Radiometric calibration intercomparison of Sentinel-2 MSI, Sentinel-3 OLCI and Landsat OLI using Deep Convective Clouds

Emphasis on the **Sentinel-2 MSI** and **Landsat OLI** DCC methods

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GSICS Meeting, July 13th, 2023
Online meeting

Context

Deep Convective Clouds for calibration monitoring

- DCC used for over two decades (*Vermote and Kaufman, 1995; Hu et al. 2004; Doelling et al. 2004…*)

- DCC properties:
  - ✓ high altitude (close to tropical tropopause)
  - ✓ high occurrence in the tropics
  - ✓ bright and white (high radiance, spectrally flat)
  - ✓ very vertically-extended, high optical thickness (low/no signal from beneath the cloud)

Expedition Crew 16, ISS, Image Science and Analysis Laboratory, Johnson Space Center

Deep Convective Clouds for calibration monitoring

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- DCC properties:
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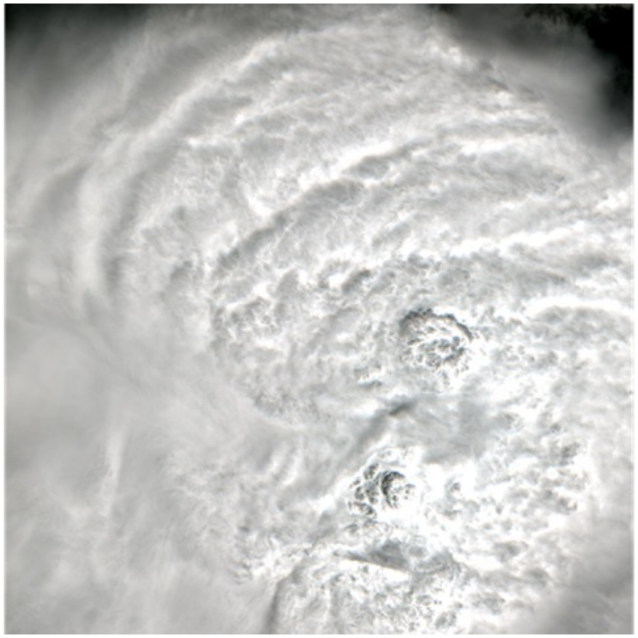
  - ✓ high occurrence in the tropics
  - ✓ bright and white (high radiance, spectrally flat)
  - ✓ very vertically-extended, high optical thickness (low/no signal from beneath the cloud)
  - ✓ can be very extended horizontally
  - ✓ nearly Lambertian



DCC extending over a complete S2 tile (~100x100 km²)

History of the ACRI-ST DCC method

DCC cross-sensor intercalibration → 2 twin sensors

- **Sentinel-3 OLCI A/B**
  - ✓ From November 2019
  - ✓ *Lamquin et al. (2020) OLCI A/B Tandem Phase Analysis, Part 3: Post-Tandem Monitoring of Cross-Calibration from Statistics of Deep Convective Clouds Observations. Remote Sens. 2020, 12, 3105. https://doi.org/10.3390/rs12183105*
- Adaptation to **Sentinel-2 MSI A/B**
  - ✓ From early 2022 to now
  - ✓ Presented at CALCON 2022: *Monitoring Sentinel-2 MSI inter-calibration using Deep Convective Clouds*
- Adaptation to **Landsat-8 OLI / Landsat-9 OLI-2**
  - ✓ From early 2022 to early 2023

DCC flowchart
Sentinel-2 MSI A and B

Methodology Sentinel-2 MSI

Copernicus data hub query

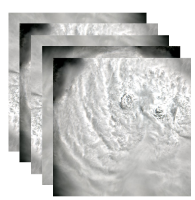
- For a given time period
- 90% min cloud cover

List of products

Filtering

- Footprint > 0.1
- -20 to 20° latitude
- B10 > 0.3 > 5e5
- Quality check

If OK



Good products list

~1200/2500 each month

For each product in Good products list:

Format data

- S2 L1C = TOA reflectance
- Down sample all bands to 60 m
- Scale to 0 - ~1 TOA reflectances

Get metadata

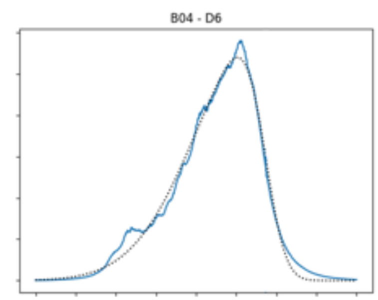
- Ozone in DU
- Sun-earth distance
- Angles (SZA, VZA)

DCC clusters extraction

- B10 > 0.4 & B8A > 0.7
- Remove small clusters
- Shadow dilation (avoid gaps)

DCC pixels processing

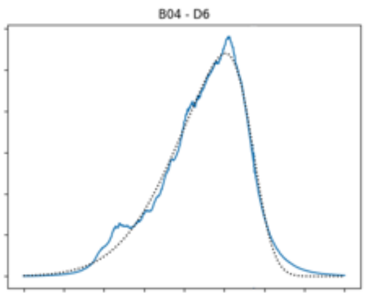
- Correction of gaseous trans.
- PDF of DCC pixels



Top of DCC reflectance PDF for each band and detector

~1200/2500 each month

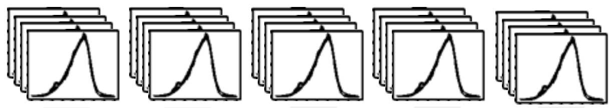
Methodology Sentinel-2 MSI



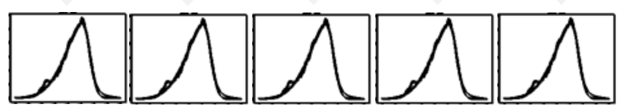
Top of DCC reflectance PDFs for each band and detector

~1200/2500 each month

5 batches of ~400 PDFs



Accumulation

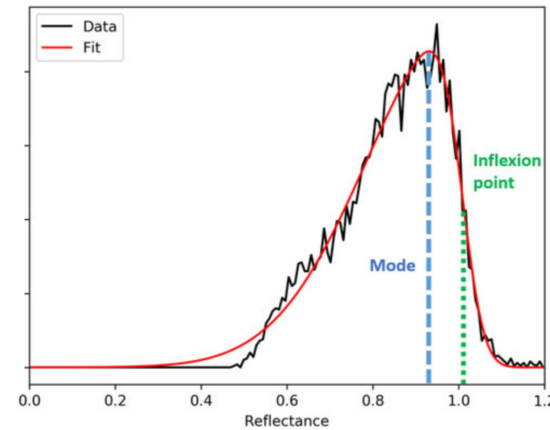


5 accumulated PDFs

For each accumulated PDF:

Skewed-Gaussian fit

Post-mode inflexion point extraction



Reflectance indicator
= $\text{mean}_{5\ \text{batches}}$ inflection points

Estimation of the random uncertainty
= $\text{STD}_{5\ \text{batches}}$ inflection points

For each band and detector

DCC flowchart
Landsat-8 and 9 OLI

Methodology Landsat OLI

Earth Explorer query

- For a given time period
- 90% min cloud cover
- -20 to 20° latitude

List of products

For each product in products list:

Filtering

- B9 > 0.3 > 2e6 (30m resolution)

If filtering OK:

Get metadata

- ~~Ozone~~
- Scaling factors
- Sun-earth distance
- Angles (SZA, VZA)

Format data

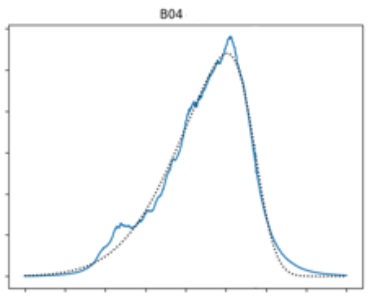
- Convert DN to reflectances using provided scaling factors

DCC clusters extraction

- B9 > 0.4 & B5 > 0.7
- Remove small clusters
- Shadow dilation (avoid gaps)

DCC pixels processing

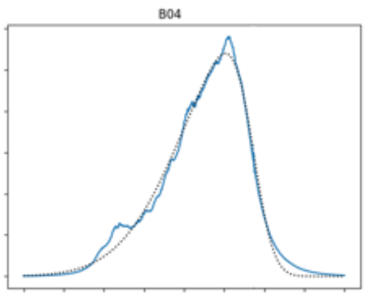
- Correction of gaseous trans.
- PDF of DCC pixels



