CEOS WGCV IVOS 35,
Oberpfaffenhofen, Germany
25-29/09/2023

CEOS

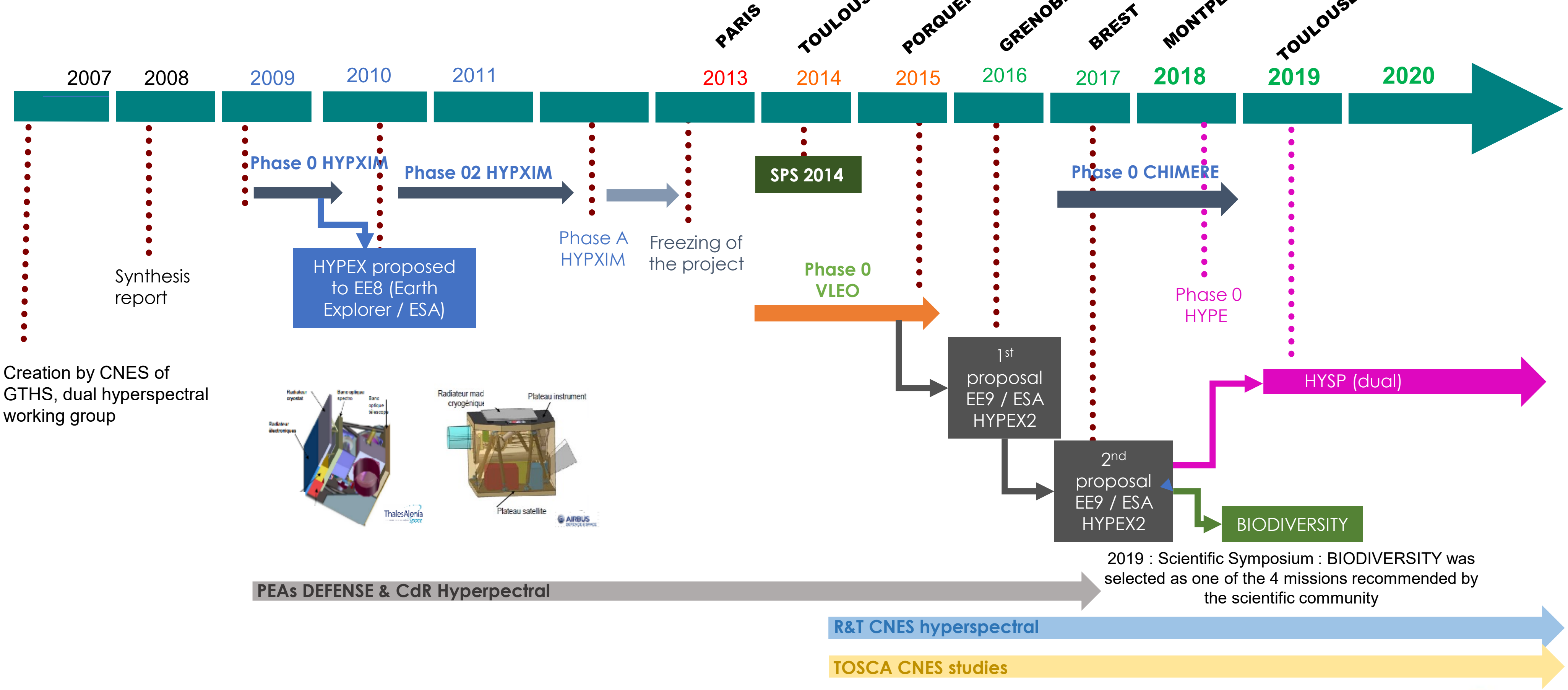
CNES ACTIVITIES FOR HYPERSPECTRAL

Aimé Meygret, Thierry Carlier, Camille Desjardins, Arthur Dick,
Thierry Erudel*, Morgan Farges**, Antoine Flipo, Bruno Lafrance*, Lucas Landier,
Xavier Lenot*, Sébastien Marcq, Robin Marron, Damien Rodat, Jean-Pascal Burochin**
Stéphanie Bourdeau, Nicolas Guilleminot***,
Ettore Lopinto****, Leandro Chiarantini*****, Francesco Sarti*****,
Raquel de los Reyes******, Martin Bachman******

* CS GROUP ** magellium *** THALES cnes **** ASI Agenzia Spaziale Italiana ***** LEONARDO ELECTRONICS ****** DLR

History

For many years, hyperspectral work carried out with scientists, DGA and CNES support



History – HYSP phases A

= Demonstration program for a dual defence/civil hyperspectral system with requirements coming from the previous studies, with 10m spatial resolution

Phase A1 : 2019-2020

System studies initiated by DGA in collaboration with an international partner.

- Study of different concepts for the instrument

⇒ The best ratio performances/complexity-cost was given by an instrument with filters for the targeted spatial resolution

Phase A2 : mid 2021 - mid 2022

Mission Group studies to optimize the instrument operating point (SNR, radiometric accuracy, spectral sampling and resolution)

Looking for a new partner

History – HYSP phases A

September 2022 : new international partner identified

October 2022-December 2022 : bilateral discussions on the sharing of the system development and the exploitation of the mission:

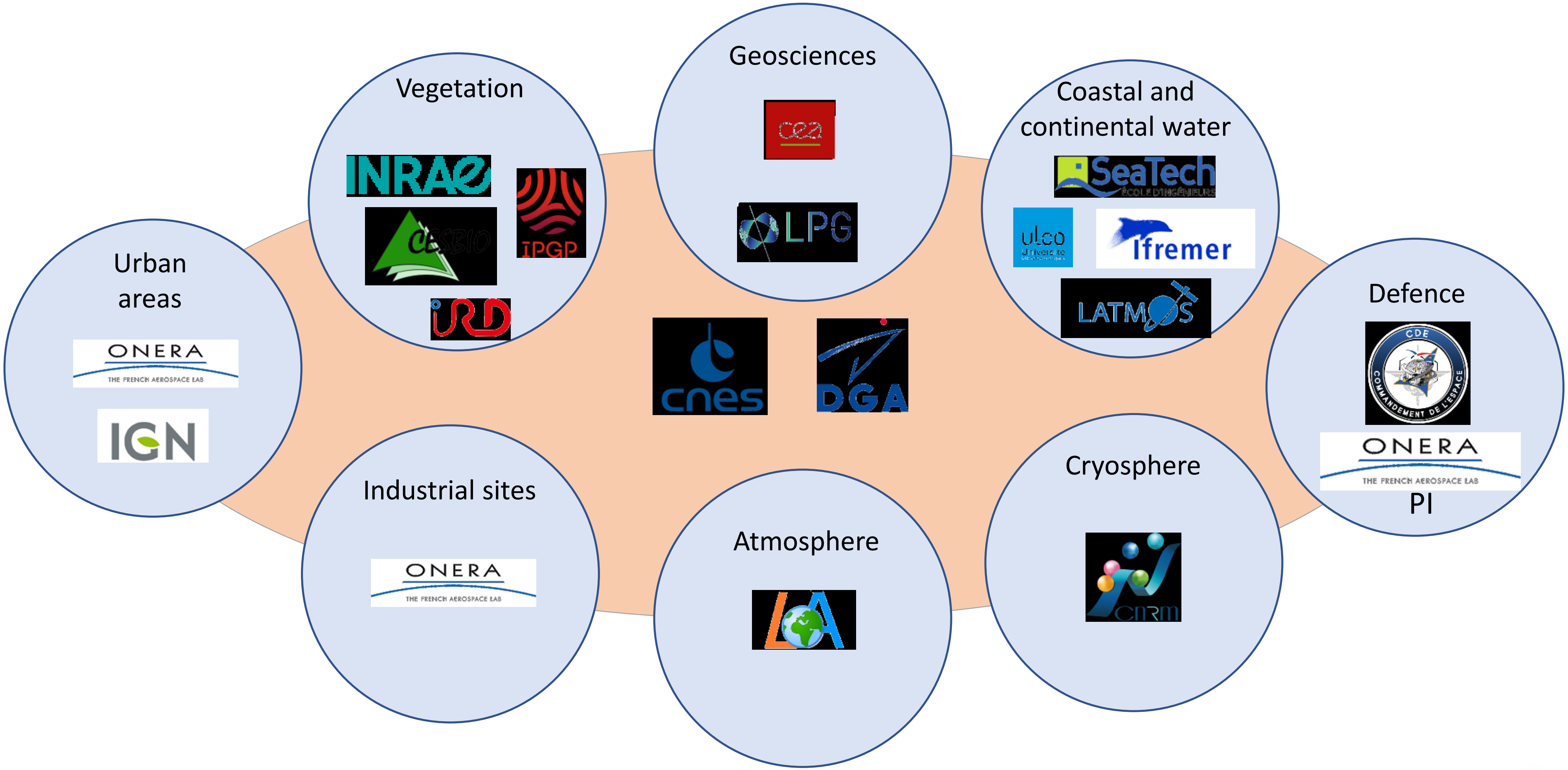
- The partner provides the platform, is in charge of the satellite integration and the control center
- France is in charge of the instrument development and its expertise center
- A user center is deployed in each country for acquisitions requests and data processing up to L2A

On French side, a phase A3 started beginning of 2023 to design an instrument with filters to be interfaced with the platform of the partner

⇒ 2 key elements for the mission performance: detectors and filters

⇒ System review planned beginning of 2024 with the objective to start phase B in 2024

The French Mission Group



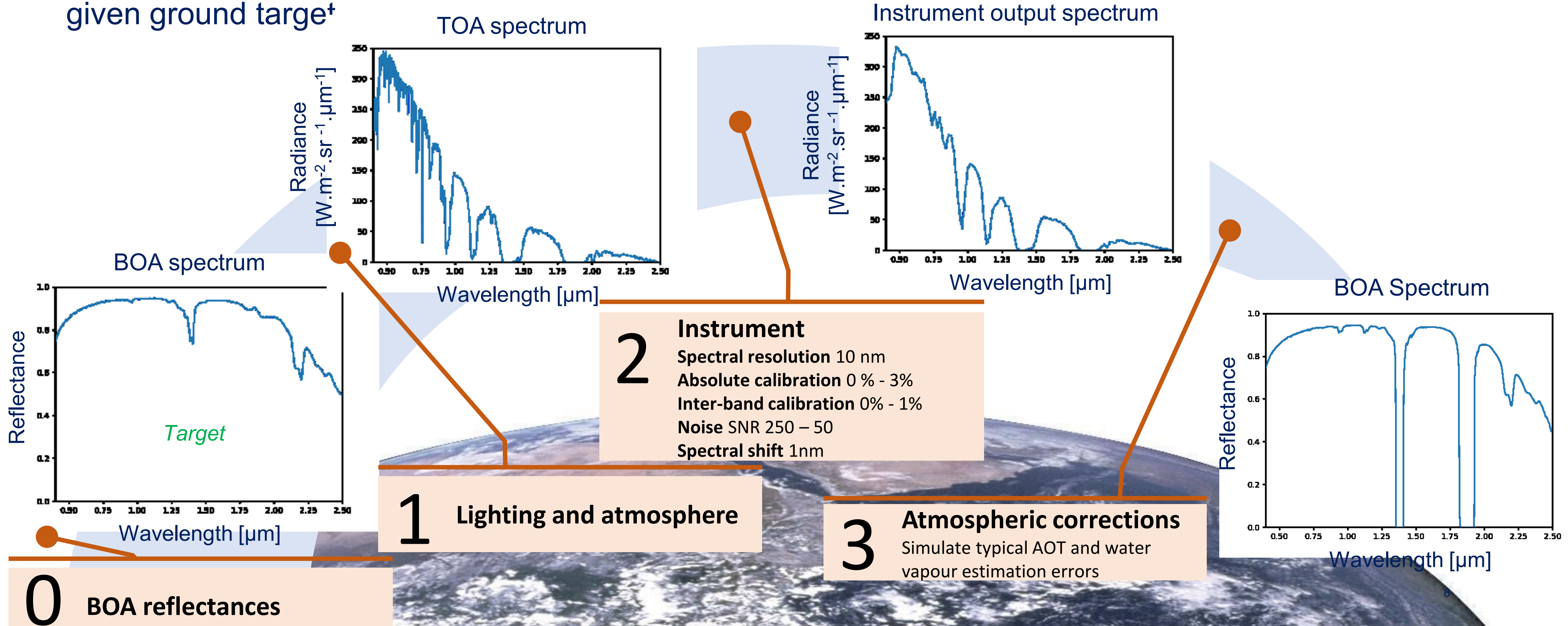
HYSP selected operating point

- **Small satellite (300 - 400 kg, instrument 100 -150 kg) :**
  - **Spatial resolution : 10 m nadir for hyperspectral bands**
    2.5 m nadir for multispectral bands : 9 bands centered over 445 nm, 490 nm, 555 nm, 610 nm, 670 nm, 760 nm, 830 or 865 nm, one band duplicated twice
  - **Swath : 10 km**
  - **Spectral range: VNIR : [400 nm – 920 nm], SWIR : [900 nm – 1800 nm] U [1950 nm – 2400 nm]**
  - **Spectral width / Spectral sampling : VNIR 10 nm, SWIR 10-14 nm**
    - **Demanding requirement for out of band rejection : <1%**
  - **SNR @ Lref : 125 VNIR, 80-95 SWIR**
  - **Absolute radiometric accuracy: 3% (2σ)**
  - **Cross-band radiometric accuracy: 1% (2σ)**
  - **Multi-temporal radiometric accuracy :1% (2σ)**
  - **Geolocation: hyperspectral GSD (2σ) with GCPs**
  - **Spectral co-registration : 0.3 pixel (3σ), after processing**
  - **Temporal co-registration: 0.3 pixel (3σ), after processing**
- **Launch / Lifetime: 2028 / 5 years**

Tuning Hyperspectral Mission Requirements to the End-User Needs

End-to-End mission performance simulation

- Objective: to assess the consistency between the main mission requirements and the end-user needs
- Method: To simulate images based on the specified instrument and use them as users do
- The main effects of the whole imaging system are taken into account to simulate the final images of a given ground target



End-user application simulation chain

- The applications are selected to cover the mission targets expressed by users and to challenge the instrument characteristics on the performances of the applications, assuming state-of-the-art algorithm. We do not challenge the end-user algorithms themselves.
- To overcome the limitation of the implemented scenarios, all performance results are analysed by comparison to the ones obtained with the initial set of requirements.
- Examples for:

