Appendix U

Development towards 3D thermography

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Abstract

The presentation reports on an activity aimed at solving the biggest issue of existing IR camera thermography, i.e. the temperature measurement of objects with significant 3D surface variability (wrinkles and folds). Such variations can alter the interpretation of images where the surfaces have significant directional emissivity variations and hot sources are brought in the field of view of the test surfaces. The latter is especially critical when measuring cold objects.
The activity covered the development of a method using IR cameras for 3D geometrical mapping of the test specimen and IR flux measurement. Correction of measured apparent temperature is based on a ray tracing approach. The method developed was validated by test.

Non-contact temperature measurement for thermal vacuum testing

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Non-contact temperature measurement for thermal (vacuum) testing

- Introduction
- Background
- Concept
- Development and validation
- Testing at ESTEC
- Conclusions

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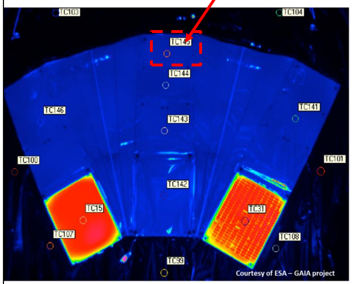
Introduction

All space-craft need a validated thermal model – tested in a TVC



Contact sensor (*limitations*)

- single point; spatially limited
- slow response time (vs camera)
- thermally disruptive (adds to thermal leakage)
- requires all sensors to be perfectly matched (and calibrated) when used in multiples
- visualisation not automatic

Non-contact sensor (*advantages*)

- visualisation available live - detect areas “missed” by contact sensors
- rapid response time (vs. contact sensors)
- non-contact i.e. no thermal disruption, no contamination, or potential for physical damage
- can read true surface temperatures (except if not corrected for ambient/material)

Objective: from captured *apparent* temperature thermal images recover *true* surface temperature

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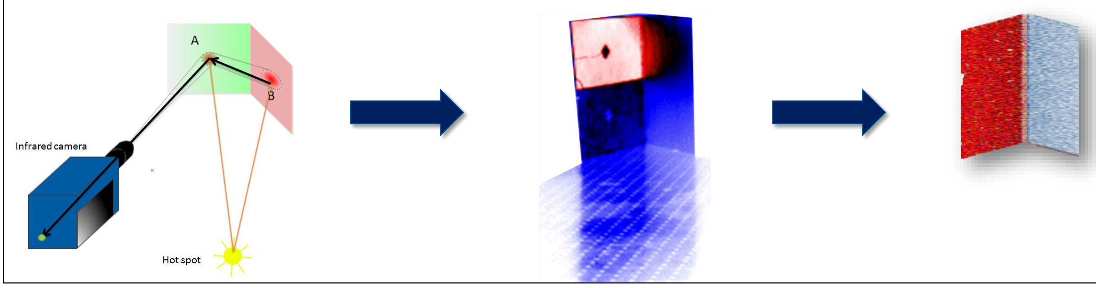
Background – Thermal imaging challenges

- Emissivity: varies with temperature, wavelength, surface angle (material structure)
- TVAC: wide temperature range (including sub ambient)
- Background radiation: external (environment & ‘hotspots’) AND local radiant sources can be reflected from the surface of interest
- Robust thermal imaging temperature measurement traceability (temperature calibration)
- Robust thermal / dimensional spatial registration (geometrical calibration)