Top of DCC reflectance PDF for each band ~~and detector~~

~200/300 each month

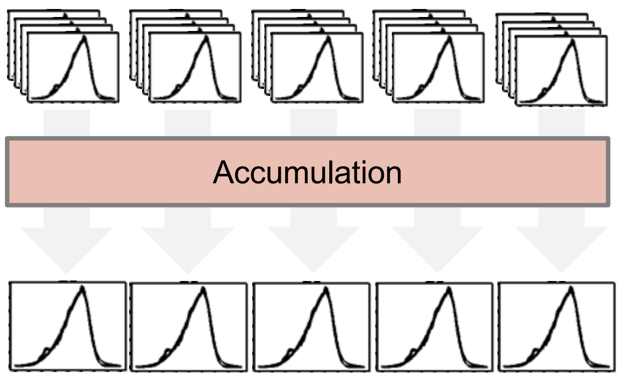
Methodology
Landsat OLI



Top of DCC reflectance PDFs for each band and ~~detector~~

~200/300 each month

5 batches of ~40/60 PDFs



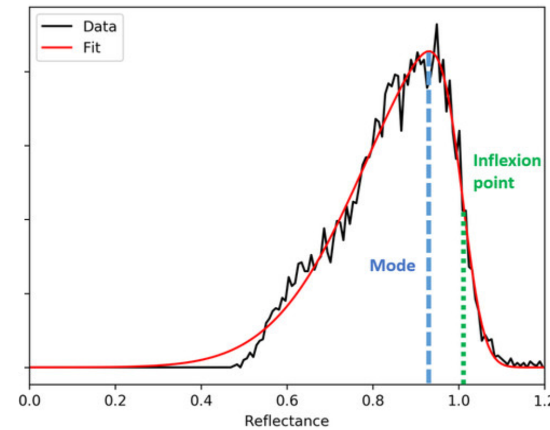
Accumulation

5 accumulated PDFs

For each accumulated PDF:

Skewed-Gaussian fit

Post-mode inflexion point extraction



Reflectance indicator
= mean$_{5\ batches}$ inflection points

Estimation of the random uncertainty
= STD$_{5\ batches}$ inflection points

For each band ~~and detector~~

Detailed methodology

Products filtering

Sentinel-2 | **Landsat-8/9**

Sentinel-2

Copernicus data hub query

- For a given time period
- 90% min cloud cover

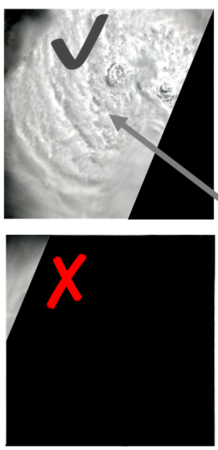
↓

List of products

↓

Filtering

- Footprint > 0.1
- -20 to 20° latitude
- B10 > 0.3 > 5e5
- Quality check



Product rejected if any missing data inside footprint area

~square area of 42 x 42 km²

Landsat-8/9

Earth Explorer query

- For a given time period
- 90% min cloud cover
- -20 to 20° latitude

↓

List of products

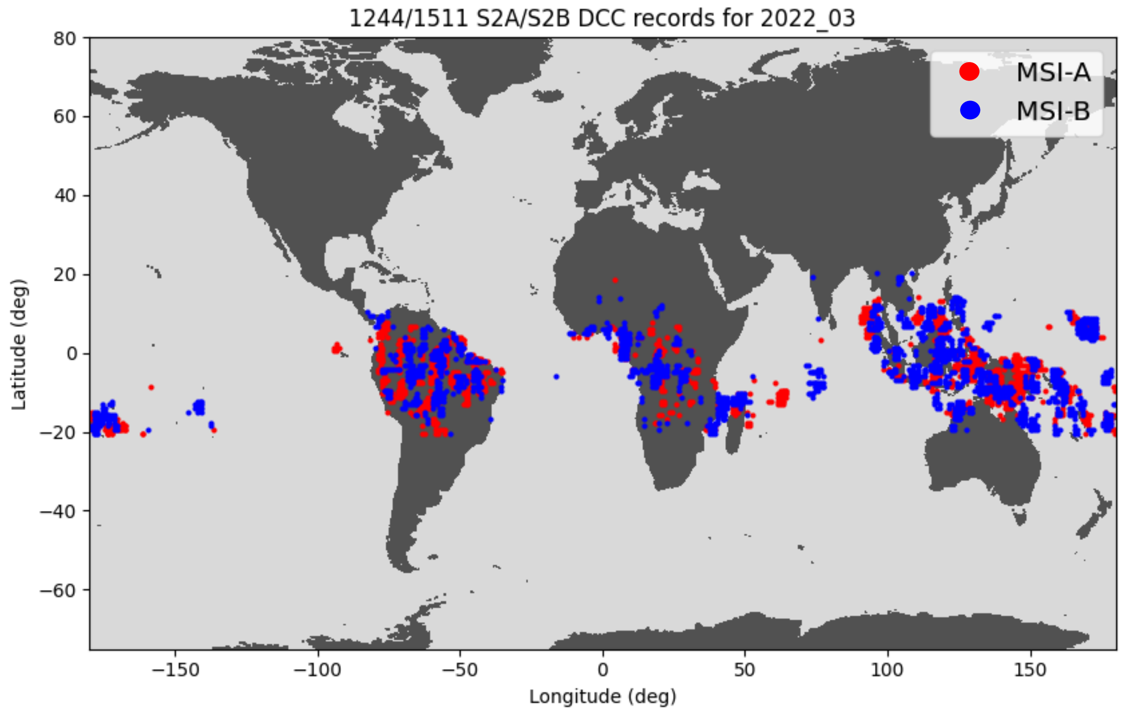
↓

For each product in products list:

Filtering

- B9 > 0.3 > 2e6 (30m resolution)

Products filtering



Example localization of the DCC products for Sentinel-2 MSI, March 2022.

Formatting

Sentinel-2 | **Landsat-8/9**

Sentinel-2

Format data

- S2 L1C = TOA reflectance
- Down sample all bands to 60 m
- Scale to 0 - ~1 TOA reflectances

Divide by 10000

Get metadata

- Ozone in DU
- Sun-earth distance
- Angles (SZA, VZA)

Provided in auxiliary data

Landsat-8/9

Get metadata

- ~~Ozone~~
- Scaling factors
- Sun-earth distance
- Angles (SZA, VZA)

Not provided

Format data

- Convert DN to reflectances using provided scaling factors

$$\rho_{TOA|\lambda} = (M_\rho\, Q_{cal} + A_\rho) / \cos(SZA)$$

With:

$\rho_{TOA|\lambda}$ the TOA reflectance,

M_ρ the band-specific multiplicative scaling factor,

Q_{cal} the quantized and calibrated standard product pixel values (DN),

A_ρ the band specific additive scaling factor,

cos(SZA) the local sun zenith angle.

Processing

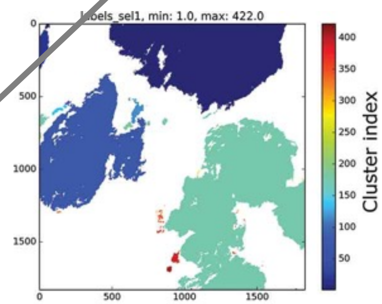
Sentinel-2

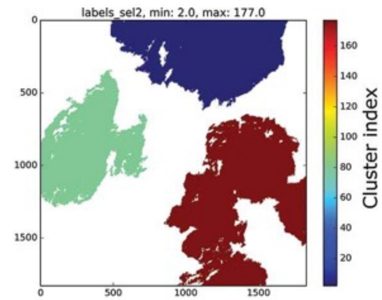
DCC clusters extraction
▪ **B10** > 0.4 & **B8A** > 0.7 ▪ Remove small clusters ▪ Shadow dilation (avoid gaps)

→ Get clusters from thresholds on cirrus and NIR bands

→ Label clusters from scipy.ndimage.label

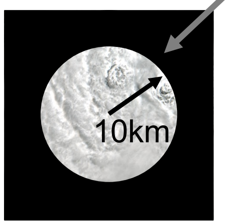
→ Remove cluster with area lower than 314 km²



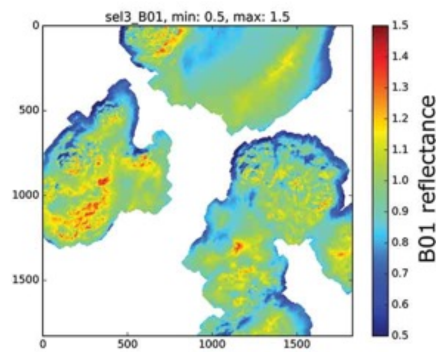


Landsat-8/9

DCC clusters extraction
▪ **B9** > 0.4 & **B5** > 0.7 ▪ Remove small clusters ▪ Shadow dilation (avoid gaps)



→ Iterative dilation (30 pixels for S2, 60 for Landsat) of clusters by binary erosion of the negative mask (scipy.ndimage.binary_erosion): remove gaps and get continuous DCCs



Processing

Sentinel-2 **Landsat-8/9**

DCC pixels processing

- Correction of gaseous trans.

