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TAKING THE PULSE OF OUR PLANET FROM SPACE

Synergistic exploitation of PV-CC in combination with Sentinel-2 towards a ML based AC

Luis Gómez-Chova, Gonzalo Mateo-García, Valero Laparra, Enrique Portalés, Fabrizio Niro, Jordi Cerdà, Arturo Sirvent

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LPS2022 – Bonn, Germany – May 23-27, 2022

Outline

Objective

- **Synergistic exploitation of PV-CC with Sentinel-2** for improving and validating the radiometric calibration and **atmospheric correction of PV-CC**

Proposal

- **ML method** to learn a general transformation **from PV-CC TOA to S-2 TOC**

Background

- Number of EO satellites carrying **similar optical sensors** constantly growing
- New **modest-size missions** may complement **institutional missions**

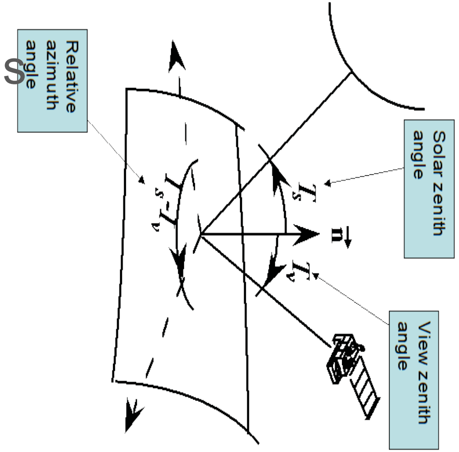
Problems

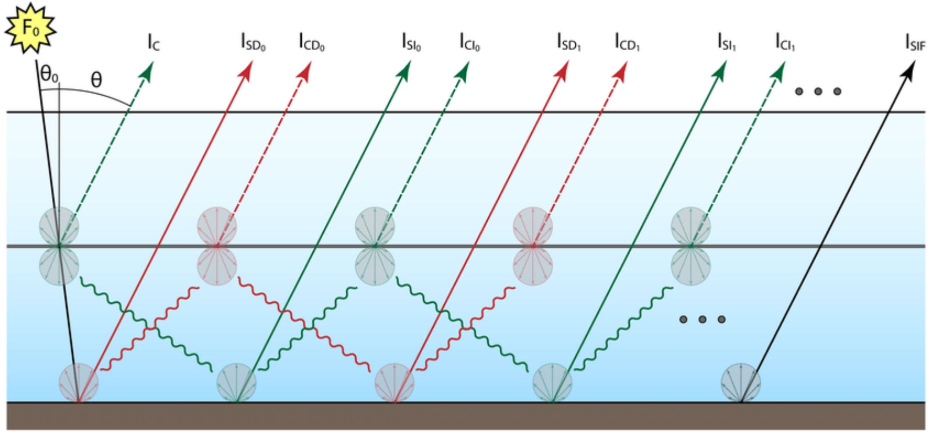
- **Cross-mission applications** require **data harmonization** not easy to meet
- CubeSats **performance usually lower**: calibration and processing algorithms

Atmospheric correction of optical images

Estimation of atmospheric contributions at sensor channels

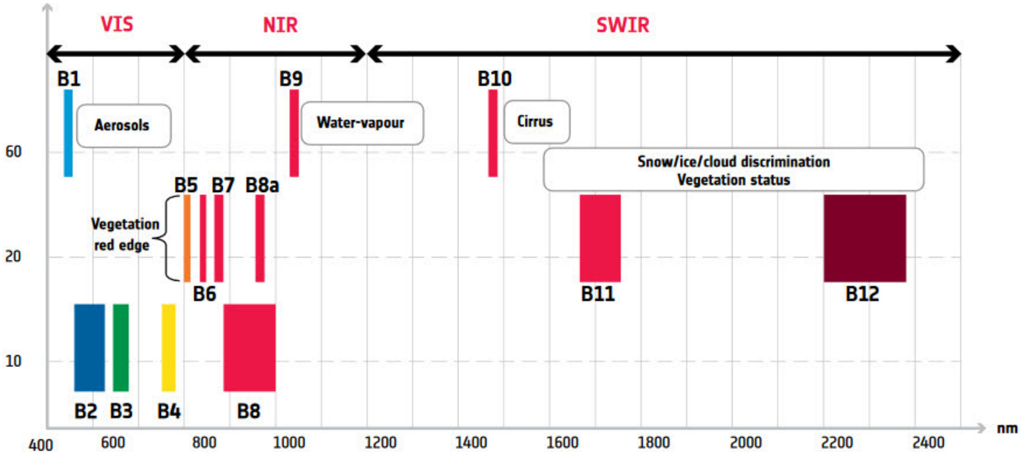
- Radiative transfer models (RTM)
- Atmospheric conditions at the acquisition time
  - Estimated from the image or from ancillary data
- Solve the radiative transfer equation