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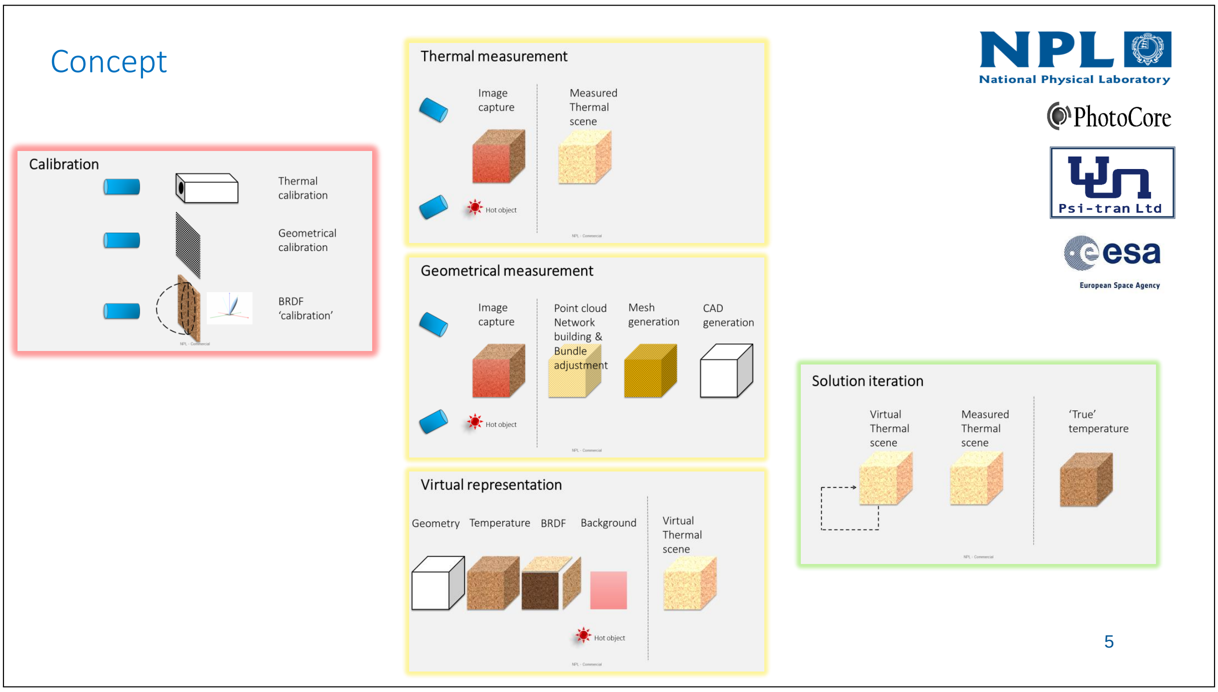
Concept
Calibration
Thermal calibration
Geometrical calibration
BRDF 'calibration'
Thermal measurement
Image capture
Measured Thermal scene
Hot object
Geometrical measurement
Image capture
Point cloud Network building & Bundle adjustment
Mesh generation
CAD generation
Hot object
Virtual representation
Geometry
Temperature
BRDF
Background
Virtual Thermal scene
Hot object
Solution iteration
Virtual Thermal scene
Measured Thermal scene
'True' temperature
NPL
National Physical Laboratory
PhotoCore
Psi-tran Ltd
esa
European Space Agency
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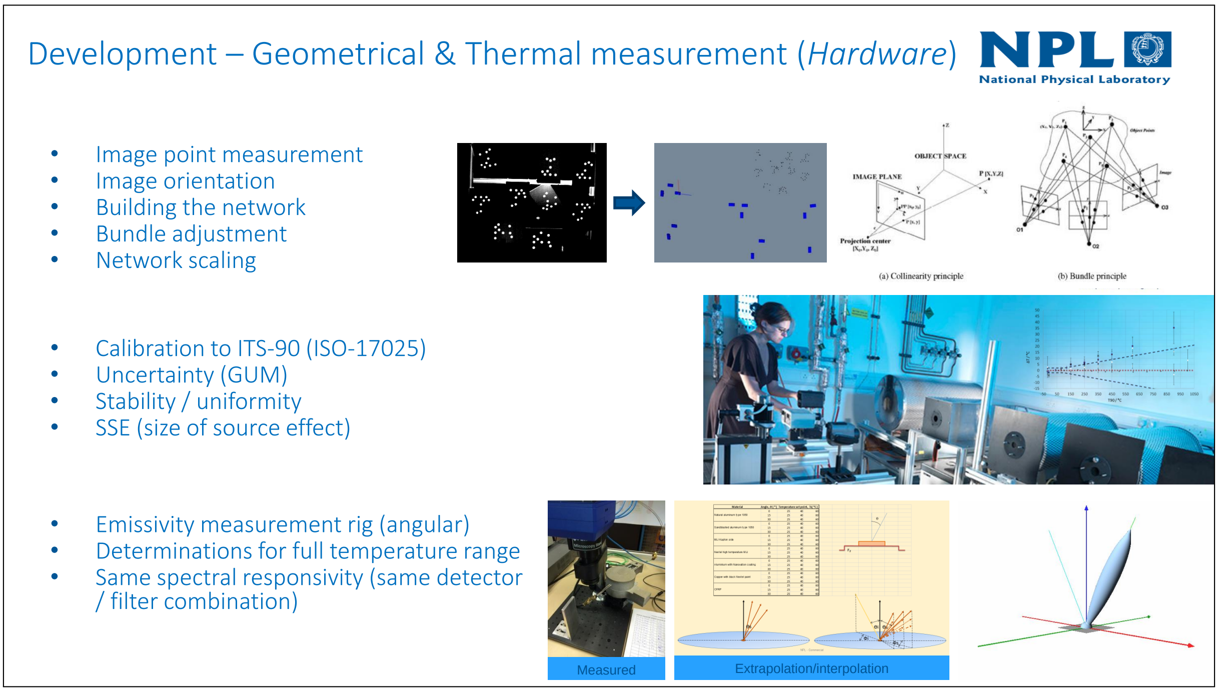
