Uncertainties in Sentinel-3 Sea and Land Surface Temperature Radiometer Thermal Infrared Calibration

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The Remote Sensing Problem
A very indirect measurement

Noise
Responsivity
Spectral Response
Resolution
Coverage
Stability…

A priori information \( (x_a) \)
And uncertainty \( (S_a) \)

Knowledge of environment

Instrument measurements \( (y_m) \)
and uncertainty \( (S_y) \)

Instrument Calibration Parameters

Atmosphere (absorption, scattering, emission), surface state, geometry, illumination…

‘Real world’
e.g. SST, cloud…

Uncertainties are introduced at ALL levels and will affect the final physical quantity of interest

Accurate Physics and Environment

Retrieval Forward model \( y(x) \)

\[
J(x) = (y(x) - y_m)S_y^{-1}(y(x) - y_m)^T + (x - x_a)S_a^{-1}(x - x_a)^T
\]

Cost function

Retrieved parameters and uncertainty \( x \) and \( S_x \)

Understanding of what was missed

Validation \( x_v \) and \( S_v \)
### SLSTR instrument

<table>
<thead>
<tr>
<th>Feature</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nadir swath</td>
<td>&gt;74° (1400km swath)</td>
</tr>
<tr>
<td>Dual view swath</td>
<td>49° (750 km)</td>
</tr>
<tr>
<td>Two telescopes</td>
<td>φ110 mm / 800mm focal length</td>
</tr>
<tr>
<td>Spectral bands</td>
<td>TIR : 3.74µm, 10.85µm, 12µm \nSWIR : 1.38µm, 1.61µm, 2.25 µm \nVIS: 555nm, 659nm, 859nm</td>
</tr>
<tr>
<td>Spatial Resolution</td>
<td>1km at nadir for TIR, 0.5km for VIS/SWIR</td>
</tr>
<tr>
<td>Radiometric quality</td>
<td>NEΔT 30 mK (LWIR) – 50mK (MWIR) \nSNR 20 for VIS - SWIR</td>
</tr>
<tr>
<td>Radiometric accuracy</td>
<td>0.2K for IR channels \n2% for Solar channels relative to Sun</td>
</tr>
<tr>
<td>On-Board Calibration</td>
<td>Blackbody Sources for TIR \nVISCAL for solar channels</td>
</tr>
</tbody>
</table>
SLSTR-A

Calibration at RAL - Jan-June 2015

Sentinel-3A launch - Feb 2016

First Image - March 2016

In-Orbit Commissioning Review – July 2016

Hurricane Ophelia 15/10/2017
SLSTR-B

Arrived at RAL for calibration – Oct 2016

In-Air Tests – October – Nov 2016

In-Vacuum Tests – Nov 2016 – Feb 2017

S3B Launch – Spring 2018

SLSTR-B = Refurbished Proto-Flight Model (PFMr)

Refurb includes:
Rebuilt BB1
New flight BB2
Recoated telescope aperture stop to reduce internal strays
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.
Calibration Flow

Component
- Detectors
  - Spectral Response
  - Linearity
  - Noise
  - Polarisation
- Filters
  - Spectral Response
  - Transmission
- Dichroics
  - Spectral Response
  - Transmission
  - Polarisation
- Thermometers
  - Temperature vs.
  - Resistance
- Black-Coating
  - Spectral Emissivity
  - Thermal Impedance
- Diffuser
  - BRDF
- Mirrors
  - Reflectance
  - Roughness

Subsystem
- IR-FPA
  - Dynamic Range
  - Linearity
  - Noise
  - Cross-Talk
  - Alignment
  - Polarisation
  - Spectral Response
- VIS-FPA
  - Dynamic Range
  - Noise
  - Linearity
  - Alignment
  - Polarisation
  - Spectral Response
- Blackbodies
  - Emissivity
  - Radiance
  - Temperature
  - Gradients
  - Temperature Stability
- VISCAL
  - Throughput
  - Polarisation
  - Stray-Light
- Fore-Optics
  - Throughput
  - Alignment
  - Image Quality
  - Cross Talk
  - Polarisation
  - Stray-Light