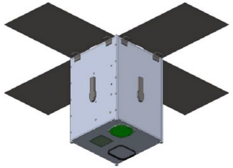


$$\rho_{app}(\theta_s,\theta_v,\phi)=\rho_{atm}(\theta_s,\theta_v,\phi)+T_{atm}(\theta_s)T_{atm}(\theta_v)\frac{\rho_{ground}}{1-\rho_{ground}S_{atm}}$$

Synergistic exploitation of PV-CC with Sentinel-2

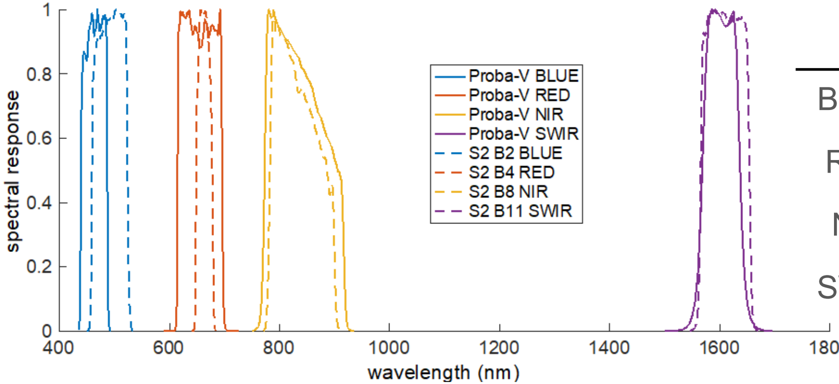


Sentinel-2
13 bands
10-20-60 m



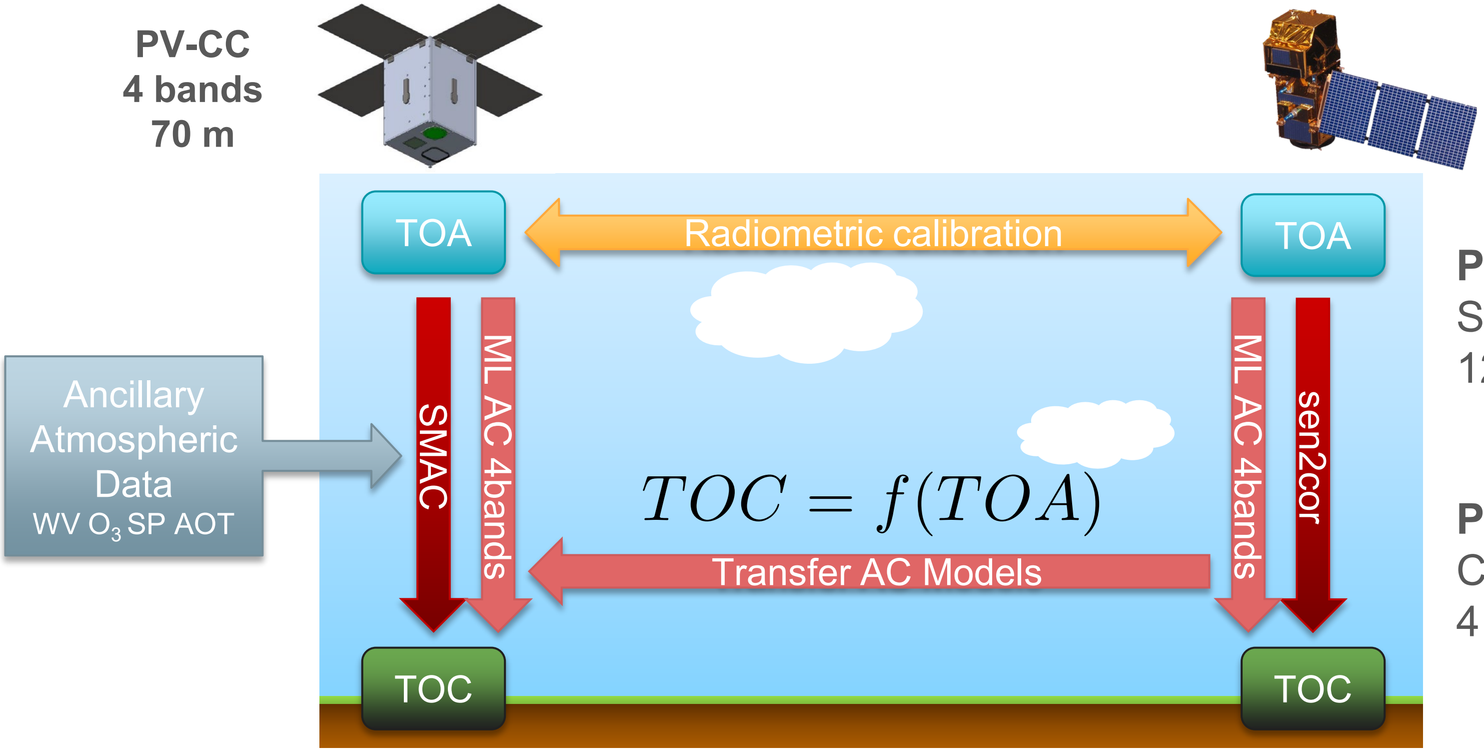
PV-CC
4 bands
70 m

Pros: no training data from PV required
Cons: differences across sensors (radiometric calibration, spectral responses, spatial resolutions)
→ lower performance expected



PV	S2
BLUE	B2
RED	B4
NIR	B8
SWIR	B11

Deep learning based Atmospheric Correction



Sentinel-2
12 bands
10-20-60 m

Pre-trained model
S2 data only
12 ⟶ 4 bands

PV-CC AC model
Cross-sensor
4 bands