Development – Geometrical & Thermal measurement (*Hardware*)
NPL
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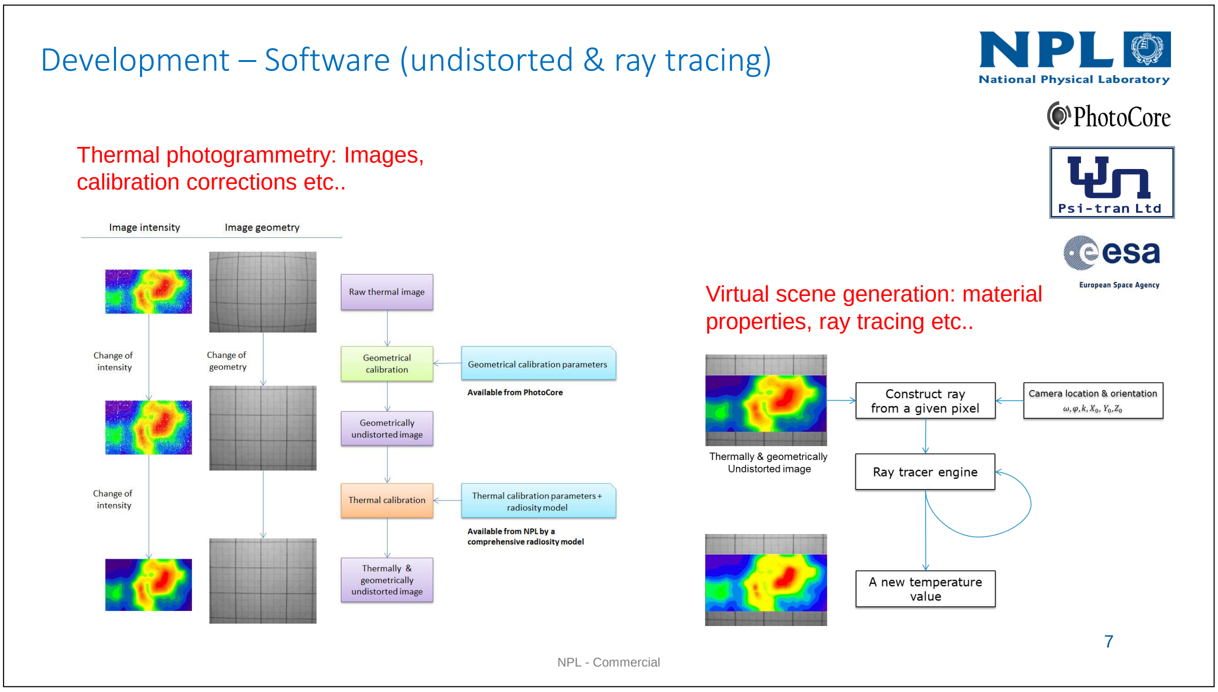
• Image point measurement
• Image orientation
• Building the network
• Bundle adjustment
• Network scaling
OBJECT SPACE
IMAGE PLANE
Projection center
(a) Collinearity principle
(b) Bundle principle
• Calibration to ITS-90 (ISO-17025)
• Uncertainty (GUM)
• Stability / uniformity
• SSE (size of source effect)
• Emissivity measurement rig (angular)
• Determinations for full temperature range
• Same spectral responsivity (same detector / filter combination)
Measured
Extrapolation/interpolation


