Challenges for In-Flight Calibration of Thermal Infrared Instruments for Earth Observation

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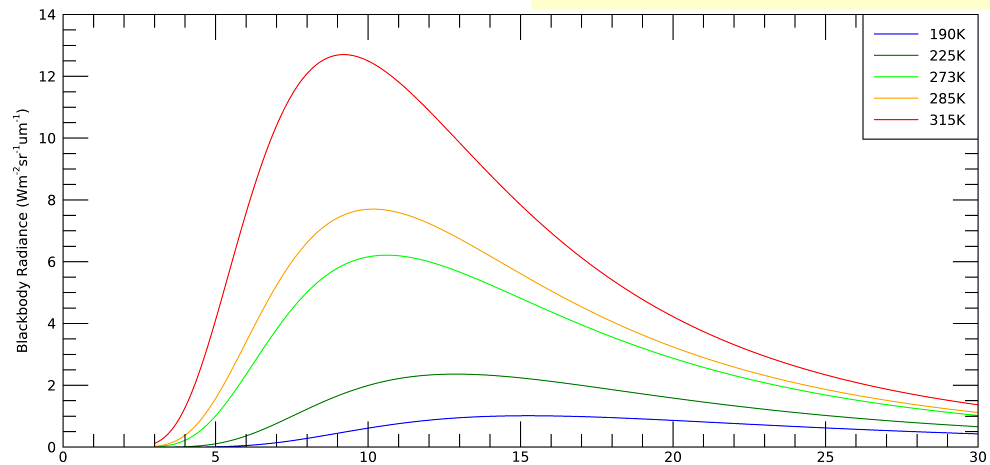
Thermal Infrared Measurements

- Observations in the thermal infrared wavelength range (3-20microns) are useful for measurements of:

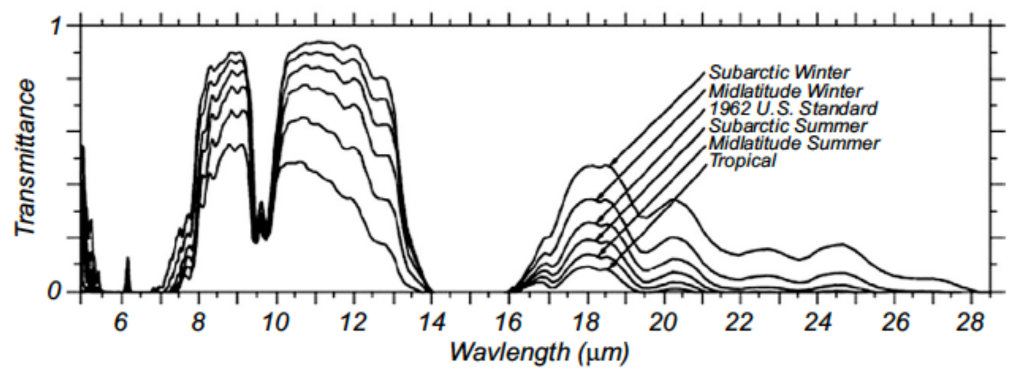
$$B(\lambda,T)=\frac{2hc^2}{\lambda^5\left(exp\left(\frac{hc}{\lambda k_b T}\right)-1\right)}$$

h = Plank's constant
c = the velocity of light in vacuum
K_b= Boltzmann's constant

- Surface Temperature Measurements
  - Oceans
  - Inland waters
  - Land
  - Fires
  - Volcanoes



- Atmospheric Sounding
  - Temperature
  - Trace gases
  - Aerosols
  - Clouds



Applications for High Resolution TIR Imagers

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Domain	Application
Volcanoes and Earthquakes	Detection of Earthquakes and Pre-eruptive volcanoes
	Hot spots and active lava flows
	Post eruptive studies on lava flows
	Eruption clouds and Tropospheric plumes
Fires	Detection of fires, potential coal fires, coal mine fires
	Estimation of burnt area, fire intensity and severity
Hydrology	Detection of water stress in crops and forests
	Detection of evapotranspiration in crops, river basins, and continents
	Prediction and monitoring of floods
	Mapping irrigated land
	Cooling Degree Day estimations
	Growing Degree Day estimations and mapping

Domain	Application
Urbanisation	UHI: Surface temperature maps, Vegetation maps, Land cover/Land Use, Building Information, Air Quality
	Security and surveillance
	Industrial/power plant monitoring
	Air pollution
	Differentiate between urban and industrial zone
	Detection of Oil spill and Plume
	Mapping malaria and/or cholera potential regions
	Arthropod vector ecology and disease distribution
	Mapping meningitis outbreak
	Asbestos-cement detection (non-accessible areas)
	Detection of minefields
	Trafficability (off-road soil moisture content)
Surface Variability	Soil composition
	Identifying geothermal resources
	Mapping geothermal anomalies
	Mapping dynamic variability of surface temperature and emissivity

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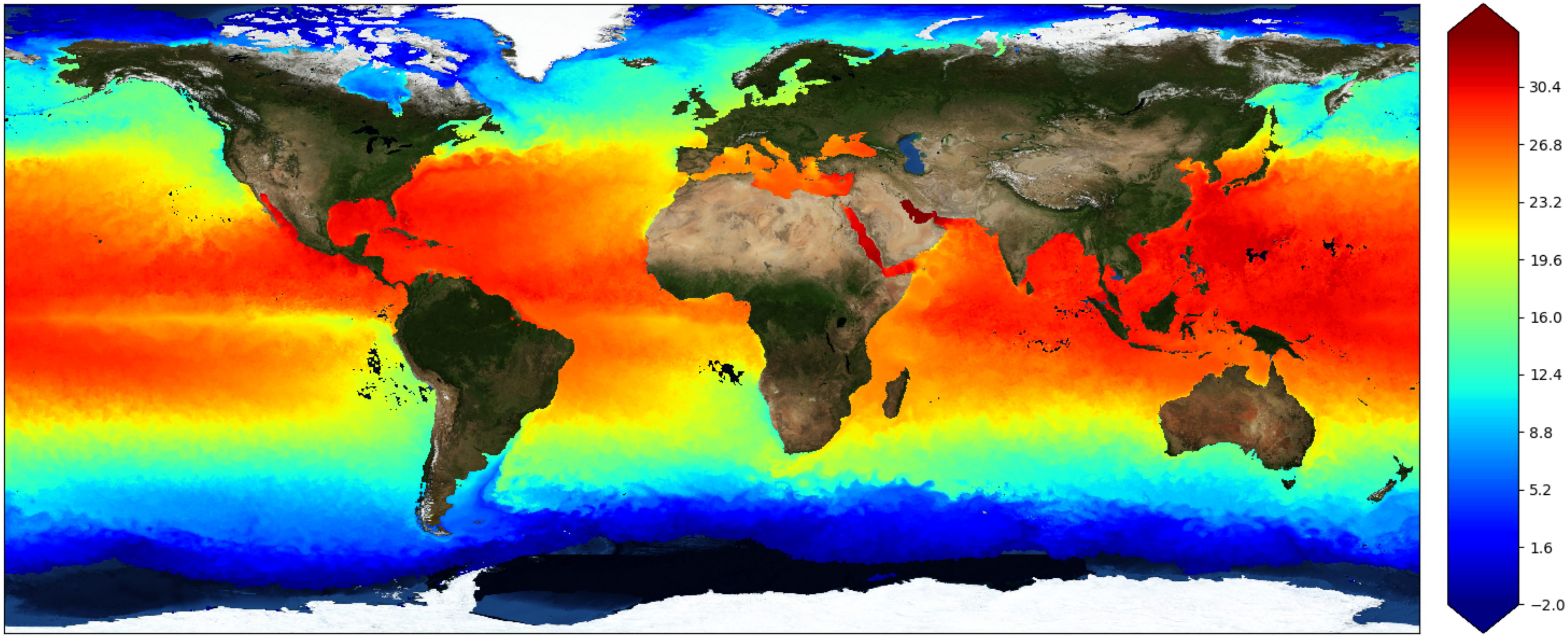
Courtesy University of Leicester

Sentinel-3A SLSTR Sea Surface Temperature – August 2016



"Measuring the small changes associated with long-term global climate change from space is a daunting task. For example, the satellite instruments must be capable of observing atmospheric and surface temperature trends as small as 0.1C decade^{-1}, ozone changes as little as 1% decade^{-1}, and variations in the sun's output as tiny as 0.1% decade^{-1}."

Ohring, G.B., B. A. Wielicki, R. Spencer, B. Emery, and R. Datla, 2005: Satellite instrument calibration for measuring global climate change: Report on a workshop. Bull. Amer. Meteor. Soc., 86, 1303–1313

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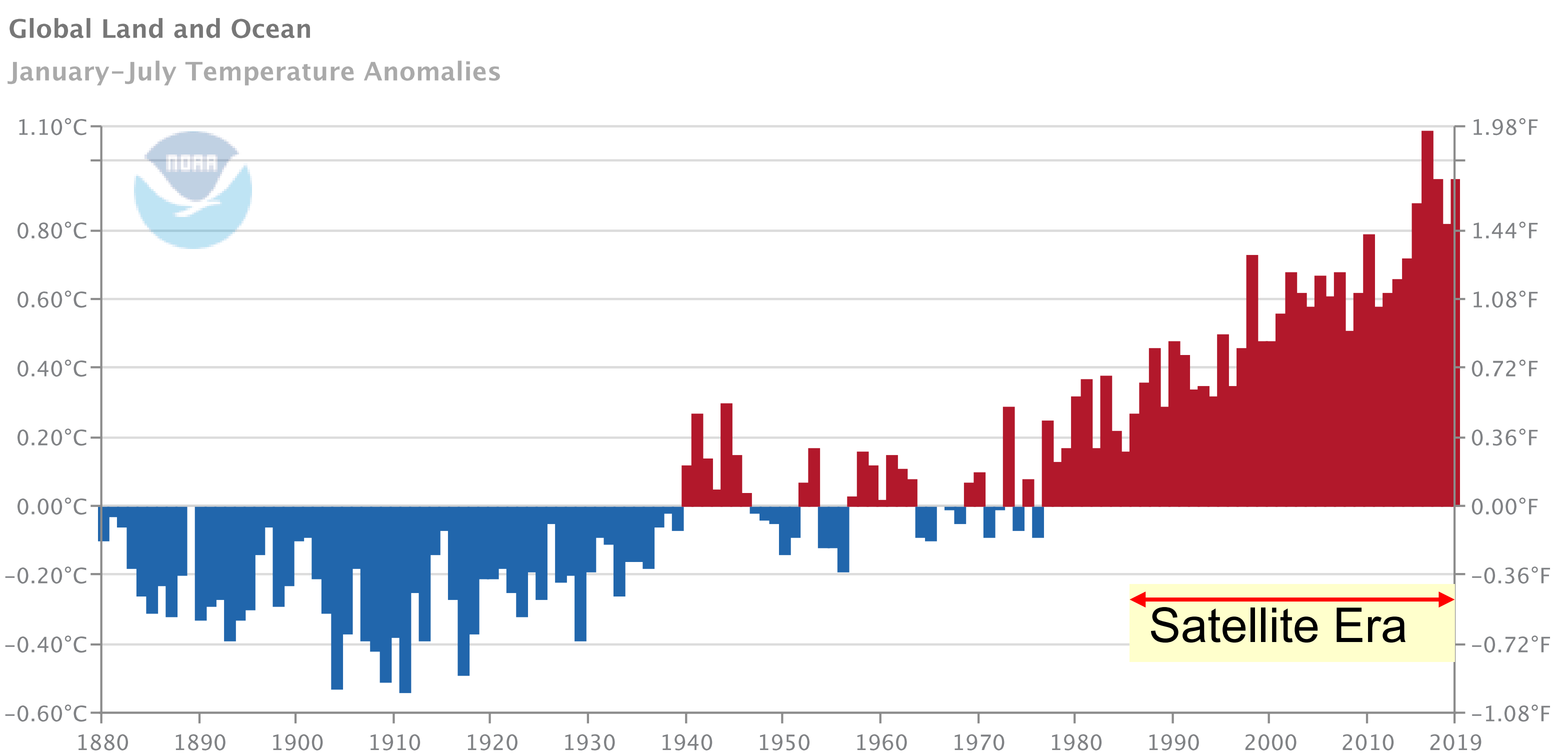
“2016 hottest year ever recorded – and scientists say human activity to blame”
Guardian 18-Jan-2017



