Sentinel-3 Validation Team Meeting #7
SLSTR Radiometric Uncertainty Analysis

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L1 Uncertainties - Status

- **L1 Products Contain Uncertainty Estimates in Quality Datasets for both TIR and VIS/SWIR channels**
  - Random noise estimates from on-board BB sources reported per scan-line
  - 'Correlated' uncertainties due to systematic effects (Calibration) are based on pre-launch estimates

- **MapNoiS3 tool developed by RAL to project uncertainty estimates to L1 product grid**
  - Works for ALL channels.
  - Funded by Eumetsat (Copernicus)

- **TIR Uncertainties have been analysed and documented**
  - Remote Sens. 2021, 13(3), 374; https://doi.org/10.3390/rs13030374
  - Funded through METEOC-3 (EMRP) and Eumetsat (Copernicus)

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Uncertainties in SLSTR L1 Products

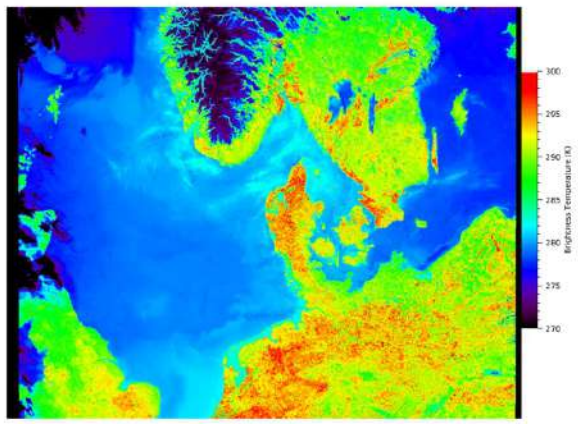
S3A - North Sea on 22-April-2020

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

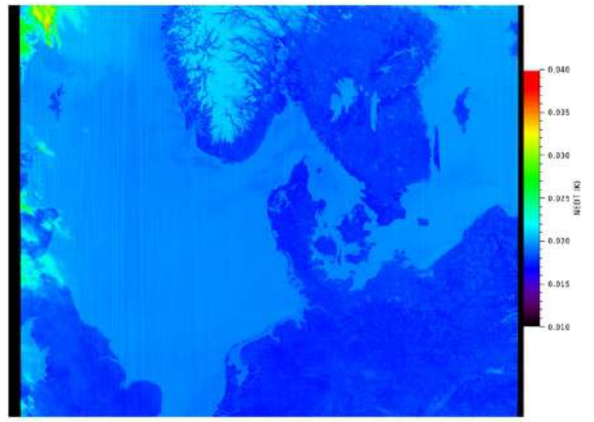
Systematic effects – radiometric calibration - tables of uncertainty vs. temperature type-B (a-priori) estimates based on the pre-launch calibration and calibration model

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

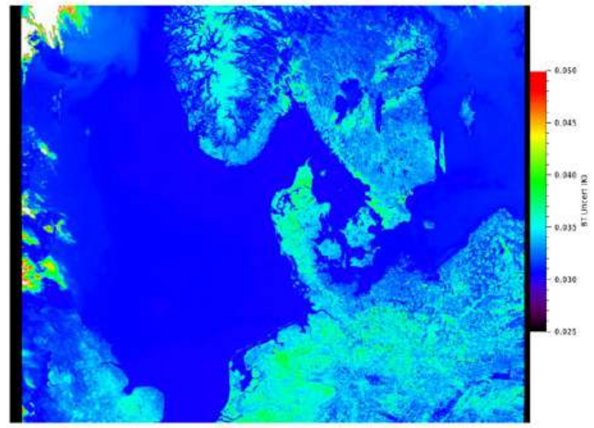
S9 - 12 µm BT



S9 - 12 µm NEDT
(Random)

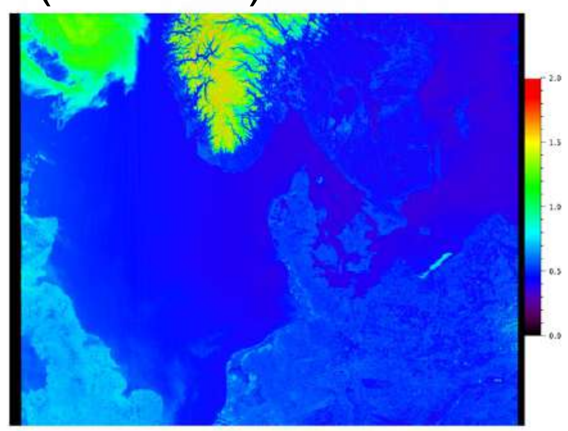


S9 - 12 µm uBT
(Systematic)

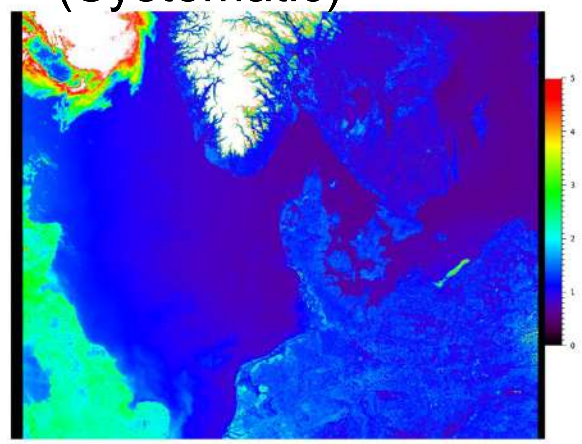


VIS/SWIR
(False Colour)

S1 - 0.56 µm NEDL
(Random)



S1 - 0.56 µm uL
(Systematic)



Note: Uncertainties are in radiometric units (K for TIR, $Wm^{-2}sr^{-1}nm^{-1}$ for VIS-SWIR) - relative uncertainties (%) in VIS-SWIR systematic effects are constant with scene radiance since they are dominated by the uncertainty in the VISCAL reflectance factor (see later slides)

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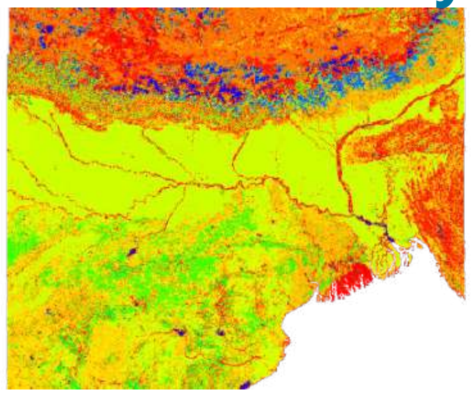
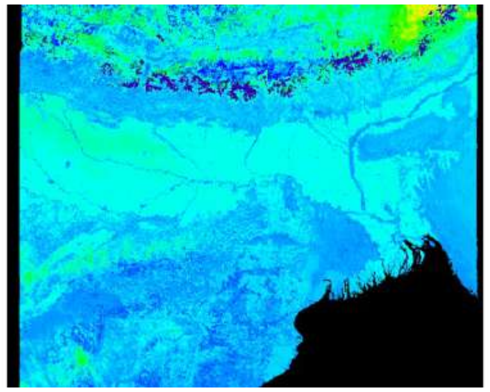
Propagating Uncertainties – E.g. SLSTR LST