Development – Software (undistorted & ray tracing)
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National Physical Laboratory
PhotoCore
Psi-tran Ltd
esa
European Space Agency
Thermal photogrammetry: Images, calibration corrections etc..
Image intensity
Image geometry
Change of intensity
Change of geometry
Change of intensity
Raw thermal image
Geometrical calibration
Geometrical calibration parameters
Available from PhotoCore
Geometrically undistorted image
Thermal calibration
Thermal calibration parameters + radiosity model
Available from NPL by a comprehensive radiosity model
Thermally & geometrically undistorted image
Virtual scene generation: material properties, ray tracing etc..
Thermally & geometrically Undistorted image
Construct ray from a given pixel
Camera location & orientation
Ray tracer engine
A new temperature value
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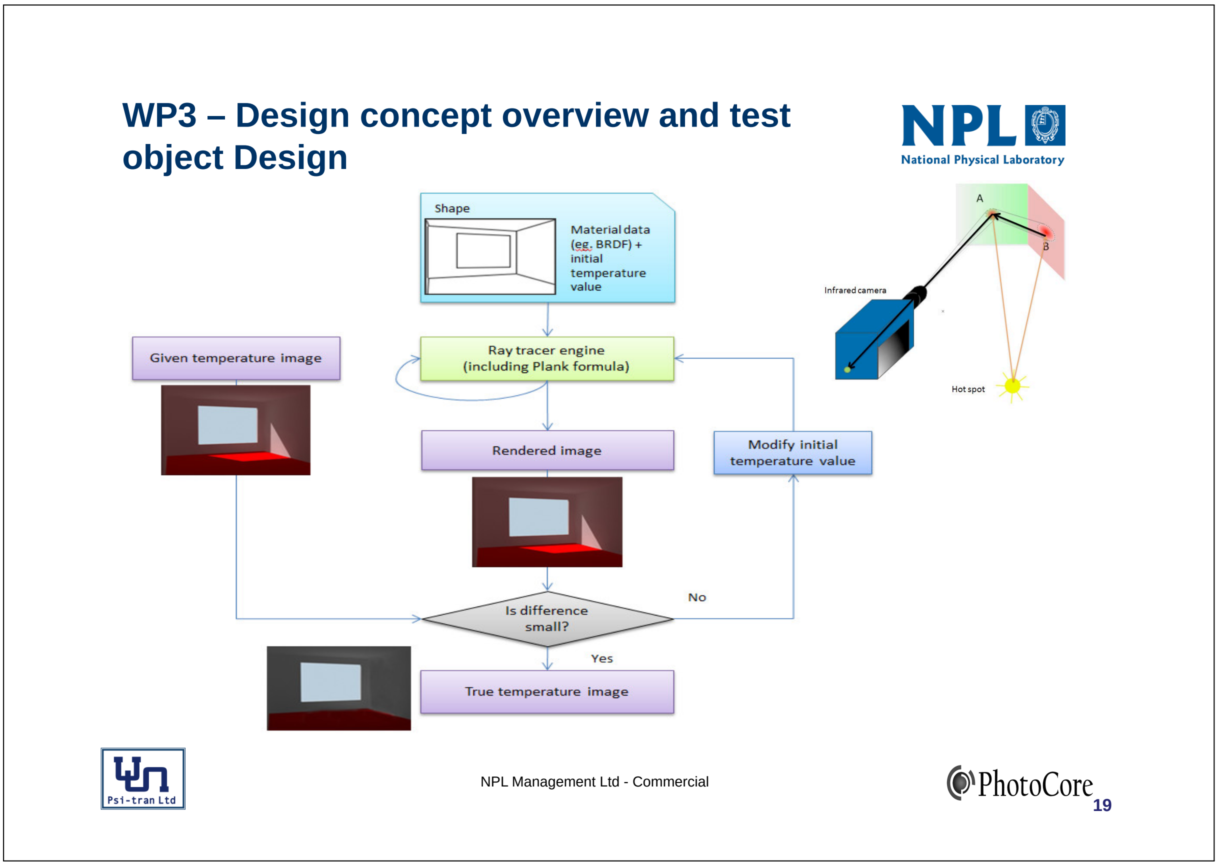
WP3 – Design concept overview and test object Design
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Shape
Material data (eg. BRDF) + initial temperature value
Given temperature image
Ray tracer engine (including Plank formula)
Rendered image
Modify initial temperature value
Is difference small?
No
Yes
True temperature image
Infrared camera
A
B
Hot spot
Psi-tran Ltd
NPL Management Ltd - Commercial
PhotoCore
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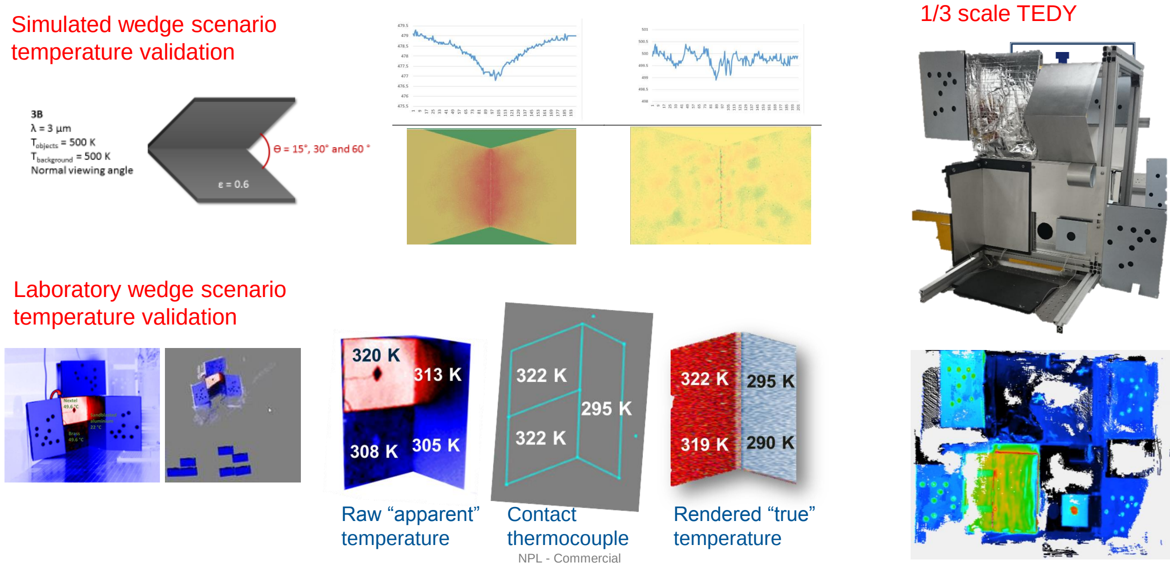
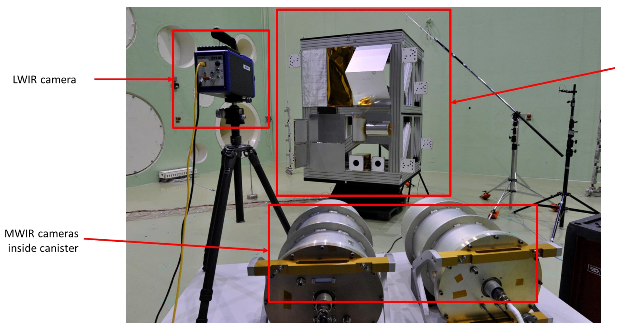
Validation – simulated and laboratory