Mineralogy (trafficability)

Soil composition

- Sand
- Silt
- Kaolinite
- Montmorillonite
- Illite

Clay types (Kaolinite, Montmorillonite, Illite)

Vegetation

Biochemical parameters

- Leaf Area Index
- Chlorophyll A and B
- Carotenoid
- Equivalent Water Thickness

Bathymetry

Water column parameters

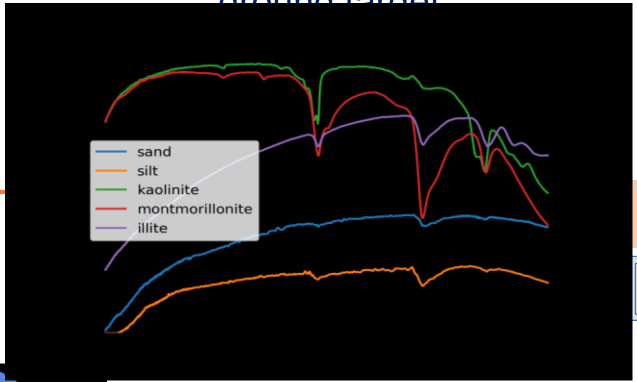
- phytoplankton
- colored dissolved organic matter
- non-algal particles
- water depth
- nature of the sea bed

End-user application simulation chain – Methodology

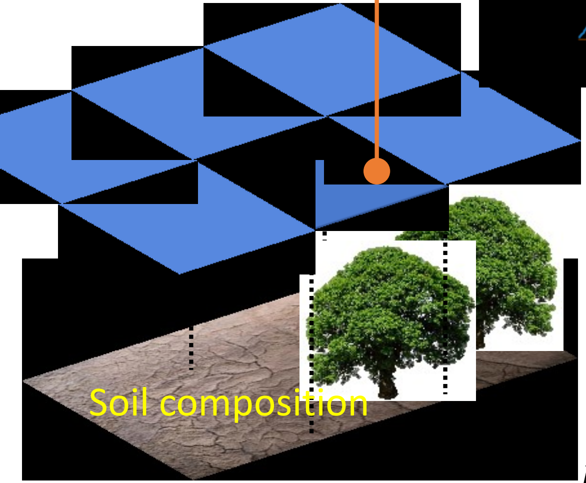
Mineralogy for trafficability

Simulated hyper-spectral pixels

BOA Spectrum of the ground target



⇒ 103 simulated BOA composite spectra

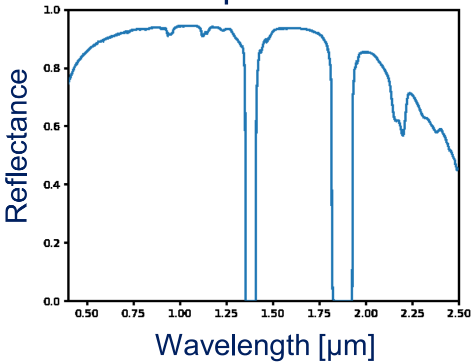


Ground target

End-to-end simulation tool

Lighting and atmosphere	Instrument	Atmospheric correction

BOA Spectrum of the target estimated from space



Estimate the soil composition (proportion clay, sand and silt) by spectral inversion

Soil composition

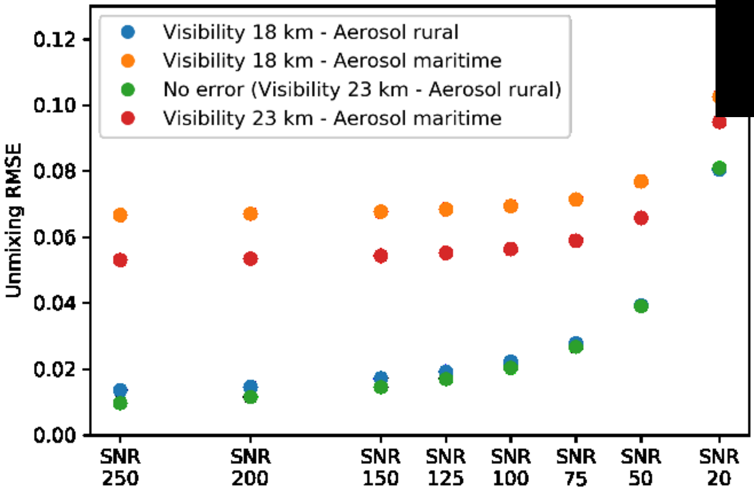
Check discrepancies

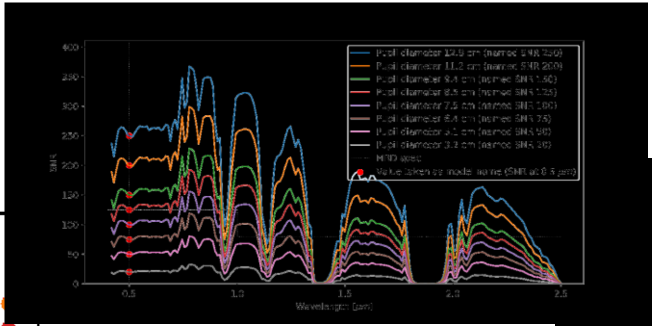
$$RMSE = \sqrt{\left(\mathrm{Real}_{\mathrm{composition}} - \mathrm{Estimated}_{\mathrm{composition}}\right)^2}$$

Atmospheric correction error vs instrument SNR

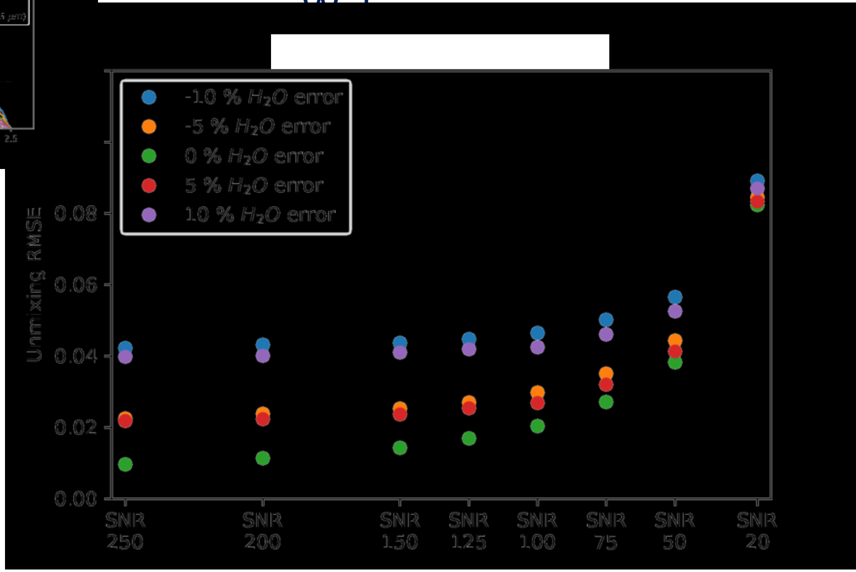
Mineralogy for trafficability

Aerosols





SNR models



5 km visibility error & aerosol model error

- ➢ **Aerosol model error (orange and red dots) induces high unmixing errors**
- ➢ **Need to estimate accurately the aerosol model**

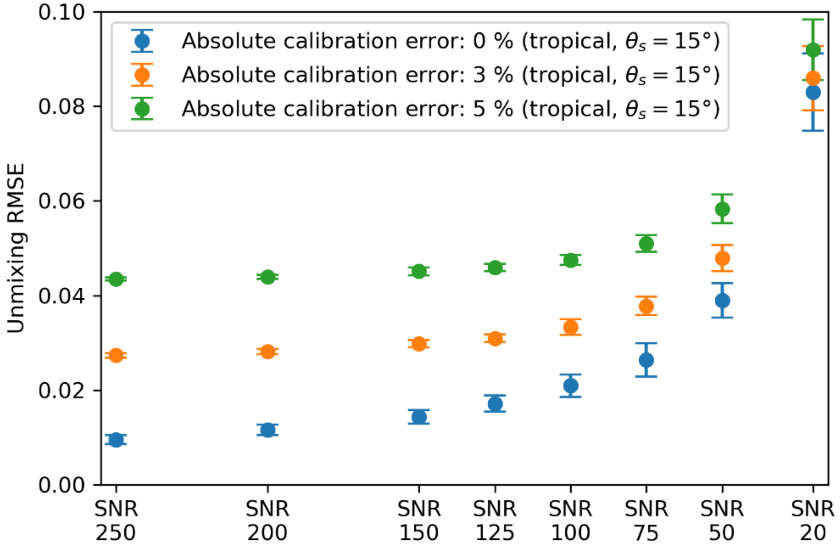
-10 -5 or +5 or 10 % error in the knowledge of the H2O profile

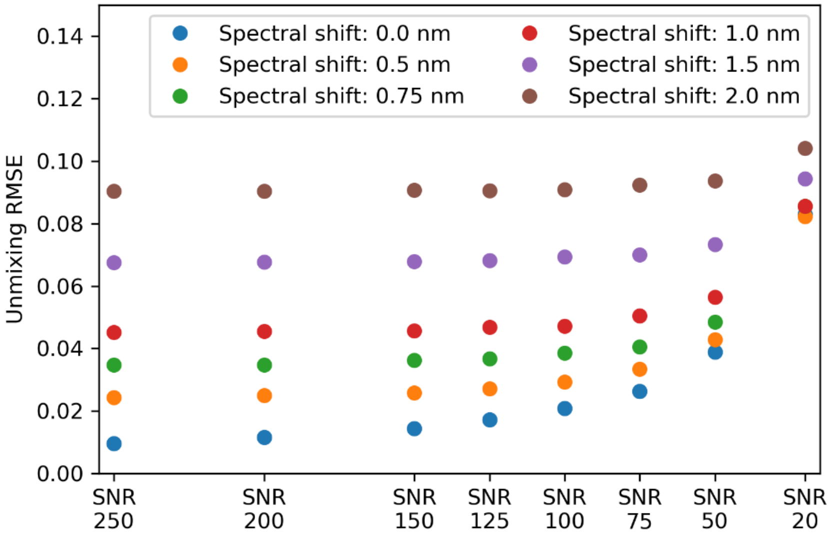
- ➢ **Water vapor content unknowledge induces significant unmixing errors**

➢ **Atmospheric correction is an important contributor for this application**

Absolute calibration and spectral errors vs instrument SNR

Mineralogy for trafficability



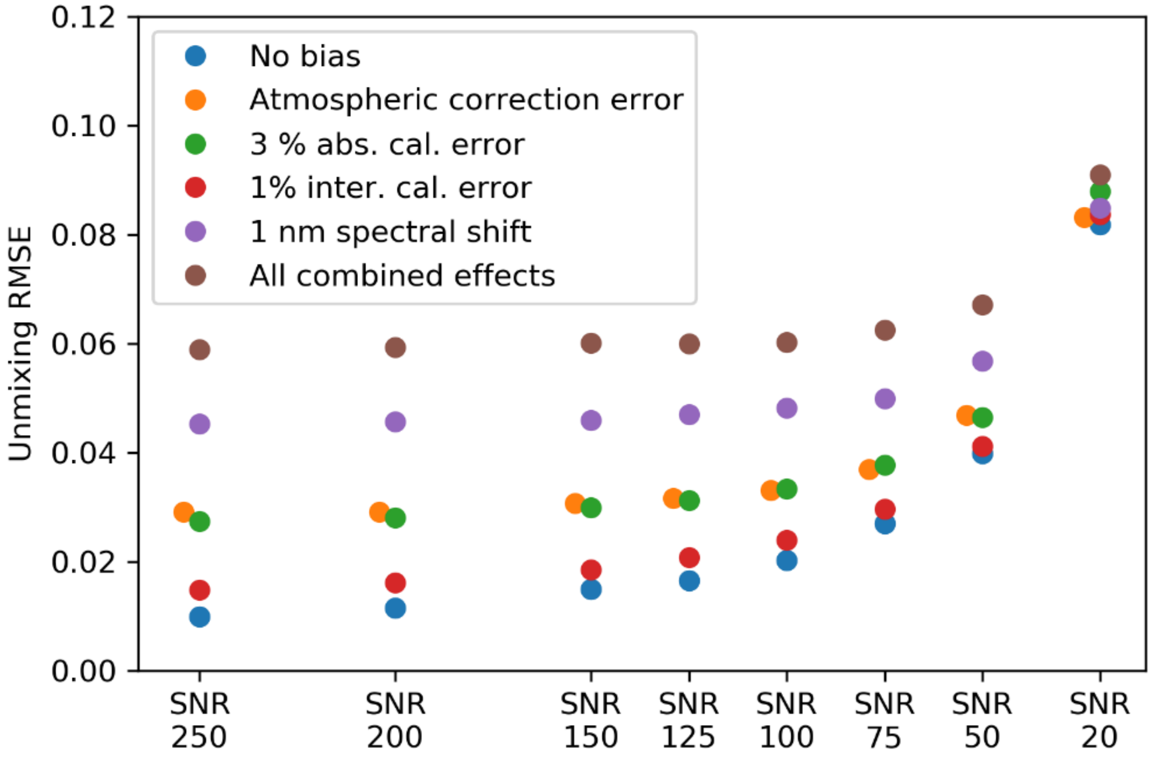


- **With an absolute calibration error : No noticeable increase of RMSE from SNR 250 to SNR 125**
- **Equivalent RMSE for SNR 250 + 3% abs. cal. error and SNR 75 + 0% abs. cal.**

- **A 0.5 nm shift causes an unmixing error equivalent to a decrease of the SNR from 250 to 75**
- **SNR 250 and SNR 100 are comparable for a 1 nm shift**

