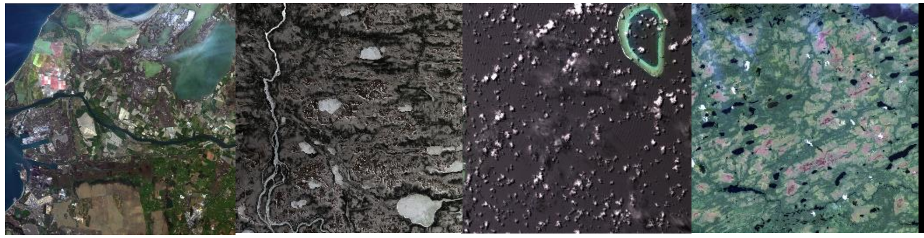

Vicarious Calibration of the DESIS Imaging Spectrometer

Emiliano Carmona[(1)], Kevin Alonso[(1)], Martin Bachmann[(2)], Kara Burch[(5)], Daniele Cerra[(1)], Raquel de los Reyes Lopez[(1)], Uta Heiden[(1)], Uwe Knodt[(3)], David Krutz[(4)], David Marshall[(2)], Rupert Müller[(1)], Mary Pagnutti[(5)], Peter Reinartz[(1)], Robert Ryan[(5)]

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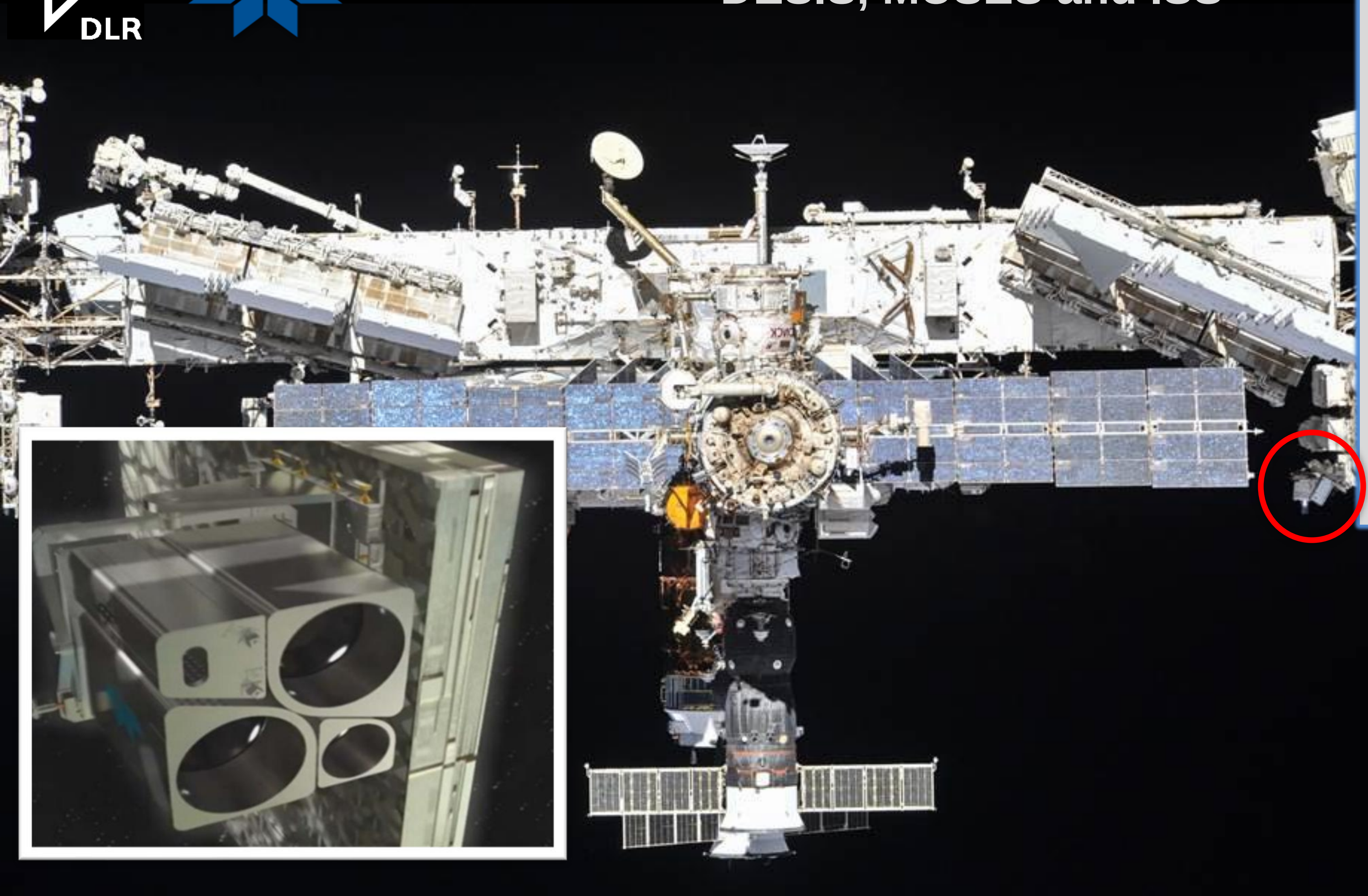
(2) DLR German Aerospace Center, German Remote Sensing Data Center, Oberpfaffenhofen , Germany
(3) DLR German Aerospace Center, DLR Headquaters, Cologne , Germany
(4) DLR German Aerospace Center, Institute of Optical Sensors, Berlin-Adlershof , Germany
(5) I2R Innovative Imaging and Research Corp, Stennis Space Center, USA

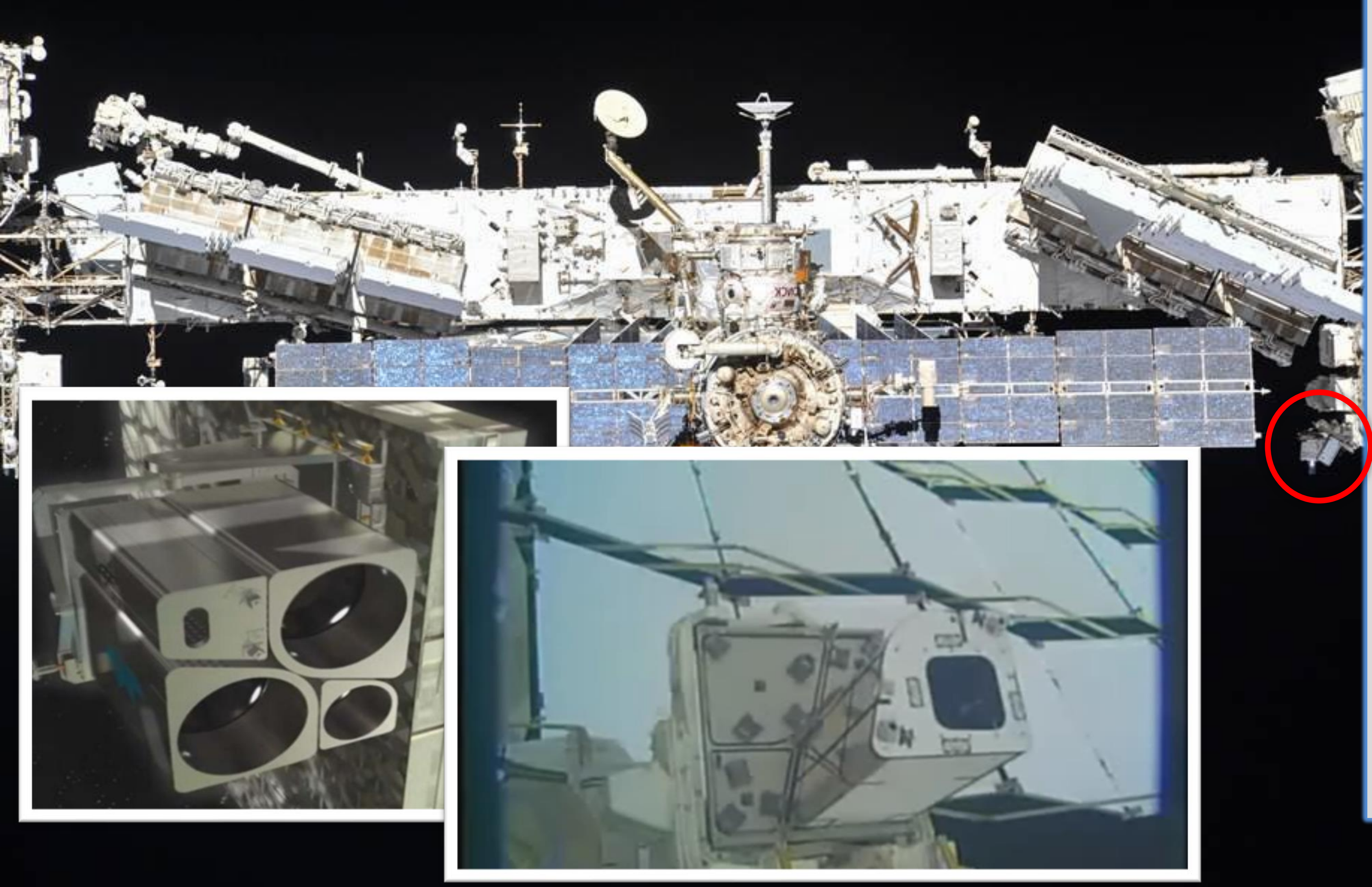
DESIS, MUSES and ISS



Teledyne Brown Engineering (USA) and **DLR** have partnered to build and operate the DLR Earth Sensing Imaging Spectrometer (**DESIS**) from the Teledyne-owned Multi-User System for Earth Sensing (**MUSES**) Platform on the ISS

MUSES provides accommodations for two large and two small hosted payloads and provides **core services** for the instruments

DESIS, MUSES and ISS



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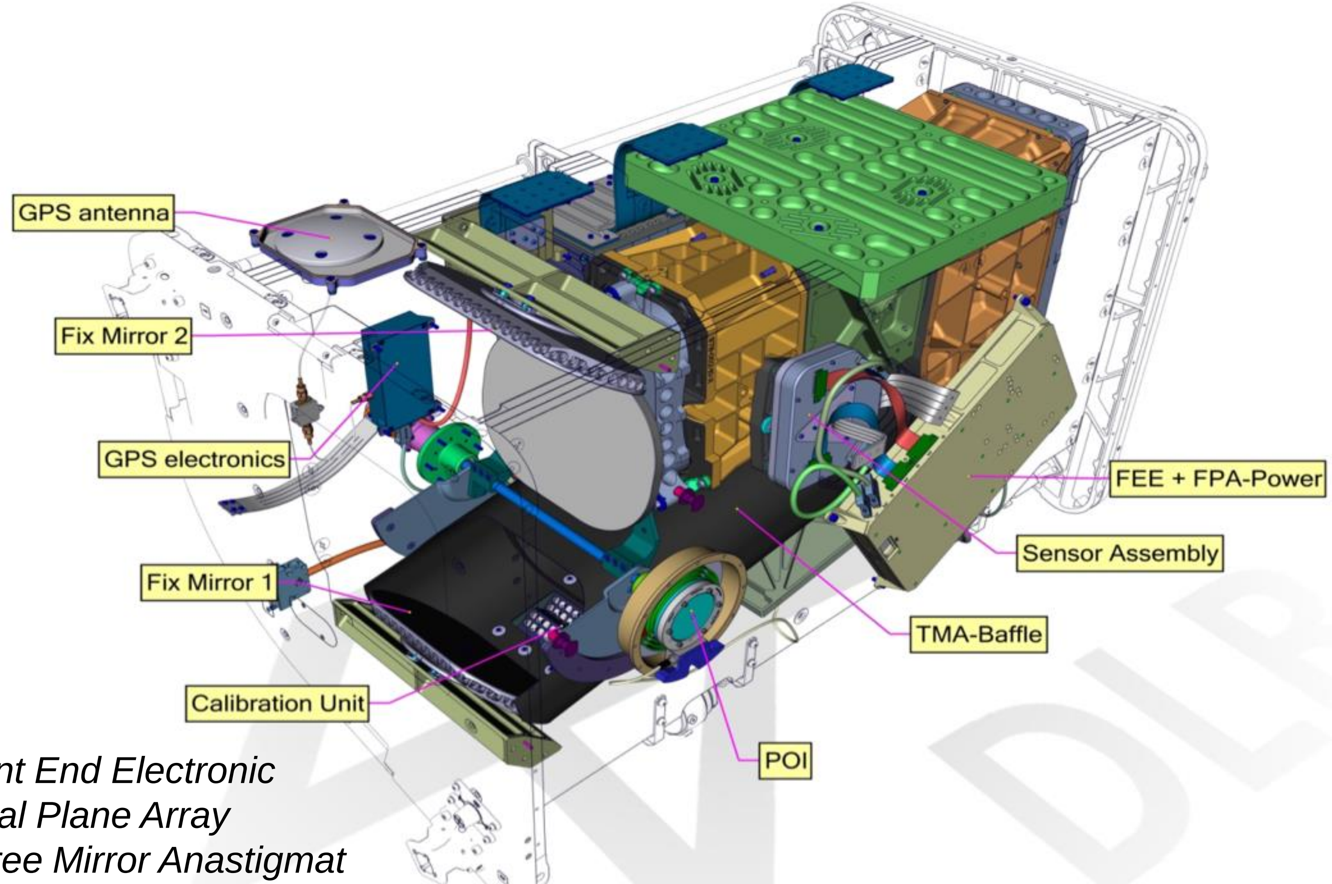
DESIS, the hyperspectral sensor developed by DLR, is currently the first payload of MUSES.

DLR also established the Ground Segment and licensed the SW processors to Teledyne running in an Amazon Cloud

DESIS Instrument

- Hyperspectral instrument consisting of a Three-Mirror-Anastigmat (TMA) telescope combined with an Offner-type spectrometer



FEE: *Front End Electronic*
FPA: *Focal Plane Array*
TMA: *Three Mirror Anastigmat*
POI: *Pointing Unit*

