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Recent improvements of MSI radiometric calibration and characterisation of the impact of differences in spectral responses between sensors

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7th Sentinel-2 Validation Team Meeting
13 – 15 October 2025 | ESA – ESRIN | Frascati (RM), Italy

Agenda

- ✓ Improvement of equalisation stability for S2C
- ✓ Impact of differences between spectral bands
  for the comparison of S2A, S2B and S2C measurements
- ✓ Radiometric alignment of S2C on S2A

Funded by the EU and ESA

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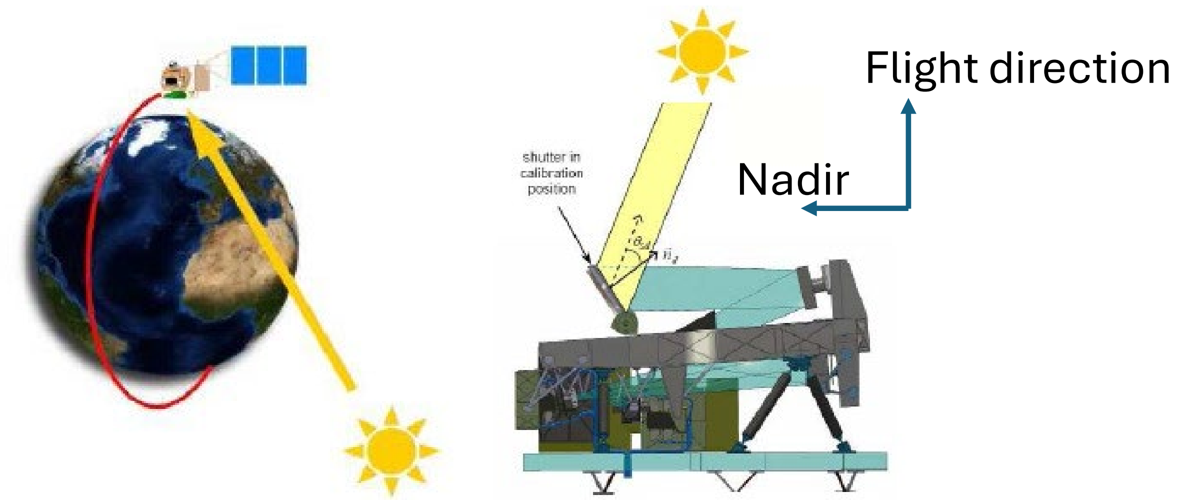
Improvement of equalisation stability

❖ Principle of calibration for absolute and relative gains

- ✓ Sun-diffuser acquisitions
  - ➢ Solar Zenith Angle (SZA) : 60°
  - ➢ Variable Solar Azimut Angle (SAA)

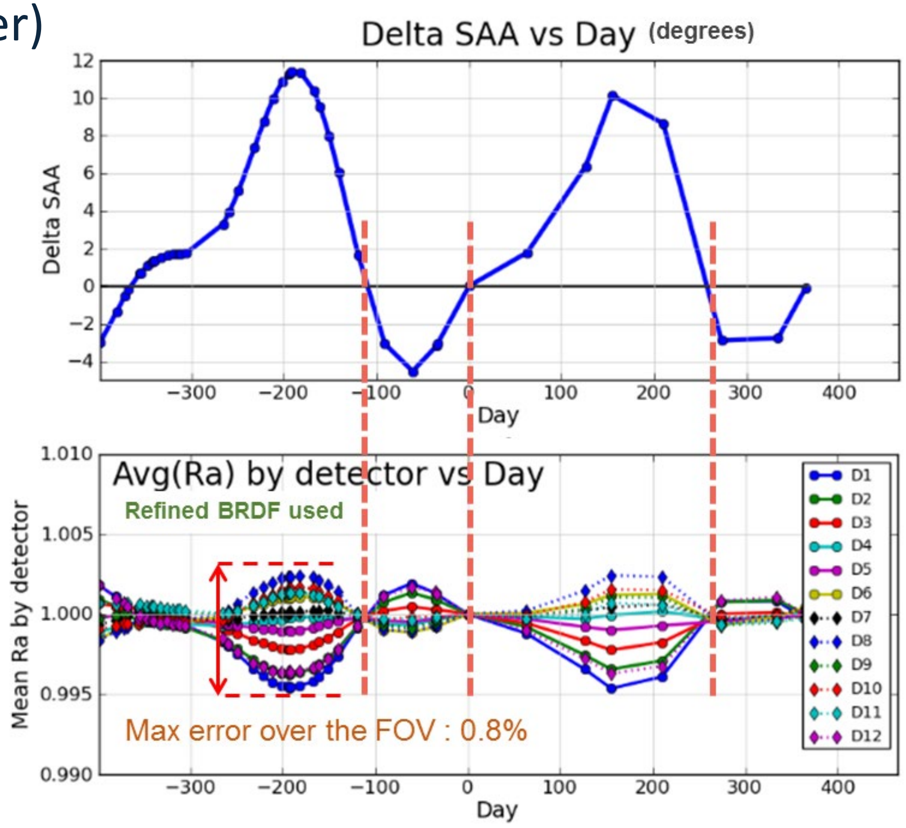
- ✓ Comparison measurements / simulations

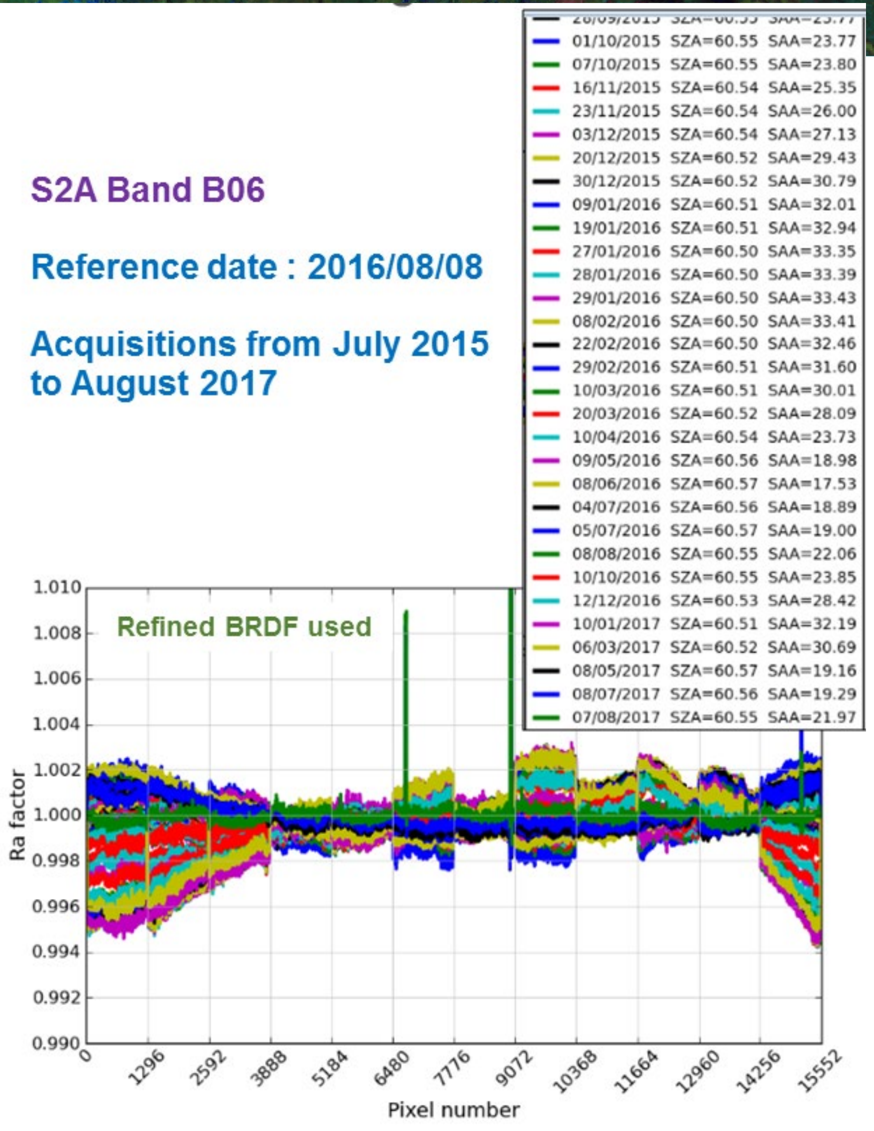


On board sun diffuser
mounted on a Calibration and Shutter Mechanism

Improvement of equalisation stability

- Slight imperfections in the Sun-diffuser BRDF characterization
  - ✓ Slight seasonal oscillations are introduced in equalisation coefficients by the calibration scheme
  - ✓ Clear correlation with the SAA angle (Solar Azimuth Angle for the incidence on sun-diffuser)





