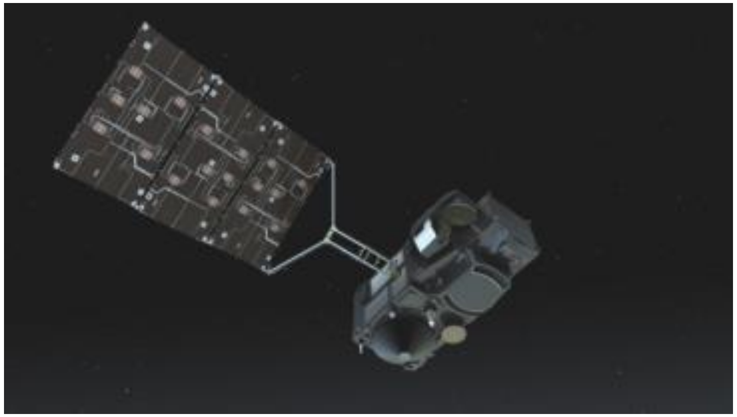
Sentinel-3 Sea and Land Surface Temperature Radiometer Pre-Flight Calibration

Dave Smith
STFC RAL Space

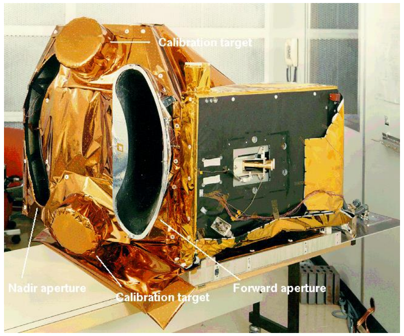
Credits: SLSTR Core team



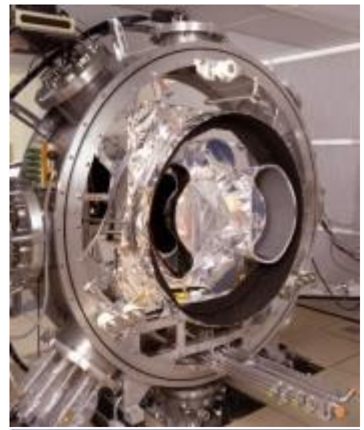
- Leonardo (formerly Selex ES), Instrument prime contractor, supply of Detector Assembly (the Focal Plane Assembly (FPA), the Front End electronics (FEE) and the Cryocooler (CCS)).
- JOP, supplier of opto-mechanical enclosure.
- RAL, responsible for calibration and systems design consultancy under ThalesAlenia as Sentinel 3A prime contactor.

ATSR Series

1991-2000 ATSR-1



1995-2008 ATSR-2



2002-2012- AATSR

SLSTR Series

2016 – Sentinel 3A

Launched 16-Feb-2016 ☺

- 2017 – Sentinel 3B
- 2021 – Sentinel 3C
- 2023 – Sentinel-3D

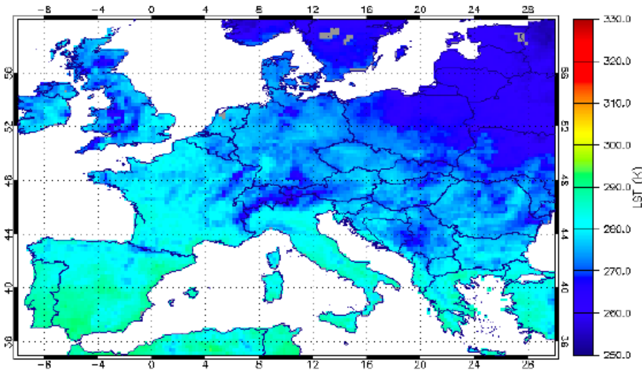
…

Sentinel-3A First Image – 3-March 2016

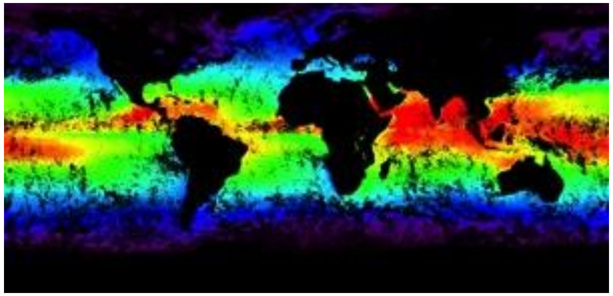
Key Requirements

- **Continuity of Sea and Land Surface Temperature datasets derived from (A)ATSR**
- **Additional bands for fire radiative power measurements and improved cloud detection**
- **Dual-View Capability**
- **On-board calibration sources**
- **Daily global coverage (with 2 satellites)**

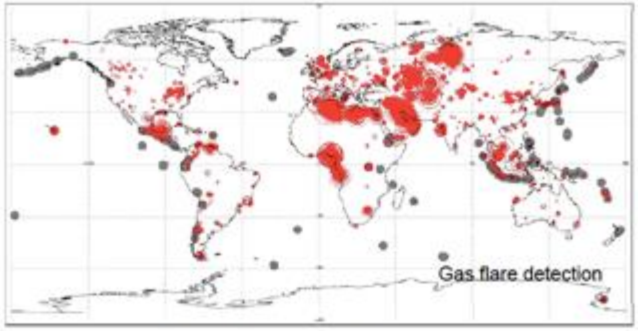
AATSR Level-3 product at user-defined spatial resolution Europe daytime Feb 2011 at 0.25°



Global SST ENVISAT AATSR monthly composite



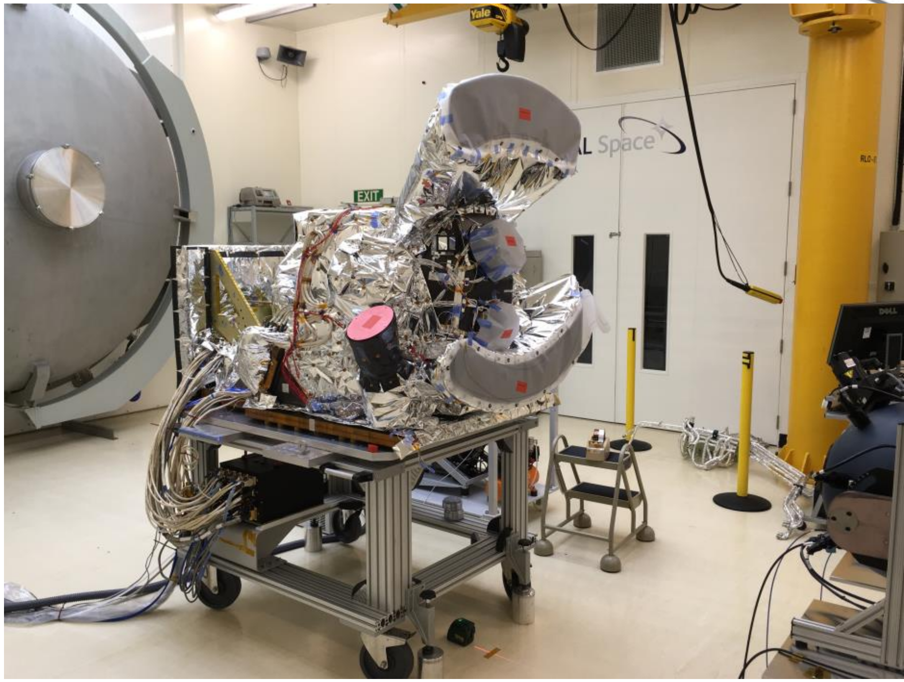
ENVISAT AATSR hot spot fires and world fire atlas



Casadio et al; ALGO3 persistent hot spot sites (1991–2009) RSE 2012

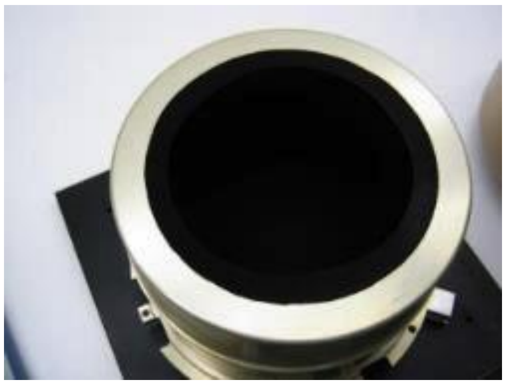
SLSTR instrument

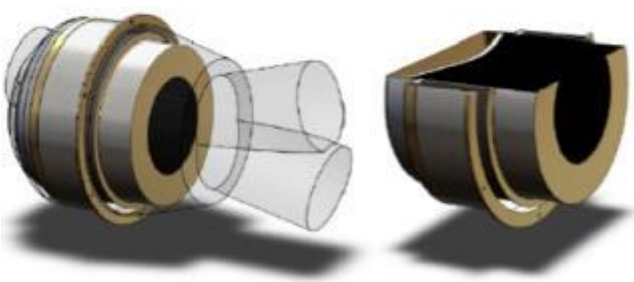
Nadir swath	>74° (1400km swath)
Dual view swath	49° (750 km)
Two telescopes	Φ110 mm / 800mm focal length
Spectral bands	TIR : 3.74µm, 10.85µm, 12µm SWIR : 1.38µm, 1.61µm, 2.25 µm VIS: 555nm, 659nm, 859nm
Spatial Resolution	1km at nadir for TIR, 0.5km for VIS/SWIR
Radiometric quality	NEΔT 30 mK (LWIR)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



On-Board Calibration systems

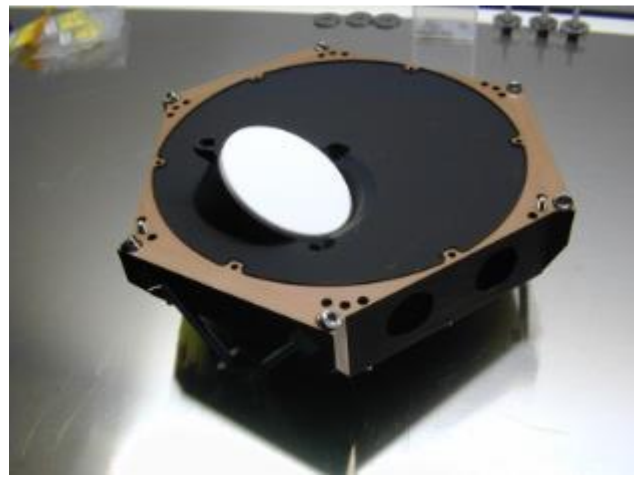
Thermal InfraRed Blackbodies





Effective e >0.998
T non-uniformity < 0.02 K
T Abs. Accuracy 0.07 K
T stability < 0.3 mK/s
8 PRT sensors + 32 Thermistors

