Harmonization of SPOT-VGT1, SPOT-VGT2, and PROBA-V Time Series, Including Per-Pixel Uncertainty: Status of the FDR4VGT Project

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GSICS 2026

> 20+ year global land dataset

Sentinel-3B

Sentinel-3A

98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20

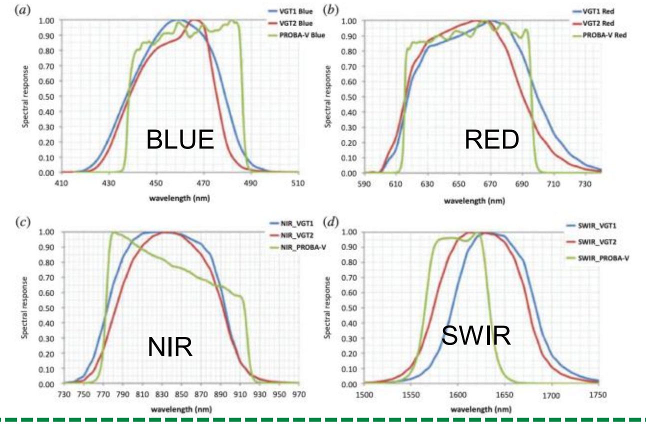
SPOT-VGT1

SPOT-VGT2

Proba-V

Global near-daily coverage

Blue, Red, NIR, SWIR bands



FDR4VGT Objectives

- Ensuring long-term data **preservation** and **valorisation** of SPOT-VGT1, SPOT-VGT-2 and PROBA-V data archives;
- **Improving consistency**, by fully characterising the radiometric, geometric and spectral differences across sensors;
- Enhancing **harmonisation and temporal stability** by quantifying and correcting inter-sensors biases and sensor-induced spurious drifts;
- Providing **uncertainty estimates at pixel level**, ensuring traceability along the full processing chain, starting from raw data;
- Generating a temporally stable and harmonised data record of reflectances at **TOA** and **TOC** level to be used as input for climate studies.

FDR4VGT phase

Phase 1 (2024-26) : Algorithm development

- Radiometric Harmonization
- Geometric Harmonization
- L1 pixel-level Uncertainty
- Consistent Cloud Masking
- Consistent A/C and Uncertainty Propagation to L2

Phase 2 (2026-28): Integration and reprocessing 20+ years archive.

FDR4VGT phases

Phase 1 (2024-26) : Algorithm development

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Phase 2 (2026-28): Integration and reprocessing 20+ years archive.

SPOT-VGT1 & 2

- Image Quality Centre (QIV) at CNES
- Processing, Archiving & Distribution at VITO

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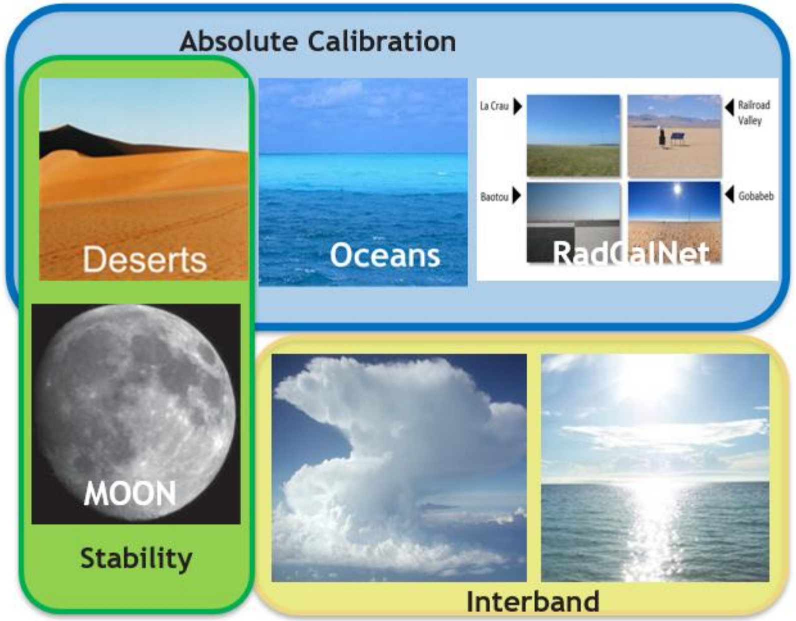
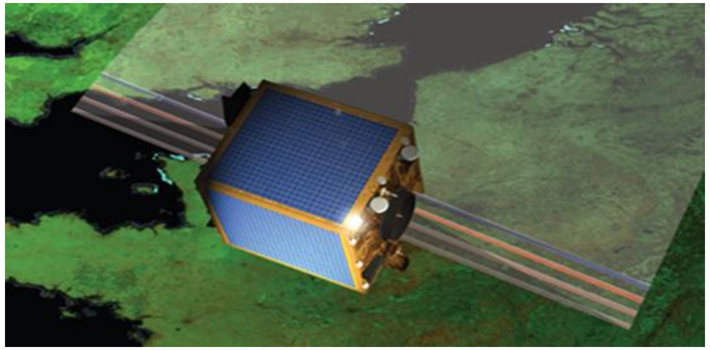
PROBA-V

- Processing, Archiving, Distribution, Image Quality Control at VITO
- Imaging Quality Center (IQC) at VITO

Radriometric Calibration

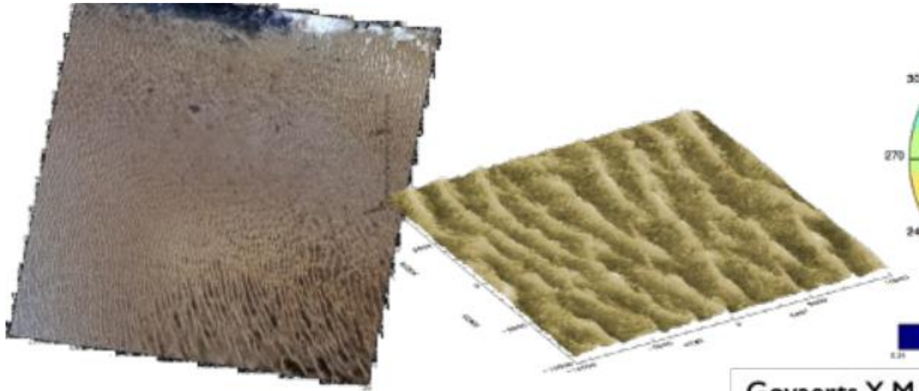
OSCAR* (Optical Sensor Calibration with simulated Radiances)

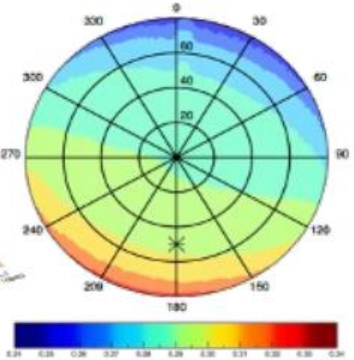




*Sterckx *et al.* IJRS, 2014; Sterckx *et al.* , TGARS, 2013; Govaerts *et al.*, RSL, 2013; Sterckx et al., RS, 2016

Rayference Radiometric Calibration Reference (RRCR)





Govaerts, Y. M. 1999. "Correction of the Meteosat-5 and -6 VIS Band Relative Spectral Response with Meteosat-7 Characteristics." *International Journal of Remote Sensing* 20 (18): 3677–82.

Govaerts, Y. M., and M. Clerici. 2004. "Evaluation of Radiative Transfer Simulations over Bright Desert Calibration Sites." IEEE TGARS, 42 (1).

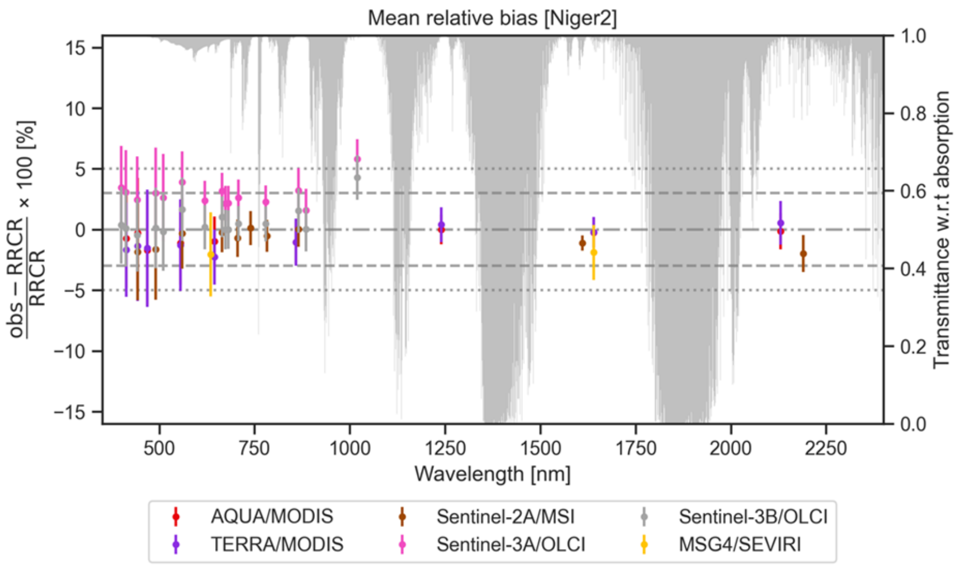
Govaerts, Yves, et al. 2013. "Use of Simulated Reflectances over Bright Desert Target as an Absolute Calibration Reference." RSE, 523-- 531.

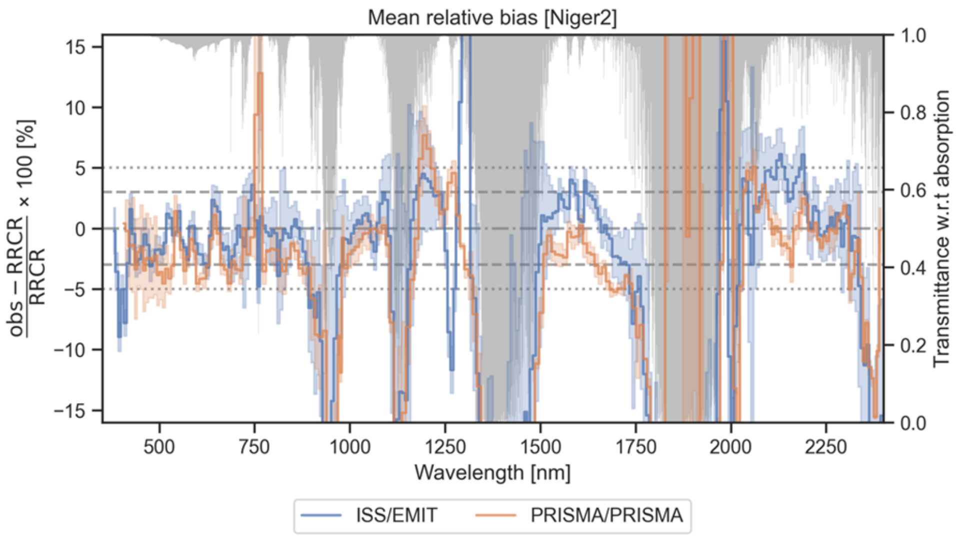
Govaerts, Y. M. 2015. "Sand Dune Ridge Alignment Effects on Surface BRF over the Libya-4 CEOS Calibration Site." Sensors 15 (2): 3453–70;

Govaerts, Y. M., et al. 2018. "Climate Data Records from Meteosat First Generation Part I: Simulation of Accurate Top-of-Atmosphere Spectral Radiance over Pseudo-Invariant Calibration Sites for the Retrieval of the In-Flight Visible Spectral Response." Remote Sensing 10 (12): 1959.