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

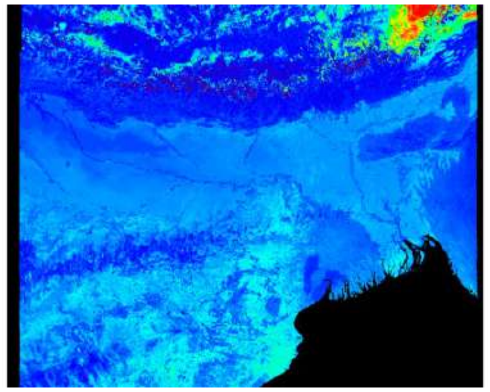
Total uncertainty



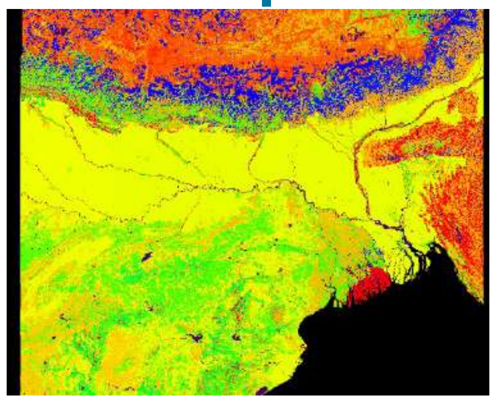
Random



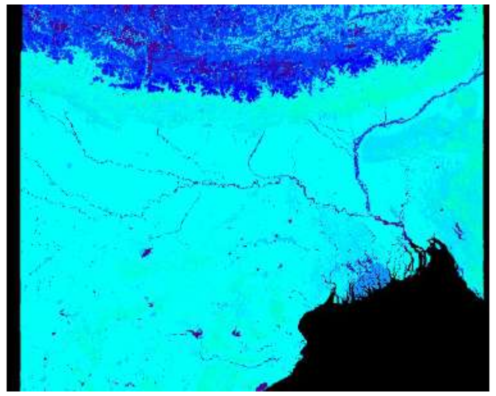
Calibration



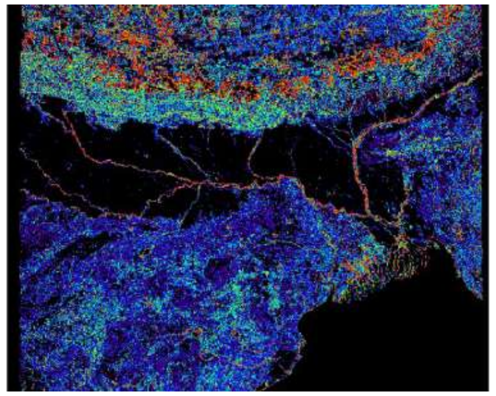
Atmosphere



Surface



Geolocation

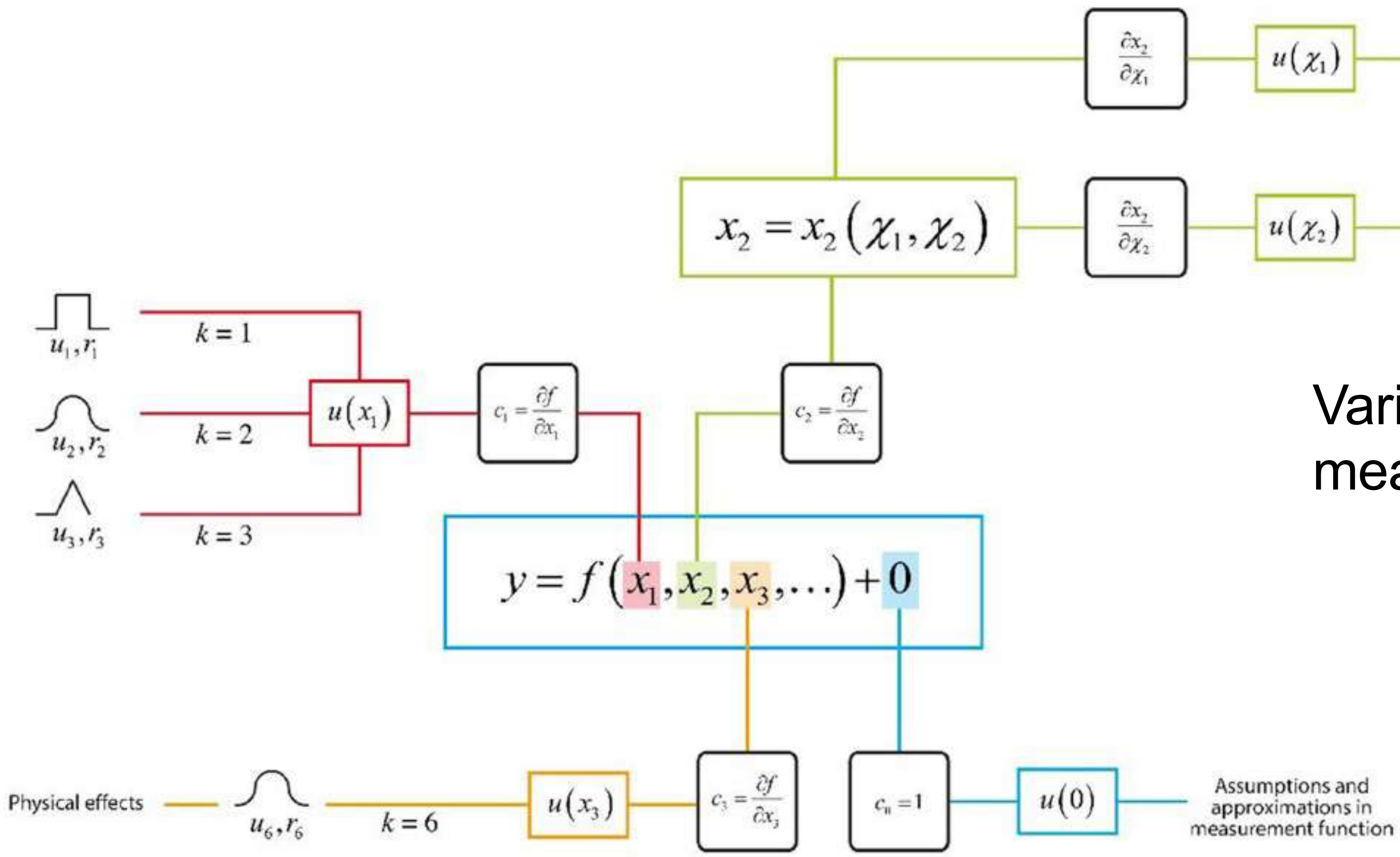


Slides courtesy of Darren Ghent University of Leicester

TIR L1 Uncertainties – Status

- **TIR uncertainty trends have been implemented in L0 monitoring tools**
- **Revised TIR uncertainty estimate tables from L0 data for single orbits have been generated**
  - Under assessment by Eumetsat
- **MapNoiS3 tool has been updated to use an external file with revised L1 uncertainty estimates instead of pre-launch estimates in L1 files**
- **TIR uncertainty model does not yet account for internal stray light effect.**

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

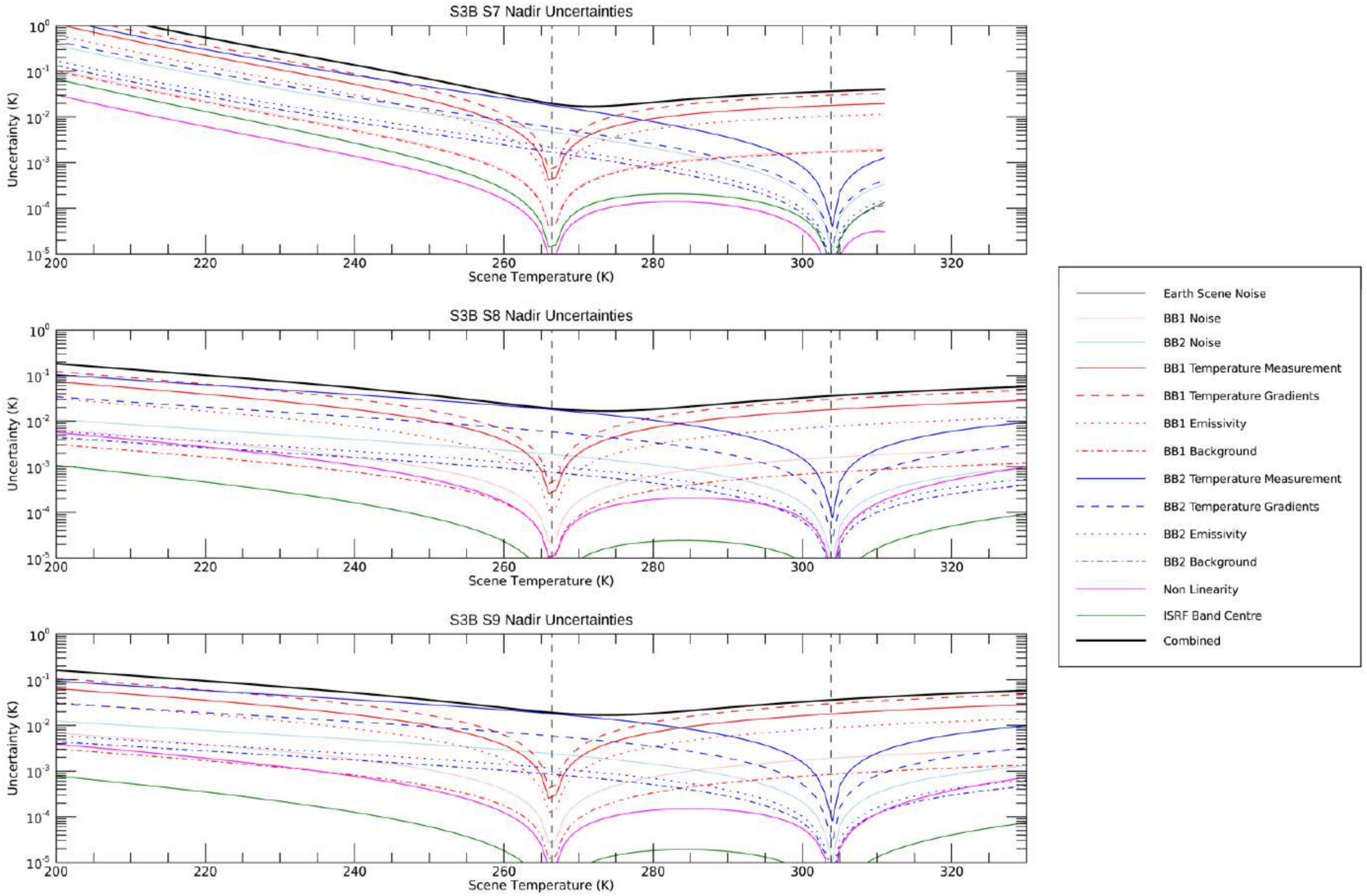
$$u^2(y) = \sum_{i=1}^{N} \left(\frac{\partial y}{\partial x_i}\right)^2 u^2(x_i) + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N} \frac{\partial y}{\partial x_i}\frac{\partial y}{\partial x_j} u(x_i)\, u(x_j) v(x_i, x_j)$$