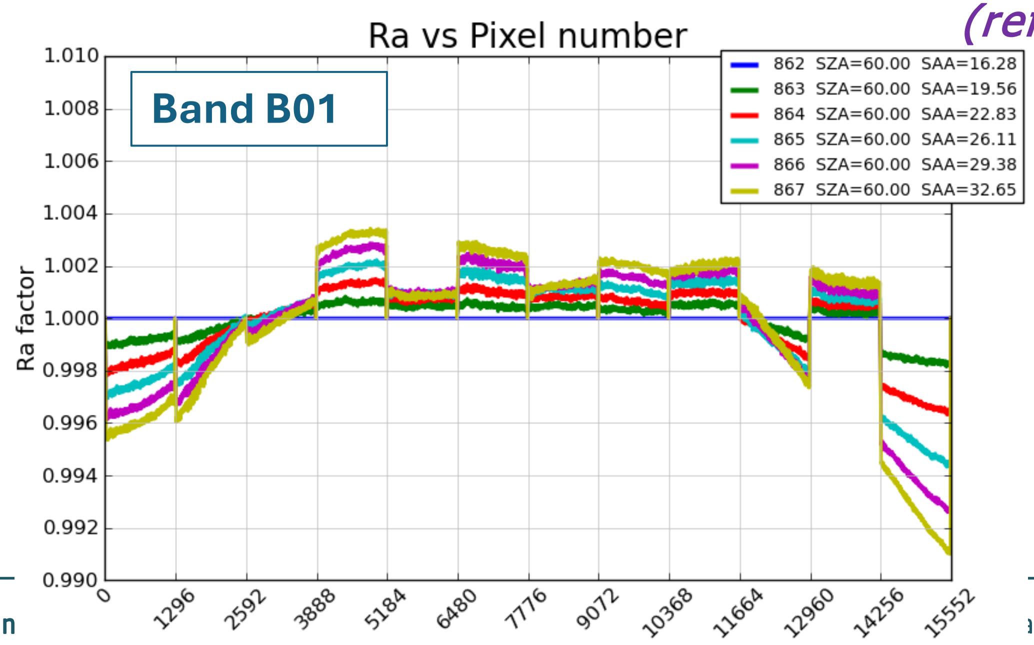
Improvement of equalisation stability

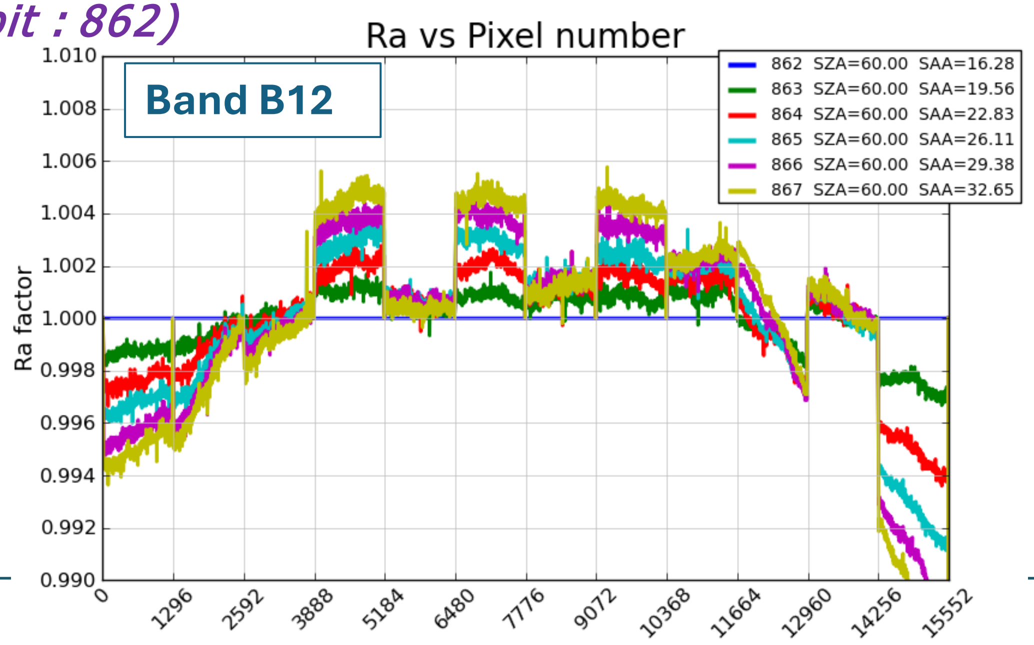
- S2C yaw manoeuvre
  - ✓ S2C in-orbit commissioning :
    → specific successive Sun acquisitions for incidences covering the yearly cycle
  - ✓ No change expected in S2C radiometric response
    ➔ Changes observed in calibration results are due to defaults in the Sun-diffuser BRDF characterization

S2C yaw manoeuvre Sun acquisitions

Orbit	Date	SZA (°)	SAA (°)
862	2024-11-04T06:18:58	60.00	16.28
863	2024-11-04T07:59:48	60.00	19.56
864	2024-11-04T09:40:40	60.00	22.83
865	2024-11-04T11:21:33	60.00	26.11
866	2024-11-04T13:02:27	60.00	29.38
867	2024-11-04T14:43:22	60.00	32.65

S2C Sun-diffuser inaccuracies
(ref. orbit : 862)





Improvement of equalisation stability

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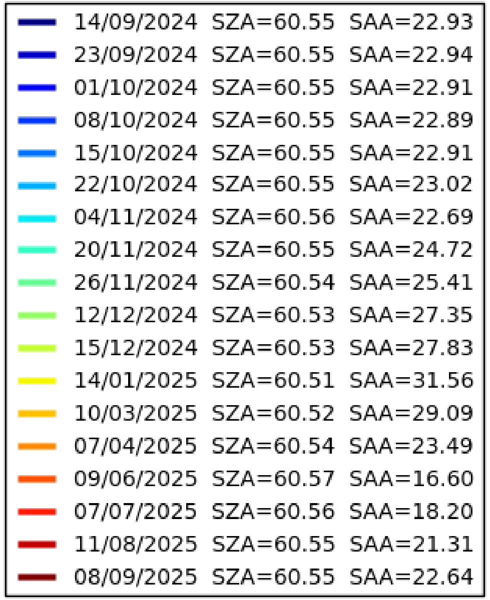
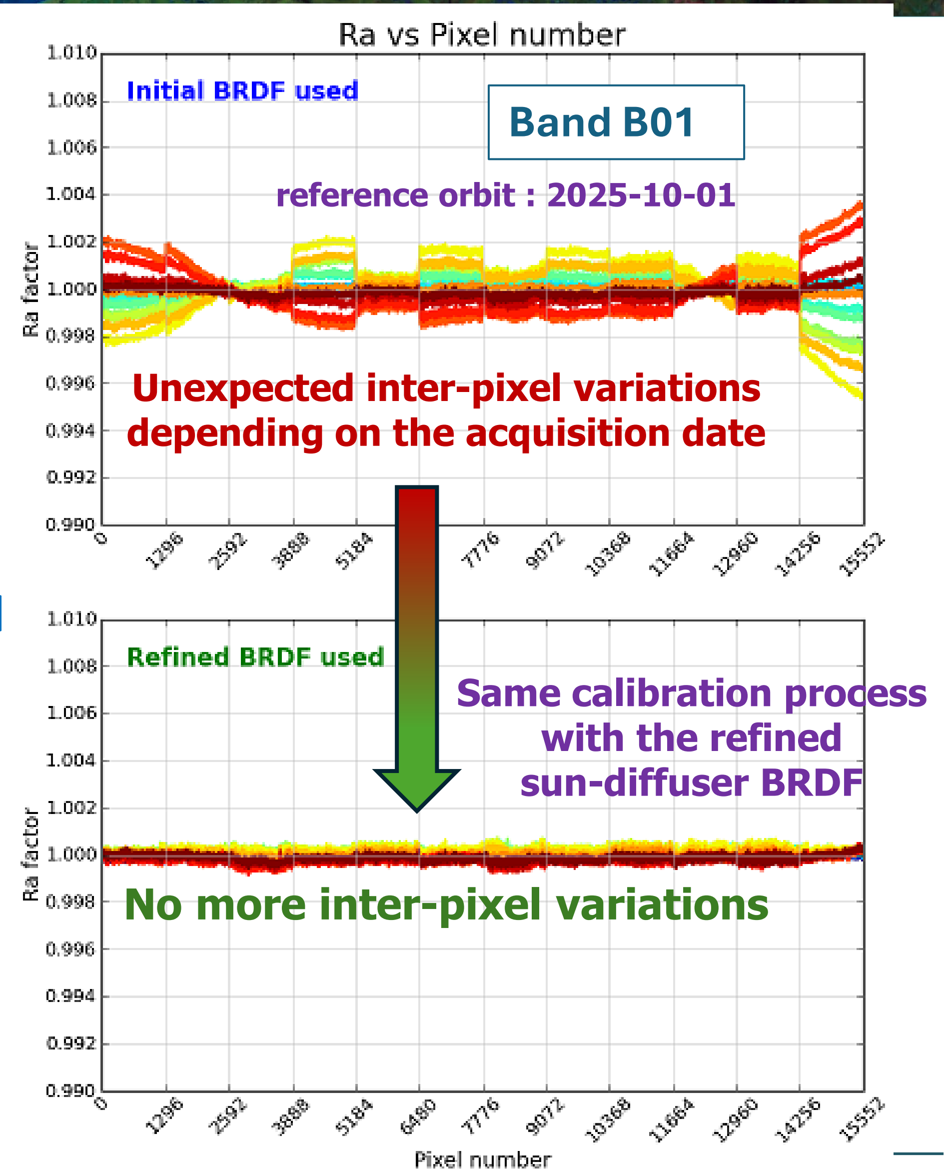
- S2C yaw manoeuvre
  - ✓ Estimate of the Ra factor for each acquisition
    ➔ Ra(pixel, SAA)
  - ✓ Refinement of the BRDF model
  - ✓ Application to time series of S2C Sun diffuser acquisitions