Rayference Radiometric Calibration Reference

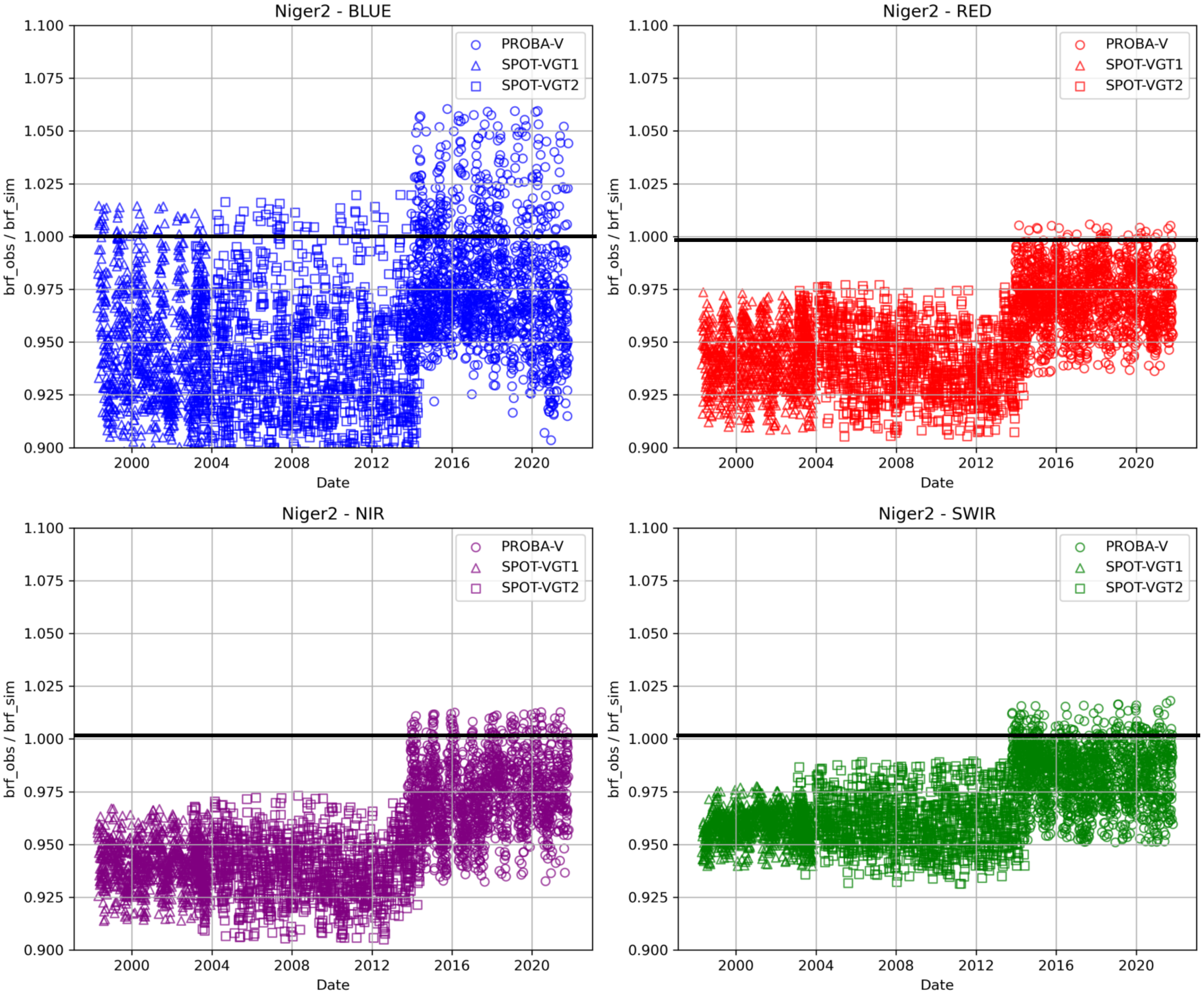
- RPV model for surface BRF at 1 nm spectral resolution;
- CAMS data for the atmospheric profile;
- CAMS data for aerosol optical thickness;
- Aerosol model based on various sources of information;
- Aerosol exponential profile;
- Spherical Earth;
- TOA simulation performed with **Eradiate** at 1 nm spectral resolution;
- Illumination and viewing geometries from the simulated observation.