VIS-SWIR Channels VISCAL



Zenith diffuser +
relay mirrors
Uncertainty <2%

The Goal

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

←

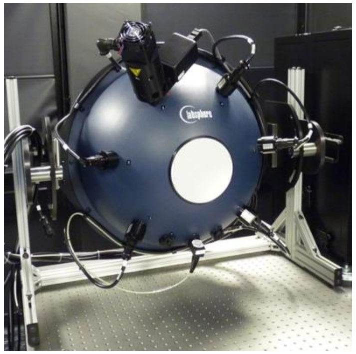
S-PRT

←

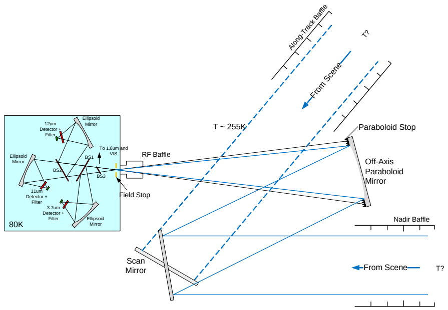
Fixed Point Cells

The Reality

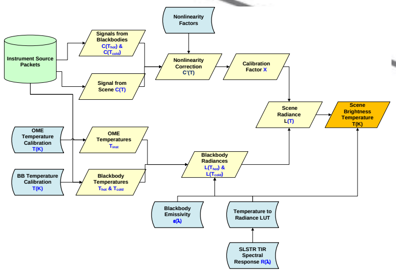
Calibration Sources



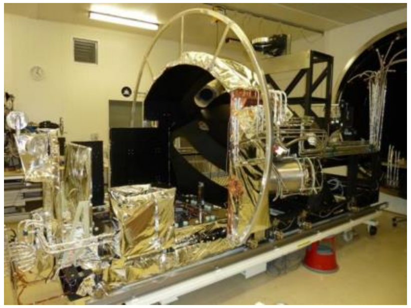
Instrument Design



Processing Model

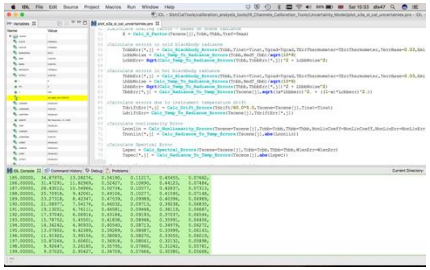


Calibration Facilities

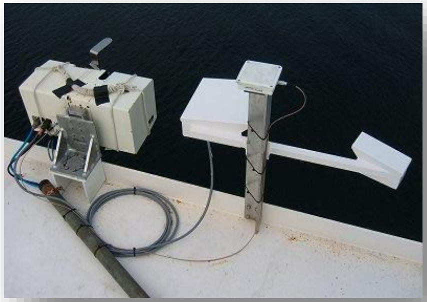


People

Software



Post Launch Activities



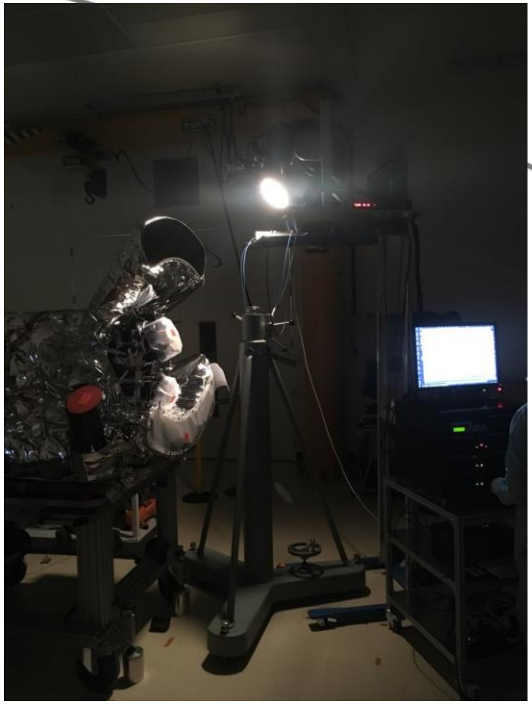
Policy

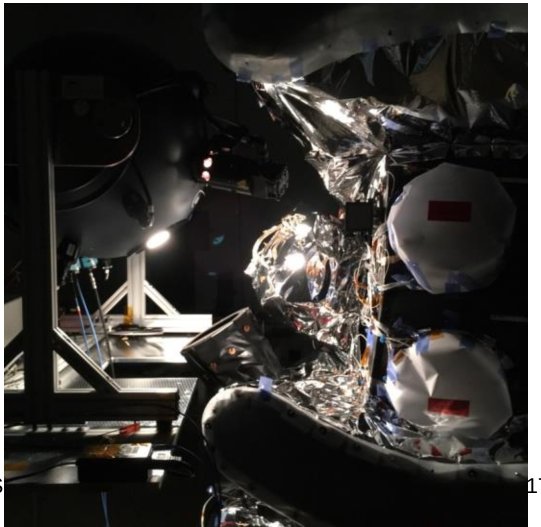
Processing Facilities

VIS/SWIR Calibration

- SLSTR VIS/SWIR channels are calibrated via a diffuser based calibration VISCAL system – based on (A)ATSR concept
  - VISCAL is illuminated once per-orbit by the Sun

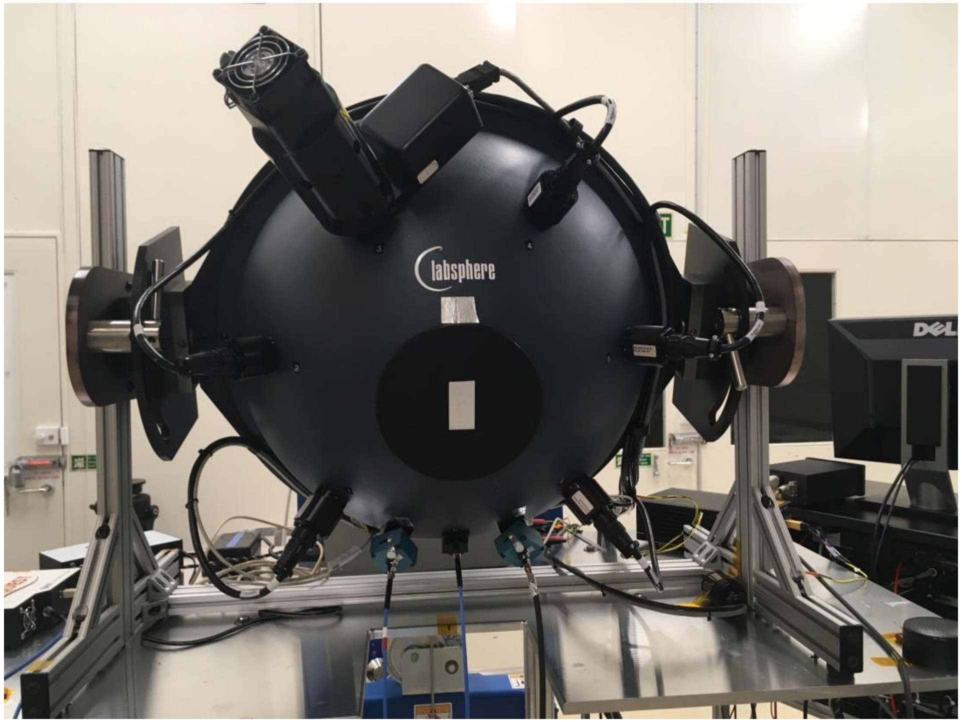
- Pre-Launch Calibration is to characterise key instrument performance
  - Radiometric response of each detector
  - Signal-to-Noise performance of each detector
  - Reflectance factor of VISCAL system
  - Polarisation sensitivity





Source Setup

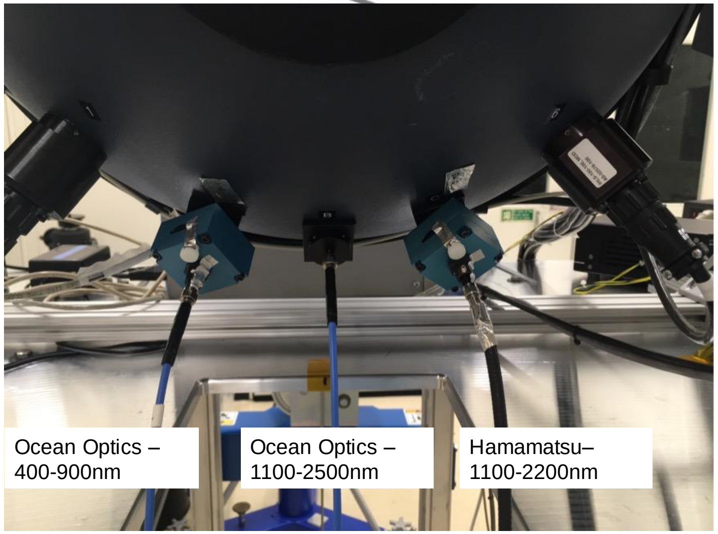
- Integrating sphere used for calibration of SLSTR
- 6 lamps, one (lamp 3) has a variable aperture. 0%=open, 100%=closed. Percentage is not proportional to open area.
- Lamp settings controlled and data recorded using labview interface on a PC



Source Setup

- Three spectrometers mounted on the sphere to monitor source output and traceability to NPL calibration
  - 2 SWIR
  - 1 for VIS-NIR

- Lamp settings controlled and data recorded using labview interface on a PC



Ocean Optics – 400-900nm

Ocean Optics – 1100-2500nm

Hamamatsu– 1100-2200nm

Calibration of spectrometers

- Integrating Sphere calibrated at NPL against standard BB source August 2015

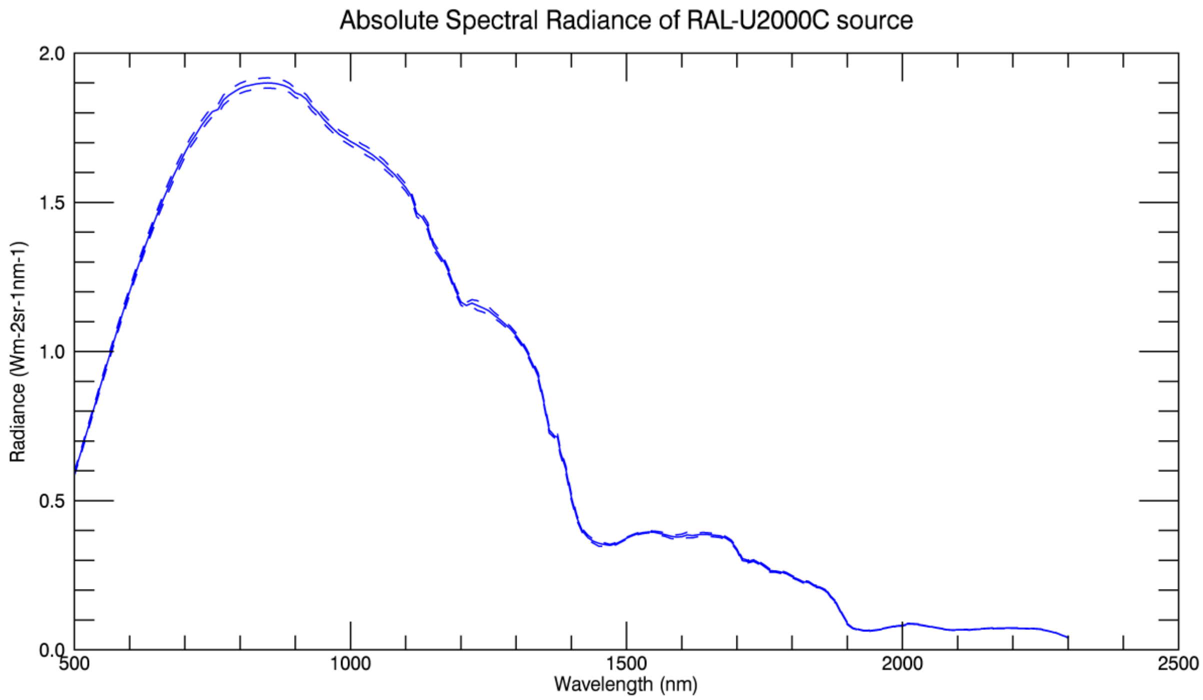


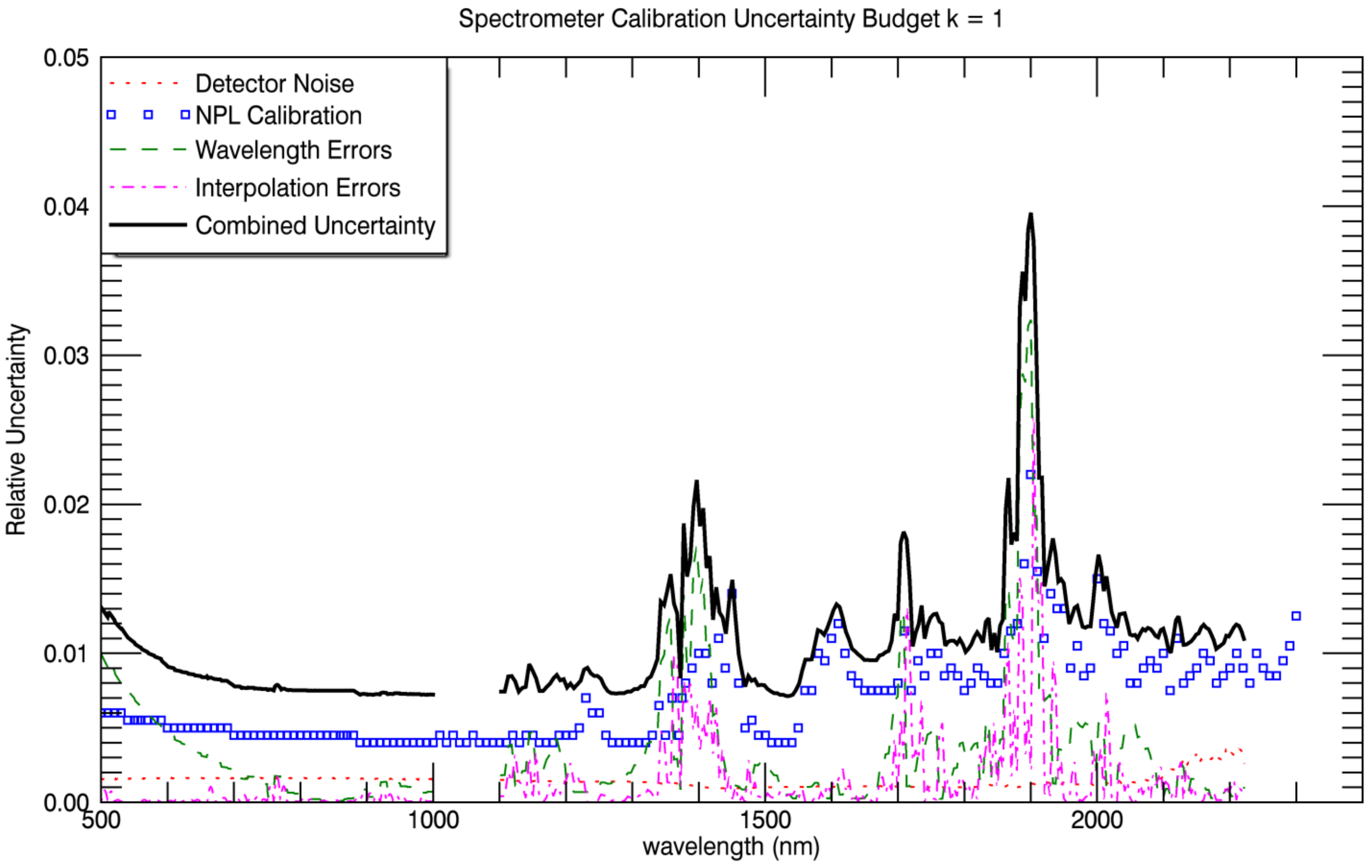
Figure 1: Absolute Spectral Radiance of RAL U2000C Integrating Sphere measured in August-September 2015. Dashed lines show the k=2 uncertainty of the measurements.