Sensors 2019, 19(7), 1622; https://doi.org/10.3390/s19071622

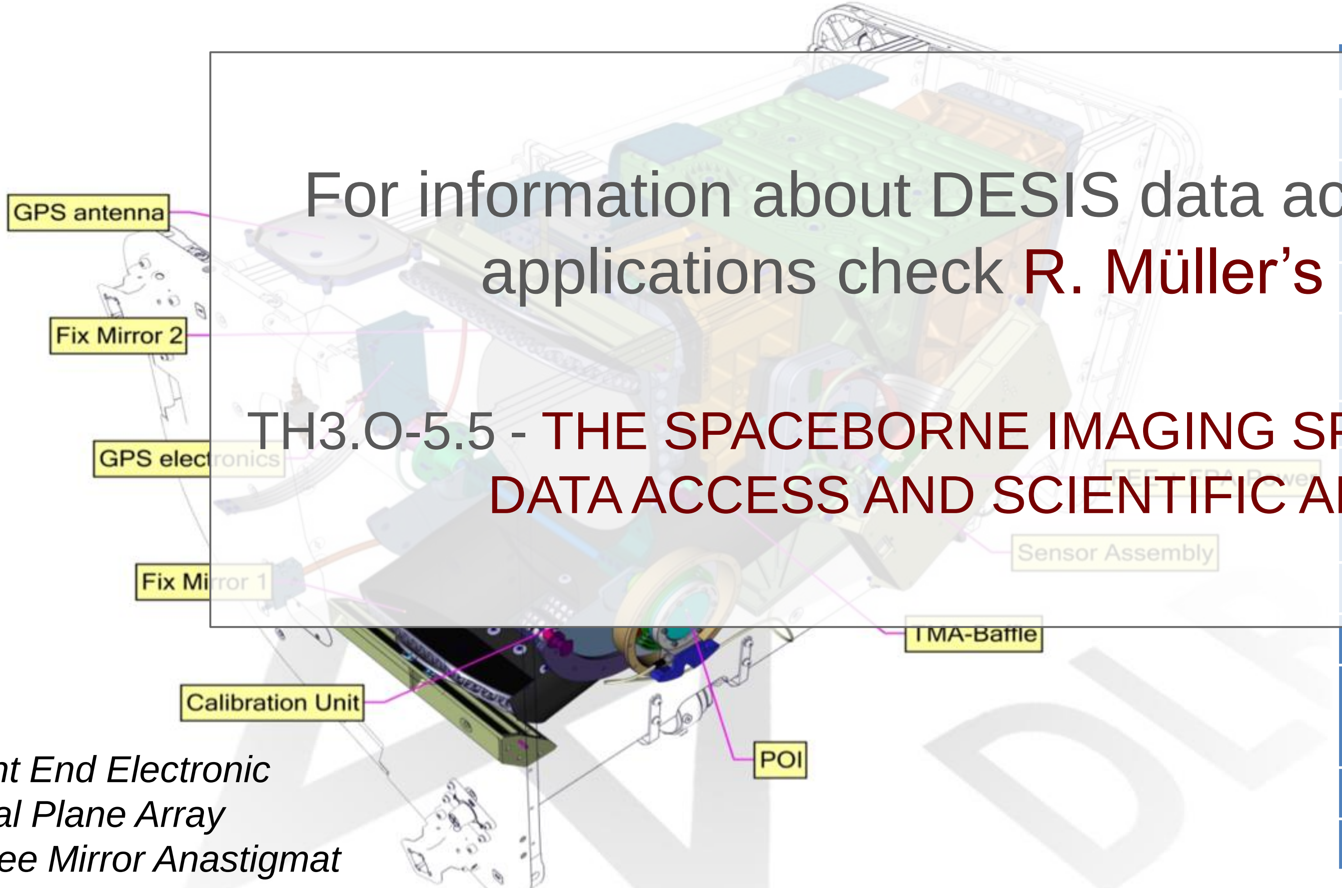
Mission Instrument	MUSES/DESIS
Target lifetime	2018-2023
Off-nadir tilting (across-track, along-track)	-45° (backboard) to +5° (starboard), -40° to +40° (by MUSES and DESIS)
Spectral range	400 nm to 1000 nm
Spectral Sampling (res., acc.,bands)	2.55 nm, 0.5 nm, 235 bands. Binning: 118 , 79 , 60 bands
Spectral response	Gaussian shape, 3.5 nm FWHM
Software Binning (sampling distance, number bands)	Binning 2 (5.1 nm, 118 bands) Binning 3 (7.6 nm, 79 bands) Binning 4 (10.1 nm, 60 bands)
Radiometry (res., acc.)	13 bits, ~10%
Spatial (res., swath)	30 m, 30 km (@ 400 km)
SNR (signal-to-noise)	195 (w/o bin.) / 386 (4 bin.) @ 550 nm
Instrument (mass)	93 kg
Capacity (km, storage)	2360 km per day, 225 GBit

DESIS Instrument

- Hyperspectral instrument consisting of a Three-Mirror-Anastigmat (TMA) telescope combined with an Offner-type spectrometer

For information about DESIS data access and scientific applications check R. Müller's contribution:

TH3.O-5.5 - THE SPACEBORNE IMAGING SPECTROMETER DESIS: DATA ACCESS AND SCIENTIFIC APPLICATIONS



Mission Instrument	MUSES/DESIS
Target lifetime	2018-2023
Off-nadir tilting (across-track, along-track)	-15° (backboard) to +5° (starboard), -40° to +40° (by MUSES and DESIS)
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Spectral Sampling (res., acc.,bands)	2.55 nm, 0.5 nm, 235 bands. Binning: 118 , 79 , 60 bands
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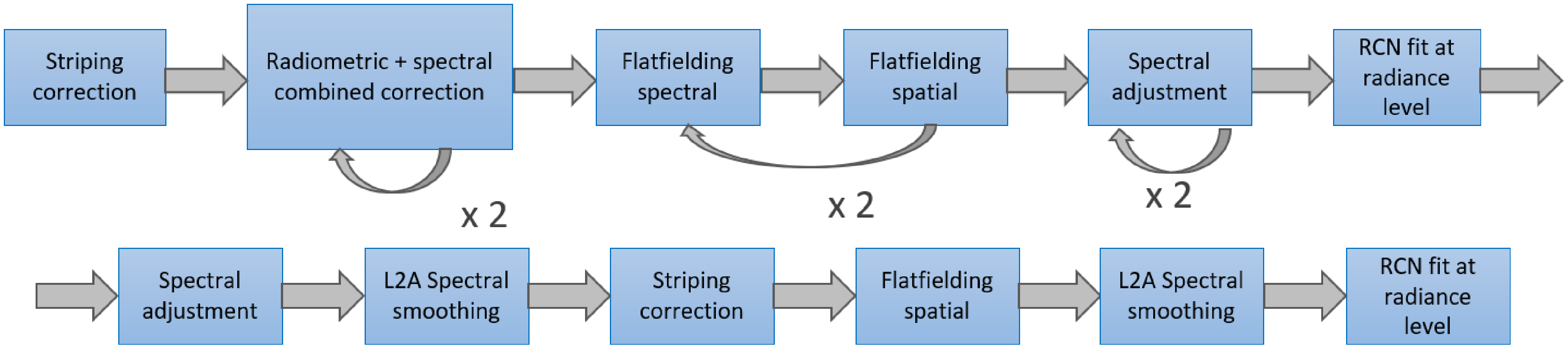
DESIS Instrument Calibration Concept

- Based on Vicarious Calibration obtained from images acquired over the instrument lifetime to update the pre-flight (laboratory) calibration
- Vicarious calibration supported by on-board calibration unit measurements (spectral)
- Main goal is to update radiometric calibration coefficients, when possible, with small adjustments on central wavelengths
- Not an easy task, among other difficulties:
  - Need to update 240640 radiometric coefficients (235 bands × 1024 spatial pixels)
  - Limited number of suitable images for calibration (not a mapping mission)
  - Very limited number of reference calibration data (currently based on RadCalNet sites)
  - Deal with Instrument effects (manufacturing defects, rolling shutter, smile, etaloning)

Vicarious calibration concept

- Two main goals:
  1. consistent relative response in spatial and spectral direction:
     - Flat response on homogenous input
     - Smooth pixel to pixel transitions
     - Consistent behavior across-track
  2. Correct absolute radiance scale
- Use a sequence of configurable steps to achieve both goals:



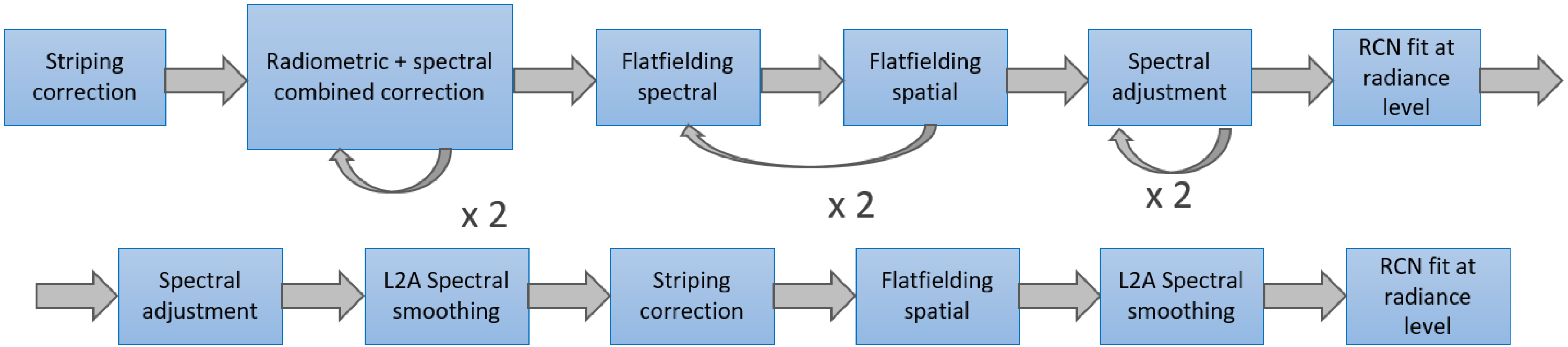
- Original sequence of steps followed on first ground-to-space calibration. Newer calibration updates require simpler sequences

Vicarious calibration concept

- Two main goals:
  1. consistent relative response in spatial and spectral direction:
     - Flat response on homogenous input
     - Smooth pixel to pixel transitions
     - Consistent behavior across-track
  2. Correct absolute radiance scale
- Use a sequence of configurable steps to achieve two goals:

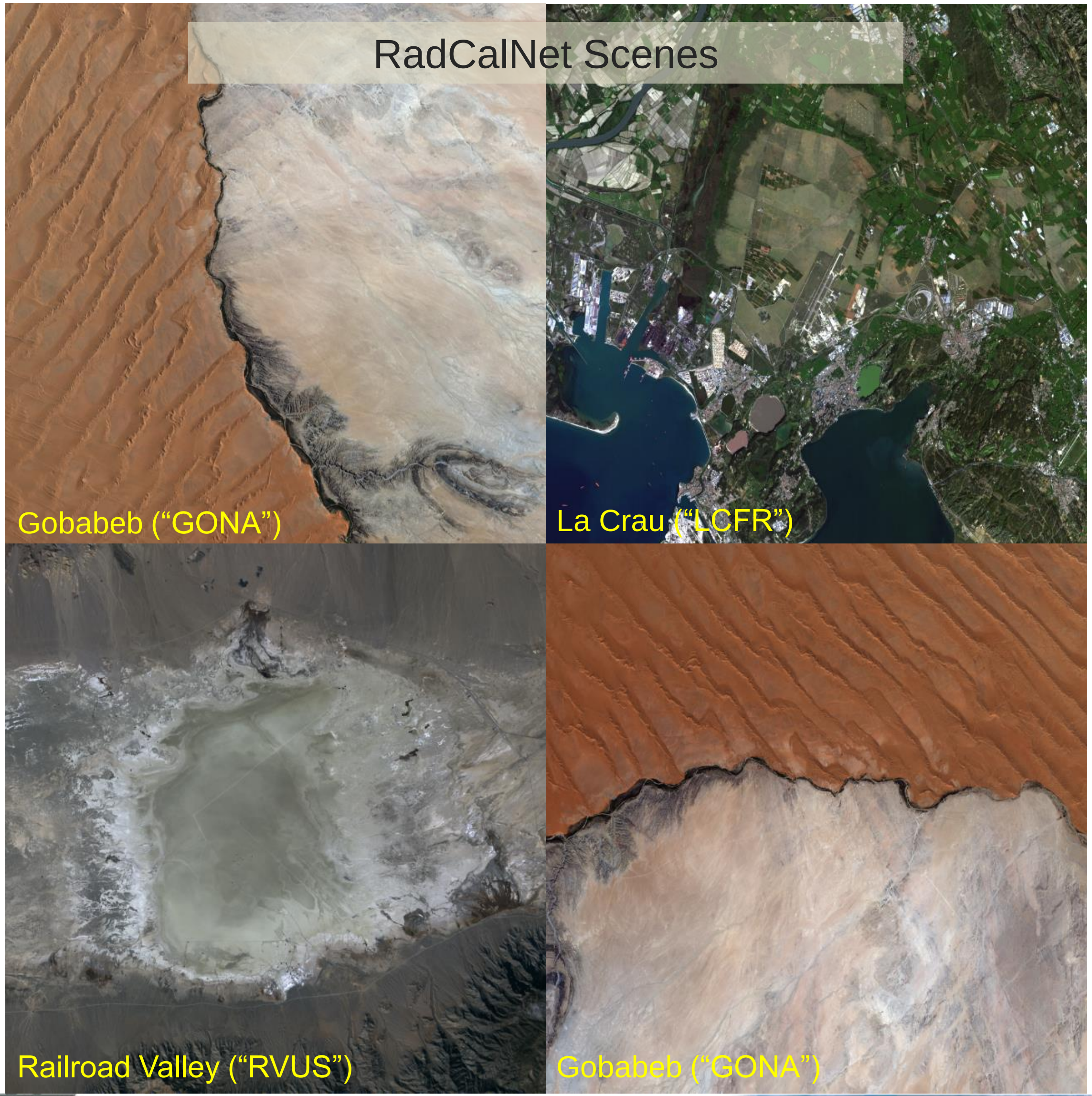
Data → Images over uniform areas (e.g. PICS)

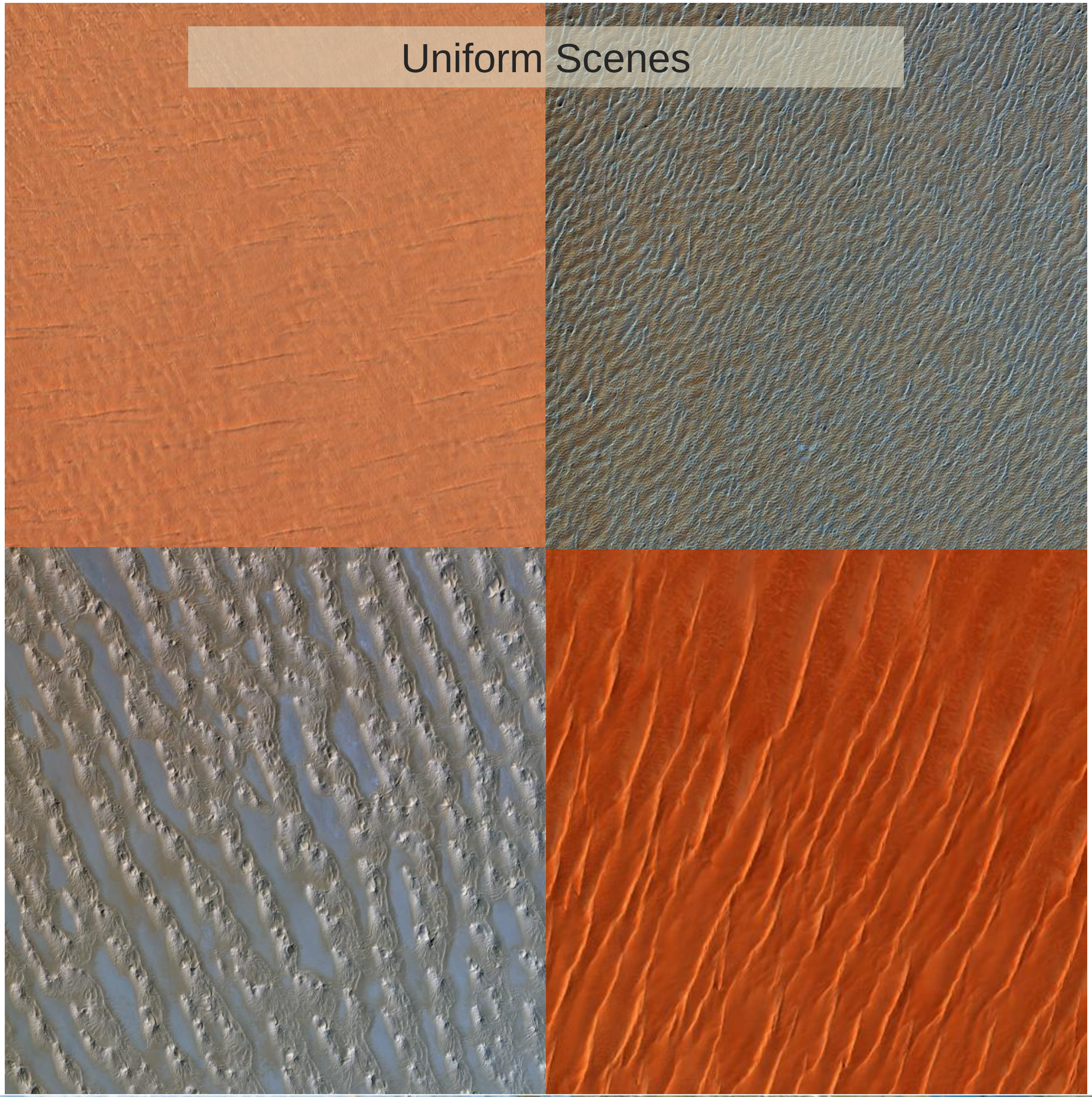
Data → Images over RadCalNet (RCN) calibration sites



- Original sequence of steps followed on first ground-to-space calibration. Newer calibration updates require simpler sequences