Validation – ESTEC



#	E1 20 °C	E2 30 °C	E3 30 °C rpt	E4 50 °C	E5 50 °C +1kW	E6 50 °C rpt	E7 50 °C +2kw	E8 70 °C	E9 70 °C + hotspot
1 [Nextel]	**None**	None	None	None	None	**None**	None	**None**	None
2 [MLI]	**20.5**	-	20.9	20.8	21.2	**21.6**	22.0	**22.4**	21.6
3 [CFRP]	**20.5**	-	20.6	20.9	22.0	**20.9**	22.7	**21.2**	21.3
4 [B1]	**20.7**	-	31.7	51.1	51.5	**51.7**	51.6	**72.3**	73.0
5 [A1]	**20.4**	-	20.6	20.9	21.3	**20.9**	21.1	**21.3**	21.4
6 [B2]	**20.7**	-	31.3	50.3	50.6	**51.2**	50.9	**71.7**	71.8
7 [A2]	**20.4**	-	20.6	20.8	21.2	**20.8**	21.2	**21.1**	21.2
8 [Roof]	**20.5**								
9 [CylHrz]	**20.9**								
10 [CylVrt]	**20.8**								
11 [BB]	**20.8**								

#	E10 50 °C rpt	E11 50 °C set up	E12 50 °C 12.5kW	E13 50 °C 25kW	E14 50 °C Cool down	E15 50 °C 25kW	E16 50 °C Cool down
1 [Nextel]	None	None	None	None	**None**	None	None
2 [MLI]	21.3	21.4	24.0	27.1	**24.5**	27.7	28.5
3 [CFRP]	21.0	21.1	25.6	34.6	**30.9**	32.2	36.3
4 [B1]	50.1	52.9	53.1	53.1	**53.4**	53.8	54.1
5 [A1]	20.8	21.1	21.3	22.9	**22.9**	22.7	23.8
6 [B2]	49.6	51.9	51.8	52.2	**52.2**	52.3	52.6
7 [A2]	20.7	21.0	21.2	22.8	**22.7**	22.4	23.5
8 [Roof]	23.0	23.3	24.0	25.9	**25.9**	25.8	27.3
9 [CylnH]	48.7	49.6	49.9	52.6	**52.6**	52.3	54.0
10 [CylnV]	48.5	49.4	49.9	52.5	**52.2**	52.2	53.9
11 [BB]	48.4	54.8	54.8	55.0	**55.0**	55.1	55.2

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8b. WP5 -Pre-test at NPL and ESA pre test and full test at ESTEC – data collection

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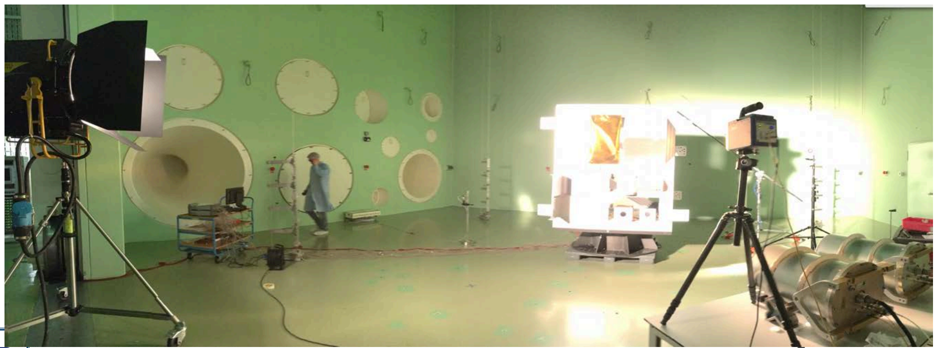
- Software validation trials at ESTEC
  - A pre-test was done to check operation of the TEDY and cameras and to trial process some data – this was successful producing similar results to the NPL test.
  - Then - ESTEC TEDY (full test) was done with project team collecting data and pre-evaluation results.
  - TEDY shown in ambient conditions and with 25kw "sun"



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8c. WP5 -Pre-test at NPL and ESA pre test and full test at ESTEC – data collection

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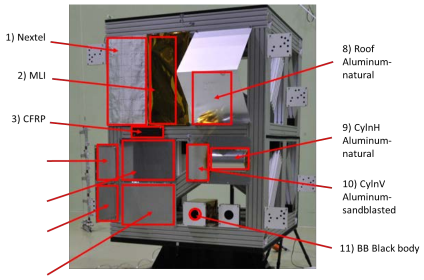
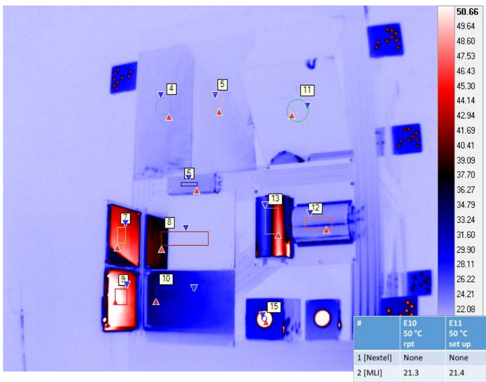
- Example test data collected – thermocouple data and example IR image from one MW camera
- 16 data sets in all collected with 2 MW and 1 LW – temperatures of heated zones from 20-70°C