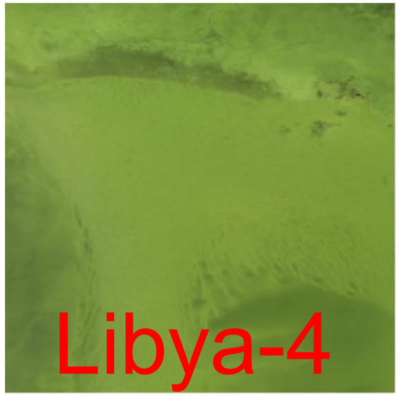




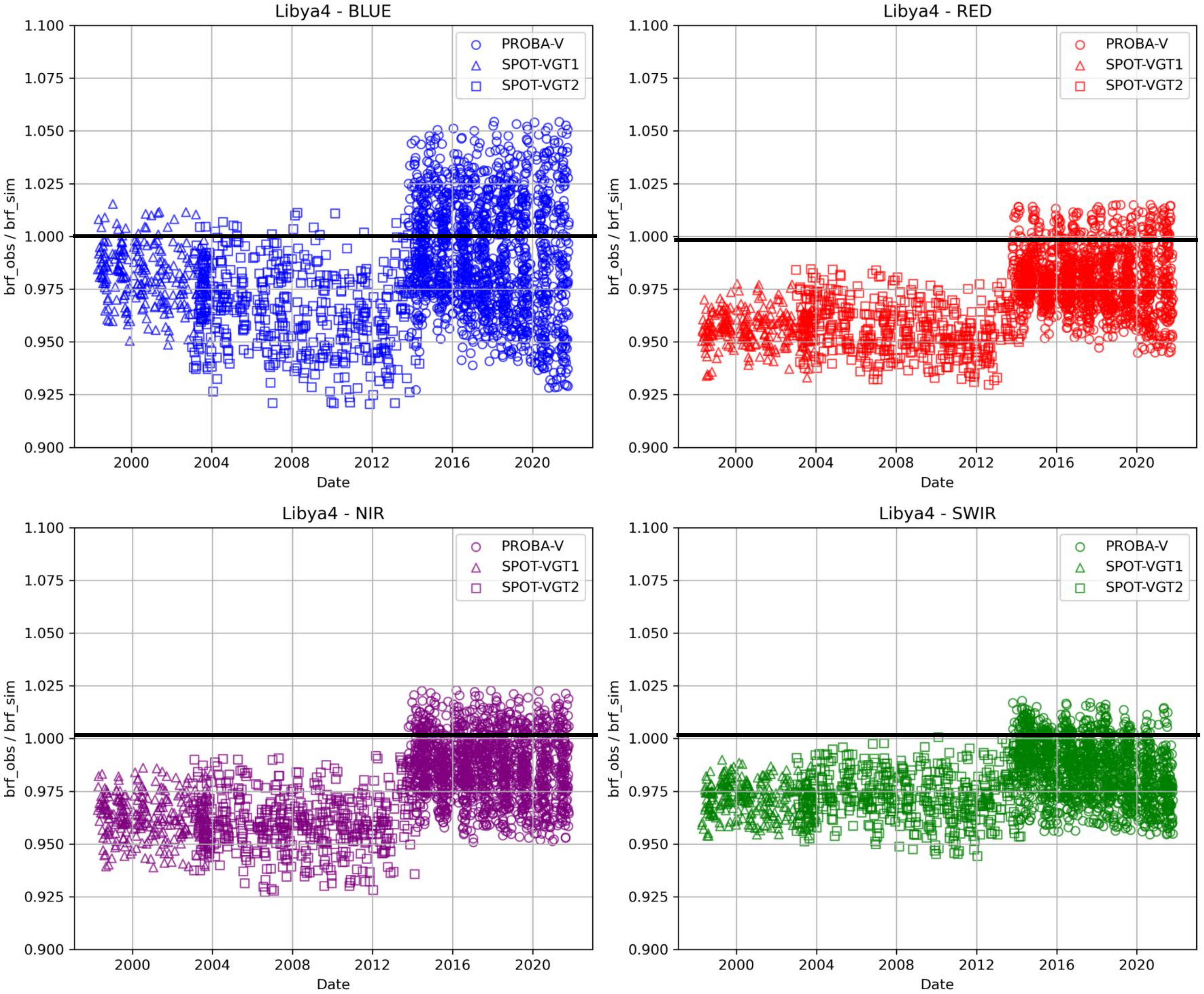
BRFmeasured
BRFsimulated

VISUAL
CLOUD
SCREENING+
OUTLIER

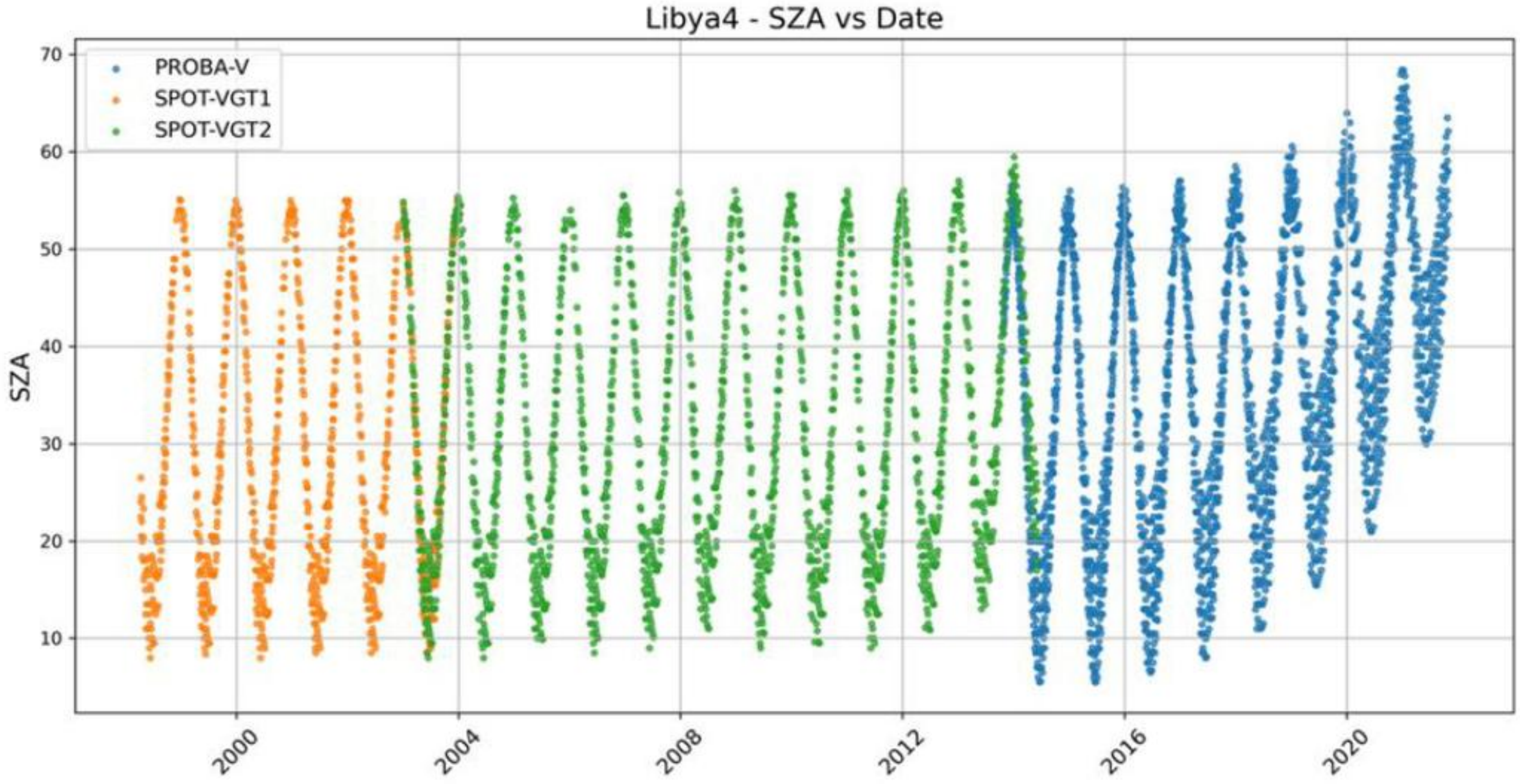




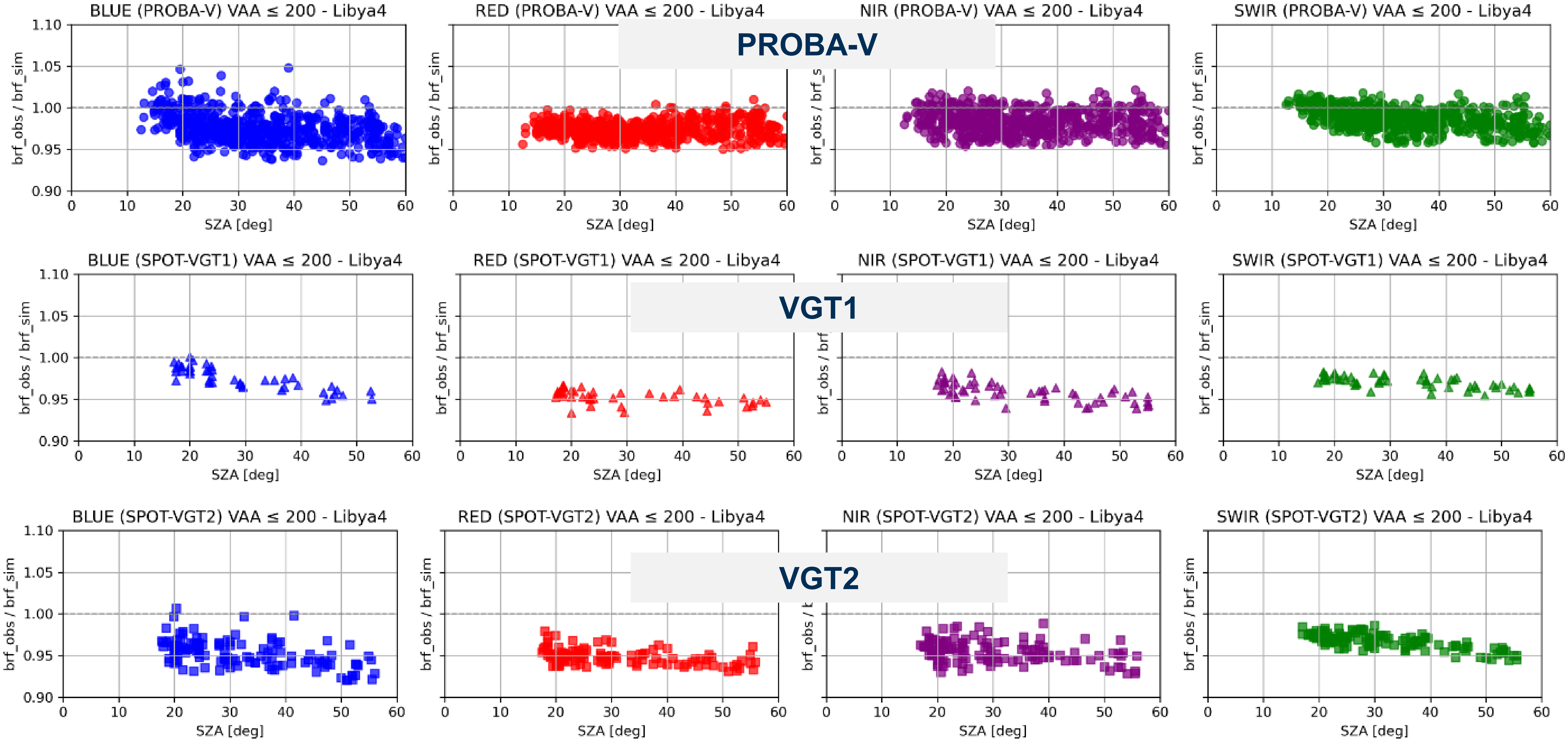
VISUAL
CLOUD
SCREENING
+
OUTLIER



Is there a SZA dependency ?


Libya4 - SZA vs Date
PROBA-V
SPOT-VGT1
SPOT-VGT2
SZA
70
60
50
40
30
20
10
2000
2004
2008
2012
2016
2020

Libya4



PROBA-V
VGT1
VGT2
BLUE (PROBA-V) VAA ≤ 200 - Libya4
RED (PROBA-V) VAA ≤ 200 - Libya4
NIR (PROBA-V) VAA ≤ 200 - Libya4
SWIR (PROBA-V) VAA ≤ 200 - Libya4
BLUE (SPOT-VGT1) VAA ≤ 200 - Libya4
RED (SPOT-VGT1) VAA ≤ 200 - Libya4
NIR (SPOT-VGT1) VAA ≤ 200 - Libya4
SWIR (SPOT-VGT1) VAA ≤ 200 - Libya4
BLUE (SPOT-VGT2) VAA ≤ 200 - Libya4
RED (SPOT-VGT2) VAA ≤ 200 - Libya4
NIR (SPOT-VGT2) VAA ≤ 200 - Libya4
SWIR (SPOT-VGT2) VAA ≤ 200 - Libya4
brf_obs / brf_sim
SZA [deg]

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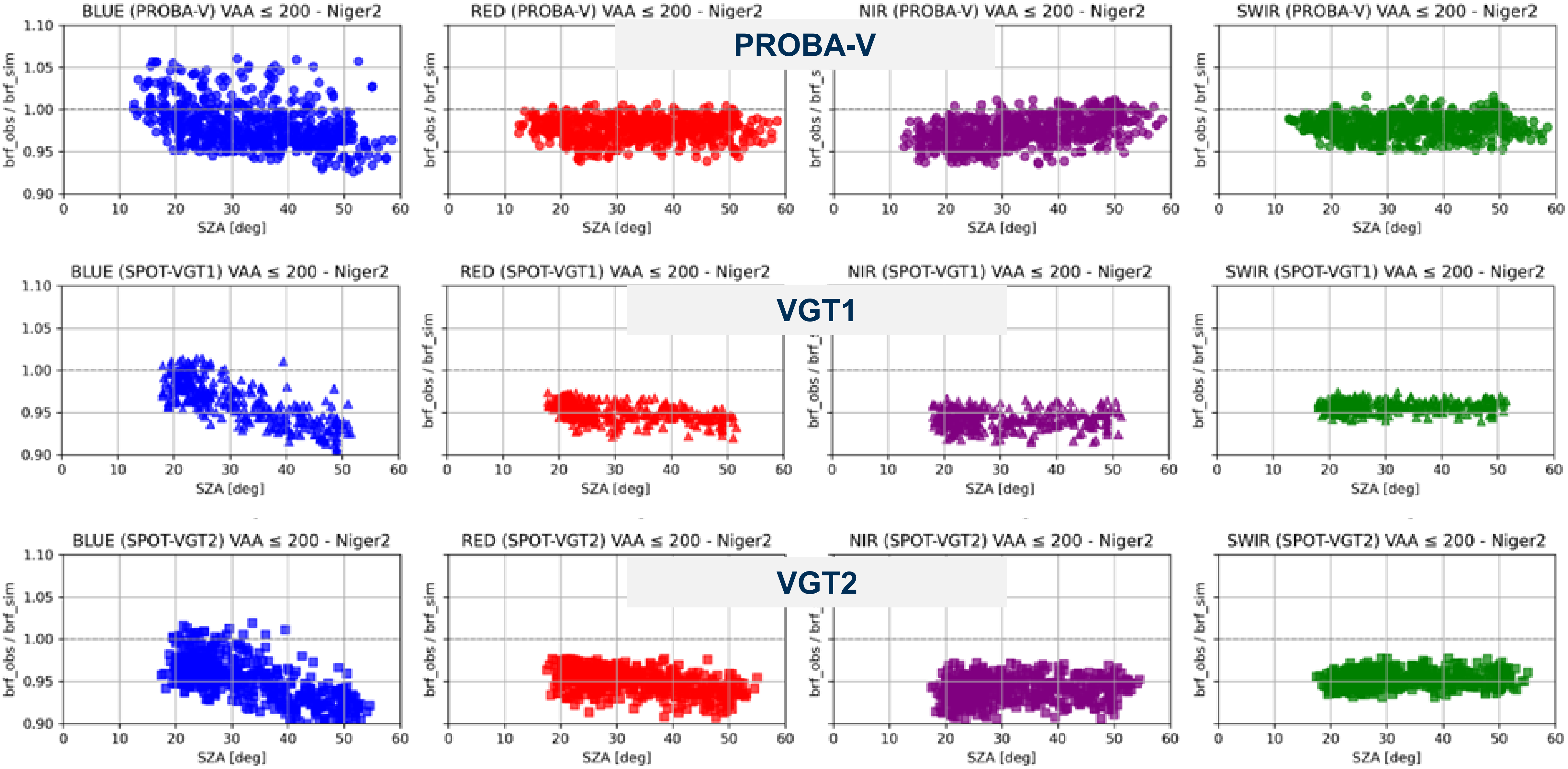
Niger-2



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Limit results to SZA <45°

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What is the overall bias ?