Requirements
- Instrument
- Product

Processing
- End-to-End Model
  - The end-to-end model takes the SST noise and bias requirements and breaks these down into specifications for the individual components

Retrieval Model
- Model
  - Retrieval Coefficients don’t get calibrated as such, but nevertheless are maintained using QA procedures

Sea Surface Temperature
- Retrieval Model
  - (ITS-90)

Land-Surface Temperature
- Retrieval Model
  - (ITS-90)

Instrument Model
- The instrument radiometric model takes the as-manufactured instrument and propagates the measured noises and biases to predictions at higher system levels

Characterisation
Calibration
Verification
Validation

Uncertainties Workshop - ESRIN 2017
Typically DN will be some function of scene radiance

$$\text{DN}_{\text{scene}} = F_{\text{ADC}} \cdot (V\{A\Omega(\tau_{\text{opt}}L_{\text{scene}} + (1-\tau_{\text{opt}})L_{\text{inst}})\} + V_{\text{off}})$$

which reduces to

$$\text{DN}_{\text{scene}} = g(L_{\text{scene}}) + \text{offset}$$

We invert this to get scene radiance as a function of DN

$$L_{\text{scene}} = g^{-1}(\text{DN}_{\text{scene}} - \text{DN}_{\text{offset}})$$

$$\approx a_0 + a_1 \text{DN}_{\text{scene}} \text{ (assuming linear function)}$$

$$uL_{\text{scene}}^2 = \sum_{i=0}^{n} (uL_i)^2$$

We obtain calibration coefficients via reference to known calibration sources
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 $<2\%$

RAL Space
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 coefficients = 40 for IR channels alone

Contained in Satellite Characterisation and Calibration Database Document (S-CCDB)
Configuration controlled by MPC
SLSTR IR Traceability Tree

Uncertainty in spectral response measurement
- Temperature dependence

\( u(R(\lambda)) \)

Thermometer Calibration Uncertainties
- Noise
- Thermometer drift
- Drift of readout electronics

\( u(T_i) \)

Uncertainty in spectral response measurement
- Temperature dependence

\( \frac{\partial T_{BB1}}{\partial R(\lambda)} \)

\( \frac{\partial T_{BB2}}{\partial R(\lambda)} \)

Temperature Gradients
- Temperature Stability

\( T_{BB1} = \sum_{i=1}^{N_{BB1}} w_i \frac{T_{i}}{\sum_{i=1}^{N_{BB1}} w_i} \)

\( T_{BB2} = \sum_{i=1}^{N_{BB2}} w_i \frac{T_{i}}{\sum_{i=1}^{N_{BB2}} w_i} \)

Reflectance of black coating
- Cavity modelling

\( u(\varepsilon) \)

\( \frac{\partial L_{BB1}}{\partial \varepsilon} \)

\( \frac{\partial L_{BB2}}{\partial \varepsilon} \)

Effective temperature of instrument
- Temperature stability during calibration

\( u(T_{back}) \)

\( u(T_{back}) \)

\( L_{scene} = L_{BB1} + (1 - \varepsilon) L_{BB2} + \theta \)

\( L_{scene} = \frac{(C_{scene} - C_{BB1})}{(C_{BB1} - C_{BB2})} \)

\( \frac{\partial L_{scene}}{\partial \varepsilon} \)

\( \frac{\partial L_{scene}}{\partial T_{back}} \)

Non-Linearity Measurement
- Noise

\( u(NL) \)

\( u(C_{scene}) \)

\( \frac{\partial C_{scene}}{\partial NL} \)

\( \frac{\partial C_{scene}}{\partial C_{BB1}} \)

Non uniformity of source

\( C_{BB1} = \frac{1}{N} \sum_{i=1}^{N} C_{BB1} \)

\( C_{BB2} = \frac{1}{N} \sum_{i=1}^{N} C_{BB2} \)

\( \frac{\partial C_{BB1}}{\partial C_{BB1}} \)

\( \frac{\partial C_{BB1}}{\partial C_{BB2}} \)

Noise

\( u(C_{BB1}) \)

\( u(C_{BB2}) \)