Application on B01 band



Improvement of equalisation stability

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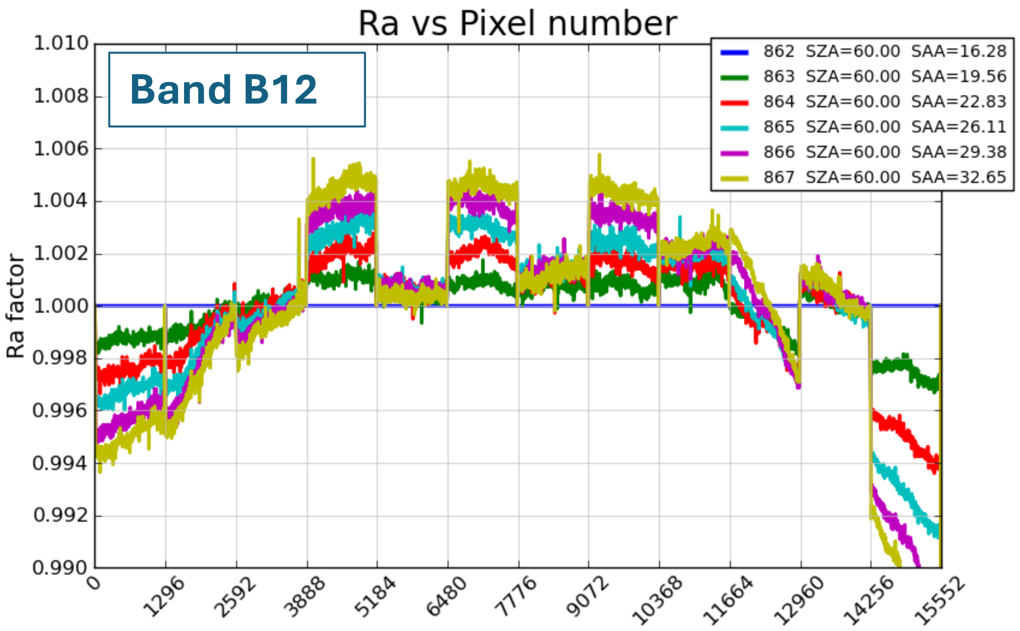
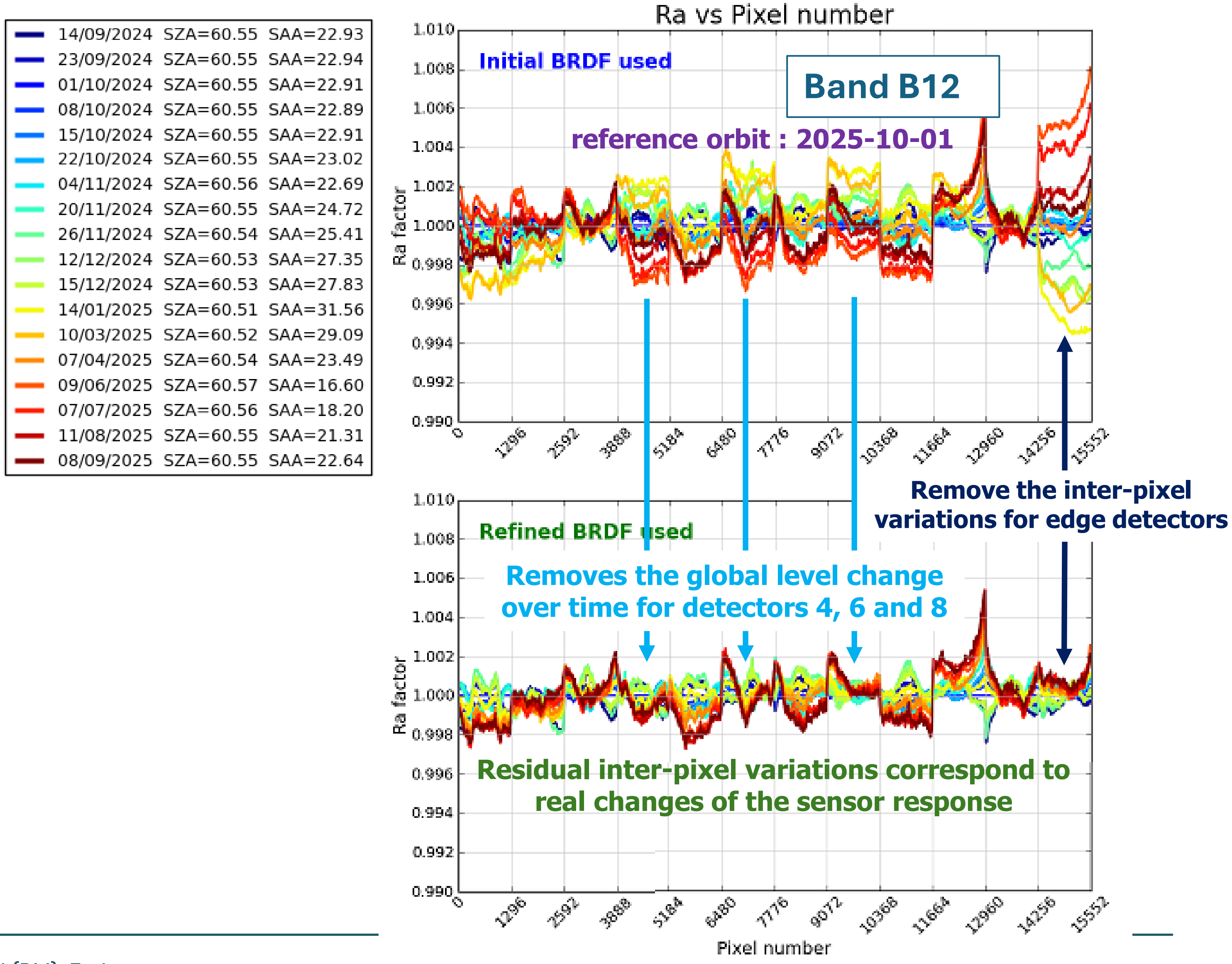
Application on B12 band

Inaccuracies estimated from yaw manoeuvre Sun acquisitions





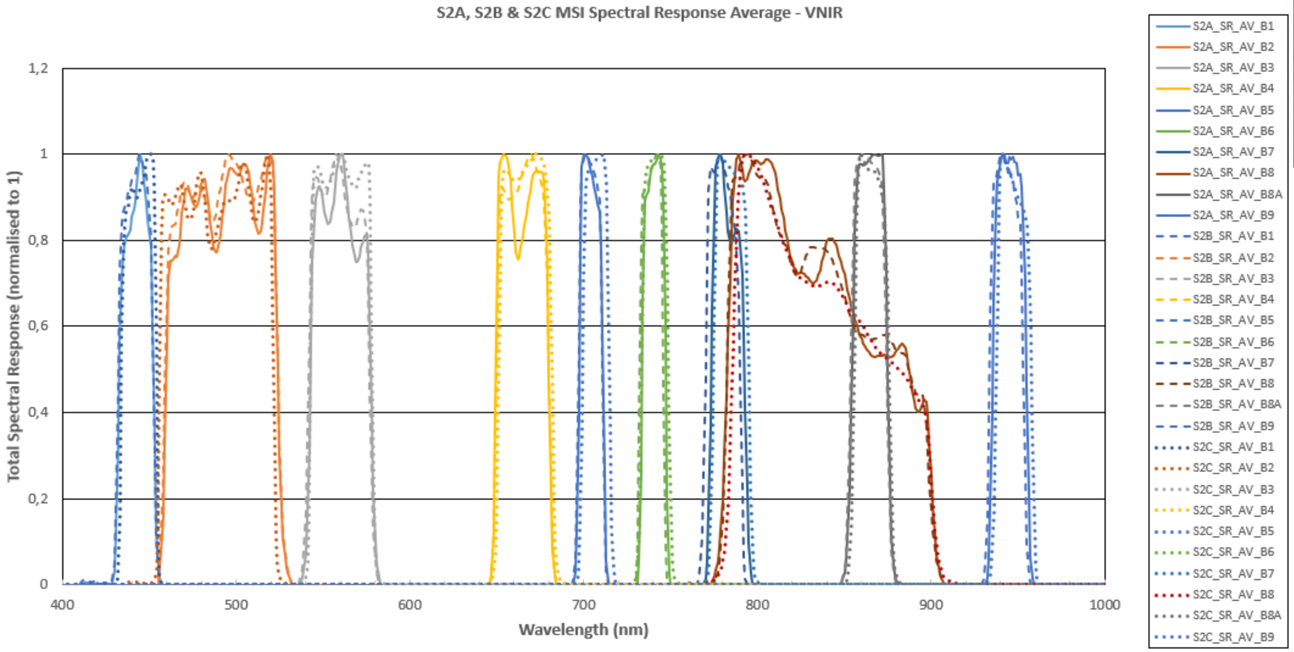
Impact of differences between spectral bands of MSI-A, B and C

