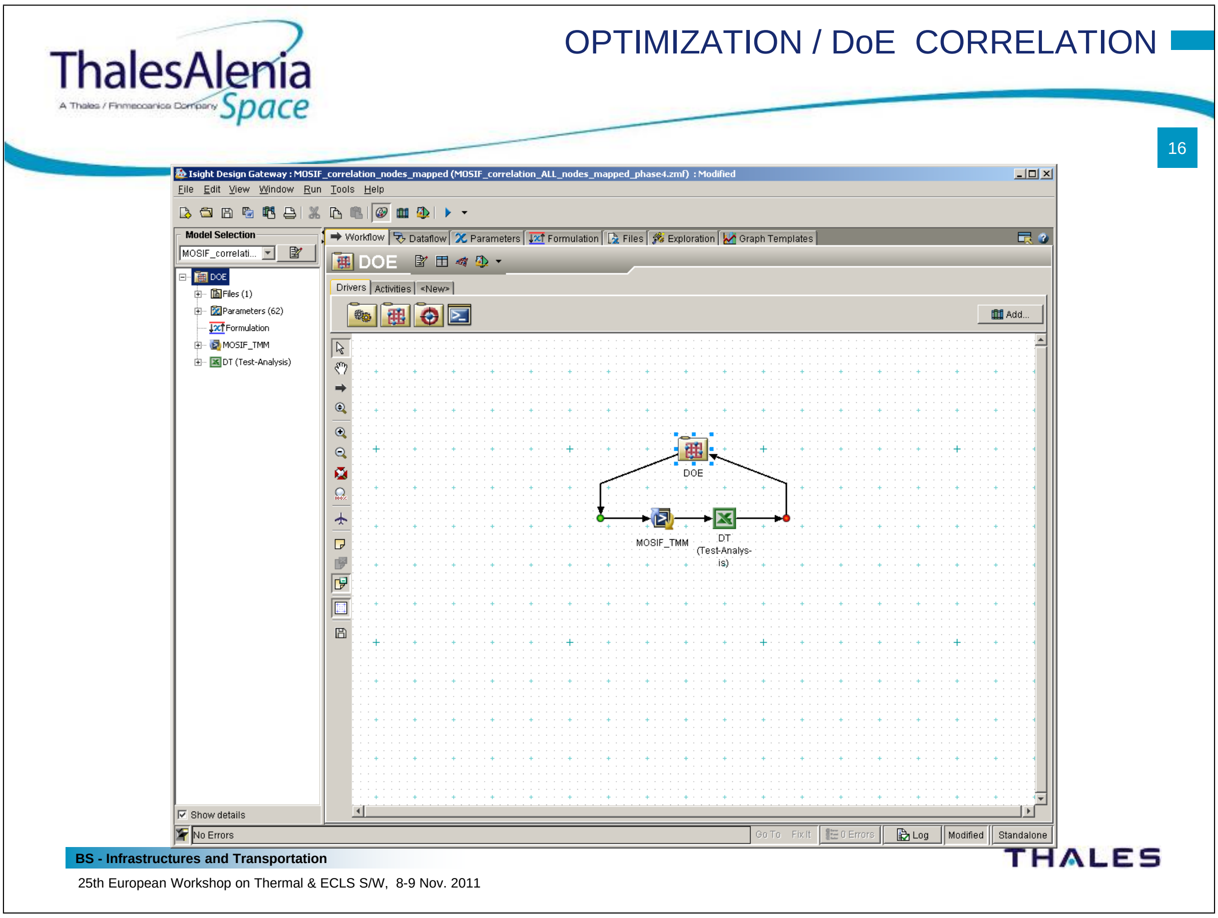
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OPTIMIZATION / DoE CORRELATION
16
Isight Design Gateway : MOSIF_correlation_nodes_mapped (MOSIF_correlation_ALL_nodes_mapped_phase4.zmf) : Modified
File Edit View Window Run Tools Help
Model Selection
Workflow Dataflow Parameters Formulation Files Exploration Graph Templates
DOE
Drivers Activities <New>
Files (1)
Parameters (62)
Formulation
MOSIF_TMM
DT (Test-Analysis)
Add...
DOE
MOSIF_TMM
DT (Test-Analysis)
Show details
No Errors
Log Modified Standalone
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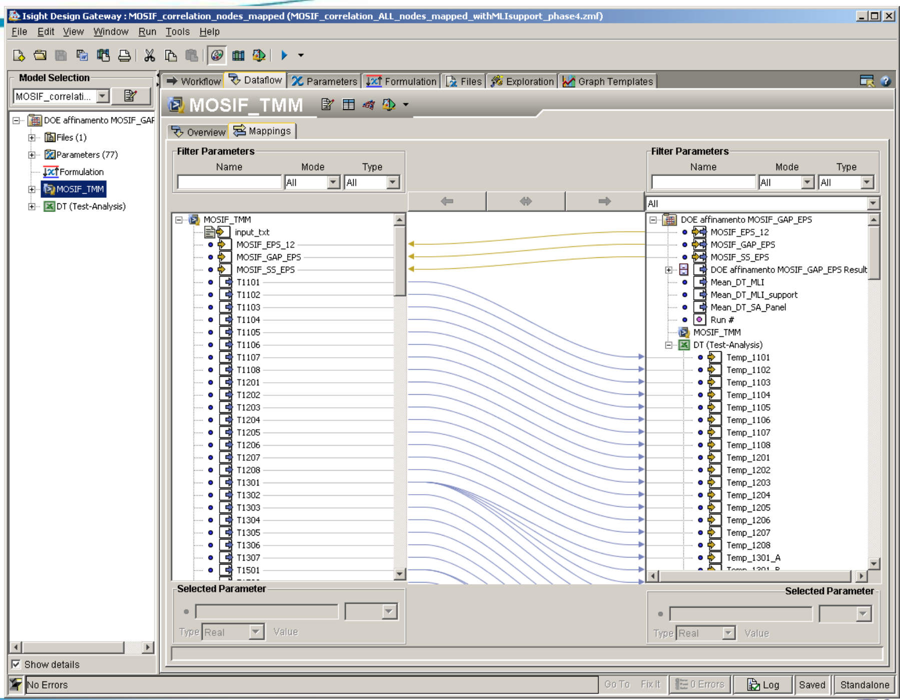
OPTIMIZATION / DoE CORRELATION