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Unertainties Workshop - ESRIN 2017
### Table 2 Principal components of the sea and land surface temperature radiometer (SLSTR) radiometric calibration uncertainty budget.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Term</th>
<th>Partial derivative</th>
<th>Characterization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper calibration source radiance</td>
<td>( uL_1 )</td>
<td>( \partial L / \partial L_1 = X )</td>
<td>On-board calibration source calibration and characterization (pre- and postlaunch)</td>
</tr>
<tr>
<td>Lower calibration source radiance</td>
<td>( uL_2 )</td>
<td>( \partial L / \partial L_2 = 1 - X )</td>
<td></td>
</tr>
<tr>
<td>Digital counts noise</td>
<td>( uDN )</td>
<td>( \partial L / \partial DN = \frac{L_1 - L_2}{(DN_1 - DN_2)} )</td>
<td>Signals from onboard calibration sources and prelaunch calibration</td>
</tr>
<tr>
<td>Upper calibration source noise</td>
<td>( u\langle DN_1 \rangle )</td>
<td>( \partial L / \partial \langle DN_1 \rangle = X \frac{L_1 - L_2}{(DN_1 - DN_2)} )</td>
<td>Signals from onboard calibration sources (negligible since calibration signals are averaged over many samples)</td>
</tr>
<tr>
<td>Lower calibration source noise</td>
<td>( u\langle DN_2 \rangle )</td>
<td>( \partial L / \partial \langle DN_2 \rangle = (X - 1) \frac{L_1 - L_2}{(DN_1 - DN_2)} )</td>
<td></td>
</tr>
<tr>
<td>Nonlinearity</td>
<td>( uNL )</td>
<td>( \partial L / \partial NL = \frac{L_1 - L_2}{(DN_1 - DN_2)} )</td>
<td>Prelaunch calibration</td>
</tr>
<tr>
<td>Offset error</td>
<td>( \Delta L_{\text{offset}} )</td>
<td>( \partial L / \partial \Delta L_{\text{offset}} = 1 )</td>
<td>Analysis and prelaunch calibration</td>
</tr>
</tbody>
</table>
### Table 3  Principal components of the uncertainty budget for the blackbody source radiance. Note that the uncertainties for the two calibration sources are treated independently and have to be included in the overall calibration budget in Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Term</th>
<th>Partial derivative</th>
<th>Characterization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emissivity errors</td>
<td>$u_\varepsilon$</td>
<td>$\frac{\partial L}{\partial \varepsilon} = L_{bb} - L_{back}$</td>
<td>Prelaunch calibration–BB level and instrument testing</td>
</tr>
<tr>
<td>Errors in the background radiance due to blackbody emissivity &lt;1.0</td>
<td>$uL_{\text{back}}$</td>
<td>$\frac{\partial L}{\partial T_{\text{back}}} = (1 - \varepsilon)\frac{\partial L}{\partial T}</td>
<td>T_{\text{back}}$</td>
</tr>
<tr>
<td>Blackbody thermometry errors</td>
<td>$uT_{\text{cal}}$</td>
<td>$\frac{\partial L}{\partial T}</td>
<td>T_{bb}$</td>
</tr>
<tr>
<td>Blackbody temperature gradients</td>
<td>$uT_{\text{grad}}$</td>
<td>$\frac{\partial L}{\partial T}</td>
<td>T_{bb}$</td>
</tr>
<tr>
<td>Blackbody temperature stability</td>
<td>$uT_{\text{stab}}$</td>
<td>$\frac{\partial L}{\partial T}</td>
<td>T_{bb}$</td>
</tr>
<tr>
<td>Knowledge of instrument spectral response</td>
<td>$u\lambda$</td>
<td>$\frac{\partial L}{\partial \lambda}</td>
<td>T$</td>
</tr>
</tbody>
</table>
This is the at-launch flight calibration budget
Pre-Launch Calibration – Objectives

• Provision of calibration data needed for data processing chain

• Does the end-to-end flight 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
  – EOL (Hot)
  – Orbital temperature variations

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Thermal IR Calibration Facility

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

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…
TIR calibration - Blackbody Source

- Precision RIRTs: < 0.01K
- Radiometric Accuracy: < 0.05K

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

Sources previously used for all ATSR instruments
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 ‘Hot’ 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
IR Calibration - Counts Vs. Temps

70us integration time shown only

Min temperature achieved is 224K

Saturation of S7 > 300K (additional step at 305K to confirm)
TIR Calibration - Measured vs Actual BT

Nadir

Oblique
Non-Linearity of S8 and S9 consistent with expected behaviour of PC MCT detectors.

