SLSTR and LSTM L1 Uncertainties

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2 LSTM Analysis funded by ESA via Airbus DS Madrid
# SLSTR instrument

<table>
<thead>
<tr>
<th>Feature</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nadir swath</td>
<td>$&gt;74^\circ$ (1400km swath)</td>
</tr>
<tr>
<td>Dual view swath</td>
<td>$49^\circ$ (750 km)</td>
</tr>
<tr>
<td>Two telescopes</td>
<td>$\Phi 110 \text{ mm} / 800\text{mm focal length}$</td>
</tr>
<tr>
<td>Spectral bands</td>
<td>TIR : 3.74µm, 10.85µm, 12µm</td>
</tr>
<tr>
<td></td>
<td>SWIR : 1.38µm, 1.61µm, 2.25 µm</td>
</tr>
<tr>
<td></td>
<td>VIS: 555nm, 659nm, 859nm</td>
</tr>
<tr>
<td>Spatial Resolution</td>
<td>1km at nadir for TIR,</td>
</tr>
<tr>
<td></td>
<td>0.5km for VIS/SWIR</td>
</tr>
<tr>
<td>Radiometric quality</td>
<td>NEΔT 30 mK (LWIR) – 50mK (MWIR)</td>
</tr>
<tr>
<td></td>
<td>SNR 20 for VIS - SWIR</td>
</tr>
<tr>
<td>Radiometric accuracy</td>
<td>0.2K for IR channels</td>
</tr>
<tr>
<td></td>
<td>2% for Solar channels relative to Sun</td>
</tr>
</tbody>
</table>
On-Board Calibration Systems

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

Zenith diffuser +

relay mirrors

Uncertainty $< 2\%$
Law of Propagation of Uncertainties

\[ y = f(x_1, x_2, x_3, \ldots) + 0 \]

\[
\begin{align*}
u^2(y) &= \sum_{i=1}^{N} \left( \frac{\partial y}{\partial x_i} \right)^2 u^2(x_i) + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \frac{\partial y}{\partial x_i} \frac{\partial y}{\partial x_j} u(x_i) u(x_j) v(x_i, x_j) \\
\text{Variance of input quantity } x_i \\
\text{Variance of measurand} \\
\text{Sensitivity of measurand to effect } x_i \\
\text{Correlation coefficient between input quantities } x_i, x_j \\
\text{Physical effects} \\
\text{Assumptions and approximations in measurement function}
\end{align*}
\]

Applying principles of metrology to historical Earth observations from satellites. Metrologia, 56 (3). ISSN 0026 1394 doi: https://doi.org/10.1088/16817575/ab1705

Calibration of IR instruments

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 defined by the Boltzmann constant realised through the International Temperature Scale of 1990.

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

\[ k_B = 1.38064852 \times 10^{-23} \text{ JK}^{-1} \]
SLSTR TIR Calibration

Starting point is the measurement equation

We include +0 term to account for additional effects

\[ L_E = X L_{BB1} + (1 - X) L_{BB2} + 0 \]

\[ \frac{\partial L_E}{\partial X} \]

\[ X = \frac{C_E - \langle C_{BB2} \rangle}{\langle C_{BB1} \rangle - \langle C_{BB2} \rangle} \]

Uniformity around scan
Stray Light
SLSTR TIR Calibration

We work outwards to determine all measurement effects

\[ L_{BB1} = \varepsilon L(T_{BB1}) + (1 - \varepsilon)L_{back} \]

\[ \frac{\partial L_E}{\partial L_{BB1}} \]

\[ \frac{\partial L_E}{\partial L_{BB2}} \]

\[ L_{BB2} = \varepsilon L(T_{BB2}) + (1 - \varepsilon)L_{back} \]

\[ L_E = XL_{BB1} + (1 - X)L_{BB2} + 0 \]

\[ \frac{\partial L_E}{\partial X} \]

\[ X = \frac{C_E - \langle C_{BB2} \rangle}{\langle C_{BB1} \rangle - \langle C_{BB2} \rangle} \]

\[ \frac{\partial X}{\partial C_E} \]

\[ \frac{\partial X}{\partial \langle C_{BB1} \rangle} \]

\[ \frac{\partial X}{\partial \langle C_{BB2} \rangle} \]

Uniformity around scan

Stray Light
Deriving L1 Uncertainties from L0

From L0 data and L1 Aux files

- BB Temps, Instrument Temps
- Counts, Noise
- Calibration Coefficients

Sensitivity of effect on measurand

- Compute Partial Derivatives
- $u^2(L_E) = \sum_{i=1}^{N} \left( \frac{\partial L_E}{\partial x_i} \right)^2 u^2(x_i) + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \frac{\partial L_E}{\partial x_i} \frac{\partial L_E}{\partial x_j} u(x_i) u(x_j) r(x_i, x_j)$

Type-A from analysis of L0 data
Type-B a-priori from pre-launch calibration, predictions....

