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SLSTR[1] and LSTM[2] L1 Uncertainties

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STFC RAL Space

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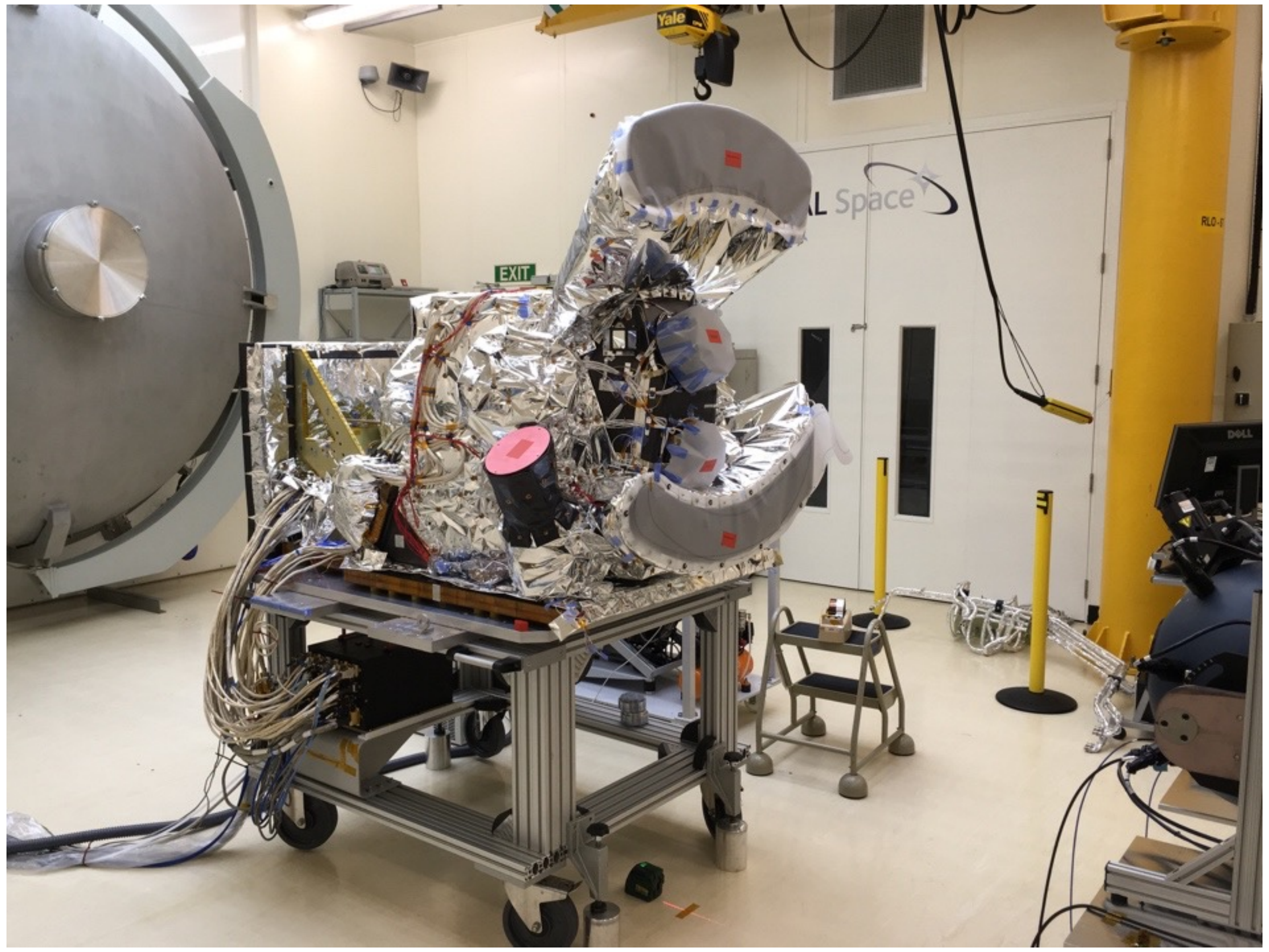
[1] SLSTR Analysis funded under the EU Copernicus Program by Eumetsat and EMPIR programme co-financed by the Participating States and from the European Union’s Horizon 2020 research and innovation programme.

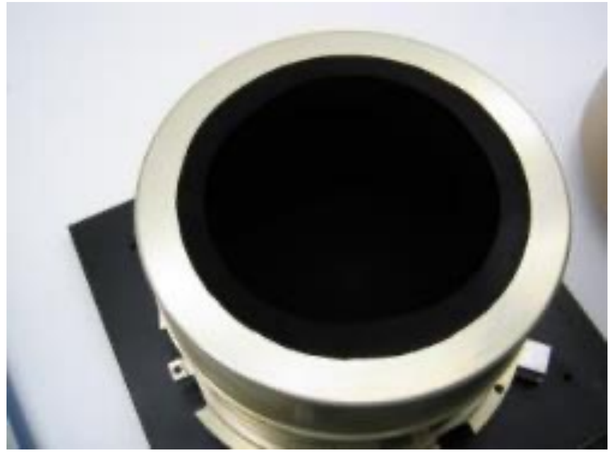
[2] LSTM Analysis funded by ESA via Airbus DS Madrid

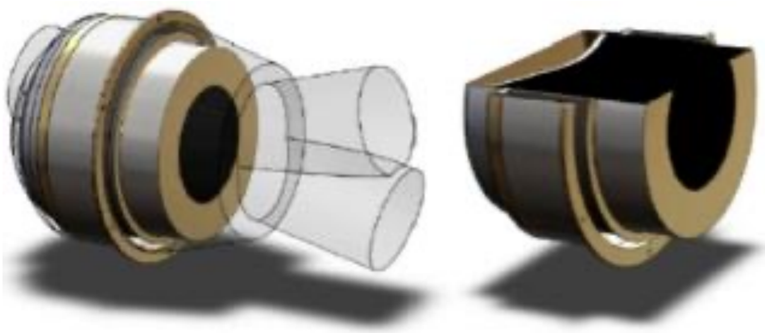
SLSTR instrument

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

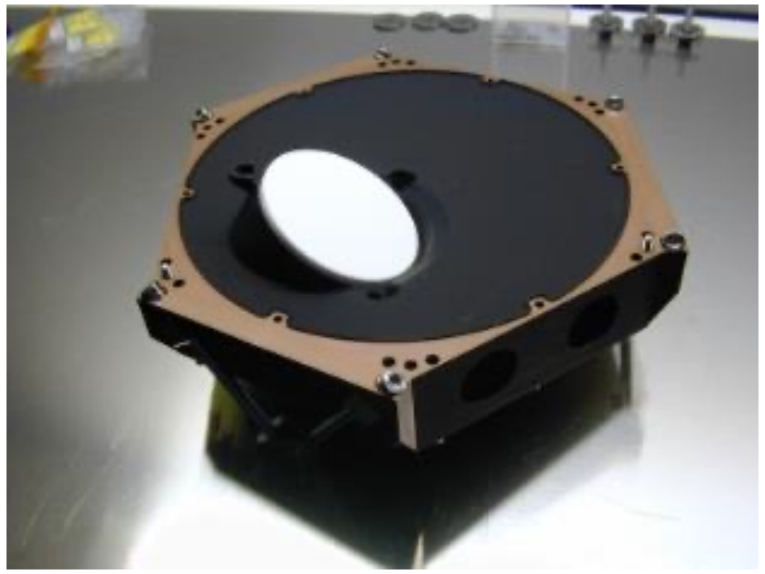


On-Board Calibration Systems





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%

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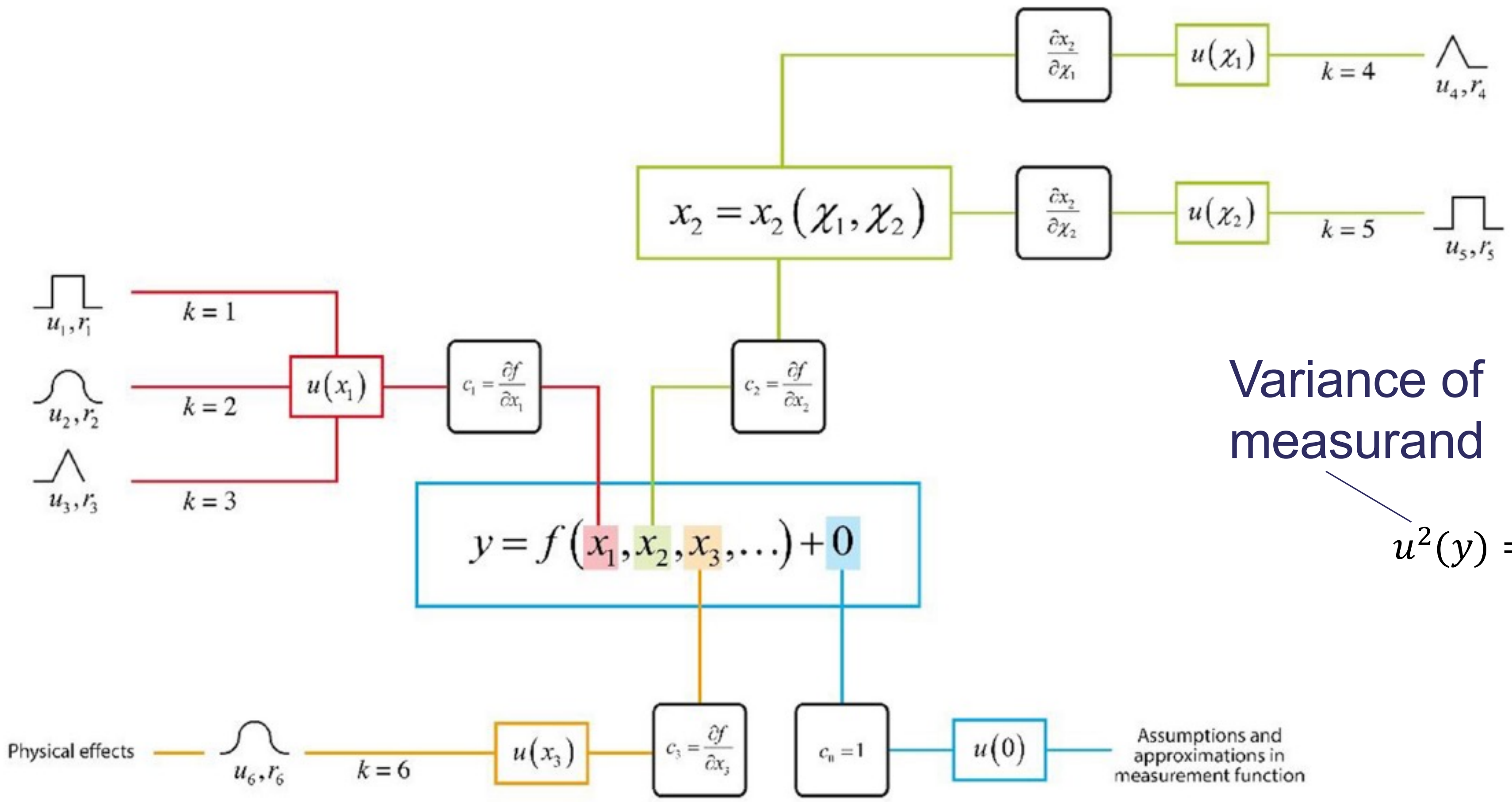
Law of Propagation of Uncertainties