S3A and S3B show very similar behaviour.
Creation of NL Table

Measured Counts and BB Radiances normalised to signal corresponding to 65535 counts

\[
y = \frac{L_{\text{actual}}(DN) - L(0)}{L(DN_{\text{ref}}) - L(0)} \quad \text{from thermometers}
\]

\[
x = \frac{DN_{\text{meas}}}{DN_{\text{ref}}} \quad \text{from SLSTR}
\]

Polynomial function fitted to data to generate coefficients for NL function

\[
NL = \sum_{i=2}^{n} \frac{a_i}{a_1} x^{i-1}
\]

Digital counts are linearized using

\[
DN = DN / (1.0 + NL(x))
\]
Measured - Actual BT SLSTR-A

Nadir

Oblique
Why the differences?

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

Measurements by PTB confirm 2015 investigation

Hence modification to stop coatings

Temperature gradients in flight BBs
Thermal modelling shows asymmetry of baseplate temperatures
Analysis of BB radiances in progress
Post launch – we can ‘check’ BB signals by comparing the signals when the BBs are at the same temperatures. This is achieved by switching the heated BB and allowing their temperatures to cross-over.

Test is performed during ground calibration as a baseline.
Comparison DN vs BB Temps

1\textsuperscript{st} Cross Over (RAD06)

2\textsuperscript{nd} Cross Over (RAD08)
### S3B BB Counts at Cross-Over

#### BB X-Over 1 - Temp = 283.529K

<table>
<thead>
<tr>
<th></th>
<th>+YBB</th>
<th>-YBB</th>
<th>ΔDN</th>
<th>ΔT</th>
</tr>
</thead>
<tbody>
<tr>
<td>S7 Nadir</td>
<td>23501</td>
<td>23554</td>
<td>53</td>
<td>0.082</td>
</tr>
<tr>
<td>S8 Nadir</td>
<td>26397</td>
<td>26394</td>
<td>-3</td>
<td>0.055</td>
</tr>
<tr>
<td>S9 Nadir</td>
<td>24735</td>
<td>24778</td>
<td>43</td>
<td>0.101</td>
</tr>
<tr>
<td>S7 Oblique</td>
<td>23524</td>
<td>23584</td>
<td>60</td>
<td>0.002</td>
</tr>
<tr>
<td>S8 Oblique</td>
<td>26560</td>
<td>26591</td>
<td>31</td>
<td>0.002</td>
</tr>
<tr>
<td>S9 Oblique</td>
<td>24872</td>
<td>24896</td>
<td>24</td>
<td>0.002</td>
</tr>
</tbody>
</table>

#### BB X-Over 2 - Temp = 285.690K

<table>
<thead>
<tr>
<th></th>
<th>+YBB</th>
<th>-YBB</th>
<th>ΔDN</th>
<th>ΔT</th>
</tr>
</thead>
<tbody>
<tr>
<td>S7 Nadir</td>
<td>25077</td>
<td>25070</td>
<td>-7</td>
<td>-0.010</td>
</tr>
<tr>
<td>S8 Nadir</td>
<td>27516</td>
<td>27511</td>
<td>-5</td>
<td>-0.011</td>
</tr>
<tr>
<td>S9 Nadir</td>
<td>25706</td>
<td>25723</td>
<td>17</td>
<td>0.038</td>
</tr>
<tr>
<td>S7 Oblique</td>
<td>25114</td>
<td>25079</td>
<td>-35</td>
<td>-0.050</td>
</tr>
<tr>
<td>S8 Oblique</td>
<td>27722</td>
<td>27700</td>
<td>-22</td>
<td>-0.046</td>
</tr>
<tr>
<td>S9 Oblique</td>
<td>25854</td>
<td>25831</td>
<td>-23</td>
<td>-0.054</td>
</tr>
</tbody>
</table>
SLSTR-A – Post Launch