NOAA National Centers for Environmental Information, State of the Climate: Global Analysis, published online September 2019, retrieved on 6-September-2019 from http://www.ncdc.noaa.gov/sotc/global/time-series/globe/land-ocean/ytd/7/1880-2019

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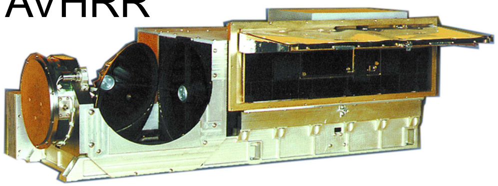
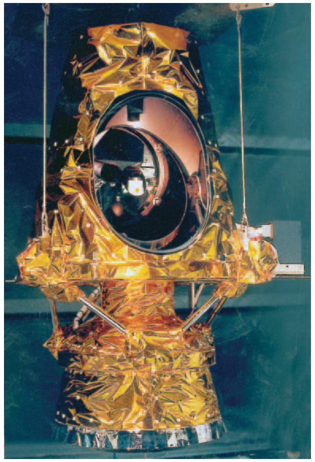
Example IR Instruments

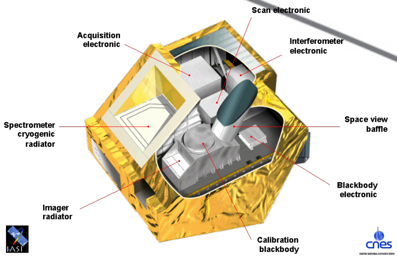
AVHRR



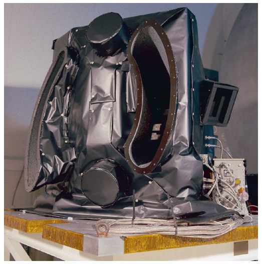
SEVIRI



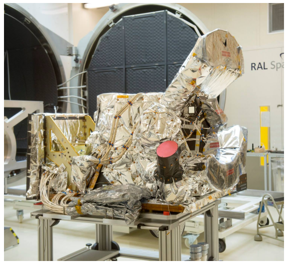
IASI



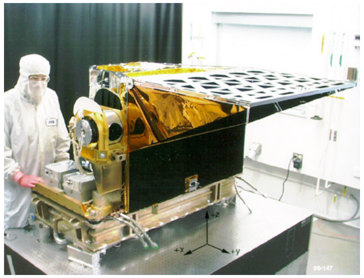
(A)ATSR



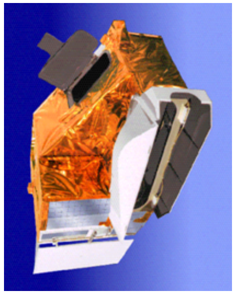
SLSTR



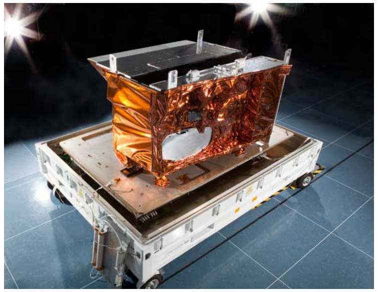
AIRS



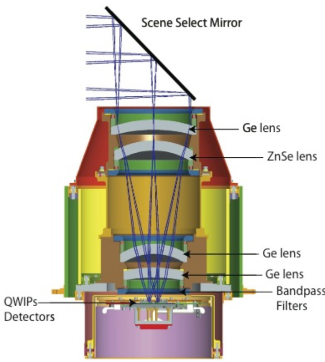
MODIS



VIIRS



Landsat 8 – TIRS



ECOSTRESS

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Future IR Missions (European)

- Copernicus Land Surface Temperature Mission
- EE9 Far-infrared Outgoing Radiation Understanding and Monitoring (explorer)
- MeteoSat 3rd Generation
  - Infrared Sounder (IRS)
  - Flexible Combined Imager (FCI)
- Metop-SG METIMAGE
- Sentinel-3 NG
- Etc…

ATSR Series

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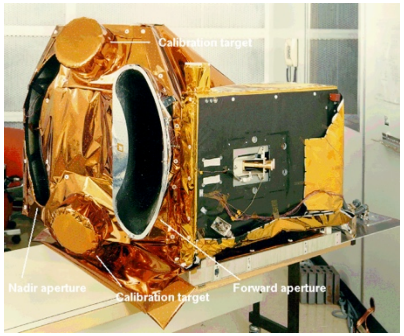
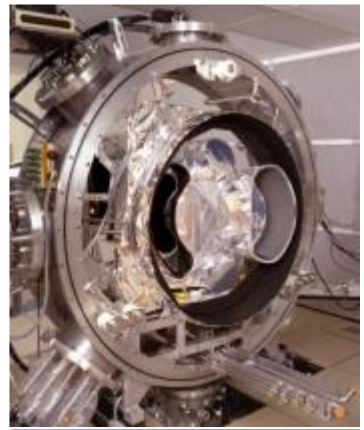
1991-2000 ATSR-1



1995-2008 ATSR-2



2002-2012- AATSR

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SLSTR

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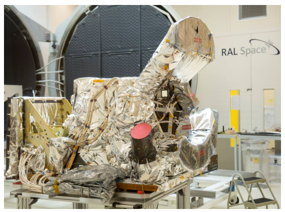
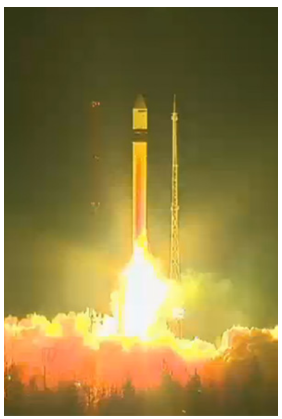
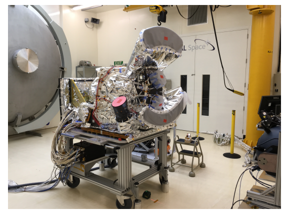
2016 – Sentinel 3A

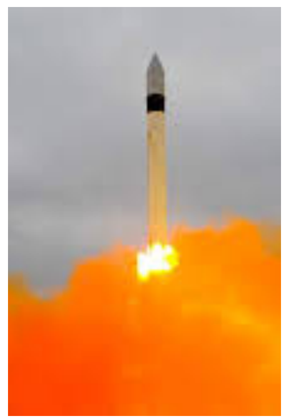




Launched 16-Feb-2016 ☺

2018 – Sentinel 3B





Launched 25-Apr-2018 ☺

- 2023 – Sentinel 3C
  - Spectral Calibration complete
  - Instrument Reduced Calibration Autumn 2019
  - Full Calibration 2021/22

- > 2024 – Sentinel-3D
  - Spectral Response Calibration Summer 2019
  - Full Calibration TBD

…

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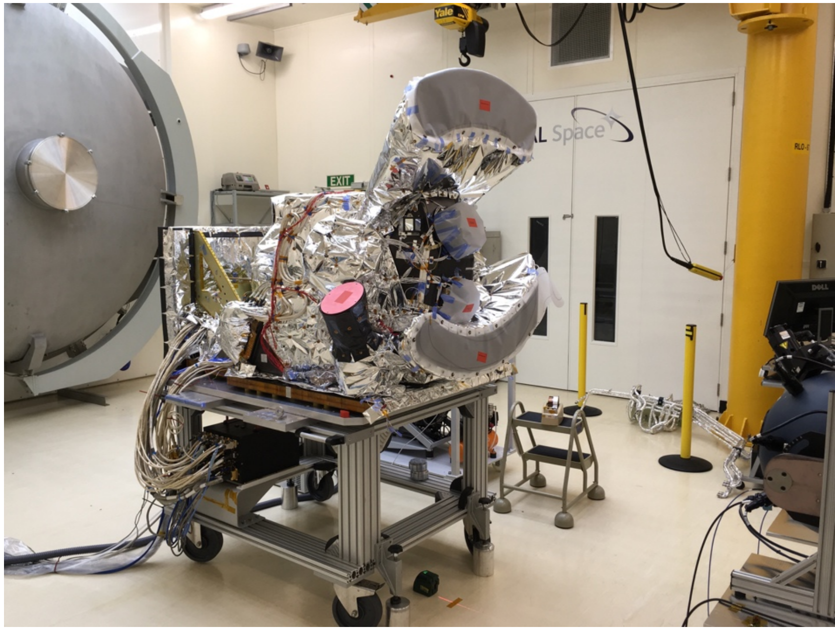
SLSTR instrument

Nadir swath	>74°	(1400km swath)
Dual view swath	49°	(750 km)
Two telescopes	Φ110 mm / 800mm focal length	
Spectral bands	TIR : 3.74µm, 10.85µm, 12µm SWIR : 1.38µm, 1.61µm, 2.25 µm VIS: 555nm, 659nm, 859nm	
Spatial Resolution	1km at nadir for TIR, 0.5km for VIS/SWIR	
Radiometric quality	NEΔT 30 mK (LWIR) – 50mK (MWIR) SNR 20 for VIS - SWIR	
Radiometric accuracy	0.2K for IR channels 2% for Solar channels relative to Sun	