SNR: resume & combined effects

Mineralogy for trafficability

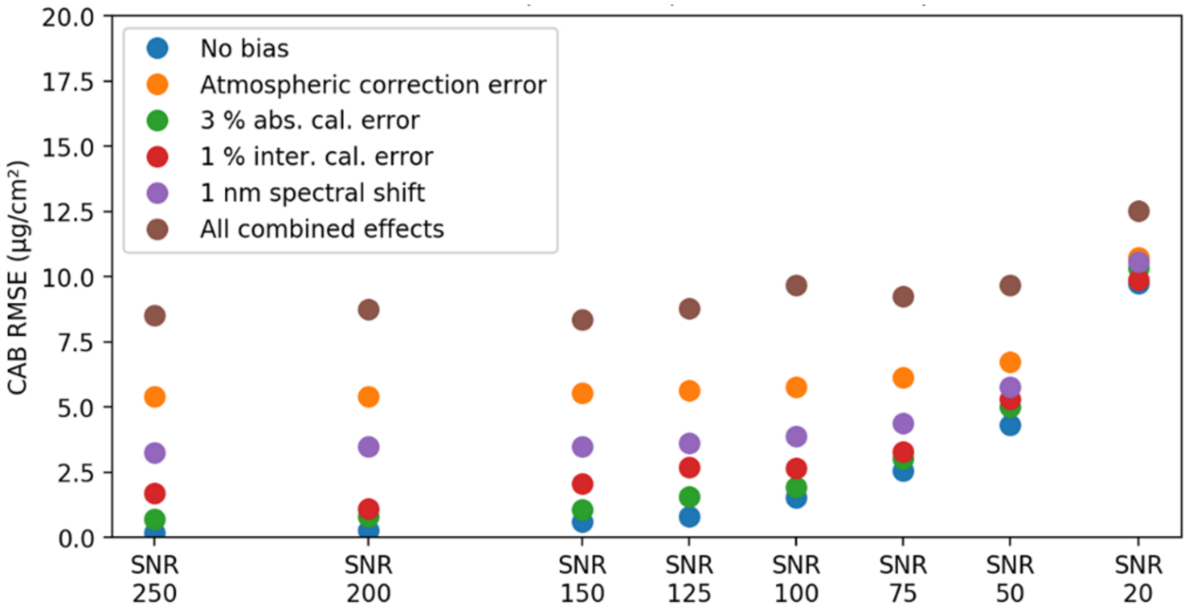


SNR 100 and 250 models give same performance for this application with instrument & atmospheric correction combined errors

Spectral shift error is the main source of error for this application then absolute calibration & atmospheric correction errors

SNR: resume & combined effects

Vegetation – Chlorophyll estimation



Crop type	θ_S [°]	φ_S [°]	LAI	CAB [µg.cm⁻²]	CAR [µg.cm⁻²]	EWT [cm]	N	Number of spectra
Citrus	15	45	0.50196 10.23	10.465 79.918	2.5648 18.924	0.003486 0.03547	1.0554 2.63	339
Citrus	55	45	0.80019 10.254	10.192 79.533	3.051 19.888	0.003979 0.029923	1.0448 2.4986	338
Maize	15	9	0.78 5.14	10.101 79.925	2.1792 19.753	0.003958 0.037881	1.0087 2.7054	878
Maize	36	76	0.78 5.14	10.302 79.978	2.1256 19.742	0.003465 0.037307	1.0026 2.6523	877

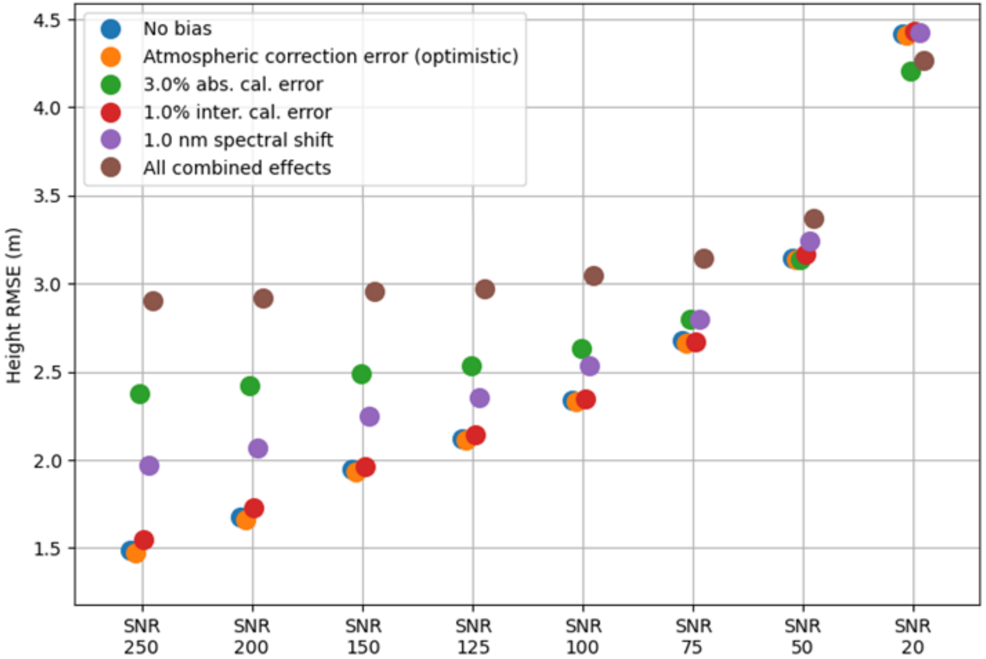
⇒ 2432 simulated BOA spectra

- Leaf Area Index (LAI), the ratio of leaf-to-soil surfaces
- Chlorophyll A and B (CAB) content
- Carotenoid (CAR) content
- Equivalent Water Thickness (EWT), the leaf water content,
- N, the structure index of leaves

- ➢ **SNR 125 and 250 models give similar performances for this application with instrument & atmospheric correction combined errors**
- ➢ **Atmospheric correction is the main source of error for this application then spectral shift error**

SNR: resume & combined effects

Bathymetry – Water depth



NAP [$mg.L^{-1}$]	PHY [$mg.m^{-3}$]	z [m]	α [w.u.]	θ_S [°]	CDOM [m^{-1}]	Image name
0.1 0.5 1 2 5 10 25 50 75 100	0.05 0.1 0.2 0.5 1 2 3 5 7 10	0.1 0.5 1 2 5 10 15 20 30 40	0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1	30	0.01	RBOA_shallow_thetas_30_results_cdom_0-01
					0.1	RBOA_shallow_thetas_30_results_cdom_0-1
					0.5	RBOA_shallow_thetas_30_results_cdom_0-5
				60	0.01	RBOA_shallow_thetas_60_results_cdom_0-01
					0.1	RBOA_shallow_thetas_60_results_cdom_0-1
					0.5	RBOA_shallow_thetas_60_results_cdom_0-5

$\Rightarrow$ 20427 BOA « reversible spectra »

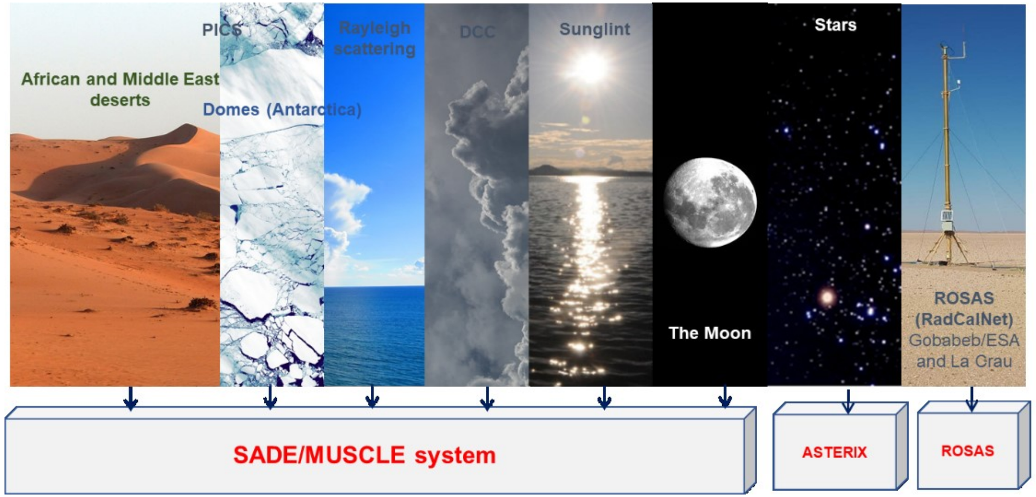
CDOM: Color Dissolved organic matter
NAP: Non Algual Particles
PHY: Phytoplankton
z: depth
α:: nature of the seabed

- **The performance degrades when the SNR decreases**
- **SNR 125 and 250 models give similar performances for this application with instrument & atmospheric correction combined errors**
- **Absolute calibration error is the major error for this application then spectral shift error**
- **Impact of atmospheric correction errors is most likely underestimated (no adjacency effect, no error on the aerosol model)**

Radiometric calibration and validation activities for Hyperspectral

CNES legacy on radiometric Cal/Val for multispectral sensors

… based on several vicarious calibration methods



- Calibration methods are
  - based on physical principles
  - statistical methods: they use several acquisitions on natural targets
- The principle of all the methods is to compare a sensor measurement to a simulated one (from a model or a reference sensor)

⇒ Adaptation needed, at least to manage the number of bands and their spectral resolution (RT models, spectral interpolation,…)

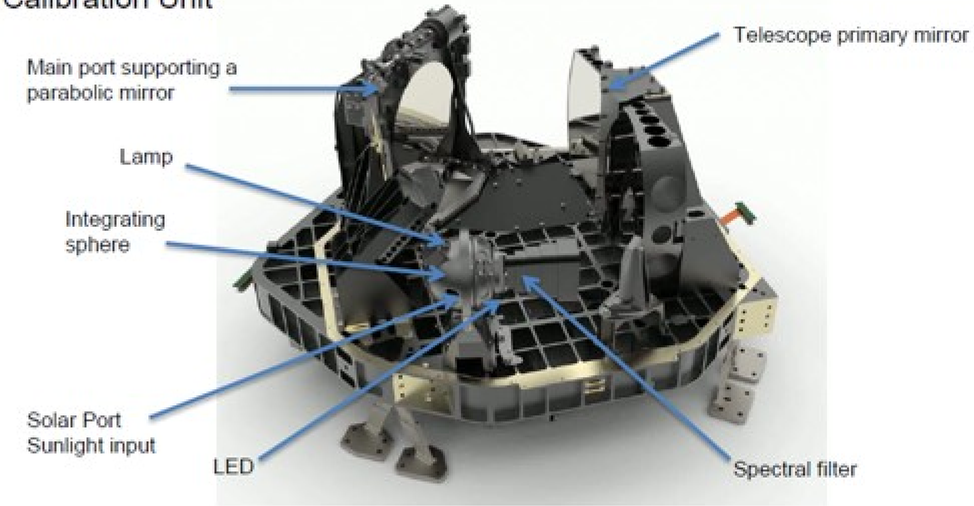
  ⇒ **MUSCLE-NEO (2024)**

⇒ Adaptation done for cross-calibration based on PICS and ROSAS (Robotic Station for Atmosphere and Surface)

Application to PRISMA calibration

Launch: 22 March 2019

Internal Calibration Unit



PRISMA payload main characteristics

Orbit parameters	
Altitude	620 km (nominal)
Period	96 min
Repeat cycle	29 days (430 orbits)
Three mirrors anastigmatic telescope (TMA)	
Effective focal length	620 mm
Entrance Pupil diameter	210 mm
Swath / FOV	30 km / 2.77°
IFOV	48urad
F#	2.95
Hyperspectral sensor	
Spectral range	VNIR 400-1010 nm SWIR 920-2505 nm
Ground Sampling Distance	30 m
Pixels (spatial x spectral)	1000 x 256 pixels
Pixel size	30 µm x 30 µm
Spectral sampling interval	<11 nm
Spectral width	<12 nm
SNR VNIR	>200:1 on 400-1000 nm >500:1 @ 650 nm
SNR SWIR	>200:1 on 1000-1750 nm >400:1 @ 1550 nm >100:1 on 1950-2350 nm >200:1 @ 2100 nm
Panchromatic sensor	
Ground Sampling Distance	5 m
Pixels	Detector 12000 Used 6000
Pixel size	6.5 µm x 6.5 µm
SNR PAN	240
Other parameters	
Abs. Radiometric accuracy	5%
Radiometric quantization	12 bit
Cooling system	Passive radiator
Lifetime	5 years

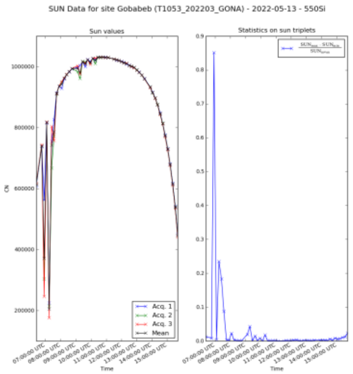
Application to PRISMA calibration

- CNES support ASI for PRISMA radiometric Cal/Val with vicarious methods

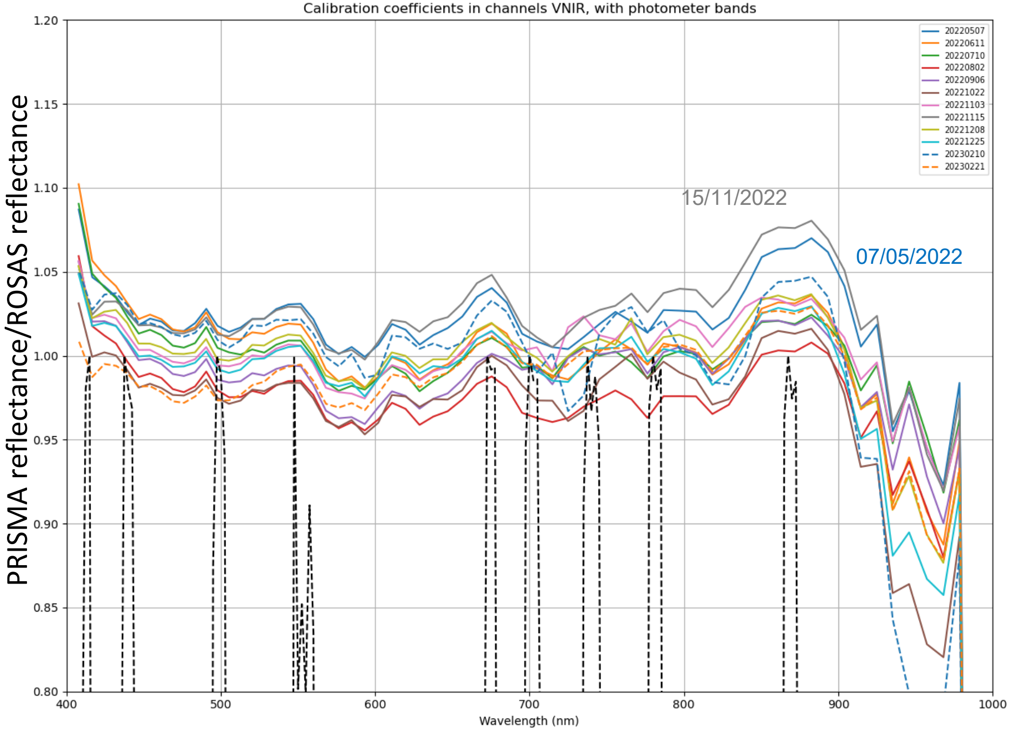
- Following the 2019 vicarious campaign, PRISMA official absolute gains have integrated the feedbacks from CNES
  ⇒ New PRISMA absolute gains based on Gobabeb and La Crau test sites