From - Mittaz, J., Merchant, C. J. and Woolliams, E. R. (2019) Applying principles of metrology to historical Earth observations from satellites. Metrologia, 56 (3). ISSN 0026 1394 doi: https://doi.org/10.1088/16817575/ab1705

Variance of measurand

Variance of input quantity x_i

Correlation coefficient between input quantities x_i, x_j

$$u^2(y) = \sum_{i=1}^{N} \left(\frac{\partial y}{\partial x_i}\right)^2 u^2(x_i) + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \frac{\partial y}{\partial \mathrm{x_i}} \frac{\partial y}{\partial \mathrm{x_j}} u(x_i)\, u(x_j) v(x_i, x_j)$$

Sensitivity of measurand to effect x_i

Ref: Evaluation of Measurement Data. Guide to the Expression of Uncertainty in Measurement (JCGM 100:2008).

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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.

Instrument ←

Blackbody Source ←

S-PRT (ITS-90) ←

Fixed Point Cells ← $k_B = 1.38064852 \times 10^{-23}\ JK^{-1}$

SI

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SLSTR TIR Calibration

Starting point is the measurement equation

We include +0 term to account for additional effects

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

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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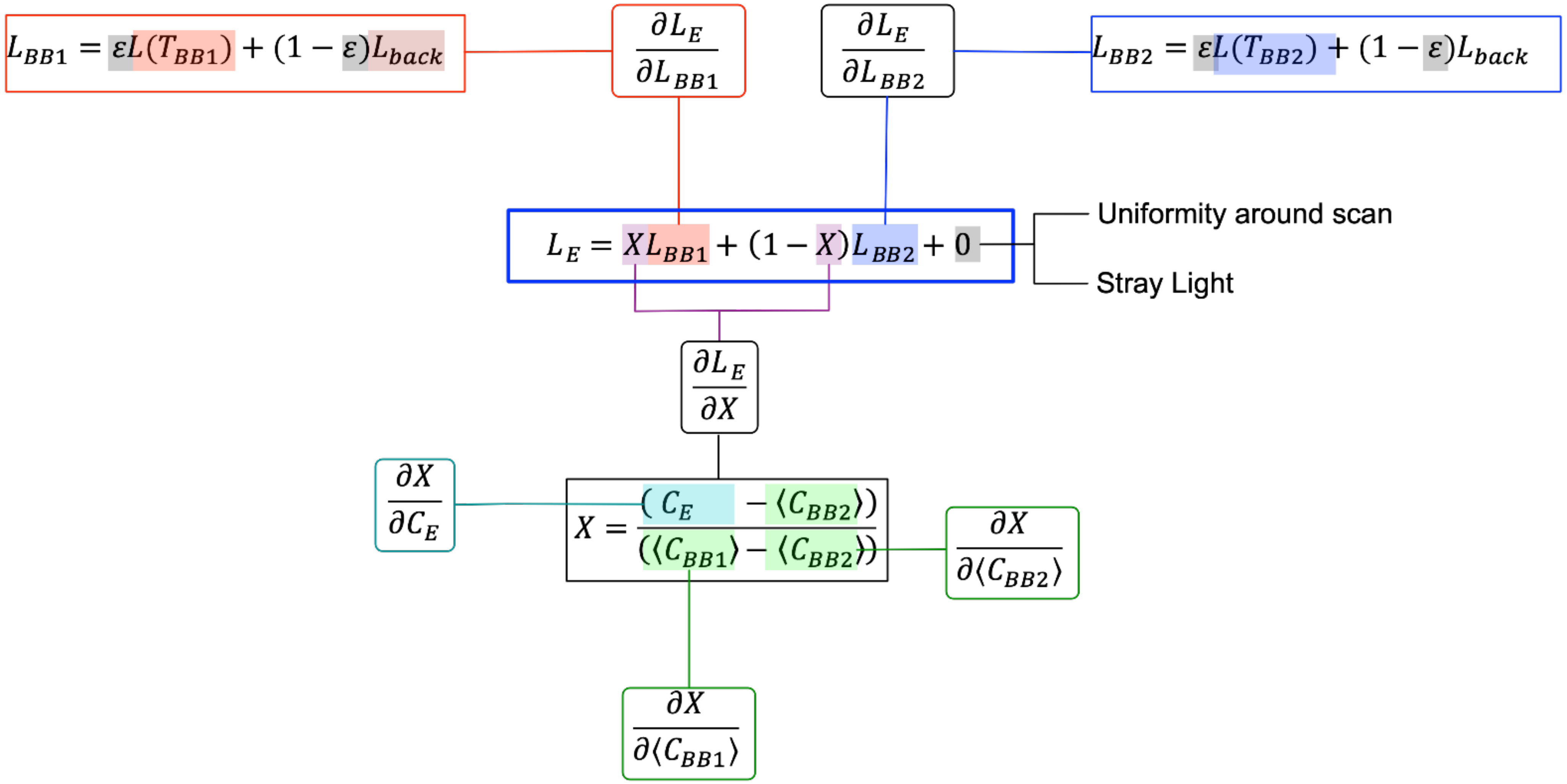
SLSTR TIR Calibration

We work outwards to determine all measurement effects



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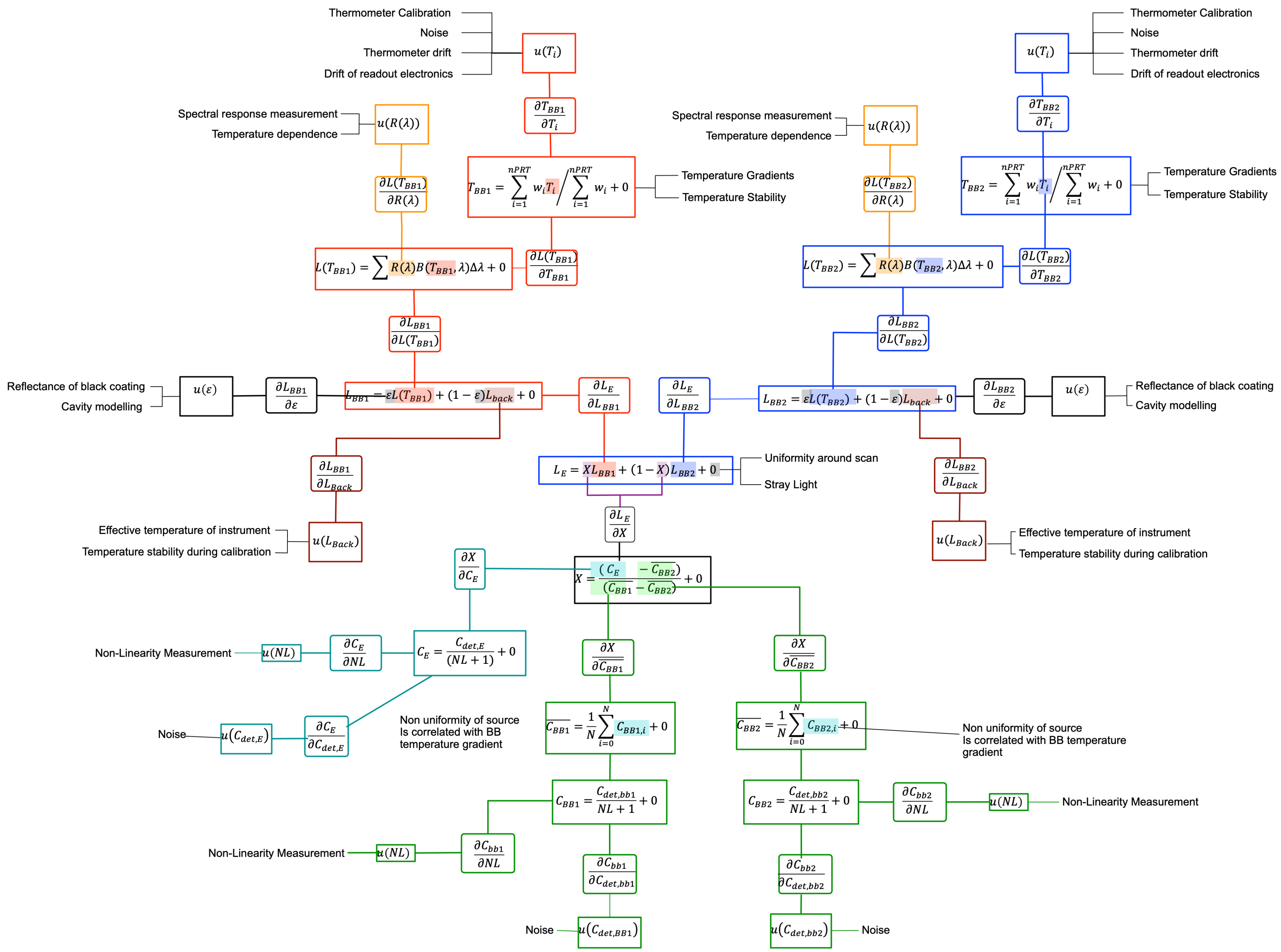
SLSTR TIR Calibration