17



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OPTIMIZATION / DoE CORRELATION

18

- At the beginning 5 DoE (Latin Hypercube -20 levels) were performed, starting with
  - MOSIF_EPS_12 starting range 0.01-0.9
  - MOSIF_GAP_EPS and MOSIF_SS_EPS starting range 0.01-0.1

- The first set of DoE are in line with the standard correlation results especially for MOSIF_EPS_12 and MOSIF_SS_EPS (see table below).

	Correlated Values (Standard Correlation)	**DoE Results**
MOSIF_EPS_12	0.14	0.123
MOSIF_GAP_EPS	0.024	0.015
MOSIF_SS_EPS	0.019	0.018

- Refinement of DoE results were carried out with an Optimization (Downhill Simplex method) run for Phase 4 (Hot Final Cruise)

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19

- Optimization results for Phase 4 – Hot Final Cruise

	Optimization Results (Phase 4)	Correlated Values (Standard Correlation)
MOSIF_EPS_12	0.1259	0.14
MOSIF_GAP_EPS	0.0258	0.024
MOSIF_SS_EPS	0.0186	0.019

Phase 4	Mean ΔT	Standard Deviation	Mean ΔT (Standard Correlation – Phase 4)	Standard Deviation (Standard Correlation – Phase 4)
MOSIF Beam	**1.88**	4.79	3.0	4.9
MOSIF Lower Ring	3.61	2.85	3.6	2.9
MOSIF Upper Ring	**3.44**	5.61	4.3	5.4
MOSIF Arms	7.76	8.57	7.1	8.7
MOSIF I/F Ring	40.5	1.33	39.8	1.4
MOSIF Internal Panels	5.40	3.80	4.6	3.9
MOSIF S/A Panels	1.98	3.69	1.0	3.6
MOSIF Sunshade MLI	**0.056**	13.79	3.1	14.1
MOSIF MLI Support	**1.89**	13.51	3.1	14.4

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OPTIMIZATION / DoE CORRELATION

20

- Phase 4 Optimization results was validated against Phase 6 (Survival) test data

Phase 6	Mean ΔT	Standard Deviation	Mean ΔT (Standard Correlation – Phase 6)	Standard Deviation (Standard Correlation – Phase 6)
MOSIF Beam	**3.01**	6.81	4.0	7.0
MOSIF Lower Ring	**1.88**	3.82	3.0	4.3
MOSIF Upper Ring	**1.04**	5.47	1.8	5.6
MOSIF Arms	9.00	8.23	8.4	8.4
MOSIF I/F Ring	39.92	2.14	39.4	2.2
MOSIF Internal Panels	4.63	5.08	4.0	5.2
MOSIF S/A Panels	0.97	4.68	0.1	4.9
MOSIF Sunshade MLI	**4.30**	14.58	7.5	15.1
MOSIF MLI Support	**1.80**	17.39	2.7	17.9

- Better results (lower Delta-T w.r.t. standard correlation) are obtained also for Phase 6

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OPTIMIZATION / DoE CORRELATION

21

- Starting from DoE results, another Optimization was performed over Phase 6 data, with a decreasing of MOSIF_EPS_12 but also an increasing of Solar Array (SA) panel Delta-T.
- Results of Phase 4 optimization are preferred since minimize the most important MMO Solar Array panels Delta-T

	Standard Correlation (Phase 4)	Standard Correlation (Phase 6)	Optimization Phase 4 Results	Optimization Phase 6 Results
MOSIF_EPS_12	0.14	0.14	0.1259	**0.1200**
MOSIF_GAP_EPS	0.024	0.024	0.0258	0.0269
MOSIF_SS_EPS	0.019	0.019	0.0186	0.0211
Mean_DT_MLI	3.1	7.5	0.056	0.731
Mean_DT_MLI_support	3.1	2.7	1.89	0.541
Mean_DT_SA_panel	1.0	0.1	1.98	**3.725**

Selected Values

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CONCLUSIONS

22

Optimization/DoE advantages w.r.t. Standard approach:

- Computes the actual emissivity values that minimize the target of correlation (ΔT and Standard Deviations) ⇨ *MOSIF_EPS_12* decreasing example
- Time saving: integrated iSight model build-up and run took about 7 working days instead of several weeks needed for the standard correlation method.

but…

- Results obtained with Optimization/DoE analyses must be critically assessed
- Always verify that the optimal **solution** is **numerically correct and also realistic**

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