Sensitivity of measurand to effect x_i

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

SLSTR TIR Uncertainty Budget

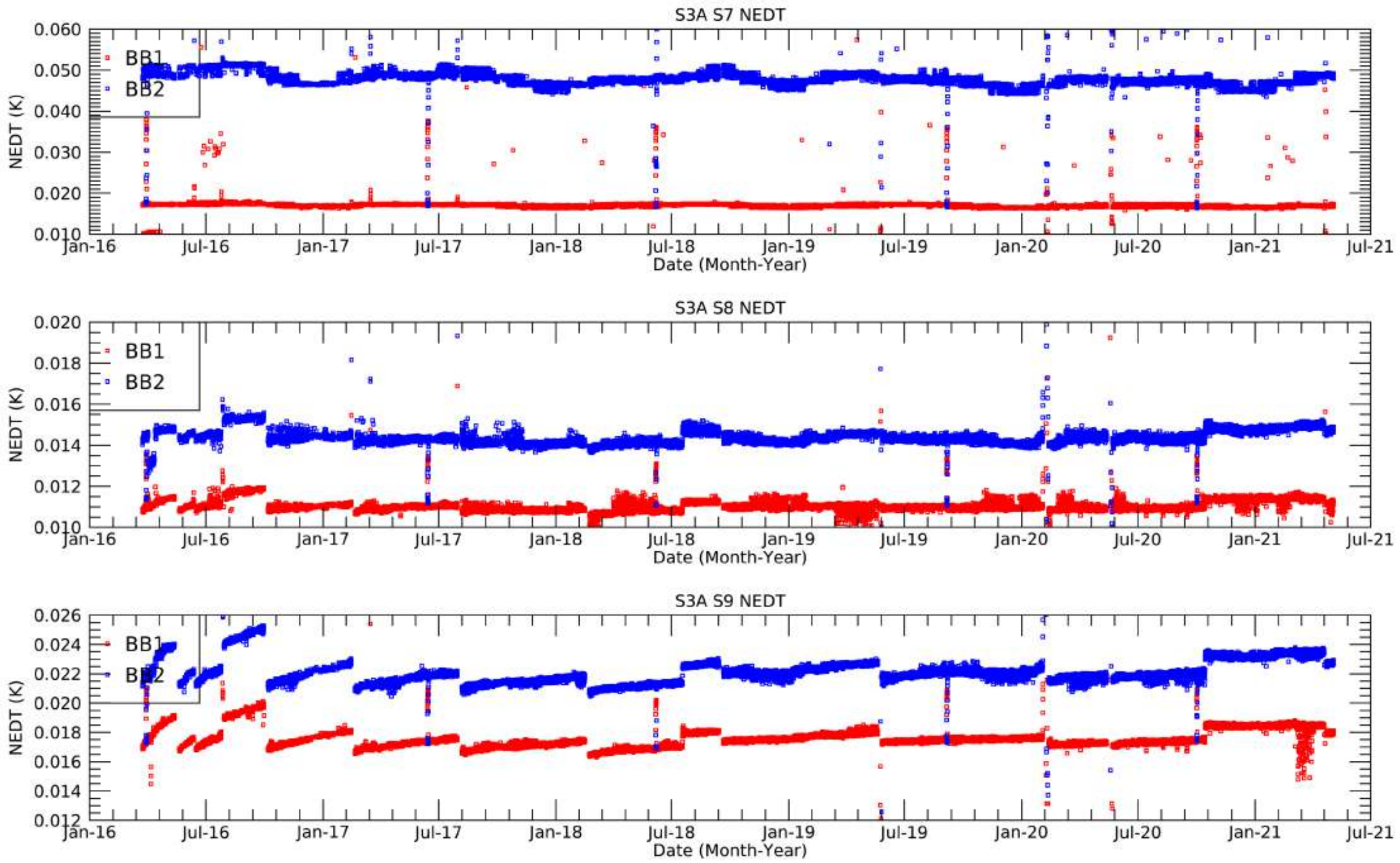
- **Black-Body Temperatures**
  - PRT calibration at subsystem level – traced to SPRT (ITS-90) -
  - Blackbody gradients, thermal analysis - RAL
- **Black-Body Cavity Emissivity**
  - Spectral Reflectance of Black Coating – NIST/NPL
  - Cavity Model – STEEP323 or SMART3D (ABSL model)
- **Spectral Response**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



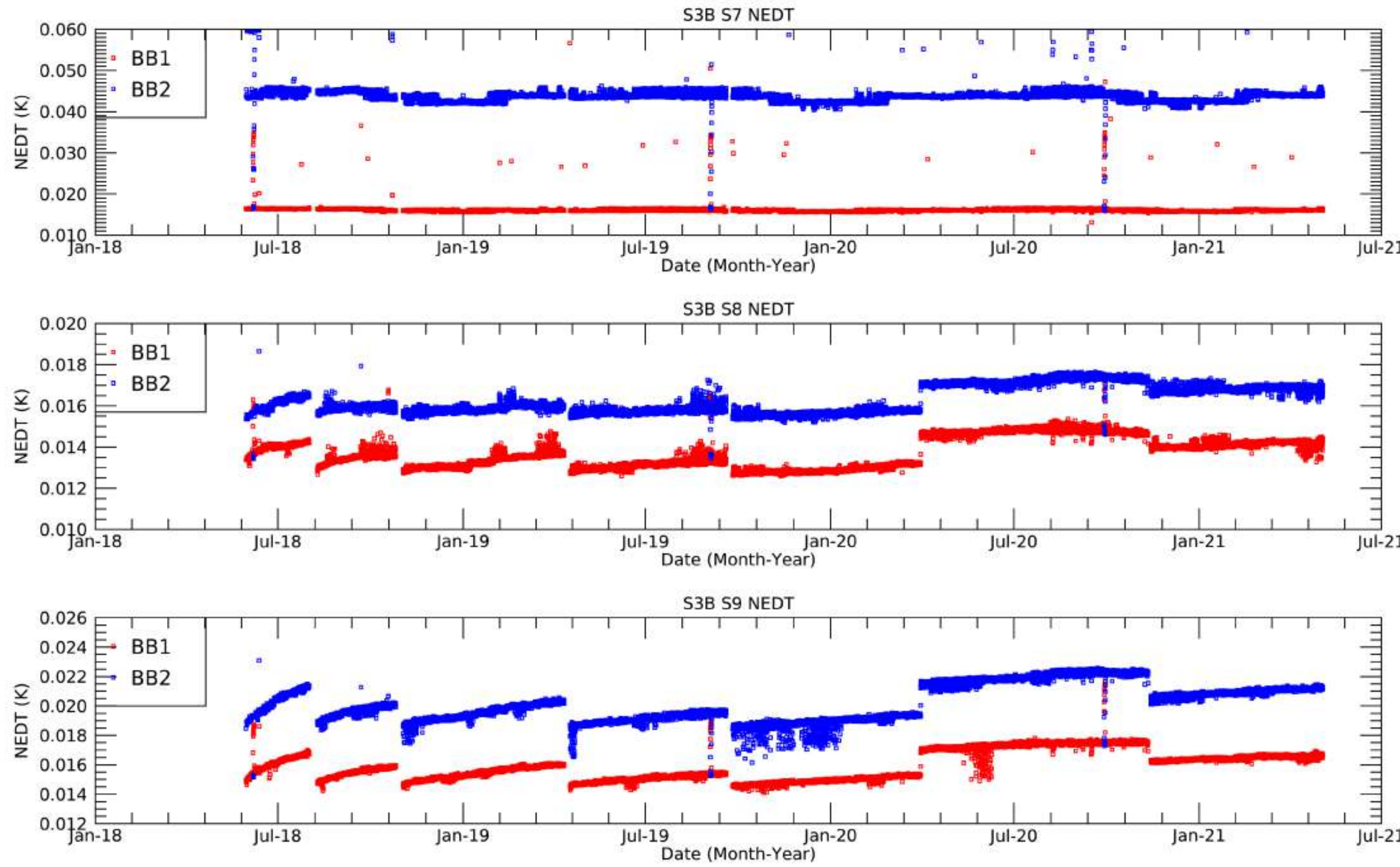
OPT-MPC

TIR Uncertainty Time Series - Random Effects (NEDT)