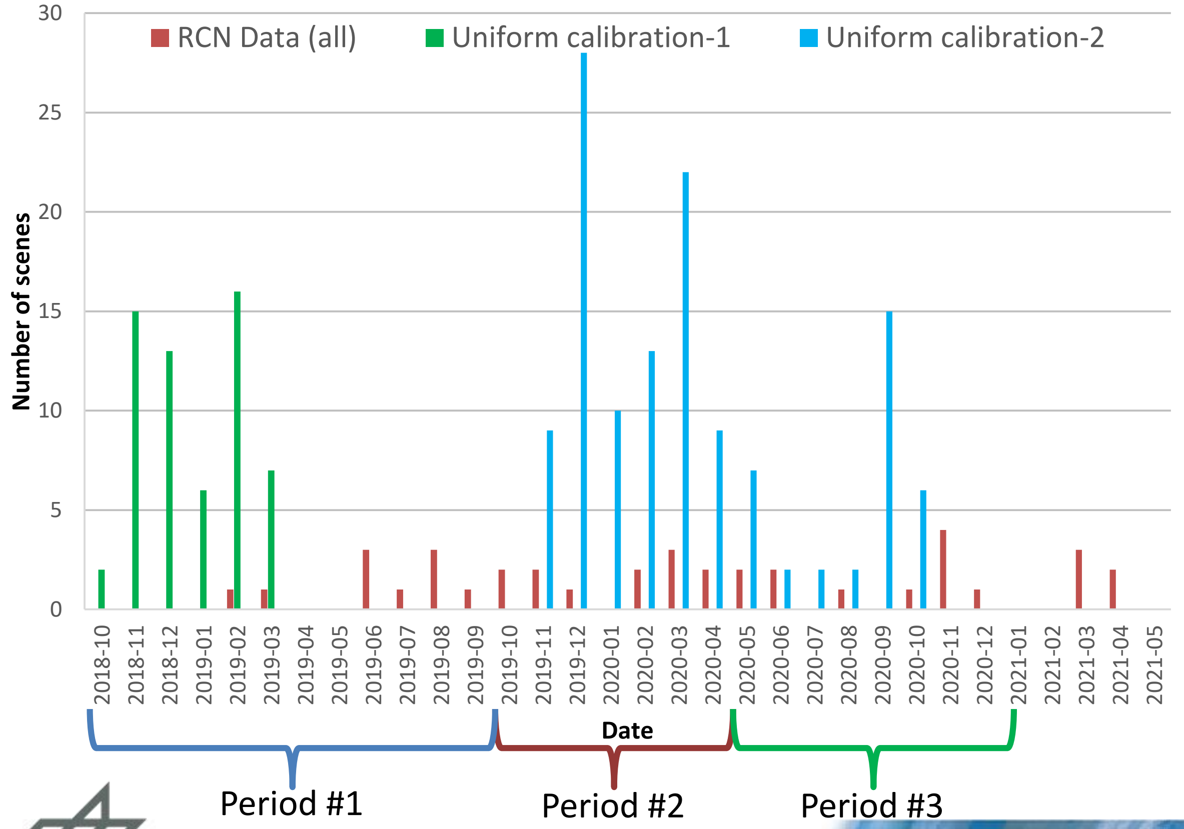
Vicarious calibration Input data

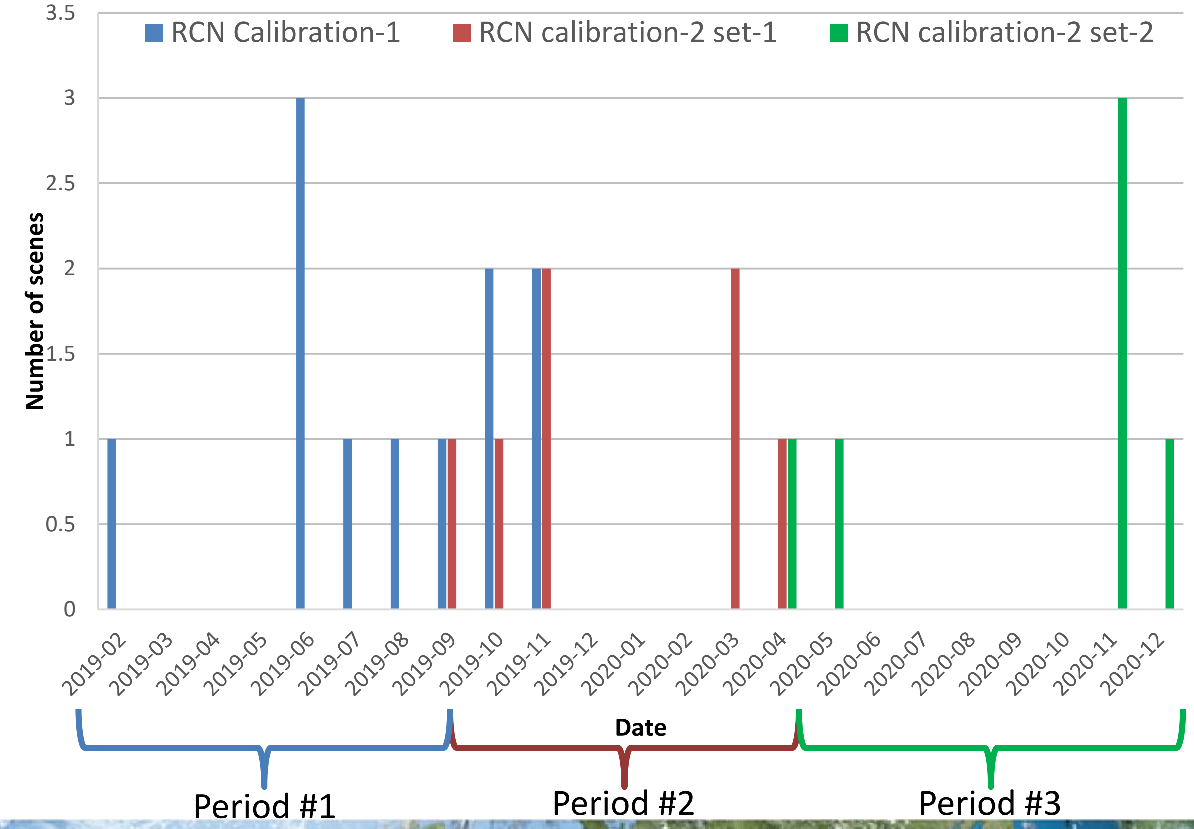




Vicarious calibration Input data

- Input scenes not evenly distributed in time
- Particularly challenging to have abundant good quality RCN scenes
- Calibration updates arrive several months after data acquisition



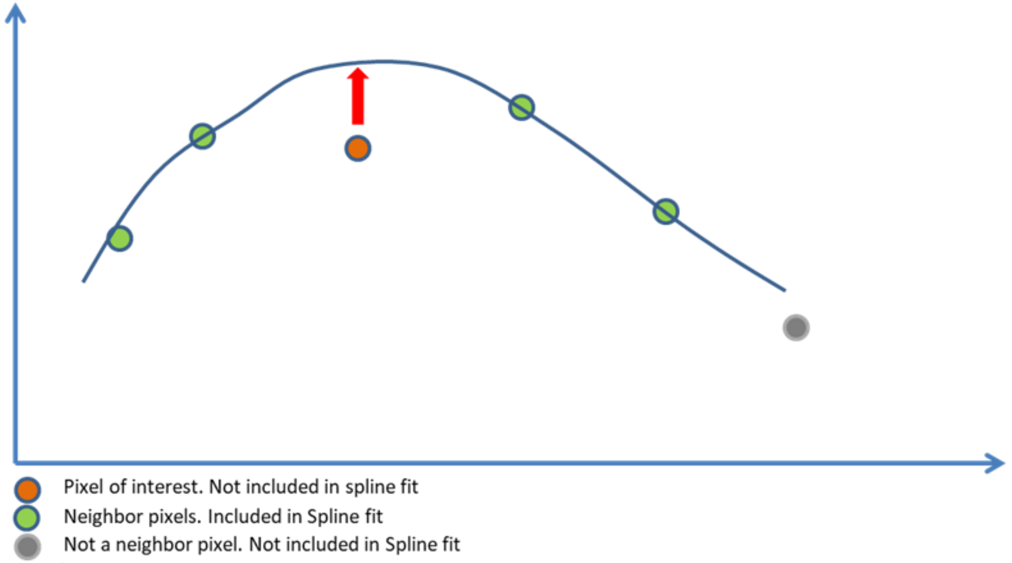


Correction Steps I: Radiometric adjustments

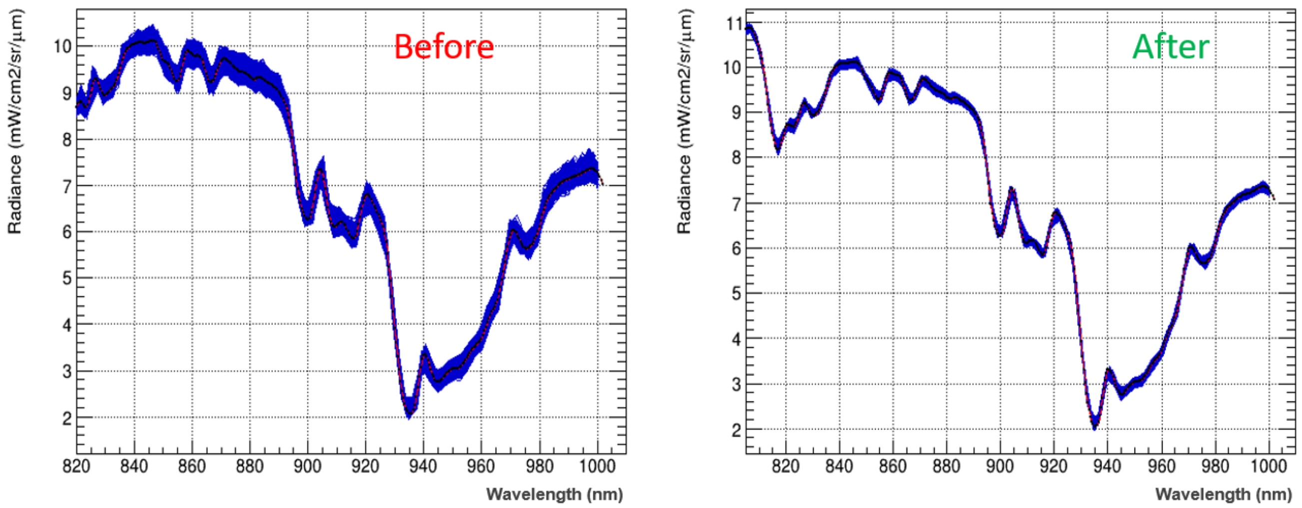
- Most steps performed with uniform scenes with L1B products averaged in the along-track direction
  - 235 bands × 1024 spatial pixels

- Most corrections are performed after smile correction (confusion of spectral and radiometric corrections)

- **Striping correction**: Compute adjustment to radiometric coefficient using spline fits. Use iterative process until convergence

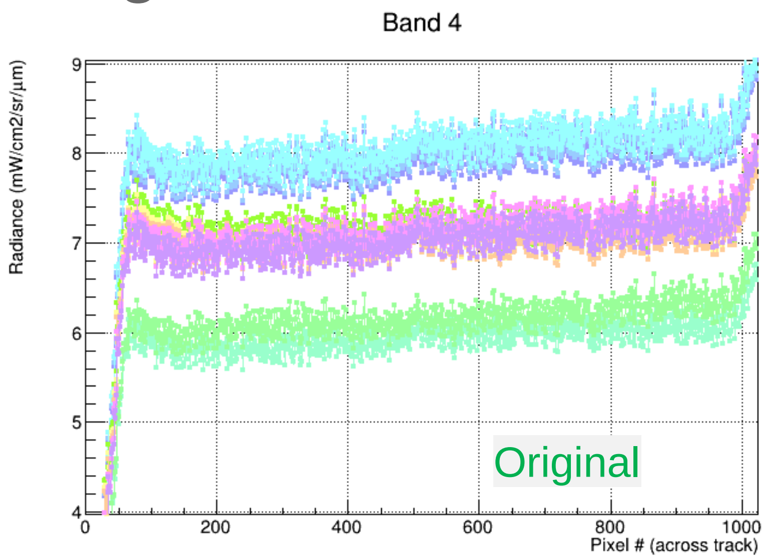


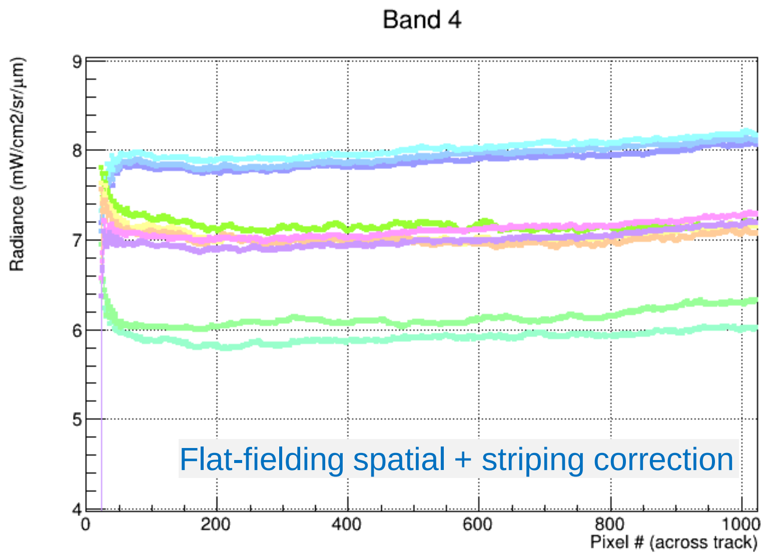
- **Rad./Spc. correction**: Use all pixels across track in one single spectrum. Compute minimum deviation to common spectrum



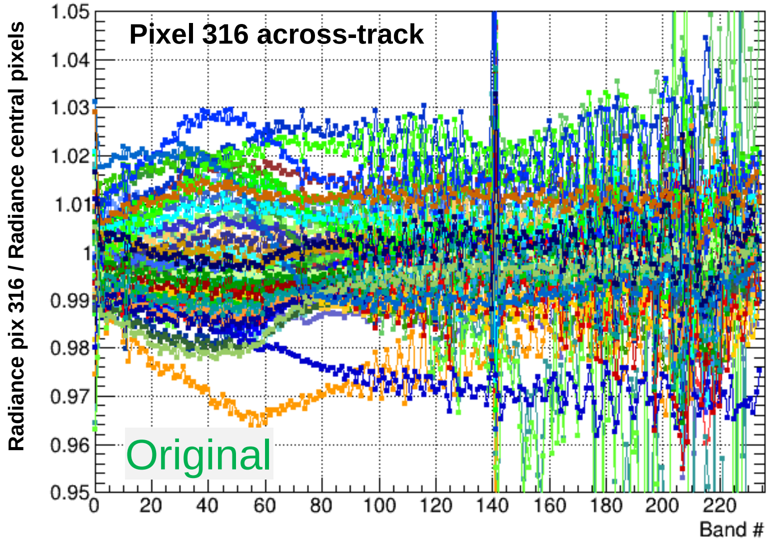
Correction Steps II: Flat-fielding

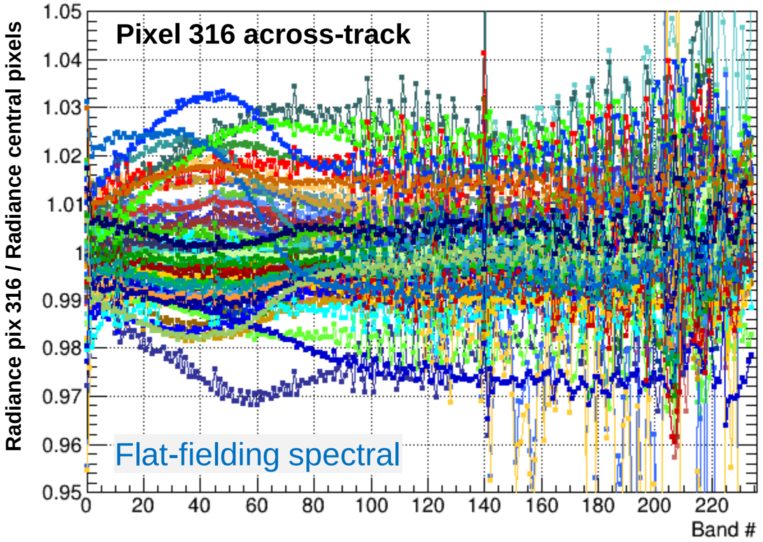
- **Flat-fielding spatial**: In homogeneous scenes all pixels across-track shall have the same value within a band