Uncertainty in Absolute Calibration

Table 1: Breakdown of uncertainties in transfer of absolute radiance calibration to sphere spectrometers.

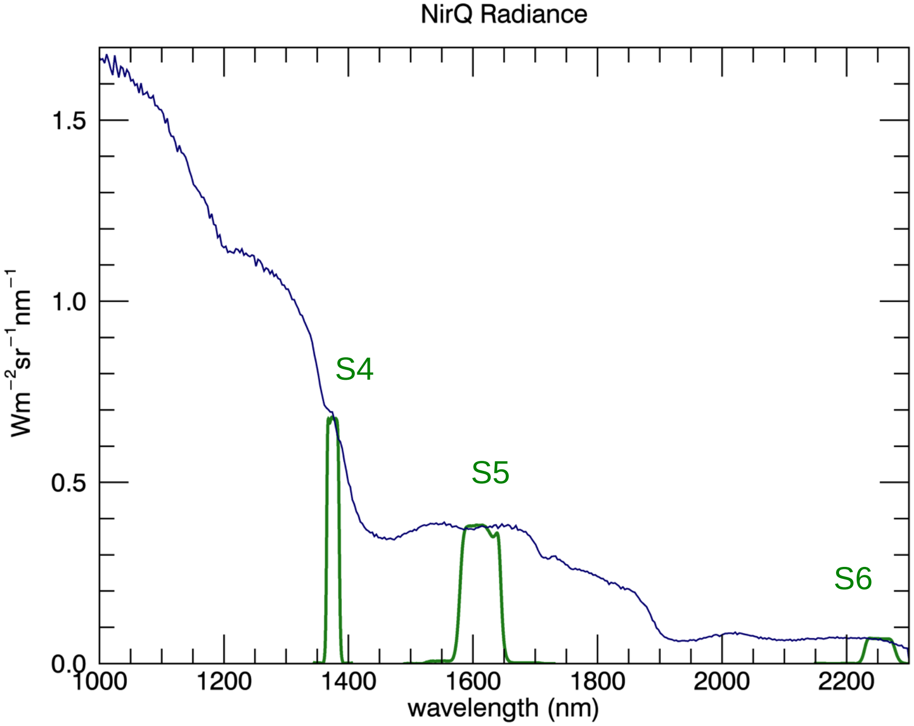
Symbol	Component	Sensitivity Coefficient	Uncertainty Estimate	Divisor	Characterisation
$u(L_{sphere})$	Sphere calibration	1	<1% (VIS) <2% (SWIR)	2	NPL Report (values quoted at k=2)
$u(L_{interp})$	Interpolation of radiance	1	<0.2% (VIS) <2.5% (SWIR)	1	Comparison of interpolation methods – linear and quadratic. Depends on wavelength and presence of spectral features.
u(Noise_All)	Spectrometer Noise full lamps	1	<0.29% (SWIR)	1	Standard deviation of signals during measurements
u(Noise_dark)	Spectrometer Noise – Dark Signal	1	<0.26% (SWIR)	1	Standard deviation of signals during measurements
u(Spec_Drift)	Spectrometer Drift	1	1%	√3	Comparison of spectrometer signals during calibration
u(l)	Spectrometer Wavelength	∂L/∂l <1%/nm (VIS) <3%/nm (SWIR)	<1nm	1	Estimate – should be calibrated with known spectral lines to get accurate wavelength registration

Uncertainty in Absolute Calibration



Processing of data from spectrometers

RAL Space



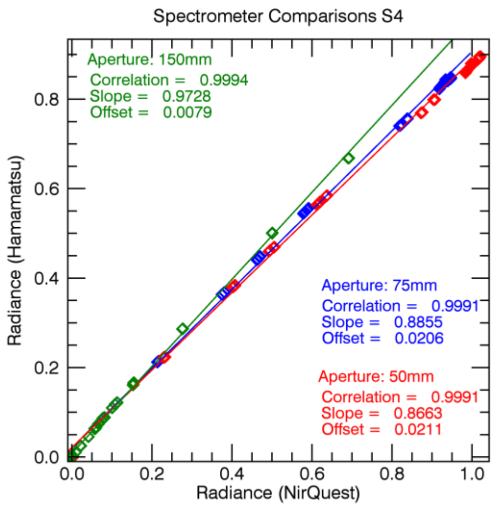
Band Averaged Spectral Radiances:

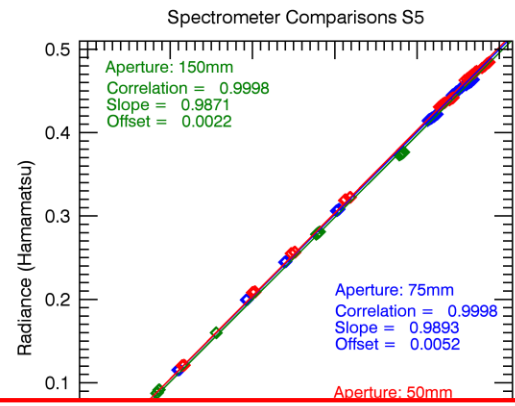
are obtained by integrating the sphere radiance, L_λ, over the spectral response R_λ, at each band, using:

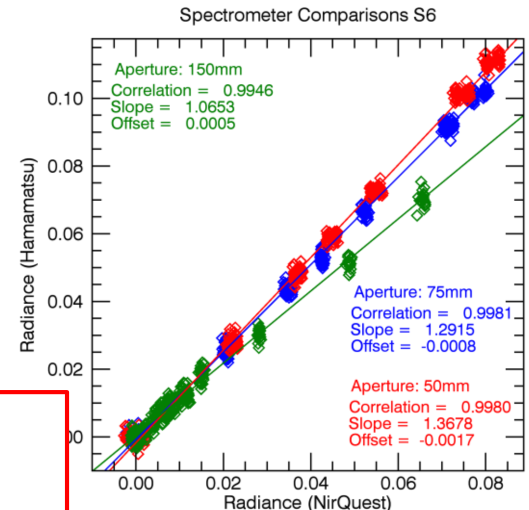
$$L_\lambda = \frac{\int R(\lambda) I(\lambda) d\lambda}{\int R(\lambda) d\lambda}$$

Spectrometer inter-comparisons

During the SLSTR testing (150mm, 75mm, & 50mm output port):



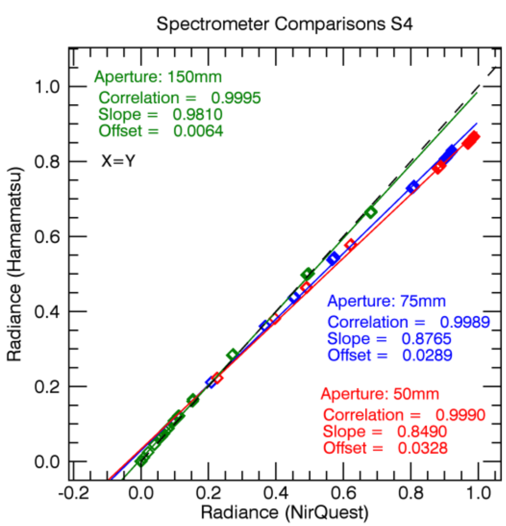


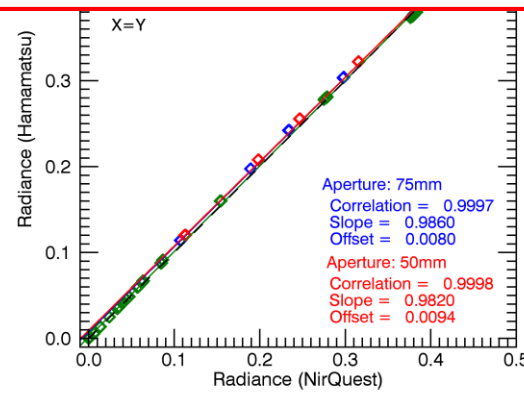


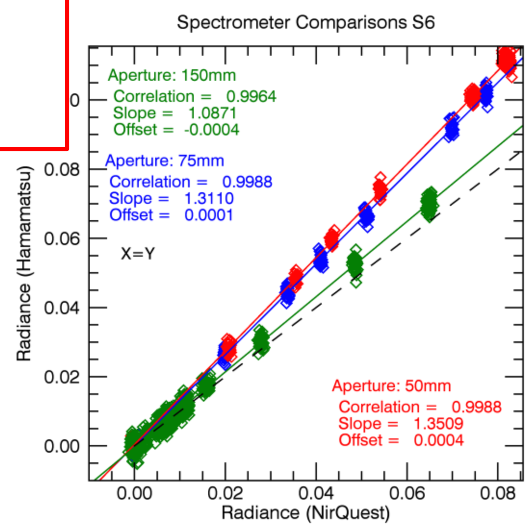
S4:
Aperture 150 mm, Hamamatsu = NirQ
Reduced Apertures: NirQ > Hamamatsu

S6:
Aperture 150 mm, Hamamatsu ≥ NirQ
Reduced Apertures: Hamamatsu > NirQ

From data measure… A & VIS13B):