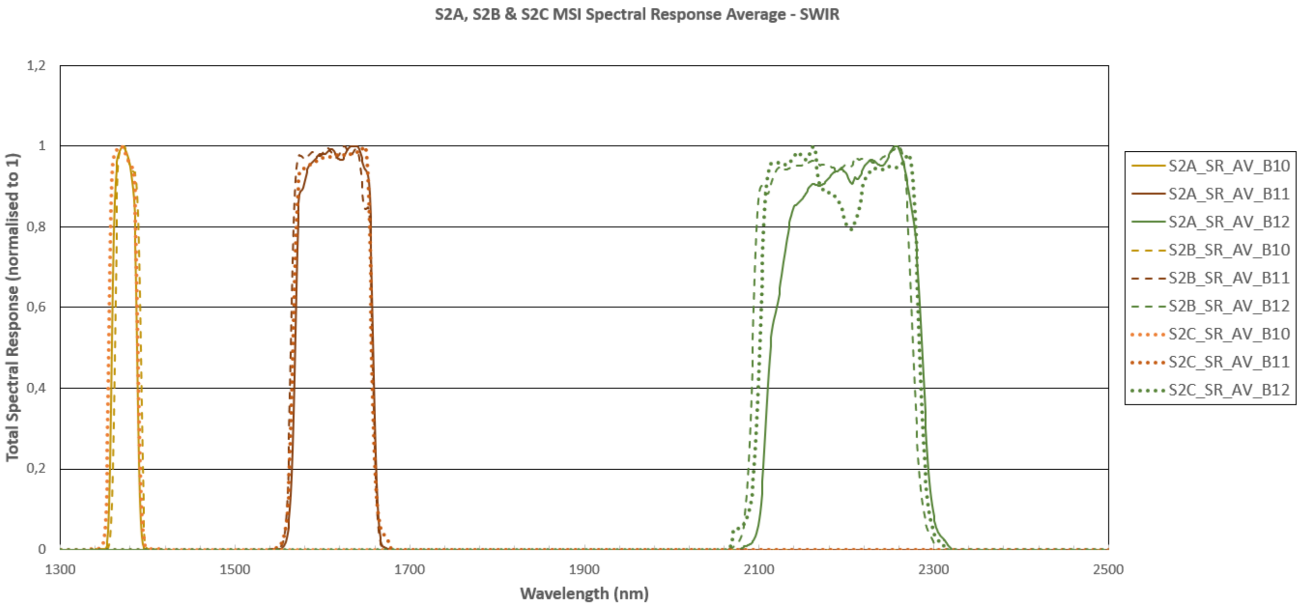
- Differences of spectral bands ➔ Impact on measurement comparisons

  - ✓ **Tandem between S2C and S2A** during S2C In-Orbit Commissioning (October 1st - December 11th 2024)
    - Comparison of TOA reflectance
    - Assessment of the consistency of their absolute radiometric calibration

  - ✓ Limitation for the comparison
    - Three MSI sensors are designed as identical sensors
    - But **slight differences of spectral bands** ➔ **impact measurements of TOA reflectance**

  - ✓ To be known for the comparison of tandem acquisitions
    - **Order of magnitude** of expected measurement differences?
    - For **which surfaces** the TOA reflectance values are the most affected by the difference between spectral bands?





- Average Sentinel-2 spectral responses
  - ✓ Shift in the equivalent wavelength
  - ✓ Difference in shapes

Equivalent wavelength (nm)

	S2A	S2B	S2C
B01	442,7	442,2	444,2
B02	492,7	492,3	489,0
B03	559,8	558,9	560,6
B04	664,6	664,9	666,5
B05	704,1	703,8	707,1
B06	740,5	739,1	741,1
B07	782,8	779,7	784,7
B08	832,8	832,9	834,6
B8A	864,7	864,0	865,6
B09	945,1	943,2	947,2
B10	1373,5	1376,9	1372,2
B11	1613,7	1610,4	1612,0
B12	2202,4	2185,7	2191,3

$$\lambda_c = \frac{\int \lambda \times S(\lambda).d\lambda}{\int S(\lambda).d\lambda}$$

Wavelength (λ)

Equivalent wavelength (λ_c) of a given spectral band

Instrument Spectral Response Function ($S(\lambda)$)

Impact of differences between spectral bands of MSI-A, B and C

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- Simulation of observations : RT code SOS-ABS (https://github.com/CNES/RadiativeTransferCode-SOS)
  - ✓ Uniform target :
    - 5 surfaces spectra:
      desert, snow, turbid water, baresoil, dense vegetation
    - Same scene over all the pixels
  - ✓ Atmosphere
    - Pressure: 1013 mbar
    - Continental aerosols: AOT_{550} = 0.5
    - Ozone: 350 Db
    - Water vapour: 4.5 g/cm^2
  - ✓ Sun zenith angle : 40°
  - ✓ Viewing direction : Nadir

Spectra of TOA reflectance: $\rho_{simu}^{TOA}(\lambda)$

↓ Solar irradiance spectrum

Convolution on the ISRF for MSI-A, B and C

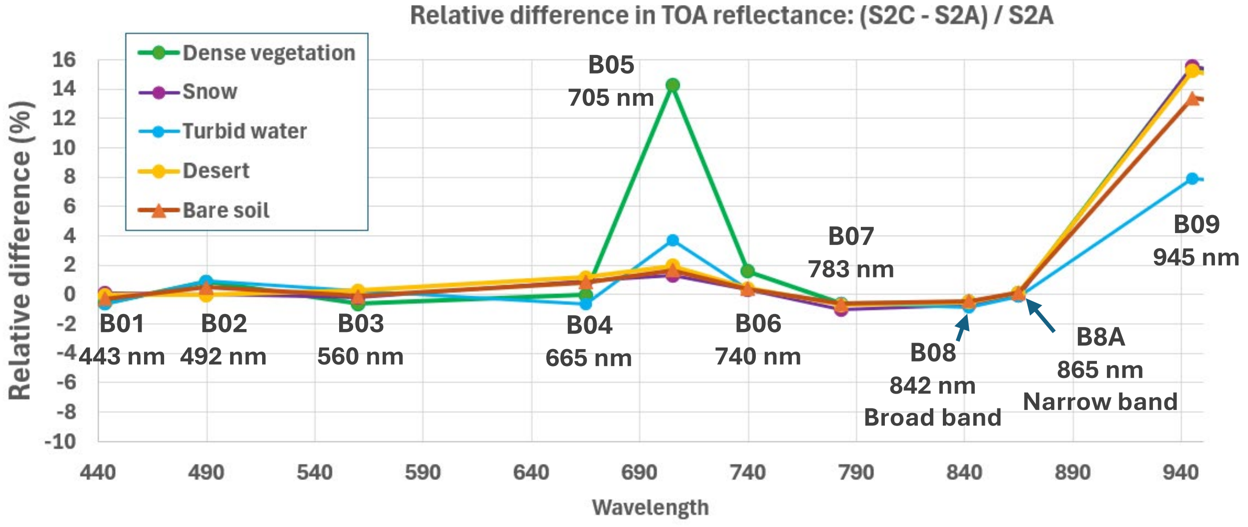
TOA reflectance per spectral band and sensor

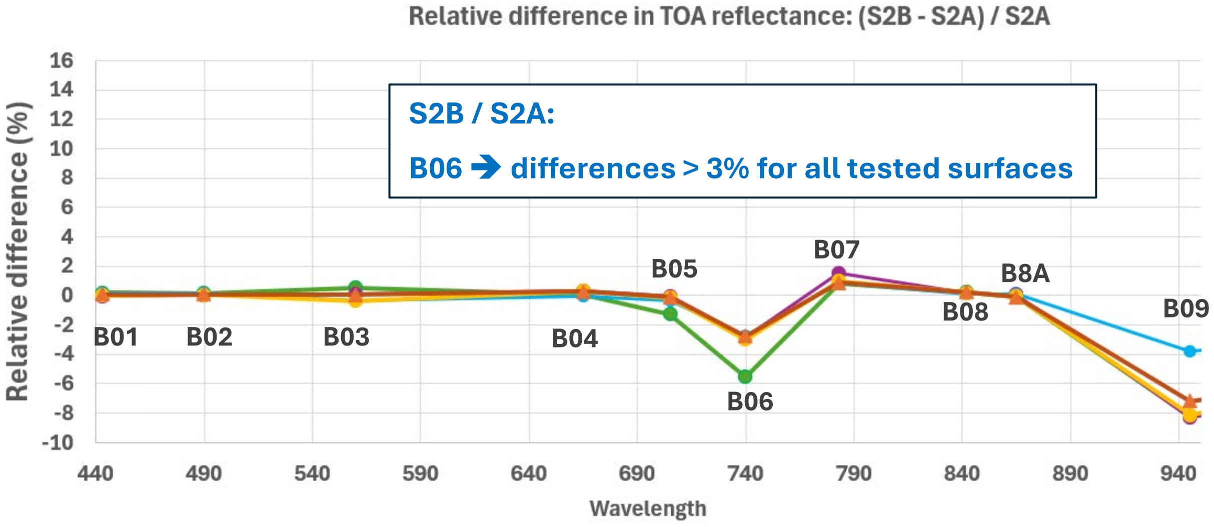
$$\rho^{TOA} = \frac{\int_0^\infty \rho_{simu}^{TOA}(\lambda).E_{Sun}(\lambda).S(\lambda).d\lambda}{\int_0^\infty E_{Sun}(\lambda).S(\lambda).d\lambda}$$