Nadir gaseous transmissions from top of DCC to TOA using RTM (ARTDECO code)
Standard profiles of H_2O, NO_2, O_2, CO_2, CH_4
Fixed DCC height of 16 km

Variable content of O_3 (from 200 to 350 DU)

Fixed content of O_3 (260 DU)

$$\rho_{DCC}(\theta_s, \theta_v, \Delta\varphi, \boldsymbol{\lambda}) = \rho_{\boldsymbol{TOA}}(\theta_s, \theta_v, \Delta\varphi, \boldsymbol{\lambda}) \;/\; T_{gas}(\theta_s, \theta_v, \boldsymbol{\lambda})$$

With:

$Tgas = T_{gas|nadir}^{airmass/2}$

airmass = 1/cos(SZA) + 1/cos(VZA)

$T_{gas|nadir}$ is the gaseous transmission, function of ozone content of the product

$T_{gas|nadir}$ is the gaseous transmission, with the assumption of a fixed content of ozone

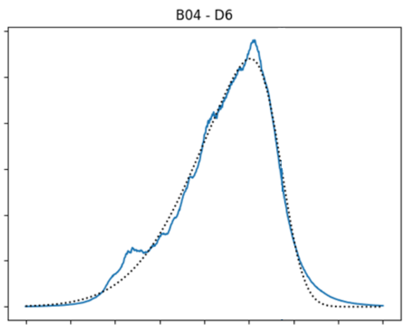
Processing

Sentinel-2 | **Landsat-8/9**

DCC pixels processing

- PDF of DCC pixels

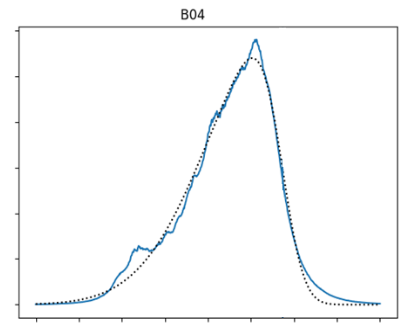
Calculation of a Probability Density Function for the selected top of DCC reflectances
From 0.5 to 1.3 with a reflectance step of 0.001 for VNIR bands
From 0 to 0.8 with the same step for SWIR bands (lower reflectances)
Typically a hundred thousand to millions of pixels selected



One distribution for **each band** and **each detector*** for each processed product

Typically, ~1200/2500 products each month both for S2A/S2B

**All 12 detectors are not present in a single image, S2 swath is of 290 km while products are about 100 width*



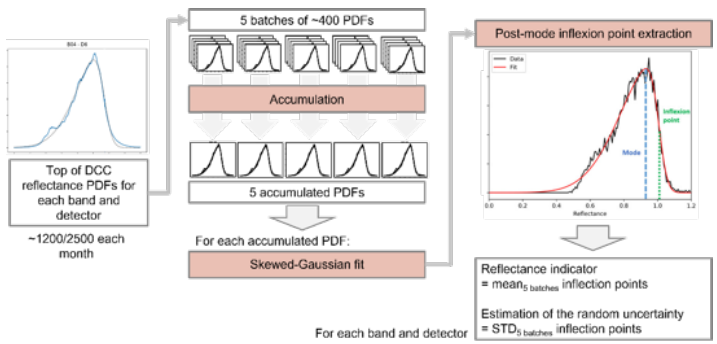
One distribution for **each band** for each processed product

Typically, ~200/300 products each month both for Landsat-8 and 9

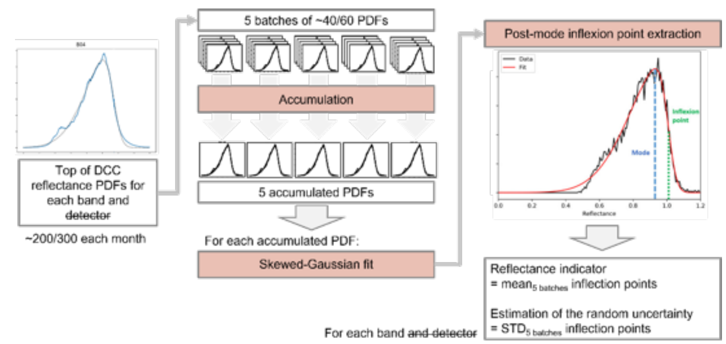
Post processing

Once a month of DCC corrected reflectance PDFs have been collected:

Sentinel-2



Landsat-8/9



→ Random draw of 5 batches of PDFs (~400 per batch for S2, 30/40 per batch for Landsat)

→ PDFs from each batch are accumulated to form one single PDF per month / per batch / per band / per det. for S2

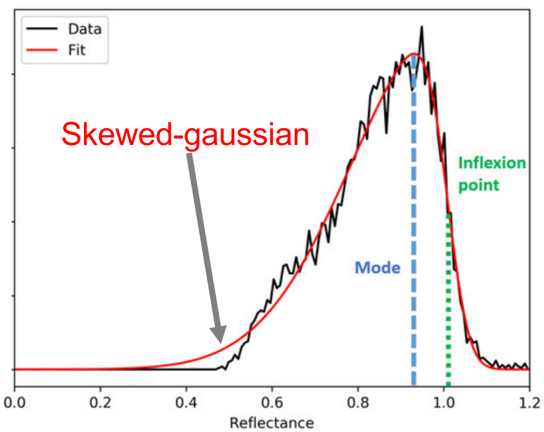
→ Fit of a skewed-gaussian function over the accumulated PDF

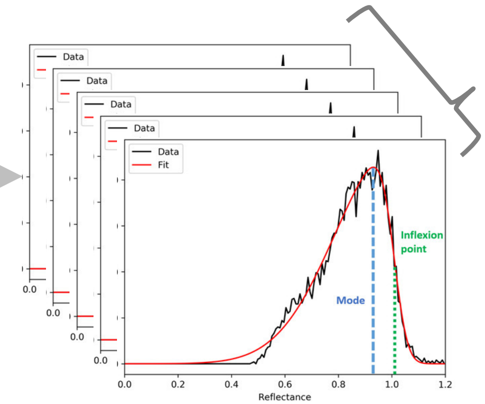
Post processing

Sentinel-2, for each band and detector

Landsat-8/9, for each band only

Post-mode inflexion point extraction



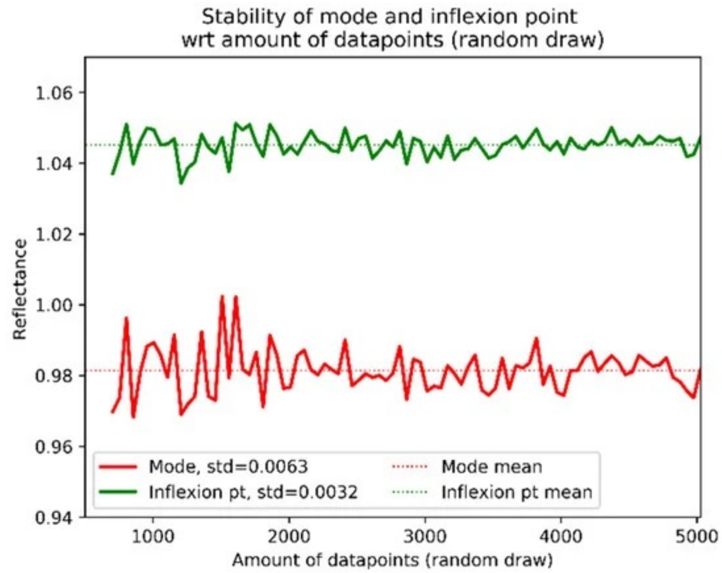


5 batches

Reflectance indicator
= $\text{mean}_{5\ \text{batches}}$ inflection points

Estimation of the random uncertainty
= $\text{STD}_{5\ \text{batches}}$ inflection points