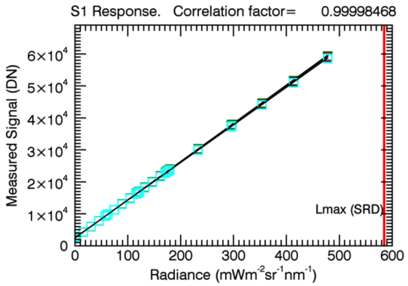


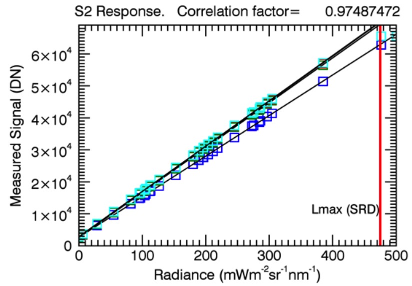


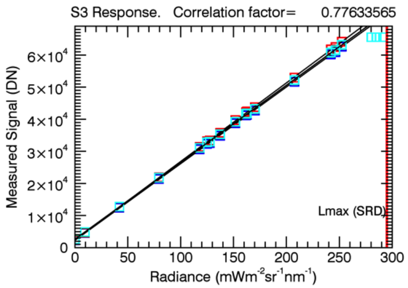


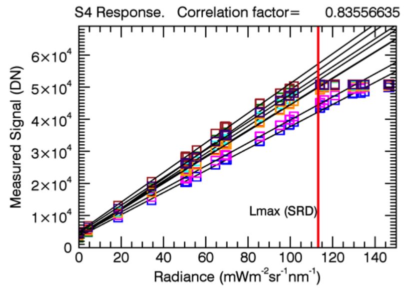
Radiometric Response – Nadir View

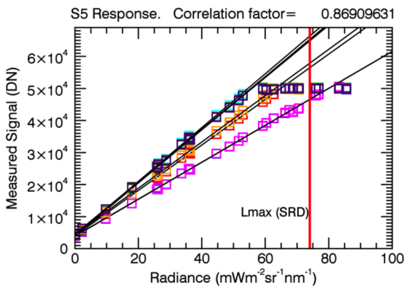
SLSTR-A

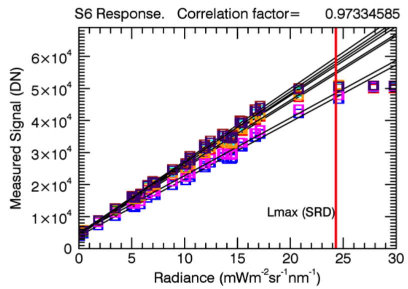




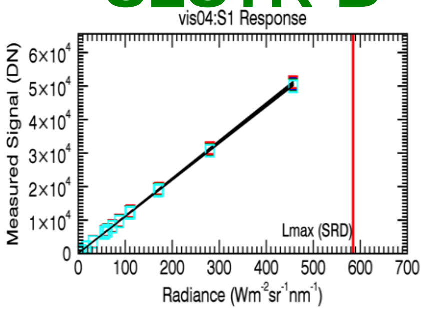


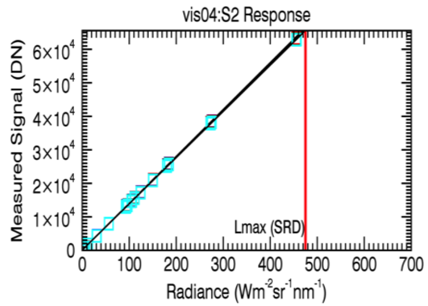


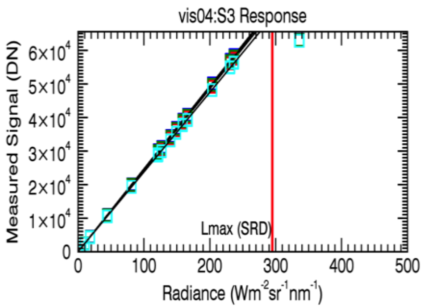


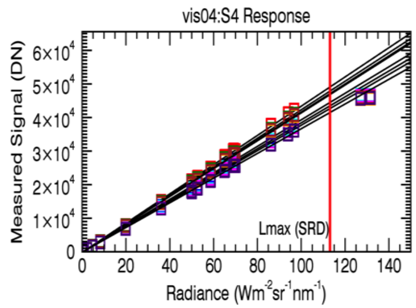


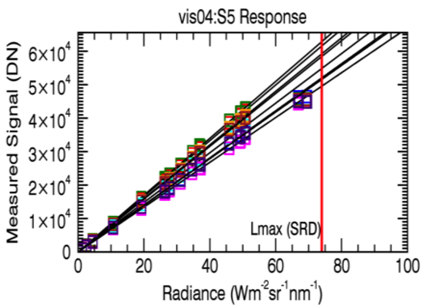
SLSTR-B

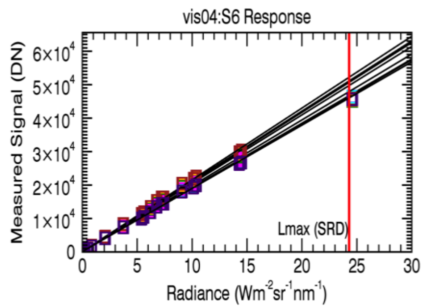






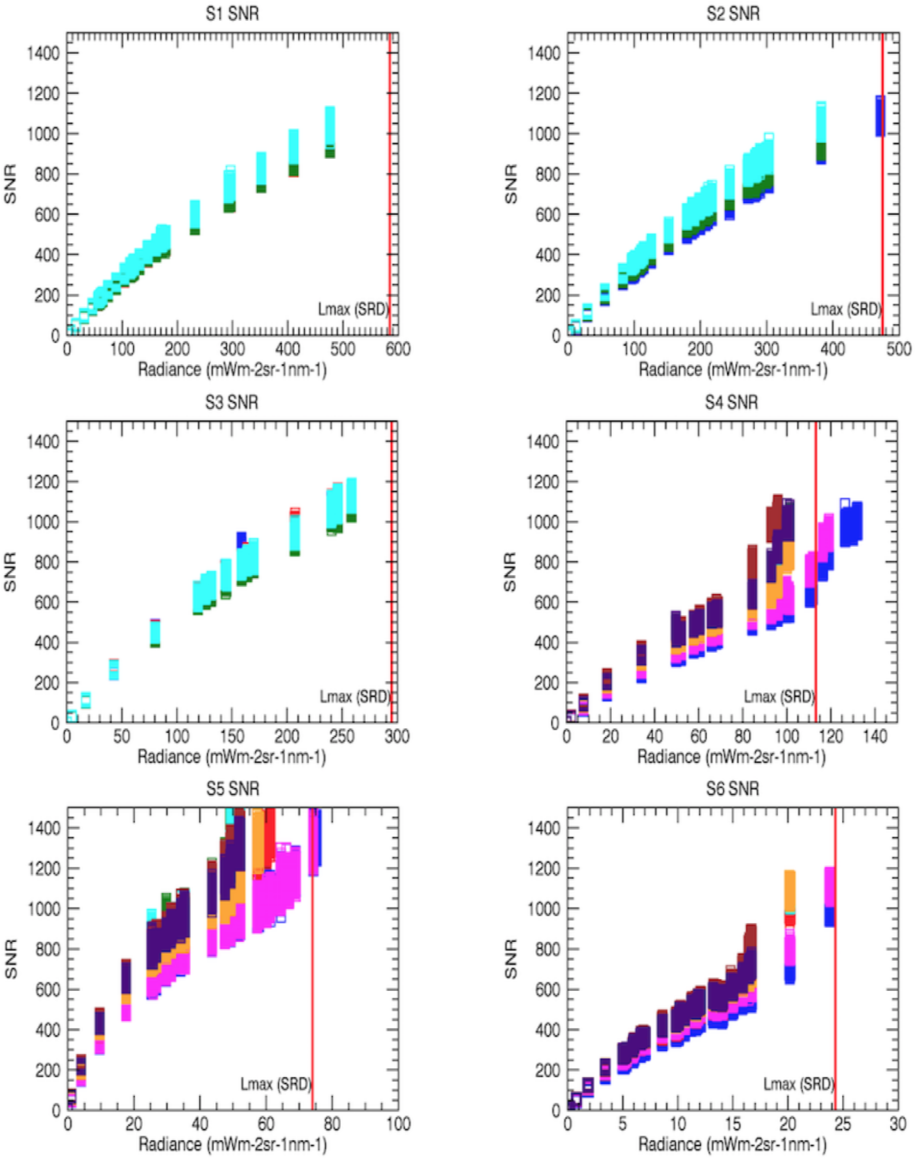




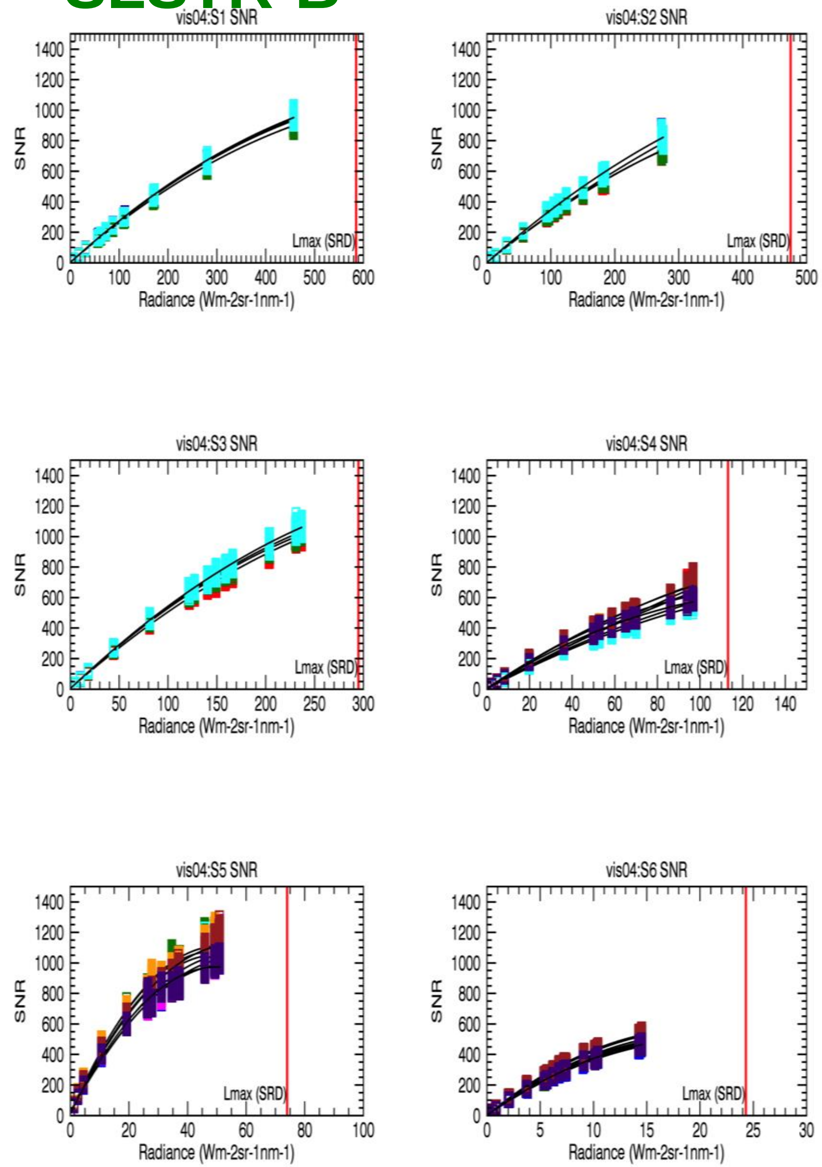


SNR Performance

SLSTR-A



SLSTR-B



Theoretical VISCAL reflectance factors

RAL Space

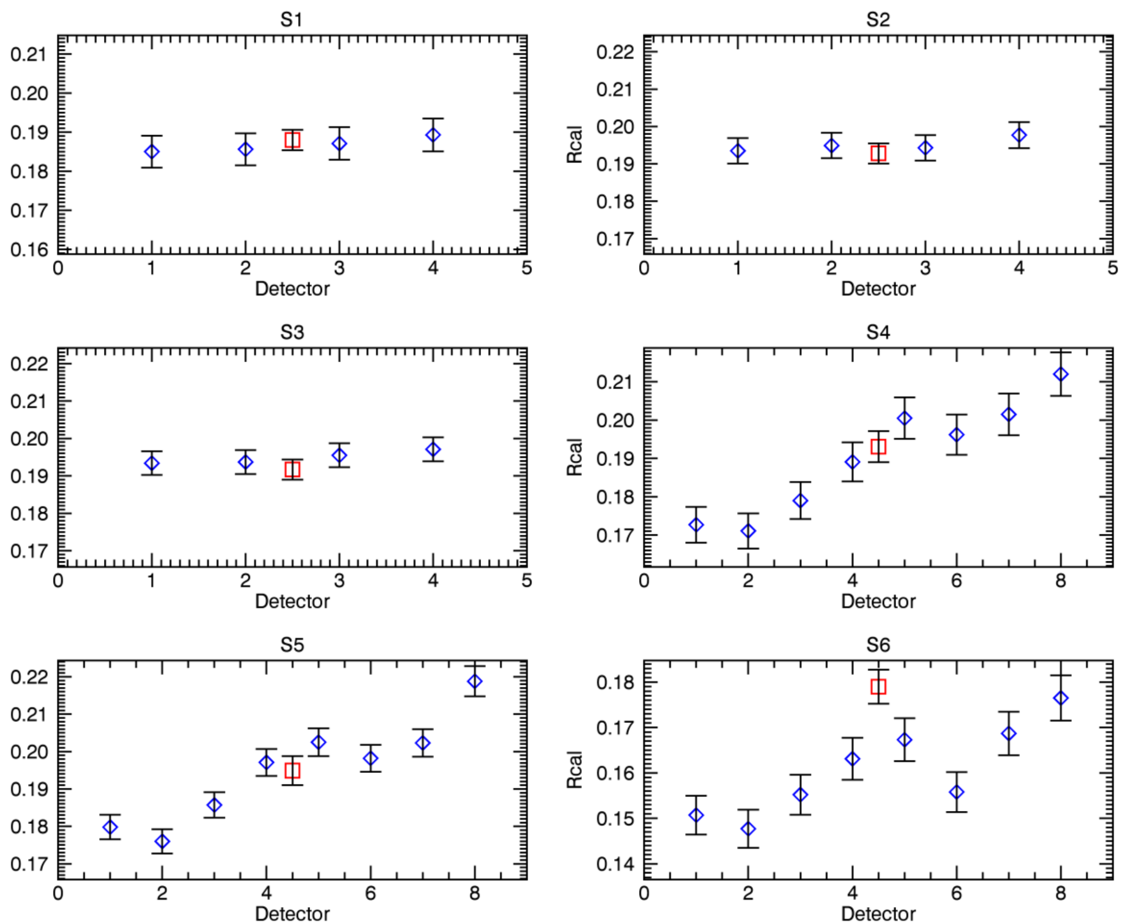
$$R_{VISCAL} = \tau_{UV} R_D(\theta_0, \theta_v, \varphi_0, \varphi_v) \rho_{m1} \rho_{m2} \rho_{m3} A_{m3} \ / \ A_{SLSTR}$$

NADIR	S1 [3σ]	S2 [3σ]	S3 [3σ]	S4 [3σ]	S5 [3σ]	S6 [3σ]
R_D	0.3257 [0.93]	0.3252 [0.94]	0.3229 [0.92]	0.3205 [2.66]	0.3218 [2.60]	0.3096 [3.01]
ρ_{m1}	97.27 [0.1]	98.13 [0.1]	98.16 [0.1]	98.62 [0.1]	98.78 [0.1]	99.21 [0.1]
ρ_{m2}	97.27 [0.1]	98.06 [0.1]	98.06 [0.1]	98.64 [0.1]	98.87 [0.1]	99.24 [0.1]
ρ_{m3}	97.33 [0.1]	98.03 [0.1]	97.97 [0.1]	98.16 [0.1]	98.32 [0.1]	98.62 [0.1]
τ_{UV}	91.95 [0.14]	92.19 [0.13]	92.38 [0.46]	92.58 [0.42]	92.56 [0.43]	87.34 [0.5]
A_{m3} / A_{SLSTR}	0.21696051 [1.44]					
R_{VISCAL}	**0.1880 [1.4]**	**0.1928 [1.4]**	**0.1917 [1.4]**	**0.1931 [2.1]**	**0.1949 [2.0]**	**0.1790 [2.1]**

OBLIQUE	S1 [3σ]	S2 [3σ]	S3 [3σ]	S4 [3σ]	S5 [3σ]	S6 [3σ]
R_D	0.3219 [0.98]	0.3211 [1.01]	0.3190 [1.00]	0.3172 [2.70]	0.3178 [2.62]	0.3060 [3.02]
ρ_{m1}	97.14 [0.1]	97.97 [0.1]	98.06 [0.1]	98.36 [0.1]	98.47 [0.1]	98.80 [0.1]
ρ_{m2}	97.32 [0.1]	98.06 [0.1]	98.03 [0.1]	98.48 [0.1]	98.58 [0.1]	98.84 [0.1]
ρ_{m3}	97.31 [0.1]	98.08 [0.1]	98.05 [0.1]	98.24 [0.1]	98.43 [0.1]	98.54 [0.1]
τ_{UV}	91.95 [0.14]	92.19 [0.13]	92.38 [0.46]	92.58 [0.42]	92.56 [0.43]	87.34 [0.5]
A_{m3} / A_{SLSTR}	0.1869269 [1.77]					
R_{VISCAL}	**0.1599 [1.6]**	**0.1638 [1.6]**	**0.1631 [1.6]**	**0.1641 [2.1]**	**0.1651 [2.1]**	**0.1510 [2.1]**

Input data from component level characterisation – part of instrument level calibration database

Measured Reflectance Factors



Measured SLSTR-A Nadir view Rcal for each detector (blue) compared to prediction (red)

Results show unexpected dispersion of measured reflectance factors.