Calibration of IR instruments

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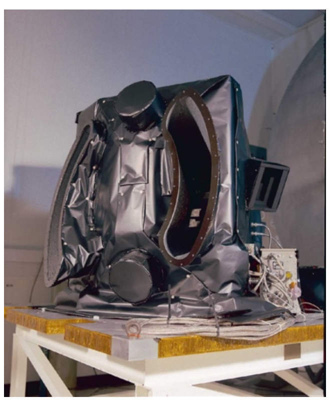
To ensure the interoperability of satellite datasets it is a requirement for their measurements to be calibrated against standards that are traceable to SI units

For temperature this is the International Temperature Scale of 1990

For IR instruments such as SLSTR the traceability is achieved via internal BB sources



Instrument

Blackbody Source

S-PRT

Fixed Point Cells

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SLSTR L1 Processing

Processing specification defined by

ATBD -> DPM

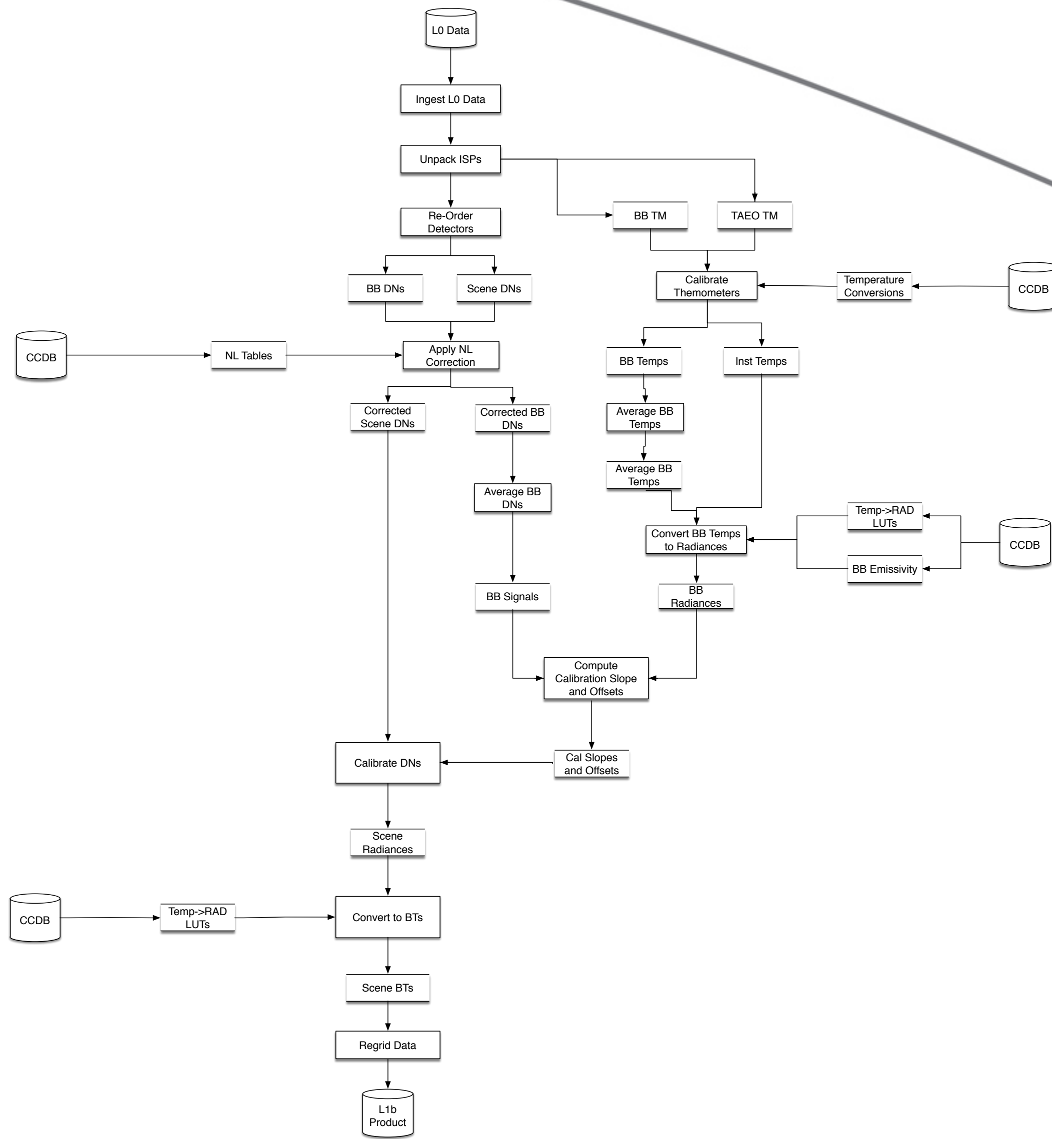
L0 and L1 Product Specifications

Each spectral band (5 thermal bands) and detector element (2x2) for each for each earth view (separate for nadir and oblique) has unique set of calibration calibration coefficients

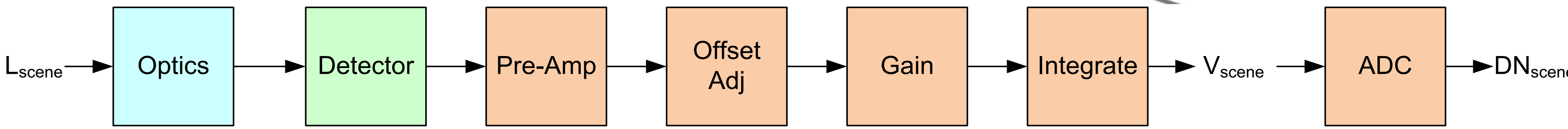
= 40 for IR channels alone

Contained in Satellite Characterisation and Calibration Database Document (S-CCDB)

Configuration controlled by MPC



Calibration Model



Typically detector counts will be some function of the earth scene radiance

$$C_E = F_{ADC}\left(V\left\{A\Omega\left(\left(\tau_{opt}L_E + (1-\tau_{opt})L_{inst}\right)\right\} + V_{off}\right)$$

which reduces to

$$C_E = \text{gain}(L_E) + \text{offset}$$

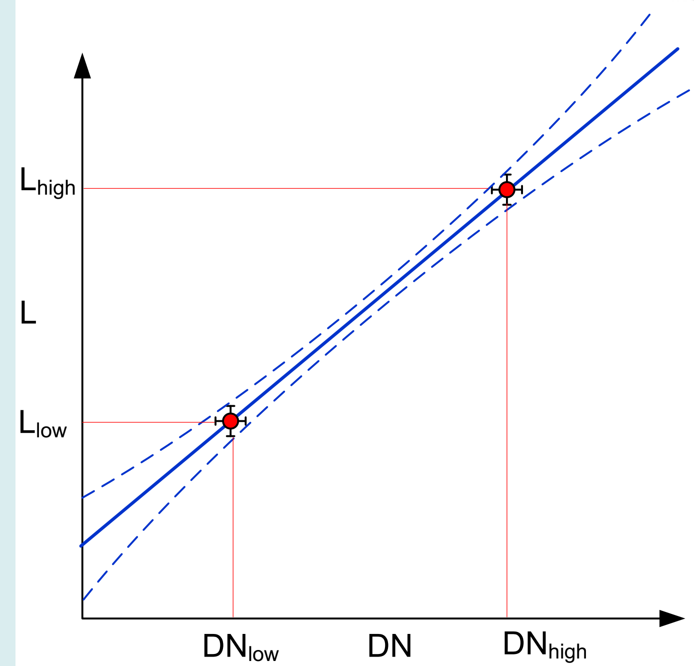
Both gain and offset must be stable during calibration interval

We invert this to get scene radiance as a function of detector counts

$$L_E = \text{gain}^{-1}(C_E - C_{offset})$$
$$\approx a_0 + a_1 C_E \text{ (assuming linear function)}$$

Uncertainty in scene radiance

$$(uL_E)^2 = \sum_{i=1}^{N}\left(\frac{\partial L_E}{\partial x_i}ux_i\right)^2 + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\frac{\partial L_E}{\partial x_i}\frac{\partial L_E}{\partial x_j}ux_i\,ux_j v(x_i, x_j)$$



We obtain calibration coefficients via reference to known calibration sources

SLSTR TIR Calibration Effects Tree

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Starting point is the measurement equation

We include +0 term to account for additional effects

$$L_E = X L_{BB1} + (1 - X) L_{BB2} + 0$$

- Uniformity around scan
- Stray Light

$$\frac{\partial L_E}{\partial X}$$

$$X = \frac{(C_E - \langle C_{BB2} \rangle)}{(\langle C_{BB1} \rangle - \langle C_{BB2} \rangle)}$$