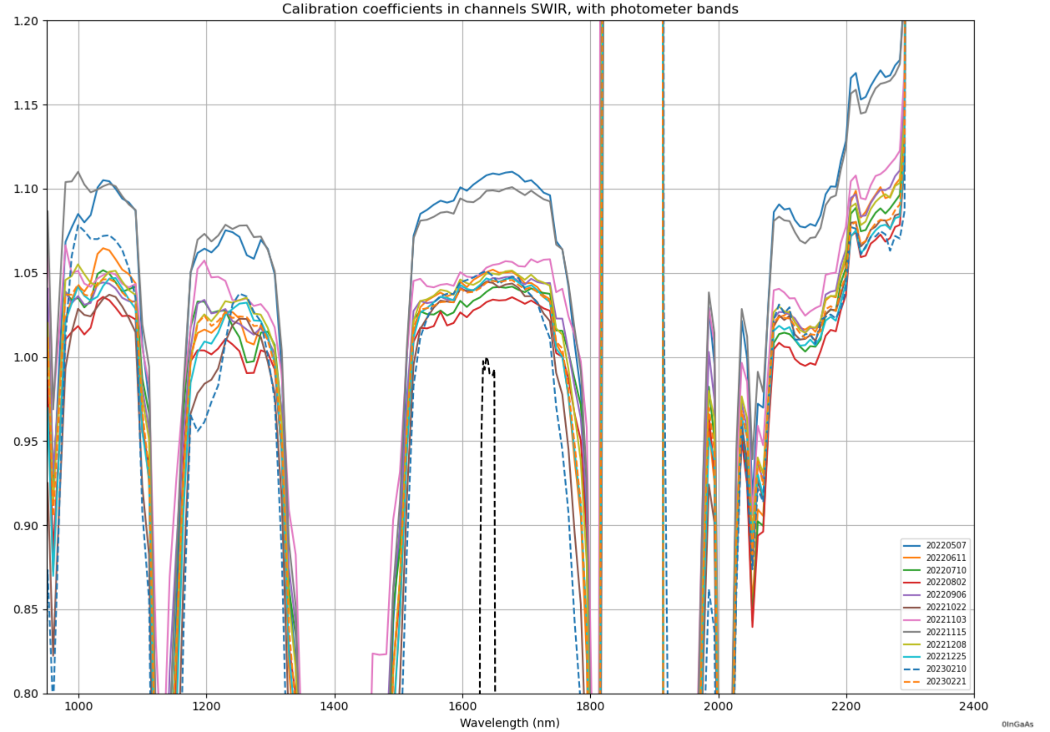
- Campaign Nov 2020 - August 2021
  ⇒ New PRISMA absolute gains based on cross-calibration with Sentinel-2 based on PICS

- Results from the May 2022 – April 2023 campaign
  PRISMA L1 data processed :
  - Gobabeb site: 20 acquisitions,12 used (3 no in situ data, 5 turbid days)
  - PICS : 86 acquisitions, 11 sites



PRISMA CALIBRATION BASED ON RADCALNET SITES: DETAILED RESULTS FOR GOBABEB

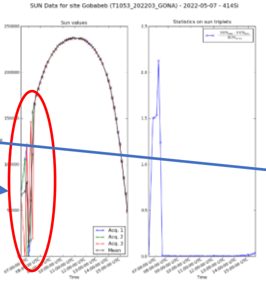


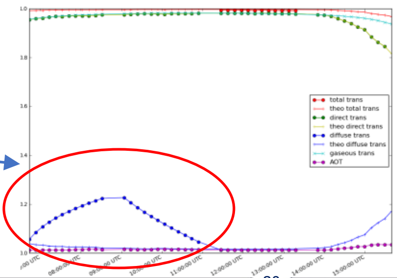


- 2 days (07/05/2022 and 15/11/2022) with results slightly different from the others:

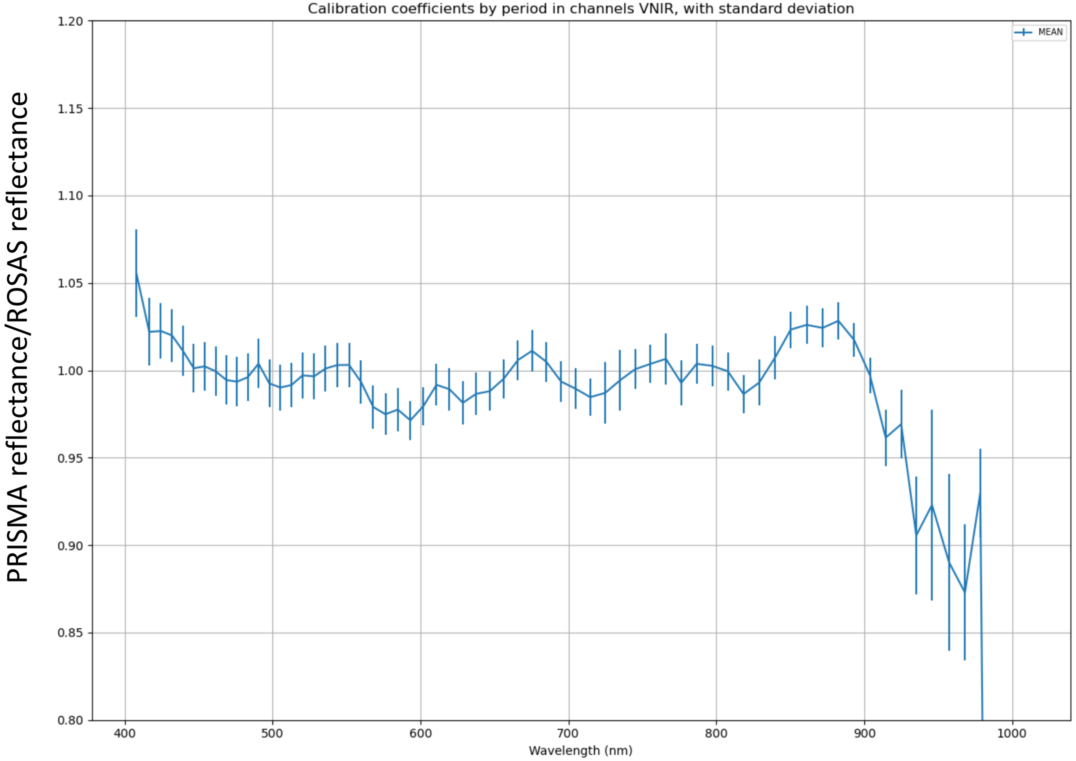
Noisy SUN measurements one hour before PRISMA pass and diffuse transmission shows turbidity in the morning

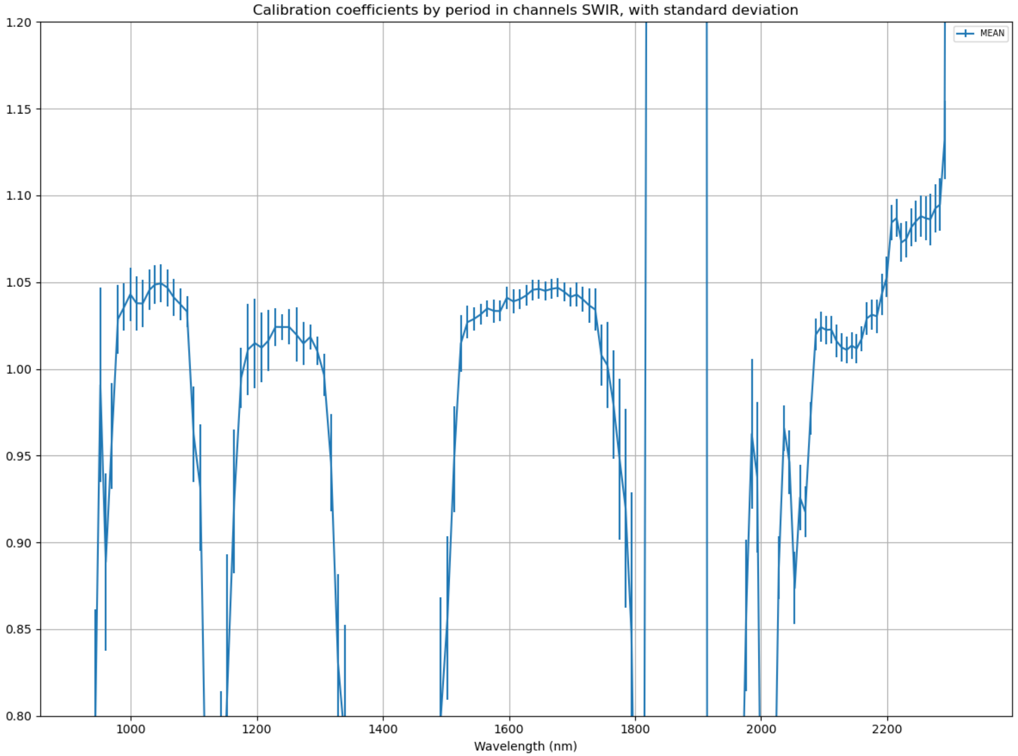
⇒ **Elimination of these 2 dates for the synthesis**





PRISMA CALIBRATION BASED ON RADCALNET SITE : MEAN RESULTS FOR GOBABEB





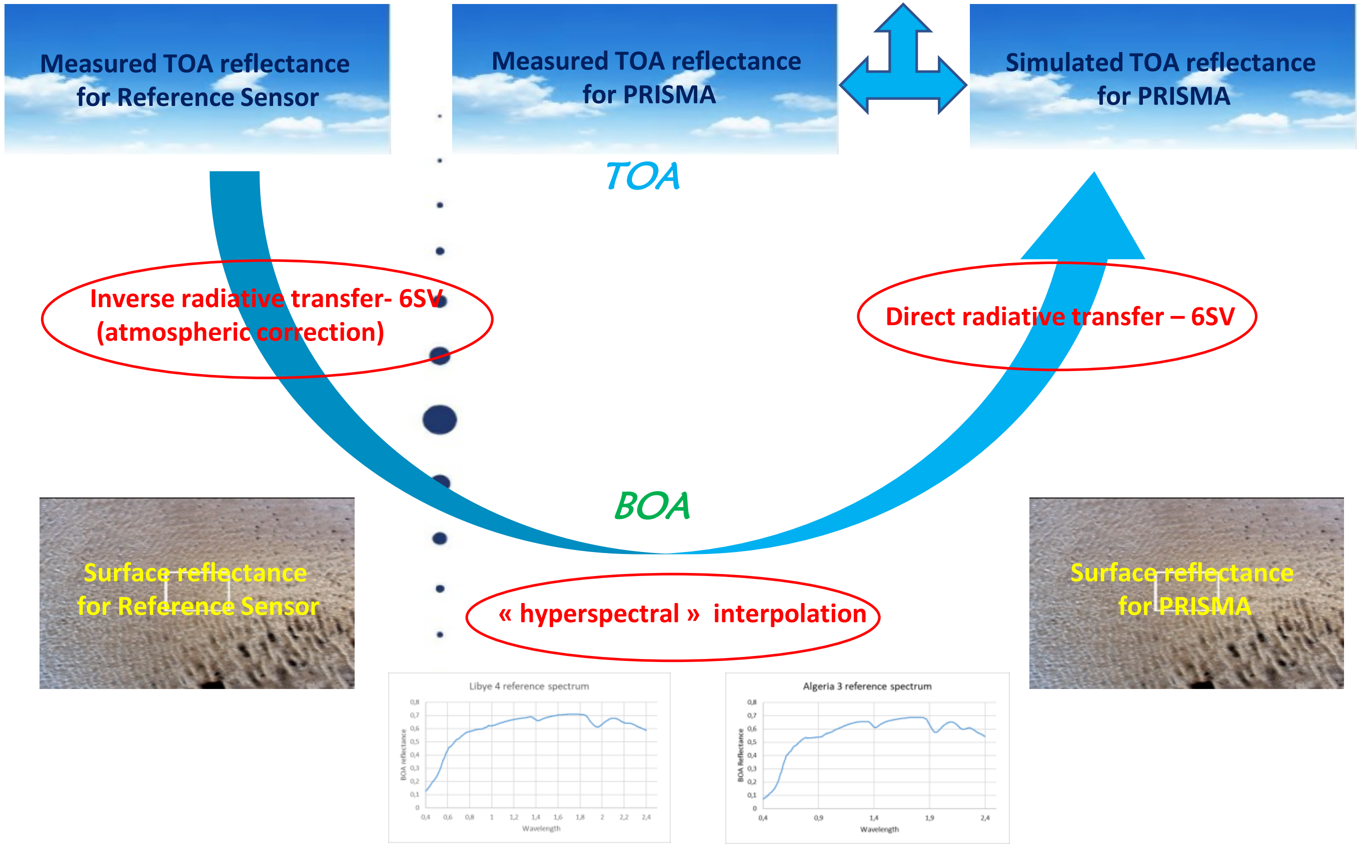
- **VNIR:**
  - **First measurement (~400 nm) not reliable (no photometer band)**
  - **Validation of the official calibration within 2-3%**

- **SWIR:**
  - **Small bias (3-5%) around 1.6µm which is the only SWIR channel of ROSAS**