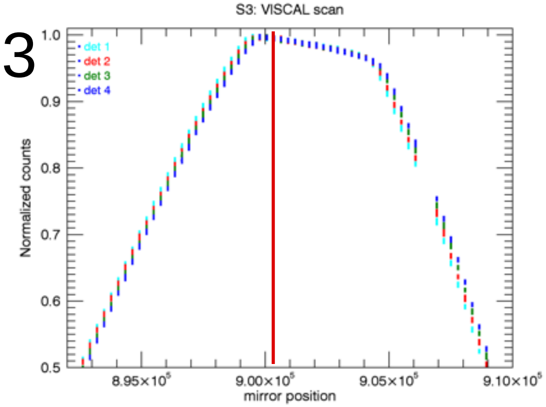
Particularly pronounced in SWIR channels.

With exception of S6, average values in good agreement with predictions.

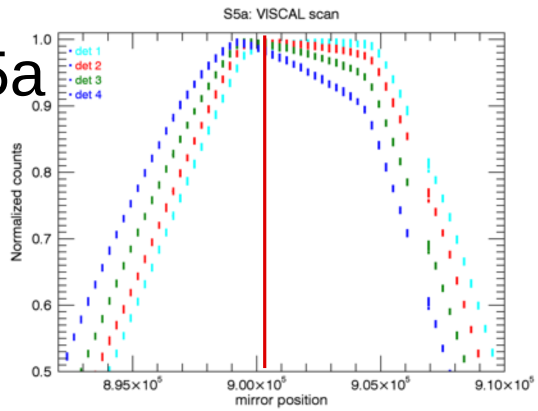
Similar results for Oblique view and SLSTR-B

VISCAL Pixel Range and Uniformity

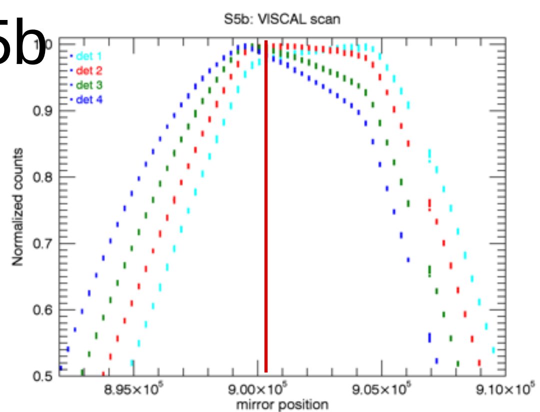
S3



S5a



S5b



We performed a set of measurements where the source illuminated the diffused and measured the signal response for different scanner positions.

Results determined the range of pixels to use on-orbit.

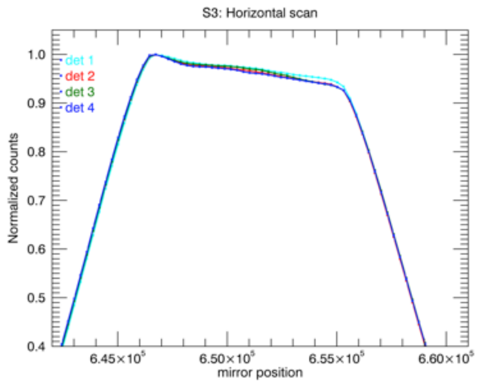
Showed a significant non-uniformity in the measured responses.

- For SWIR channels different for each detector
- Greater than expected variation in diffuser BRDF

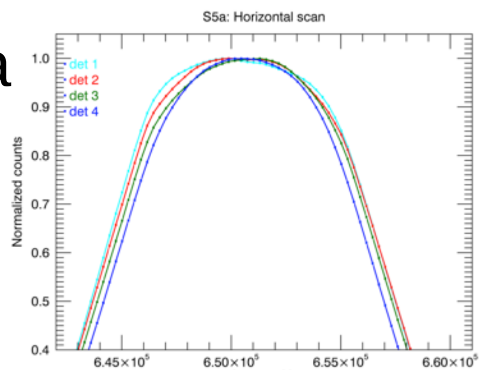
Why?

Pupil Uniformity – Along Scan

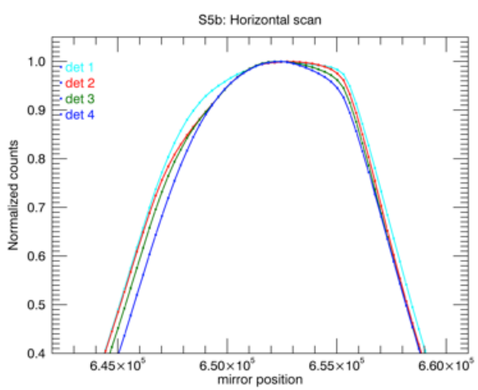
S3



S5a



S5b



To investigate cause of non uniformity we performed some additional measurements at centre of earth view.

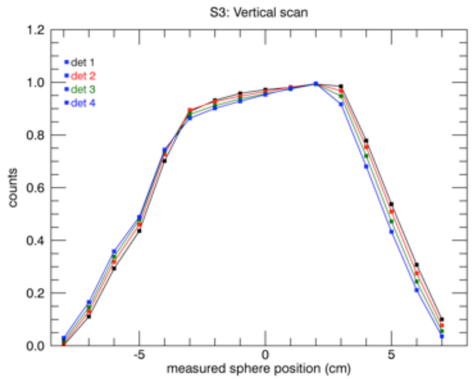
We illuminate the earth view with a 50mm diameter source (i.e. underfilling the pupil) and measure the instrument response as a function of scanner position (along scan direction)

Results show all VIS channels appear to fill main aperture uniformly.

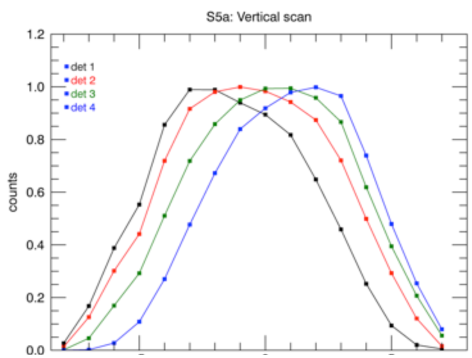
Differences seen in SWIR channel A and B stripes. Less uniform response

Pupil Uniformity – Along Track

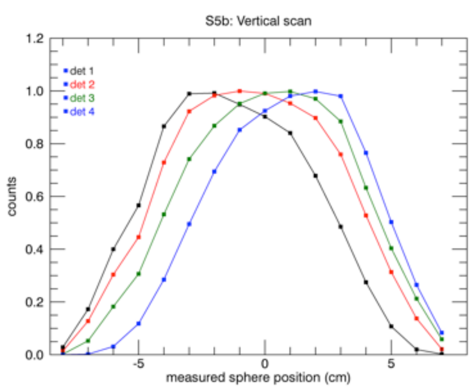
S3



S5a



S5b



We then repeated the measurements, this time moving source in vertical direction (along track direction)

Results show all VIS channels appear to fill main aperture uniformly.

Noticeable differences seen in each SWIR detector.

Conclusion:
Main telescope aperture is not the primary pupil for the SWIR channels

Provides root cause for variations in measured instrument response and Rcal

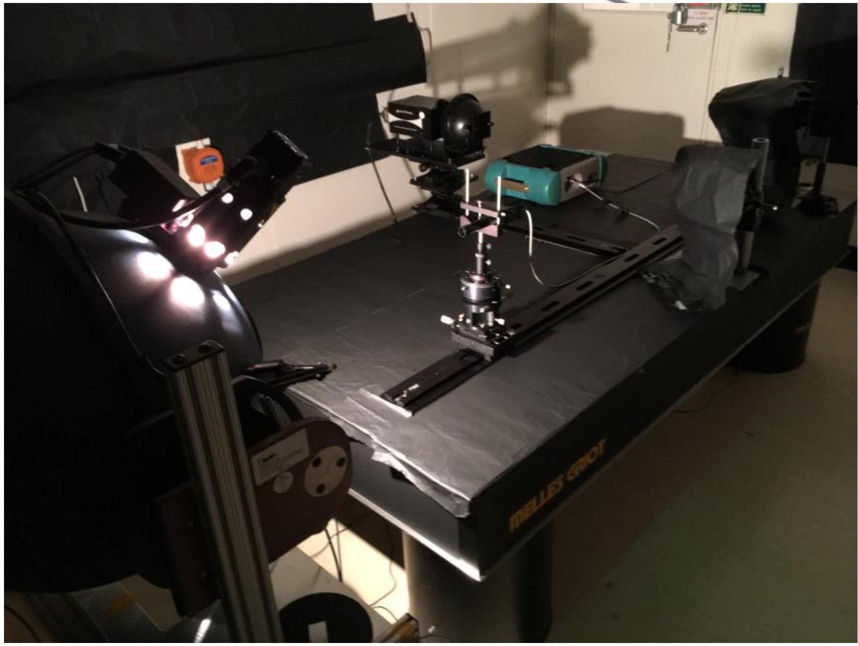
NPL-RAL-TAS Sphere Intercomparisons

An exercise has been initiated to compare spectral radiances of integrating sphere sources used for SLSTR (RAL Space) and OLCI (Thales Alenia Space, France) calibrations.

NPL are performing measurements using spectroradiometers and reference source at host institution.

Measurements performed at RAL in December during SLSTR calibration campaign. Data being processed.

Dates for OLCI to be confirmed - but close to instrument calibration



NPL’s ASL spectrometer and source viewing RAL integrating sphere source.

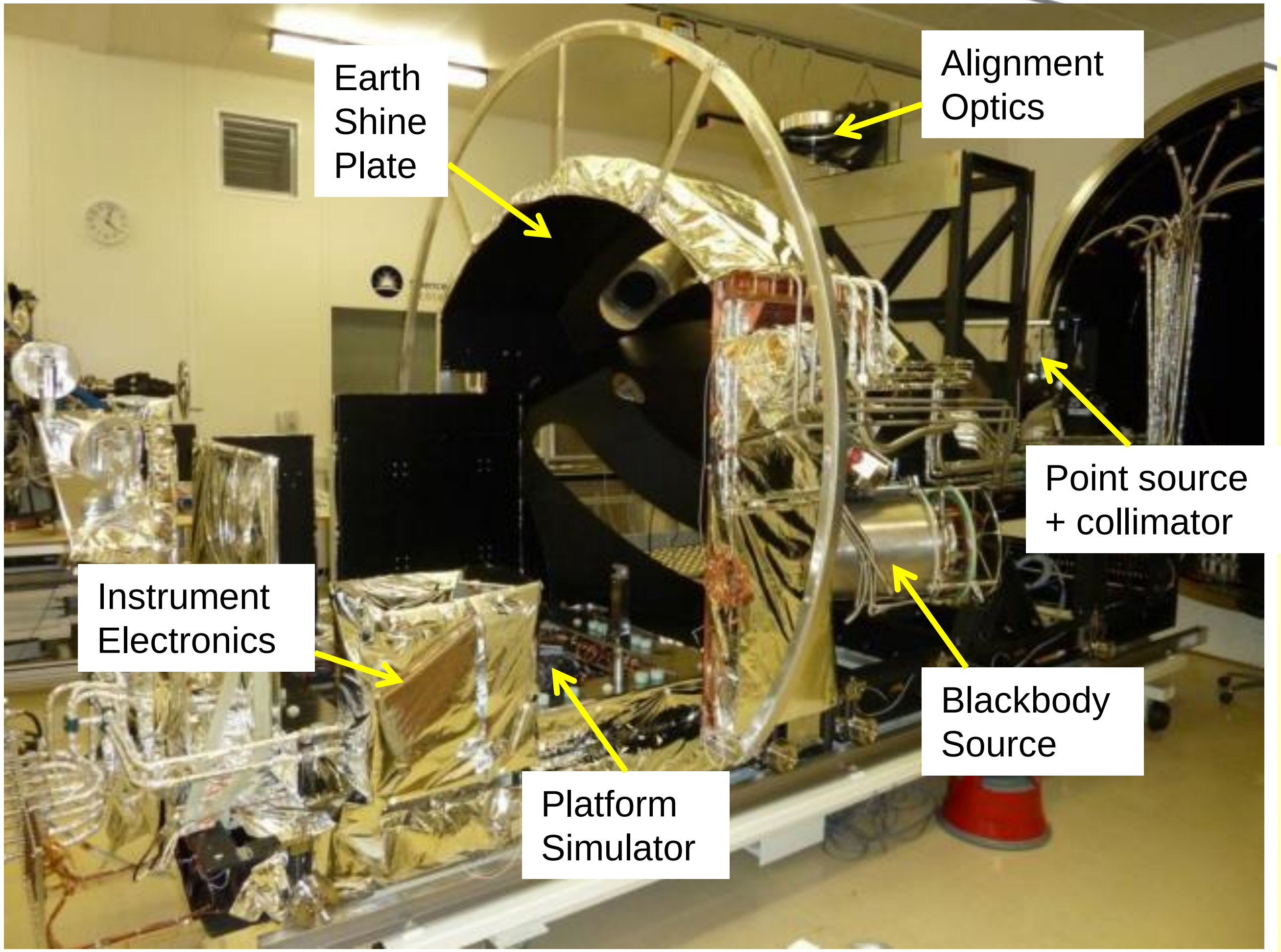
IR Instrument Calibration – Objectives

- **Does the end-to-end instrument calibration scheme work?**
  - New optical design – 2 telescopes not 1, multiple detectors per channel
  - OME thermal design – not based on AATSR heritage