Data requirements for training ML models

- Proba-V will be used as the best **proxy for PV-CC**
- Training requires a comprehensive dataset of **cloud-free TOA/TOC images**

Sentinel-2 model (to be transferred to PV-CC)

- **Input:** Sentinel-2 Level-1C TOA images
- **Output:** Sentinel-2 Level-2A BOA images (Sen2Cor)

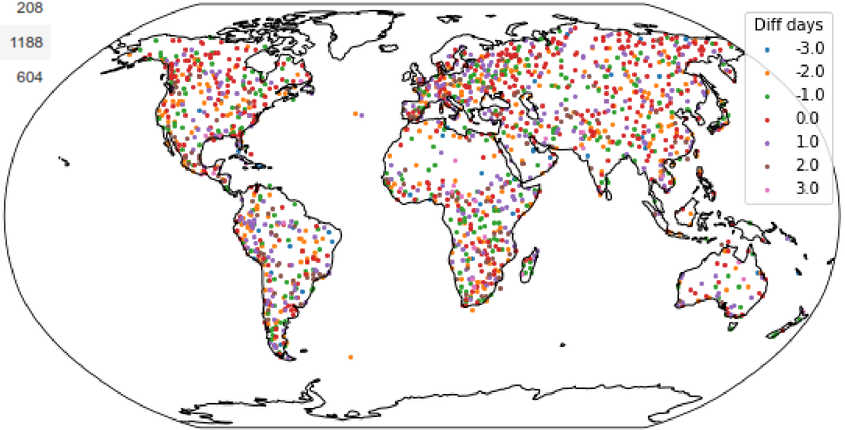
Proba-V model (to be used as baseline)

- **Input:** Proba-V 100m S1 TOA images
- **Output:** Proba-V 100m S1 TOC images (SMAC)

Sentinel-2 & Proba-V dataset

- Geographically diverse database covering **all seasons and biomes**
- **Sentinel-2** cloud-free images in 2000 locations (2018-2020)
- **Proba-V matches** with Sentinel-2 within 3days
  - Sentinel-2 (1900 train-100 test)
  - Proba-V (1781train-100test)