Part 1

Part 2
# S3A BB Counts Comparison at X-Over

## Post Launch – 29 Mar-2016

### BB X-Over 1 - Temp = 289.1392K

<table>
<thead>
<tr>
<th></th>
<th>+YBB</th>
<th>-YBB</th>
<th>ΔDN</th>
<th>ΔT</th>
</tr>
</thead>
<tbody>
<tr>
<td>S7 Nadir</td>
<td>24658</td>
<td>24745</td>
<td>87</td>
<td>0.108</td>
</tr>
<tr>
<td>S8 Nadir</td>
<td>29764</td>
<td>29777</td>
<td>13</td>
<td>0.026</td>
</tr>
<tr>
<td>S9 Nadir</td>
<td>27087</td>
<td>27093</td>
<td>6</td>
<td>0.017</td>
</tr>
<tr>
<td>S7 Oblique</td>
<td>24585</td>
<td>24685</td>
<td>100</td>
<td>0.128</td>
</tr>
<tr>
<td>S8 Oblique</td>
<td>30162</td>
<td>30171</td>
<td>8</td>
<td>0.017</td>
</tr>
<tr>
<td>S9 Oblique</td>
<td>27363</td>
<td>27364</td>
<td>1</td>
<td>0.004</td>
</tr>
</tbody>
</table>

### BB X-Over 2 Temp = 290.5619K

<table>
<thead>
<tr>
<th></th>
<th>+YBB</th>
<th>-YBB</th>
<th>ΔDN</th>
<th>ΔT</th>
</tr>
</thead>
<tbody>
<tr>
<td>S7 Nadir</td>
<td>25904</td>
<td>25896</td>
<td>-8</td>
<td>-0.010</td>
</tr>
<tr>
<td>S8 Nadir</td>
<td>30454</td>
<td>30443</td>
<td>-11</td>
<td>-0.022</td>
</tr>
<tr>
<td>S9 Nadir</td>
<td>27490</td>
<td>27481</td>
<td>-9</td>
<td>-0.024</td>
</tr>
<tr>
<td>S7 Oblique</td>
<td>25821</td>
<td>25794</td>
<td>-27</td>
<td>-0.031</td>
</tr>
<tr>
<td>S8 Oblique</td>
<td>30849</td>
<td>30821</td>
<td>-28</td>
<td>-0.054</td>
</tr>
<tr>
<td>S9 Oblique</td>
<td>27762</td>
<td>27742</td>
<td>-20</td>
<td>-0.052</td>
</tr>
</tbody>
</table>

## Pre Launch – 29 Mar-2016

### BB X-Over 1 - Temp = 280.85K

<table>
<thead>
<tr>
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<th>+YBB</th>
<th>-YBB</th>
<th>ΔDN</th>
<th>ΔT</th>
</tr>
</thead>
<tbody>
<tr>
<td>S7 Nadir</td>
<td>18868</td>
<td>18898</td>
<td>31</td>
<td>0.053</td>
</tr>
<tr>
<td>S8 Nadir</td>
<td>25543</td>
<td>25531</td>
<td>-12</td>
<td>-0.025</td>
</tr>
<tr>
<td>S9 Nadir</td>
<td>22593</td>
<td>22581</td>
<td>-12</td>
<td>-0.036</td>
</tr>
<tr>
<td>S7 Oblique</td>
<td>18819</td>
<td>18857</td>
<td>37</td>
<td>0.065</td>
</tr>
<tr>
<td>S8 Oblique</td>
<td>25830</td>
<td>25809</td>
<td>-21</td>
<td>-0.043</td>
</tr>
<tr>
<td>S9 Oblique</td>
<td>22797</td>
<td>22777</td>
<td>-20</td>
<td>-0.059</td>
</tr>
</tbody>
</table>