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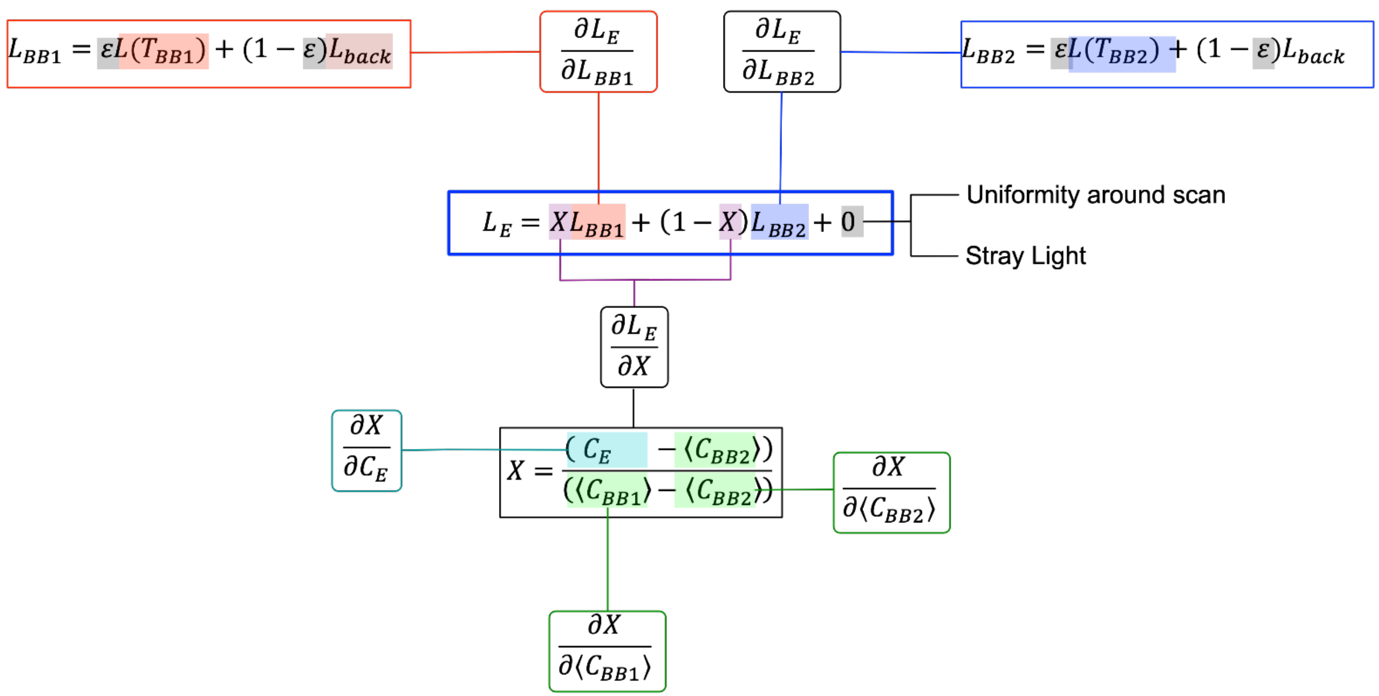
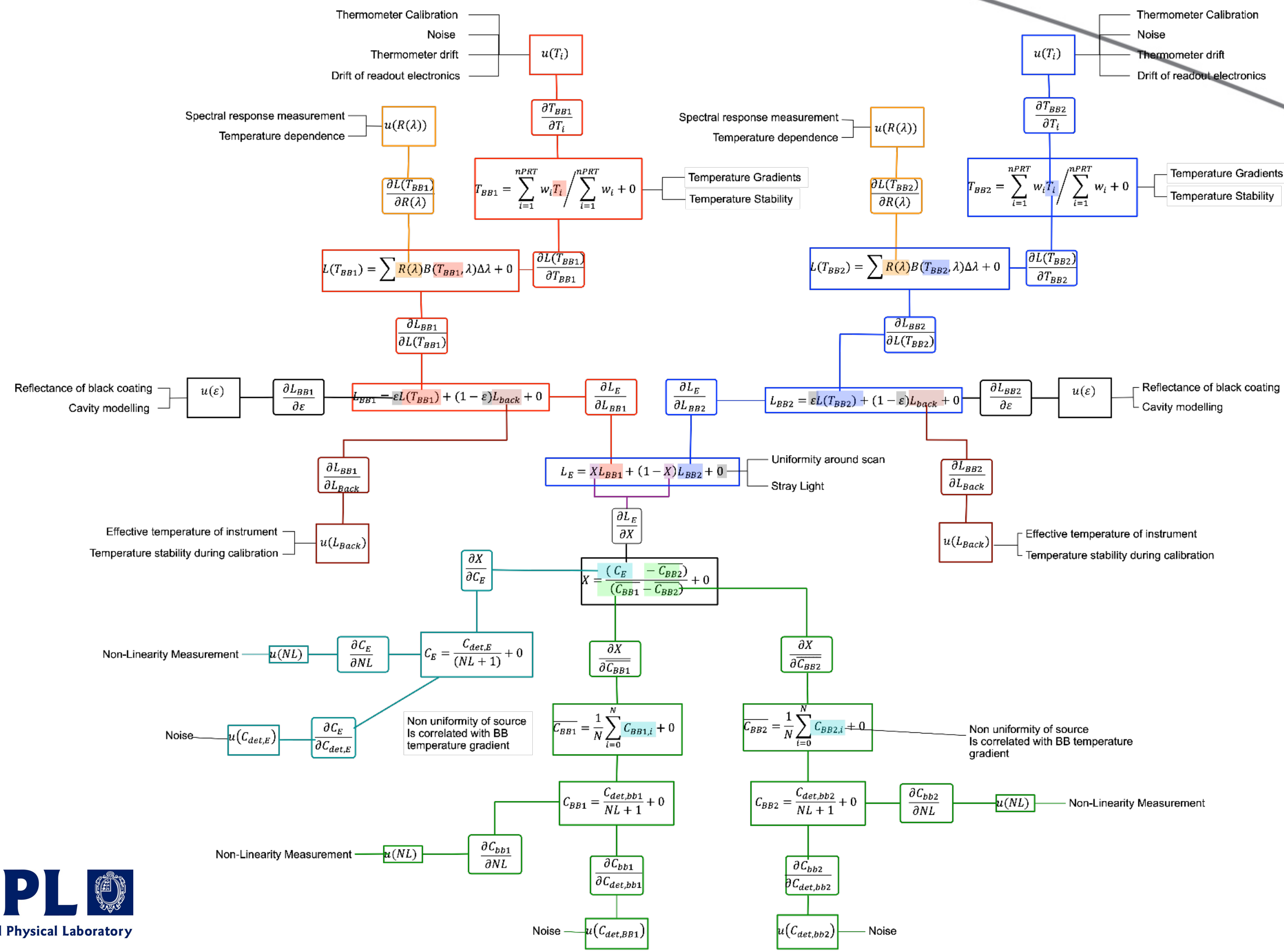
SLSTR TIR Calibration Effects Tree

We work outwards to determine all measurement effects



SLSTR TIR Calibration Effects Tree



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Primary Sources of Uncertainty in TIR calibration

- Black-Body Temperatures
  - PRT calibration at subsystem level – traced to SPRT (ITS-90) – NPL/NIST
  - Blackbody gradients, thermal analysis - RAL
- Black-Body Cavity Emissivity
  - Spectral Reflectance of Black Coating – NIST/NPL
  - Cavity Model – STEEP323 or SMART3D (ABSL model)
- Spectral Response
  - FPA measurements – RAL reports [S3-RP-RAL-SL-102 (S3A), S3-RP-RAL-SL-114 (S3B)]
- Non-Linearity
  - Instrument level calibration tests – RAL reports
- Detector Noise
  - Instrument level calibration tests, on-board BB sources

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Flight Calibration Systems: Thermal Infrared (λ > 3000nm)

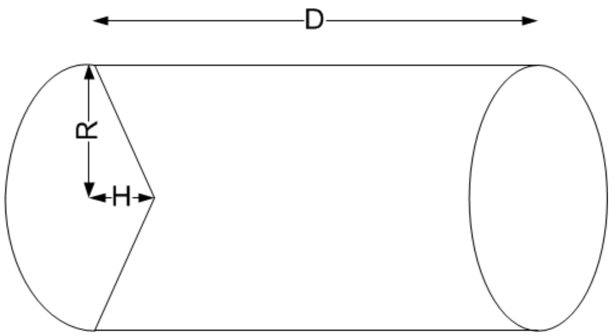
Blackbodies

Radiances are traced via the Planck function to temperature (ITS-90) and cavity emissivity

Temperature calibration is achieved by calibrating thermometer systems to ITS-90
- Well established procedures

Emissivity is more difficult to achieve for large targets
- Most reliable figures for emissivity are obtained by calibration of witness samples + modelled geometry.

Long term traceability relies on estimates



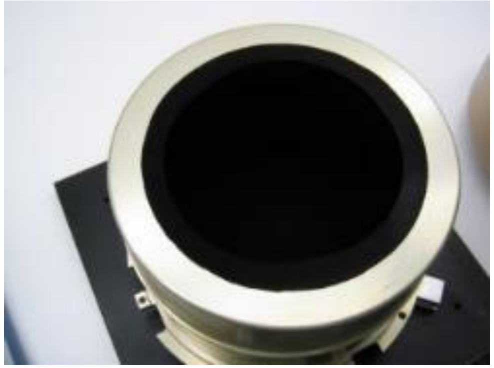
$$L_{BB} = \varepsilon L(T_{BB}) + (1 - \varepsilon) L_{back}$$

Example BB Sources

AATSR

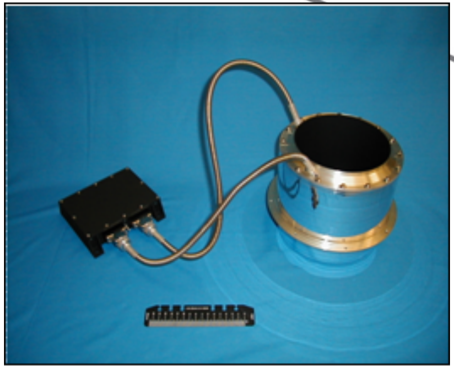
ABSL/MSSL

SLSTR



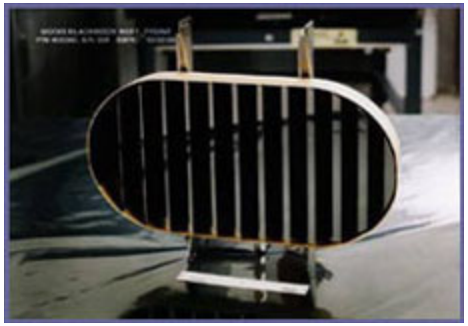
RAL Space/ABSL

IASI



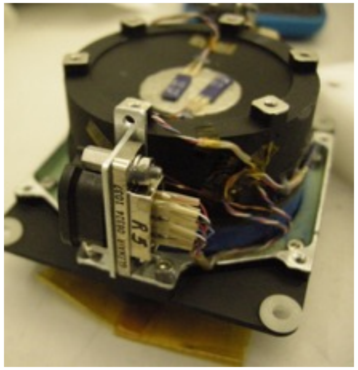
ABSL ltd.

MODIS/VIIRS



NASA-GSFC

EarthCARE BBR



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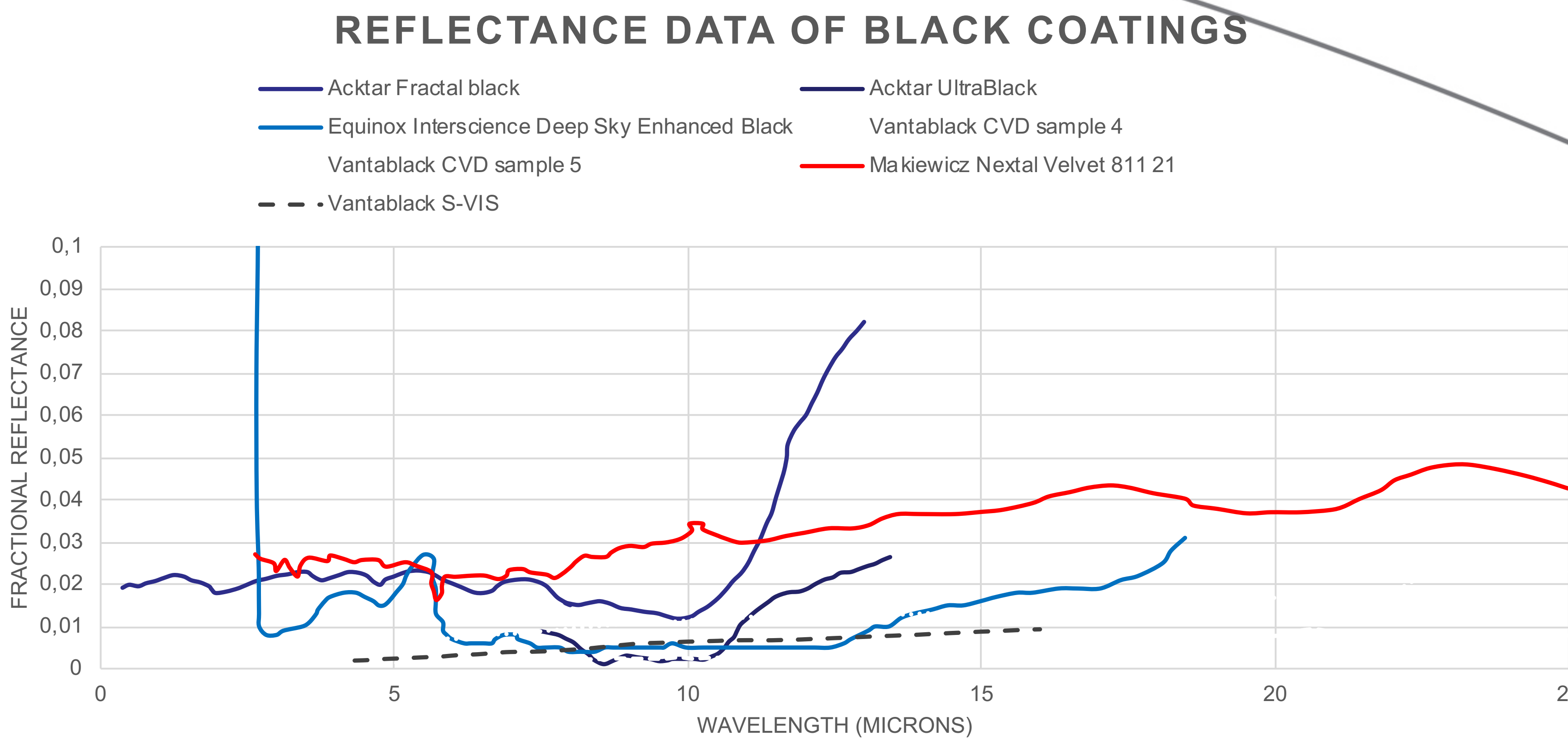
FCI – Meteosat 3rd Gen