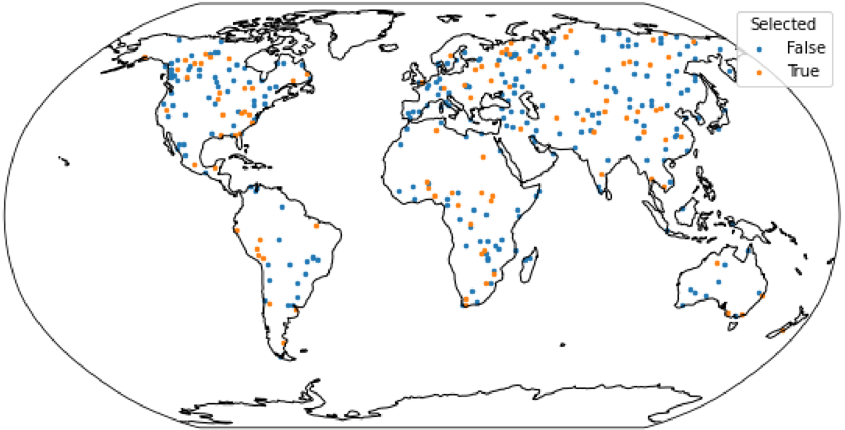
year	ROI
2018	208
2019	1188
2020	604



Proba-V vs Sentinel-2 comparison

Test set: same day, no clouds, no missing data

• 100 test locations



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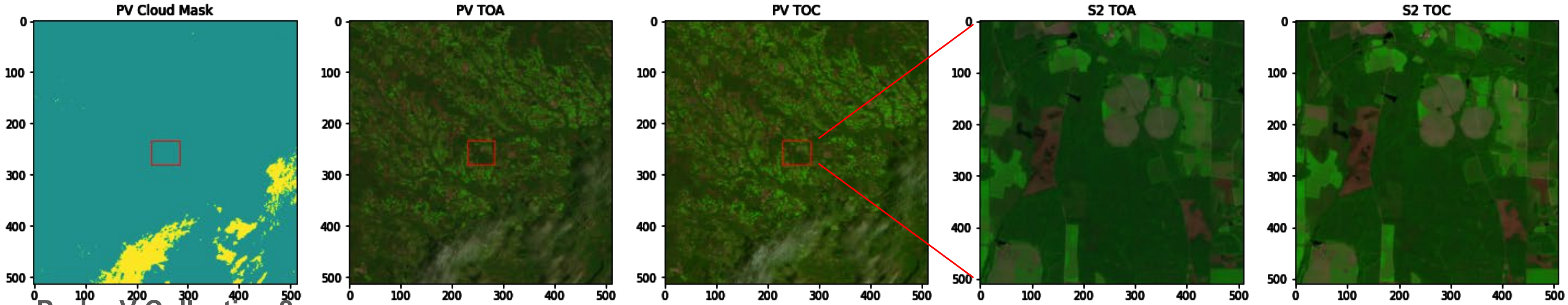
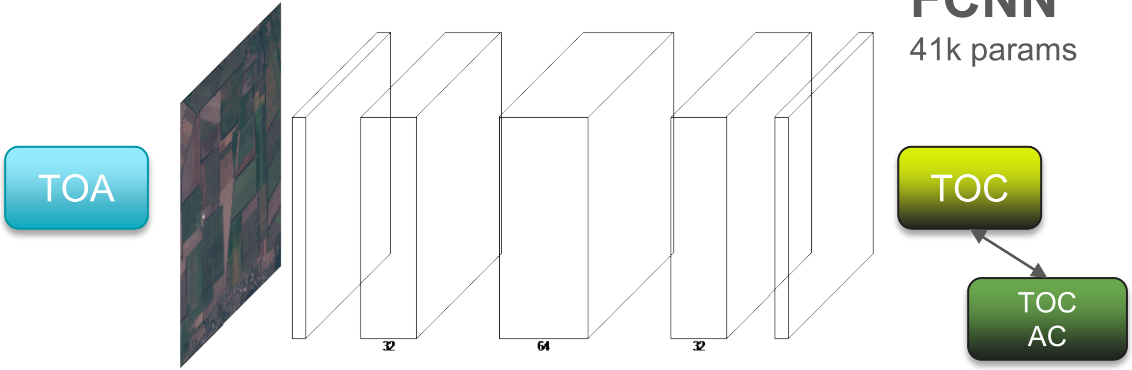