### BB X-Over 2 Temp = 285.65K

<table>
<thead>
<tr>
<th></th>
<th>+YBB</th>
<th>-YBB</th>
<th>ΔDN</th>
<th>ΔT</th>
</tr>
</thead>
<tbody>
<tr>
<td>S7 Nadir</td>
<td>22010</td>
<td>22016</td>
<td>6</td>
<td>0.009</td>
</tr>
<tr>
<td>S8 Nadir</td>
<td>27963</td>
<td>27955</td>
<td>-8</td>
<td>-0.017</td>
</tr>
<tr>
<td>S9 Nadir</td>
<td>24311</td>
<td>24304</td>
<td>-7</td>
<td>-0.019</td>
</tr>
<tr>
<td>S7 Oblique</td>
<td>21942</td>
<td>21937</td>
<td>-5</td>
<td>-0.007</td>
</tr>
<tr>
<td>S8 Oblique</td>
<td>28280</td>
<td>28257</td>
<td>-24</td>
<td>-0.047</td>
</tr>
<tr>
<td>S9 Oblique</td>
<td>24527</td>
<td>24509</td>
<td>-18</td>
<td>-0.049</td>
</tr>
</tbody>
</table>
Correction for Offset Error (1)

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

- 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
  - $\text{DN}_{\text{BB}} = g(L_{\text{BB}}) + \text{DN}_{\text{Offset}}$

- This gives
  - $L_{\text{scene}} = XL_{\text{hbb}} + (1-X)L_{\text{cbb}} + 0$

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

- Both $g$ and $\text{DN}_{\text{offset}}$ MUST be constant during the calibration interval.
Correction for Offset Error (2)

- What if $\text{DN}_{\text{offset}}$ is not constant during the scan cycle?

- Lets consider as a function of pixel position, a scan dependent radiance perturbation of $\pm \Delta L(\text{pos})$ which in turn gives rise to a perturbation in the background signal $\pm \Delta \text{DN}(\text{pos})$.

- The calibration model now becomes

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

where

$$X = \frac{((\text{DN}_{\text{scene}}+\Delta \text{DN}(\text{scene})) - (\text{DN}_{\text{cbb}}+\Delta \text{DN}(\text{cbb})))}{(\text{DN}_{\text{hbb}}+\Delta \text{DN}(\text{hbb}) - (\text{DN}_{\text{cbb}} + \Delta \text{DN}(\text{cbb})))}$$

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

$$\Delta L_{\text{error}} = \Delta L(\text{scene}) - X\Delta L(\text{hbb}) - (1-X) \Delta L(\text{cbb})$$
Correction for Offset Error (3)

- 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 intercomparisons with IASI performed by EUMETSAT suggest that on-orbit stray-light error correction is not necessary.
Current State of SLSTR Traceability

• Pre-Launch reports contain most information
  – Write up as reviewed papers in progress
  – Includes uncertainty estimates of measurements

• L1 Products
  – Detector noise expressed as NEDT (TIR channels) and NEDL (VIS/SWIR channels) for each scan line
  – Uncertainties in the radiometric calibration are included in the quality annotation datasets as a table of uncertainty vs. temperature type-B (a-priori) estimates based on the pre-launch calibration and calibration model (see later slides)

• Per pixel estimation of the radiometric uncertainty for either random effects or systematic effects has not been implemented
  – Significant impact on product size and processing time
  – User requirements poorly defined!
SLSTR Traceability Document

• This is a key document that needs to be maintained and updated when new information on uncertainty estimates come to light.
• Much information already exists in different formats which needs collating
• Content should be published in reviewed journal
• Identifies key sources of uncertainty
  – Collates known uncertainty estimates – e.g. BB temperatures + Emissivity
• Records the current Traceability Chain
  – I.e. Documents that can link uncertainty estimates to standards – e.g. BB emissivity
  – Identify gaps – e.g. degradation model for BB electronics
Conclusions

• Pre-Launch Calibration allows us to validate the end-to-end instrument flight calibration systems against known reference targets.
  – Not possible after launch
  – Provides a reference dataset against which the processing algorithms can be verified.

• Papers on calibration results are being prepared

• L1 products contain basic uncertainty estimates
  – Noise derived from BB sources
  – Estimates of calibration uncertainties from pre-launch characterisation
  – Improvements are foreseen…

• Traceability chain needs to be documented in-order for SLSTR to become a reference sensor.
References

Calibration Plan
David L. Smith, Tim J. Nightingale, Hugh Mortimer, Kevin Middleton, Ruben Edeson, Caroline V. Cox, Chris T. Mutlow, Brian J. Maddison, Peter Coppo
[doi:10.1117/1.JRS.8.084980]

Description of SLSTR design