Proceedings Volume 10563, International Conference on Space Optics — ICSO 2014; 1056323 (2017) https://doi.org/10.1117/12.2304144

Black Coating Materials



Most black coatings used have some reflectance in TIR range

Even carbon nanotubes have reflectance ~1% at 12um (Emissivity ~0.99)

Hence need for structured baseplate or cavity to increase emissivity >0.999

BB Effects

	Effect	Value	Uncertainty	Impact on BB BT	Comments
Heated (Hot) BB	BB Thermometer Calibration	302.440K	±0.018K	±0.018K	Systematic - uncorrelated
	Thermometer Ageing (at end of life)		±0.042K	±0.042K	Systematic Correlated
	Thermometer Noise		±0.004K	±0.004K	Random
	BB Temperature Gradients		±0.045K	±0.045K	Systematic, uncorrelated
	Emissivity	0.999	±0.0005	±0.018K	Systematic Correlated
	Optics Enclosure Temp	260.0K	±5.0K	±0.005K	Systematic Correlated
	BT (at 12um)	**302.404K**		**±0.052K**	
Ambient (Cold) BB	Thermometer Calibration	264.360K	±0.018K	±0.018K	Systematic - uncorrelated
	Thermometer Ageing (at end of life)		±0.042K	±0.042K	Systematic Correlated
	Thermometer Noise		±0.004K	±0.004K	Random
	BB Temperature Gradients		±0.010K	±0.010K	Systematic, uncorrelated
	Emissivity	0.999	±0.0005	±0.002K	Systematic Correlated
	Optics Enclosure Temp	260.0K	±5.0K	±0.005K	Systematic Correlated
	BT (at 12um)	**264.356K**		**±0.022K**	Systematic - uncorrelated

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Pre-Launch Calibration

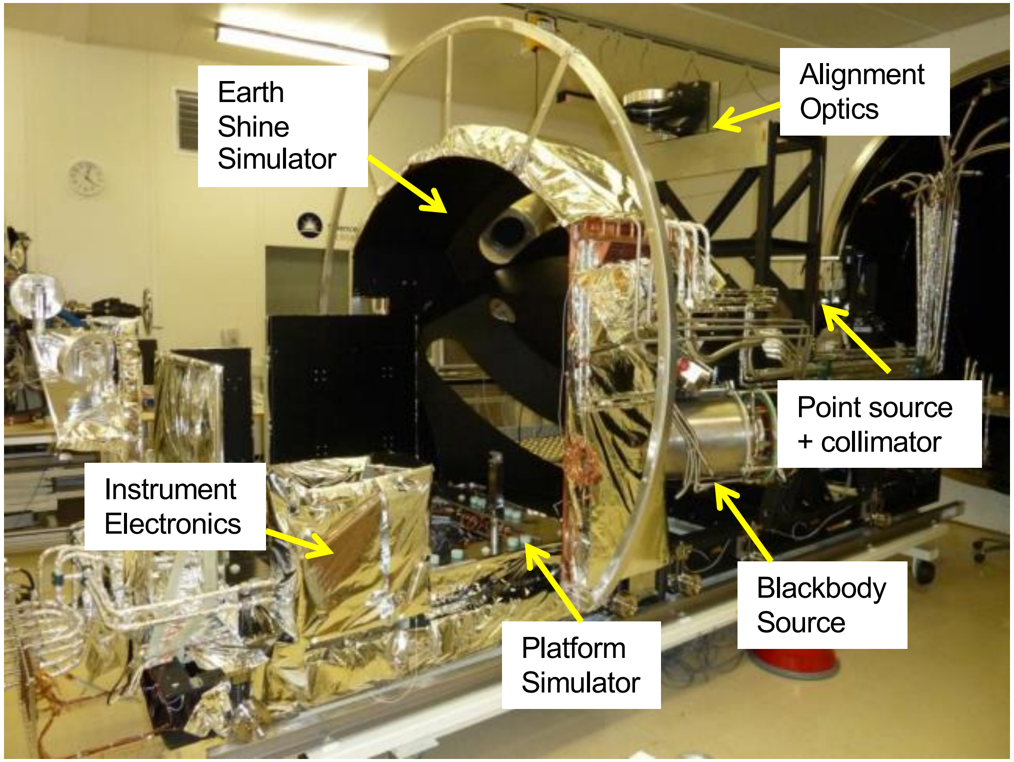
Solar Channel Radiometry
- Calibration of VISCAL system
- Radiometric response over dynamic range
- Linearity
- Radiometric noise performance
- Polarisation

IR Radiometry
- Blackbody calibration
- Radiometric accuracy over dynamic range
- Linearity
- Radiometric noise performance
- Orbital Stability
- Polarisation

Geometric Calibration
- Pointing Direction (LoS)
- Spatial Sampling
- Co-Registration
- Image Quality (MTF)

Spectral Response Calibration
- In-band response
- Out of band response
- Temperature dependency of response

Thermal IR Calibration Facility



Calibration facility was designed to perform the radiometric calibration and optical alignment checks under **flight representative thermal vacuum conditions with the instrument fully operational in its flight configuration**

Initial Trials with STM completed April 2012

S3A March-May 2015

S3B Oct 2016 – Feb 2017

S3C Autumn 2019

S3D 2020…

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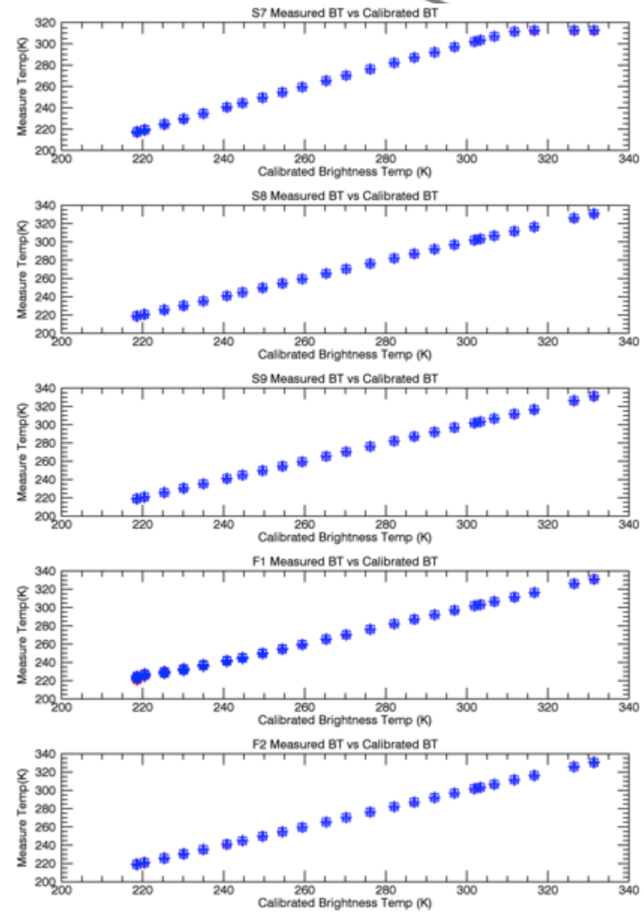
TIR Calibration Procedure

- Measurements are performed at different thermal environment conditions and for different instrument configurations

- Data are processed using calibration algorithms and subsystem characterisation data as used for flight

- Raw data provides input to verifiy L0-L1 processing chains



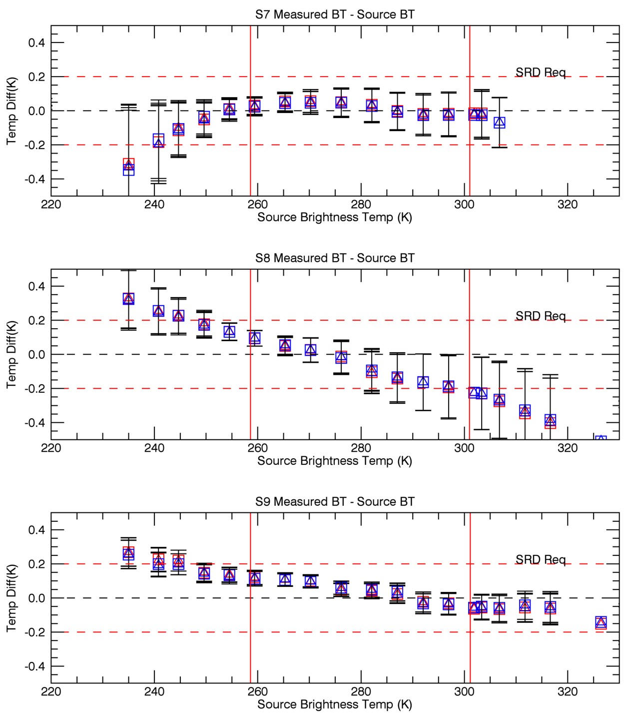
Measured - Actual BT

Plots show the differences between the BT measured by SLSTR and the BT derived from the BB thermometry

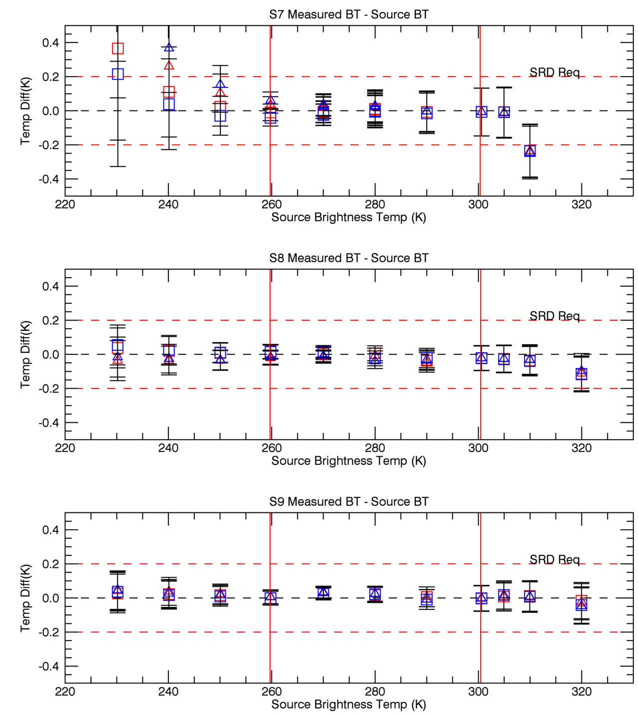
Uncertainties are combined uncertainty estimates – k=1

Only S7-S9 shown for clarity

SLSTR-A



SLSTR-B



Why the differences?