Proba-V Collection 2 Cloud Mask

Deep Machine Learning Models

FCNN
41k params

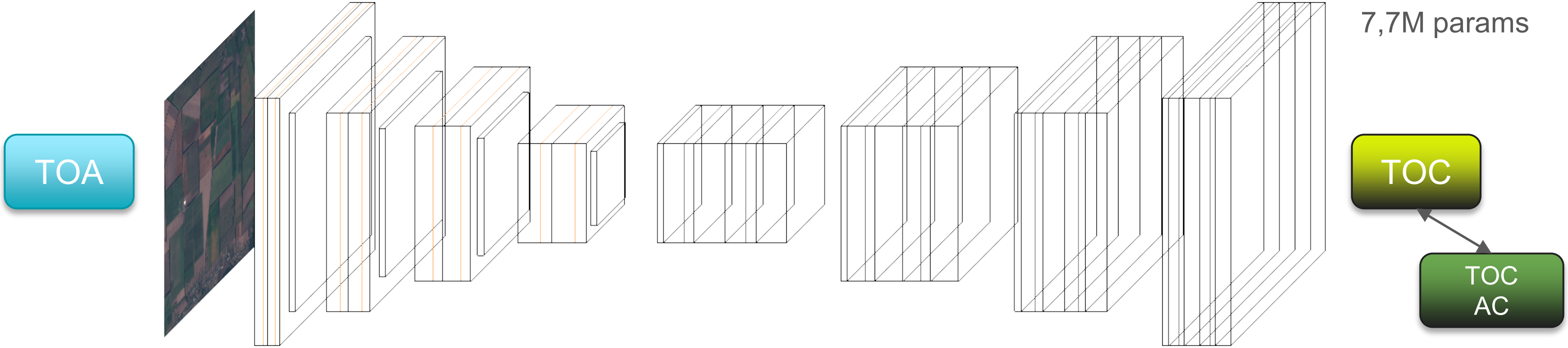


Inputs: TOA reflectance
Outputs: TOC reflectance
Ground truth reference: TOC reflectance

- sen2corr for Sentinel-2
- SMAC for Proba-V

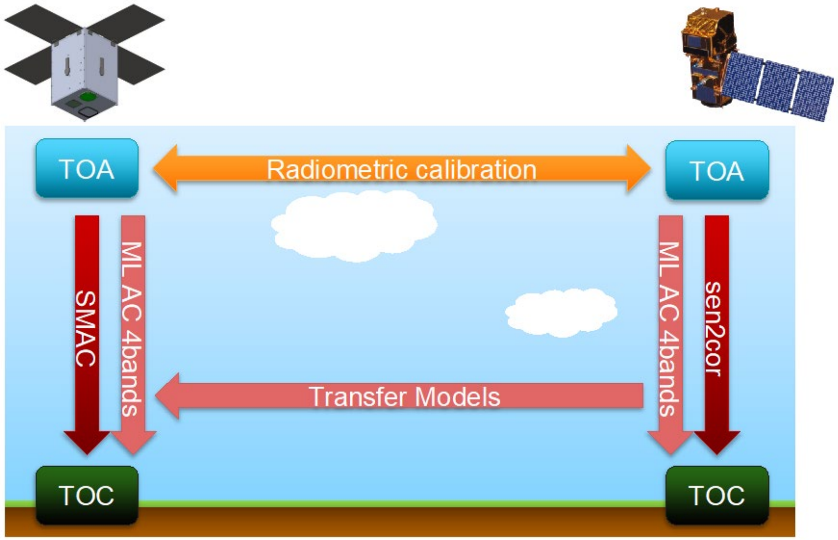
Training cost function: MSE
Evaluation metrics: RMSE and PSNR

UNET
7,7M params



Validation Results

- Sentinel-2 results: trained and tested with Sentinel-2 images (sen2corr)
- Proba-V results: trained and tested with Proba-V images (SMAC)
- Cross-sensor results: trained and tested with Sentinel-2 and Proba-V images