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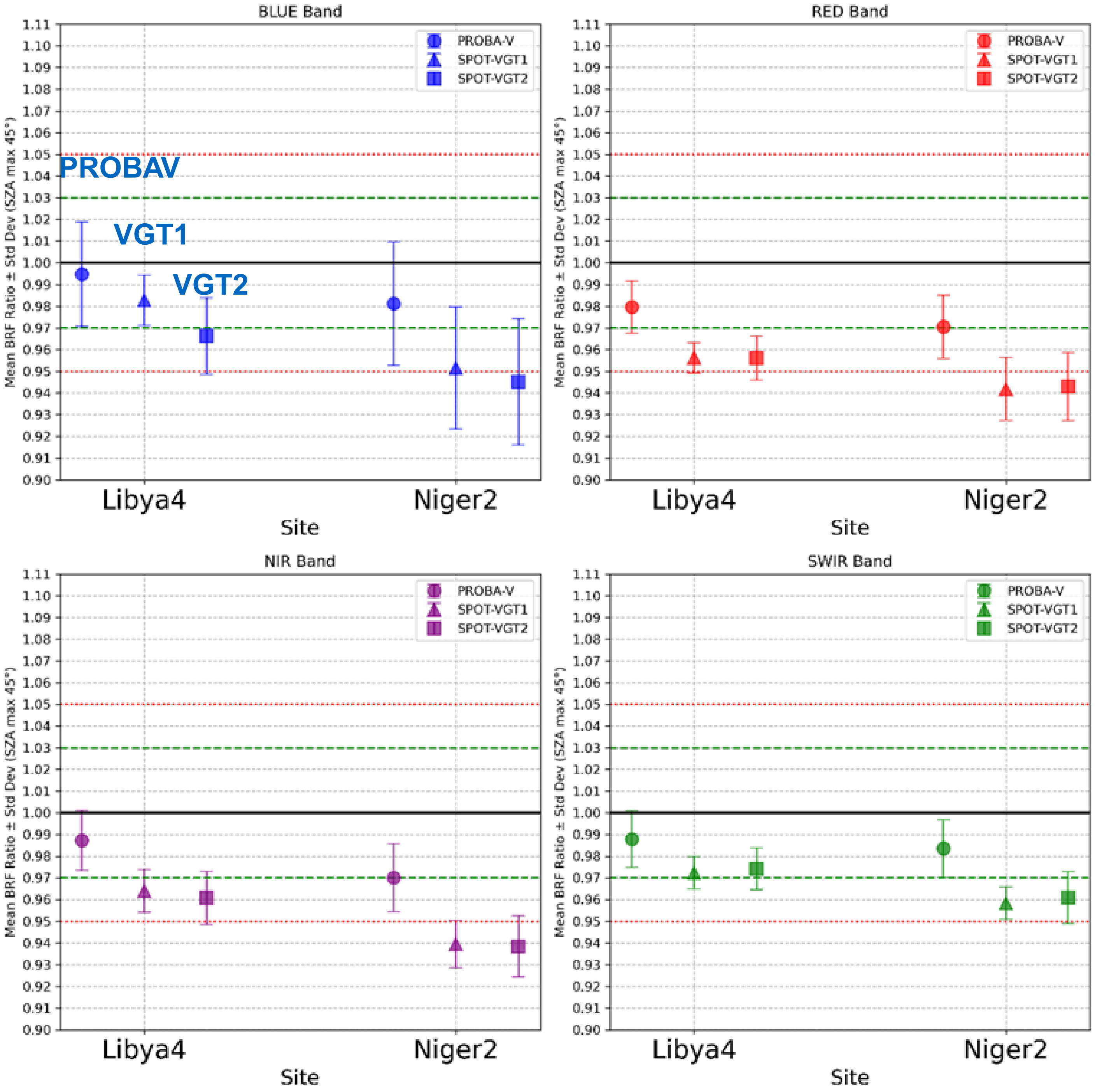
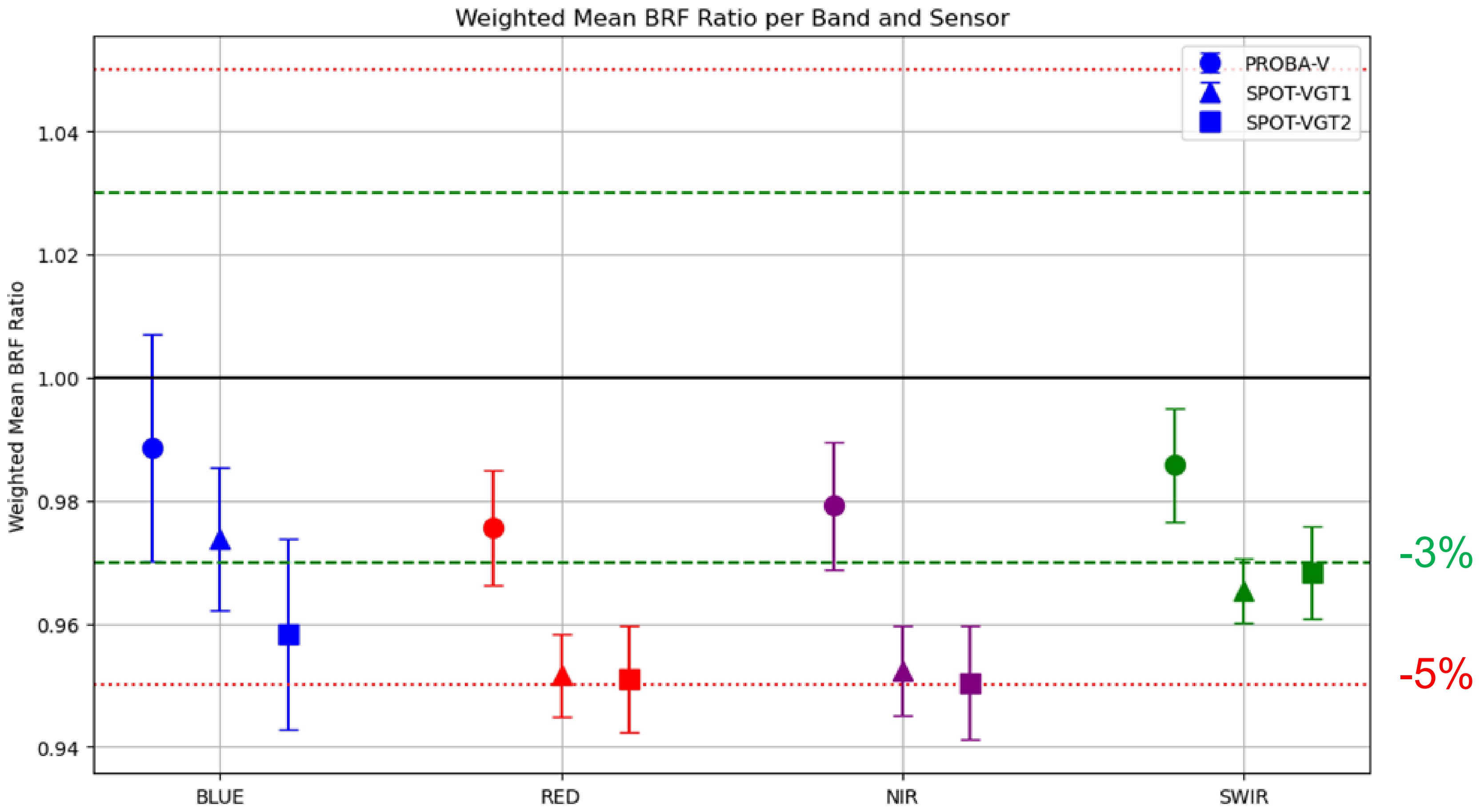
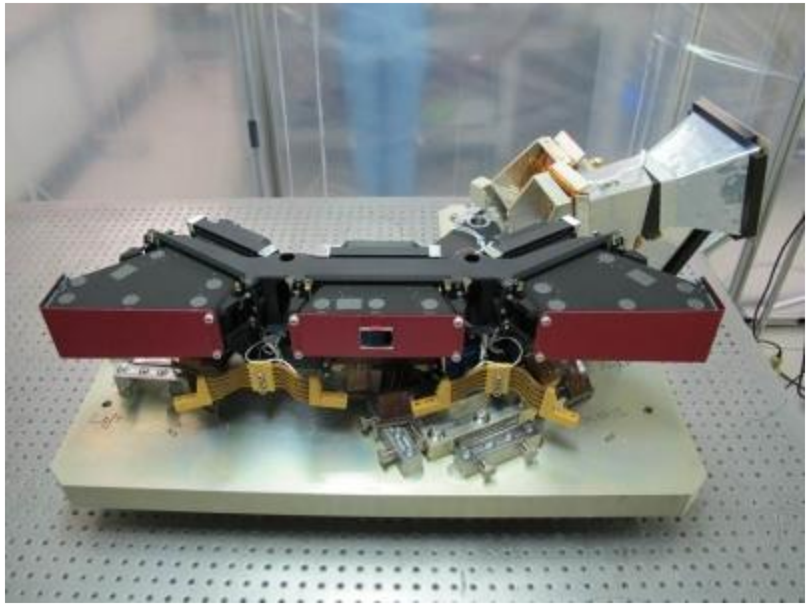
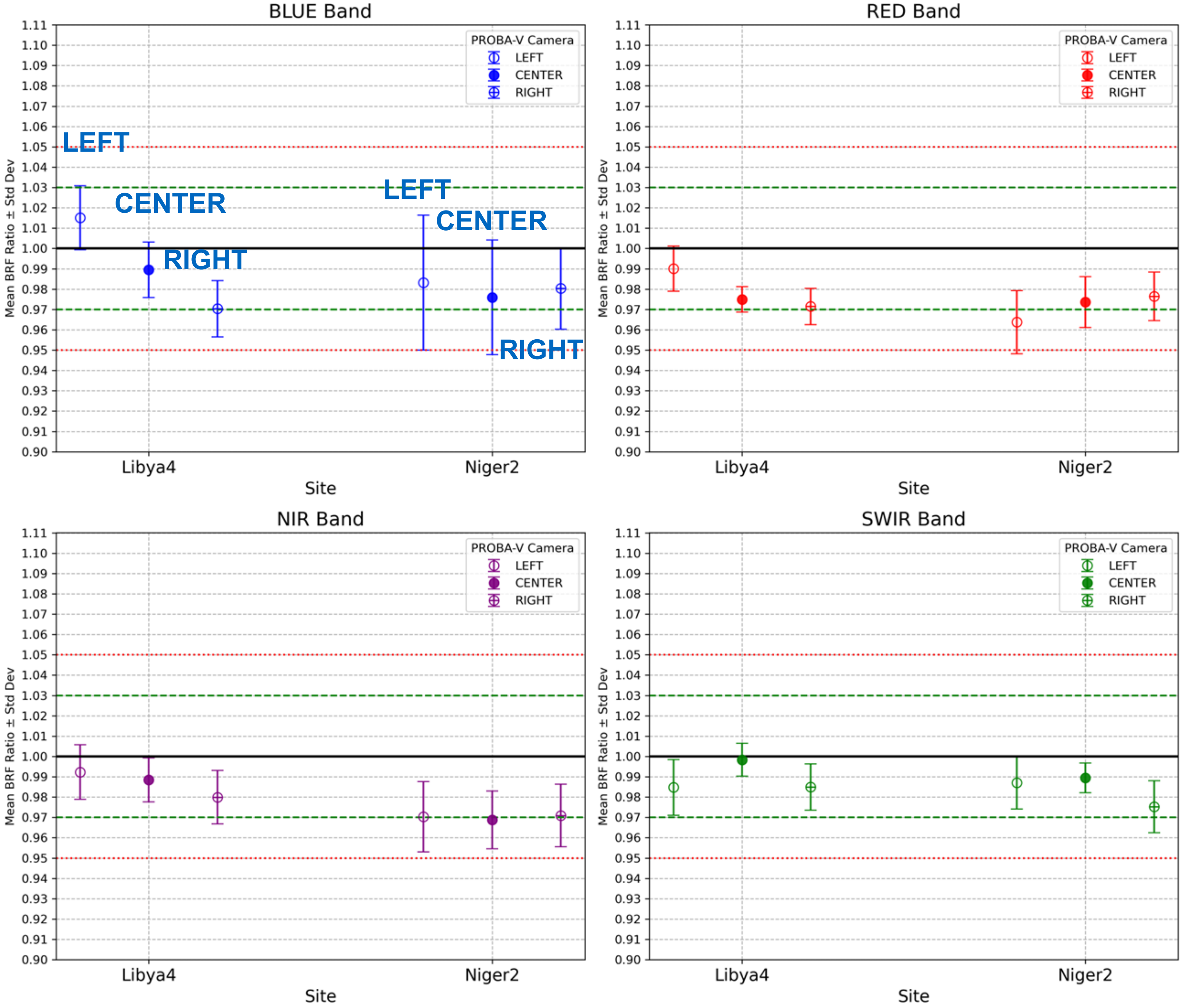