- Estimate standard Uncertainties
- $U$

Determine Correlations
- $R$

E.g. Emissivity, Instrument Temperature drifts

Combined Uncertainty
- $u^2(L_E) = cURUc^T$
SLSTR Uncertainty Budget

- **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
Uncertainty Time Series - Random Effects (NEDT)

Noise estimates derived from on-board BB sources
Uncertainty Time Series - Systematic Effects

Uncertainties derived from analysis of L0 data from Instrument Temperatures, BB signals, Gain-Offset variations, Noise…
Uncertainties in SLSTR L1 Products

- Random effects - detector noise expressed as NEDT (TIR channels) and NEDL (VIS/SWIR channels) for each scan line

- Systematic effects – radiometric calibration - tables of uncertainty vs. temperature type-B (a-priori) estimates based on the pre-launch calibration and calibration model

- MapnoiS3 tool developed by RAL allows mapping of uncertainty information to L1 images

Propagation to L2…

- We apply the same method except that inputs are the output of the L1 uncertainty analysis.

- Start with measurement function – e.g.

\[ SST_a = a_0 + \sum_{i=1}^{N} a_i T_i \]

So from L1 key inputs are the BTs, \( T_i \) from all channels.

- Build up effects tree to and trace back to root effects
- Document effects – distribution, correlation scales…
- Propagate Uncertainties to L2

- Can be extended to L3 and beyond
Propagating Uncertainties – E.g. SLSTR LST

L1 Uncertainty Effects propagate to L2 products again adapting the law of propagation of uncertainties
Users have been advised to adopt the following correction factors for the radiometric calibration based on the combined averages of the vicarious calibration results.
Long Term Stability

Nadir View

Oblique View

Drift Rates for Oblique View are via AATSR for matching geometry – hence no match-ups for S6
SLSTR VIS/SWIR Uncertainty Estimates

• L1 Uncertainties are based on the pre-launch calibration test analysis.

• Post launch effects not accounted for
  • Vicarious Calibration Adjustment Factor
  • Destriping correction
  • Orbital Stability of radiometric gain – in particular S1-S3 which are affected by ice contamination + motional chopping.
  • Long-Term Degradation
  • Noise corresponding to VISCAL is affected by non-uniformity of signal – hence noise is overestimated.
    • Update to L1 IPF should address this.

• VIS/SWIR L1 uncertainties are being reviewed to account for all effects
VIS-SWIR Uncertainty Analysis

We can propagate further to examine effects due to changes between ground-to-orbit of optical chain:

- Diffuser BRDF ($R_{diff}$)
- Optical Components (uv window transmission $\tau_{uv}$, relay mirror reflectances $r_{m1}, r_{m2}, r_{m3}$)
- Geometric Factors ($\Omega_{cal}, \Omega_{slstr}$)
The measurement equation -

\[ L_E = \frac{I_0}{\pi} R_{cal} (C_E - C_{off,E})/(C_{cal} - C_{off,cal}) \cdot K_{drift} \cdot K_{orbital\_stability} + 0 \]

<table>
<thead>
<tr>
<th>Affected Term</th>
<th>Description</th>
<th>Characterisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_{CAL} )</td>
<td>Reflectance Factor For VISCAL</td>
<td>Pre-Launch Calibration – VISCAL and Instrument level</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Post-Launch Vicarious Calibration</td>
</tr>
<tr>
<td>( K_{orbital_stability} )</td>
<td>Orbital Gain Stability</td>
<td>By design &amp; Pre-Launch Testing</td>
</tr>
<tr>
<td>( K_{drift} )</td>
<td>Degradation of VISCAL Reflectance Factor</td>
<td>Post-Launch Vicarious Calibration</td>
</tr>
<tr>
<td>( C_E )</td>
<td>Earth Scene Counts</td>
<td>Earth Scene counts</td>
</tr>
<tr>
<td>( C_{off,E} )</td>
<td>BB Counts during observation of earth scene</td>
<td>Observation of BB signals - noise</td>
</tr>
<tr>
<td>( C_{cal} )</td>
<td>Signal Counts at full solar illumination</td>
<td>Observation of VISCAL Signal at full solar illumination</td>
</tr>
<tr>
<td>( C_E )</td>
<td>BB Counts during observation of VISCAL</td>
<td>Observation of BB signals - noise</td>
</tr>
<tr>
<td>( NL )</td>
<td>Non-Linearity Correction</td>
<td>Pre-Launch Testing</td>
</tr>
<tr>
<td>( F(\lambda) )</td>
<td>Instrument spectral response</td>
<td>Pre-Launch Testing</td>
</tr>
<tr>
<td>( I_0 )</td>
<td>Solar Irradiance</td>
<td>Solspec Reference Spectrum</td>
</tr>
</tbody>
</table>
SLSTR-B VIS-SWIR Uncertainty Estimates

Assumes non-linearity correction is applied correctly
SLSTR VIS-SWIR Next Steps

- Add orbital effects (gain variations, noise…)
- Produce time-series of uncertainties from L0 data
- Update uncertainty estimates in L1 products
Land Surface Temperature Mission