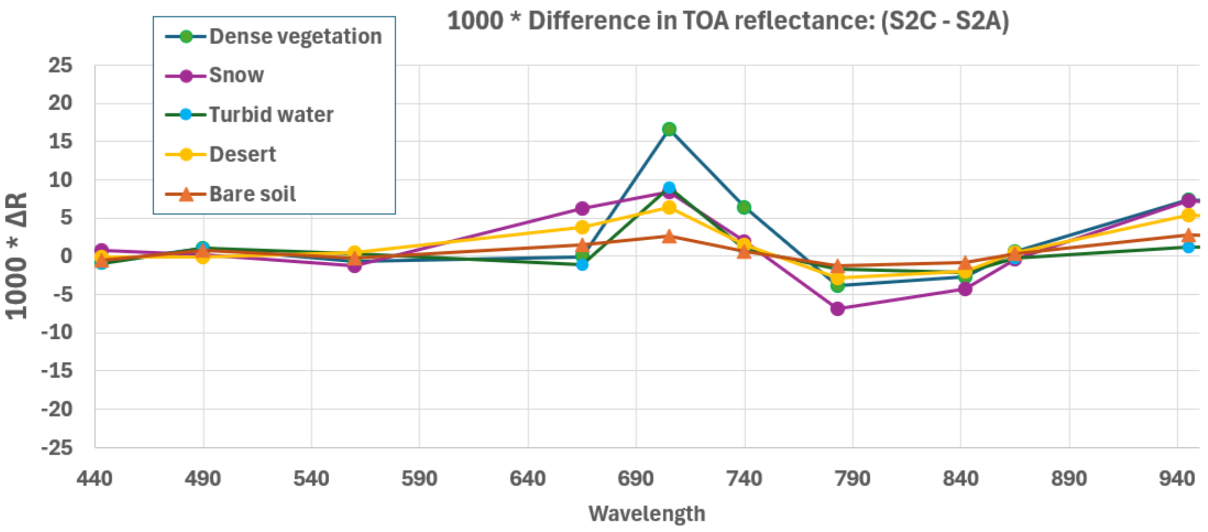
Highest impacts for red-edge and vegetation bands

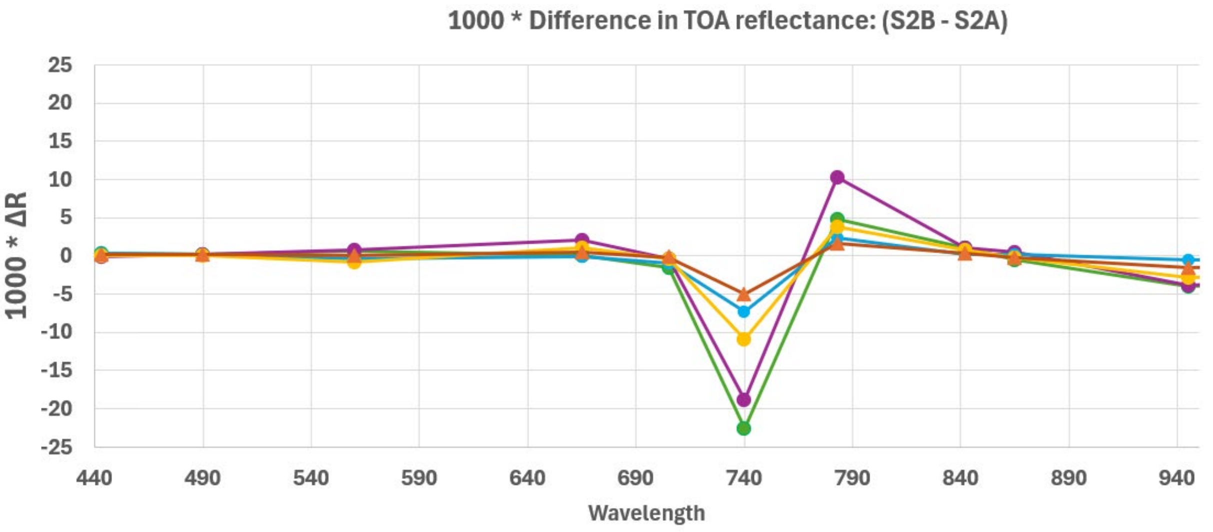
Lowest relative differences for Desert and bare soil ➔ to be considered for the tandem S2A/S2C in B05

Lowest sensitive bands: B8A, B08 ➔ highest confidence in tandem comparison









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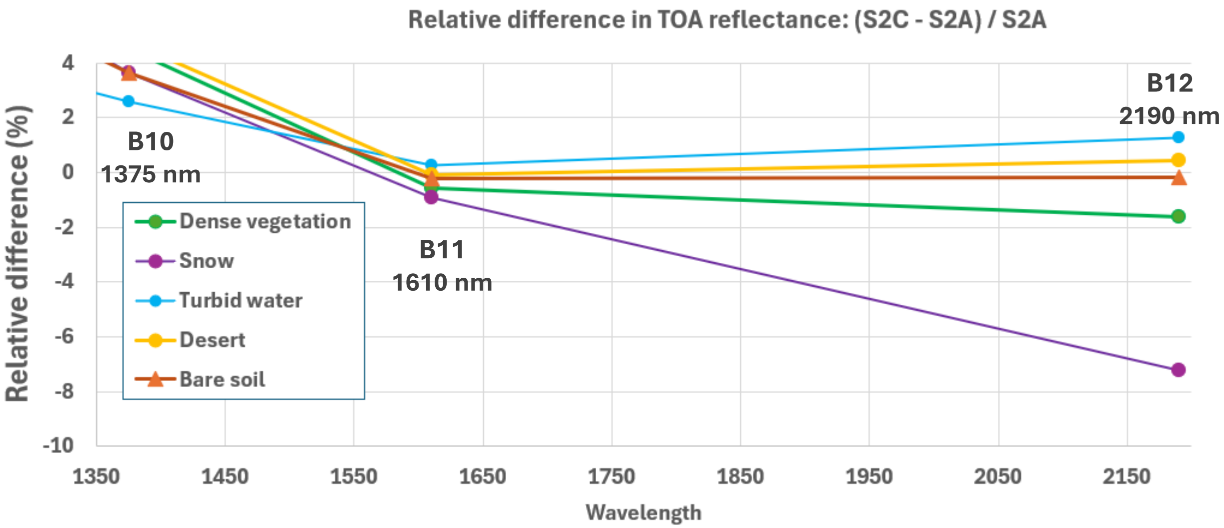
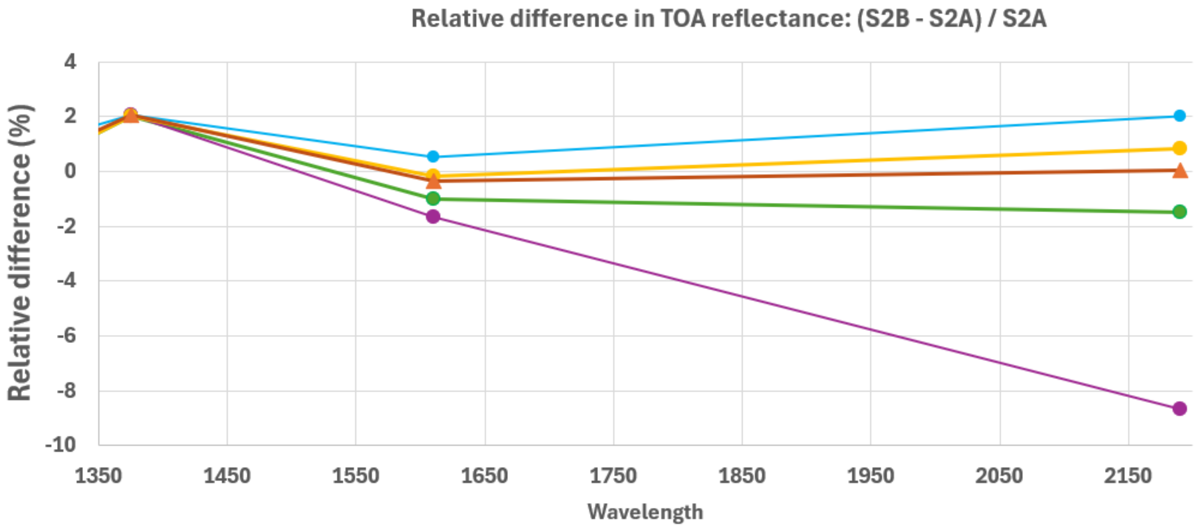
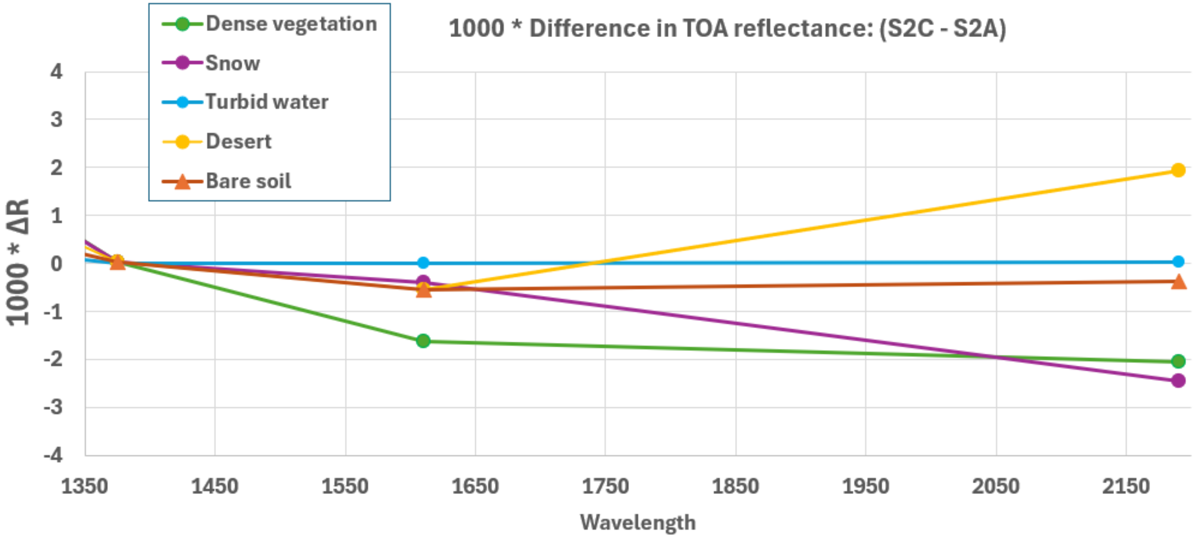
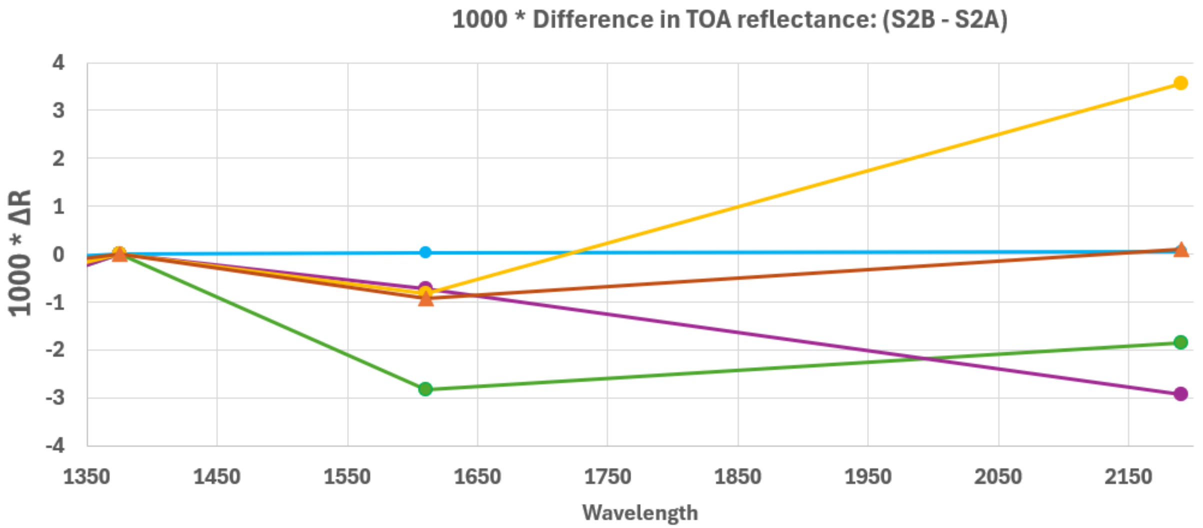
Lowest relative differences for Desert and bare soil
➔ to be considered for the tandem S2A/S2C in SWIR