Satellite	BLUE	RED	NIR	SWIR
PROBA-V	0.989	0.976	0.979	0.986
SPOT-VGT1	0.974	0.952	0.952	0.965
SPOT-VGT2	0.958	0.951	0.950	0.968

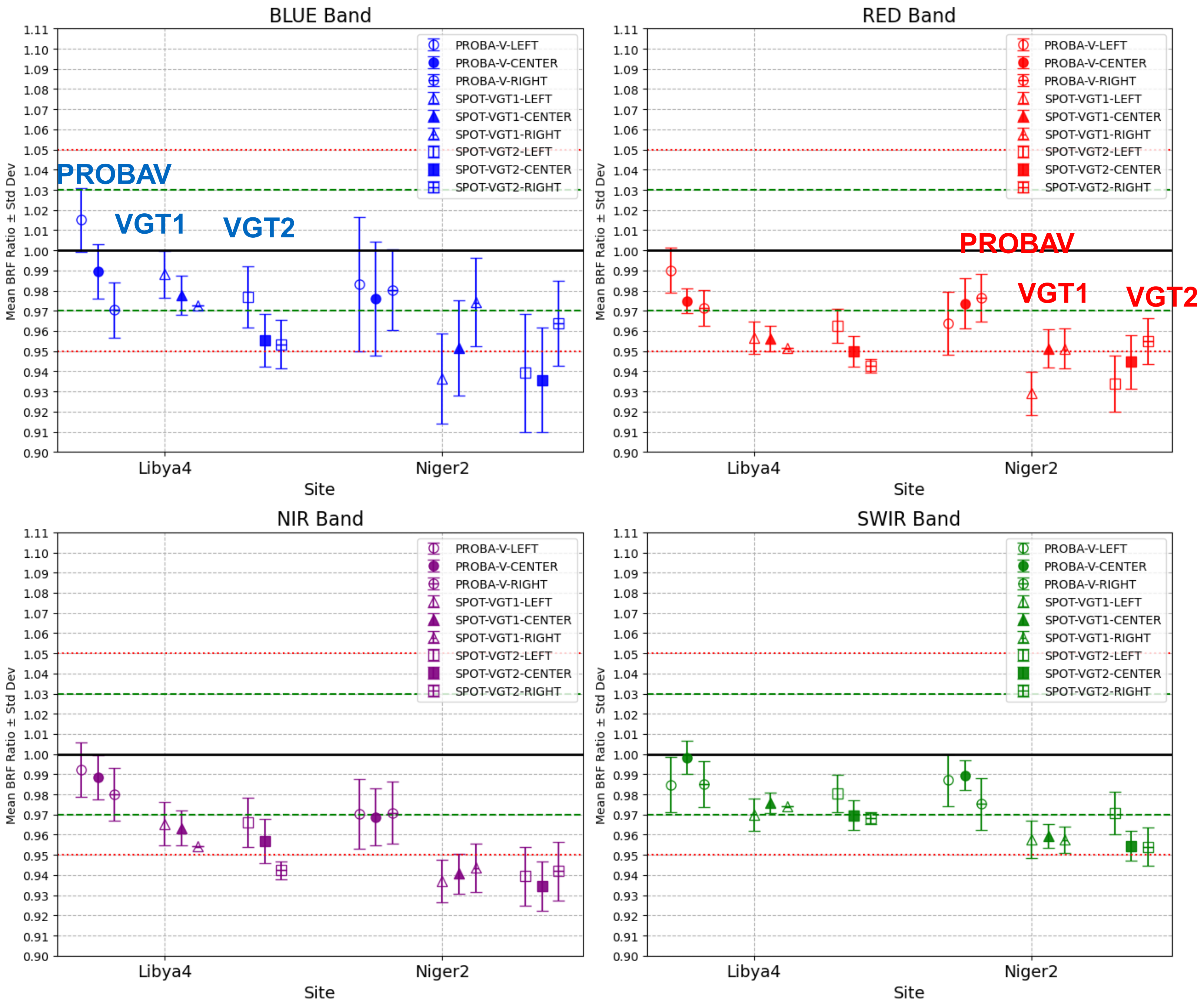


Is there a camera dependency in PROBA-V?



BLUE Band
RED Band
NIR Band
SWIR Band
PROBA-V Camera
LEFT
CENTER
RIGHT
Mean BRF Ratio ± Std Dev
Libya4
Niger2
Site

Remote Sensing



It is justified to apply a single overall bias correction across all three PROBA-V cameras

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Is there any residual radiometric trends in the data?

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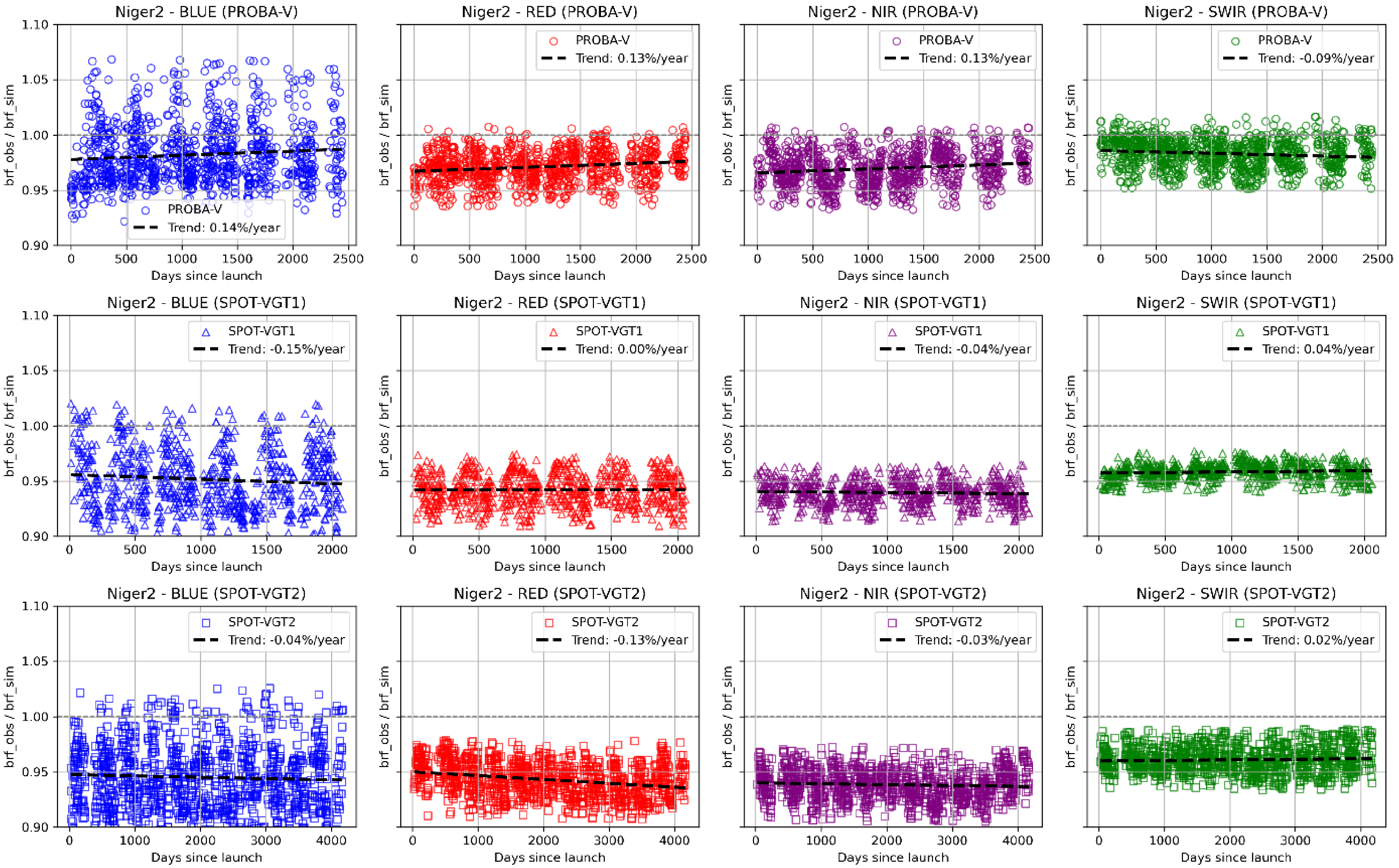
Niger-2