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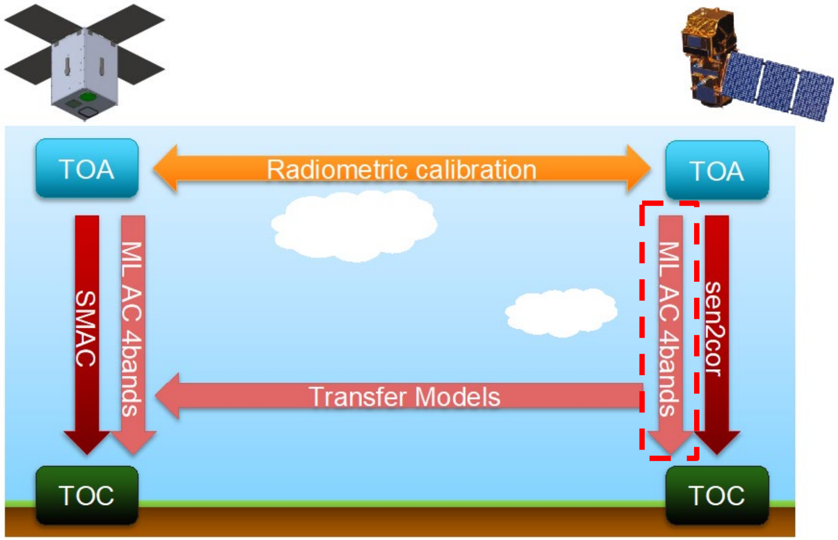
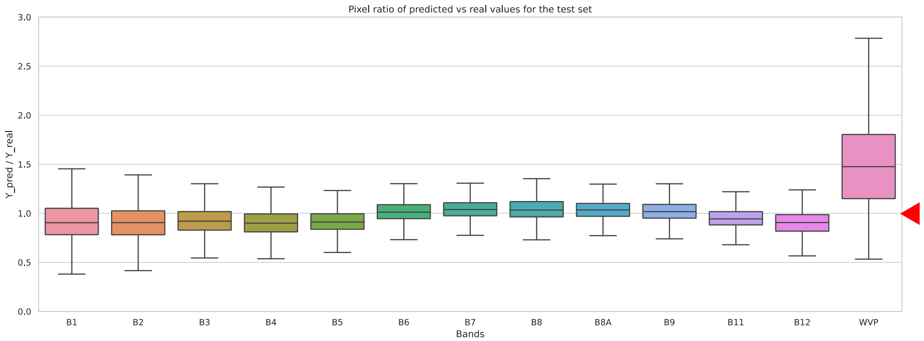


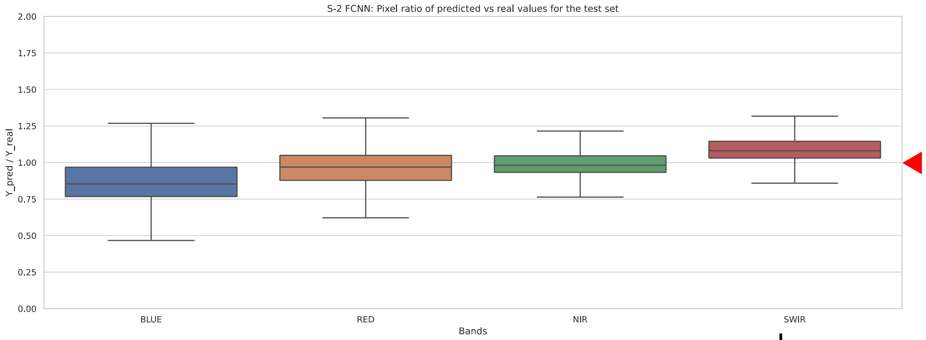
Sentinel-2 FCNN results (model trained with S2)

- Ratio of predicted values (S2 FCNN TOC) vs. reference values (sen2corr AC)