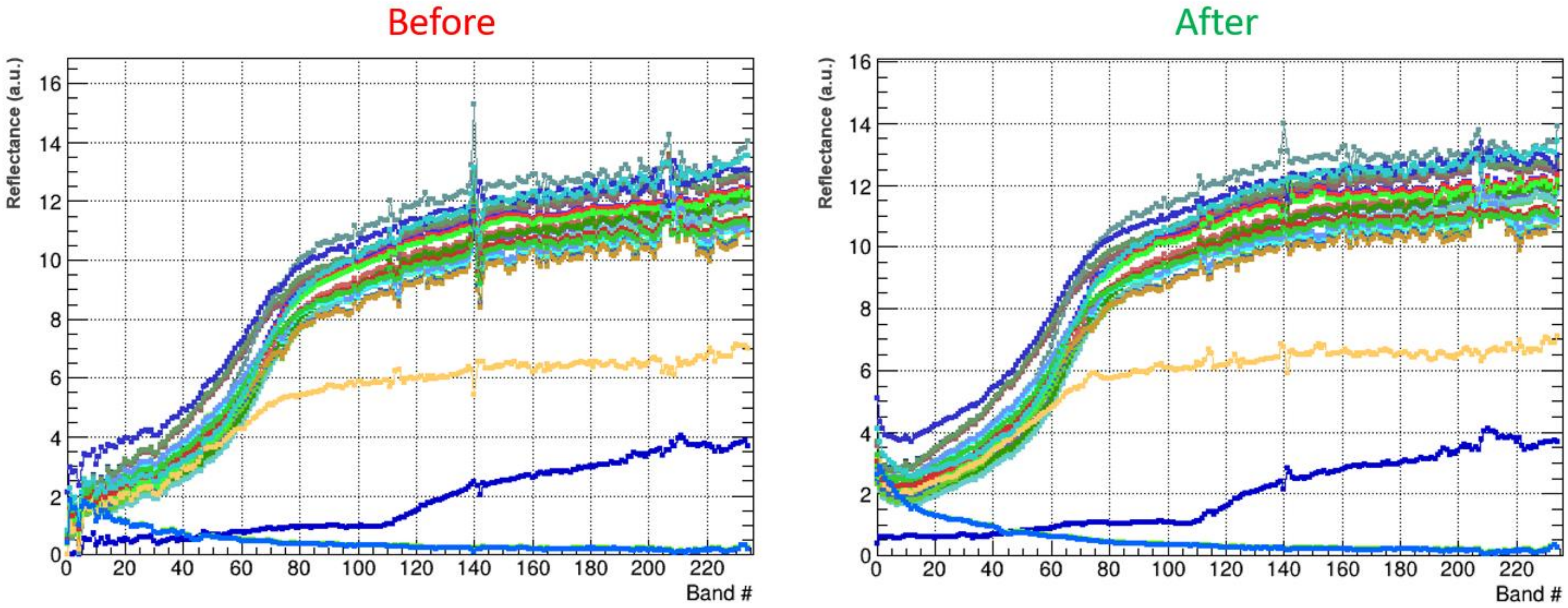
- **Flat-fielding spectral**: In homogeneous scenes all across-track pixels shall deliver the same spectra as the central pixels





Correction Steps III: L2A spectral smoothing

- Fine tuning of individual pixels radiometric factors obtained using L2A data to avoid atmospheric features
- Compute correction to minimize pixel to pixel fluctuations. Effect visible at lower wavelengths. Fluctuations at larger wavelengths dominated by spectral calibration errors and etaloning/fringing effect in the detector

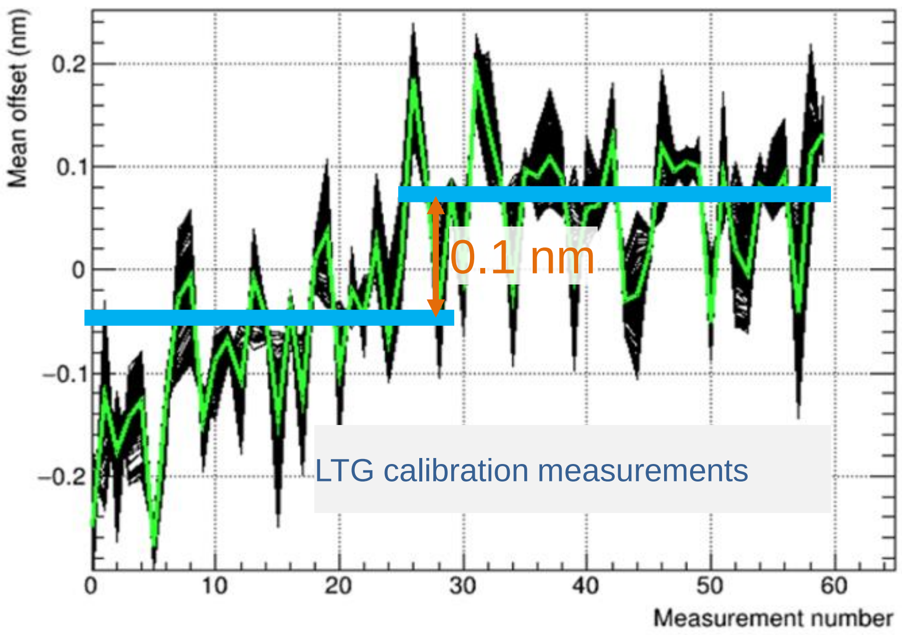


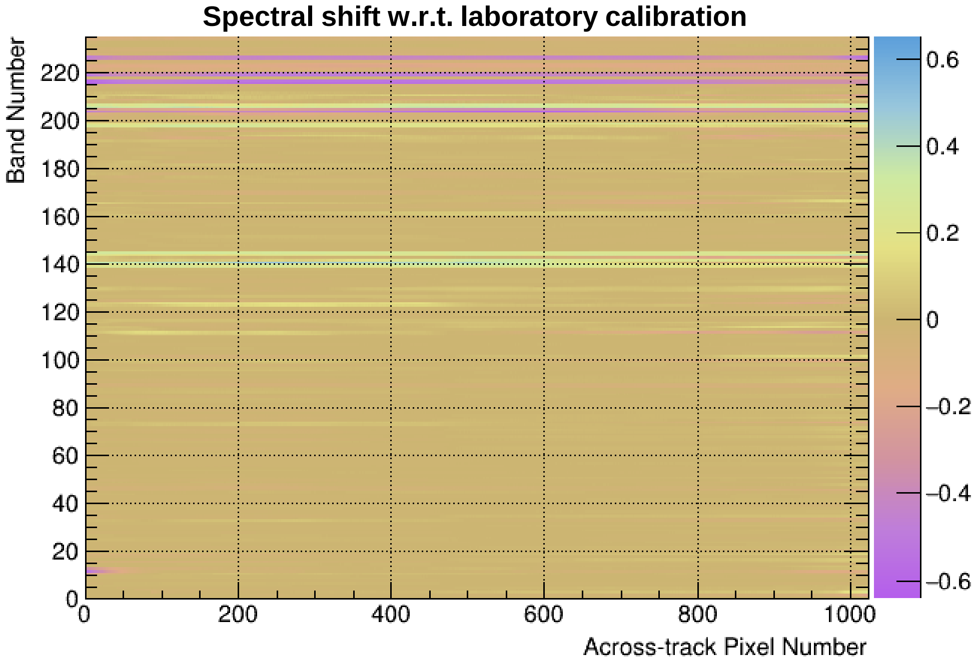
Correction Steps IV: Spectral adjustment vicarious

- Spectral calibration very difficult to obtain in-flight. Only small adjustments on central wavelengths possible

- **Global shift**: based on LED calibration measurements. Change of trend in September 2019. More stable since then. 0.10 nm shift included in calibration update

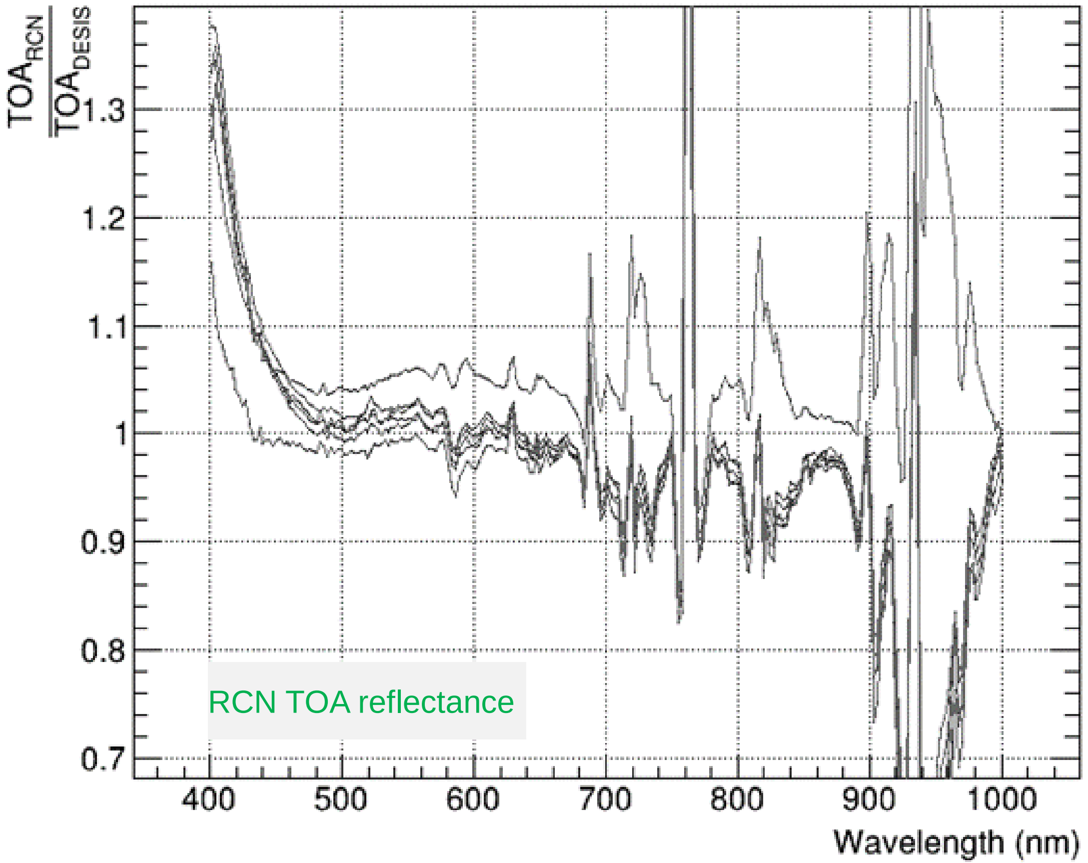
- **Spectral adjustment**: Certain L2A spectral features after calibration can only be fixed adjusting central wavelengths (around strong atmospheric absorption features)

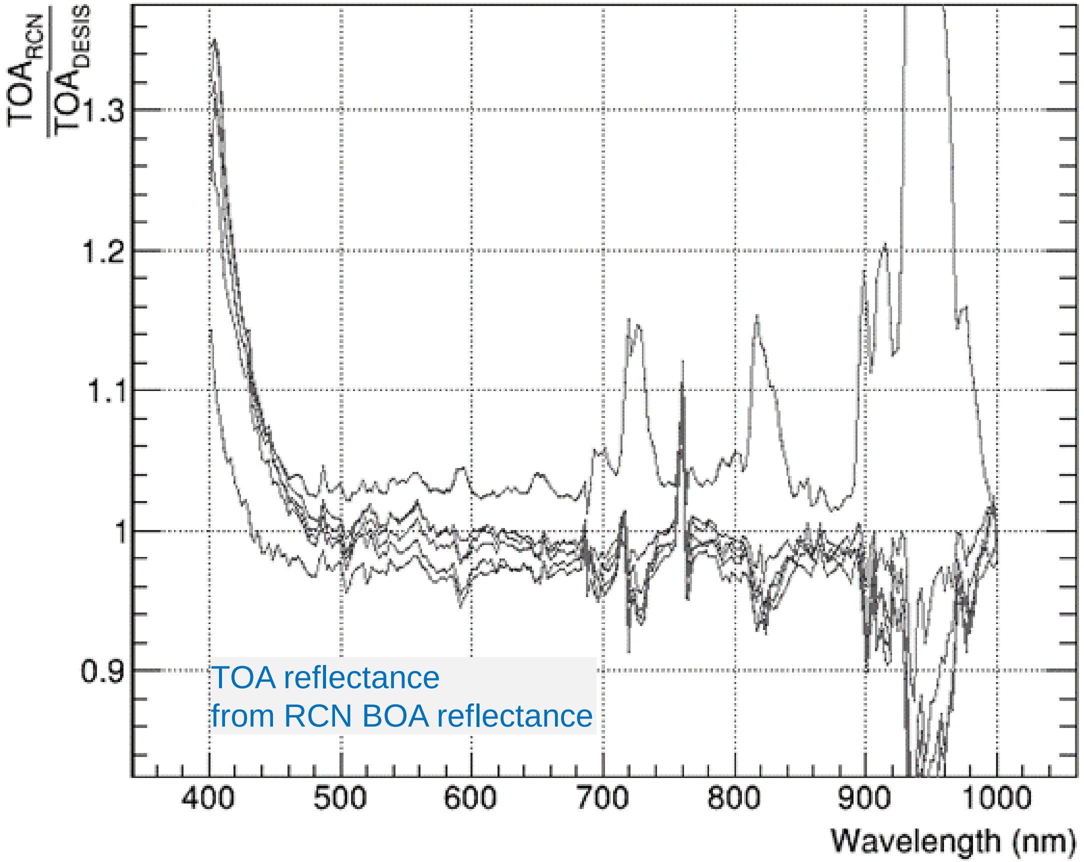




Absolute radiometric scale

- Use selected "calibration" scenes from RCN and perform a fit to mean value (2 times in steps sequence) in order to obtain a per-band factor
- Use Average from 2 TOA reference data: RCN provided (10 nm), from RCN BOA calculated (DESIS resolution)