- Copernicus Expansion Mission to measure Land Surface Temperatures at spatial resolution of 50m (30m Goal).
  - Support to agriculture (crop stress, water use, land use, climate variability…)
  - Complements Sentinel-2
  - Currently in Phase B2
  - Launch 2028

- Multi-Channel Scanning Radiometer
  - TIR channels at 8.6, 8.9, 9.2, 10.9 and 12.0 µm.
  - VIS-SWIR Channels – 0.490, 0.665, 0.865, 0.945, 1.375 and 1.610 µm

- On-Board Calibration
  - BB for TIR
  - Solar Diffuser for VIS-SWIR Channels
  - Space view
LSTM Uncertainty Effects Tree

\[ L_E = \Delta R_{em}(\theta)L(BB) \frac{C_E - C_{space}}{\bar{C}_{BB} - C_{space}} + (1 - \Delta R_{em}(\theta))L_{em}(T_{em}) + \Delta L_{stray} + 0 \]
LSTM Uncertainty Effects Tree
## LSTM Uncertainty Effects

<table>
<thead>
<tr>
<th>Variable</th>
<th>Variable name</th>
<th>Effect</th>
<th>Correlation Scale</th>
<th>Characterisation/(SI traceability chain)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_E$</td>
<td>Linearised earth scene detector counts</td>
<td>Noise</td>
<td>Fully random</td>
<td>Design analysis, Pre-launch testing, on orbit monitoring, BB views, space views</td>
</tr>
<tr>
<td>$T_{sm}$</td>
<td>Scan mirror temperature</td>
<td>Changes in optics emission</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$g$</td>
<td>Gain</td>
<td>Gain variation</td>
<td>Random</td>
<td>Design analysis, Pre-launch testing, on orbit monitoring,</td>
</tr>
<tr>
<td>$NL$</td>
<td>Non linearity model</td>
<td>Non-Linearity</td>
<td>Systematic – Correlated</td>
<td>Design analysis, Pre-launch testing</td>
</tr>
<tr>
<td>$C_{bb}$</td>
<td>Linearised blackbody detector counts</td>
<td>Noise</td>
<td>Fully random</td>
<td>Design analysis, Pre-launch testing, on orbit monitoring, BB views</td>
</tr>
<tr>
<td>$C_{space}$</td>
<td>Linearised blackbody detector counts</td>
<td>Noise</td>
<td>Random but Correlated within calibration interval.</td>
<td>Design analysis, Pre-launch testing, on orbit monitoring, space views</td>
</tr>
<tr>
<td>$I(T_{BB})$</td>
<td>Calibration blackbody radiances</td>
<td>Temperature read out noise</td>
<td>Full random</td>
<td>Design analysis, Pre-launch testing, on orbit monitoring, BB views, space views</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Temperature measurement uncertainty</td>
<td>Systematic – Correlated</td>
<td>Design analysis, Thermometer calibration, Pre-launch testing, on orbit monitoring</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Temperature gradients</td>
<td>Systematic – Correlated</td>
<td>Design analysis, Pre-launch testing, on orbit monitoring</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Emissivity</td>
<td>Systematic – Correlated</td>
<td>Design analysis, Pre-launch testing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reflection, rades reflected from surroundings.</td>
<td>Systematic – Correlated</td>
<td>Design analysis, Pre-launch testing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Scan angle effects (space view and BB not at same angle)</td>
<td>Systematic – Correlated</td>
<td>Design analysis, Pre-launch testing, on orbit monitoring (by pitch up and extrapolation)?</td>
</tr>
<tr>
<td>$I_{sm}(T_{sm})$</td>
<td>Scan mirror emission</td>
<td>Temperature read out noise</td>
<td>Full random</td>
<td>Design analysis, Pre-launch testing, on orbit monitoring,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Temperature measurement uncertainty</td>
<td>Systematic – Correlated</td>
<td>Design analysis, Thermometer calibration, Pre-launch testing, on orbit monitoring</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mirror emissivity</td>
<td>Systematic – Correlated</td>
<td>Design analysis, Pre-launch testing, on orbit monitoring,</td>
</tr>
<tr>
<td>$\Delta I_{sm}(T_{sm})$</td>
<td>Relative variation of scan mirror reflectivity#</td>
<td>Systematic – Correlated within earth view</td>
<td></td>
<td>Design analysis, Pre-launch testing, on orbit monitoring,</td>
</tr>
<tr>
<td>$\Delta l_{stray}$</td>
<td>Stray light correction</td>
<td>Uncertainty in correction</td>
<td>Systematic – Correlated with surrounding pixels</td>
<td>Design analysis, Pre-launch testing, on orbit monitoring</td>
</tr>
</tbody>
</table>
LSTM L1 Uncertainties

Example – TIR Band 4 – 10.9µm
LSTM Next Steps

- LSTM is at phase B2 (up to PDR)
  - Hence uncertainties in L1 are based on specifications.
  - Model is aligned to L1 ATBD
  - Model outputs to be compared with the performance budgets produced by instrument prime.
  - Will be used to define requirements for pre-launch calibration

- During phase C/D
  - Model and outputs to be updated as more information provided from subsystems + calibration

- Implementation in L1 processor is TBD