Full S2 model: 12 S2 bands + WV

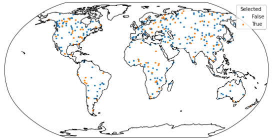


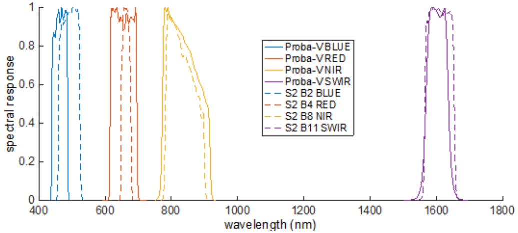
PV-like S2 model: 4 common bands



Ratio = TOC S2FCNN / TOC sen2corr

All results computed with the 100 test locations





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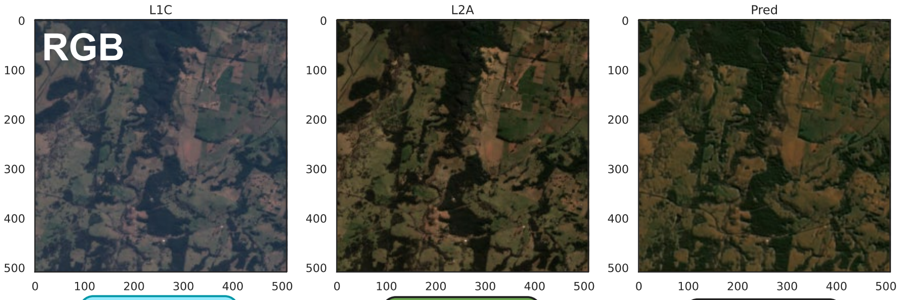
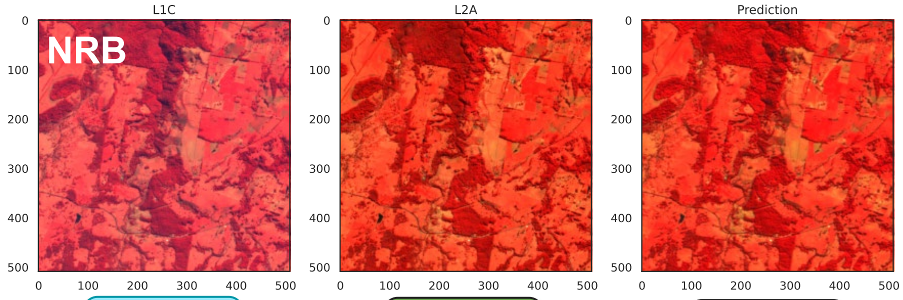
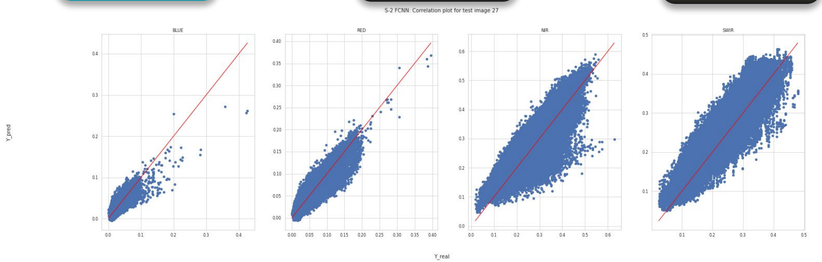