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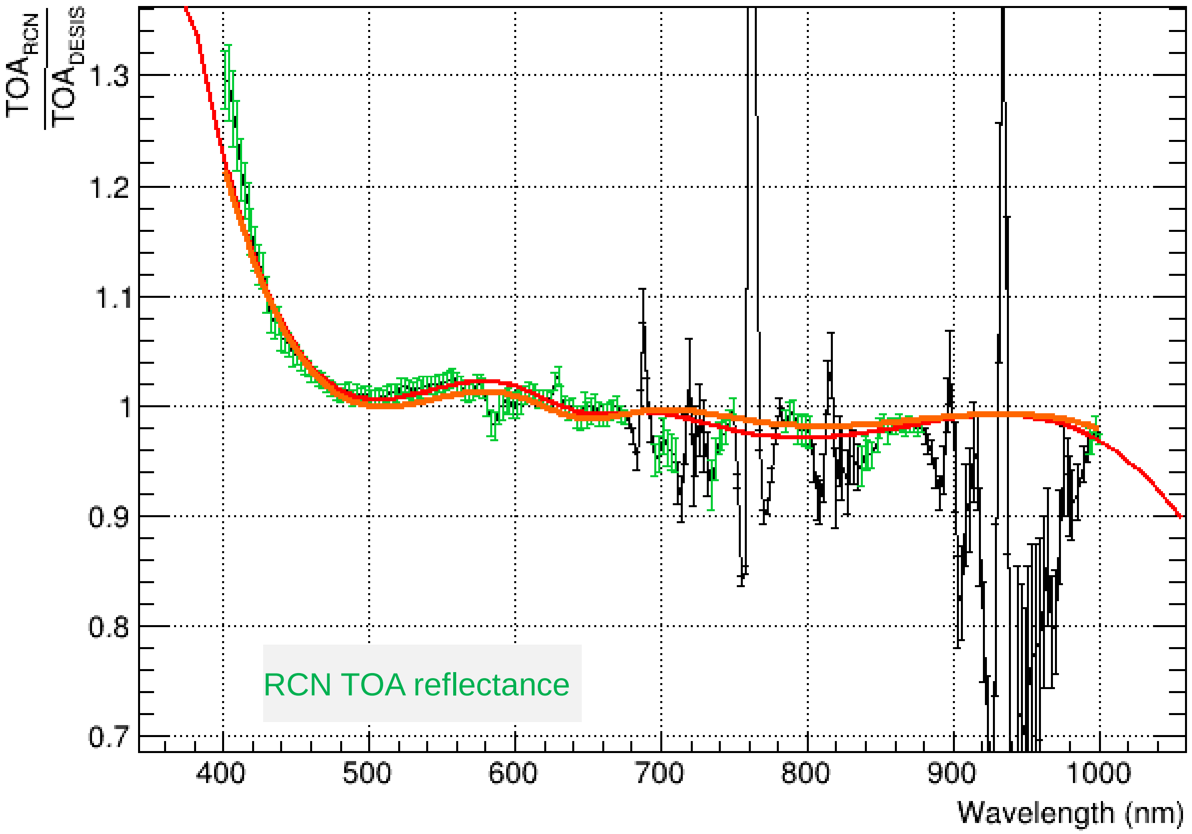
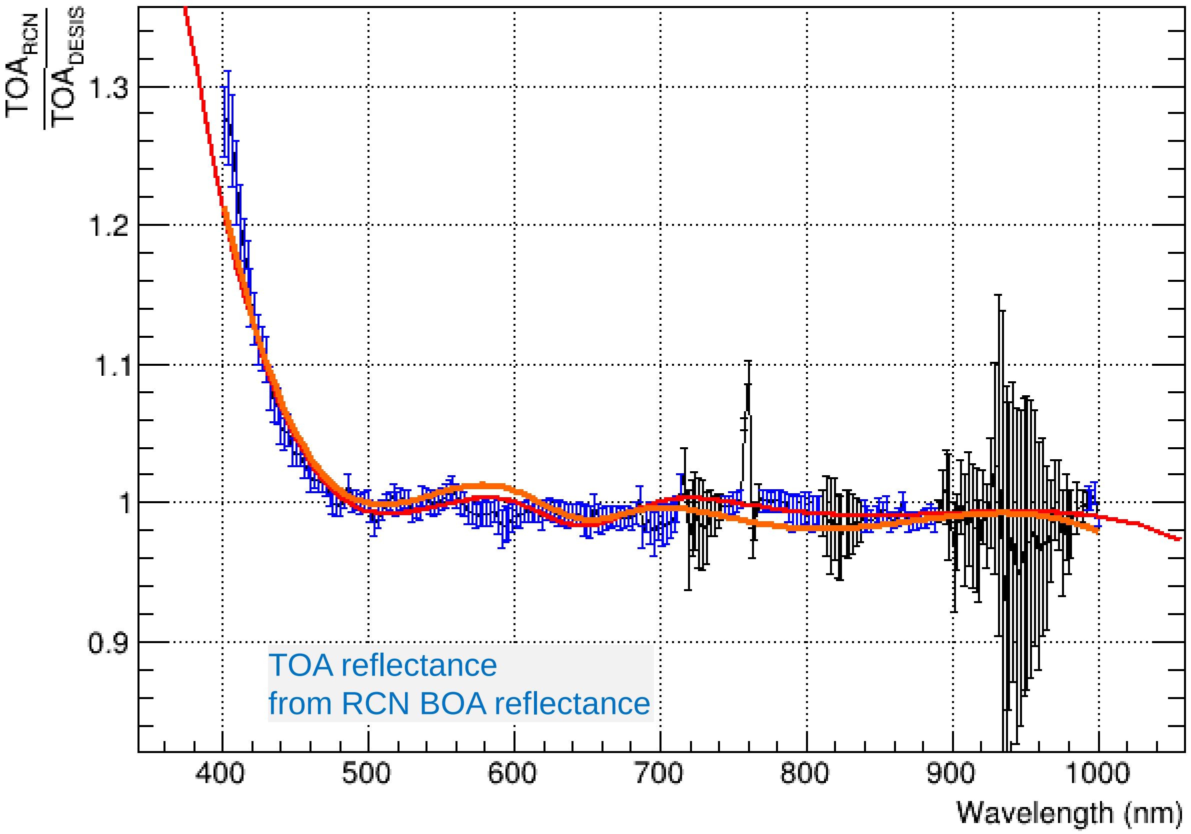
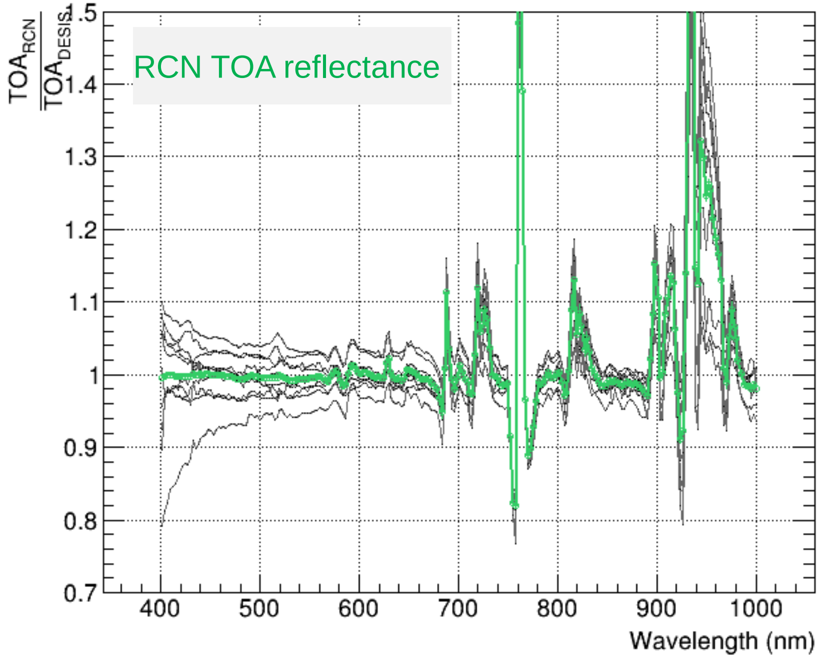
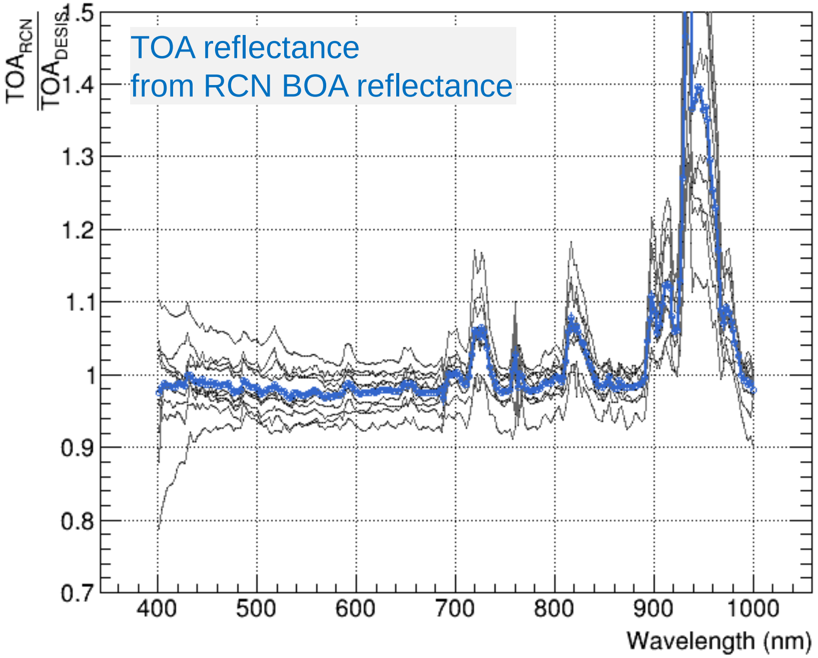


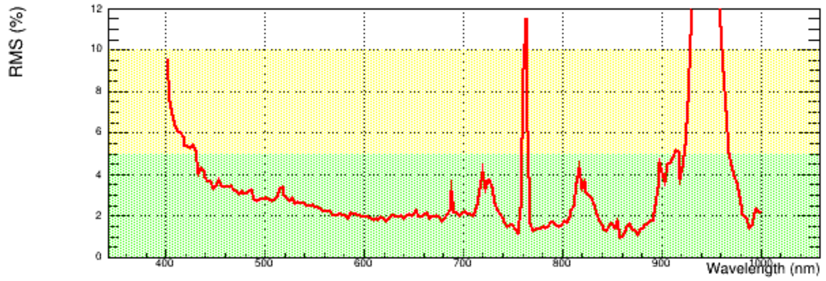


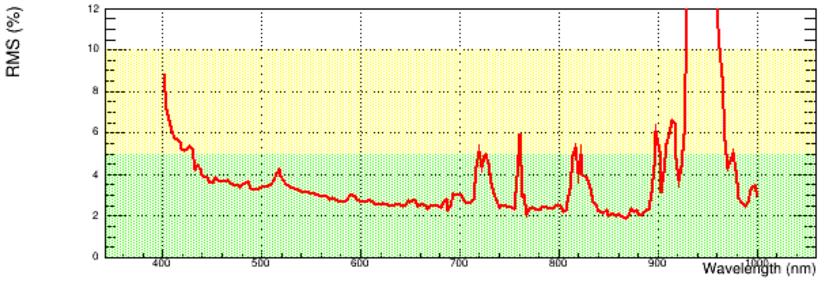
Results First Vicarious calibration (2018-10 – 2019-09)

- 11 RCN scenes used for absolute calibration (3 RVUS, 8 GONA)
- Mean bias after calibration <~2% (w.r.t. RCN)
- RMS after calibration <3% (above 500 nm)





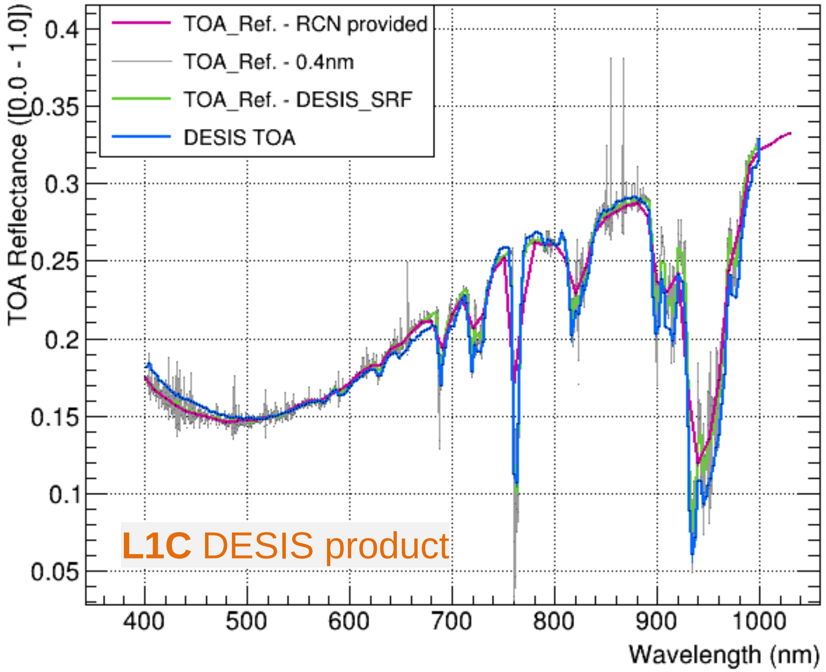


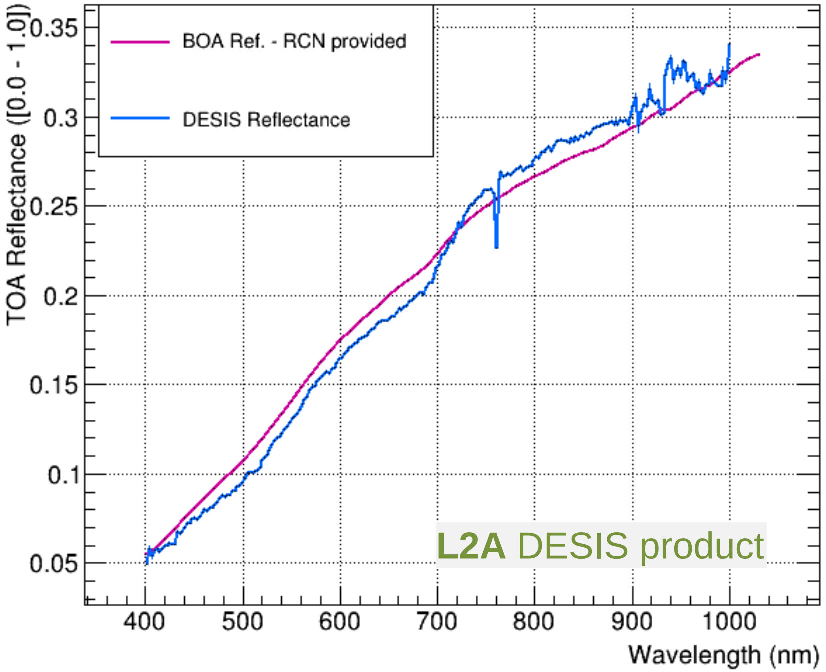


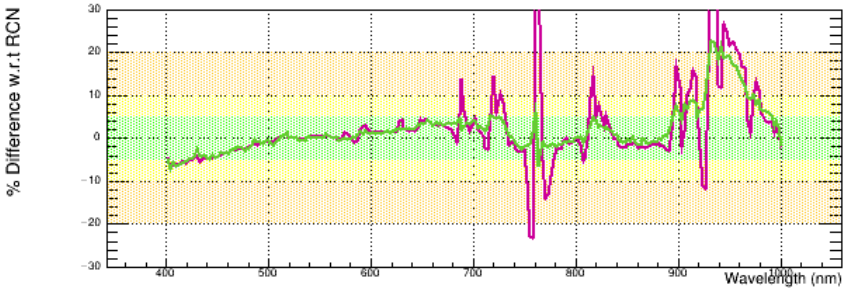
DLR

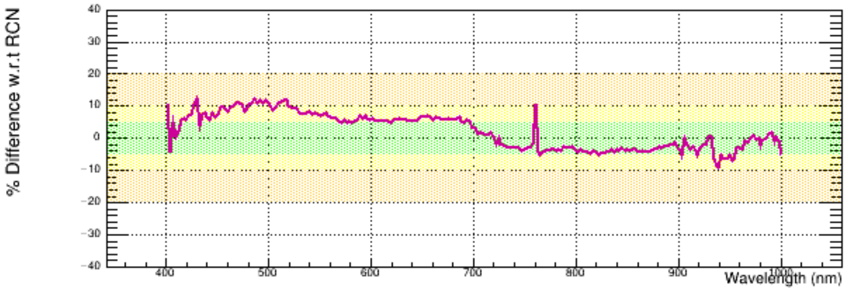
Results First Vicarious calibration (2018-10 – 2019-09)

- Crosscheck using independent scene from RCN LCFR
  - TOA reflectance (left, 2 references)
  - BOA reflectance (right, 1 reference)