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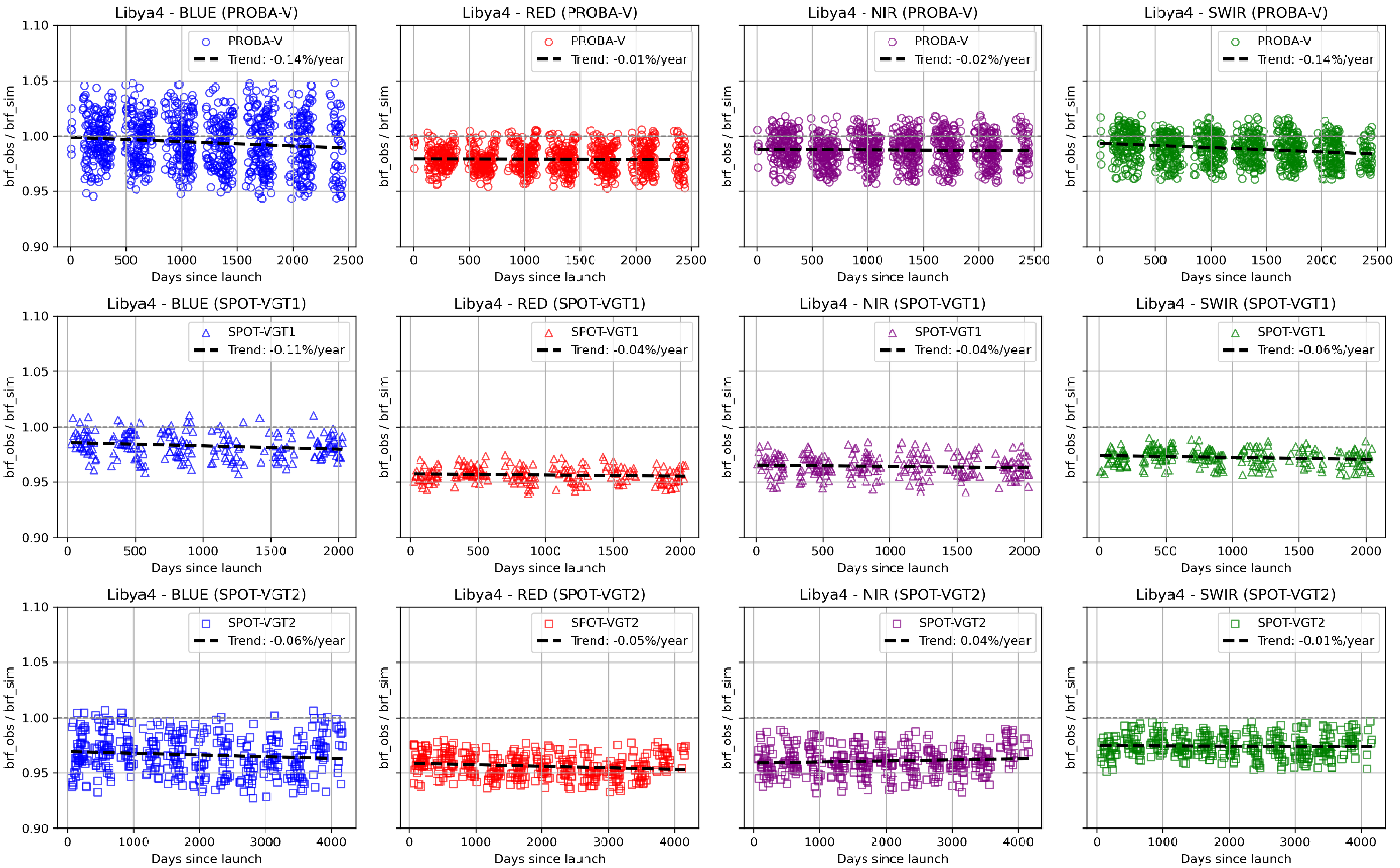
Libya-4



There is no consistent or systematic deviation suggesting the need for a revision of the degradation models.

Key Findings

- Bias Assessment
  PROBA-V closest to absolute reference
  VGT1/VGT2 show systematic underestimation
- SZA Dependency
  Clear SZA effect (notably BLUE, Niger-2) ; Analyses limited to **SZA < 45°**

- Camera Dependency (PROBA-V)
  Minor differences between cameras, site-dependent ;Attributed to radiative transfer uncertainties

- Trend Analysis
  Stable time series (VGT C3 & PROBA-V C2)
  No evidence supporting model revision

👉 Final Conclusion:

Only inter-sensor bias adjustment needed — no update to degradation models required

FDR4VGT phases

Phase 1 (2024-26) : Algorithm development

Radiometric Harmonization

Geometric Harmonization

L1 pixel-level Uncertainty

Consistent Cloud Masking

Consistent A/C and Uncertainty Propagation to L2

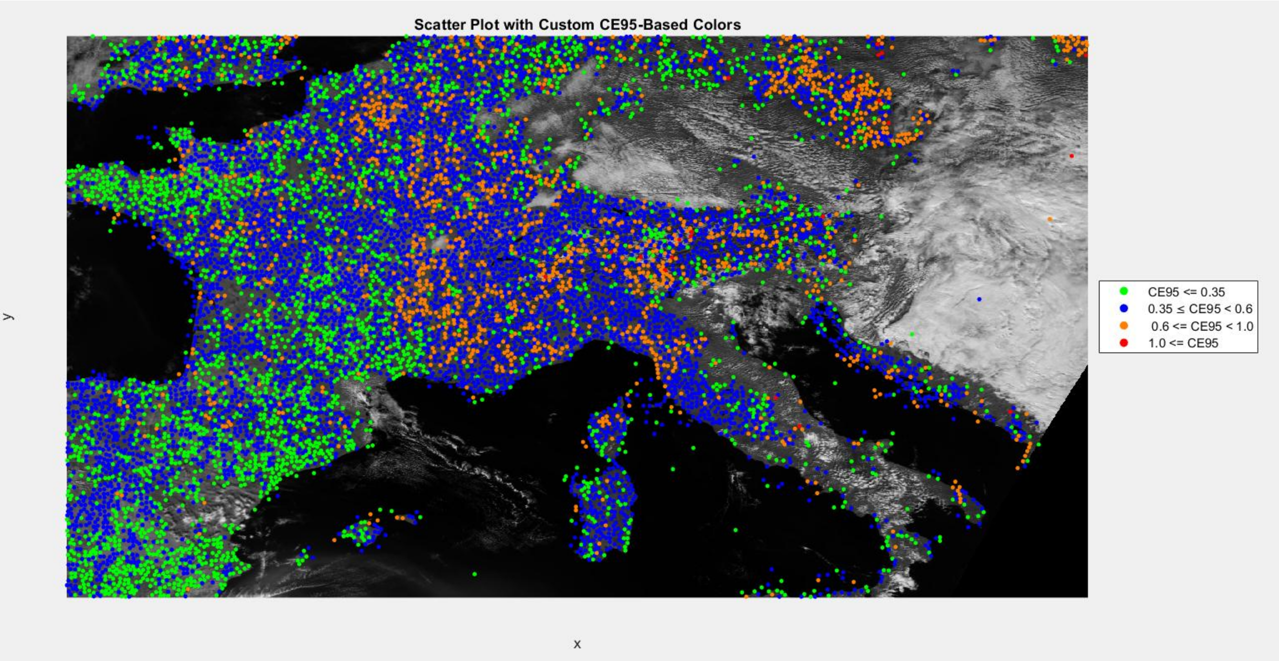
Phase 2 (2026-28): Integration and reprocessing 20+ years archive.

Geometric harmonisation

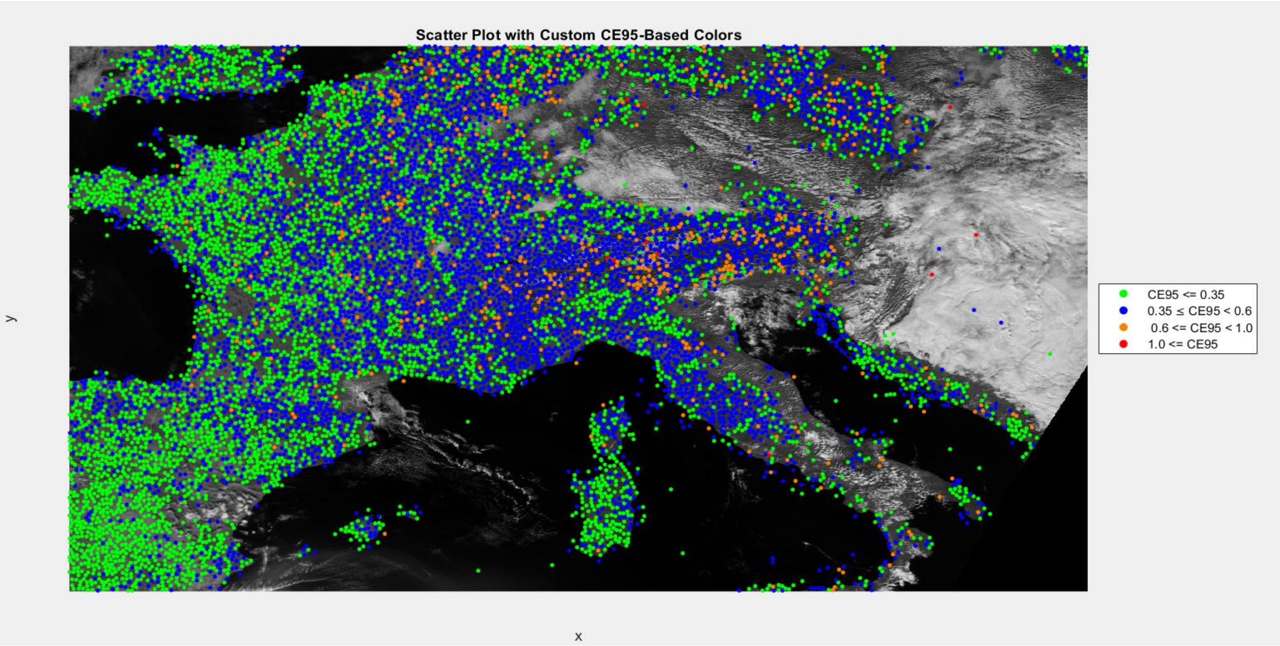
- **DEM Harmonisation**
  - Use of Copernicus DEM for both missions
- **Common Database of Ground Control Points (GCPs)**
  - Use of Sentinel 2 Global Cloud free Imagery
- **Geometric Calibration harmonisation**
  - Use of VITO’s geometric calibration approach based on bundle adjustment