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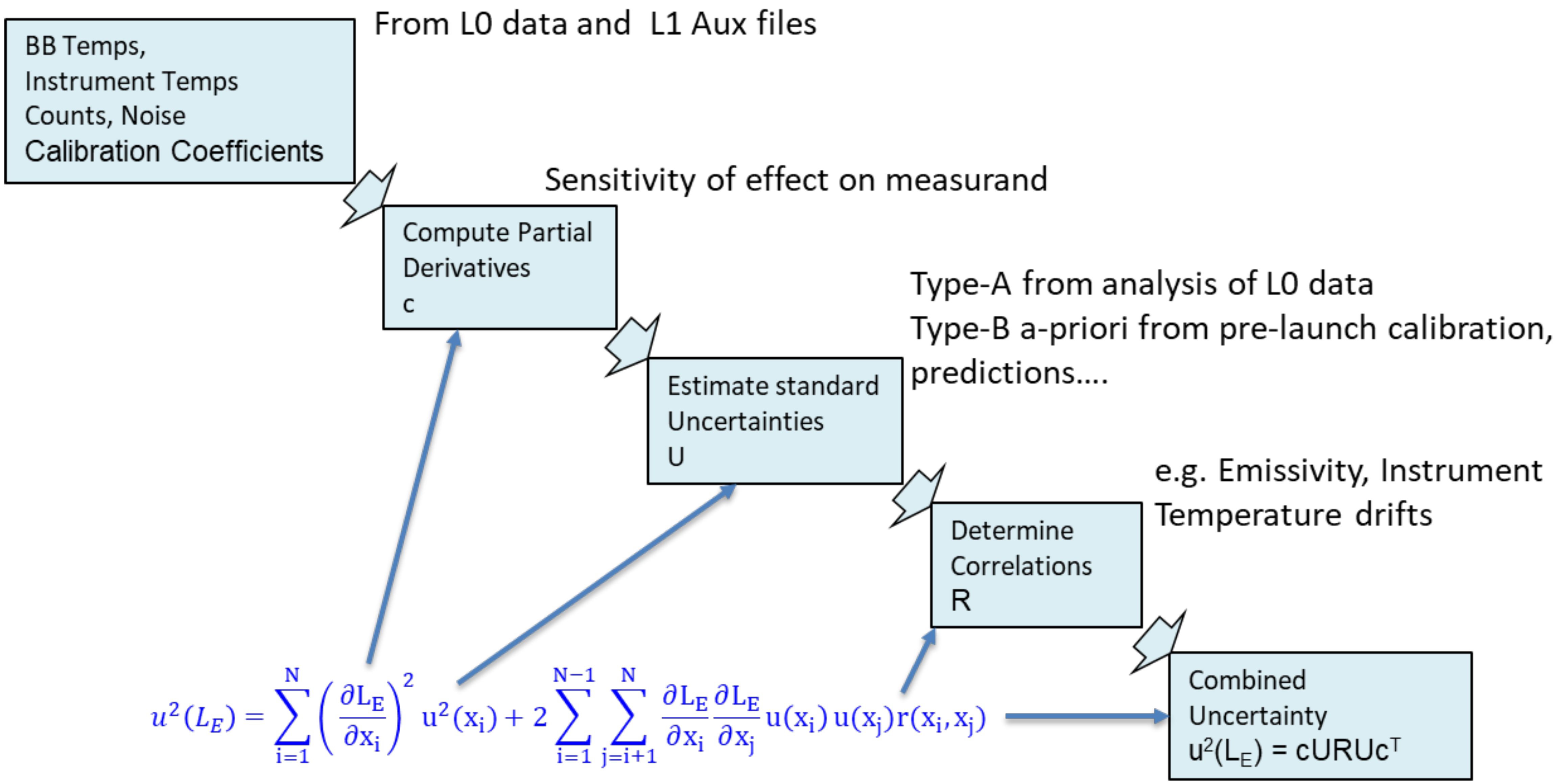
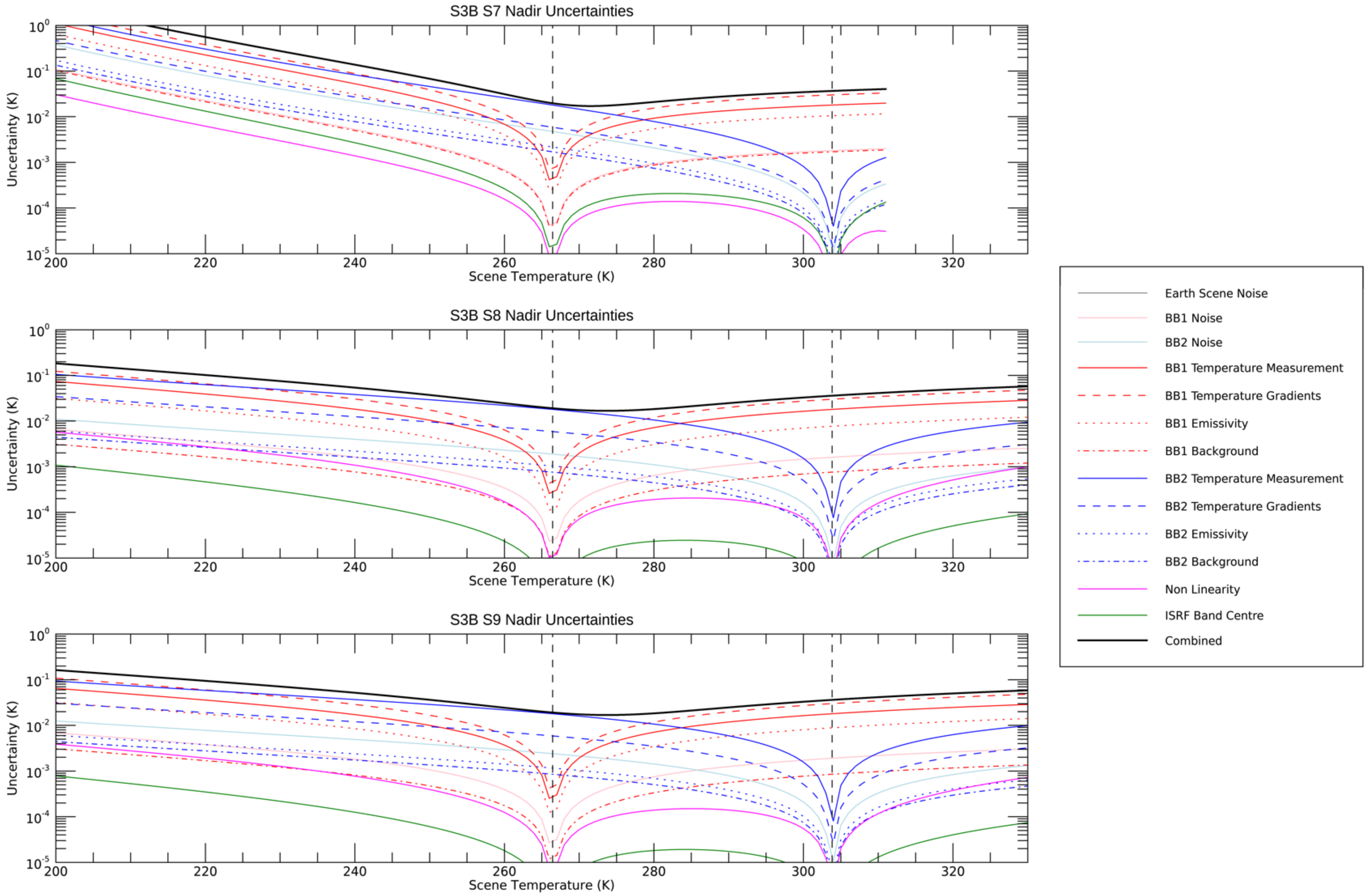
Deriving L1 Uncertainties from L0



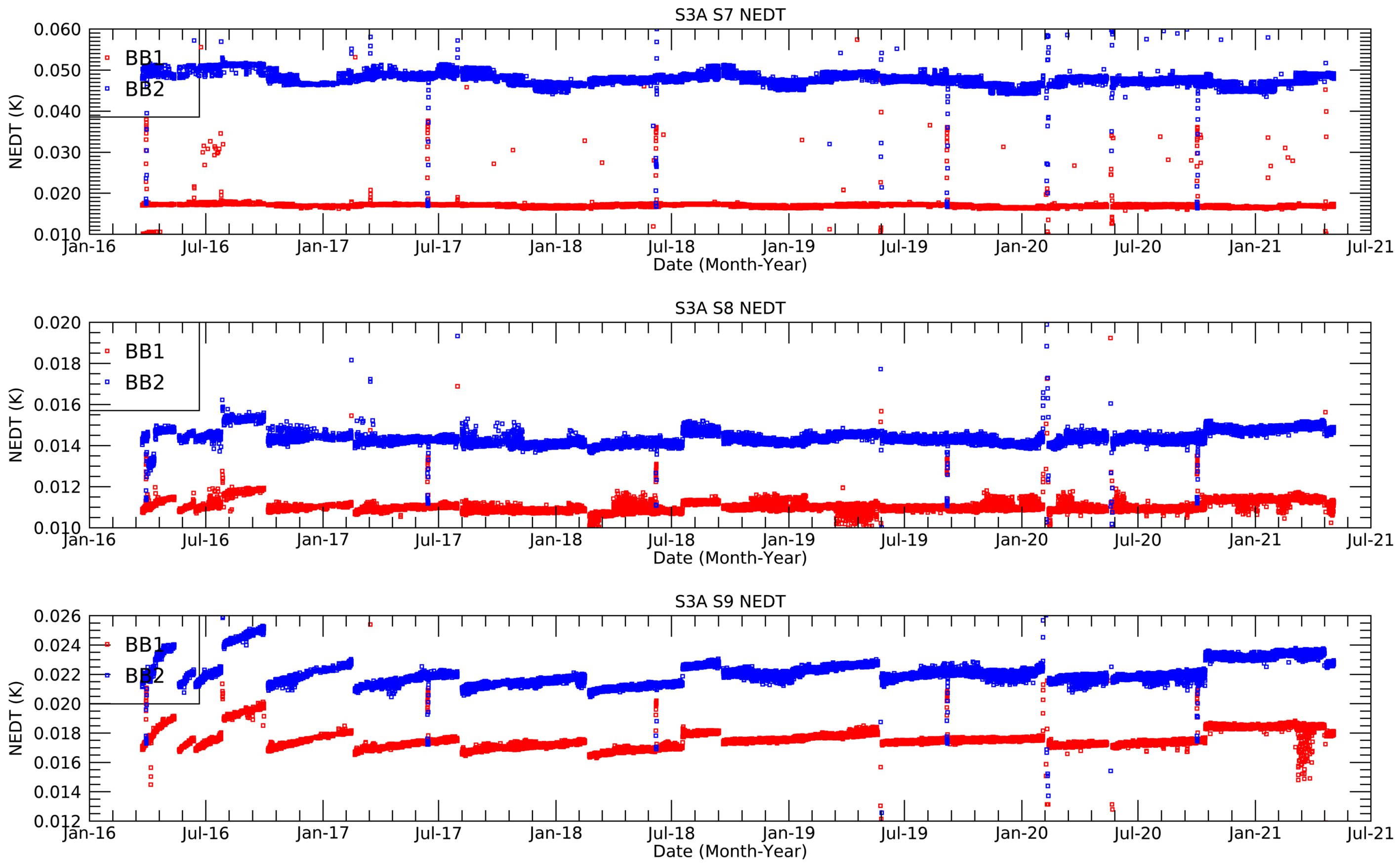
SLSTR Uncertainty Budget

- 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.