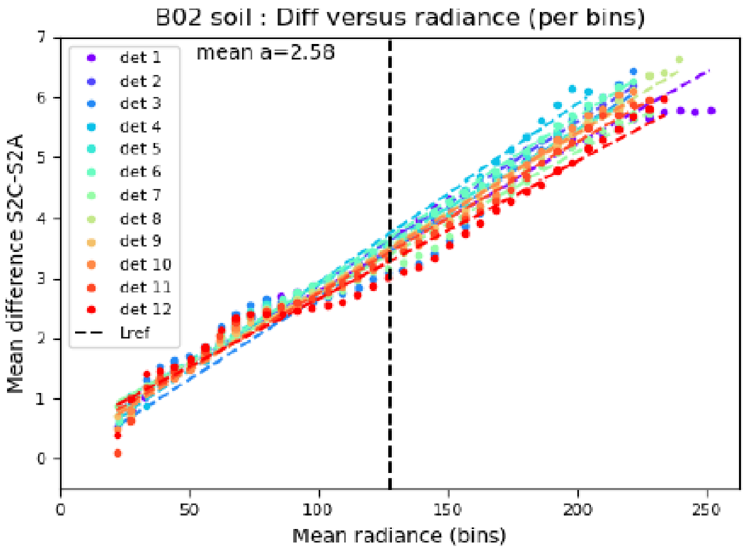
B11 B12

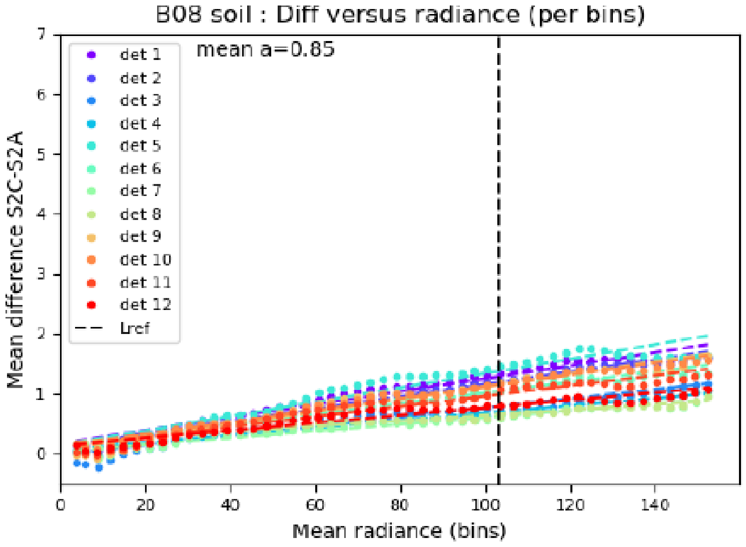
Alignment of S2C radiometry on S2A

- S2C / S2A tandem cross-calibration
  - ✓ Pixel to pixel direct comparison over 3 periods of 6 days
    - From 1st to 6th November: 506 tiles
    - From 7th to 13th November: 558 tiles
    - From 14th to 20th November: 647 tiles
  - ✓ 3 classifications of pixels: bare soil, vegetation and water
  - ✓ Computation of a linear model: difference versus radiance, per bin of radiance, for each detector

$$Mean(\Delta L_{bin}) = a * Mean(L_{bin}) + b$$

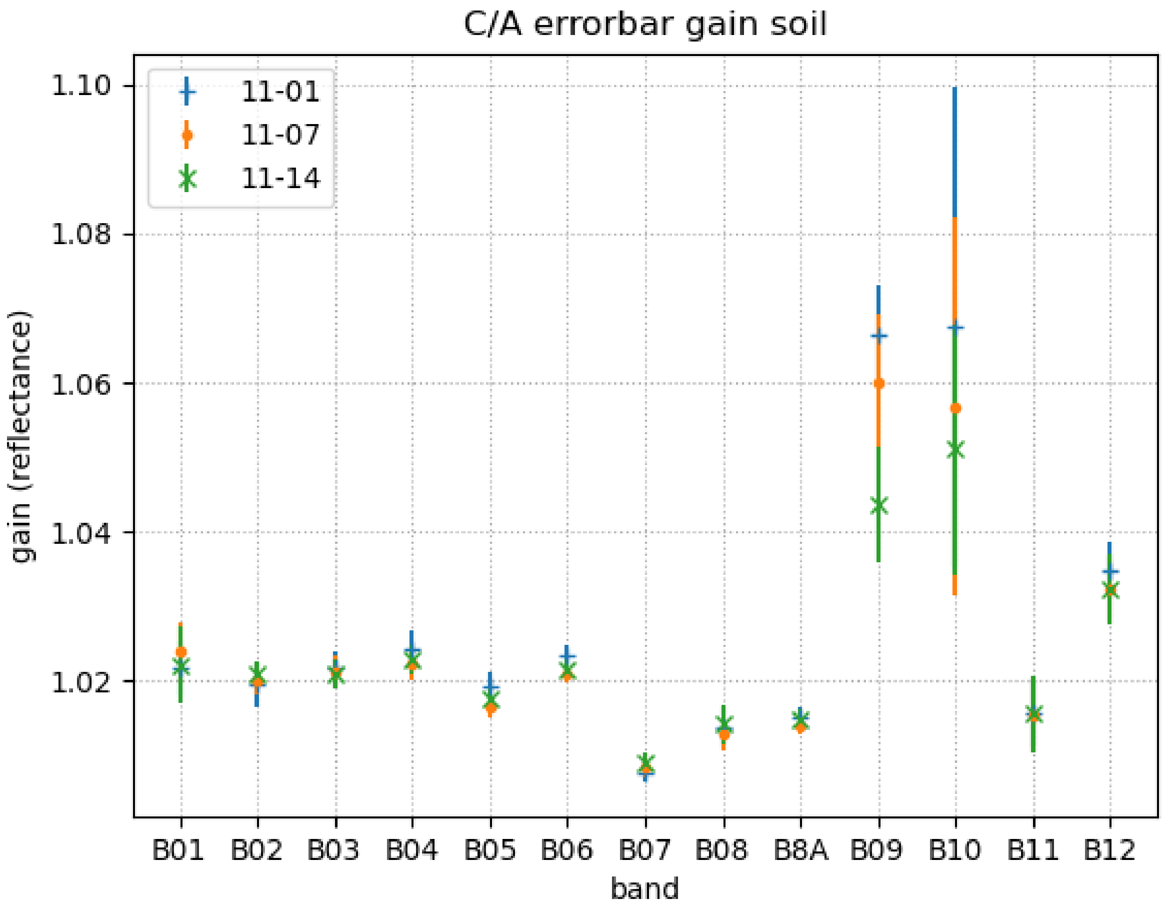
  - ✓ Linear coefficient " a " gives the reflectance intercalibration gain