Geometric multi-temporal accuracy

Multi-temporal results (ROI 1)



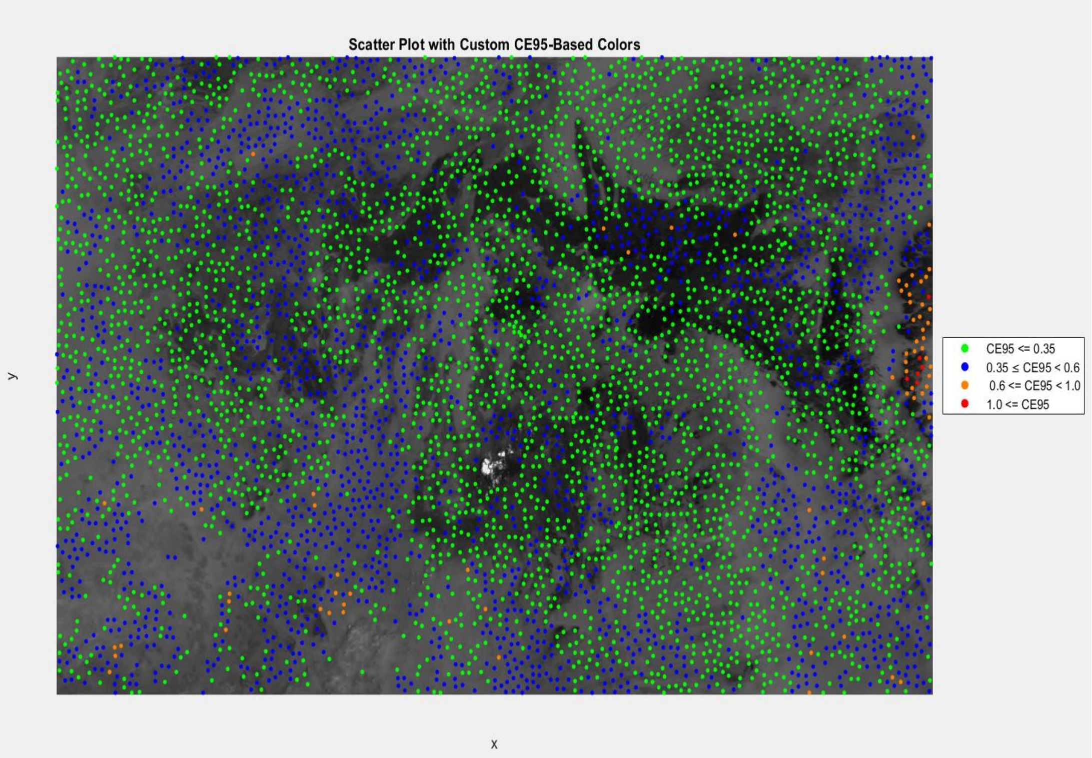
SPOT-VGT C3 (old)



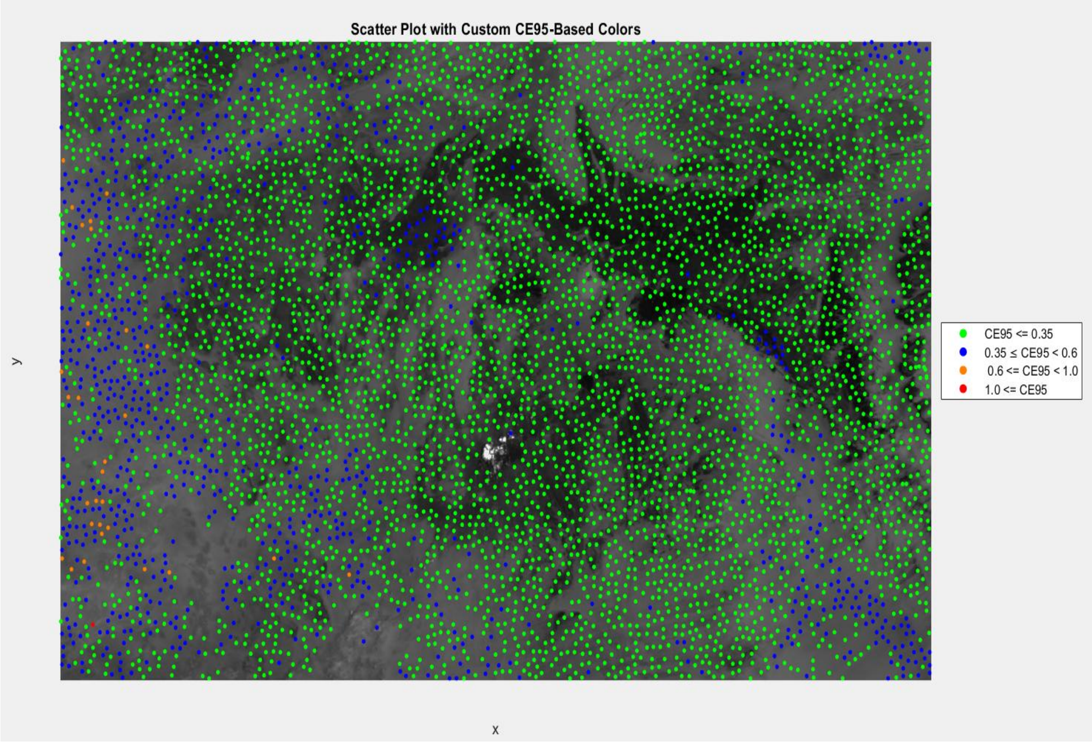
SPOT-VGT recalibrated (new)

Geometric multi-temporal accuracy

Multi-temporal results (ROI 2)



SPOT-VGT C3 (old)



SPOT-VGT recalibrated (new)

FDR4VGT phase

Phase 1 (2024-26) : Algorithm development

Radiometric Harmonization

Geometric Harmonization

L1 pixel-level Uncertainty

Consistent Cloud Masking

Consistent A/C and Uncertainty Propagation to L2

Phase 2 (2026-28): Integration and reprocessing 20+ years archive.

L1 pixel-level Uncertainty

Objective: *Provide a data product exposing uncertainty images expressed in the L1C projected coordinates, accounting for:*

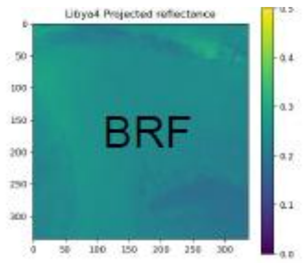
- *digital count*
- *radiometric calibration*
- *ancillary data*
- *geometric processing*

Uncertainty sources

L1 pixel-level Uncertainty

1. Uncertainty Diagrams

Observation



Measurement eq

$$\text{e1: } \rho_{TOA}^{k} = \frac{\pi D^2 L_{TOA}^{k}}{E_0^k \cos(\theta_s)} + \varnothing$$

Sensitivity | Uncertainty

Sensitivity	Uncertainty
c1: $\frac{\partial}{\partial E_0^k}\rho_{TOA}^{k}$	u1: $u(E_0^k)$
c2: $\frac{\partial}{\partial \theta_s}\rho_{TOA}^{k}$	u2: $u(\theta_s)$
c3: $\frac{\partial}{\partial D}\rho_{TOA}^{k}$	u3: $u(D)$
c4: $\frac{\partial}{\partial L_{TOA}^{k}}\rho_{TOA}^{k}$	u4: $u(L_{TOA}^{k})$

2. Digital Effect Table (DET)

Table Descriptor		Quantity
Name of effect		Uncertainty on the Spectral Solar Irradiance
Affected term in measurement function		TOA reflectance
Bands		All
Correlation type and form	within scanline [pixels]	rectangle_absolute (systematic)
	from scanline to scanline [scanlines]	rectangle_absolute (systematic)
	between orbit [orbits]	rectangle_absolute (systematic)
	between bands	None
	over time	rectangle_absolute (systematic)