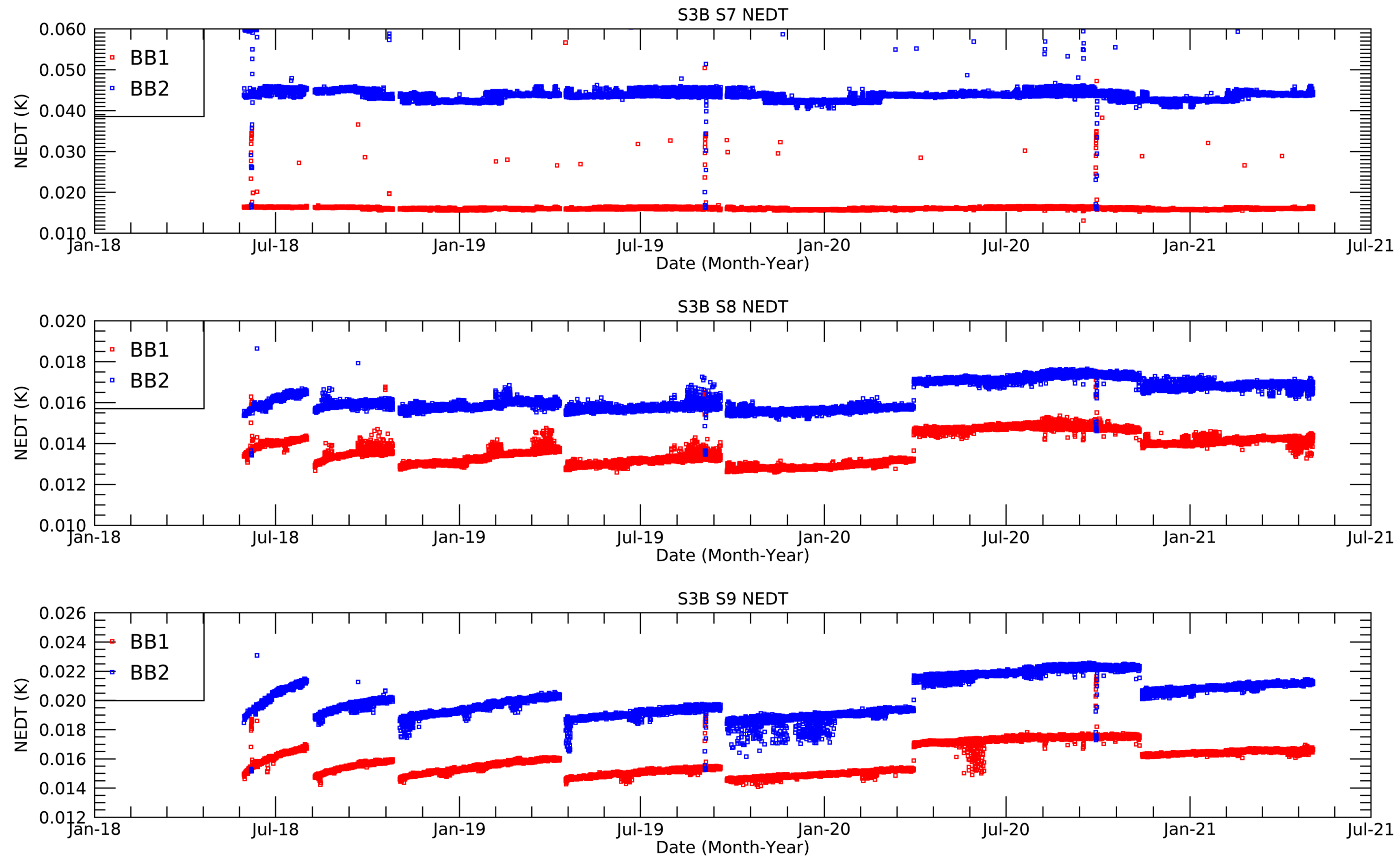


Uncertainty Time Series - Random Effects (NEDT)

SLSTR-A



SLSTR-B



Noise estimates derived from on-board BB sources

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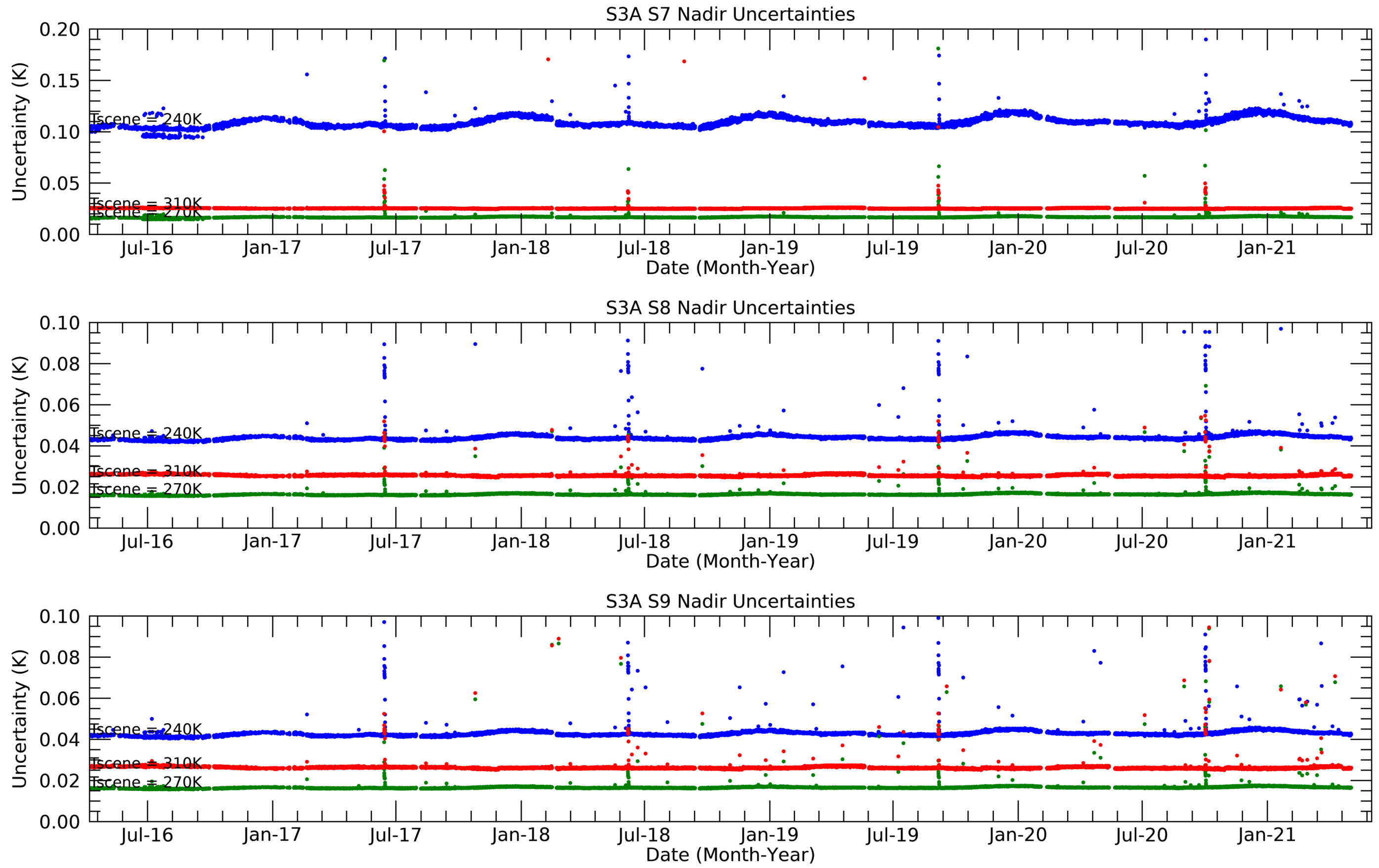
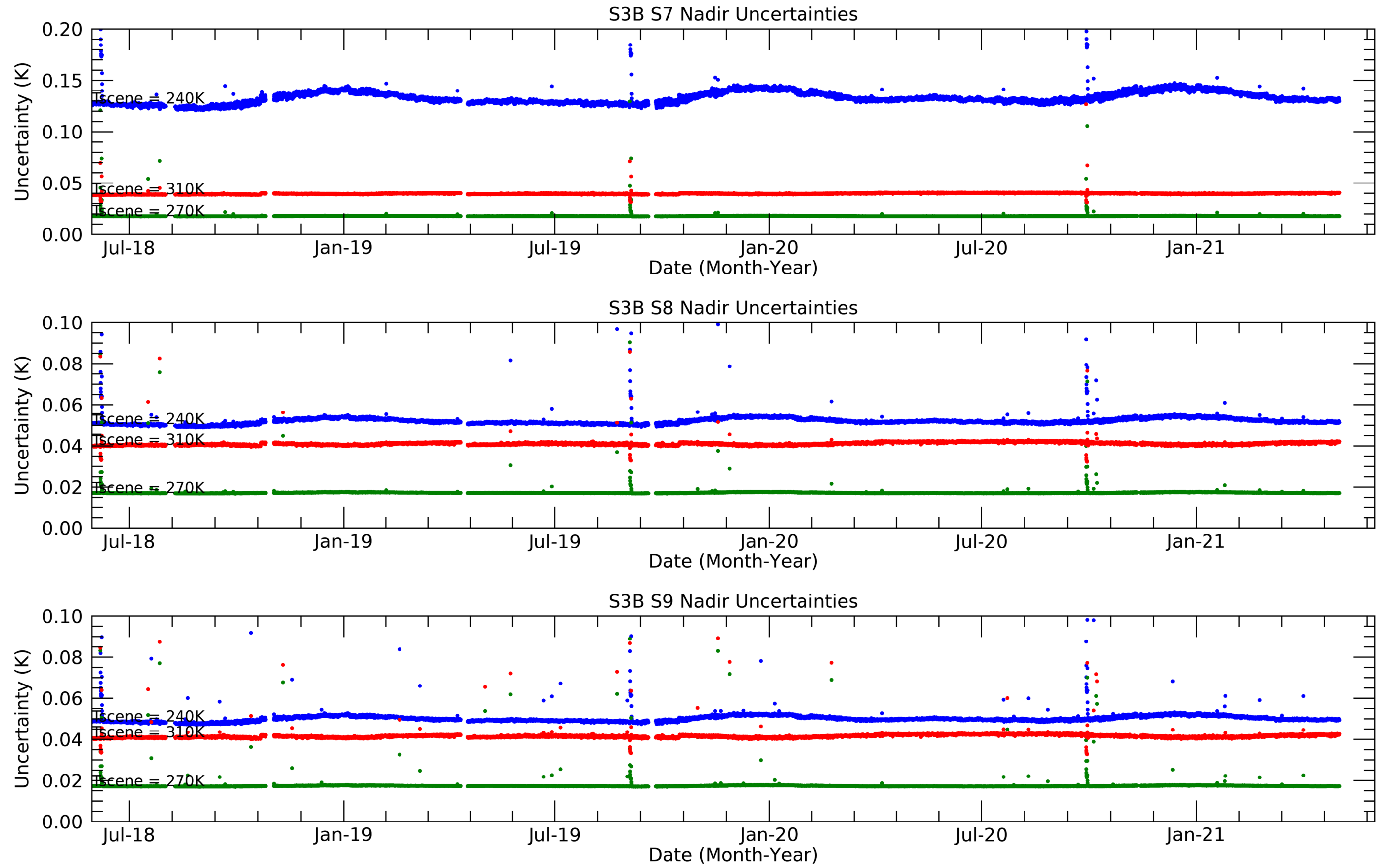
Uncertainty Time Series - Systematic Effects