Alignment of S2C radiometry on S2A

- Temporal stability between analysis periods
  - ✓ VNIR: good stability, especially soil and water
  - ✓ B09 & B10: high variability between periods for all surfaces
  - ✓ B11: very stable for all surfaces and all periods
  - ✓ B12: high variability for water but consistent over soil and vegetation



Alignment of S2C radiometry on S2A

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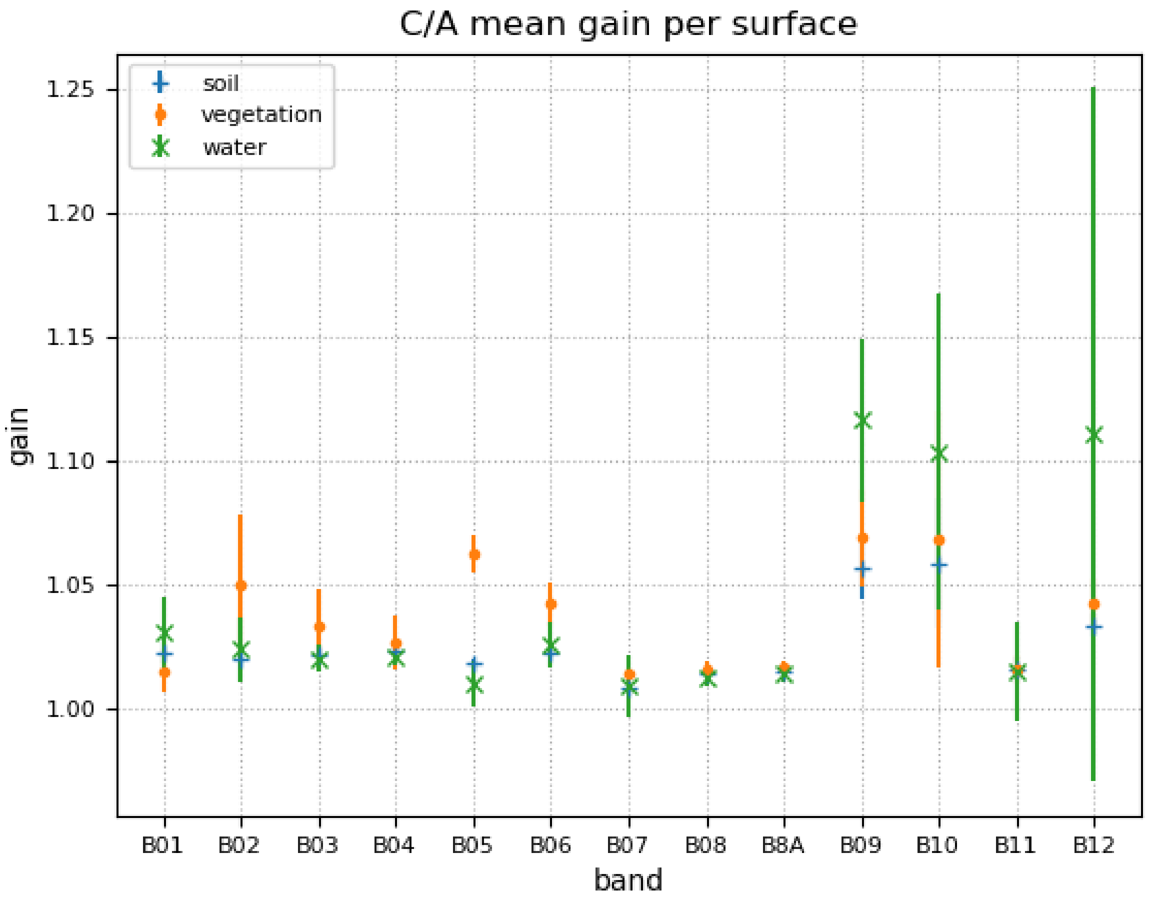
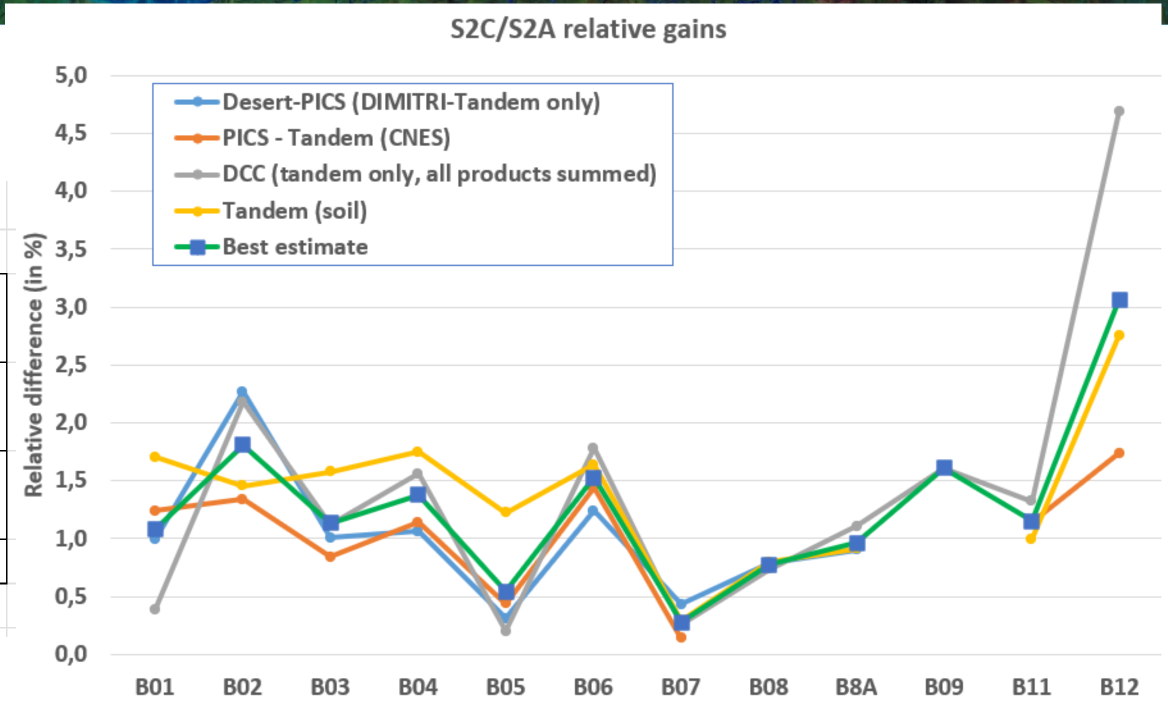
- Stability according to surface type
  - ✓ Vegetation impact for B05 & B06 expected (spectral difference between S2A & S2C)
  - ✓ Vegetation result over B02 is not fully undestood
  - ✓ Water not relevant in SWIR for the cross-comparison: very high standard deviation



Alignment of S2C radiometry on S2A

❖ Synthesis

	Relative gains 100*(C-A)/A (%)											
	B01	B02	B03	B04	B05	B06	B07	B08	B8A	B09	B11	B12
Desert-PICS (DIMITRI) Tandem only	0,99	2,27	1,01	1,06	0,31	1,24	0,43	0,79	0,90			
PICS - Tandem (CNES) Tandem only	1,24	1,34	0,84	1,14	0,44	1,44	0,14		0,94		1,14	1,74
DCC Tandem only	0,38	2,18	1,12	1,56	0,20	1,78	0,26	0,74	1,11	1,61	1,32	4,69
Tandem (soil only)	1,70	1,46	1,58	1,75	1,23	1,64	0,29	0,80	0,91		1,00	2,76
Best estimate	**1,08**	**1,81**	**1,14**	**1,38**	**0,54**	**1,52**	**0,28**	**0,78**	**0,96**	**1,61**	**1,15**	**3,06**



- ✓ **MSI-C reflectance values were higher than those of MSI-A** (during the IOC)
- ✓ Proposed alignment:
  - ➢ **Bands B01 to B09 and B11** :
    Apply a constant correction based on the mean value of various validation results: **~1.1 %**
  - ➢ **Band B12** (2190 nm): large dispersion → mean value ~ **3.1 %**
  - ➢ **Band B10** (1375 nm): no consistent results → kept unchanged

Conclusions

- Yaw manoeuvre performed for S2C
  - ✓ Beneficial for a better stabilisation of the equalisation → in operation since August 2025
  - ✓ Would be of interest for S2B and S2A too

- Differences of spectral bands between MSI sensors
  - ✓ Impact on comparison of measurements between S2A, S2B and S2C has been estimated
  - ✓ Red-edge and vegetation bands are the most impacted
  - ✓ Comparison over deserts and bare soils are the least impacted

- S2C radiometry has been aligned on S2A measurements

Thank you for your attention !