Post processing

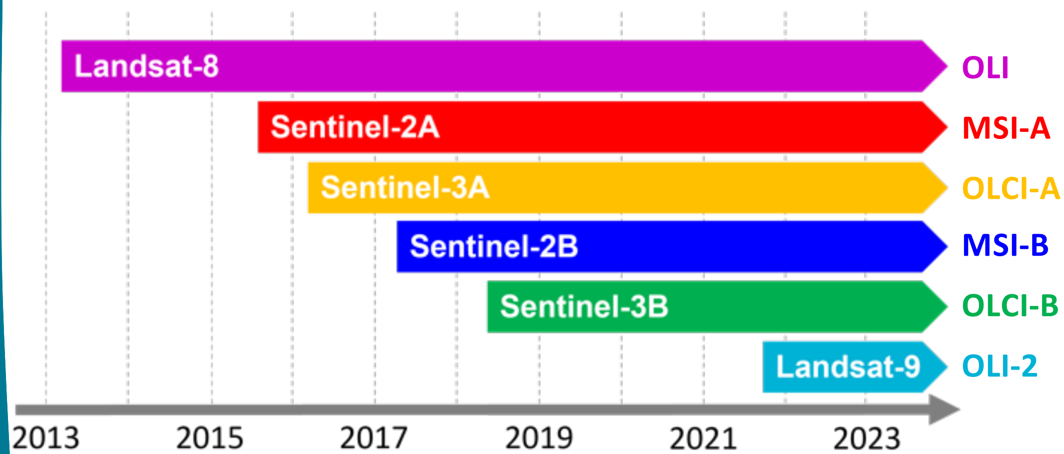


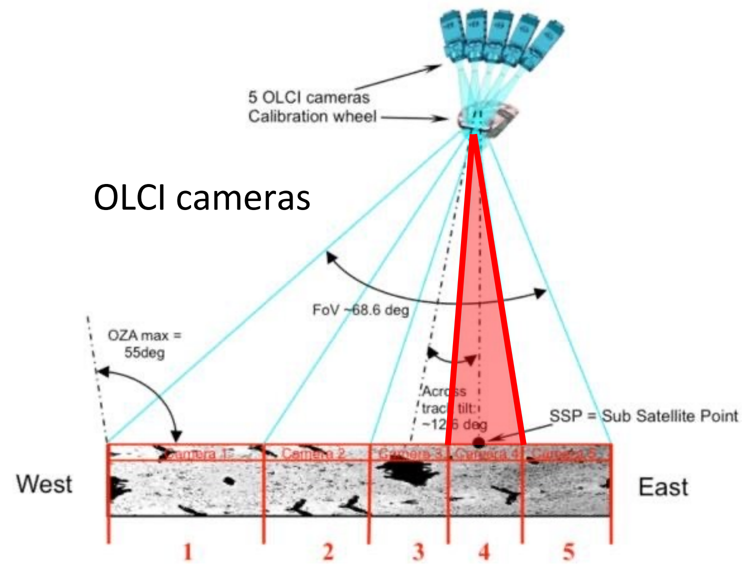
From *Lamquin et al. (2020) OLCI A/B Tandem Phase Analysis, Part 3: Post-Tandem Monitoring of Cross-Calibration from Statistics of Deep Convective Clouds Observations. Remote Sens. 2020, 12, 3105. https://doi.org/10.3390/rs12183105*

Definition of the objectives

Objectives definition

Application of DCC method to 6 multispectral sensors



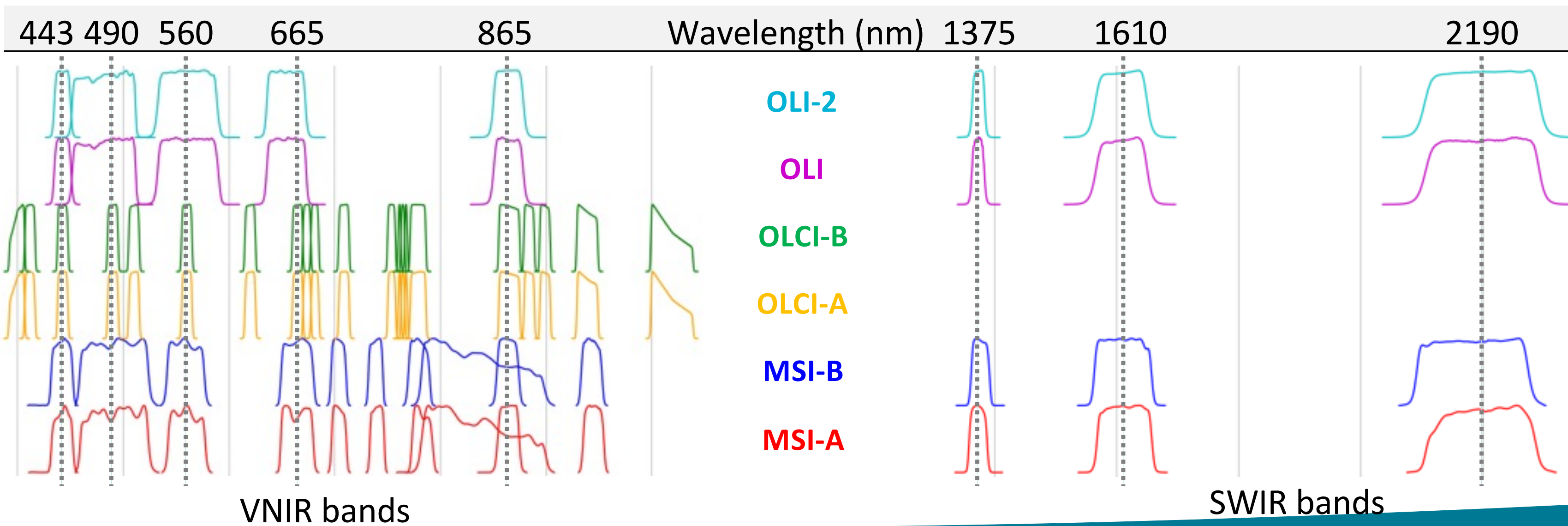


- Comparisons between twin sensors (cross-comparisons)
- 185, 290 and 1270 km swath for Landsat, S2 and S3
  - ✓ Use of near-nadir camera only for S3 (cam-4)
- Comparisons between all sensors (time-series intercomparisons) from March 2022 to January 2023

Objectives definition

Bands of interest

- Focus on several "comparable" bands
  - ✓ 5 in the VNIR (for all sensors)
  - ✓ 3 in the SWIR (OLCI excepted)



Objectives

Objectives are:

- Follow the intercalibration of each pair of "twin" sensors
- Follow the relative levels of the comparable bands of the different missions
- Detect a potential drift

Objectives aren't:

- Provide an absolute level of radiometric calibration
- Rank the sensors in terms of radiometric accuracy

Results

Results

Average spectra

OLI-2

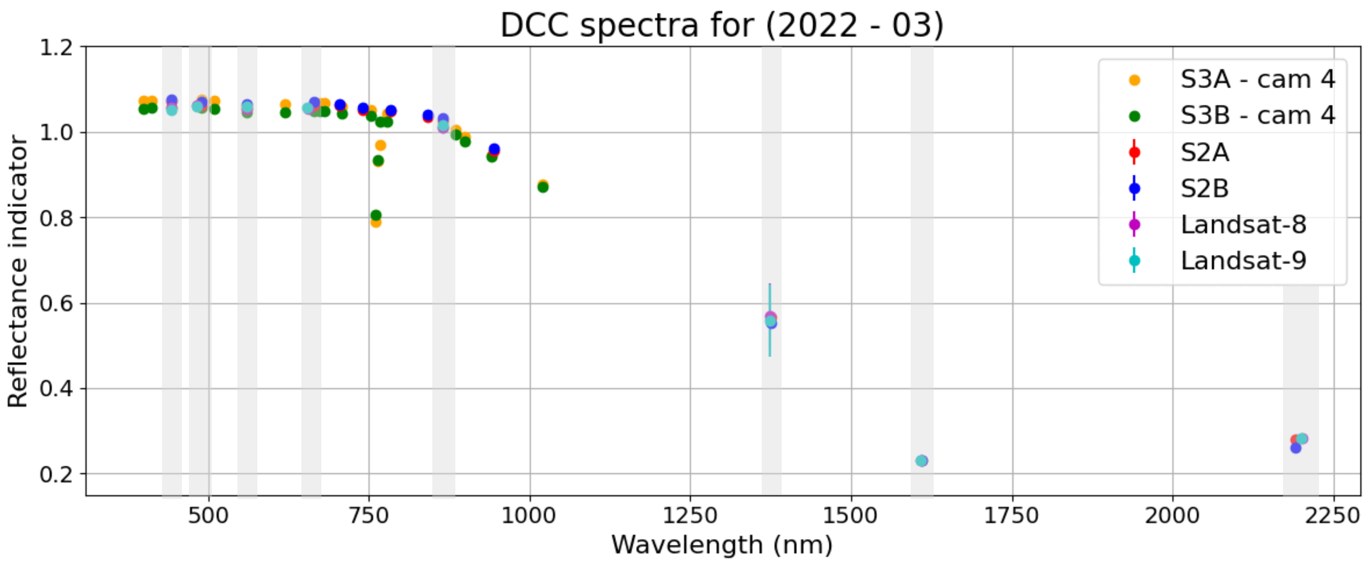
OLI

OLCI-B

OLCI-A

MSI-B

MSI-A



Sensor-wise:

- VNIR: 3 % dispersion (except 01/2023 443nm, ~4%)
- Alignment of 1610 nm SWIR band ~correct
- More dispersion in cirrus and last SWIR band

Temporally:

- Each sensor’s VNIR band within 2 %
- More variability in the SWIR (cirrus band)