PRISMA CALIBRATION BASED ON PICS

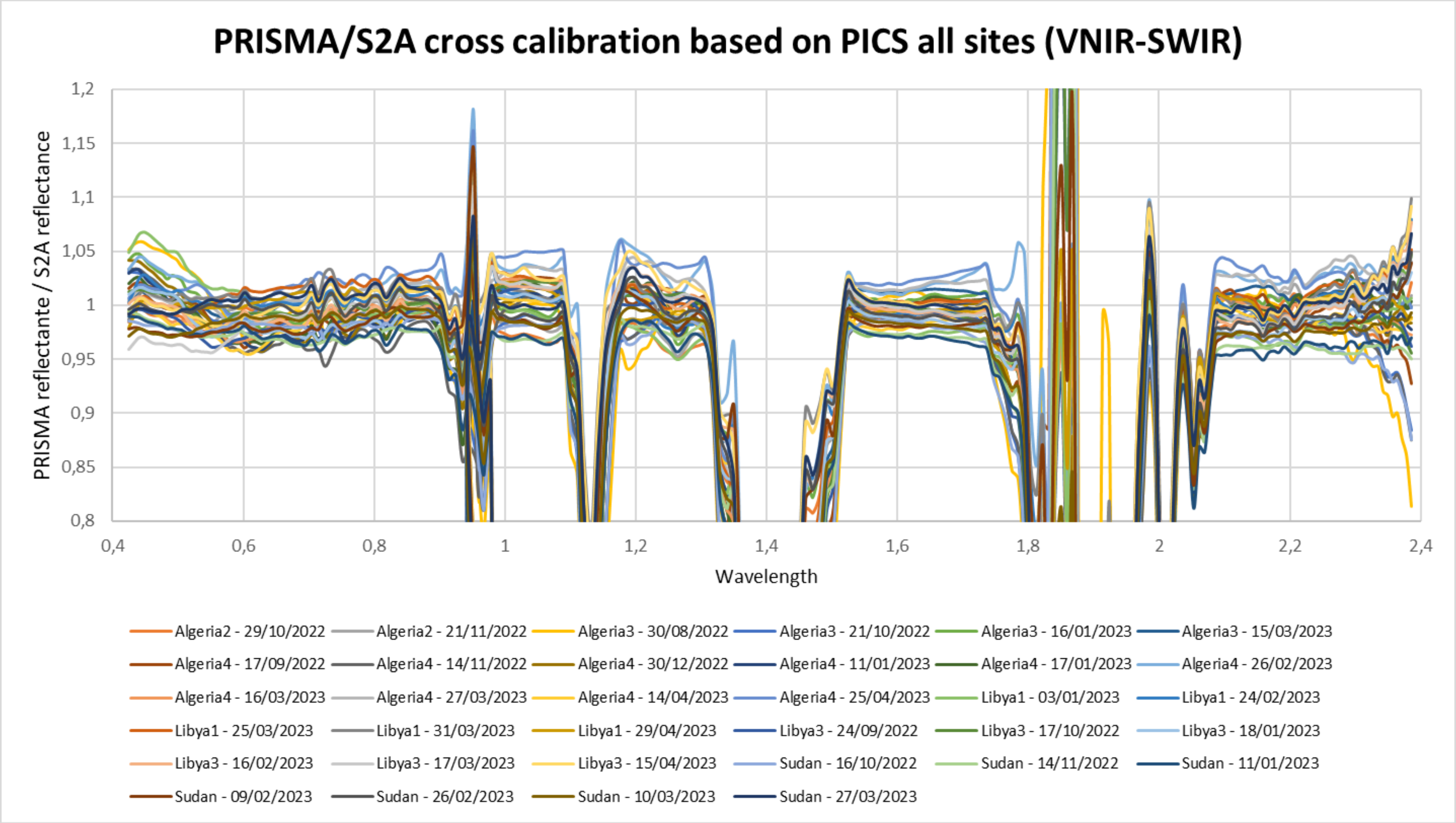
⇒ **Cross calibration method**

⇒ **Similar viewing and sun geometry between PRISMA and the reference sensor**



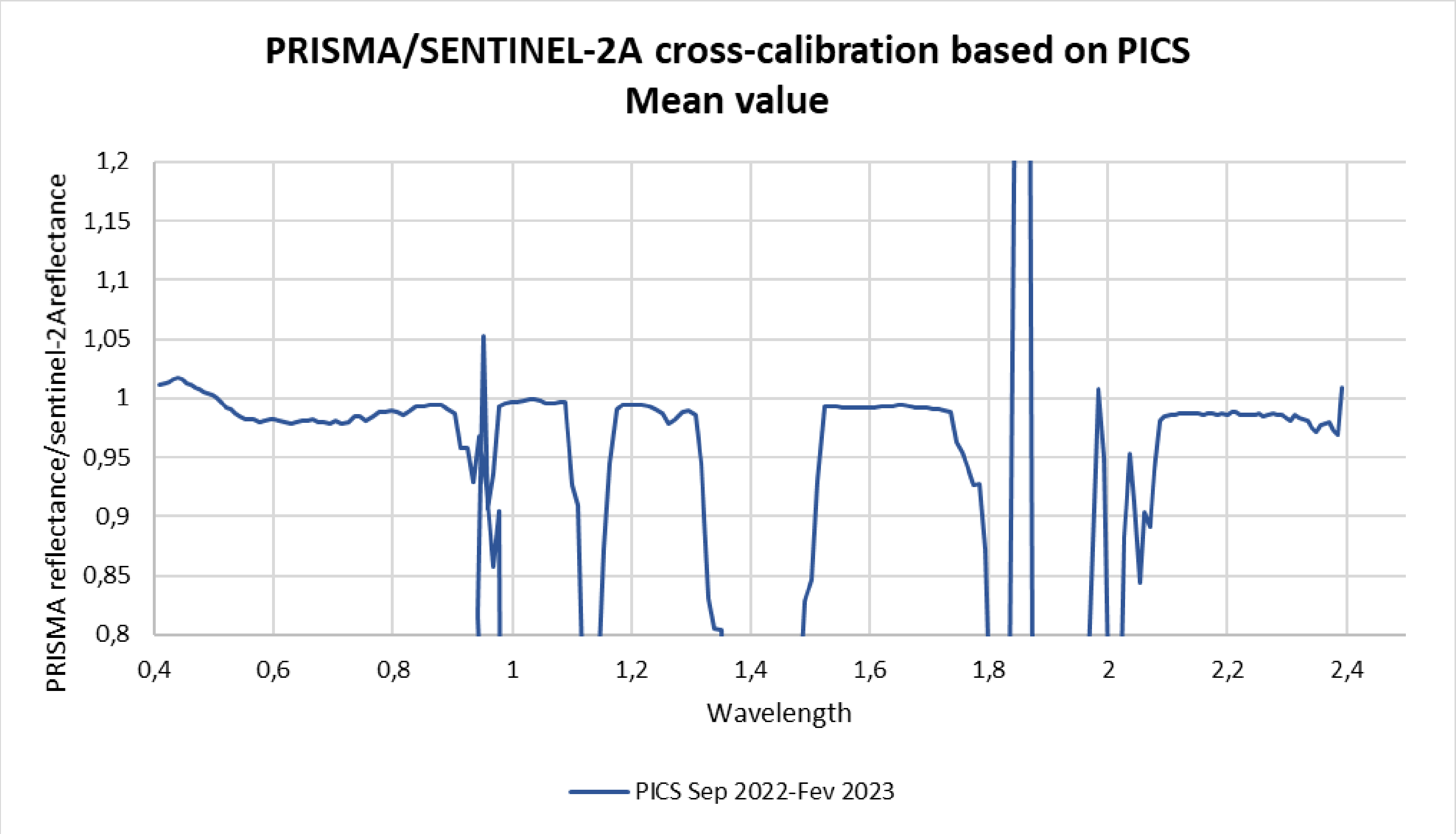
⇒ **Reference sensor used: Sentinel-2A and Sentinel-3B**

PRISMA CALIBRATION BASED ON PICS: DETAILED RESULTS (ALL DATES)



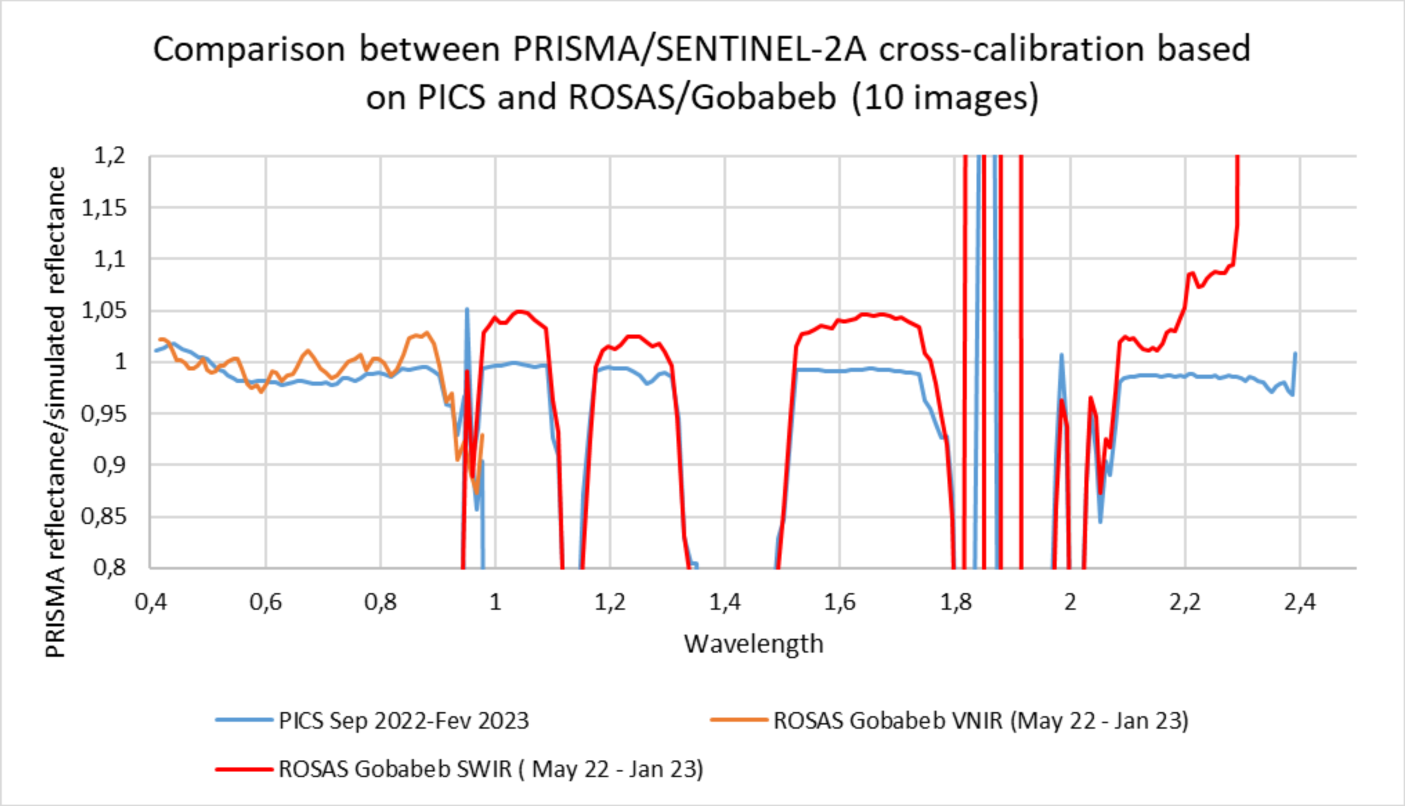
⇒1163 PRISMA/S2A couples of images processed for calibration

PRISMA CALIBRATION BASED ON PICS: SYNTHESIS



- **Small sensitivity variation for VNIR ~2%**
- **Good stability for SWIR bands**

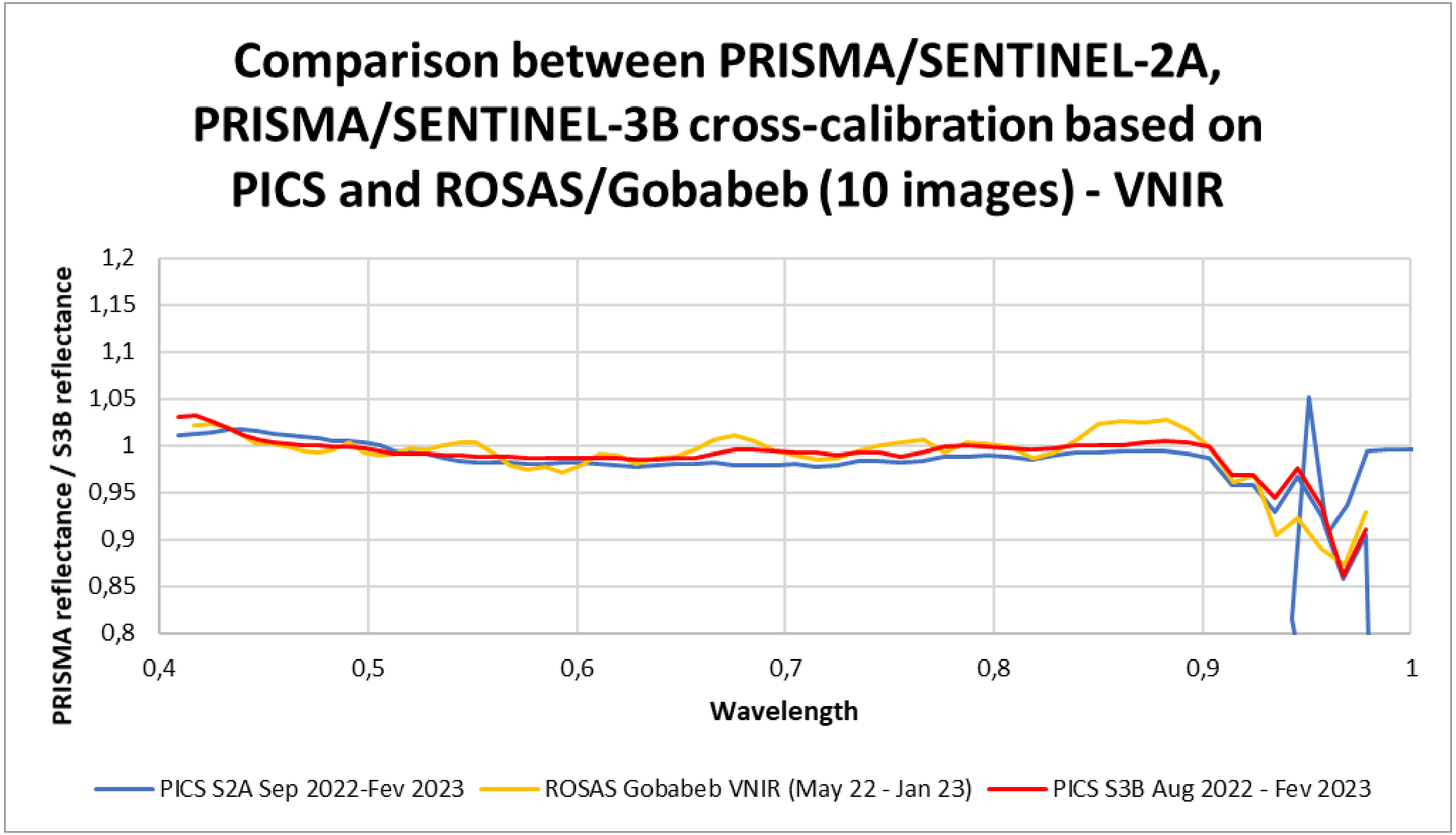
PRISMA CALIBRATION : COMPARISON BETWEEN PICS AND ROSAS