SLSTR-A



SLSTR-B



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

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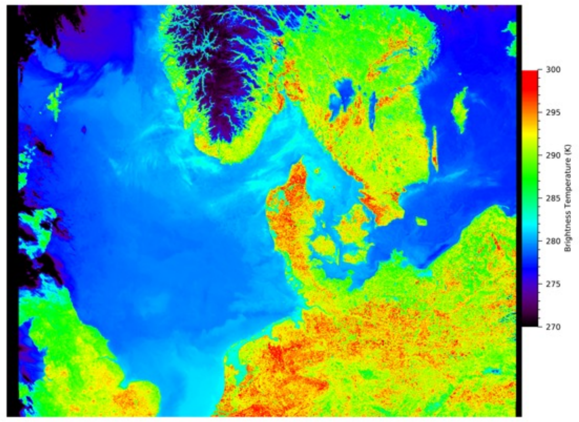
Uncertainties in SLSTR L1 Products

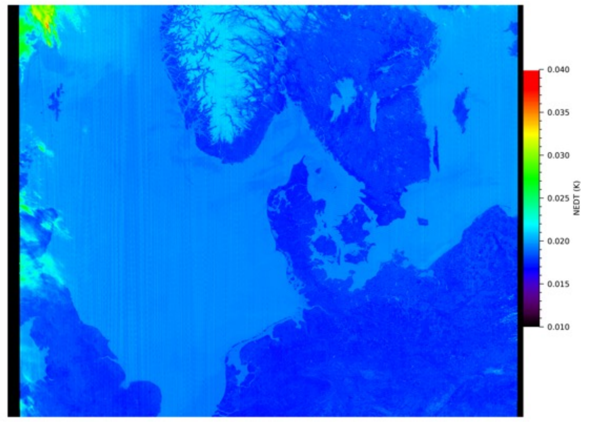
- Random effects - detector noise expressed as NEDT (TIR channels) and NEDL (VIS/SWIR channels) for each scan line
- Systematic effects – radiometric calibration - tables of uncertainty vs. temperature type-B (a-priori) estimates based on the pre-launch calibration and calibration model
- MapnoiS3 tool developed by RAL allows mapping of uncertainty information to L1 images

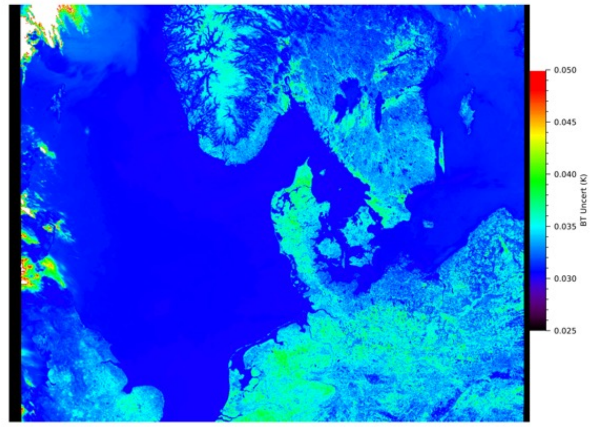
12µm BT

12µm NEDT (Random)

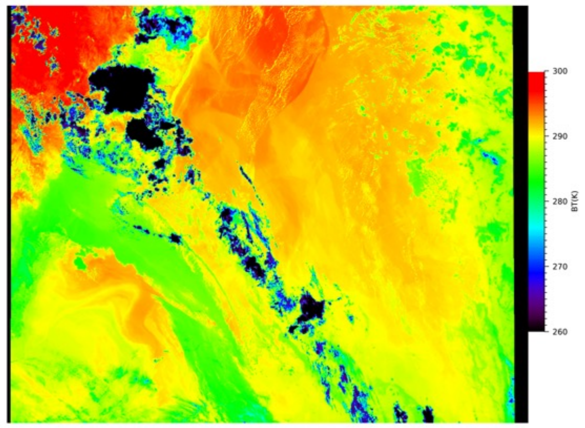
12µm uBT (Systematic)

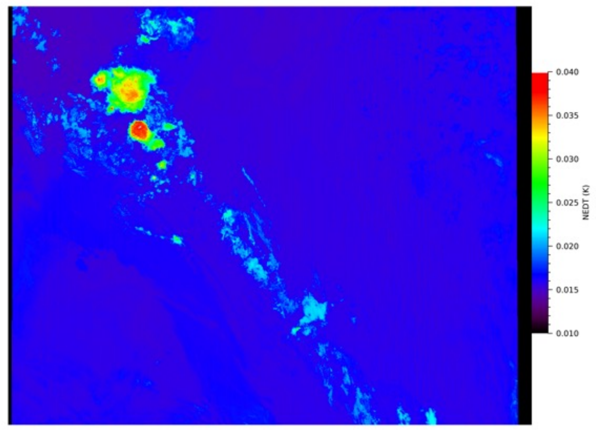


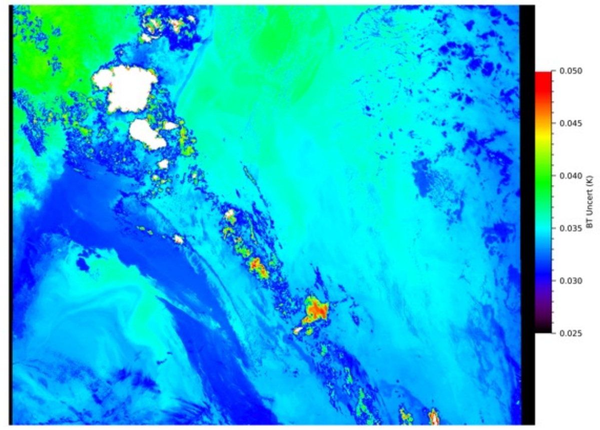




North Sea on 22-April-2020







Australia on 01-Jan-2020

Images from Smith D. et al, **Traceability of the Sentinel-3 SLSTR Level-1 Infrared Radiometric Processing** , Remote Sens. 2021, 13(3), 374; https://doi.org/10.3390/rs13030374

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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

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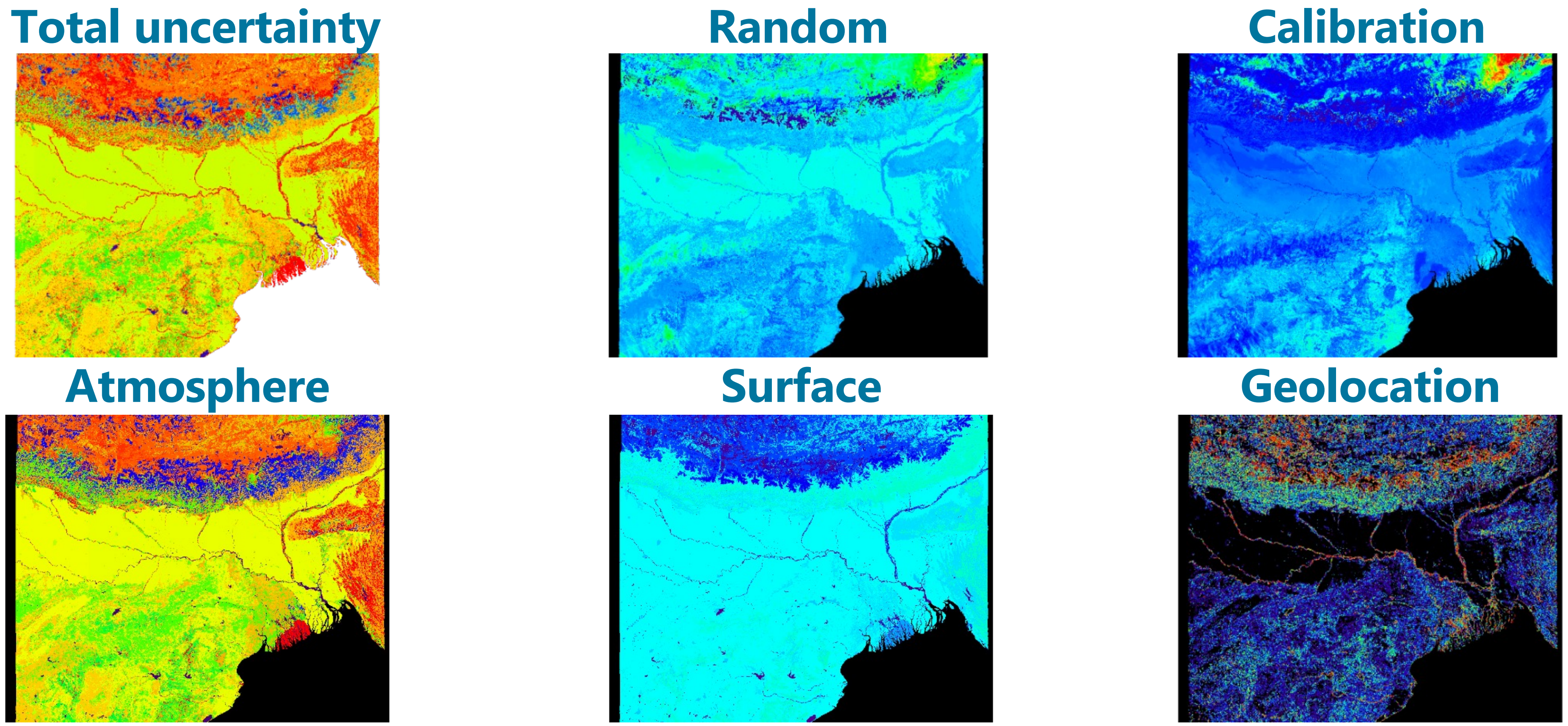
Propagating Uncertainties – E.g. SLSTR LST