- **Does the instrument calibration work over the full field of view and dynamic range?**
  - Wider instrument swath compared to AATSR
  - Nonlinearity, Noise performance, Dynamic range

- **Does calibration work in flight representative environment?**
  - Nominal BOL – is this defined?
  - EOL (Hot)
  - Orbital temperature variations

Thermal IR Calibration Facility



Initial Trials with STM completed April 2012

TV and calibration of S3A instrument March-May 2015

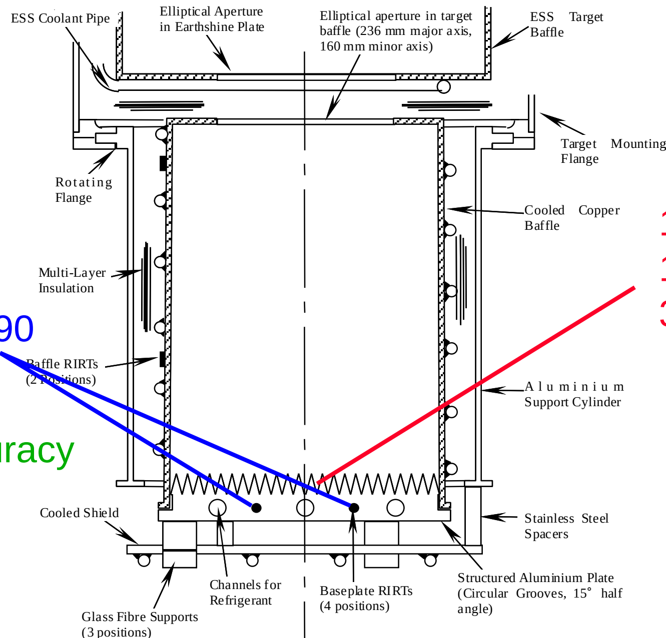
S3B Calibration Oct 2016 – Feb 2017

S3C 2019

S3D 2020…

- ESA requirement to perform calibration tests under flight representative conditions.
  - *Thermal balance*
  - *Steady State*
  - *Instrument fully operational*

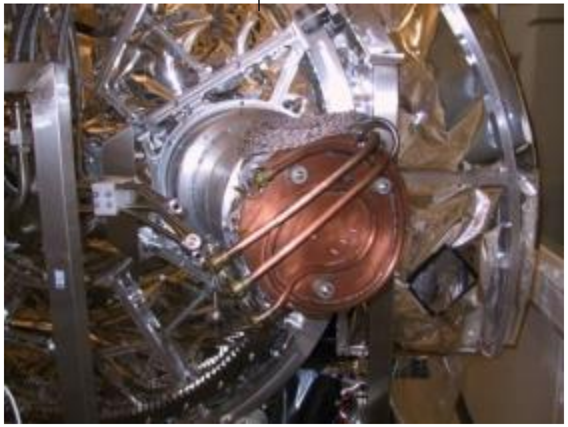
TIR calibration- Blackbody Calibration Source



Precision RIRTs Calibrated to ITS90 < 0.01K

Radiometric Accuracy < 0.05K

Emissivity
12µm = 0.99871
11µm = 0.99870
3.7µm = 0.99911



Sources previously used for all ATSR instruments

Standards

ATSR

ATSR-2

AATSR

S3 SLSTR

IR Calibration Test Summary

- Calibration at 'Nominal' BOL conditions
  - Centre of Nadir/Oblique views
  - On-Board BBs at nominal settings (250K, 300K)
  - Test over full dynamic range (5K intervals)
  - Test over full swath (reduced number of scene temperatures)

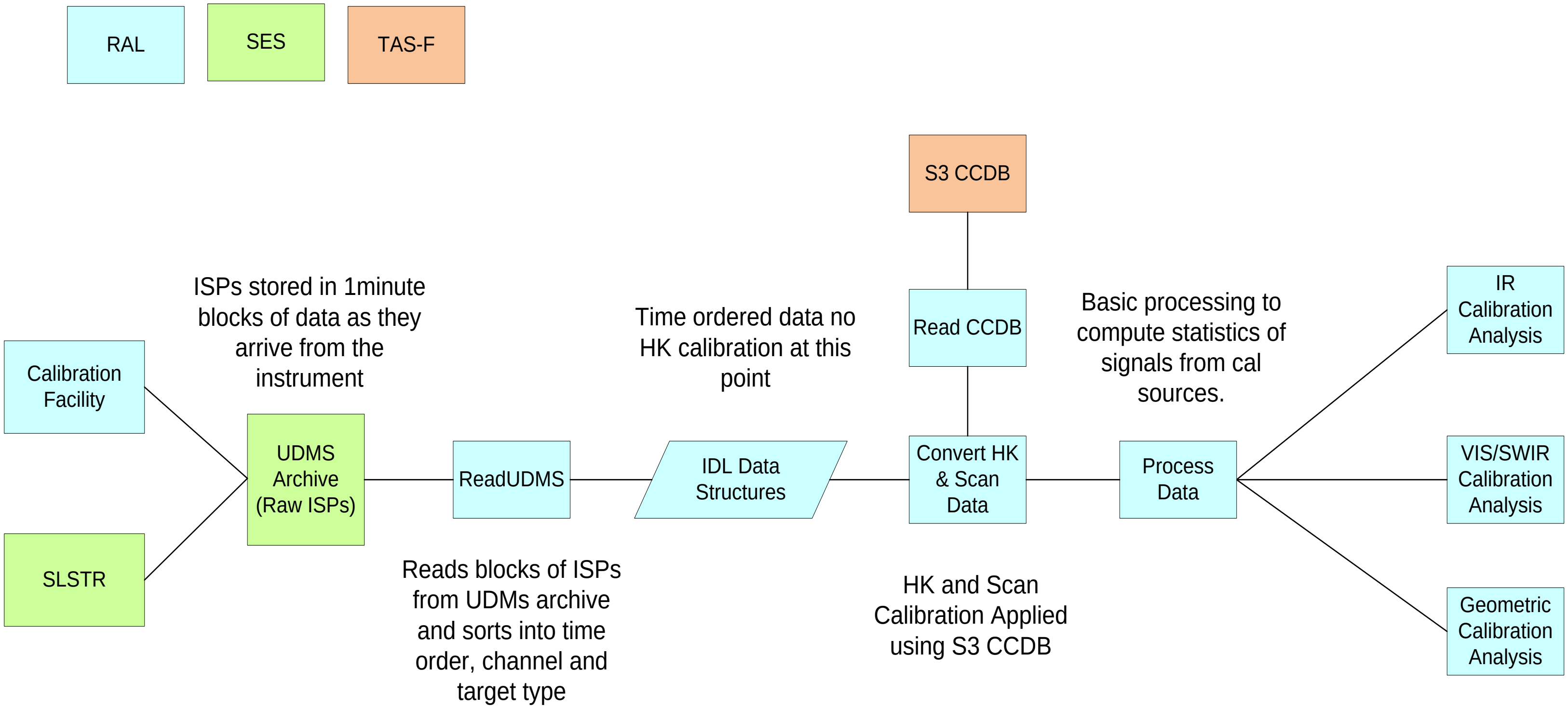
- Calibration at 'Nominal' EOL conditions
  - Centre of Nadir/Oblique views
  - On-Board BBs at nominal settings (250K, 300K)
  - Test over part dynamic range (10K intervals)

- Tests with different on-board BB temperatures
  - Test performed at 'Nominal' BOL conditions
  - Currently at 'low', 'medium', 'high' power settings
  - +Y and –Y BBs will be switched
  - Test over part dynamic range (10K intervals)

- Orbital simulation tests

Data Processing

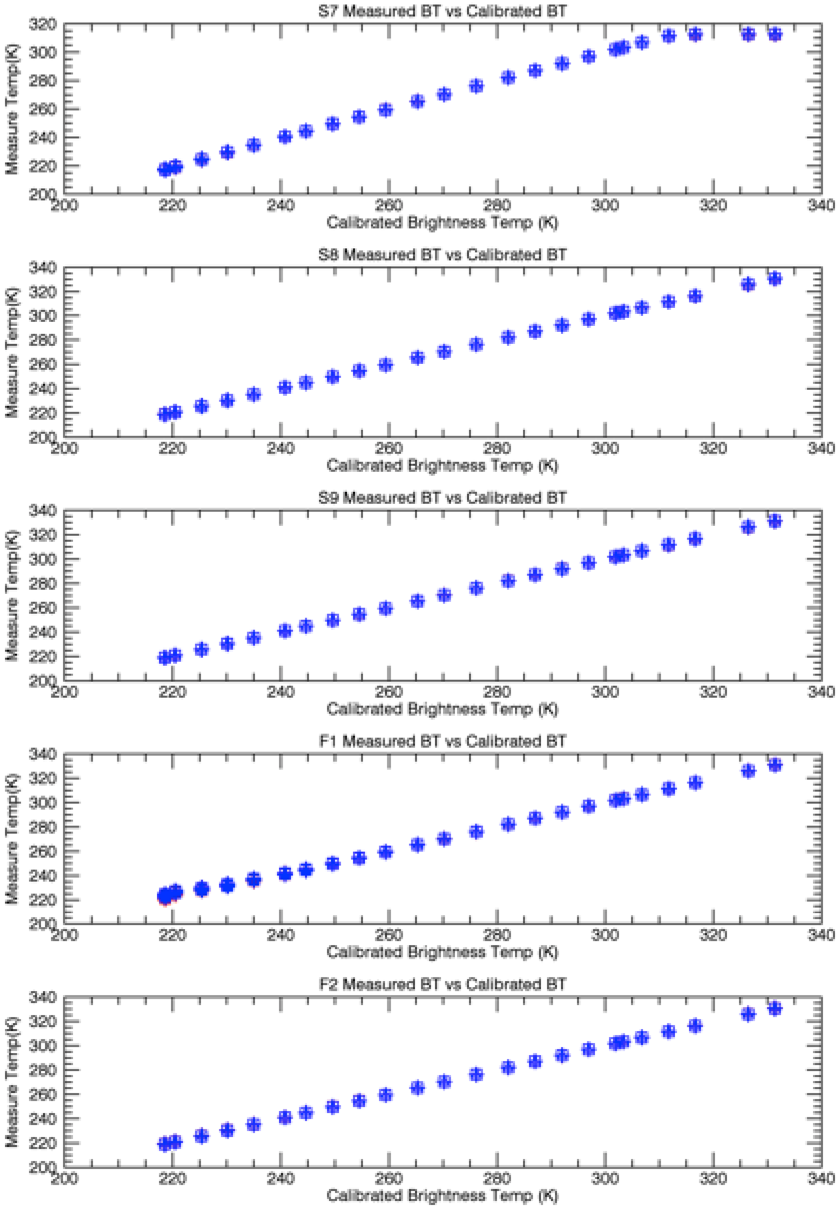
- For SLSTR (as for ATSR series) we process data using calibration algorithms and input data as used by IPF.