- **VNIR: consistency better than 2% and 3% around absorption bands**
- **SWIR: 3 to 5% variation between ROSAS and S2A but ROSAS has no band around 2.2 µm while Sentinel-2A has one.**

⇒ We are more confident in S2A cross calibration than ROSAS for SWIR bands

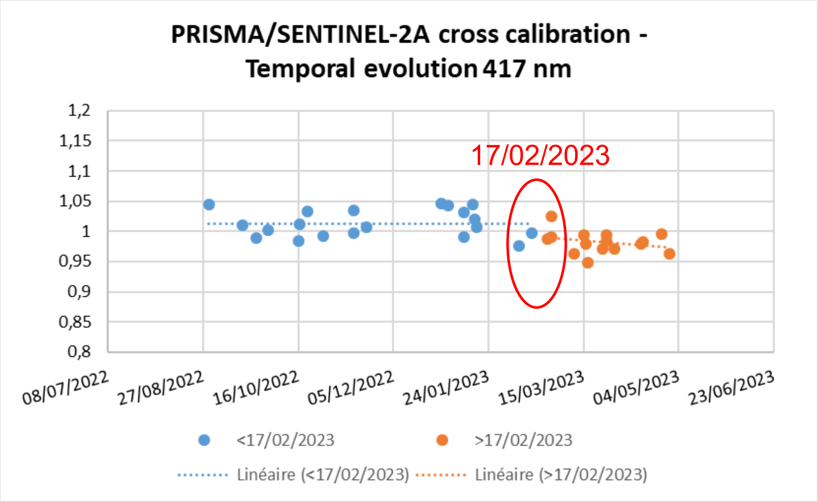
PRISMA CALIBRATION : COMPARISON BETWEEN PICS AND ROSAS

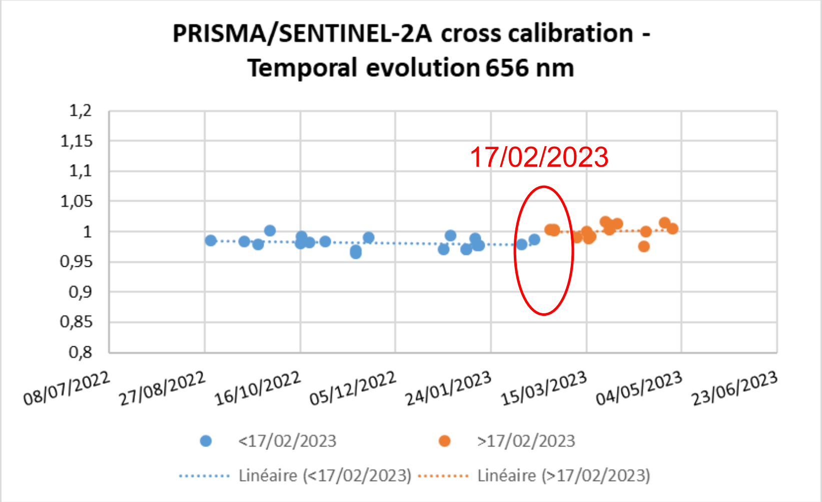


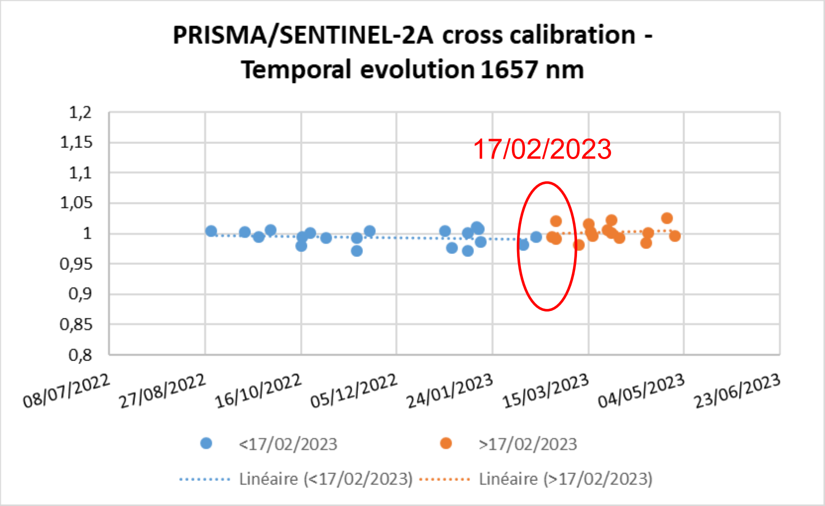
⇒148 PRISMA/S3B couples of images processed for calibration

- **Very good consistency between cross calibration results against S2A and S3B**
- **VNIR: consistency better than 2% and 3% around absorption bands between all results**

PRISMA CALIBRATION BASED ON PICS: TEMPORAL EVOLUTION – VNIR BANDS

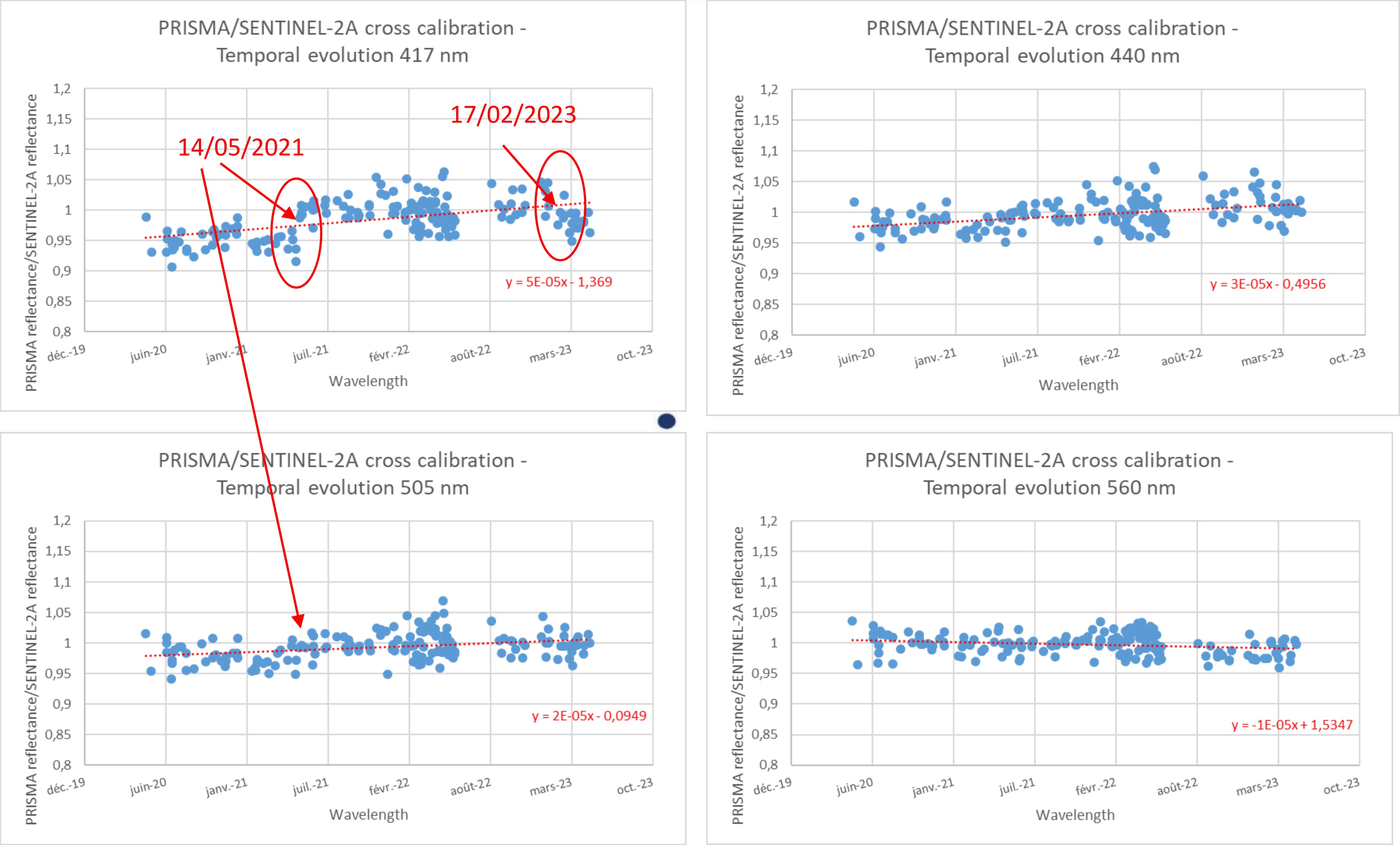






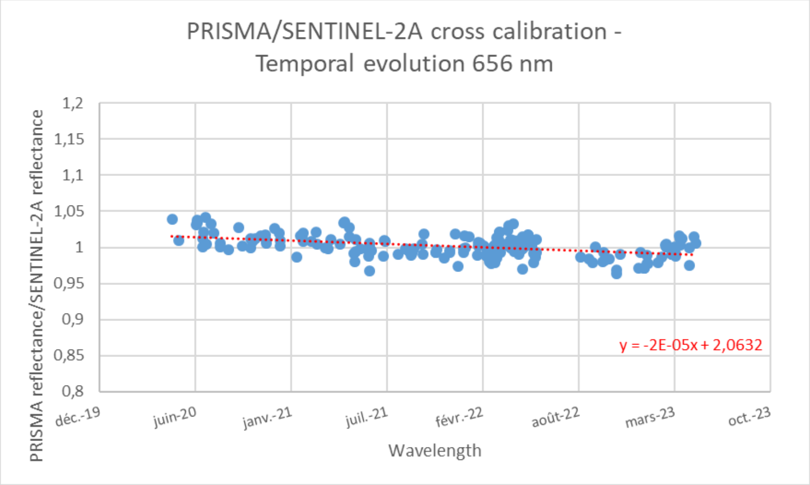
- **Impact of the on board event of Feb 2023 to be decorrelated from the seasonal cycle**

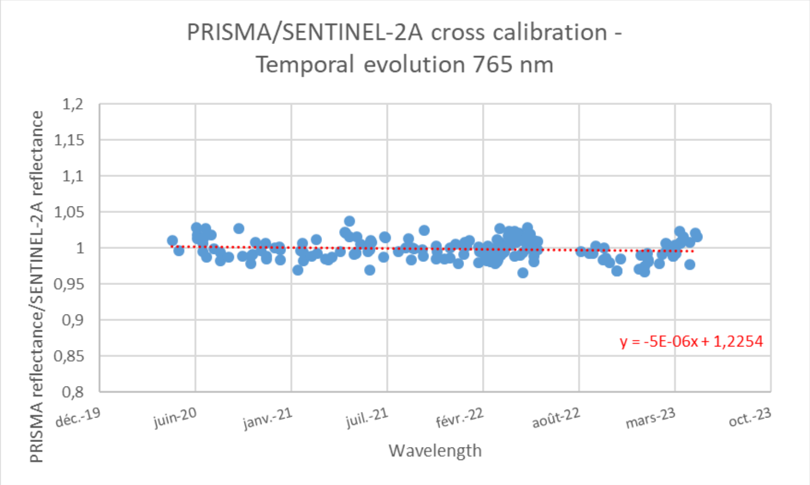
PRISMA CALIBRATION BASED ON PICS: TEMPORAL EVOLUTION – VNIR BANDS

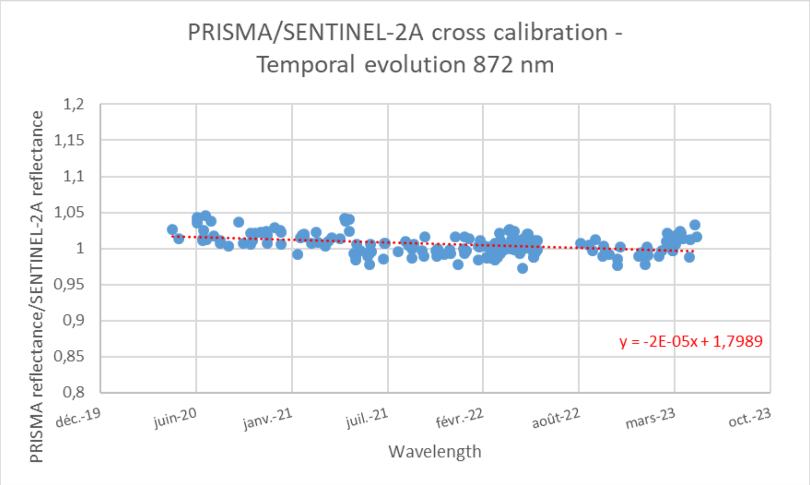


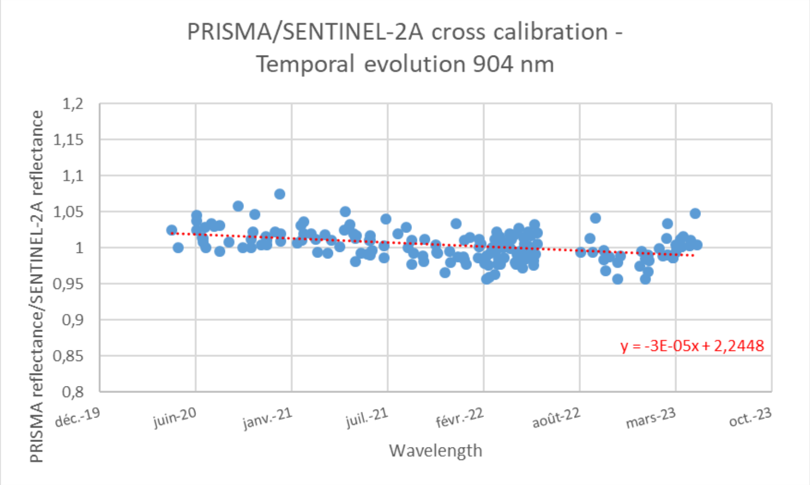
- **Period processed: 04/2020-04/2023**
- **Short wavelengths: 3 periods with a relative stability : on board event in May 2021 and February 2023**