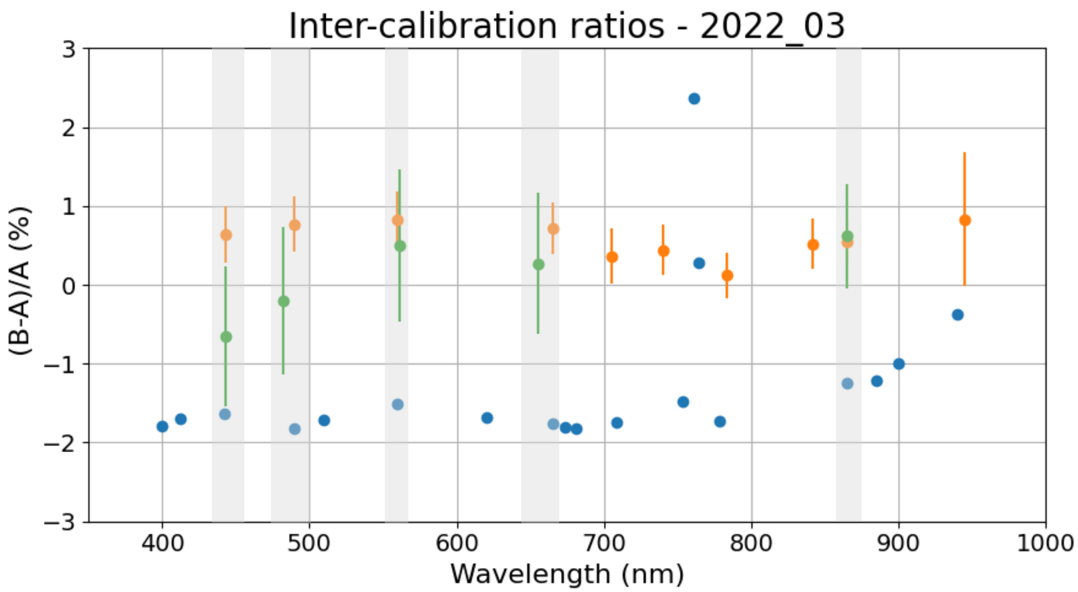
Results

VNIR inter-calibration ratio

$$\frac{OLI2 - OLI}{OLI} \times 100$$

$$\frac{MSIB - MSIA}{MSIA} \times 100$$

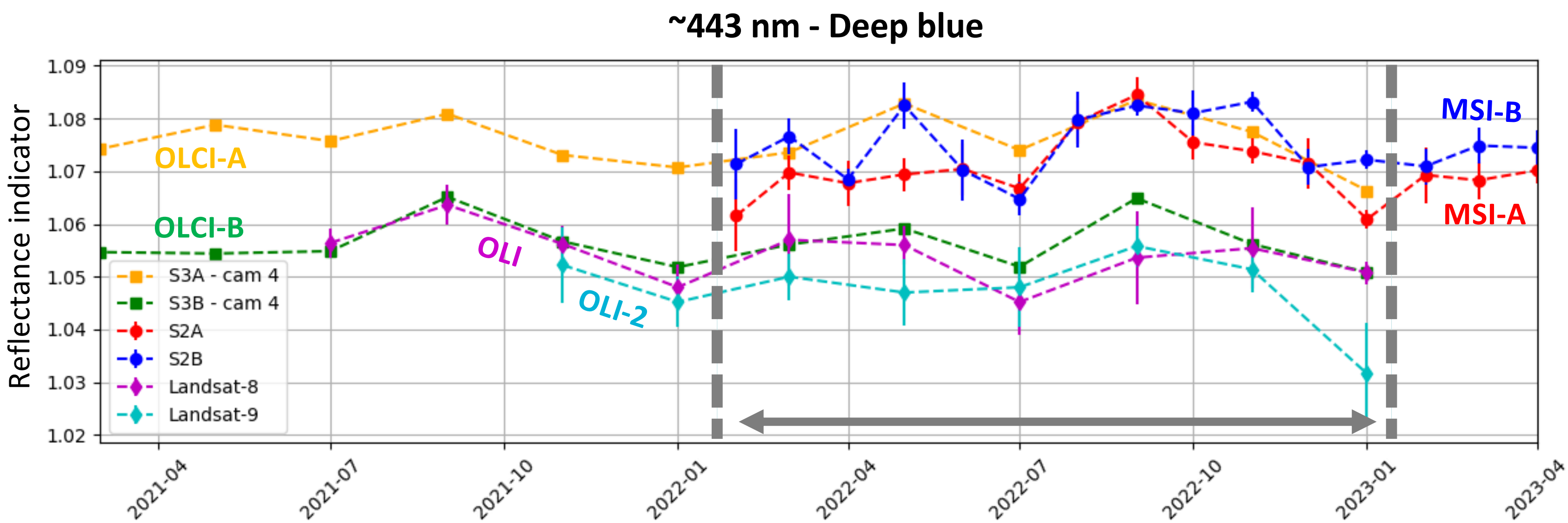
$$\frac{OLCIB - OLCIA}{OLCIA} \times 100$$



- S3 bias: ~2 % in the VIS, ~1 % in the NIR, OLCI-A brighter
- S2 ratios: around 0, up to 1.5 %
- Landsat: similar with more dispersion (lower number of products)

Results

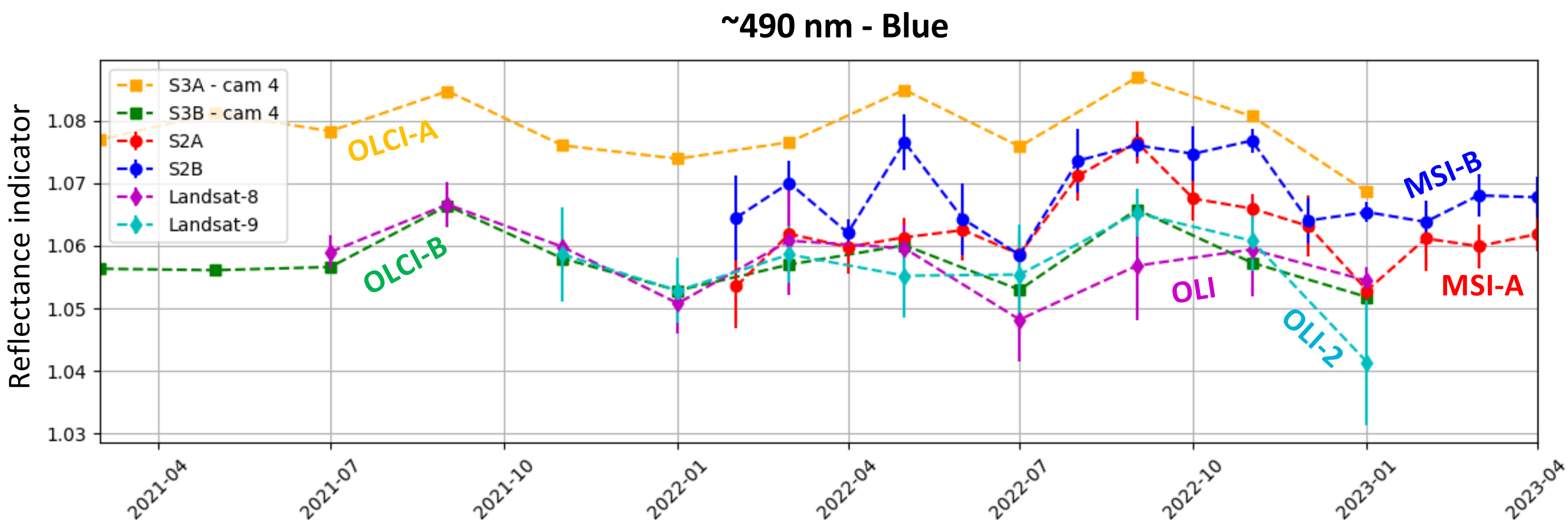
Time-series



- OLCI-A and OLCI-B : 1.5 to 2% stable bias
- MSI-A and MSI-B ~aligned with OLCI-A
- OLI and OLI-2 ~aligned with OLCI-B
- MSI-A and MSI-B within 1%
- OLI and OLI-2 within 1% (except 01/2023)
- Overall dispersion of 3% max. (except 01/2023)