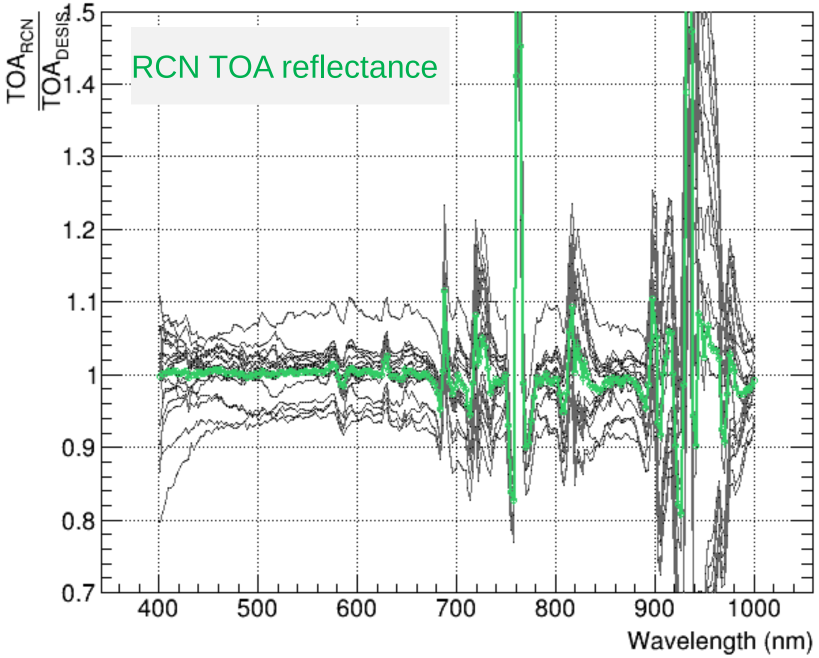


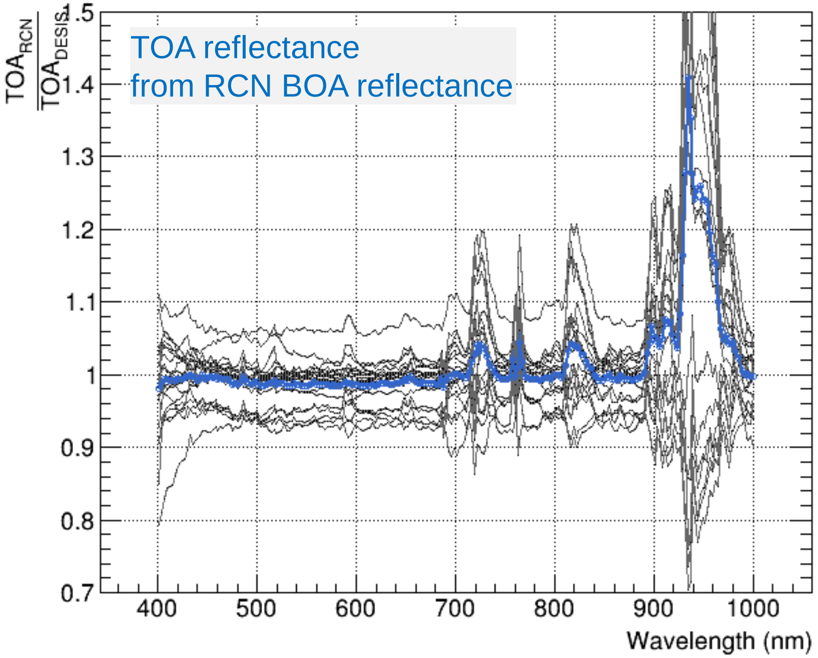
Results from 3 calibration periods: All RCN Data Results

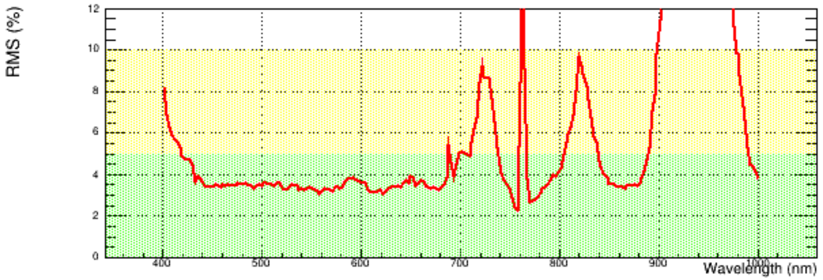
- Absolute calibration adjusted with RCN data for 3 different periods

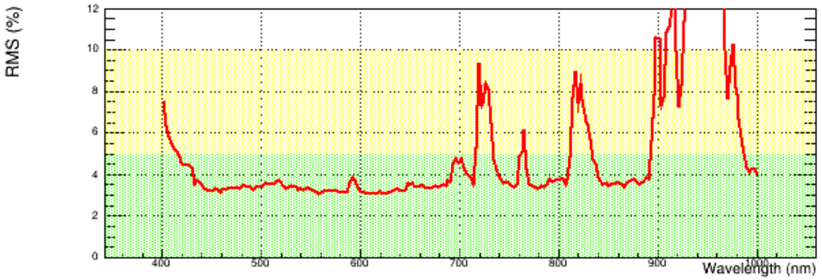
- Absolute calibration uses only part of RCN scenes (19)
    - good atmospheric conditions
    - below 50 degrees Sun Zenith Angle

- These summary plots show **19** RCN scenes used for calibration









Results from 3 calibration periods: All RCN Data Results

- Absolute calibration adjusted with RCN data for 3 different periods
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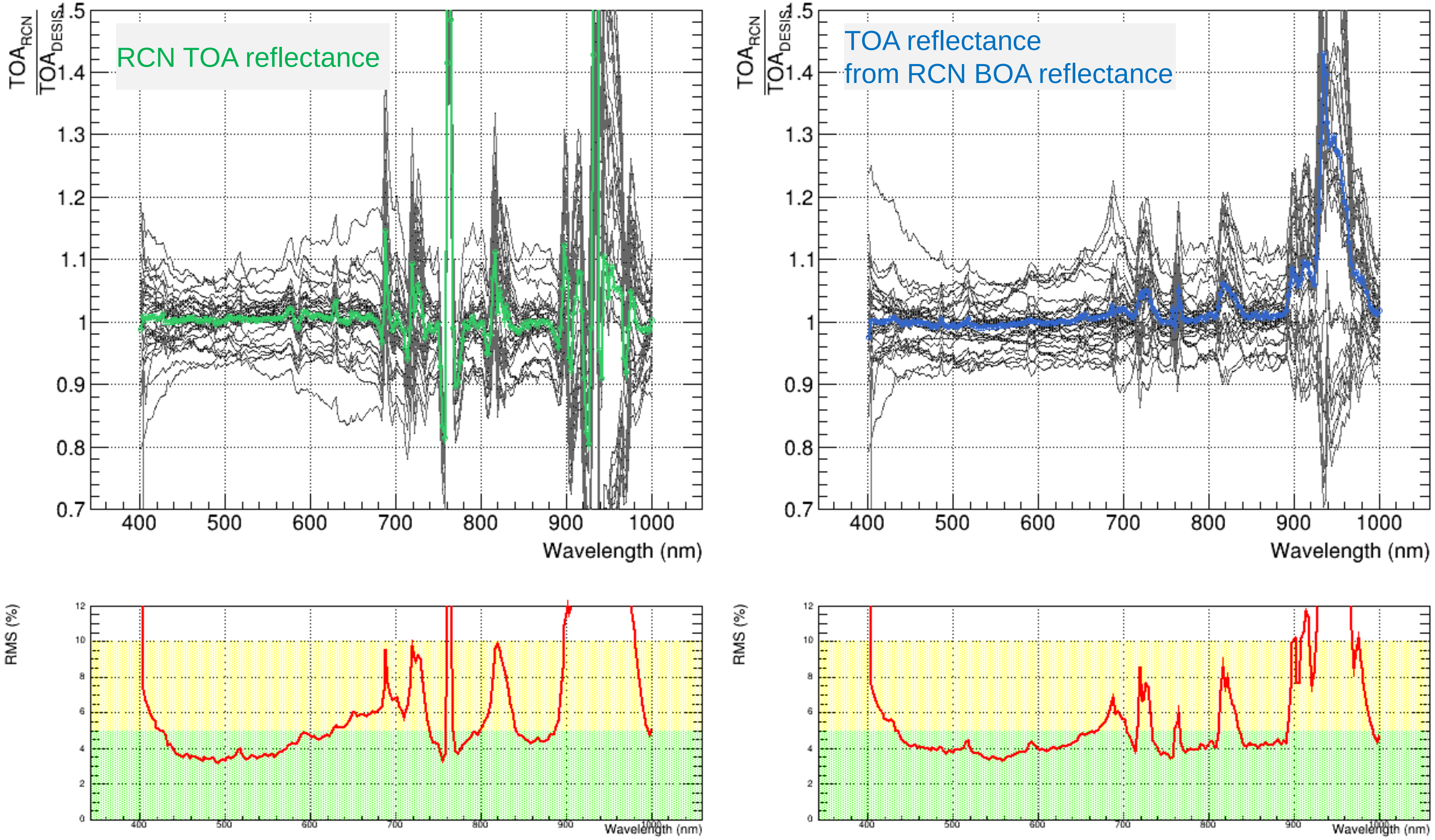
  - good atmospheric conditions
  - below 50 degrees Sun Zenith Angle
- These summary plots show **all** RCN scenes (**30** scenes)

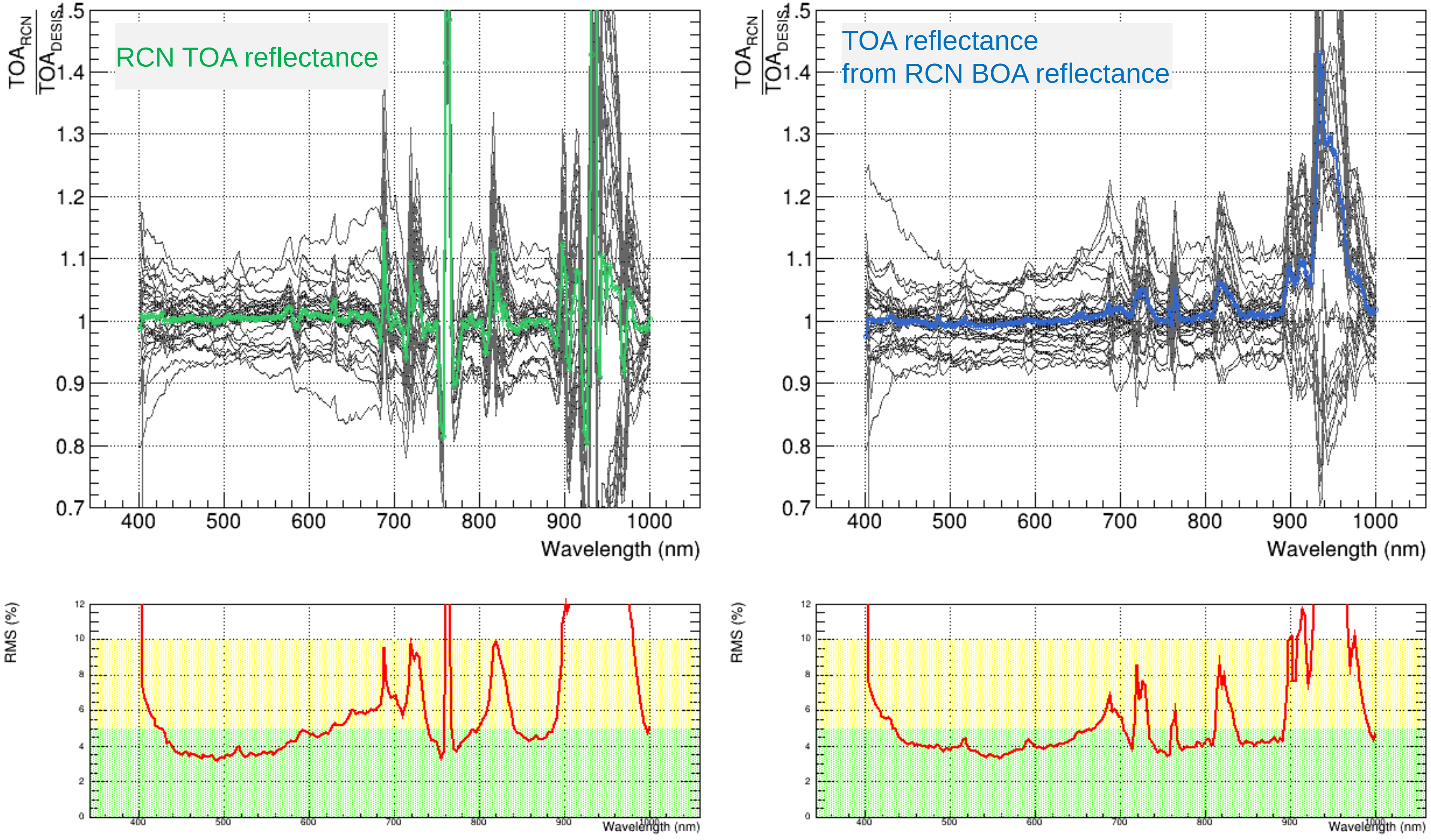


Results from 3 calibration periods: All RCN Data Results

- **Bias** is kept <1-2% on average
  - Limitation of the method, probably never better than 1-2%
  - Differences between the two TOA calculations ~1%

- **RMS** is typically ~4% outside strong absorption bands
  - Smaller for reduced Sun zenith range and good atmospheric conditions

- **Problematic area below 450 nm**:
  - Sensor not very stable
  - Degradation of up to ~20% / year at 400 nm



DLR

Summary & Outlook

- DESIS radiometric calibration is based on a vicarious calibration method adapted to DESIS data and operations

- Calibration results show that mean absolute calibration bias can be kept within 1-2% with respect to RCN while RMS (measurement to measurement variance) is better than 5% (~4%)

- Additional crosschecks performed with Sentinel-2 data by our I2R colleagues show similar level of agreement

- **Future work** to improve the DESIS calibration. A few ideas:

    - Rapid changes below 450 nm could be better addressed (time dependent calibration coefficients)

    - Build a calibration model combining on board LED calibration measurements with vicarious calibration

    - Reduce spectral-radiometric confusion

Thank you !