#	E1 20 °C	E2 30 °C	E3 30 °C rpt	E4 50 °C	E5 50 °C +1kW	E6 50 °C rpt	E7 50 °C +2kw	E8 70 °C	E9 70 °C + hotspot
1 [Nextel]	None	None	None	None	None	None	None	None	None
2 [MLI]	20.5	-	20.9	20.8	21.2	21.6	22.0	22.4	21.6
3 [CFRP]	20.5	-	20.6	20.9	22.0	20.9	22.7	21.2	21.3
4 [B1]	20.7	-	31.7	51.1	51.5	51.7	51.6	72.3	73.0
5 [A1]	20.4	-	20.6	20.9	21.3	20.9	21.1	21.3	21.4
6 [B2]	20.7	-	31.3	50.3	50.6	51.2	50.9	71.7	71.8
[illegible]	[illegible]	[illegible]	0.6	20.8	21.2	20.8	21.2	21.1	21.2
[illegible]	[illegible]	[illegible]	1.3	22.9	23.1	23.2	23.4	25.2	25.1
[illegible]	[illegible]	[illegible]	1.4	50.3	50.4	50.4	50.3	70.0	70.0
[illegible]	[illegible]	[illegible]	1.0	49.9	50.3	49.9	49.8	69.3	69.2
[illegible]	[illegible]	[illegible]	8.0	53.4	54.3	53.4	53.8	70.3	70.6

#	E10 50 °C rpt	E11 50 °C set up	E12 50 °C 12.5kW	E13 50 °C 25kW	E14 50 °C Cool down	E15 50 °C 25kW	E16 50 °C Cool down
1 [Nextel]	None	None	None	None	None	None	None
2 [MLI]	21.3	21.4	24.0	27.1	24.5	27.7	28.5
3 [CFRP]	21.0	21.1	25.6	34.6	30.9	32.2	36.3
4 [B1]	50.1	52.9	53.1	53.1	53.4	53.8	54.1
5 [A1]	20.8	21.1	21.3	22.9	22.9	22.7	23.8
6 [B2]	49.6	51.9	51.8	52.2	52.2	52.3	52.6
7 [A2]	20.7	21.0	21.2	22.8	22.7	22.4	23.5
8 [Roof]	23.0	23.3	24.0	25.9	25.9	25.8	27.3
9 [CylnH]	48.7	49.6	49.9	52.6	52.6	52.3	54.0
10 [CylnV]	48.5	49.4	49.9	52.5	52.2	52.2	53.9
11 [BB]	48.4	54.8	54.8	55.0	55.0	55.1	55.2

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9b. WP6 – Overview of Test data analysis, performance assessment, conclusions, recommendations and forward outlook

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- Effect of reflections and external hot spots reproduced in the ray traced simulations of the IR temperature field.
- Ray-traced/rendered corrected temperature of all regions agrees to thermocouple almost within uncertainties at k=2 (95%confidence)

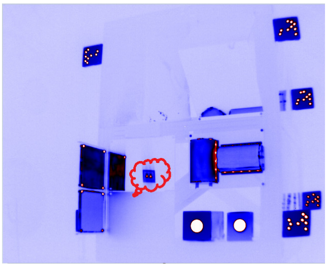
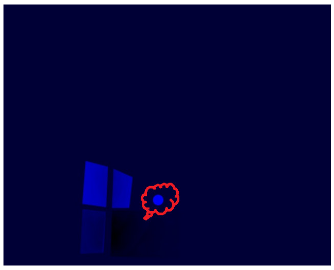
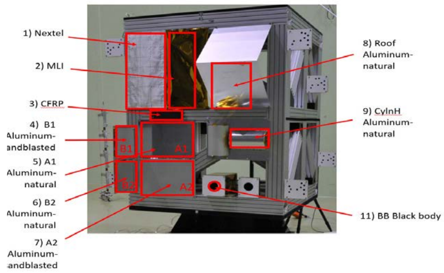



Table 1. Epoch 14 – 50d – after 25kw cool down.

Material and pbrt internal BDRF function	Apparent temperature	Thermocouple temperature	True temperature	Difference temperature
Nextel (0.8, matte)	300	N	301	N
MLI (0.7, mirror)	299	297	302	+5
CFRP (0.9 matte)	306	304	304	0
B1 (0.3, matte)	305	327	330	+3
A1 (0.1, mirror)	306, 297	295	300	+5
B2 (0.1, mirror)	300	325	330	+5
A2 (0.3, matte)	298	295	305	+10
Roof (0.1, mirror)	298	297	302	+5
CylinH (0.1, mirror)	300	326	336	+10
Black body (0.99, matte)	327	328	328	0



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Validation – ESTEC: 50 °C (no illumination)