Results

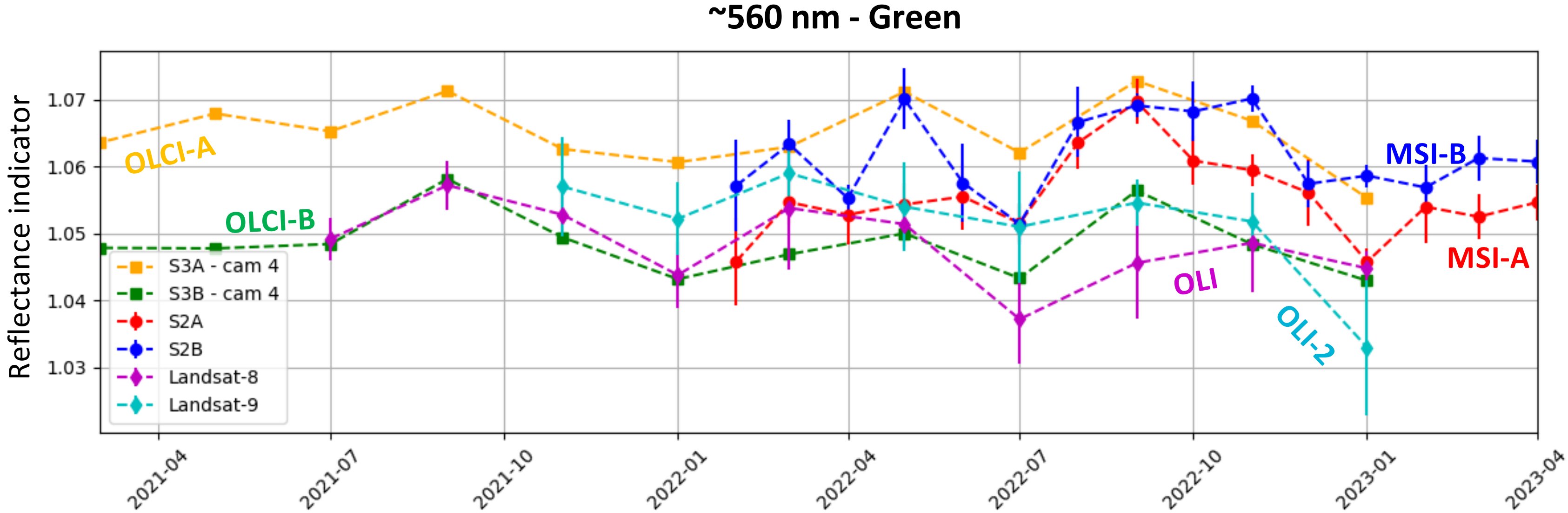
Time-series



- OLCI-A and OLCI-B : 1.5 to 2.5% stable bias
- OLI and OLI-2 ~aligned with OLCI-B
- MSI-A and MSI-B between OLCI-A and OLCI-B
- Overall dispersion of 3% max.

Results

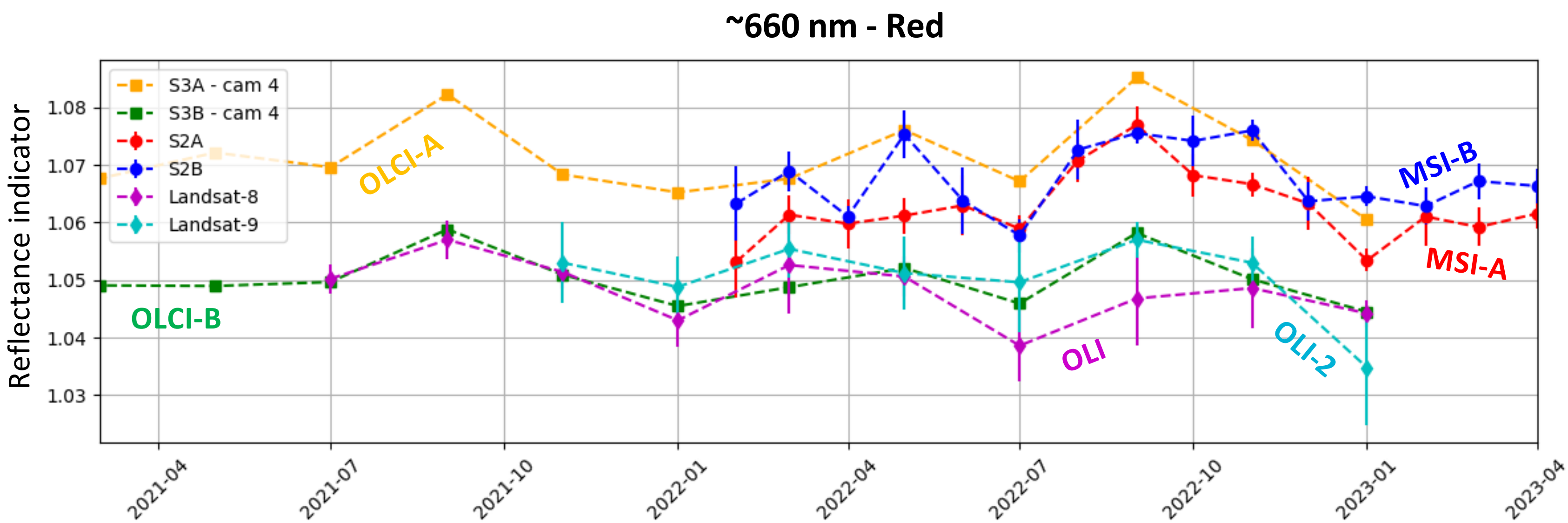
Time-series



- Lower bias between OLCI-A and OLCI-B (1 - 2% max.)
- Lower overall dispersion: 2.5% max. in July and Sept. 2022, January 2023