DLR

EXTRA slides

DLR

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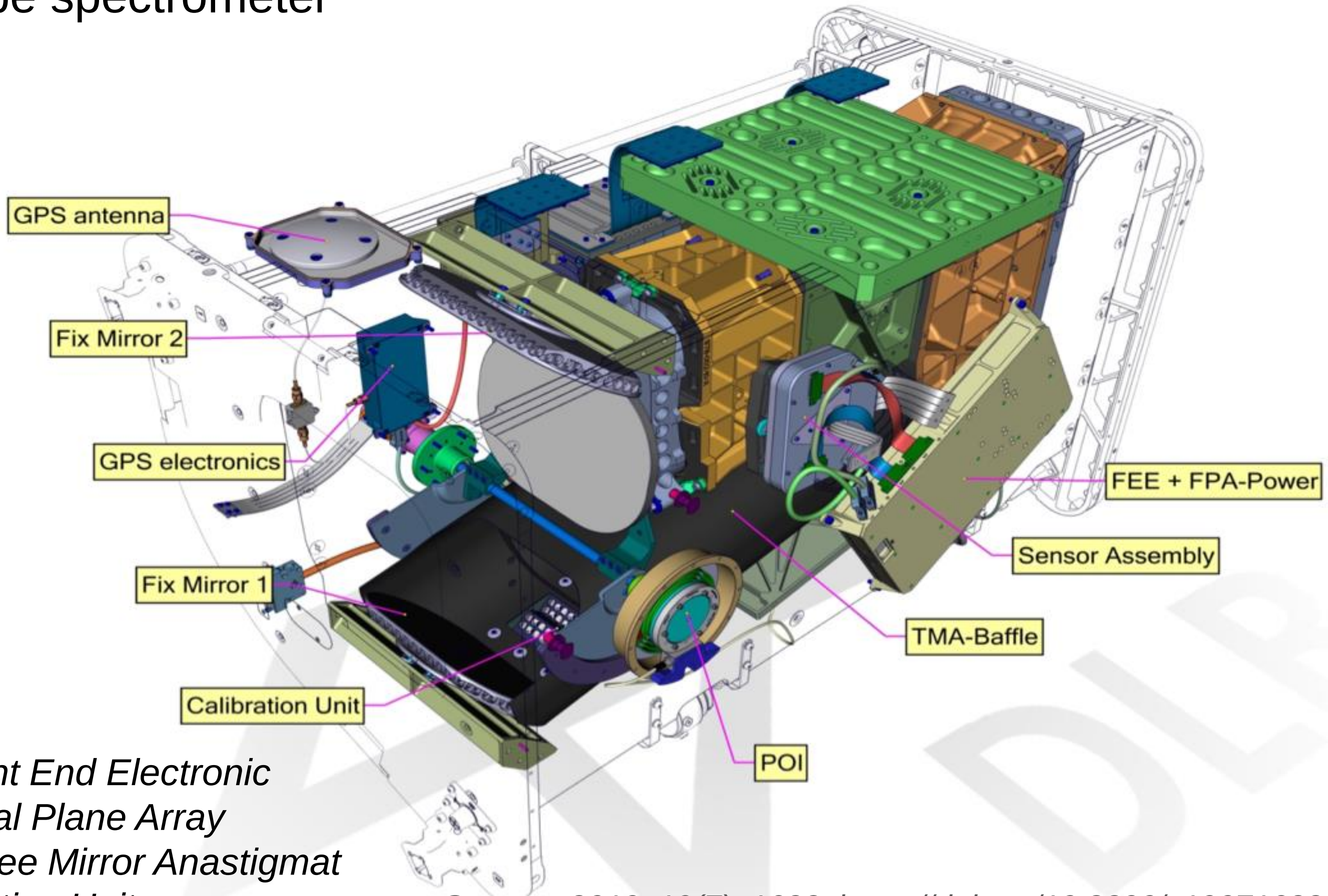

Sensors 2019, 19(7), 1622; https://doi.org/10.3390/s19071622

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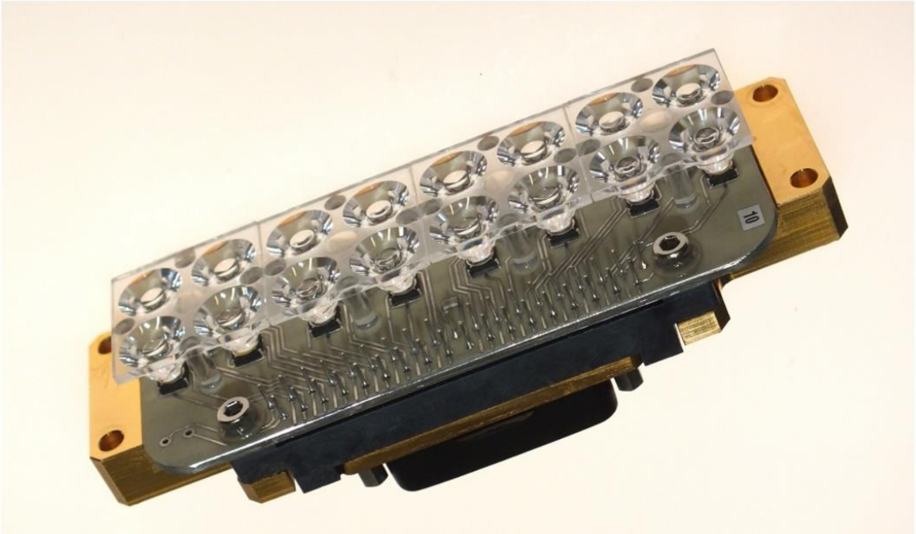
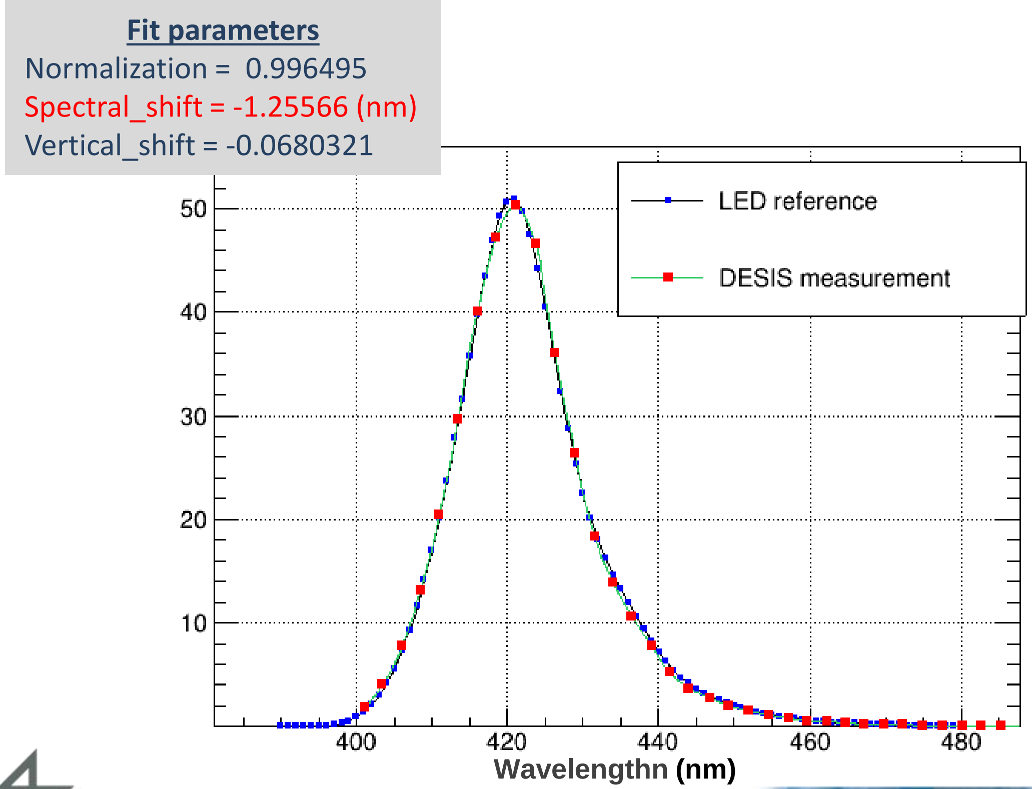
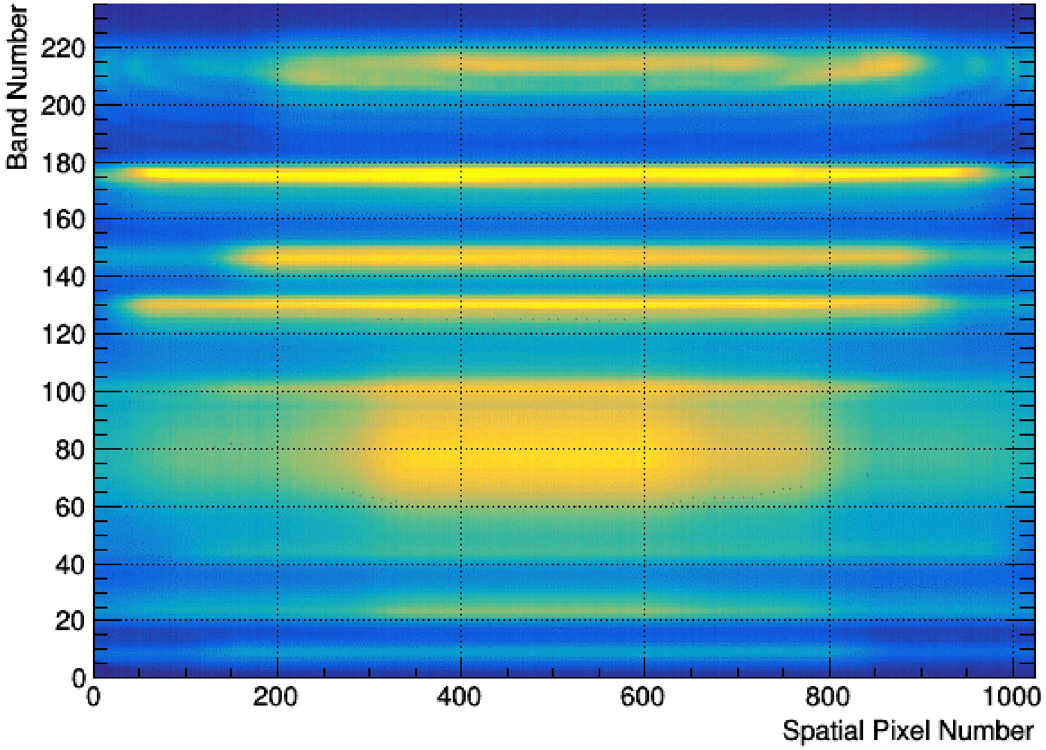
- Equipped with:
  - GPS receiver: working as a time calibration unit for latency calibration and jitter measurement
  - Calibration Unit: 2 banks with 9 LED types. Allows for Radiometric & Spectral calibration/monitoring
  - Pointing Unit: Changes the instrument line of sight in the along-track direction between ±15°
    Allows for stereo *observation mode*

On Board calibration unit

- LED Bank with 9 different LED types (7 used for spectral calibration)
- Data from sensor can be fitted for different LED type

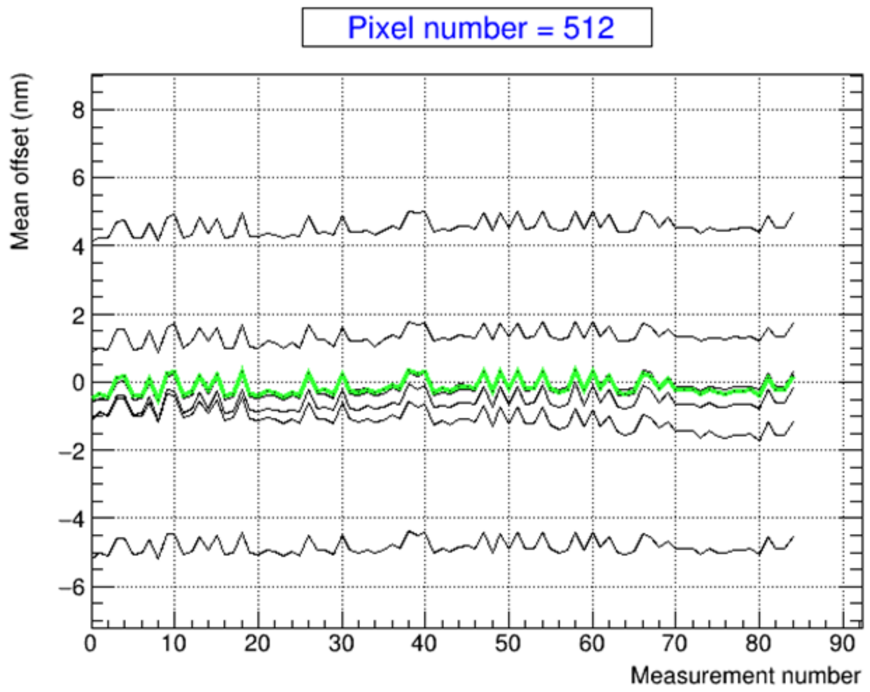


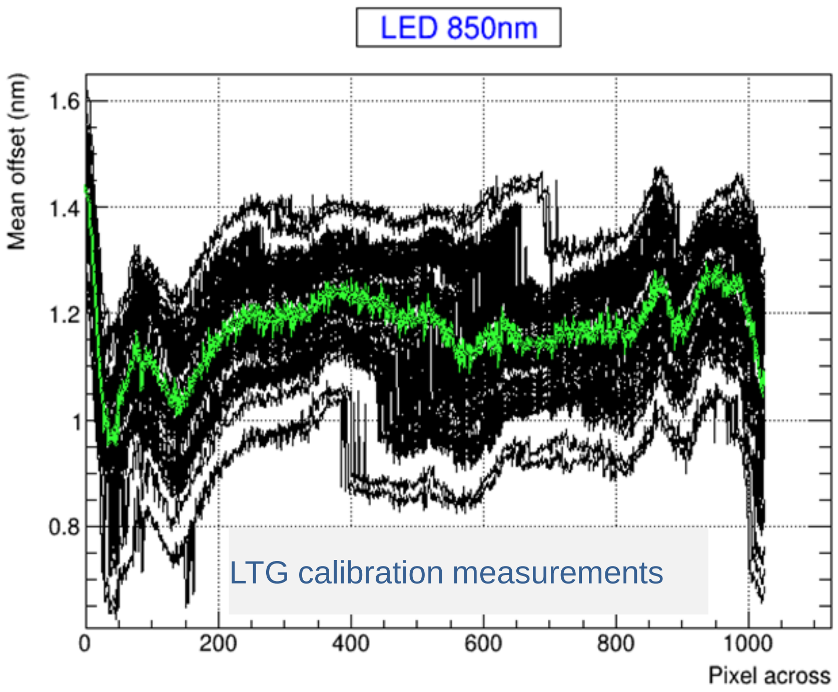




Correction Steps IV: Spectral adjustment

- Mostly obtained from on-board Spectral Calibration. Very precise measurement of LEDs profile provides accurate values
- Observed simultaneous jumps of 0.5 nm in all LEDs and all pixels across-track. Correlated with different temperature gradients inside DESIS sensor. Two populations: low-temperature gradient (LTG) and high-temperature gradient (HTG)





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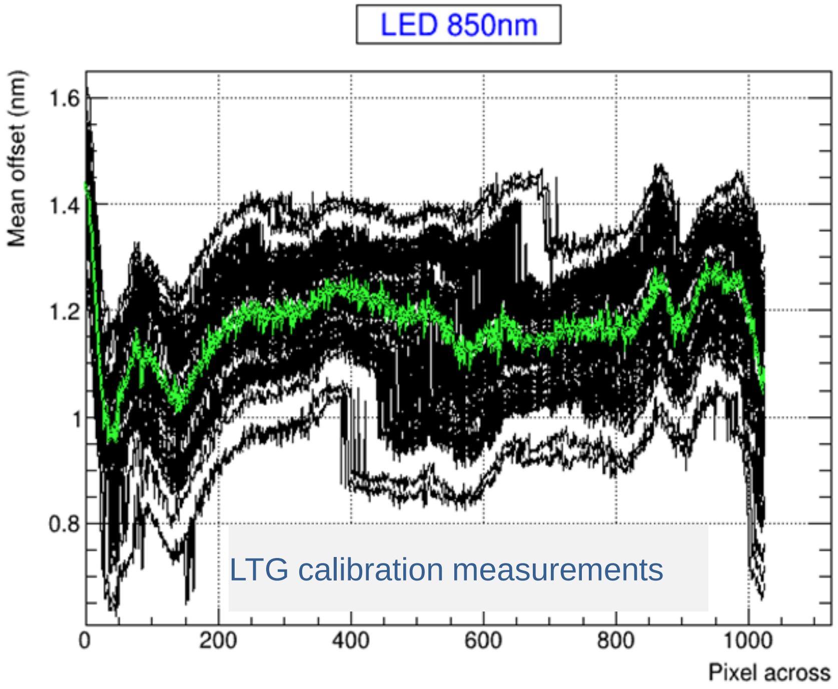
- Observed simultaneous jumps of 0.5 nm in all LEDs and all pixels across-track. Correlated with different temperature gradients inside DESIS sensor. Two populations: low-temperature gradient (LTG) and high-temperature gradient (HTG)

- For any of the two populations, most measurements within 0.10 nm. Small fraction of measurements can deviate as much as 0.3 – 0.4 nm