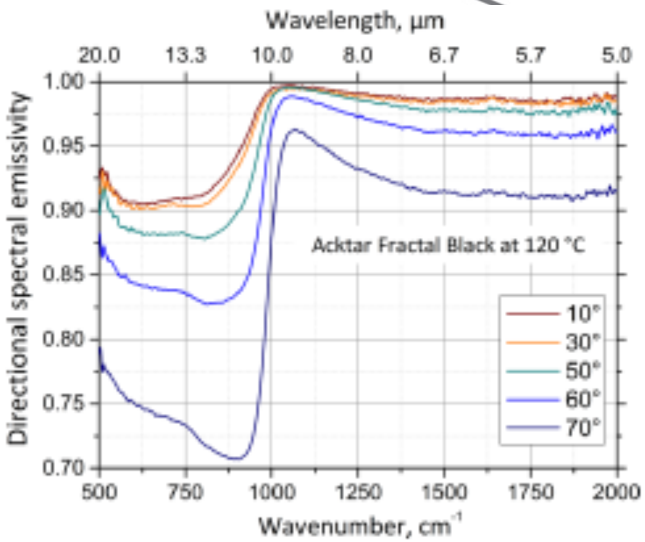
Non-Blackness of optical stops (i.e. ε < 0.9) causing non-uniform thermal background

Measurements by PTB confirm issue with black coatings

Hence modification to main apertutre stop coatings

We use pre-launch calibration to derive 'corrections'

Instrument design is an important consideration in providing SI traceable measurements



On-Orbit Performance

Establishing absolute radiometric calibration of TIR sensors using terrestrial sites is restricted by:

- Knowledge of surface emissivity
- Surface non-uniformity
- Temporal variations over short time (effect of surface winds, cloud shadow, solar elevation)
- Contribution of Atmosphere to the measured signal

Hence limited to:

- Monitoring of instrument parameters
- Satellite inter-comparisons
- Validation of L2 data products

On-Orbit Monitoring

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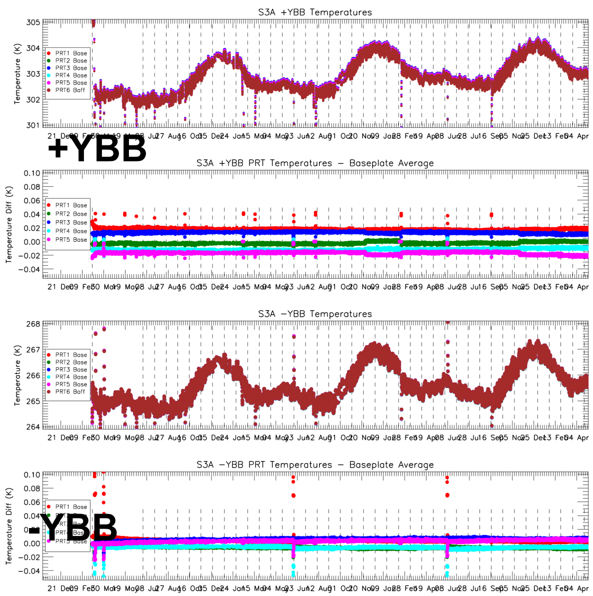
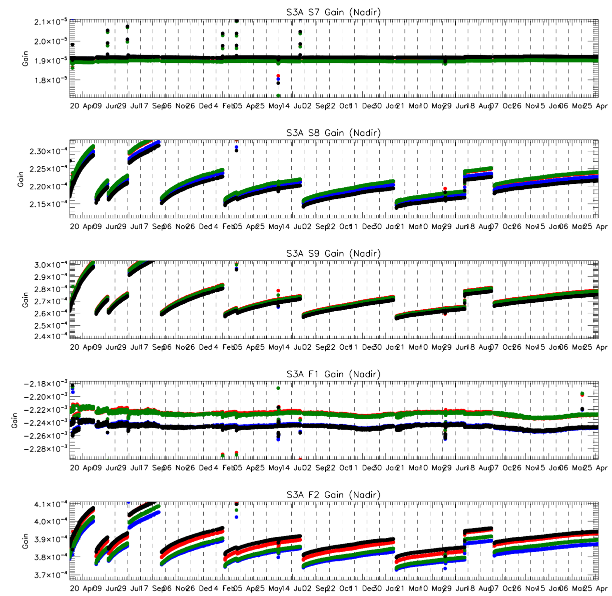
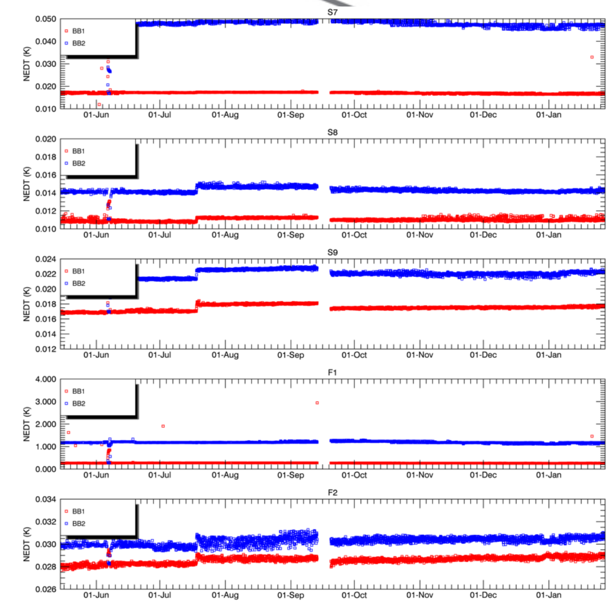
BB Temperatures



Gain Stabilty



Radiometric Noise



Routine monitoring of key instrument parameters from L0 data analysis allows us to assess low level data quality.

Demonstrating instrument stability

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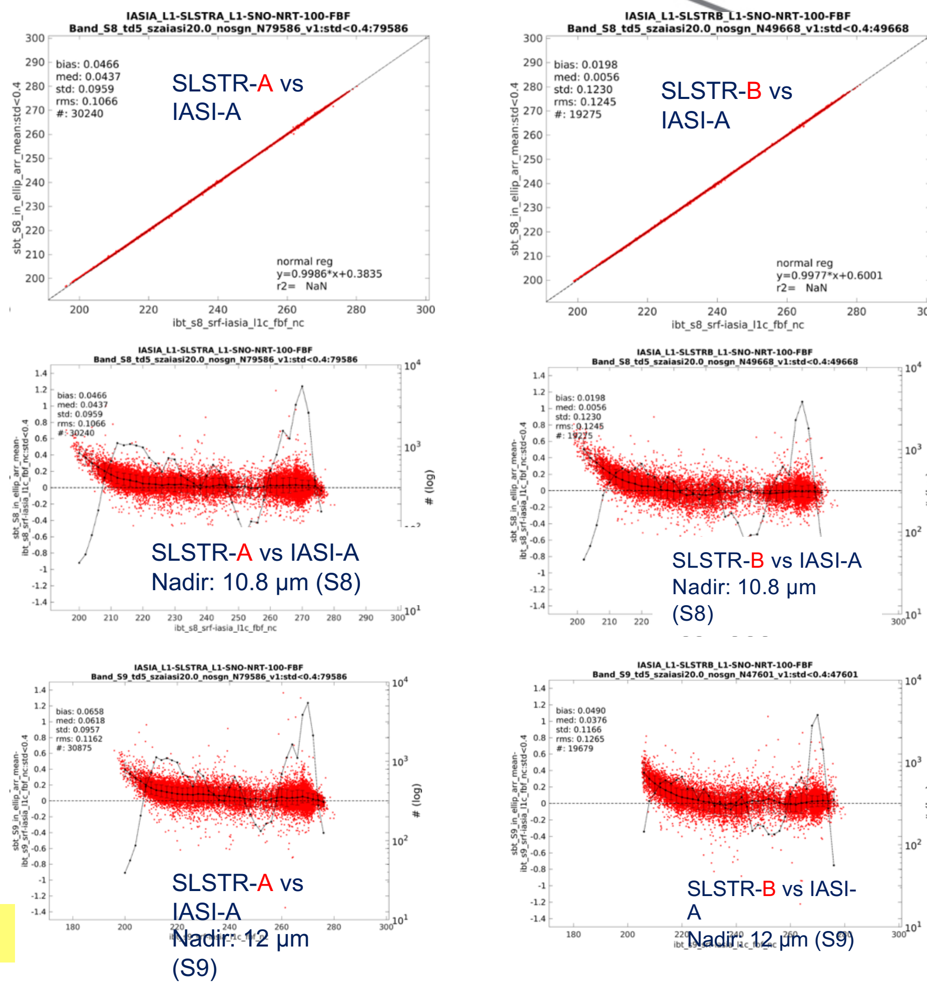
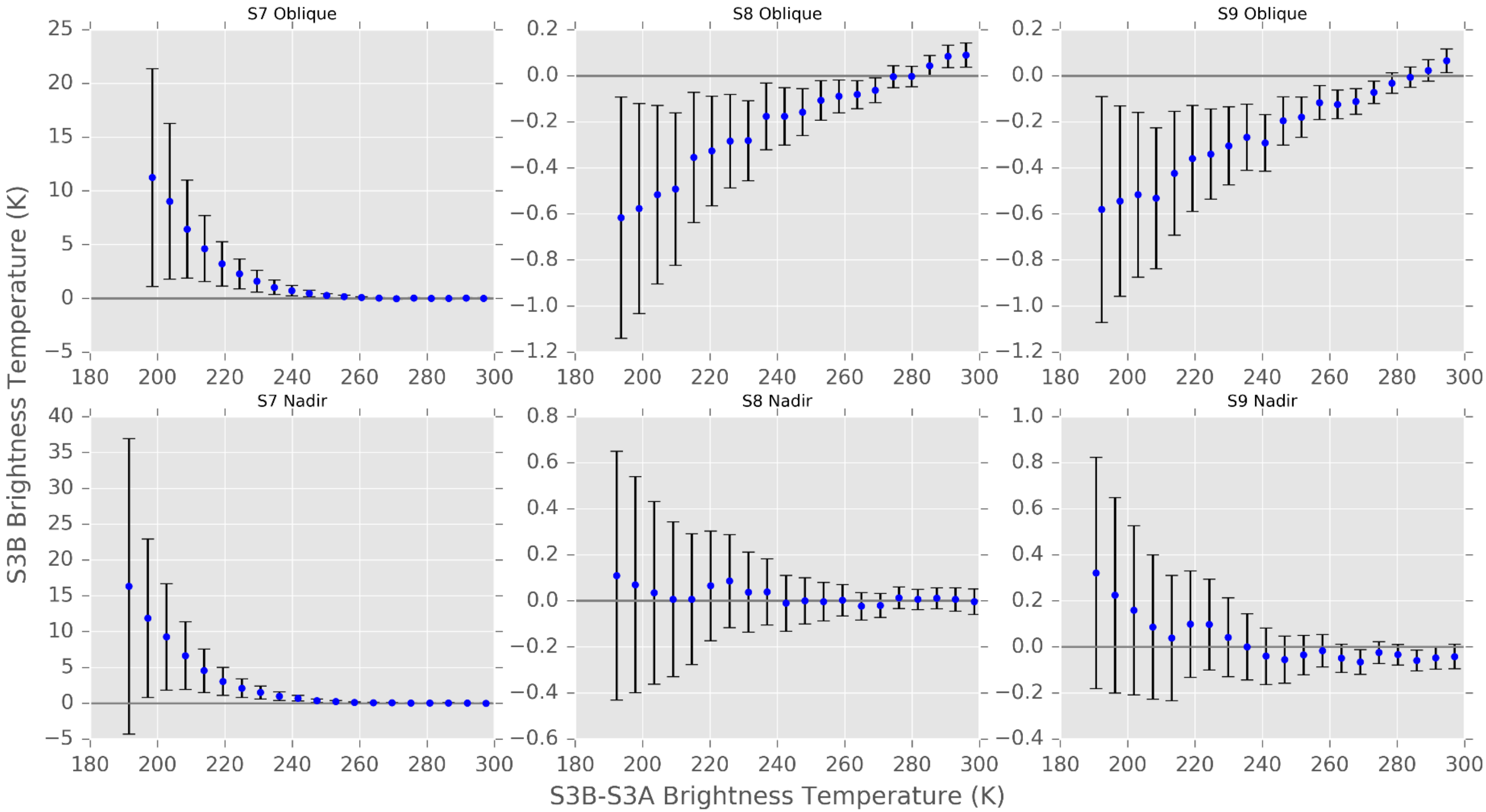
IASI-SLSTR Co-Locations from Eumetsat
SLSTR-A/B vs IASI-A