L1 Uncertainty Effects propagate to L2 products again adapting the law of propagation of uncertainties



Slide courtesy of Darren Ghent University of Leicester

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SLSTR VIS/SWIR Radiometric Calibration – Current Status

- Users have been advised to adopt the following correction factors for the radiometric calibration based on the combined averages of the vicarious calibration results

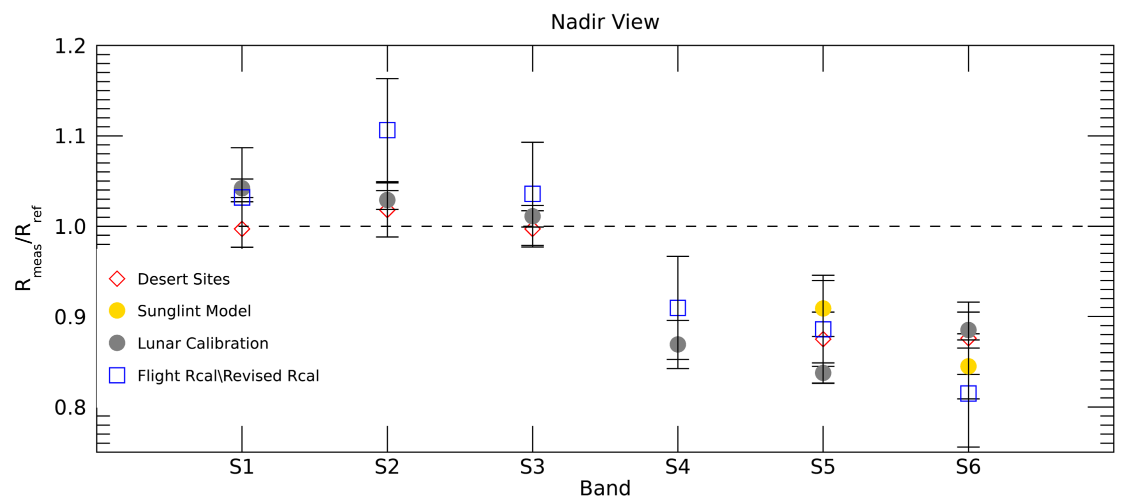
Nadir View

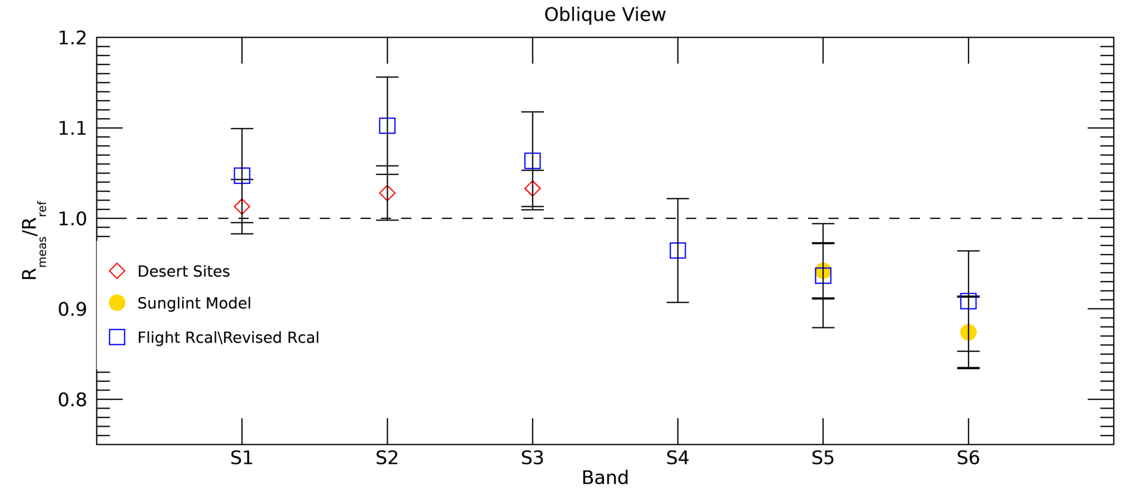
	S1	S2	S3	S5	S6
Correction	0.97	0.98	0.98	1.11	1.13
Uncertainty	0.03	0.02	0.02	0.02	0.02
Input Analysis	UoAz Rayference CNES	UoAz MPC (RAL) Rayference CNES	UoAz MPC (RAL) Rayference CNES	UoAz MPC (RAL) Rayference CNES	UoAz MPC (RAL) Rayference CNES

Oblique View

	S1	S2	S3	S5	S6
Correction	0.94	0.95	0.95	1.04	1.07
Uncertainty	0.05	0.03	0.03	0.03	0.05
Input Analysis	Rayference CNES	MPC (RAL) Rayference CNES	MPC (RAL) Rayference CNES	MPC (RAL) Rayference CNES	Rayference CNES

Note: Uncertainty estimates are at k=1.





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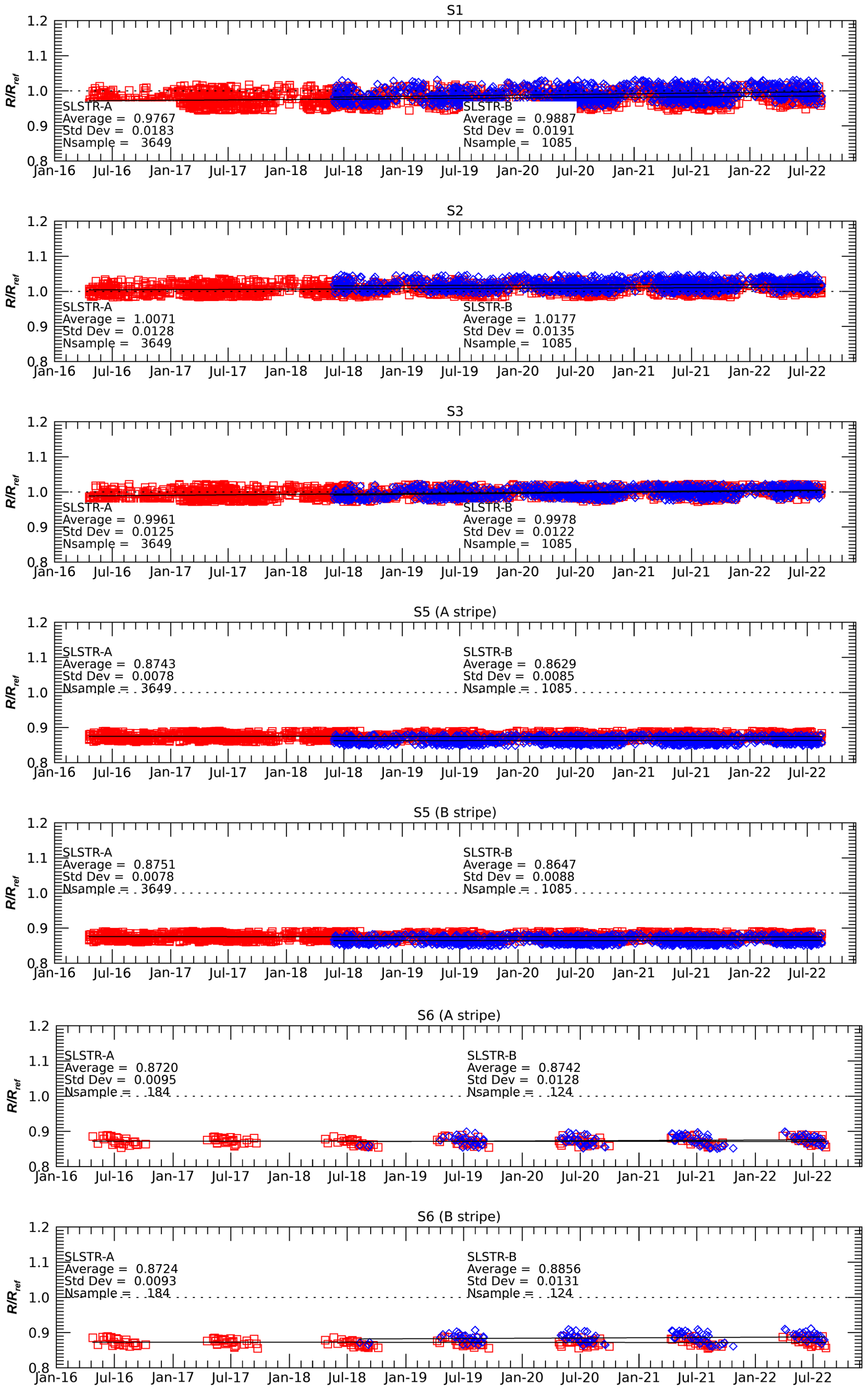
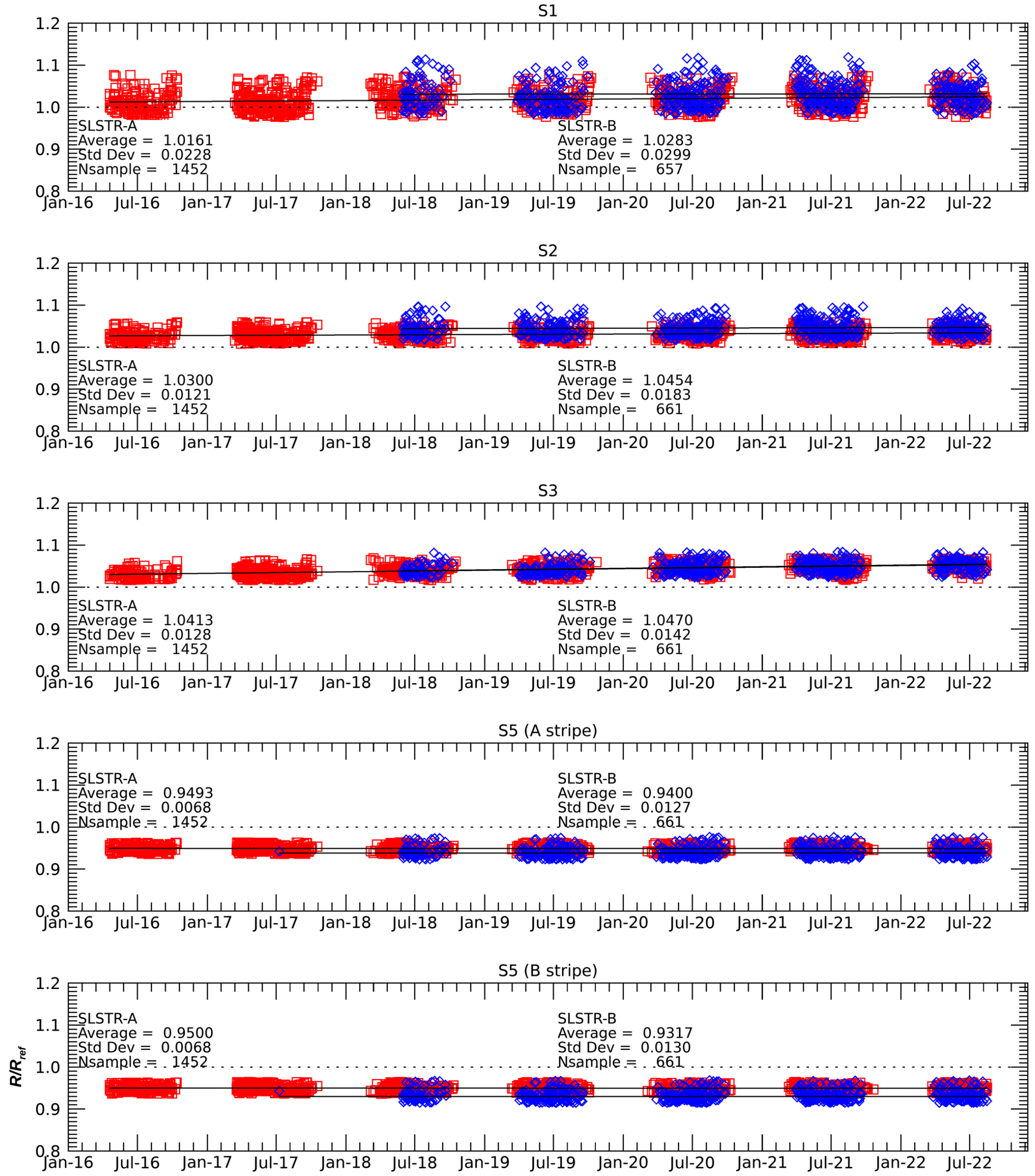
Long Term Stability