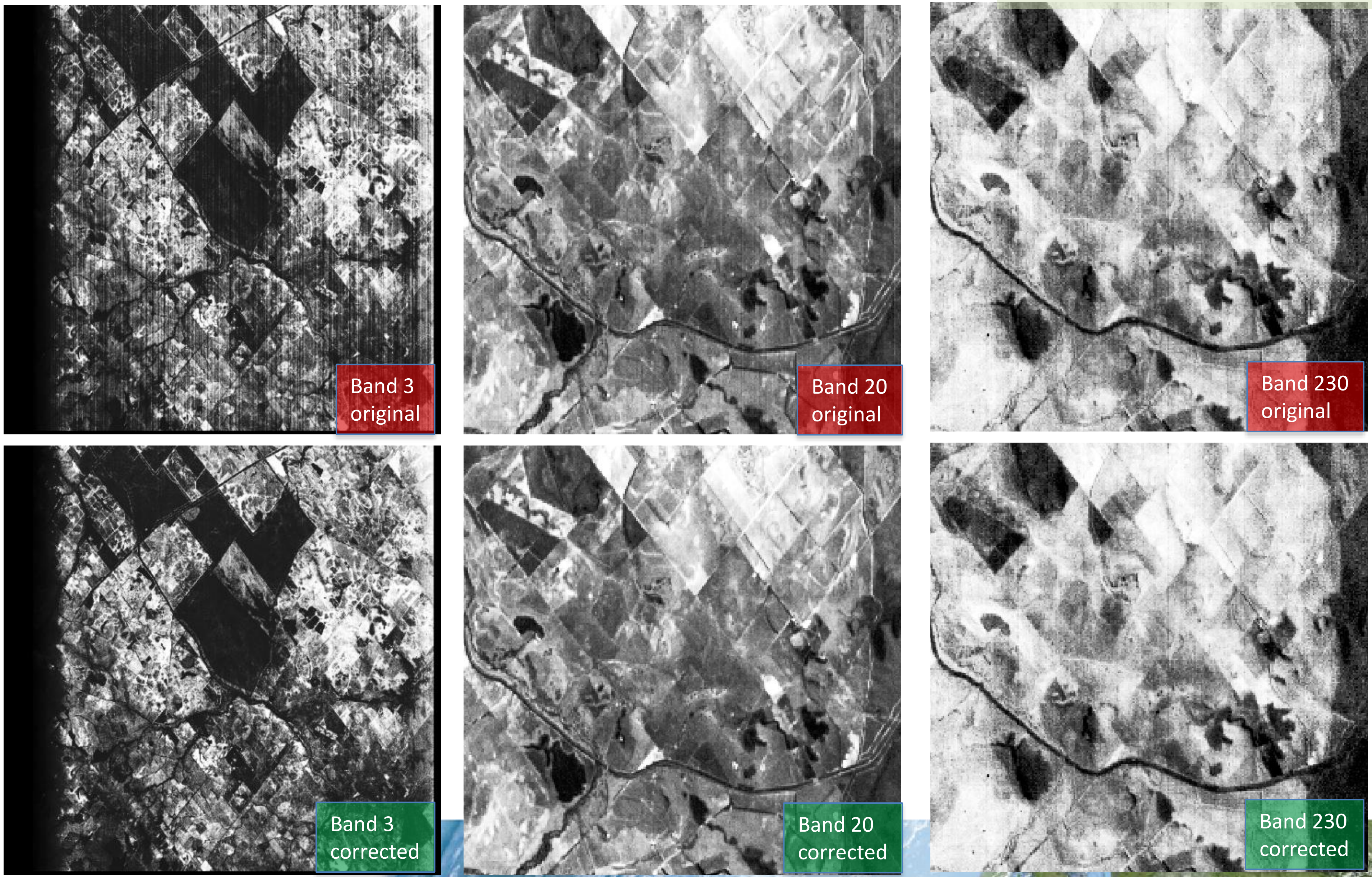
- Spectral stability (RMS of LED spectral measurements) is 0.10 nm for LTG and 0.08 for HTG. Equal for all LEDs except for 470 nm LED

- A correction of the 0.5 nm jumps between populations implemented inside smile resampling



Striping Correction

L1B radiance range stretched to highlight striping

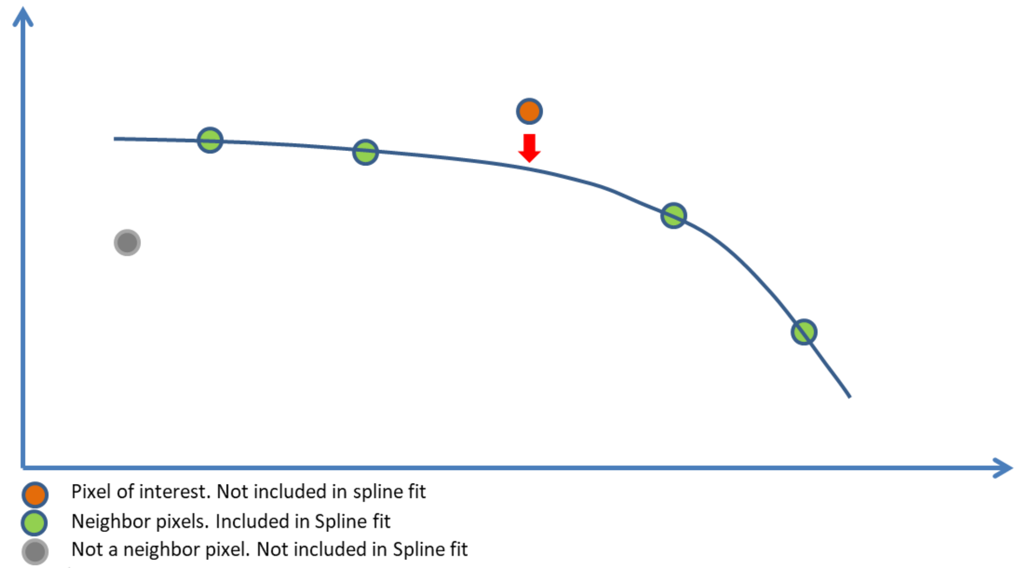


Correction Steps I: Radiometric adjustments

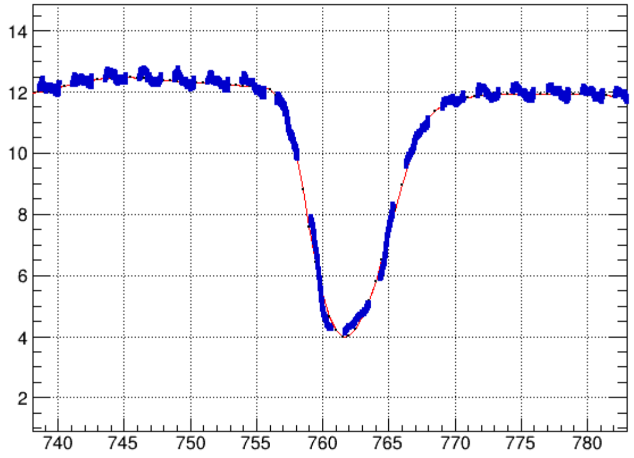
- Most steps performed with uniform scenes with L1B products **averaged in the along-track direction**
    - 235 bands × 1024 spatial pixels

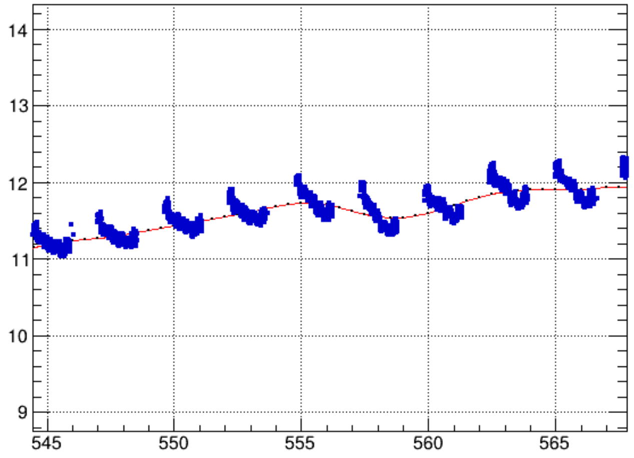
- Most corrections are performed after smile correction (confusion of spectral and radiometric corrections)

- **Striping correction**: Compute adjustment to radiometric coefficient using spline fits. Use iterative process until convergence



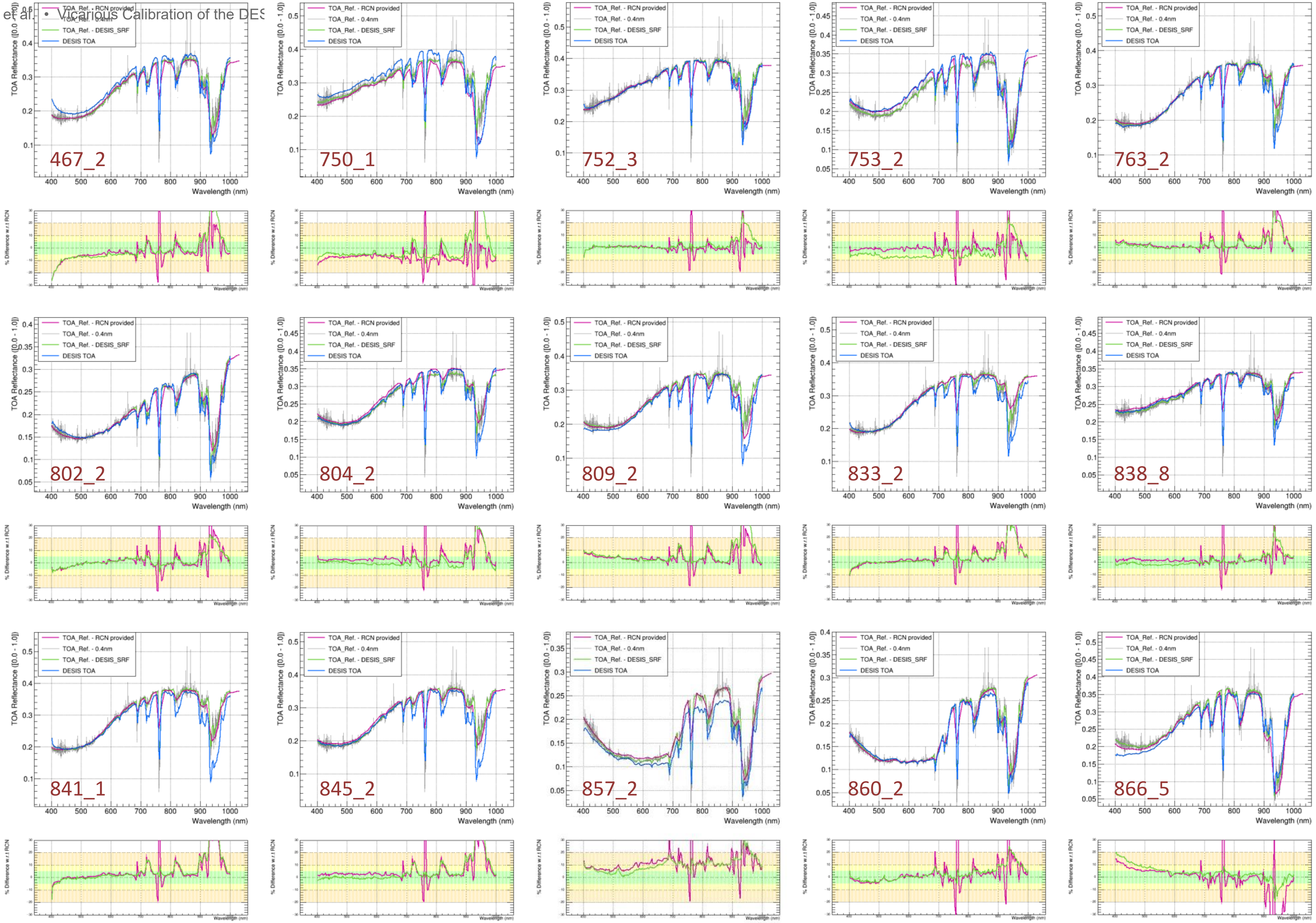
- **Rad./Spc. correction**: Exploits smile effect to use all pixels across track in one single spectrum. Compute minimum deviation to common spectrum





- Comparison of all (30) RCN TOA reflectance and DESIS TOA reflectance

- Comparison with 2 reference:
  1. As provided by RCN (10 nm resolution)
  2. Computed by us using RCN BOA (DESIS resolution)



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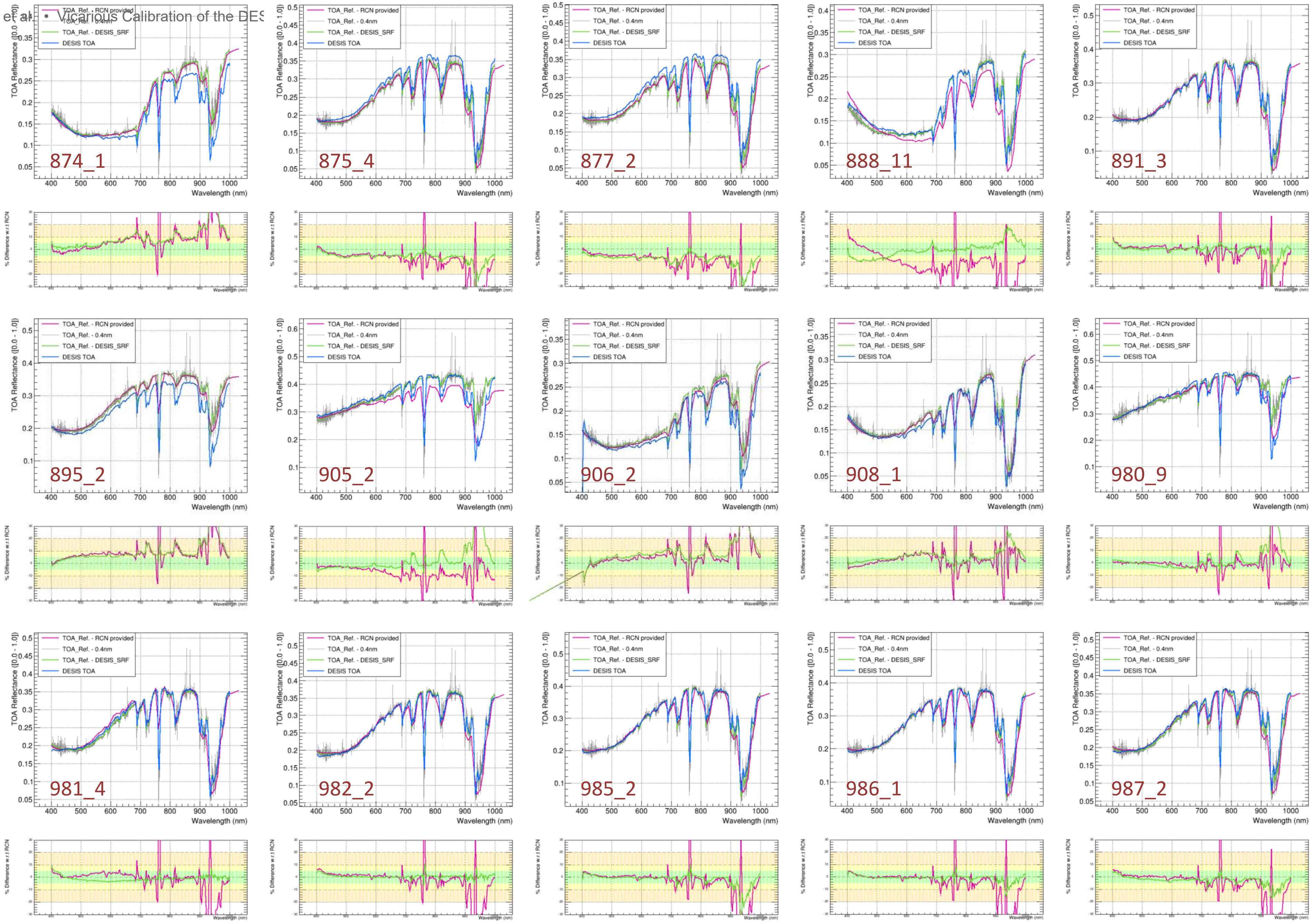

DLR

Atmospheric Correction inversion of RadCalNet (RCN) BOA (10 nm)

- Interpolate the 10 nm RCN BOA to 0.4 nm.
- Invert the L2A atmospheric correction assuming RadCalNet atmospheric conditions.
  - Aerosols: ‘rura’ and AOT= AOT_{RCN}.
  - WV = WV_{DESIS} (to avoid inconsistencies)
- Atmosphere/solar model as it is used in DESIS L2A processor:
  - L2A processor: PACO SW (de los Reyes, 2020)
  - RT using MODTRAN 5.4 (Berk et al, 2008)
  - Solar model: Fontenla 2011 (Fontenla et al, 2011)
- DESIS acquisition metadata of the RadCalNet scene:
  - Digital Elevation Model (mainly altitude)
  - Sun zenith and azimuth angle
  - Sensor off-nadir and azimuth angle
  - Season (summer/winter)