- Simultaneous Nadir Observations (SNO) performed by Eumetsat following GSICS methodology based on the approach developed for AATSR/IASI comparisons.
  - IASI data are spectrally averaged over SLSTR bands
  - SLSTR data are spatially aggregated over IASI footprint
- Results shown for SNO event (20-22.06.2018) during the S3 tandem phase
- Analysis for both S3A and S3B are performed separately for the two detectors of the two nadir view channels S8 and S9
- Comparisons are shown for homogenous scenes (ΔT <0.1K)

Courtesy I.Tomazic (Eumetsat)



Sentinel-3 Tandem Mission



Sentinel-3B and 3A were flying on same orbit track 30s apart for 4 months during commissioning phase

Towards In-Flight Traceability

- Despite having on-board calibration systems, pre-launch calibration, in-flight monitoring, cross-calibration methods, demonstrating traceability to SI in the TIR is difficult!

- Many assumptions are made:
  - Knowledge of on-board source radiances
  - Stability of on-board sources
  - Stability of spectral response
  - Etc…

- How to provide on-orbit traceability?

Next Generation InfraRed Source (NGenIRS)

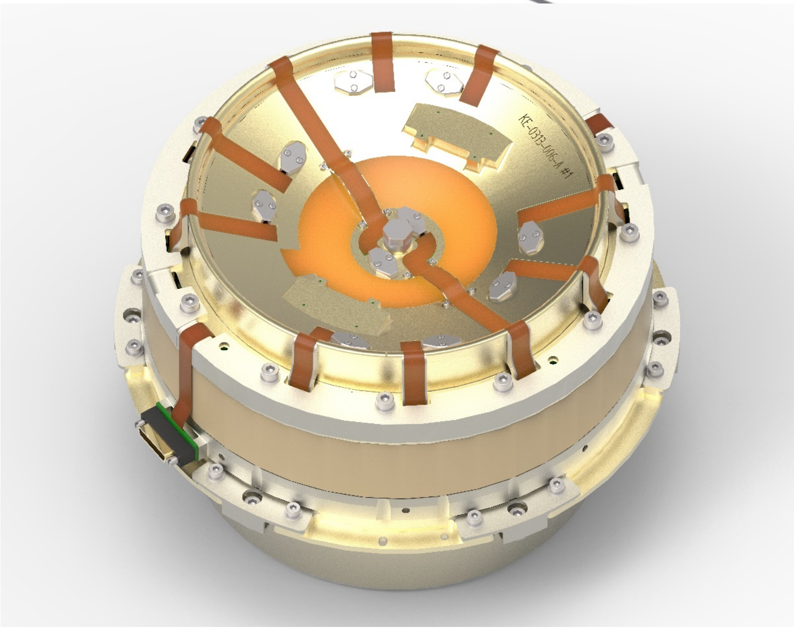
RAL Space

NGenIRS is a UK CEOI funded development to improve on-orbit traceability of IR sensors.

Joint study with RAL Space, NPL and Surrey Nanosystems

Aim is to demonstrate the performance of novel readout electronics, carbon-nanotube black coatings and a phase-change cell within an existing SLSTR like blackbody cavity geometery.

- PRT (thermometer) and electronic readout calibration, as SLSTR flight procedures
- Demonstrate cross calibration of PCC in cavity against central PRT using heater assisted transition
- Demonstrate transfer of calibration of central PRT against other PRTs
- Goal TRL-5/6



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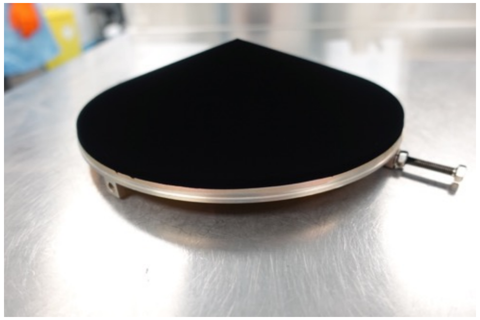
BB Technology Developments

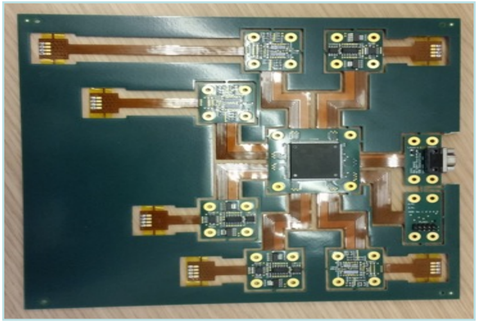
Black Coating Technology



Surrey Nano Systems (SNS) black coating based on carbon nano-tubes with high intrinsic emissivity

Applied to SLSTR BB target Geometry

Integrated BB electronics



True ratiometric measurements of thermometer impedances

Very high accuracy, low power, low mass, locally redundant thermometers, all-digital interface

Phase Change Cells

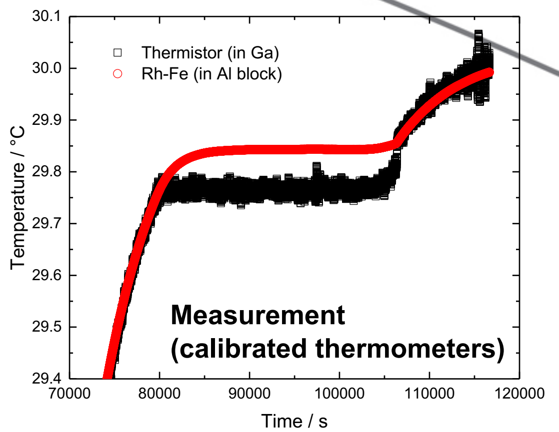
Melting point of Ga 29.7646 ºC

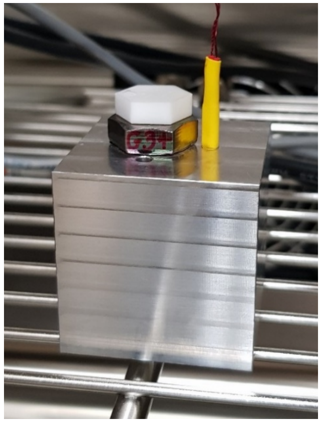
Traceable to ITS-90

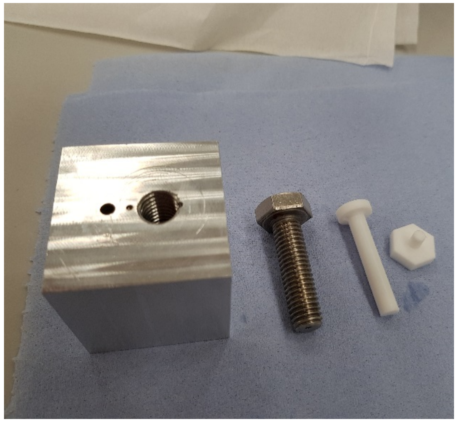
Uncertainty < 10 mK

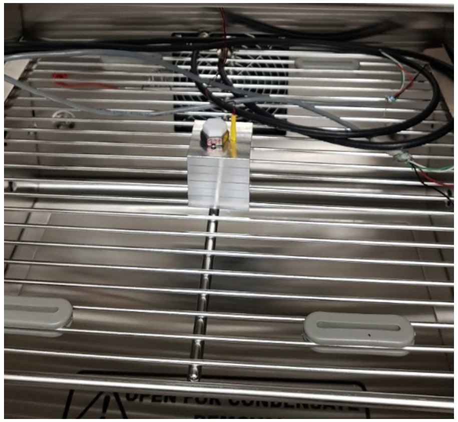
Miniature phase-change cells (1)