Results

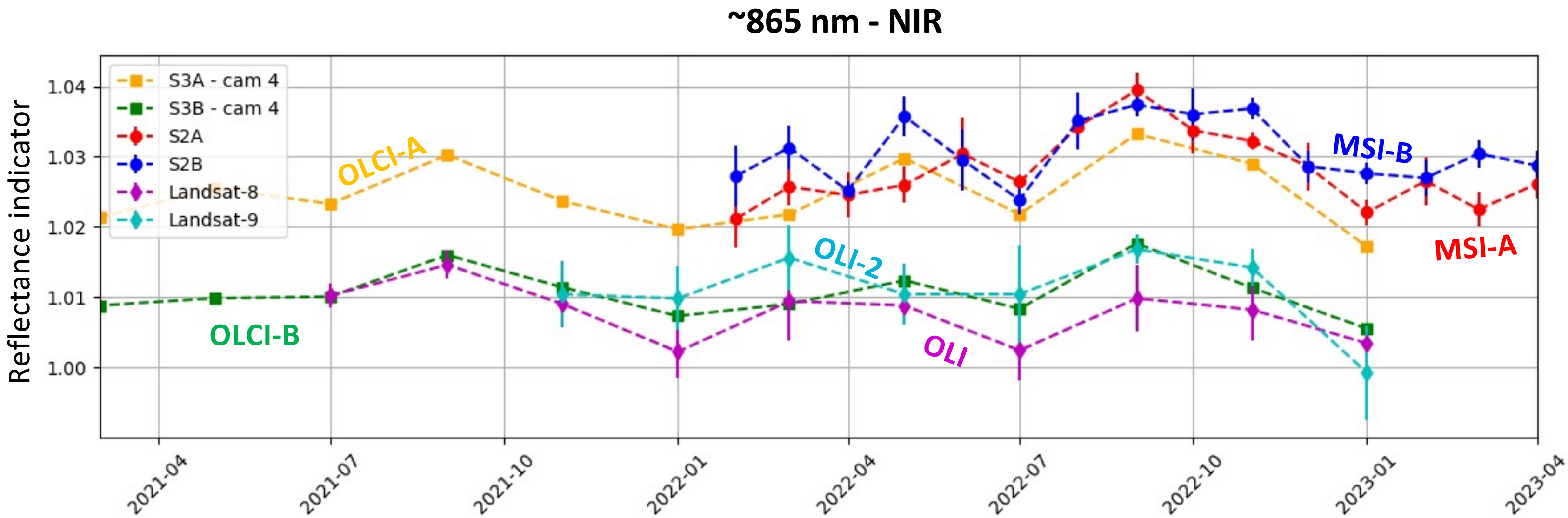
Time-series



- Like green band with higher overall dispersion: 2 to ~4 % max. in Sept. 2022

Results

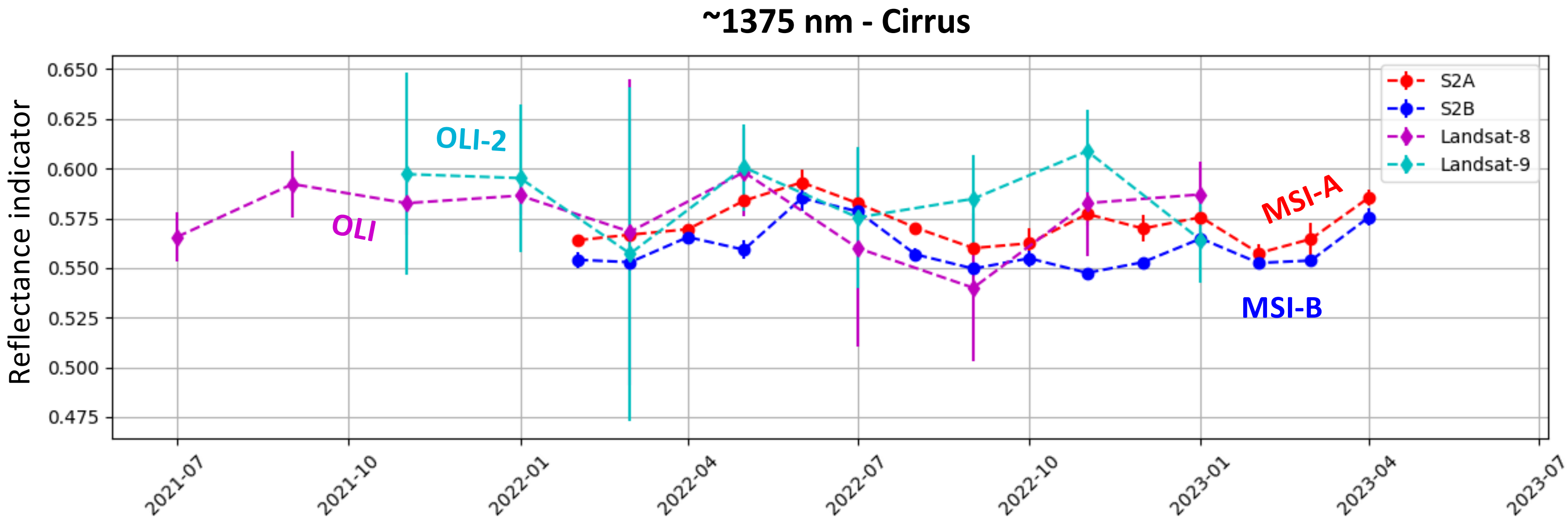
Time-series



- Lower bias between OLCI-A and OLCI-B (1.5% max.)
- Like 443 nm deep blue band:
  - ✓ MSI-A and MSI-B ~aligned with OLCI-A
  - ✓ OLI and OLI-2 ~aligned with OLCI-B

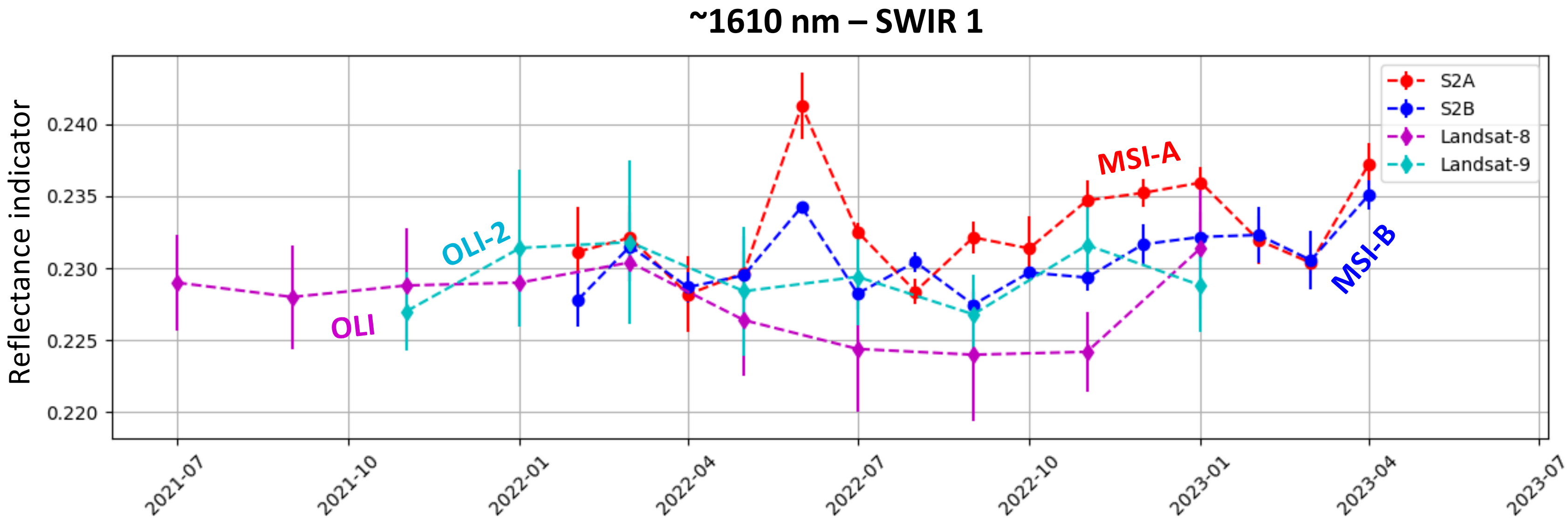
Results

Time-series



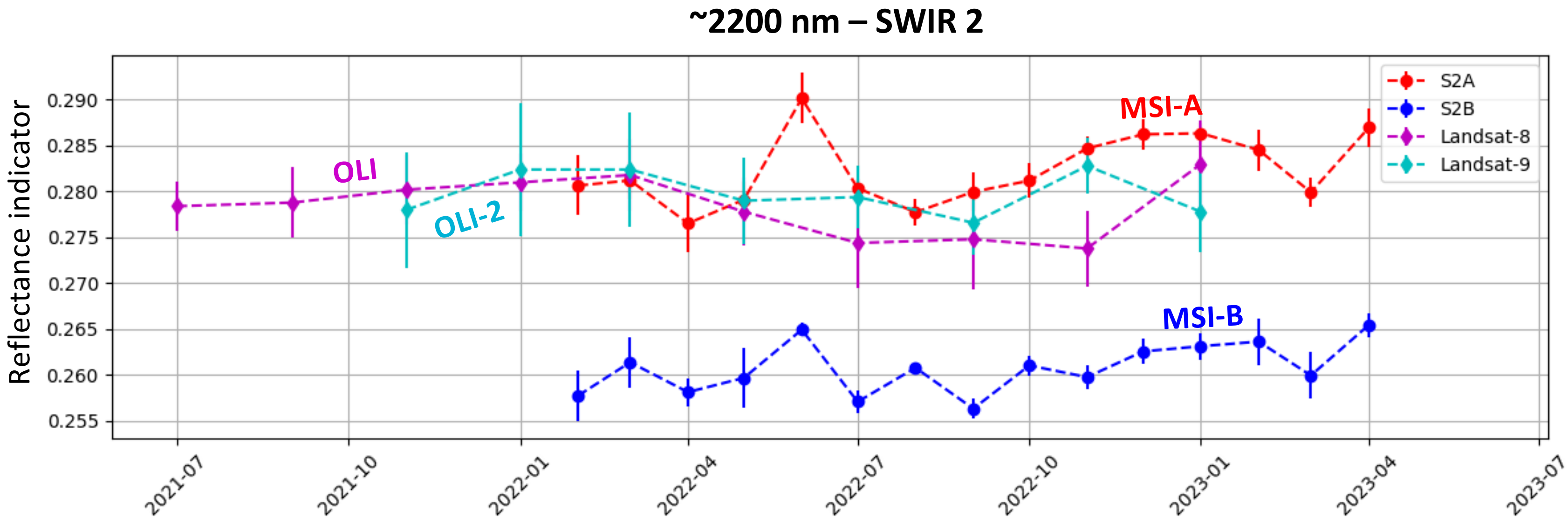
- Curves squeezed by big error bars
- Overall dispersion: ~11% max. (Nov. 2022)
- Overall dispersion: < 4% min. (March 2022)
- Known saturation effects for **MSI-A** and **MSI-B**

Time-series



- Peak in June 2022 for **MSI-A** and **MSI-B**
- Good alignment of **OLI** / **OLI-2** and **MSI-A** / **MSI-B** early 2022
- Deviation until Nov. 2022, converge again in Jan. 2023

Time-series



- Important bias between **MSI-A** and **MSI-B** (~8%)
- **OLI** / **OLI-2** aligned with **MSI-A** early 2022, slight deviation after

Conclusions and perspectives

Conclusions and perspectives

Conclusions

- **In the VNIR:**
  - ✓ **MSI-A** and **MSI-B** bias from 0 to 1.5%
  - ✓ **OLI** and **OLI-2** bias from 0 to 1.5%
  - ✓ **OLCI-A** and **OLCI-B** cam-4 bias from 1 – 2.5% (very stable)
  - ✓ **MSI-A** and **MSI-B** between **OLCI-A** and **OLCI-B** cam-4 levels
  - ✓ **OLI** and **OLI-2** aligned with **OLCI-B** (cam-4)

- **In the SWIR:**
  - ✓ 4 to 11% overall dispersion in cirrus band
  - ✓ Strong bias between **MSI-A** and **MSI-B** for 2200 nm band (8%)
  - ✓ **OLI** and **OLI-2** aligned with **MSI-A** for 2200 nm band
  - ✓ Peak in June 2022 for **MSI-A** and **MSI-B** in SWIR 1 and 2, TBC with **OLI** and **OLI-2** data

- **Overall:**
  - ✓ No systematic drift

Conclusions and perspectives

Perspectives

- In-progress work
  - ✓ Missing months for Sentinel-3 and Landsat
  - ✓ Automation of the Landsat DCC
  - ✓ Automation of the Sentinel-3 DCC (+ saturation effects correction)

- Foreseen activities
  - ✓ Use the 5 OLCI cameras (+ directional effects correction)
  - ✓ Saturation effects for Landsat OLI and Sentinel-2 MSI ?
  - ✓ Generic DCC tool for any multi/hyperspectral sensor

Thank you !