SLSTR-A



SLSTR-B



Noise estimates derived from on-board BB sources

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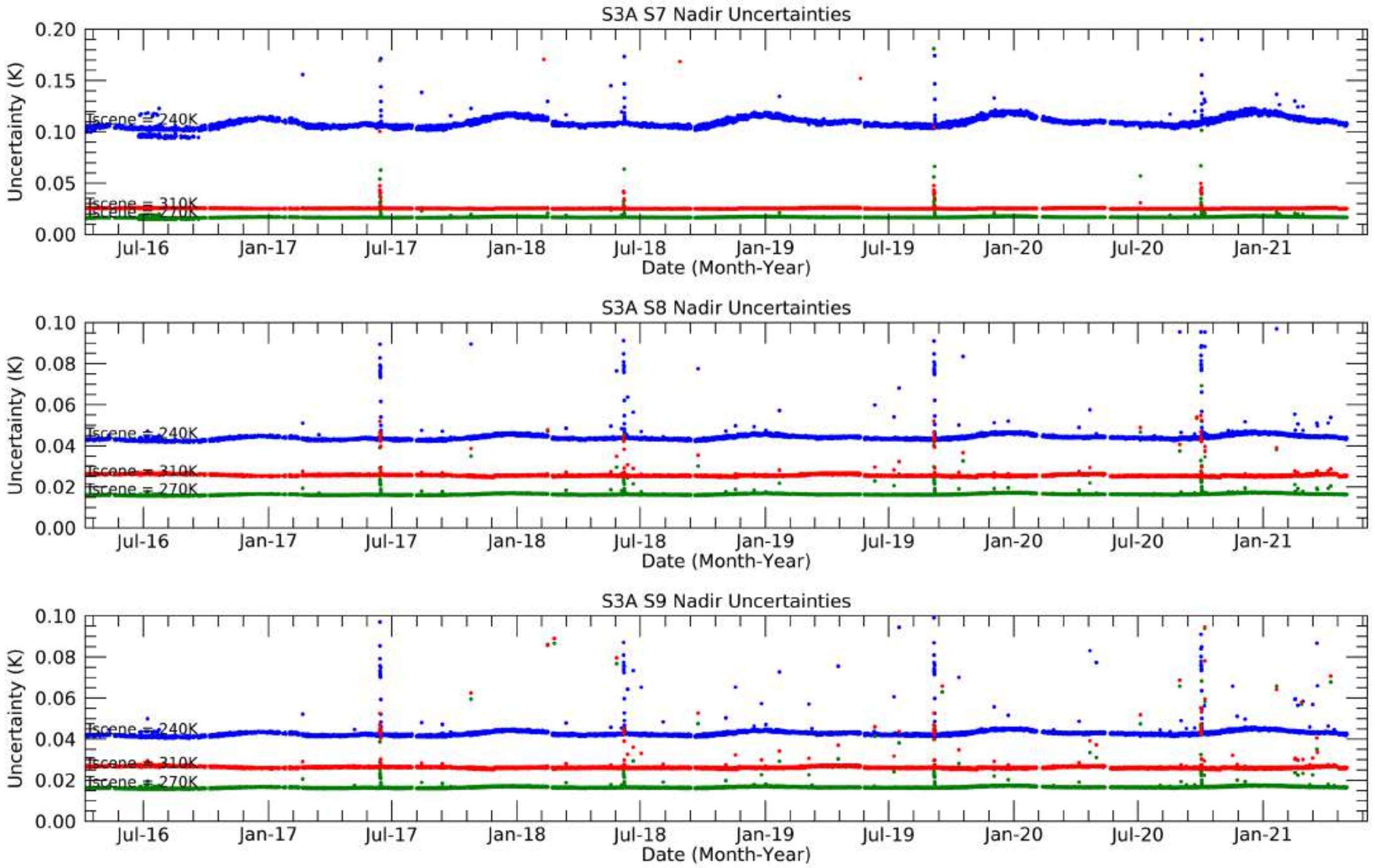
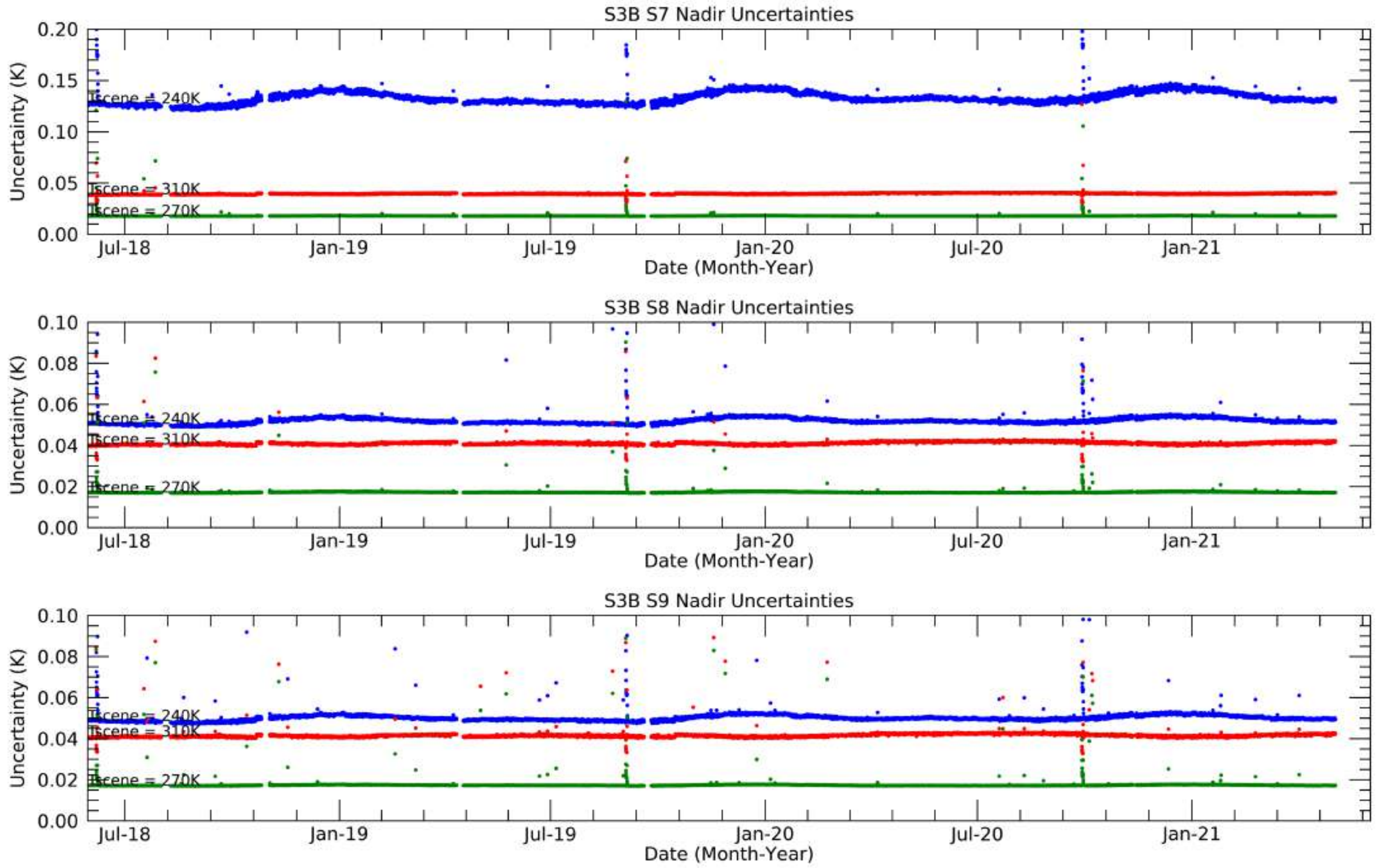
TIR Uncertainty Time Series - Systematic Effects

SLSTR-A



SLSTR-B



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

Status of VIS/SWIR Uncertainty Estimates

- **L1 Uncertainties in the L1 products are based on the pre-launch calibration test analysis.**

- **VIS/SWIR L1 uncertainties need to be updated to account for post-launch effects**
- 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 Uncertainty analysis

- **Uncertainty Analysis of SLSTR VIS/SWIR channels in progress following Fiduceo methodology as used for TIR channels**
  - Describe measurement equation (the calibration model)
  - Build up effects tree to and trace back to root effects
  - Document effects – distribution, correlation scales…
  - Estimate uncertainties in input effects
  - Determine sensitivity coefficients
  - Propagate uncertainties through calibration model

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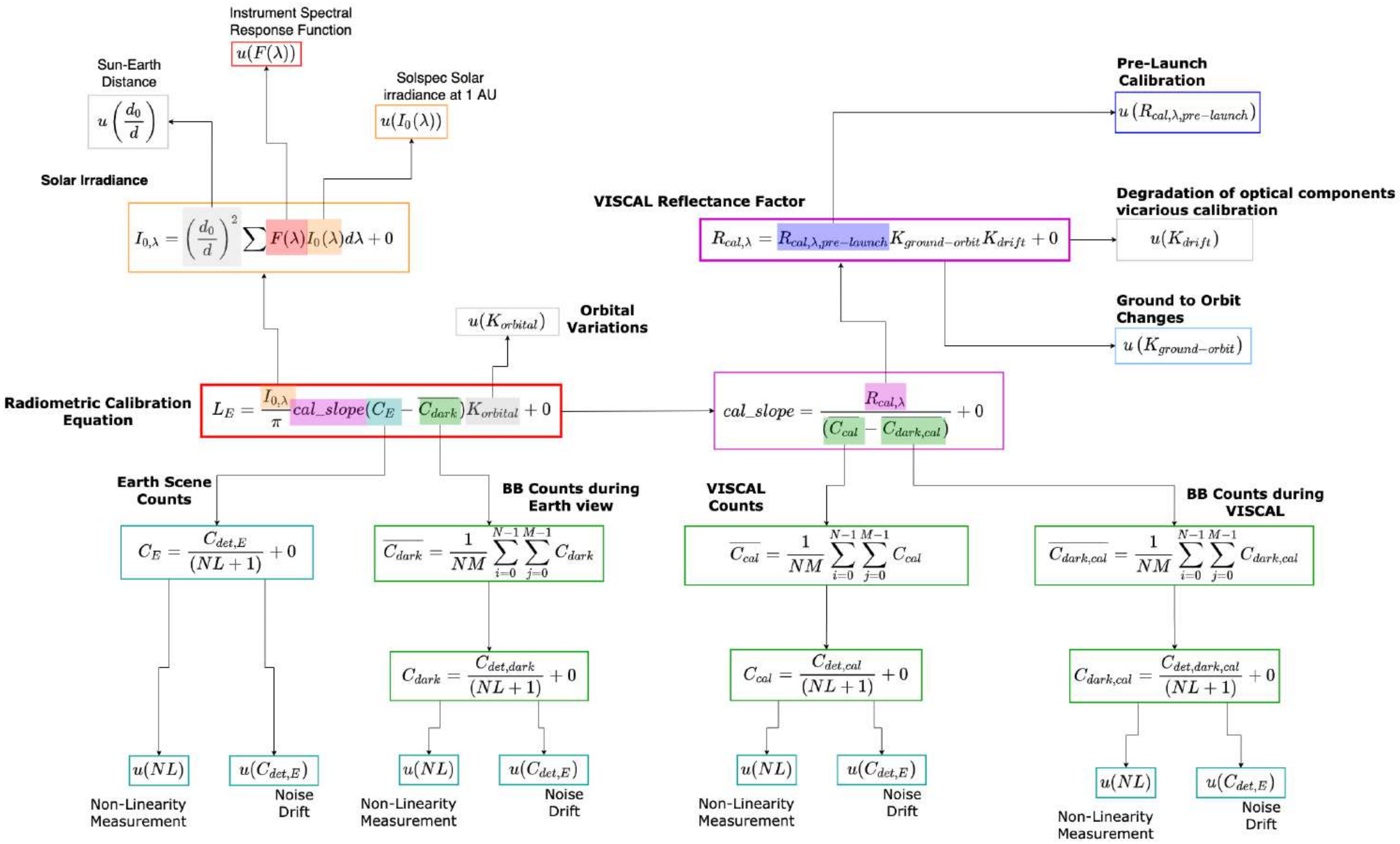
VIS-SWIR Uncertainty Analysis