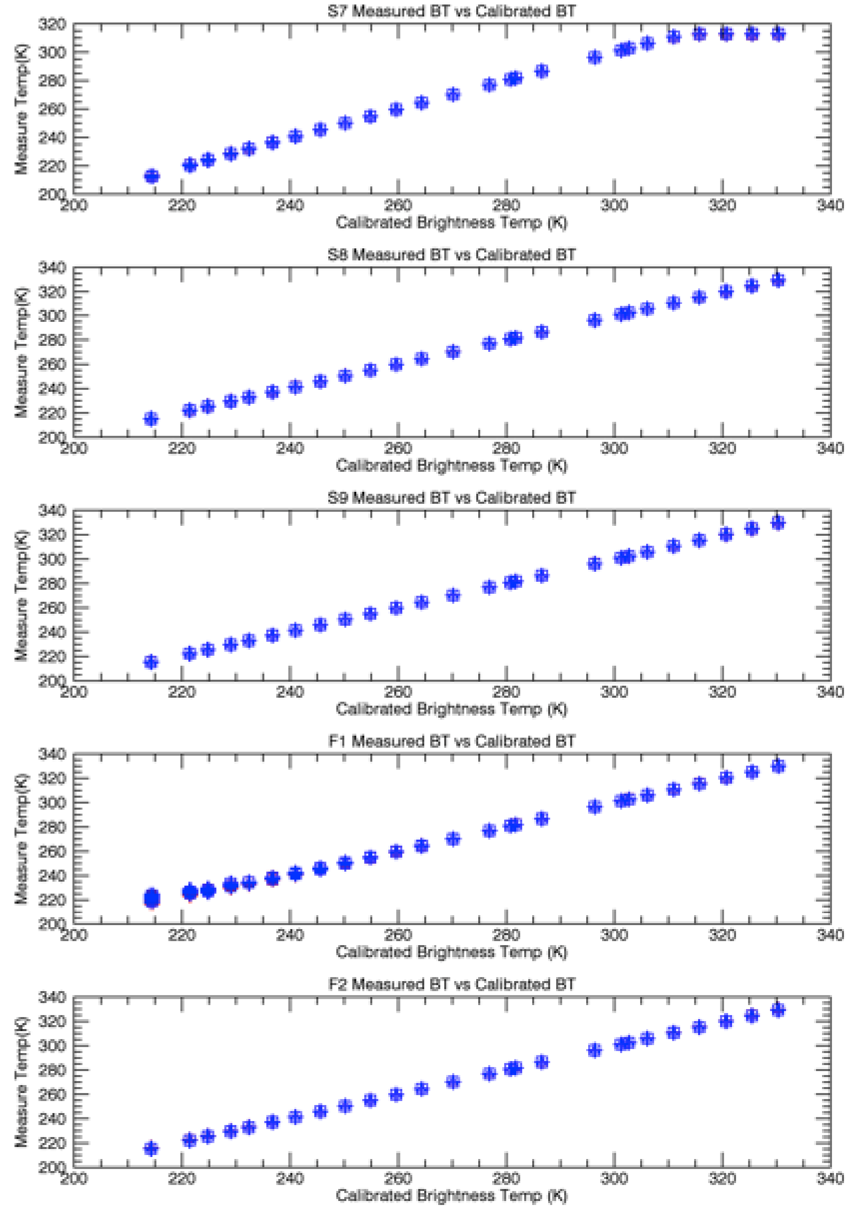
TIR Calibration - Measured vs Actual BT

RAL Space

Nadir

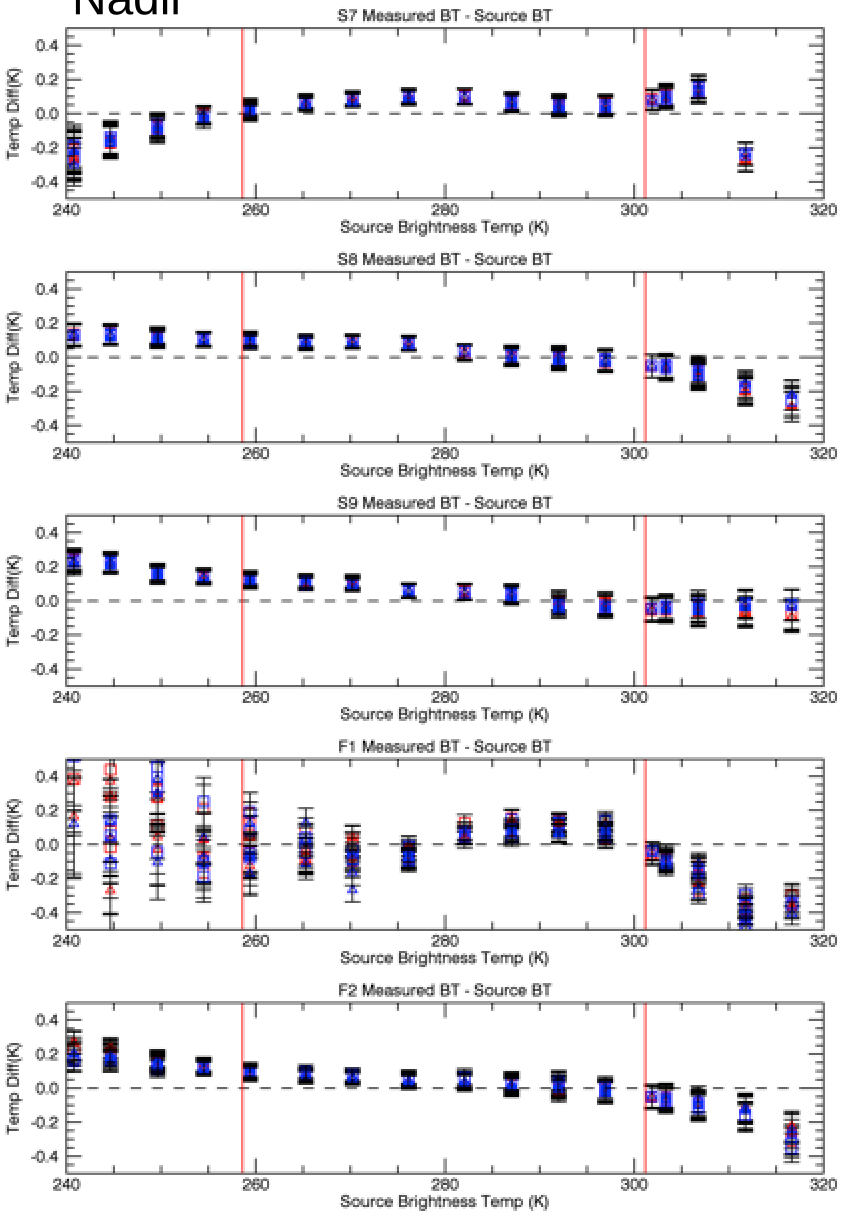


Oblique

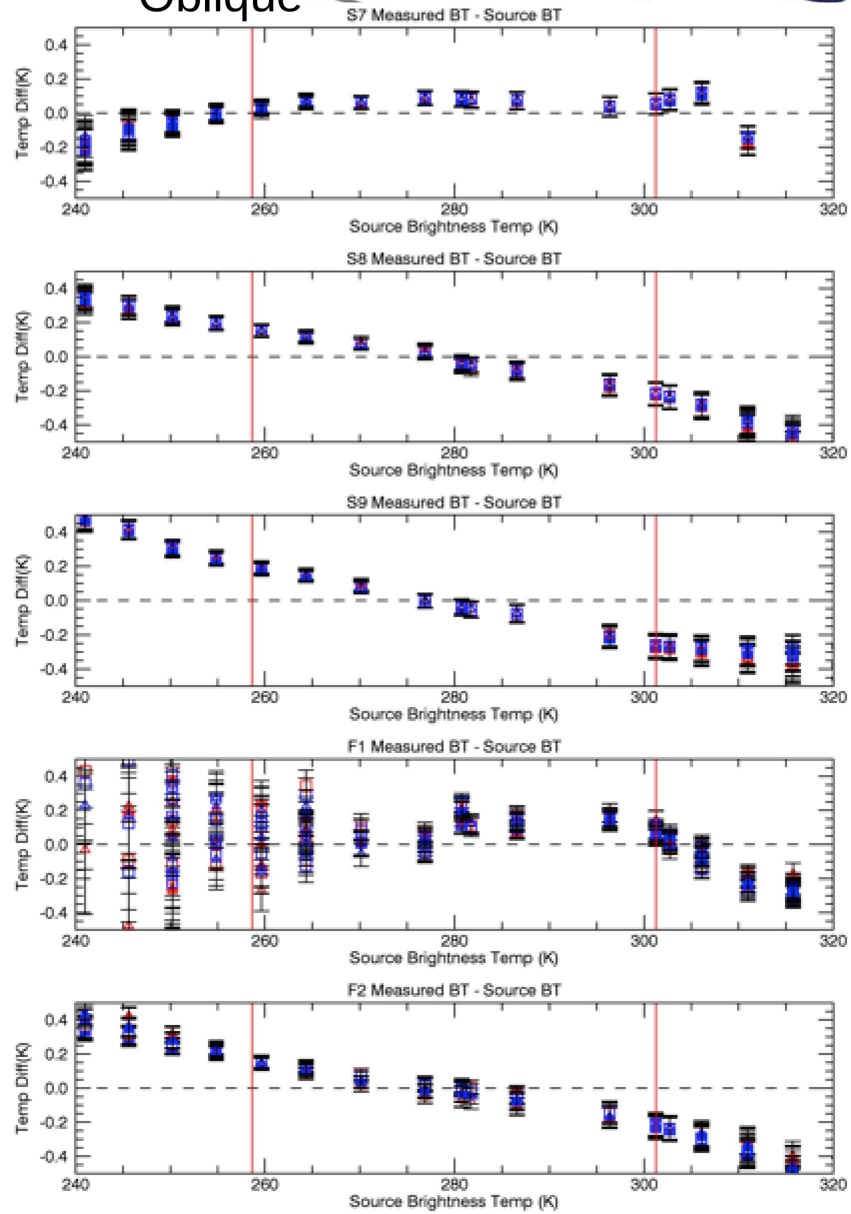


Measured - Actual BT SLSTR-A

Nadir



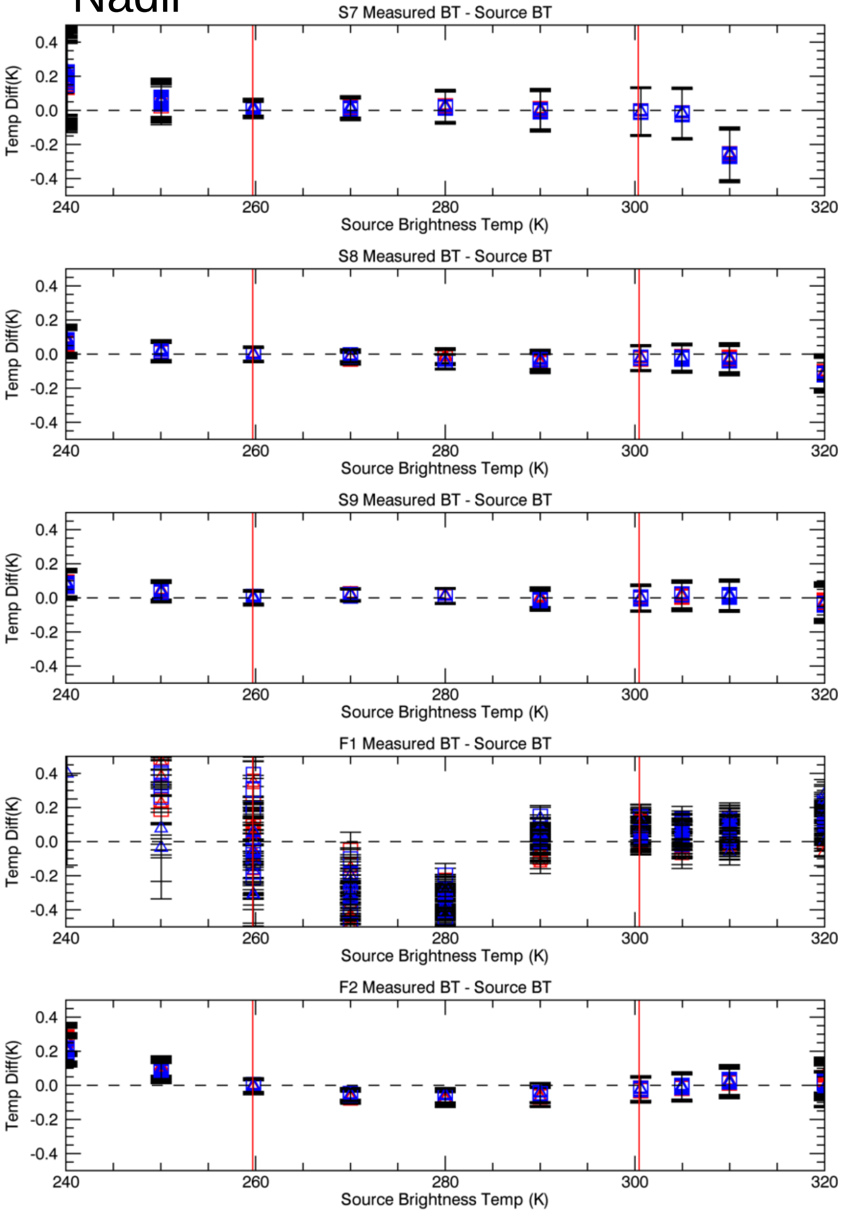
Oblique



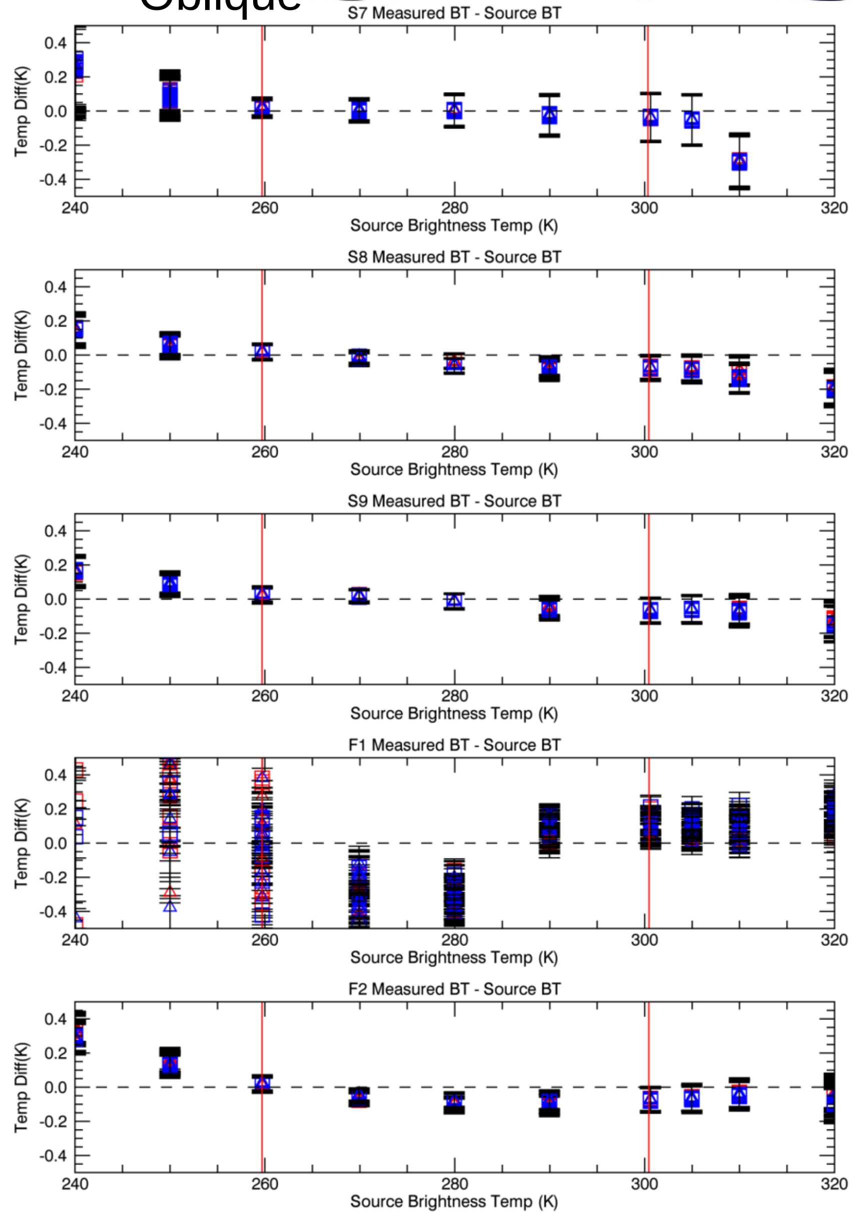
RAL Space

Measured - Actual BT SLSTR-B

Nadir



Oblique



RAL Space

Calibration Model

- From the measured DN we wish to obtain the scene radiance L_{scene}

- Assuming that the radiometric response of the system is linear with radiance (or adjusted for detector non-linearity), we can derive the gain using two calibration sources of known scene radiance
  - i.e. Blackbodies
  - $DN_{BB} = g(L_{BB}) + DN_{Offset}$

- This gives
  - $L_{scene} = XL_{hbb} + (1\text{-}X)L_{cbb}$

  Where

  $X = (DN\text{-}DN_{cbb})/(DN_{hbb}\text{-}DN_{cbb})$

- **Both g and DN_{offset} MUST be constant during the calibration interval.**

Stray light effects on calibration

- At TIR wavelengths specifically, the offset signal DN_{offset} is a combination of
  – Offset voltage

  AND

  \- Thermal emissions from instrument (about 10-20% of the detected signal)

- A fundamental requirement for the calibration to work is that the thermal emission as viewed by the detector is constant for the full scan and over the calibration period (~10s).

- Stray light paths from other parts of the instrument should not cause a problem where they contribute to thermal background signal
  – Provided that they are NOT dependent on scan mirror position

Scan Dependent strays

- What if DN_{offset} is not constant during the scan cycle?
- Lets consider as a function of pixel position, a scan dependent radiance pertubation of $\pm\Delta L(pos)$ which in turn gives rise to a pertubation in the background signal $\pm\Delta DN(pos)$.
- The calibration model now becomes

$$L_{scene} + \Delta L(scene) = X(L_{hbb} + \Delta L(hbb)) + (1-X)(L_{cbb} + \Delta L(cbb))$$

where

$$X = ((DN_{scene} + \Delta DN(scene)) - (DN_{cbb} + \Delta DN(cbb)))/$$
$$(DN_{hbb} + (\Delta DN(hbb) - (DN_{cbb} + \Delta DN(cbb)))$$

- But we are assuming the ideal calibration model, so the error we observe in the calibration is

$$\Delta L_{error} = \Delta L(scene) - X\Delta L(hbb) - (1-X)\,\Delta L(cbb)$$

which can be rewritten as