Nadir View



Oblique View



Drift Rates for Oblique View are via AATSR for matching geometry – hence no match-ups for S6

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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

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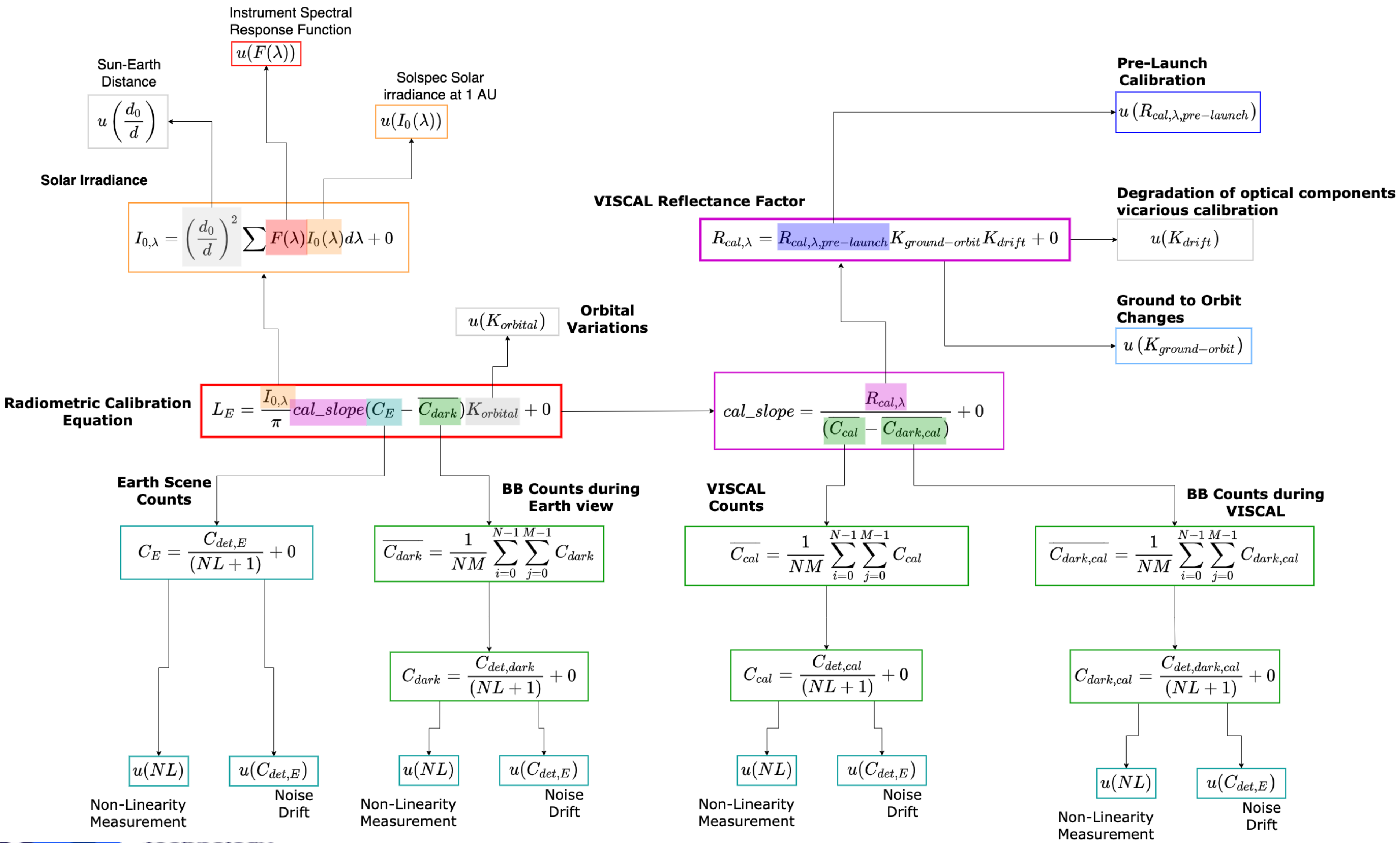
VIS-SWIR Uncertainty Analysis

SLSTR - VIS-SWIR Radiometric Calibration Model



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 τ_{uv}, relay mirror reflectances r_{m1}, r_{m2}, r_{m3})
- Geometric Factors ($\Omega_{cal}, \Omega_{slstr}$)

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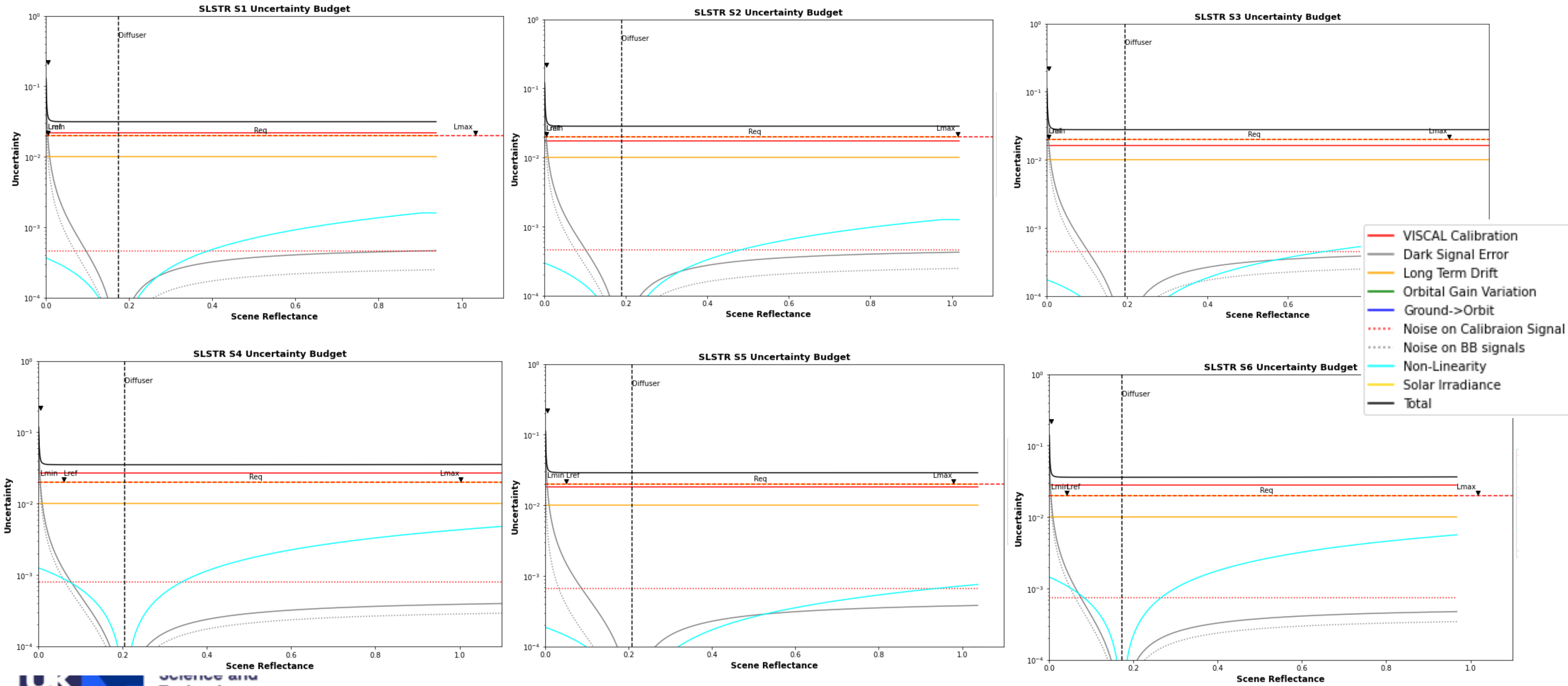
SLSTR VIS/SWIR Radiometric Calibration Model

The measurement equation - $L_E = \frac{I_0}{\pi} R_{cal} \left(C_E - C_{off,E}\right) / \left(C_{cal} - C_{off,cal}\right) . K_{drift} . K_{orbital\_stability} + 0$