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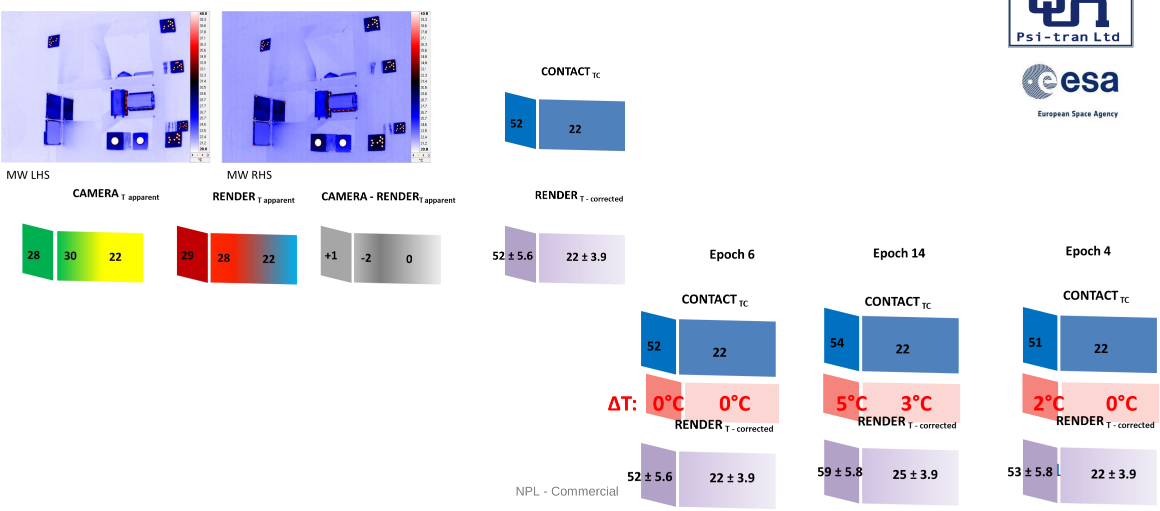

Validation – Uncertainty model

First model uncertainty

Measurement temperarure (IR) =	326	K
Background temperature =	295	K
Surface emissivity =	0.3	
Wavelength =	4.00E-06	µm
c2/lamba Tapparent-1	1.61E-05	
c2/lamba Tsurroundings-1	5.06E-06	
L(TI)+U(emiss) =	-11.54	
L(TI)-U(emiss) =	-11.86	

Symbol	Source of Uncertainty	Value ± std unit	Type	Divisor	Conversion std/°C	Ui
U1	Camera calibration	2.00	B (normal)	1	1	2.0
U2	SSE	0.05	B (normal)	1.73205	0.99999	0.0
U3	Image non-uniformity	5.00	B (rectangular)	1.73205	1	2.9
U4	Distance effect	0.06	B (rectangular)	1.73205	0.88786	0.0
U5	Digitalisation of signal	0.01	B (rectangular)	1.73205	1	0.0
U6	Camera responsivity	0.03	A (normal)	1.00000	1	0.0
U7	T determination of hot objects	2.00	B (rectangular)	1.73205	1	1.2
U8	T determination of background	2.00	B (rectangular)	1.73205	1	1.2
U9	Emissivity of material	0.12	B (normal)	2.00000	70.01	4.2
U10	Camera location	0.06	B (rectangular)	1.73205	1	0.0
U11	Software processing	0.35	A (normal)	1.73205	1	0.2
U12	Ray tracing (BRDF)	1.06	A (normal)	1.73205	1	0.6
				k = 1	U combined	5.8
				k = 2	U combined	11.5

T1	T2
K	K
324	322
330	324

U1	Camera calibration	Value used from manufacturers calibraiton uncertainty and assumed to be k
U2	SSE	Value taken from recent assessment of size of source effect, NPL LW calibra
U3	Image non-uniformity	Value taken from recent calibration assessment of LW IR camera for this tem
U4	Distance effect	Value taken from recent NPL LW IR camera assessment for this temperature
U5	Digitalisation of signal	Estimate from NPL MW IR camera for this temperature set point
U6	Camera responsivity	Estimate from NPL MW IR camera for this temperature set point
U7	T determination of hot objects	Estimate of tempeature determination assuming type T thermocouple used
U8	T determination of background	Estimate of tempeature determination assuming type T thermocouple used
U9	Emissivity of material	Unknown, however estimate taken from recent emissivity investigation with ESTEC and adjusted for this temperature
U10	Camera location	Unknown, likely small effect alignment error from recent NPL LW IR calibration used
U11	Software processing	Multiple runs of software to determine statistical uncertainty
U12	Ray tracing (BRDF)	Multiple runs of software using different BRDF fitted data

Symbol	Source of Uncertainty	Value ± std unit	Type	Divisor	Conversion std/°C	Ui
U1	Camera calibration	1.00	B (normal)	1	1	1.0
U2	SSE	0.05	B (normal)	1.73205	0.99999	0.0
U3	Image non-uniformity	1.00	B (rectangular)	1.73205	1	0.6
U4	Distance effect	0.06	B (rectangular)	1.73205	0.88786	0.0
U5	Digitalisation of signal	0.01	B (rectangular)	1.73205	1	0.0
U6	Camera responsivity	0.03	A (normal)	1.00000	1	0.0
U7	T determination of hot objects	1.00	B (rectangular)	1.73205	1	0.6
U8	T determination of background	1.00	B (rectangular)	1.73205	1	0.6
U9	Emissivity of material	0.05	B (normal)	2.00000	69.64	1.7
U10	Camera location	0.06	B (rectangular)	1.73205	1	0.0
U11	Software processing	0.18	A (normal)	1.73205	1	0.1
U12	Ray tracing (BRDF)	0.64	A (normal)	1.73205	1	0.4
				k = 1	U combined	2.3
				k = 2	U combined	4.6