PRISMA CALIBRATION BASED ON PICS: TEMPORAL EVOLUTION – VNIR BANDS



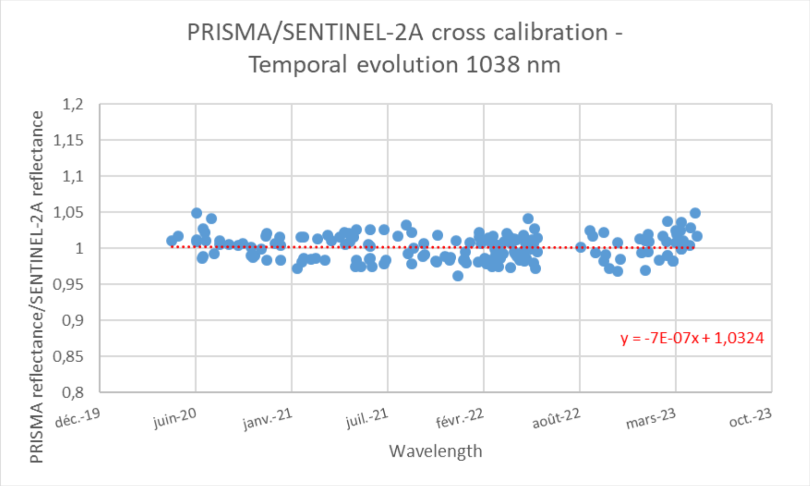


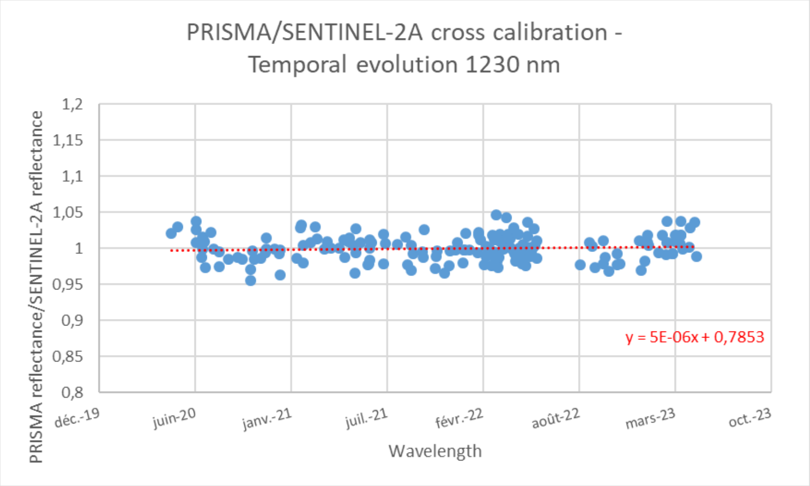


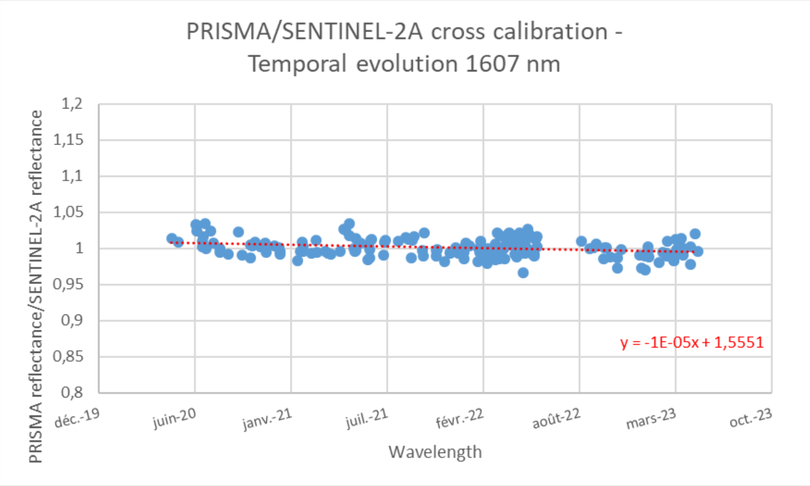


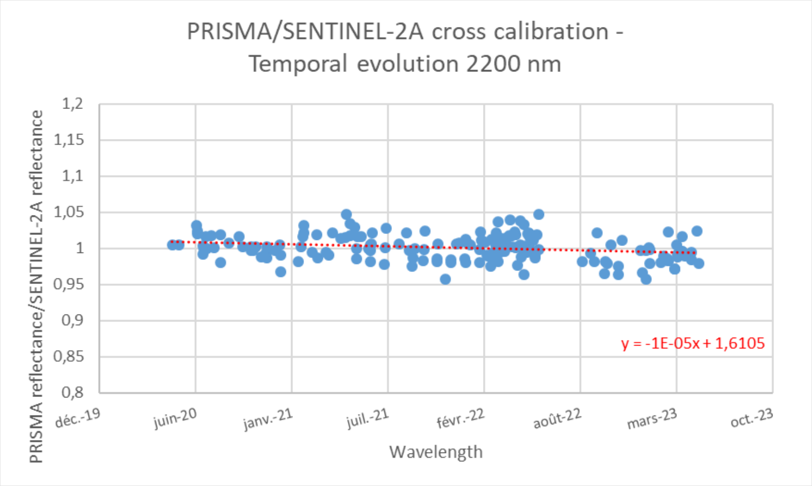
- **Small sensitivity variation for VNIR bands < 1% / year**

PRISMA CALIBRATION BASED ON PICS: TEMPORAL EVOLUTION – SWIR BANDS









- **Very small sensitivity variation for SWIR bands < 0,4% / year**

PRISMA CALIBRATION RESUME

- **Good stability of PRISMA instrument over 3 years:**
  - **Weak temporal variation < 1% / year**
  - **« Step » for short wavelengths in May 2021 and in February 2023 (on-board event)**
- **PRISMA official calibration is based on cross-calibration with Sentinel-2A over PICS**
- **Validation with ROSAS in-situ measurements at Gobabeb site:**
  - **Good consistency between ROSAS and PICS for VNIR bands (2-3%)**
  - **Higher variation for SWIR bands (4% for 1.6µm) but the in situ photometer has one band only in the SWIR spectrum**

APPLICATION TO ENMAP CALIBRATION

Launch: 01 April 2022

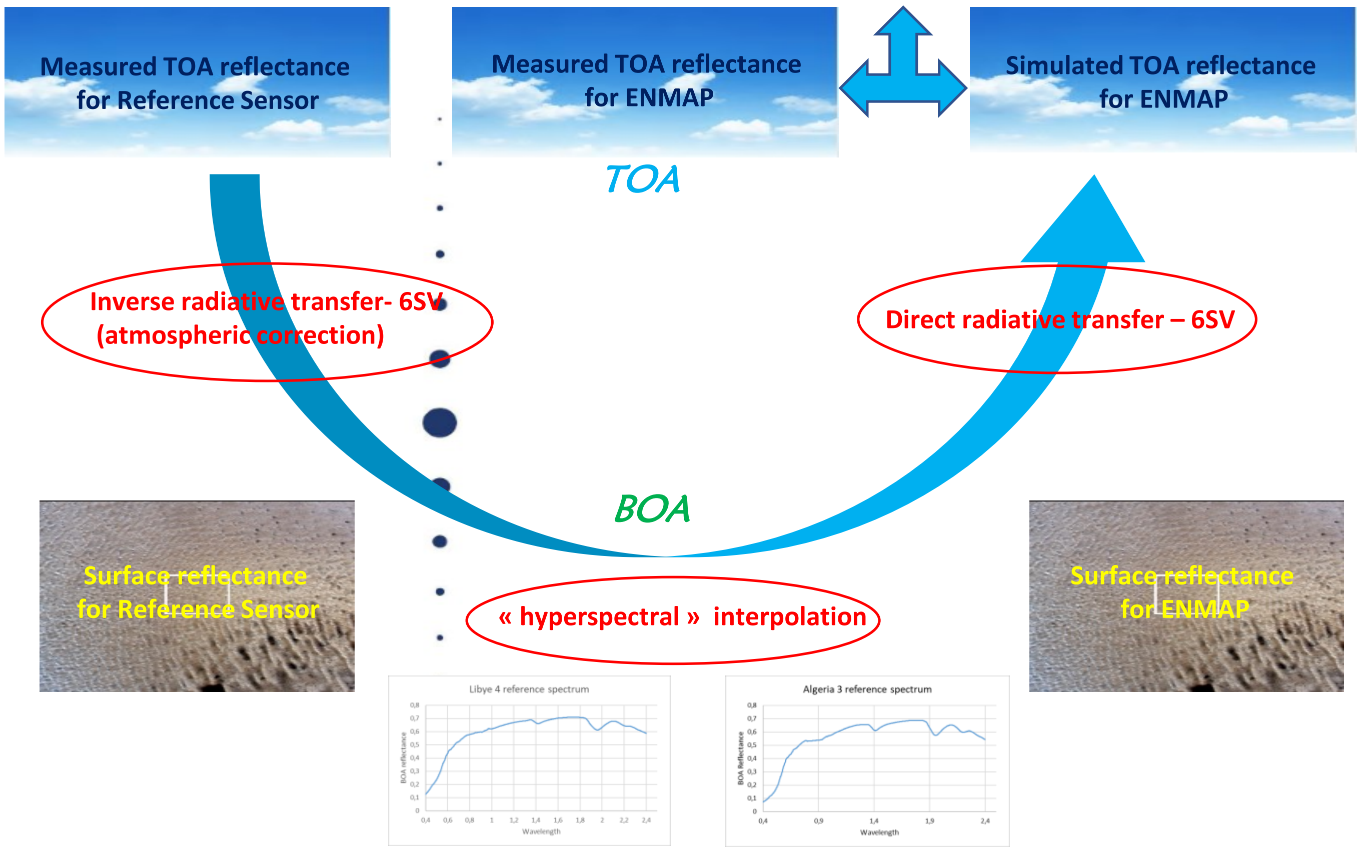
EnMAP HSI Instrument Specification

Spectral range:	420 nm - 2450 nm
Spectral sampling distance:	6.5 nm (420 nm - 1000 nm; VNIR) 10 nm (900 nm - 2450 nm; SWIR)
Spectral accuracy / stability:	0.5 nm / 0.5 nm (VNIR) 1.0 nm / 0.5 nm (SWIR)
Signal-to-Noise ratio*:	> 500 (at 495 nm; VNIR) > 150 (at 2200 nm; SWIR)
Smile and keystone:	< 0.2 pixel
Polarization sensitivity:	< 5%
Radiometric resolution:	≥ 14 bits
Radiometric accuracy / stability:	5% / 2.5% (between two consecutive calibrations)
On-board calibration:	Full aperture diffuser Integrated sphere with various calibration lamps Shutter for dark measurements
Telescope:	Three-mirror anastigmat Focal length: 522.4 mm Aperture: 174 mm in diameter F-number: 3.0
Geometric resolution:	30 m × 30 m (swath width: 30 km) (IFOV 9.5 arcsec × integration time 4.4 ms (FOV 2.63 deg)) swath length of 5000 km per day with 512 Gbit on-board mass memory
Modulation Transfer Function:	> 0.25 @ 60m across track > 0.16 @ 60m along track > 0.64 @ 240m across track > 0.62 @ 240m along track
Geometric co-registration:	< 0.2 pixel (at Level 1C)
Pointing:	Accuracy: < 500 m Knowledge: < 100m Stability: < 1.5 m in 4 ms Agility: 30° in 5 min with pointing stabilization

*reference radiance level represents 30% surface albedo, 30° Sun zenith angle, ground at sea level, and 40 km visibility with rural atmosphere

ENMAP CALIBRATION BASED ON PICS

⇒ **Cross calibration method**
⇒ **Similar viewing and sun geometry between ENMAP and the reference sensor**

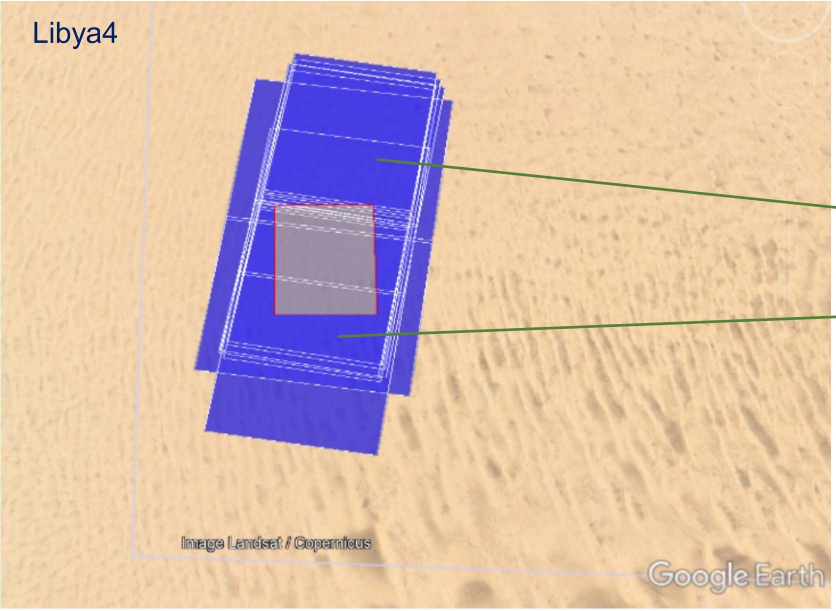


⇒ **Reference sensor used: Sentinel-2A (soon PRISMA and Sentinel-3B)**

ENMAP CALIBRATION BASED ON PICS: PROCESSED DATA

- 27 ENMAP images (Algeria 3 & Libya 4)
- 10 ENMAP images (29/07/2022 – 11/12/2022 - 5 dates x 2) having similar sun and viewing geometry as SENTINEL-2A images