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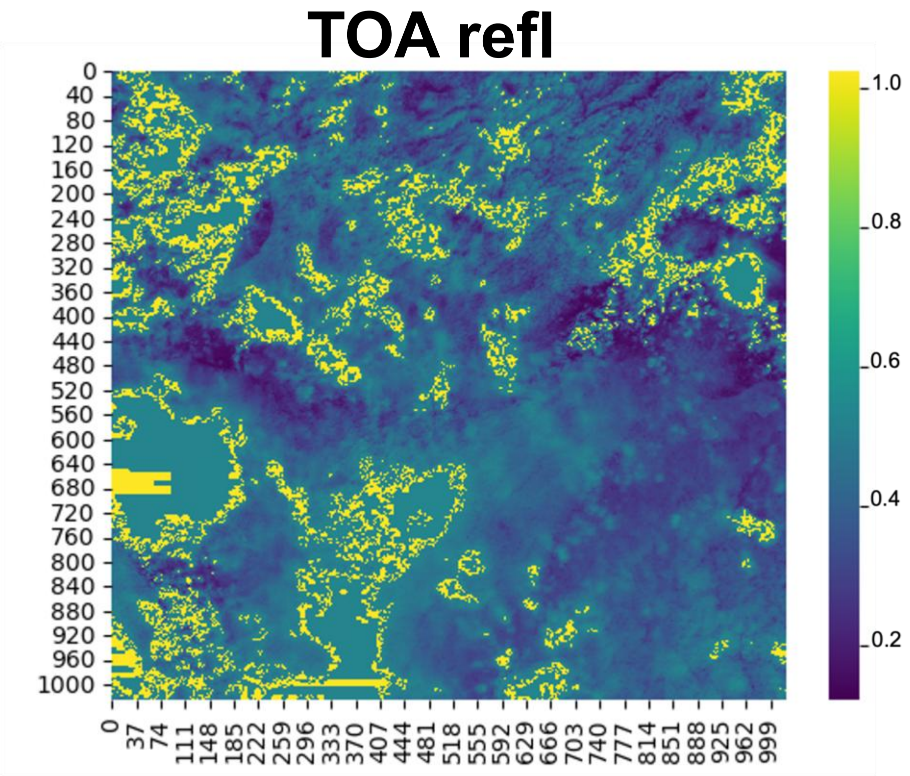
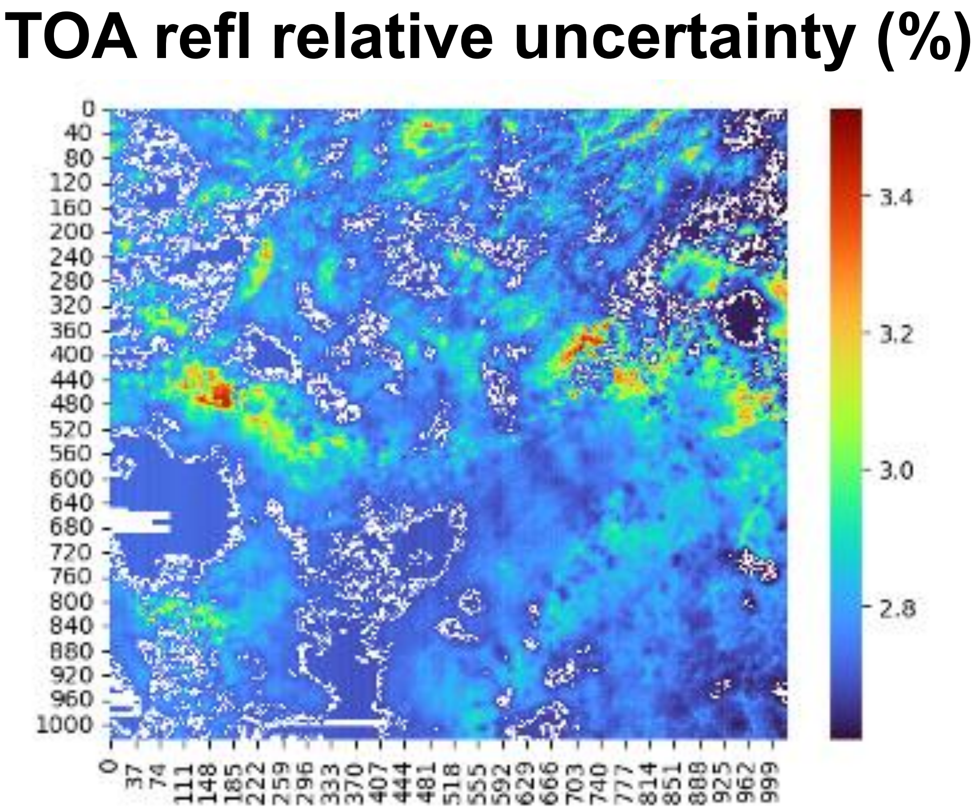
Pixel level-uncertainty

RAYFERENCE





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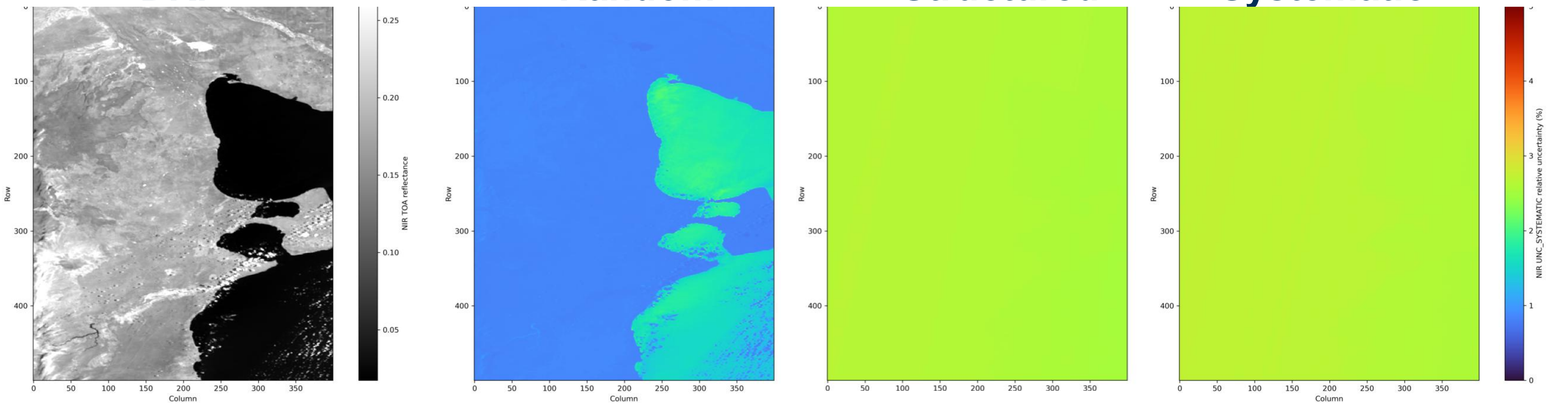
Pixel level-uncertainty

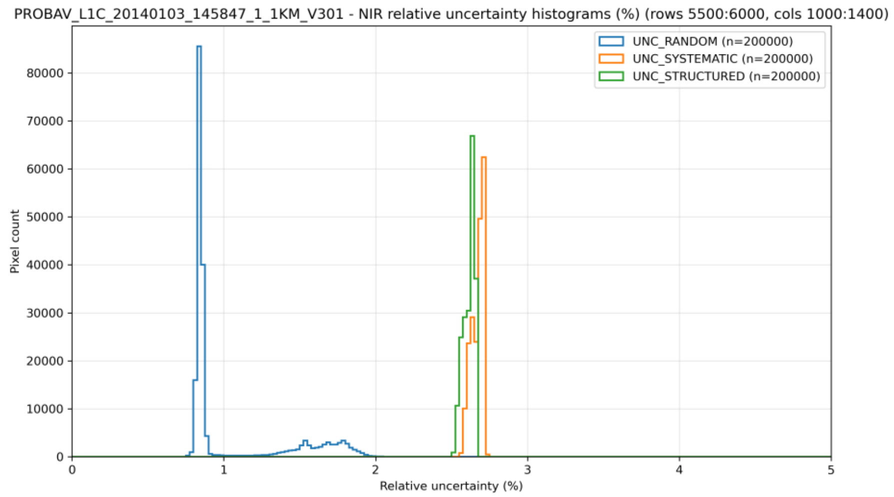
RAYFERENCE

- Uncertainty Decomposition:
  - **Random**: detector noise, dark current, digitization errors
  - **Systematic**: calibration coefficients, equalization parameters
  - **Structured**: correlated effects (e.g. SRFs, inter-detector variations)

Relative uncertainty (in %)

BRF Random Structured Systematic





FDR4VGT phase

Phase 1 (2024-26) : Algorithm development

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Phase 2 (2026-28): Integration and reprocessing 20+ years archive.

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Cloud masking

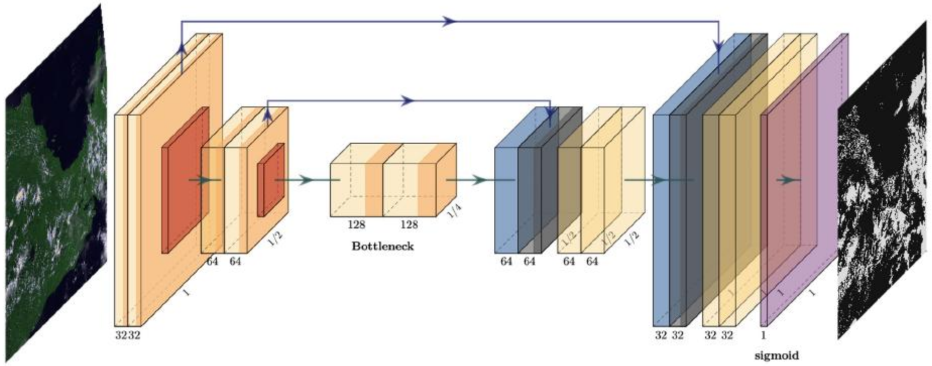
FDR4VGT Requirements :

- Development of reliable and consistent cloud masking algorithm

Approach:

- PROBA-V C2: Fully Convolution Neural Network (FCNN)
  - ➢ Significant improvements in Cloud Detection
- Transfer learning from PROBA-V to SPOT-VGT1/2

Input: TOA reflectance



Output: cloud mask

Pixel-wise MLP NN → Image-based FCNN
* simplified multiband version of a U-Net

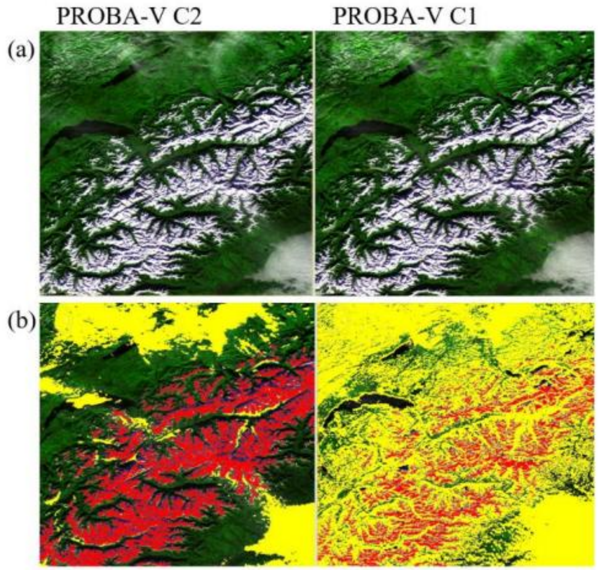


Figure 1: Visual comparison of PROBA-V L3 S1 TOC 333m C2 (left) and C1 (right) for 21/12/2014; (a) false colour composite (Red-NIR-Blue); (b) overlay with identification of clouds (yellow) and snow/ice (red).

L2 – Atmospheric Correction

FDR4VGT Requirements :

- Harmonize A/C between VGT1, VGT2, PROBA-V
- Propagation of uncertainty to L2

- **Approach:**
  - SMAC-CL processor
  - Ancillary atmospheric data from MERRA-2
  - Use FIDUCEO uncertainty propagation

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FDR4VGT phase : Where are we ?

Phase 1 (2024-26) : Algorithm development

- ✓ Radiometric Harmonization
- ✓ Geometric Harmonization
- ✓ L1 pixel-level Uncertainty
- ✓ Consistent Cloud Masking
- ✓ Consistent A/C and Uncertainty L2

✓ *Algorithms defined*

✓ *Prototype software implemented*

🔄 *Production of sample datasets ongoing for validation*

Phase 2 (2026-28): Integration and reprocessing 20+ years archive.

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Geo intelligence
for real world
answers

Thank You

+ Stay informed

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