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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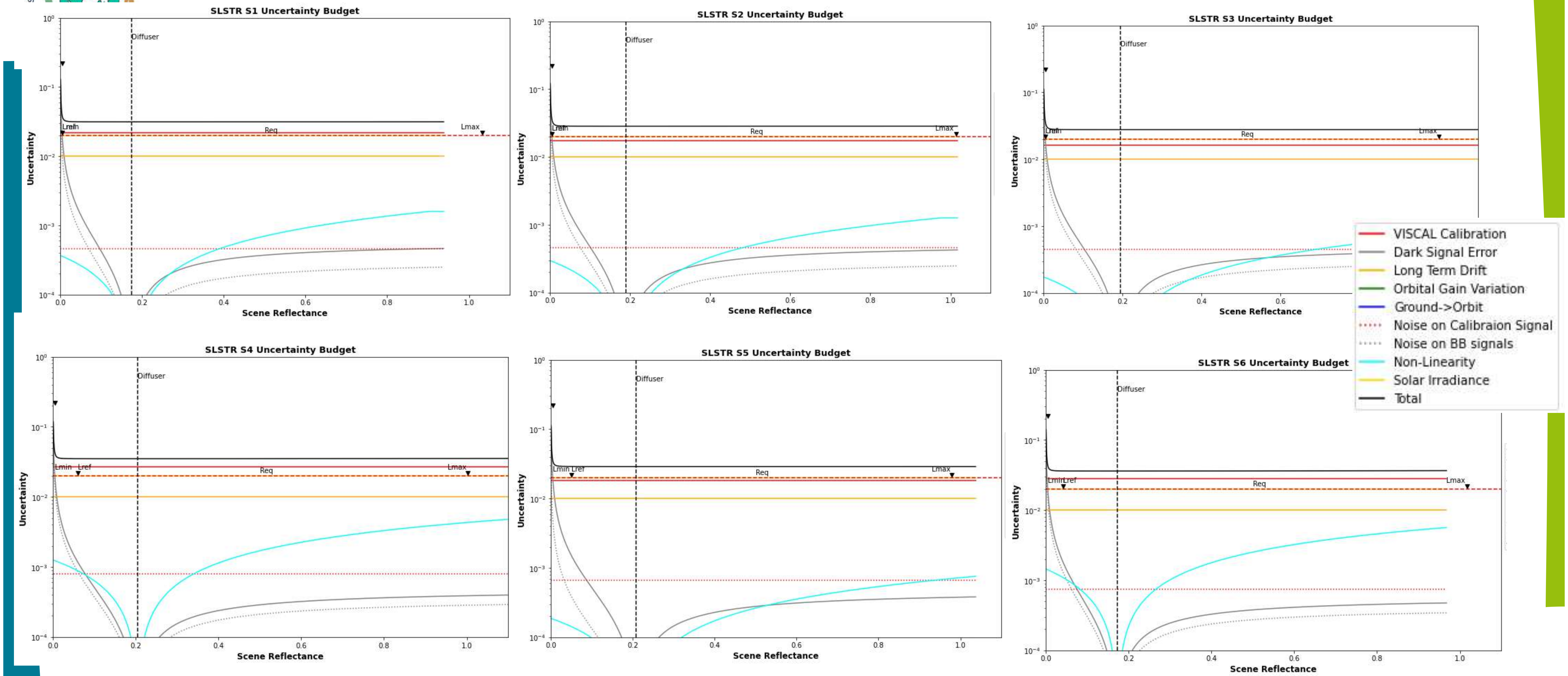
L1 Radiometric Calibration Model

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 L1 Combined Uncertainty



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

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VISCAL Reflectance Factor R_{cal} from component measurements

The measurement equation

$$R_{cal} = \pi \frac{\Omega_{cal}}{\Omega_{slstr}} \tau_{uv} R_{diff}(\theta_0, \theta_v, \phi_0, \phi_v) r_{m1} r_{m2} r_{m3} + 0$$

Affected Term	Description	Characterisation	Ref
Ω_{slstr}	Solid angle of SLSTR	Defined by Telescope aperture and focal length – assumed to be same for all SLSTR Channels For SWIR channels this is affected by intermediate stop	S3-RC-JOP-SL-53595
Ω_{cal}	Solid angle of m3	Optical modelling of PMA to M3 aperture area by JOP	S3-TN-JOP-SL-41119
τ_{uv}	Transmission of UV window	Component level measurements on witness sample – assume flight is identical	S3-RC-JOP-SL-53595
$R_{diff}(\theta_0, \theta_v, \phi_0, \phi_v)$	Diffuser BRDF	TNO measurements on flight components	S3-RP-TNO-SL062055 issue 3
r_{m1}	m1 mirror reflectance	Component level measurements on witness sample – assume flight is identical	S3-RC-JOP-SL-53595
r_{m2}	m2 mirror reflectance	Component level measurements on witness sample – assume flight is identical	S3-RC-JOP-SL-53595
r_{m3}	m3 mirror reflectance	Component level measurements on witness sample – assume flight is identical	S3-RC-JOP-SL-53595

Original VISCAL Reflectance Factors – From Components

OPT-MPC
Copernicus Sentinel
Optical Mission Performance Cluster

SLSTR-A

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	S1	S2	S3	S4	S5	S6
R_{diff}	0.32496 [0.93%]	0.324463 [0.93%]	0.322018 [0.9%]	0.31880 [2.7%]	0.320281 [2.6%]	0.308127 [3.03%]
r_{m1}	0.9729 [0.1%]	0.9794 [0.1%]	0.9785 [0.1%]	0.9853 [0.1%]	0.9876 [0.1%]	0.9923 [0.1%]
r_{m2}	0.9731 [0.1%]	0.9815 [0.1%]	0.9820 [0.1%]	0.9839 [0.1%]	0.9859 [0.1%]	0.9897 [0.1%]
r_{m3}	0.9718 [0.1%]	0.9885 [0.1%]	0.9776 [0.1%]	0.9787 [0.1%]	0.9815 [0.1%]	0.9722 [0.1%]
τ_{UV}	0.9196 [0.14%]	0.9217 [0.13%]	0.9237 [0.45%]	0.9252 [0.45%]	0.9254 [0.42%]	0.8732 [0.42%]
Ω_{cal} / Ω_{SLSTR}	0.2170 [5%]					
R_{cal}	**0.1874 [5.1%]**	**0.1937 [5.1%]**	**0.1905 [5.1%]**	**0.1908 [5.7%]**	**0.1931 [5.7%]**	**0.1751 [5.9%]**

Oblique

	S1	S2	S3	S4	S5	S6
R_{diff}	0.32070 [0.96%]	0.320032 [1.02%]	0.317676 [1.02%]	0.315852 [2.7%]	0.316671 [2.61%]	0.305262 [3.03%]
r_{m1}	0.9703 [0.1%]	0.9780 [0.1%]	0.9779 [0.1%]	0.9834 [0.1%]	0.9855 [0.1%]	0.9893 [0.1%]
r_{m2}	0.9717 [0.1%]	0.9786 [0.1%]	0.9784 [0.1%]	0.9886 [0.1%]	0.9906 [0.1%]	0.9937 [0.1%]
r_{m3}	0.9712 [0.1%]	0.9796 [0.1%]	0.9712 [0.1%]	0.9816 [0.1%]	0.9835 [0.1%]	0.9863 [0.1%]
τ_{UV}	0.9190 [0.14%]	0.9215 [0.12%]	0.9230 [0.28%]	0.9255 [0.41%]	0.9250 [0.47%]	0.8731 [0.5%]
Ω_{cal} / Ω_{SLSTR}	0.1869 [5%]					
R_{cal}	**0.1585 [5.1%]**	**0.1623 [5.1%]**	**0.1600 [5.1%]**	**0.1638 [5.7%]**	**0.1651 [5.7%]**	**0.1517 [5.9%]**