Affected Term	Description	Characterisation
R_{CAL}	Reflectance Factor For VISCAL	Pre-Launch Calibration – VISCAL and Instrument level Post-Launch Vicarious Calibration
$K_{orbital\_stability}$	Orbital Gain Stability	By design & Pre-Launch Testing
K_{drift}	Degradation of VISCAL Reflectance Factor	Post-Launch Vicarious Calibration
C_E	Earth Scene Counts	Earth Scene counts
$C_{off,E}$	BB Counts during observation of earth scene	Observation of BB signals - noise
C_{cal}	Signal Counts at full solar illumination	Observation of VISCAL Signal at full solar illumination
C_E	BB Counts during observation of VISCAL	Observation of BB signals - noise
NL	Non-Linearity Correction	Pre-Launch Testing
$F(\lambda)$	Instrument spectral response	Pre-Launch Testing
I_0	Solar Irradiance	Solspec Reference Spectrum

SLSTR-B VIS-SWIR Uncertainty Estimates



Assumes **non-linearity correction is applied** correctly

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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

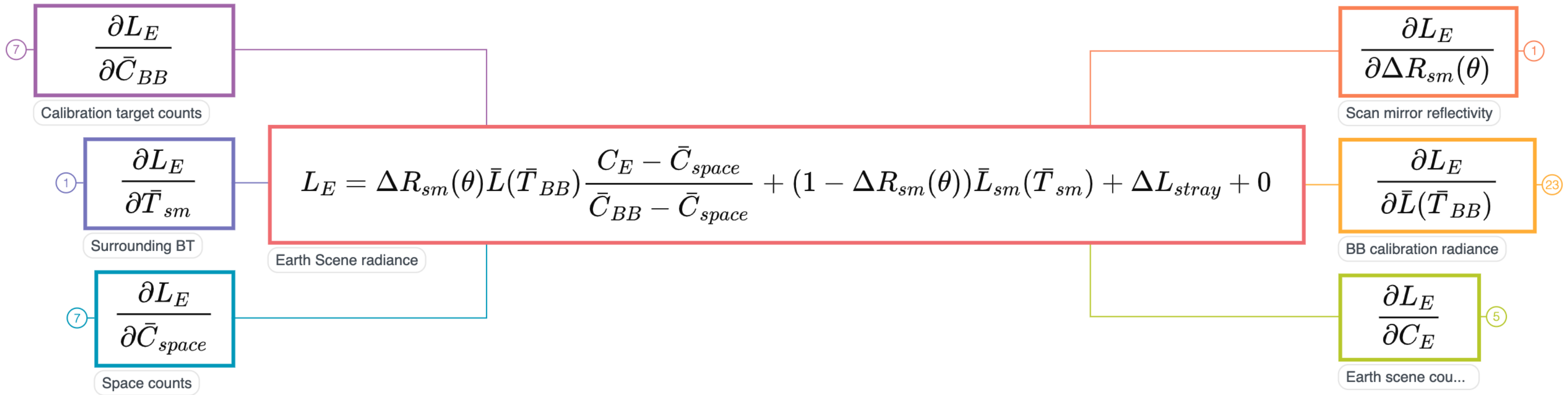
Land Surface Temperature Mission

- 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

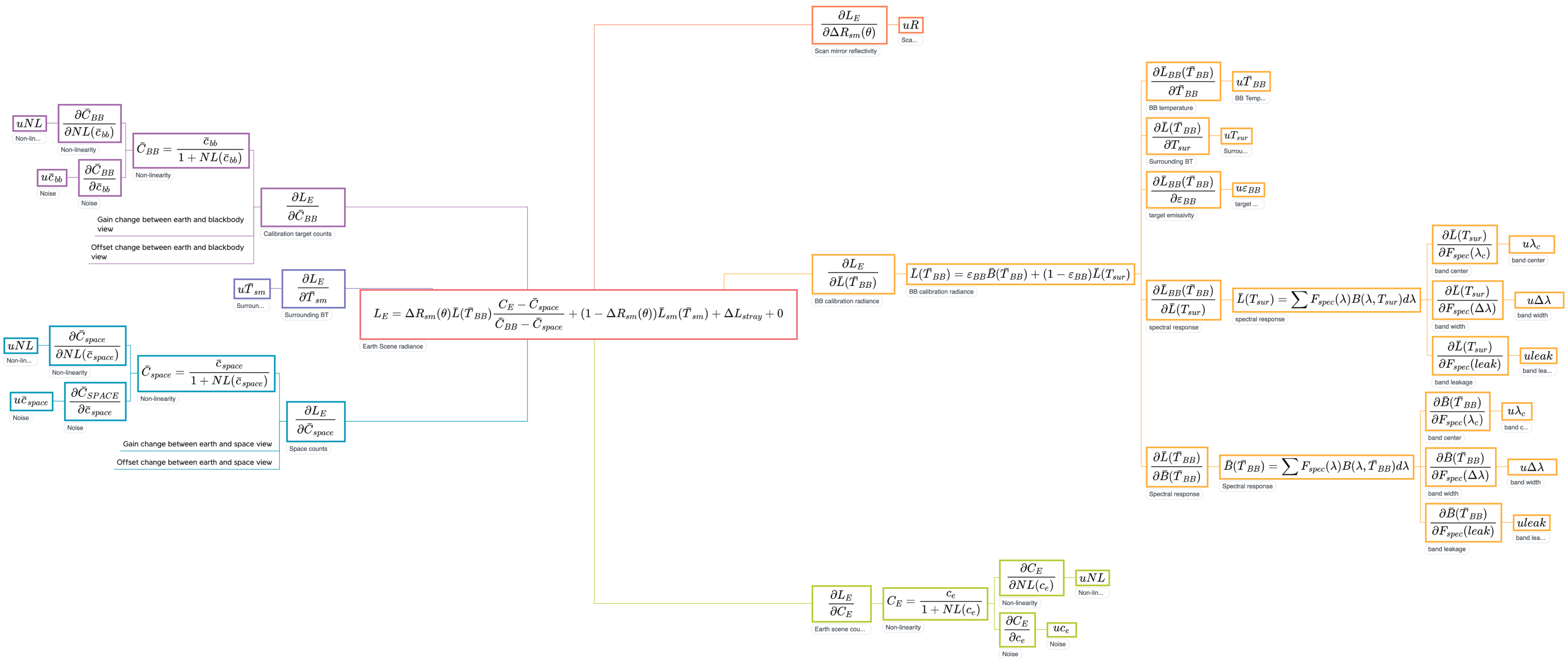
- Multi-Channel Scanning Radiometer
  - TIR channels at 8.6, 8.9, 9.2, 10.9 and 12.0 µm.
  - VIS-SWIR Channels – 0.490, 0.665, 0.865, 0.945, 1.375 and 1.610 µm

- On-Board Calibration
  - BB for TIR
  - Solar Diffuser for VIS-SWIR Channels
  - Space view

LSTM Uncertainty Effects Tree



LSTM Uncertainty Effects Tree



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LSTM Uncertainty Effects

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

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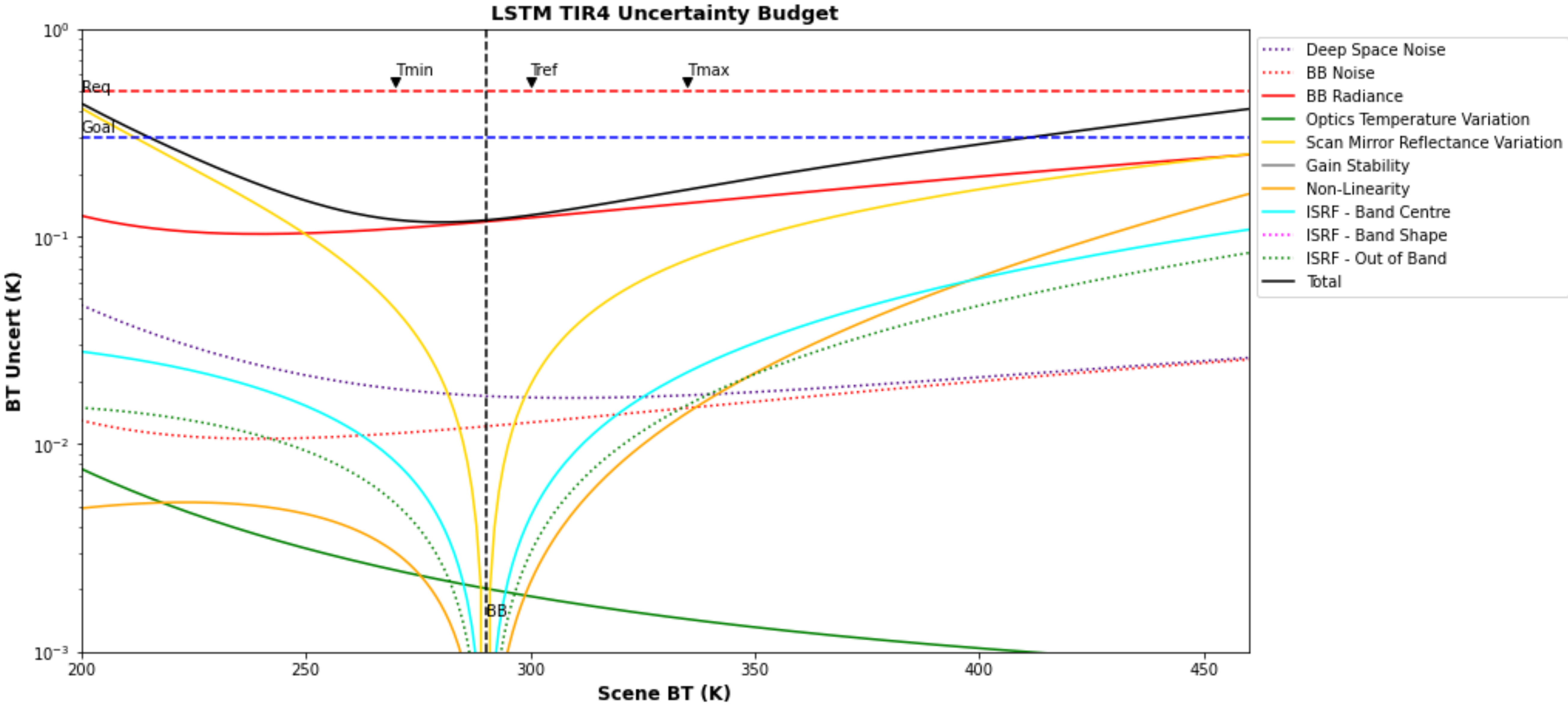
LSTM L1 Uncertainties



Example – TIR Band 4 – 10.9μm

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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