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OPT-MPC

Copernicus Sentinel

Optical Mission Performance Cluster

L1 processing chain

Dark signal correction

$DS_b\ (p,\ell) + PC_b^{masked}(p,\ell)$

Relative gain correction (non-linearity and non-uniformity of sensor response)

$X_b\ (p,\ell)$ → $Y_b\ (p,\ell) = X_b\ (p,\ell) - D_b\ (p,\ell)$ → $Z_b\ (p,\ell) = A_b \times L_b\ (p,\ell)$

Decompressed and on-board calibration removed

Dark corrected measurement

Equalized signal (in LSB)

Absolute gain

Equalised radiance (L1B) (in $W.m^{-2}.sr^{-1}.\mu m^{-1}$)

- Absolute and relative gains are obtained considering
  - ✓ Non-equalised measurement : $Y_{meas}(\mathrm{p},\ell)$
  - ✓ Equalised measurement: $Z_{meas}(\mathrm{p},\ell)$
  - ✓ Simulation of the measured radiance : $L_{simu}(\mathrm{p},\ell)$

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L1 processing chain

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Simulation of measured solar radiance :

$$L_{simu}(t,p,\ell) = K_{slt} \times \frac{BRDF_{dif}\big(ZSA(t,p,\ell), SAA(t,p,\ell)\big).E_{sun}.\cos(SZA(t,p,\ell))}{\pi.d_{sun}^2(t)}$$

Stray-light correction

Sun-diffuser BRDF
Pre-flight characterization

Earth to Sun distance (in A.U)
Fine calculation by Orekit flight dynamics library [2]

Solar irradiance for 1 A.U (pondered by its incidence angle)

Absolute gain estimate:

$$A_b = \frac{1}{N_\ell.N_p} \times \sum_{\ell,p} \frac{Z_{meas}(\mathrm{p},\ell)}{L_{simu}(\mathrm{p},\ell)}$$

L1 processing chain

Dark signal correction

$DS_b\ (p,\ell) + PC_b^{masked}(p,\ell)$

$X_b\ (p,\ell)$ → $Y_b\ (p,\ell) = X_b\ (p,\ell) - D_b\ (p,\ell)$ → $Z_b\ (p,\ell) = A_b \times L_b\ (p,\ell)$

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Equalised radiance (L1B) (in $W.m^{-2}.sr^{-1}.\mu m^{-1}$)

Cubic model for VNIR bands :

$$Z_{meas}(p,\ell) = G_1^{op}(p) \times Y_{meas}(p,\ell) + G_2^{op}(p) \times Y_{meas}^2(p,\ell) + G_3^{op}(p) \times Y_{meas}^3(p,\ell)$$

Operational relative gain coefficients

For each pixel and band,
updated equalisation coefficients can be obtained by:

$$\begin{cases} G_1^{up} = G_1^{op} \times R_a \\ G_2^{up} = G_2^{op} \times R_a^2 \\ G_3^{up} = G_3^{op} \times R_a^3 \end{cases}$$

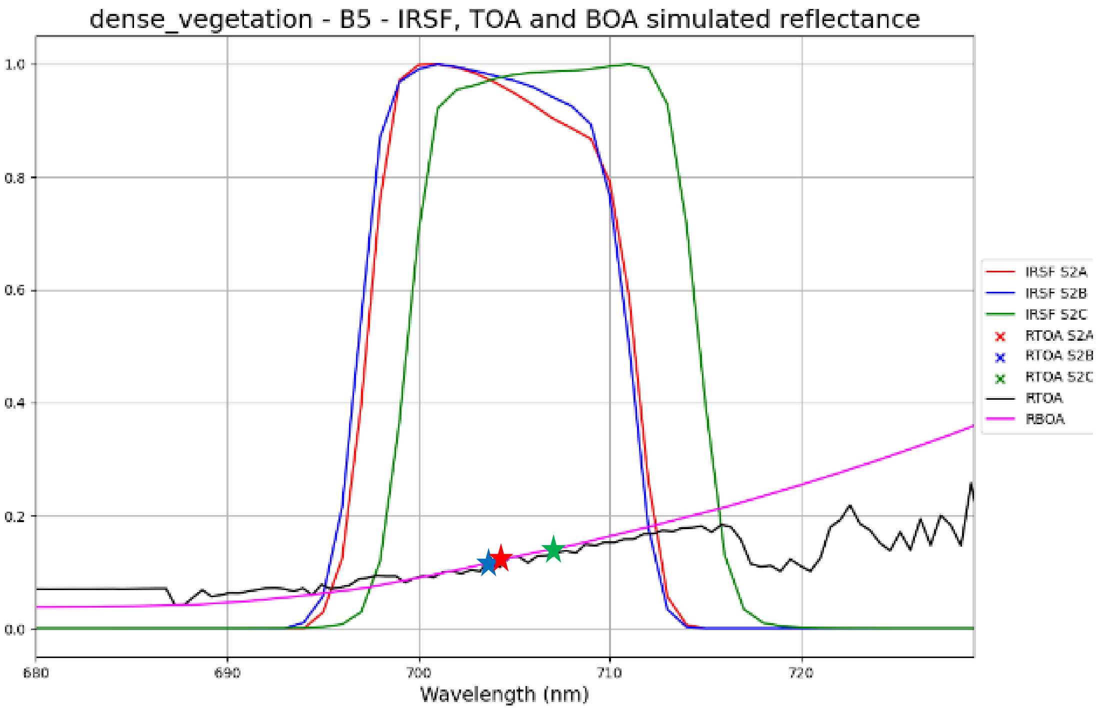
with

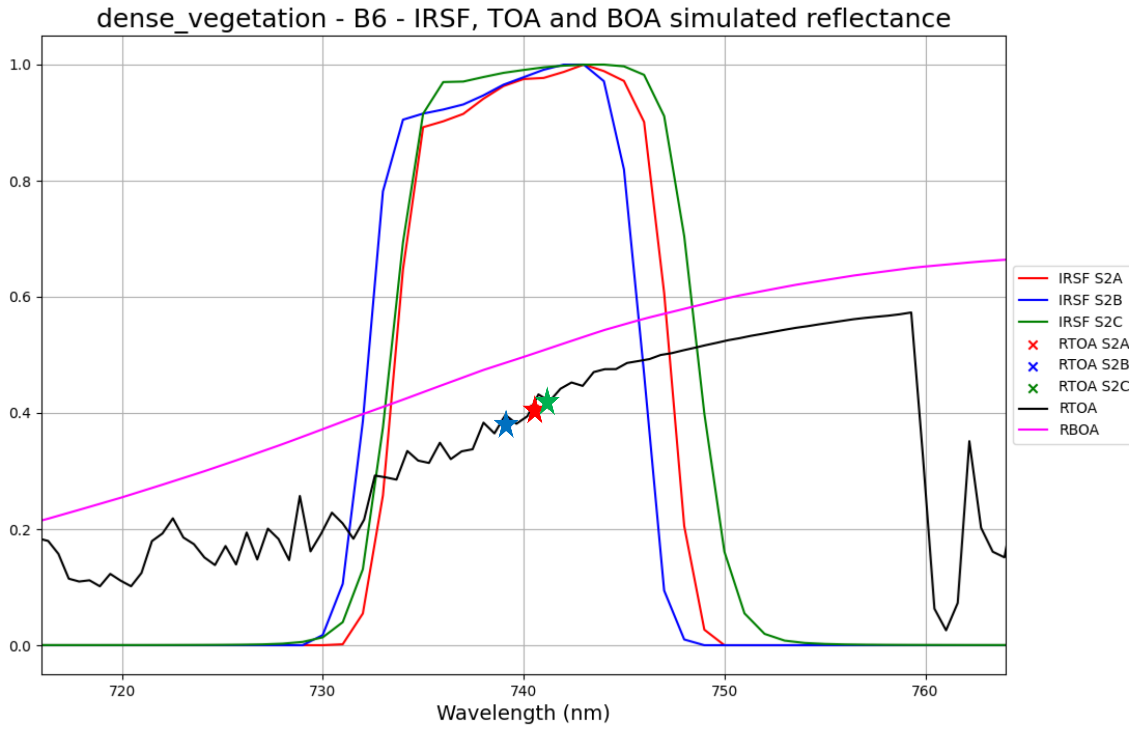
$$R_a(p) = \frac{\bar{Y}_{simu}(p)}{\bar{Y}_{meas}(p)}$$

Simulation (average line)

measurement (average line)

Simulation of measurements for bands B05 and B06 over dense vegetation





Simulation of measurements for bands B06 other snow

Shift toward short wavelengths for S2B + slope of TOA spectrum due to absorption
➔ Impact in relative comparison with S2A even if snow reflectance is high

Much more similar spectral bands for S2A and S2C
➔ very low relative differences of TOA reflectance over snow between S2A and S2C