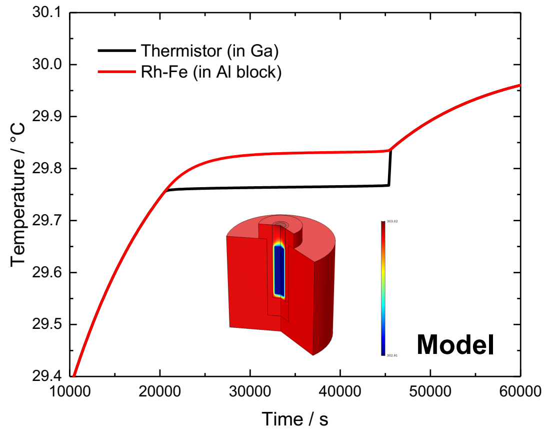
- Less than 1 gram
- Optimised with modelling – subsequently validated
- Overcome difficulty of excessive undercool – **now have repeatable phase changes** and simple freezing procedure (only requires 2-3 °C undercool)
- Thermistor in the gallium, Rh-Fe sensor in the block, nearby
- First design iteration was affected by poor thermal conductivity leading to temperature gradients





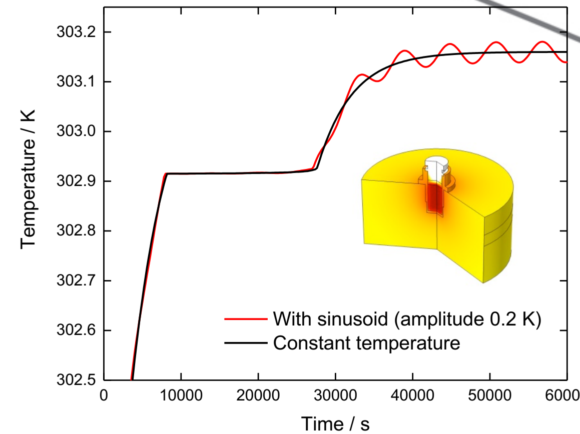


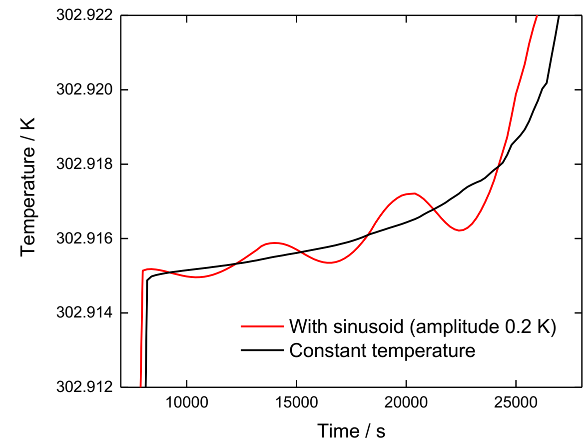




Miniature phase-change cells (2)

- 2nd iteration addressed thermal gradients and designed to be implemented in an existing ‘flight’ black-body design.
- Demonstrated viability for PRT calibrations even when PRT is remote from the phase-change cell – in air and in vacuum
- Modelled effect of orbital temperature variations





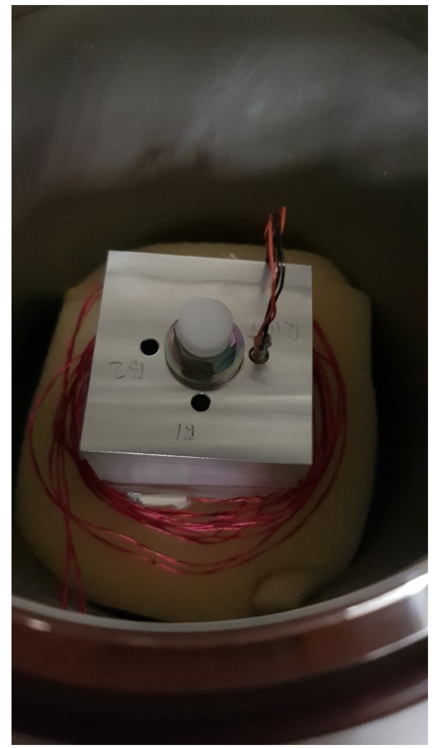
Phase Change Cell Testing

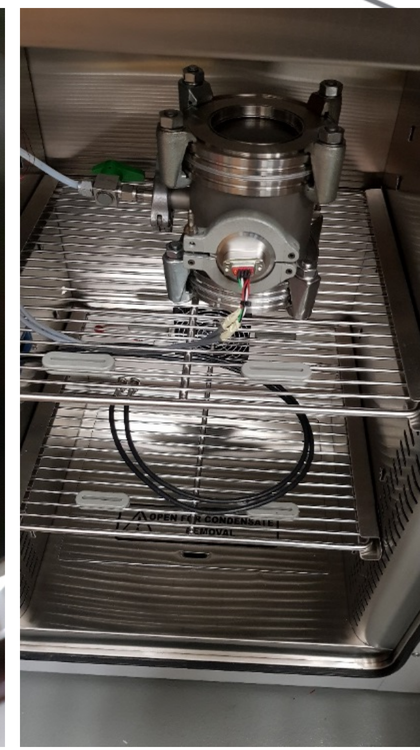
RAL Space

Cell Ga 18/11 contains 2.07 g gallium

Rhodium-iron resistance thermometer (Rh-Fe)

Metal block placed in vacuum chamber, within temperature-controlled air bath





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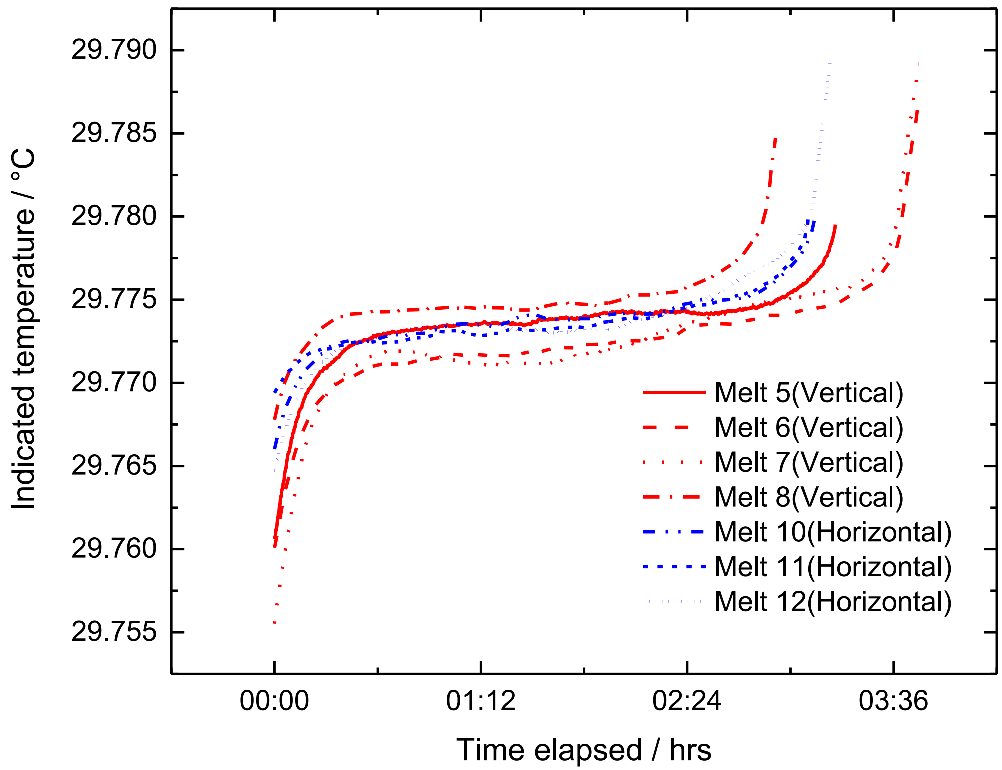
Melting plateau reproducibility

Reproducibility < 5 mK

Melt duration 3-12 hours

Independent of orientation

Easily frozen and re-melted



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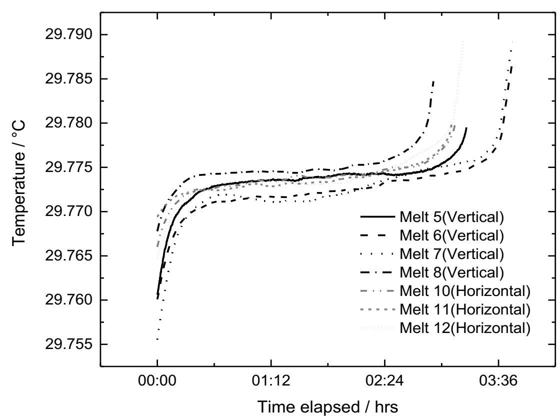
NGenIRS Next steps

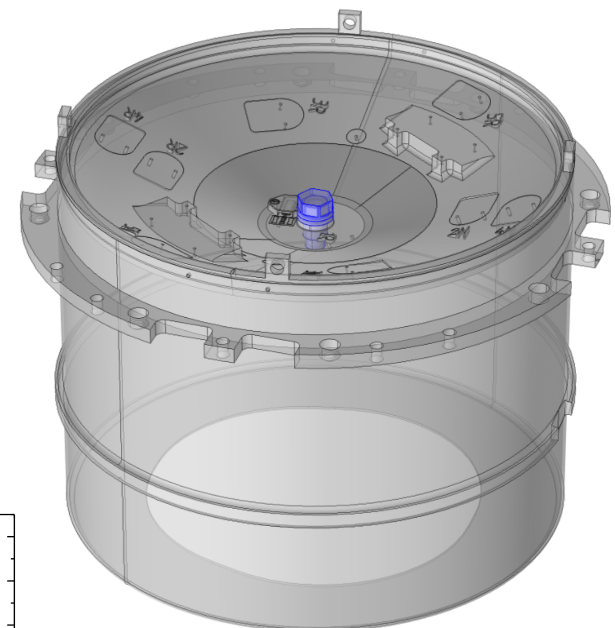
RAL Space

RAL Space

- Phase change cell implemented in flight-ready configuration
- Hermetic sealing
- TRL3 -> TRL5/6
- Trials in thermal vacuum testing facility
- Assignment of temperature to phase-change cell
- Characterisation of temperature gradients in real-world system
- Detailed testing of cell
  - Mechanical robustness
  - Orientation dependence
  - Longevity
  - Repeatability

Current work so far shows the cell is fit for purpose





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Conclusions

- Instrument design is fundamental to achieving traceable measurements in the TIR
  - Control of stray light sources – internal as well as external
  - Traceability chain needs to be developed during instrument design phase to identify all calibration effects.
- On-board black-body sources are the primary route to SI traceability
  - Developments of miniature phase change cells can be used to provide direct traceability
- Pre-launch calibration is essential to validate end to end calibration model
  - Must be done in flight representative conditions
- All of above requires £££

Thank you!