$$\Delta L_{error} = (\Delta L(scene) - \Delta L(cbb)) + X(\Delta L(cbb) - \Delta L(hbb))$$

Error Model

Calibration Error Model due to offset errors is given by

$\Delta L_{error} = \Delta L(scene) – X\Delta L(hbb) - (1-X)\, \Delta L(cbb)$
Where
$X = (L_{scene} - L_{CBB})/(L_{hbb} - L_{cbb})$

Stray light model gives each term

$\Delta L(scene) = f(L_{stray,scene} – L_{scene})$
$\Delta L(cbb) = g(L_{stray,cbb} – L_{cbb})$
$\Delta L(hbb) = g(L_{stray,hbb} – L_{hbb})$

f and g are stray light factors derived from pre-launch calibration

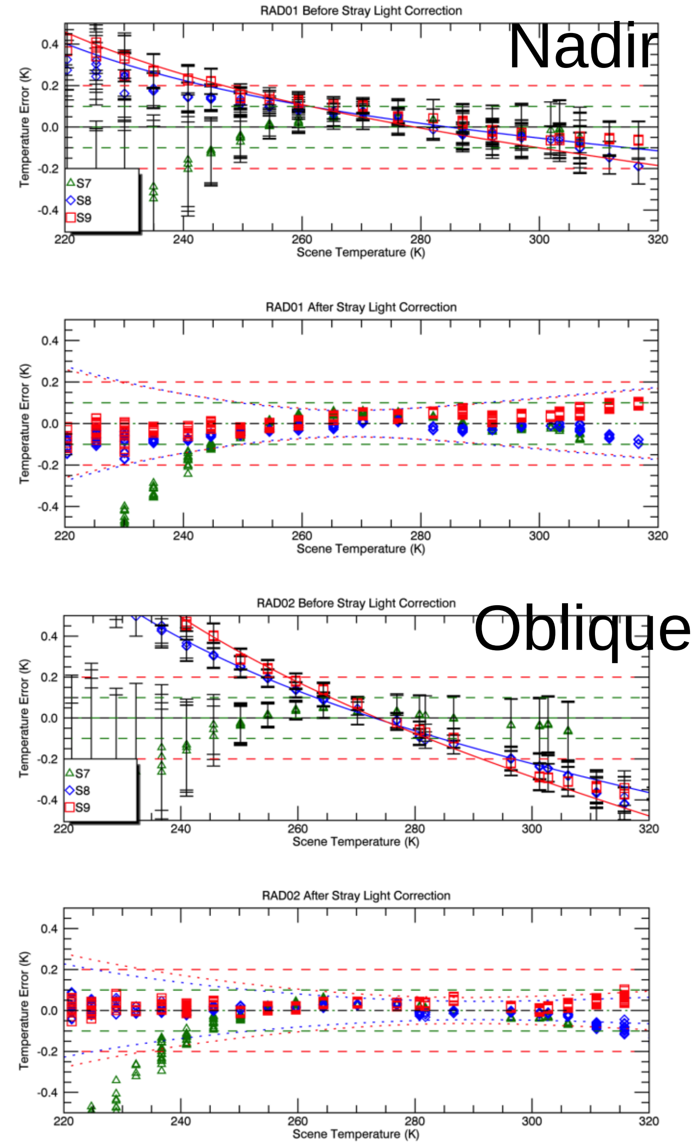
L_{stray} are derived from instrument temperatures (from instrument telemetry)
$L_{cbb,}$ L_{hbb} are derived from blackbody thermometers (from instrument telemetry)
L_{scene} is a function of temperature

Correction to BT is then

BTcorrected = BTmeasured – $\Delta T(\Delta I_{error})$

‘Stray Light’ Model Correction

- Model provides good estimate measured calibration errors. Hence conclusion that this is best explanation for discrepancy.
- Input parameters derived from instrument temperatures available in HK.
  - These provide an approximation of the stray light source.
- Model has been coded and tested in Prototype Instrument Processing Facility (IPF-P)
- Early intercomparsions with IASI performed by EUMETSAT suggest that on-orbit stray-light error correction is not necessary.



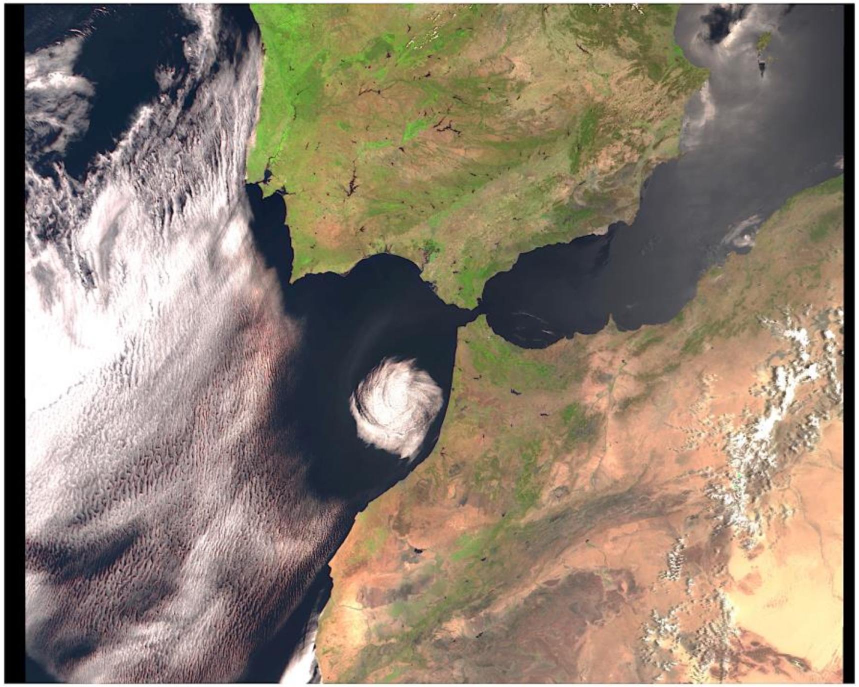
Conclusions

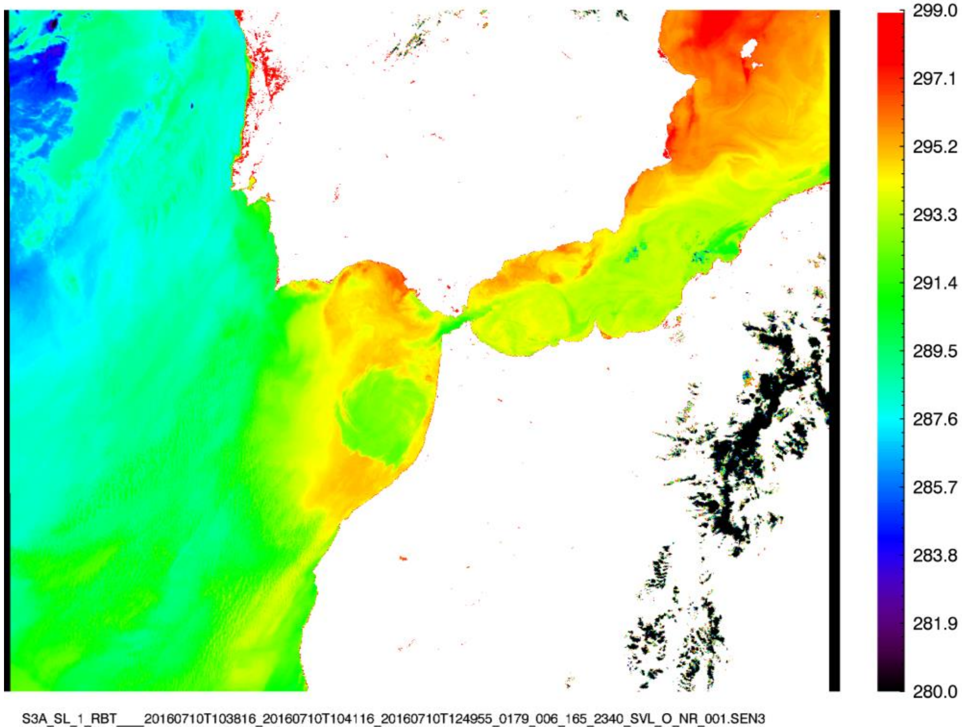
- Pre-launch calibration testing under flight representative is essential:
  - For TIR instruments this is particularly true since vicarious calibration – extremely challenging
  - Necessary for demonstrating end-to-end instrument calibration model
  - Allows identification, analysis and correction of measurement errors
  - Provides reference data that are needed for validating data processors and for post-launch activities

- Calibration testing takes time and resources to perform and process data in timely manner
  - As usual calibration is the last activity in an instrument build …. Huge pressure on schedule, budgets … pressure to descope calibration activities.

- Maintaining a user perspective and objectivity are critical!
  - Vendor's focus is usually on meeting project requirements

Thank You For Your Attention





SLSTR L1b 10-Jul-2016