SLSTR-B

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	S1	S2	S3	S4	S5	S6
R_{diff}	0.3257 [0.93%]	0.3252 [0.94%]	0.3229 [0.92%]	0.3205 [2.66%]	0.3218 [2.60%]	0.3096 [3.01%]
r_{m1}	0.9727 [0.1%]	0.9813 [0.1%]	0.9816 [0.1%]	0.9862 [0.1%]	9878 [0.1%]	0.9921 [0.1%]
r_{m2}	0.9727 [0.1%]	0.9806 [0.1%]	0.9806 [0.1%]	0.9864 [0.1%]	9887 [0.1%]	0.9924 [0.1%]
r_{m3}	0.9733 [0.1%]	0.9803 [0.1%]	0.9797 [0.1%]	0.9816 [0.1%]	9832 [0.1%]	0.9862 [0.1%]
τ_{UV}	0.9195 [0.14%]	0.9219 [0.13%]	0.9238 [0.46%]	0.9258 [0.42%]	0.9256 [0.43%]	0.8734 [0.5%]
Ω_{cal} / Ω_{SLSTR}	0.2170 [5%]					
R_{cal}	**0.1880 [5.1%]**	**0.1928 [5.1%]**	**0.1917 [5.1%]**	**0.1931 [5.7%]**	**0.1949 [5.7%]**	**0.1790 [5.9%]**

Oblique

	S1	S2	S3	S4	S5	S6
R_{diff}	0.3219 [0.98%]	0.3211 [1.01%]	0.3190 [1.00%]	0.3172 [2.70%]	0.3178 [2.62%]	0.3060 [3.02%]
r_{m1}	0.9714 [0.1%]	0.9797 [0.1%]	0.9806 [0.1%]	0.9836 [0.1%]	0.9847 [0.1%]	0.9880 [0.1%]
r_{m2}	0.9732 [0.1%]	0.9806 [0.1%]	0.9803 [0.1%]	0.9848 [0.1%]	0.9858 [0.1%]	0.9884 [0.1%]
r_{m3}	0.9731 [0.1%]	0.9808 [0.1%]	0.9805 [0.1%]	0.9824 [0.1%]	0.9843 [0.1%]	0.9854 [0.1%]
τ_{UV}	0.9195 [0.14%]	0.9219 [0.13%]	0.9238 [0.46%]	0.9258 [0.42%]	0.9256 [0.43%]	0.8734 [0.5%]
Ω_{cal} / Ω_{SLSTR}	0.1869 [5%]					
R_{cal}	**0.1599 [5.1%]**	**0.1638 [5.1%]**	**0.1631 [5.1%]**	**0.1641 [5.7%]**	**0.1650 [5.7%]**	**0.1510 [5.9%]**

Uncertainties reported at k = 3

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On-Ground Measurement of Reflectance Factor

We measure two responses:

- Earth View Response (Counts vs. Sphere Radiance) g_{Earth_View}
- VISCAL View Response (Counts vs. Sphere Irradiance) g_{VISCAL}

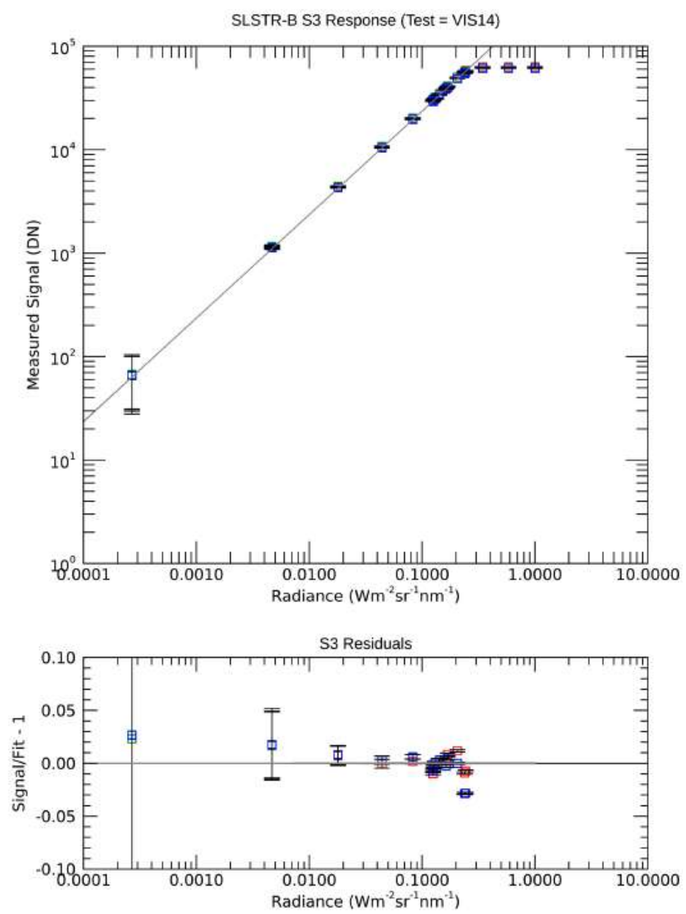
So

$$R_{cal} = \frac{\pi}{\Omega} g_{VISCAL} / g_{Earth\_View}$$

Ω = View factor from source to VISCAL diffuser

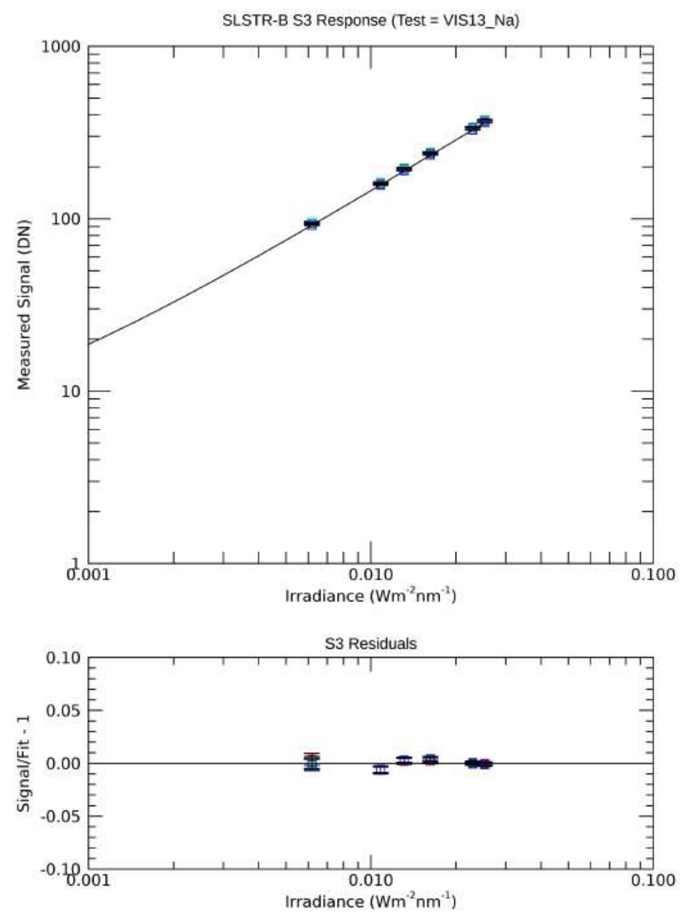
Non-Linearity Correction has been applied to detector counts before deriving slope

Earth View Response



Slope = g_{Earth_View}

VISCAL Response



Slope = $\frac{\pi}{\Omega} g_{VISCAL}$

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Re-Analysis of SLSTR-B VISCAL Reflectance Factors