Backup slides

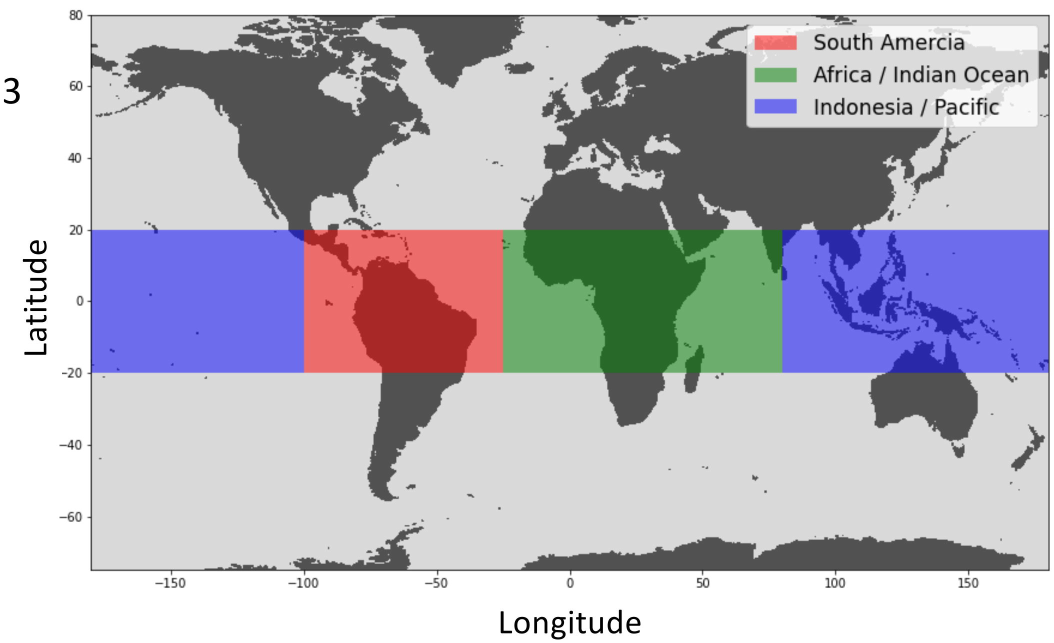
Limitations

- Payloads and missions have some major differences: swath, resolution, revisit, bands…
- Sentinel-2 and Landsat for land monitoring, Sentinel-3 for marine observation: acquisition plan differs.
- Sentinel-3 DCC detection uses a different method, taking advantage of SLSTR 10.8 µm TIR band.
- Transmission spectra used for Sentinel-3 slightly differs from spectra used for Sentinel-2 and Landsat.
- Transmissions corresponding to a mean ozone content are used for Landsat.
- Products from a greater latitude range are considered for Sentinel-3 (-25° – 25°).
- The use of post-mode inflexion point may depend on the context, it is subject to discussion.
- The effects of spectral band shape are currently being investigated at ACRI-ST, in a different context.

Per-zone results

Distinction of geographical regions

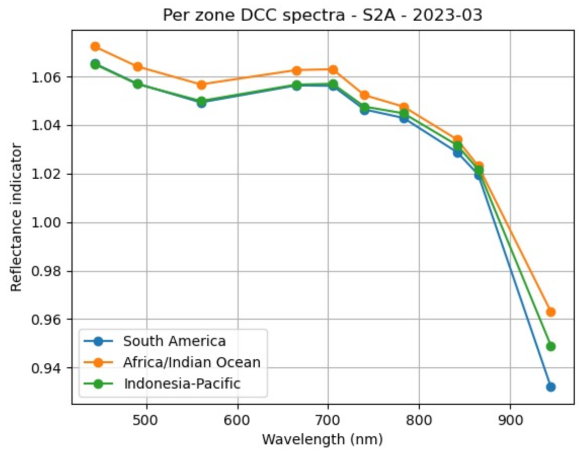
- To investigate regional effects
- Exact same methodology + distinction of 3 zones:
  - ✓ South America (-100°: -25° lat.)
  - ✓ Africa / Indian Ocean (-25°: 80° lat.)
  - ✓ Indonesia / Pacific (80°: -100° lat.)

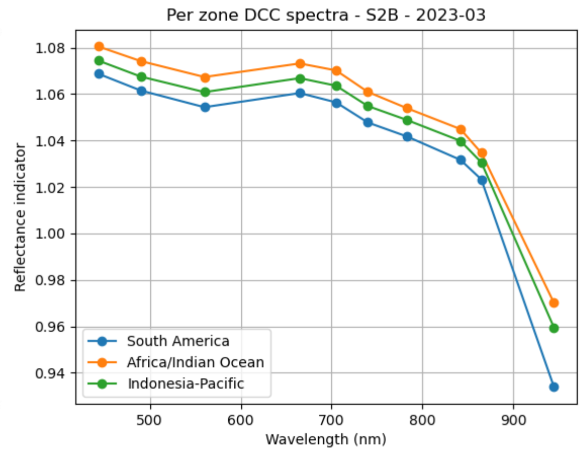


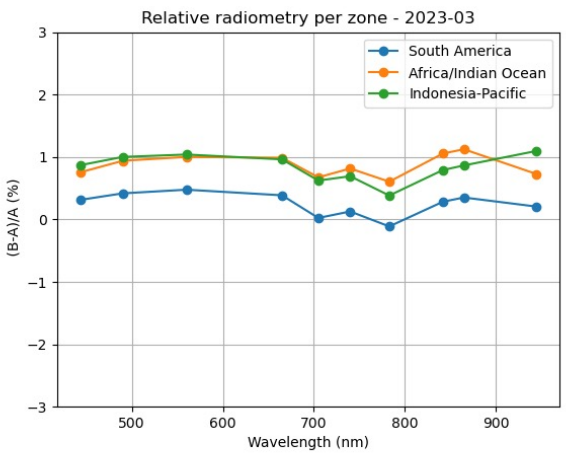
Per-zone results

Per-zone

- Coming soon
- Examples for Sentinel-2, March 2023



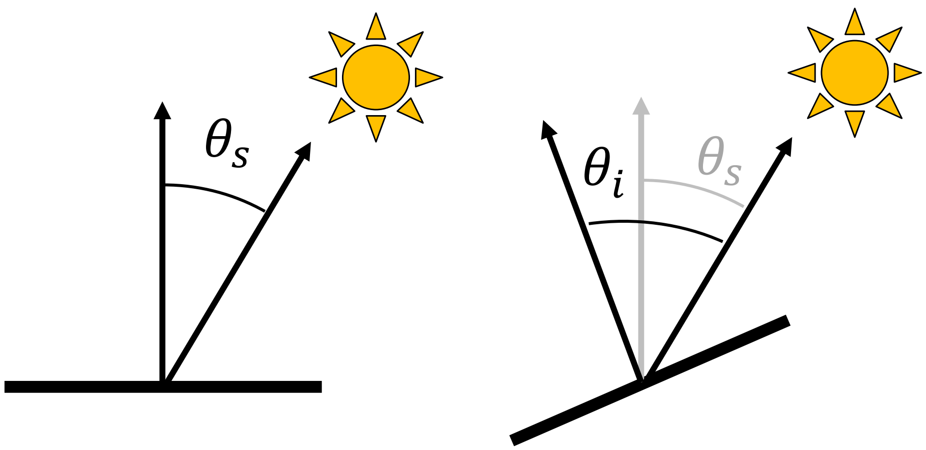




Why is there reflectances greater than 1 ?

Topology of the clouds and reflectance conversion

$$\rho(\theta_s, \phi_s, \theta_v, \phi_v) = \frac{\pi . L(\theta_s, \phi_s, \theta_v, \phi_v)}{Es. cos(\theta_s)}$$



- Reflectance normalized by cos(θ_s), the angle between the direction of the sun and the vertical
- Should be normalized by cos(θ_i), the angle between the direction of the sun and the normal to the surface, but the "topography" of the cloud is unknown