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9f. WP6 – main conclusions

- The 3-D thermography system can detect most surfaces and reconstruct the surface angles successfully where there is thermal contrast / texture in the image, or where external patterning is “achieved” on mirror surfaces – to better than 1mm at 3m standoff.
- The ray tracing process for correcting temperatures compares well to thermocouple data within the combined standard uncertainty of the system based on a GUM assessment / estimate.
- The system can correct apparent T(IR) temperatures for internal reflections within the structure and external hot sources (where the hot source is correctly modelled or imported into pbrt).
- The system has illustrated how correcting T(IR) temperatures can improve on poorly located thermocouples or where heating is dynamic.
- Uncertainties are on average +/-5°C at 68% confidence with the largest sources of uncertainty being the image non-uniformity and the hemispherical emissivity measurement.
- Uncertainties can be reduced by full traceable calibration of the instruments.

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Conclusions

- A non-contact temperature measurement solution (hardware + software) is fully operational for testing (in ambient scenario)
- Validation tests proved the uncertainty of the true temperature for the mean case to be within the anticipated range, but can be improved as we see the largest sources of uncertainty can be readily reduced
- The method gives confidence in situations where thermocouples are erroneous (placement / malfunction / transient heating)
- A robust metrological approach (calibration, traceability, uncertainty mapping and standardised procedure) ensuring confidence in the geometrical and thermal outputs

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Applications:

- In general where:
  - Non-contact thermometry is beneficial or necessary
  - Higher thermal nodes (measurement points) are of benefit / required
  - Additional measurement (e.g. geometric / dynamic) information is required
  - Thermocouples are missed or read wrong due to their location or local transient heating

Future development:

- In situ thermal and geometrical calibration of sensors
- Use of higher resolution IR cameras
- Combining the visible and IR images
- Improving the true temperature estimation
- Speed-up of the computation

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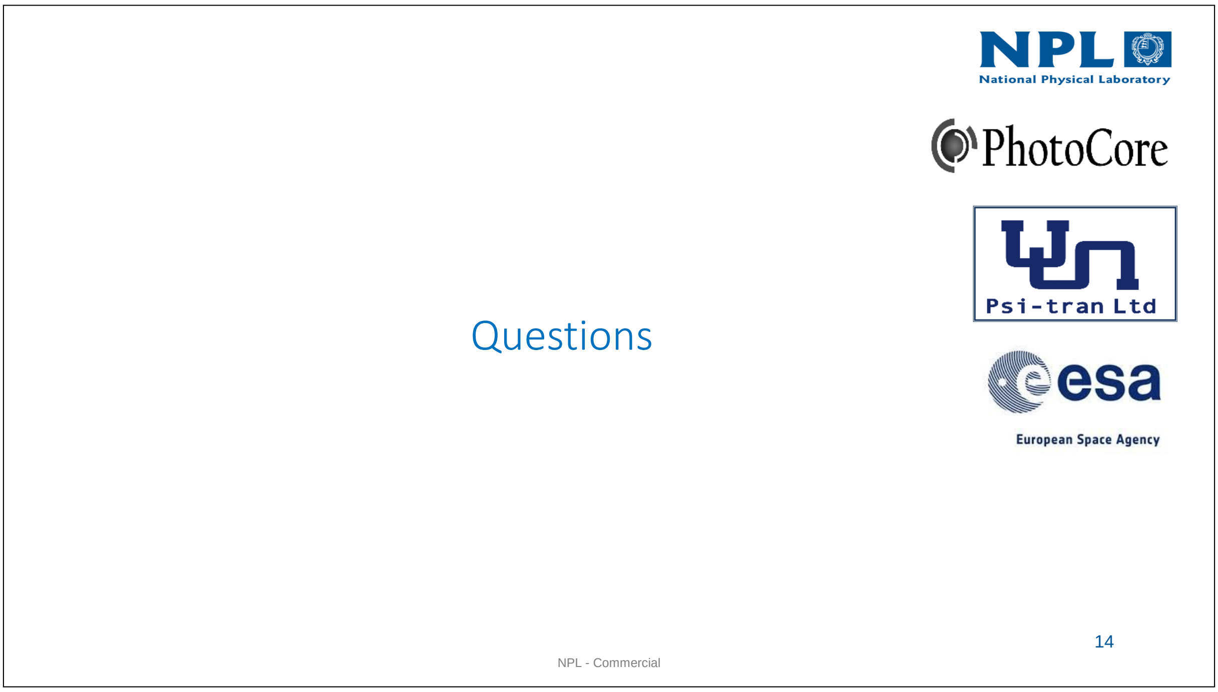
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Questions
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