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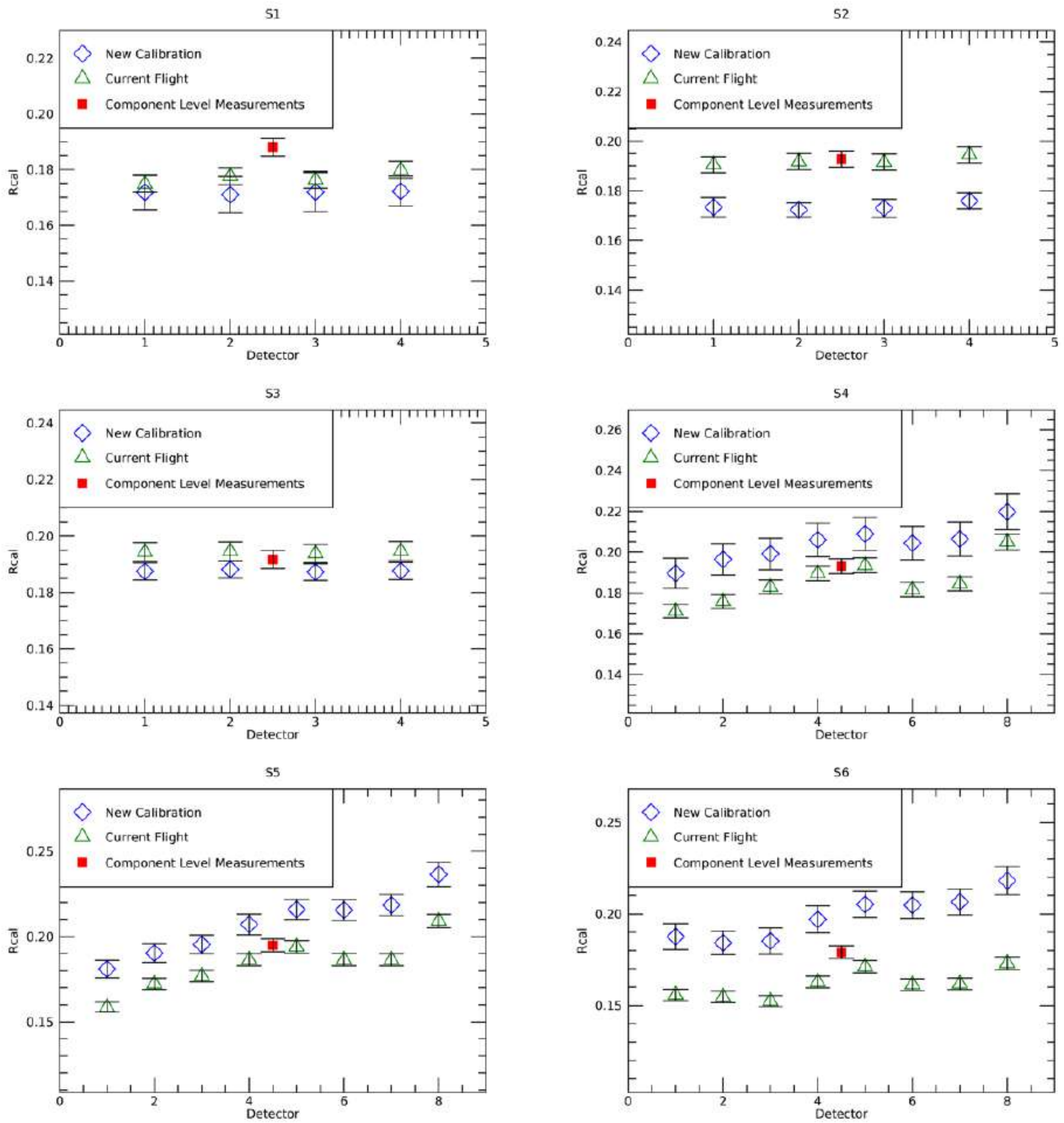
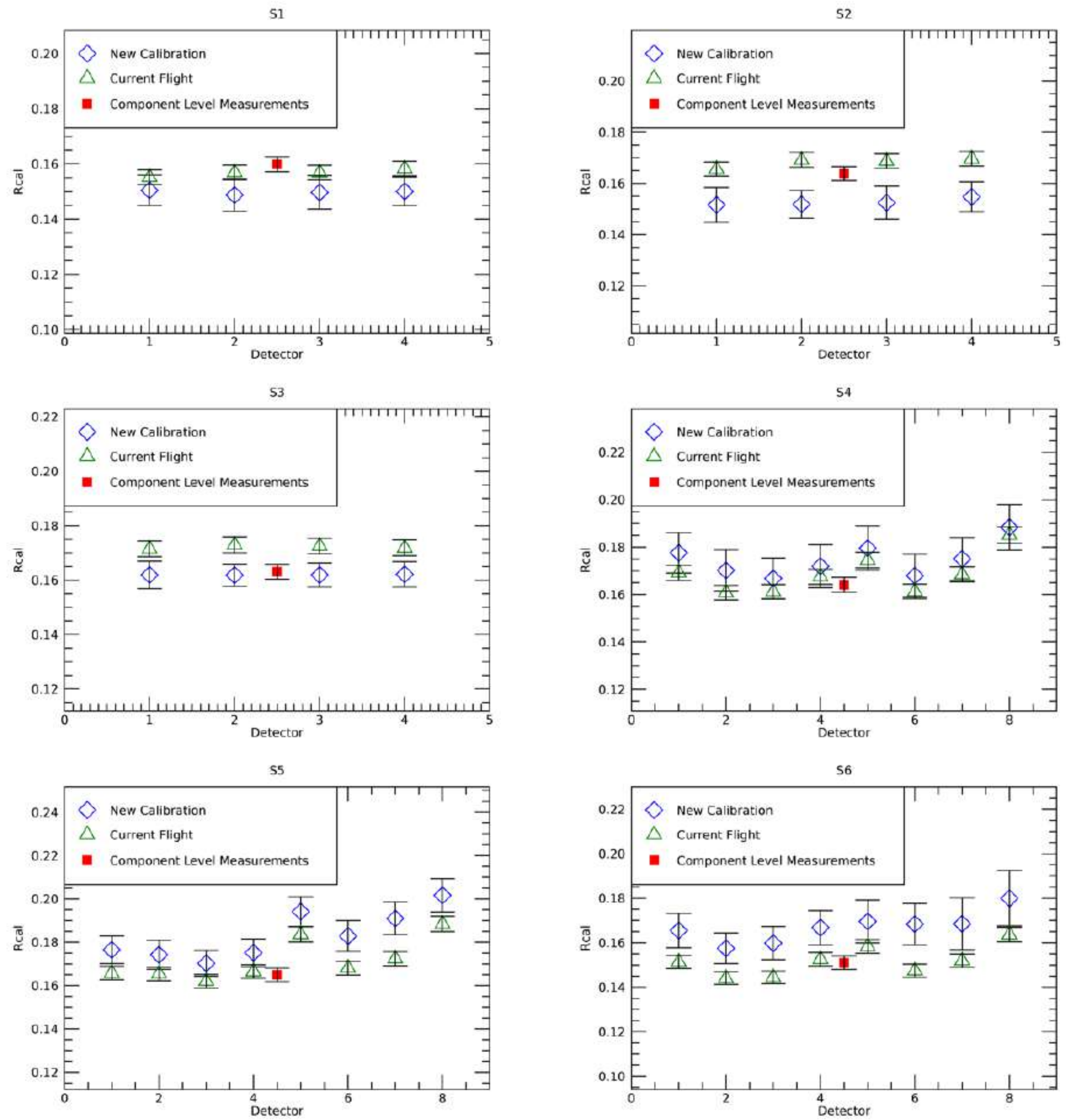
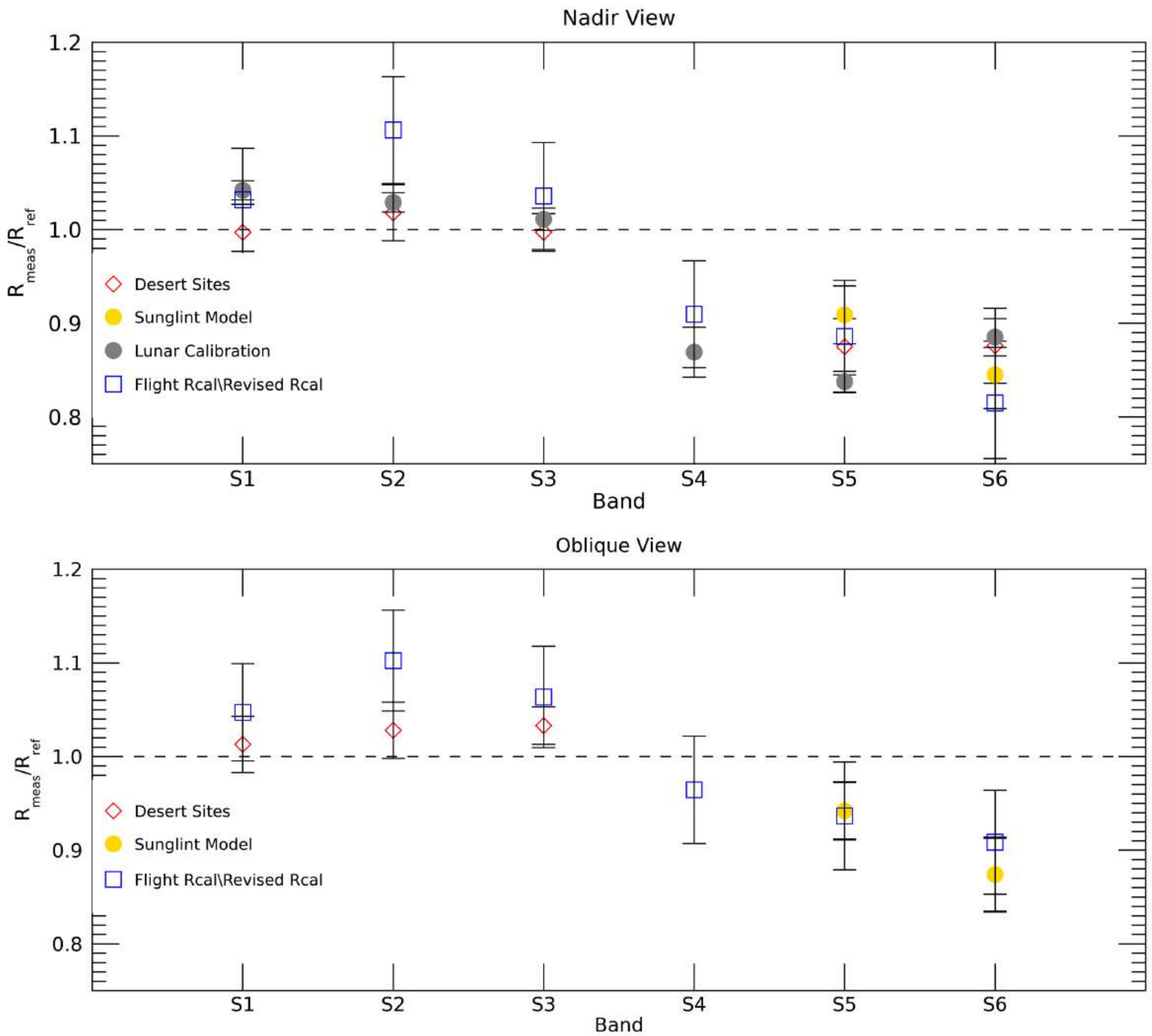


Oblique



Uncertainties reported at k = 1

Comparison with Vicarious Methods



Reprocessed SLSTR-B pre-launch calibration factors are consistent with the vicarious calibration measurements within uncertainties

S2 is the exception still to be investigated

Investigation of pre-launch tests found that the measurements are very sensitive to small drifts in the instrument response.