⇒ 359 ENMAP/S2A couples of images processed for calibration



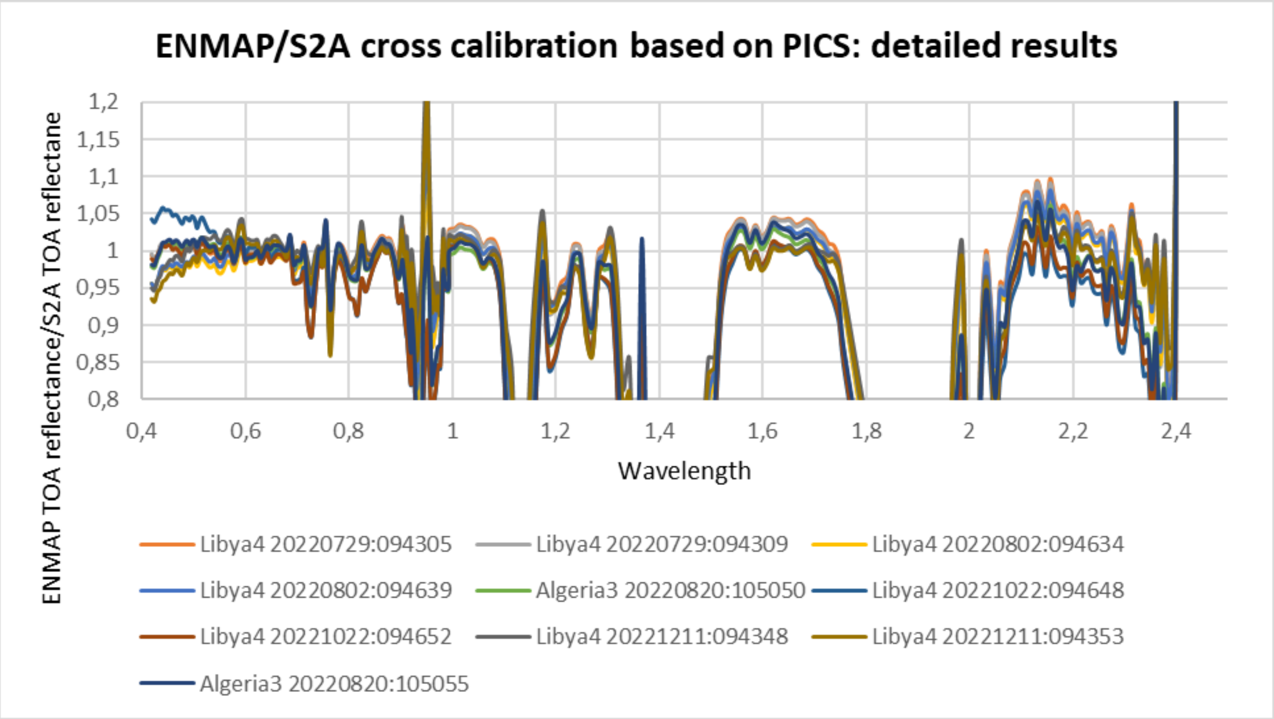
Site	Date & product reference	Number of matched Sentinel-2A images
Algeria3	ENMAP01-____L1C-DT0000002705_20220820T105050Z_001_V010111_20230	48
Algeria3	ENMAP01-____L1C-DT0000002705_20220820T105055Z_002_V010111_20230	48
Libya4	ENMAP01-____L1C-DT0000001969_20220729T094305Z_001_V010111_20230	39
Libya4	ENMAP01-____L1C-DT0000001969_20220729T094309Z_002_V010111_20230	39
Libya4	ENMAP01-____L1C-DT0000002032_20220802T094634Z_001_V010111_20230	39
Libya4	ENMAP01-____L1C-DT0000002032_20220802T094639Z_002_V010111_20230	39
Libya4	ENMAP01-____L1C-DT0000004688_20221022T094648Z_002_V010111_20230	21
Libya4	ENMAP01-____L1C-DT0000004688_20221022T094652Z_003_V010111_20230	23
Libya4	ENMAP01-____L1C-DT0000006087_20221211T094348Z_002_V010111_20230	31
Libya4	ENMAP01-____L1C-DT0000006087_20221211T094353Z_003_V010111_20230	32

ENMAP CALIBRATION BASED ON PICS: PRELIMINARY RESULTS (ALL DATES)

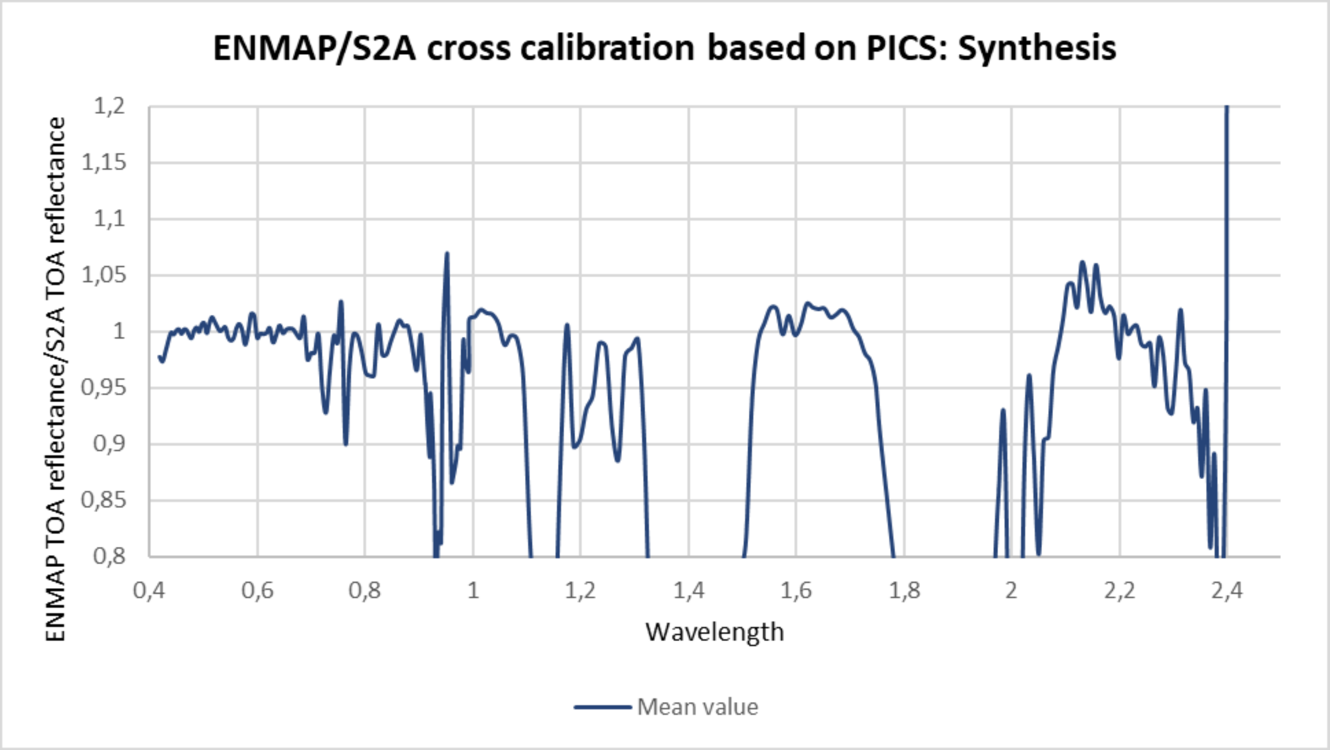
@ CNES 2014: Comparison between small sites (20x20km^2) and standard (100x100km^2) sites: 8 years of MERIS data analysed (01/01/2004 - 31/12/2011)

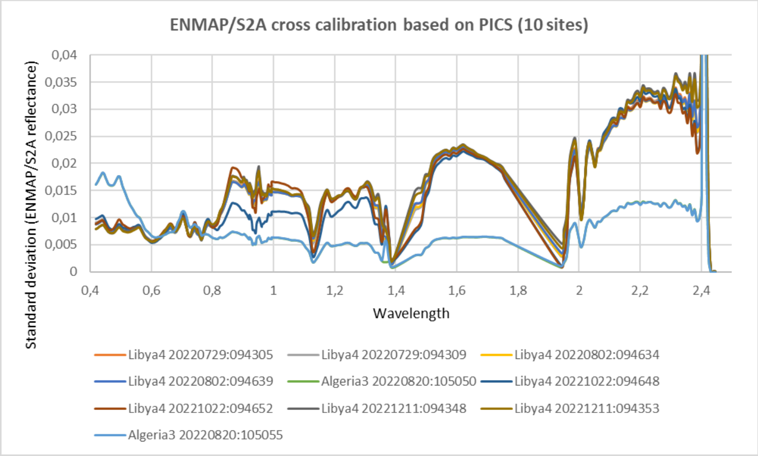
Site	Homogeneity	TRMS (%)	Standard deviation (%)	Comments
Algeria 3	Homogeneous	0.62	0.29	Weak deviation except B5 (~1%)
Libya 4	Acceptable	0.79	0.24	High variations : +2% for short wavelengths -2% for high wavelengths

TRMS: Temporal Root Mean Square



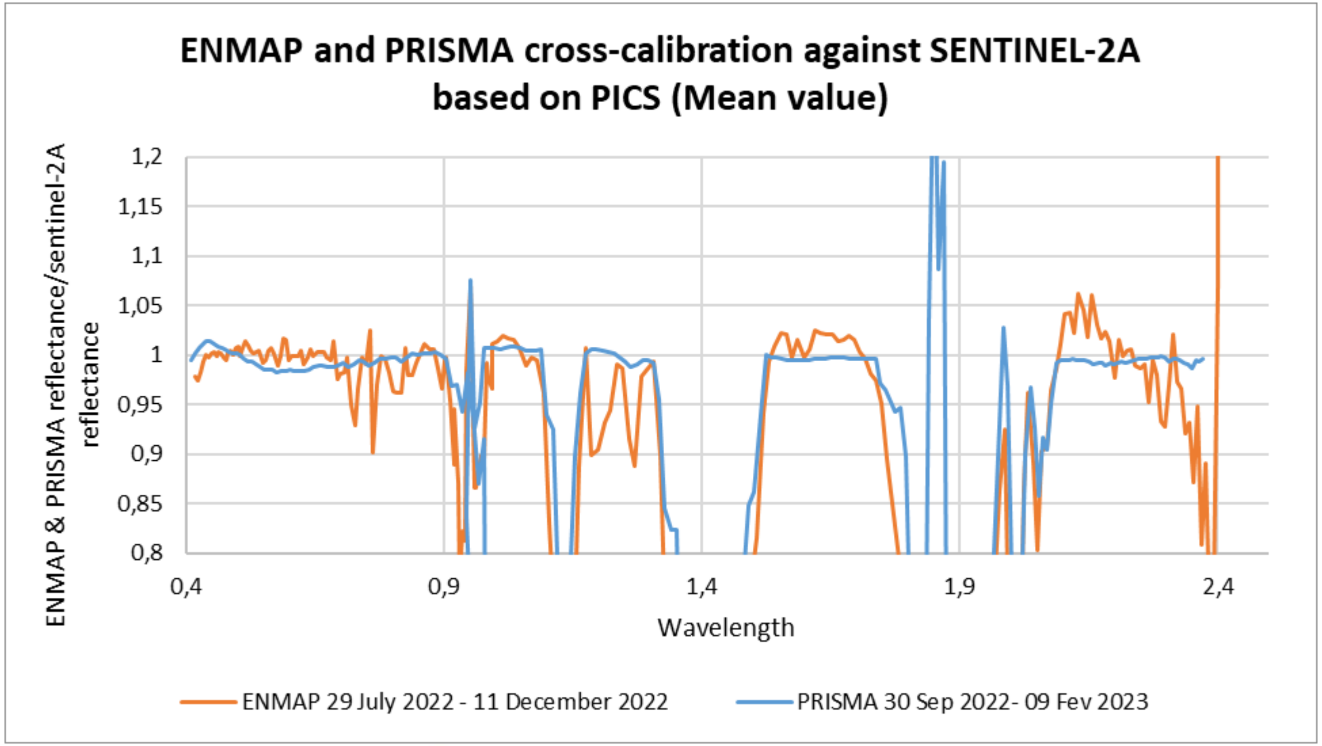
ENMAP CALIBRATION BASED ON PICS: PRELIMINARY RESULTS / SYNTHESIS





- **VNIR: Good consistency with SENTINEL-2A outside absorption bands**
- **SWIR: Good consistency around 1,6 µm**
  Spectral variations around 1.3 µm and 2.2 µm

ENMAP CALIBRATION BASED ON PICS: SYNTHESIS

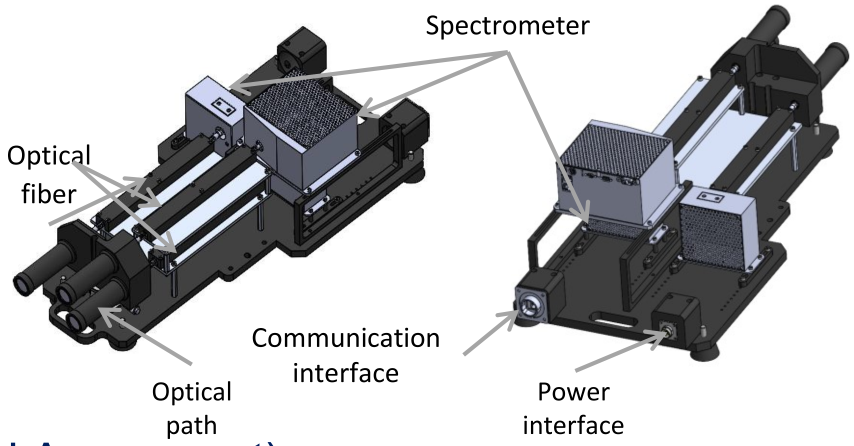


⇒ **Better consistency between PRISMA and SENTINEL-2A but :**

- ⇒ **Very preliminary results for ENMAP to be spatially and statistically refined (assess the spatial variation and increase the number of images and sites)**
- ⇒ **Direct ENMAP/PRISMA cross-calibration on going**
- ⇒ **ROSAS (La Crau and Gobabeb) processing ongoing for ENMAP**

FUTURE WORK

- On going activities for the optimization of HYSP operating points and the rationale for absolute and spectral onboard calibration
- Ongoing adaption of multispectral vicarious methods for hyperspectral sensors
- Development of an hyperspectral photometer to improve in-situ measurements (prototype to be deployed in 2024 at La Crau)



- On orbit radiometric Cal/Val activities:
  - Collaboration with ASI on PRISMA (renewed Agreement)
  - Calibration activities ongoing for Desis & EnMAP with DLR