For model-C and D calibration more attention is being given to measurements at low radiance levels.

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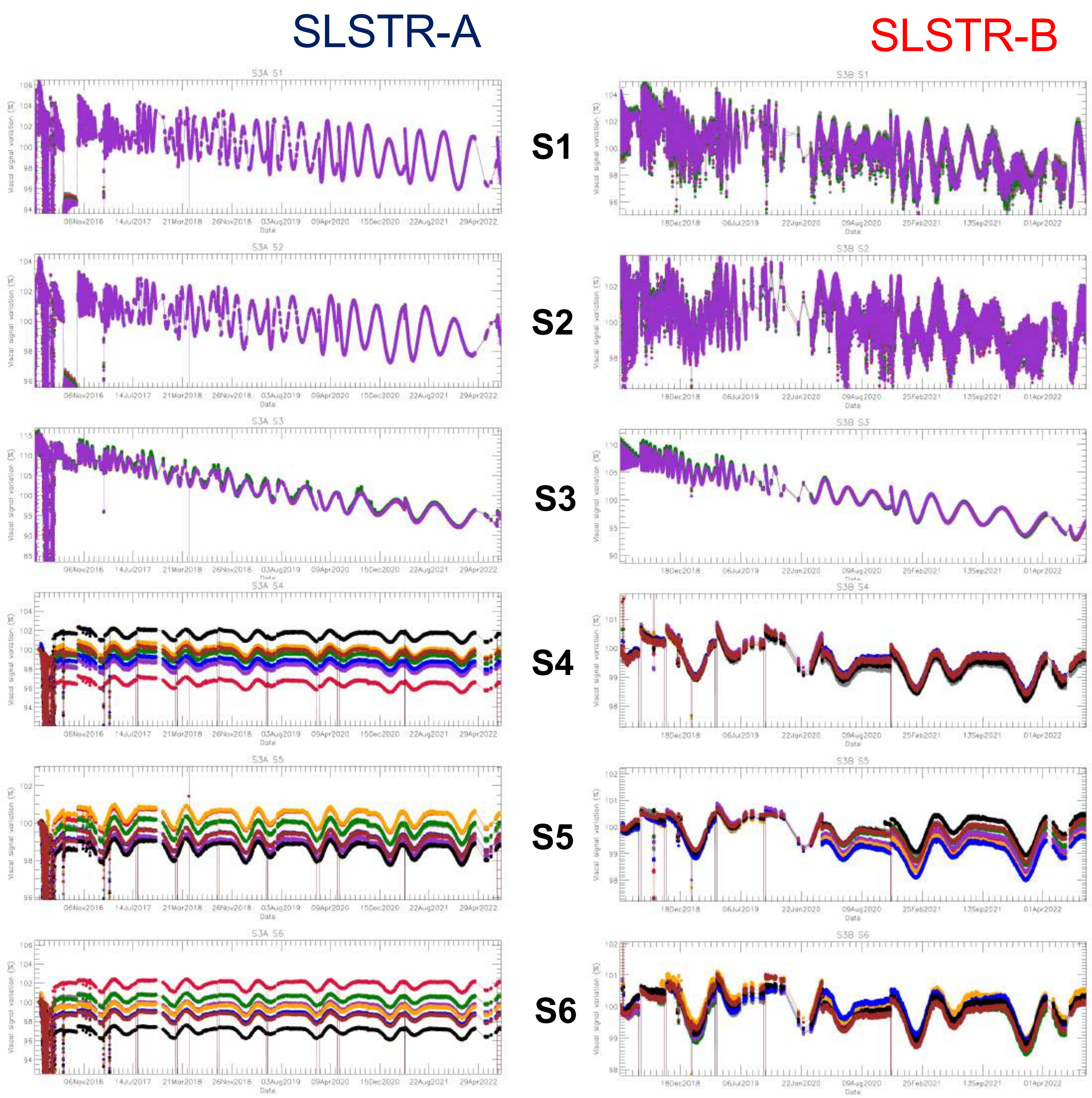
OPT-MPC
Copernicus Sentinel
Optical Mission Performance Cluster

On-Orbit Effects - Gain Variations



Diffuser based VISCAL system is illuminated once per orbit to provide radiometric gain for VIS-SWIR Channels

S1-S3 Affected by build up of water ice on cryogenic optics

S1 & S2 on SLSTR-B exhibits noisy behaviour (ref NC-ESA-COM-00038)

S4-S6 Not affected by water ice – but shows seasonal variation in signal – otherwise stable

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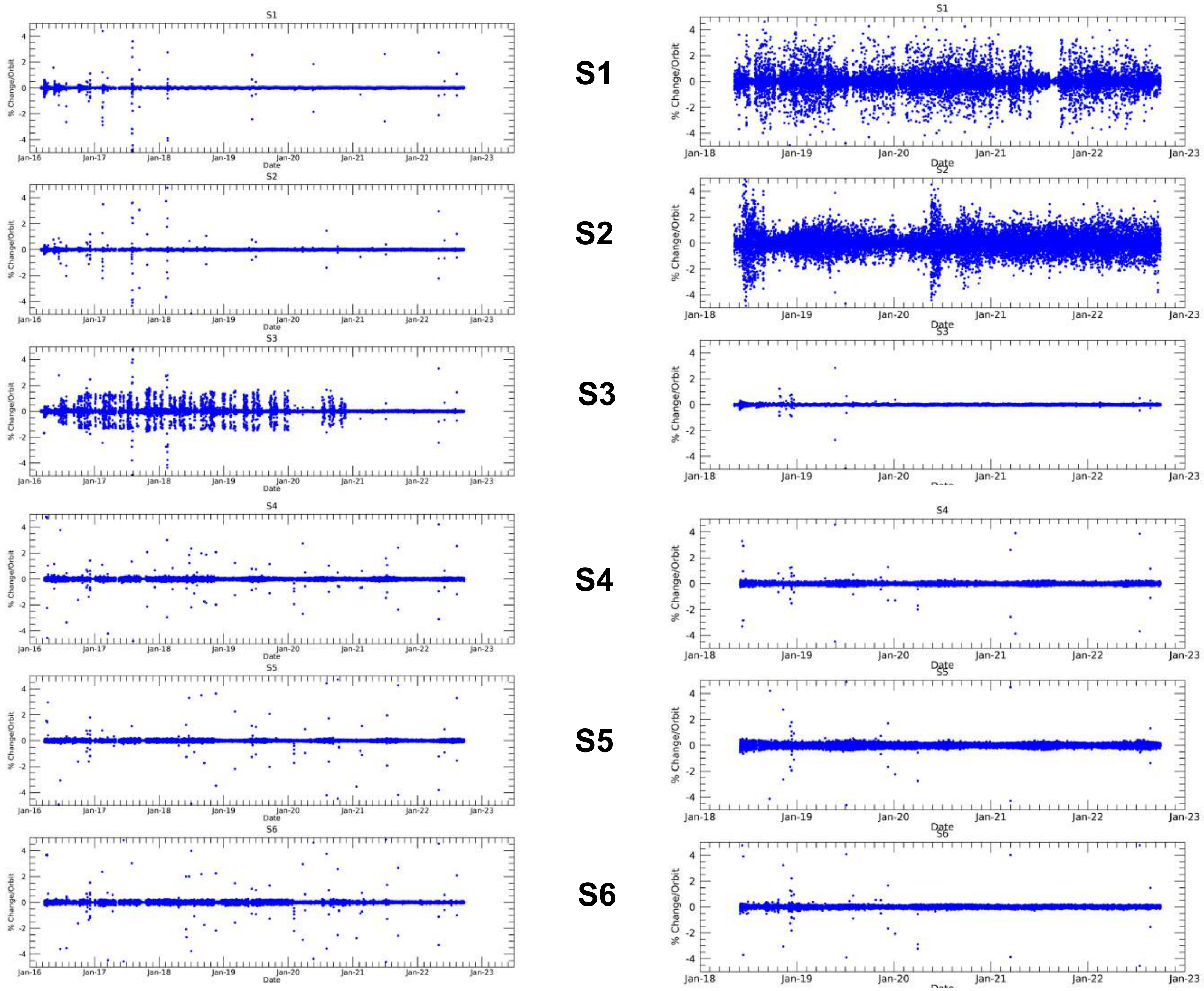
On-Orbit Effects – Orbital Stability

SLSTR-A | SLSTR-B



Using time-series of calibration signals we can estimate orbit-orbit stability of each channel

S1-S3. Water ice build up does not affect orbital stability

S1 & S2 on SLSTR-B is affected by noise signal giving ~ 1% orbital variations (ref NC-ESA-COM-00038)

S3 on SLSTR-A exhibited some periods of noisy behaviour.

S4-S6 show very good orbital stability.

Conclusions

- **Uncertainty analysis for all channels is an on ongoing process as new information arises.**
- **TIR uncertainties in L1 products are consistent with on-orbit analysis – but revised estimates are available**
- **Analysis of VIS/SWIR Uncertainties is in progress**
- **Original uncertainty estimates underestimated effects due to:**
  - Geometric effects, Stability of instrument during measurements, Non-linearity
- **Uncertainty model is being updated to include post launch effects**
  - Orbital stability, Long Term Drift, Detector Noise, Vicarious Calibration Analysis