TOA S2 | TOC sen2corr | TOC S2FCNN

PV-like S2 model: 4 common bands



TOA S2 | TOC sen2corr | TOC S2FCNN



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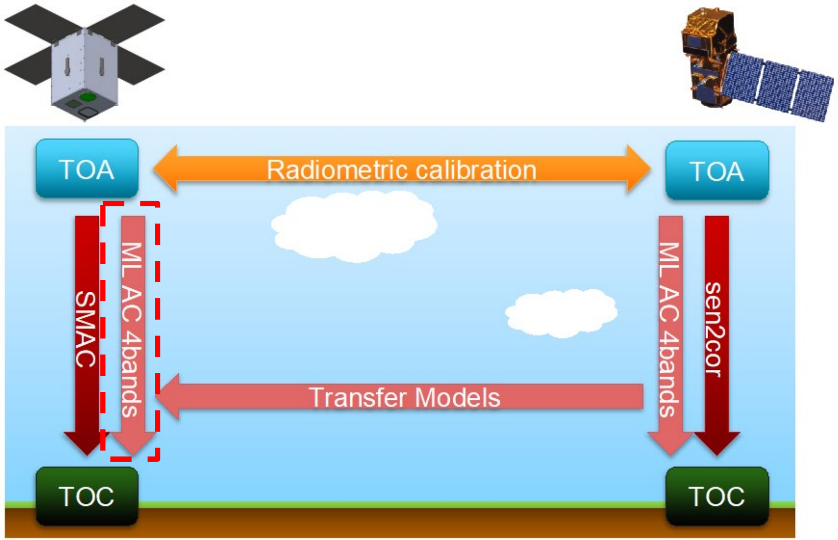
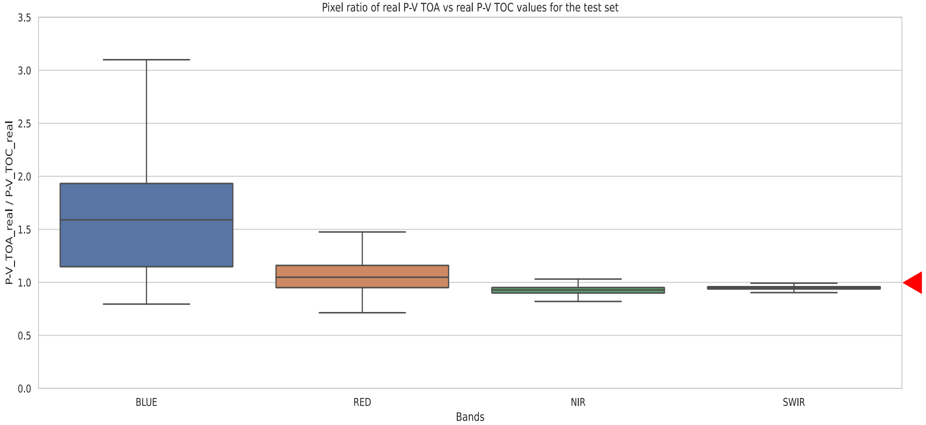


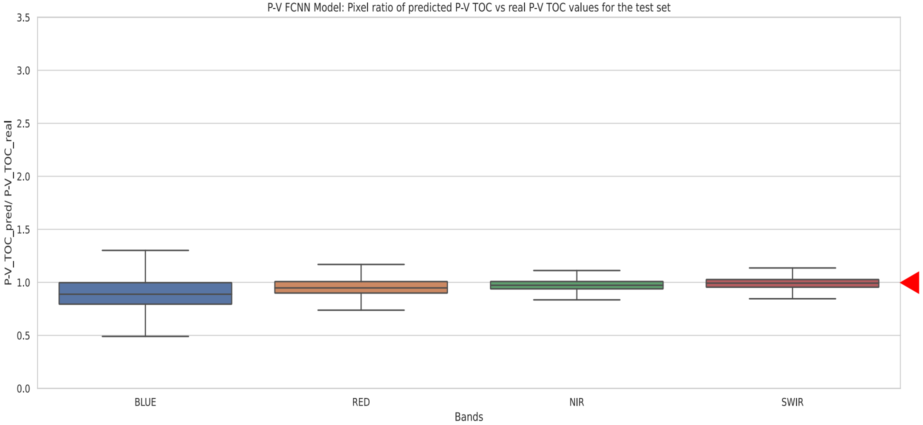
Proba-V FCNN results (model trained with Proba-V)

- Ratio of predicted values (PV FCNN TOC) vs. reference values (SMAC AC)

No atmospheric correction



Corrected by PV FCNN



Ratio = TOA Proba-V / TOC SMAC

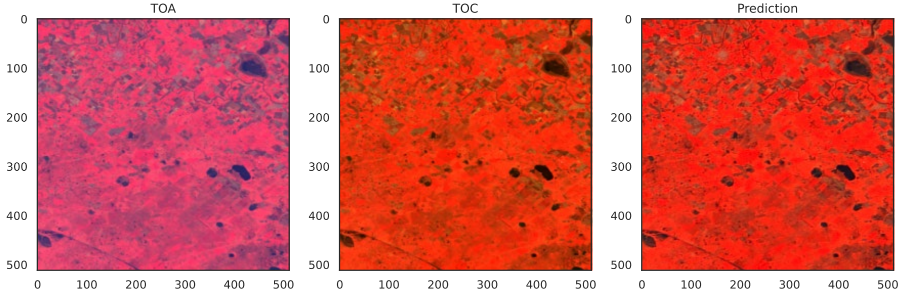
Improvement after the ML model →

Ratio = TOC PVFCNN / TOC SMAC

Proba-V FCNN results (model trained with Proba-V)

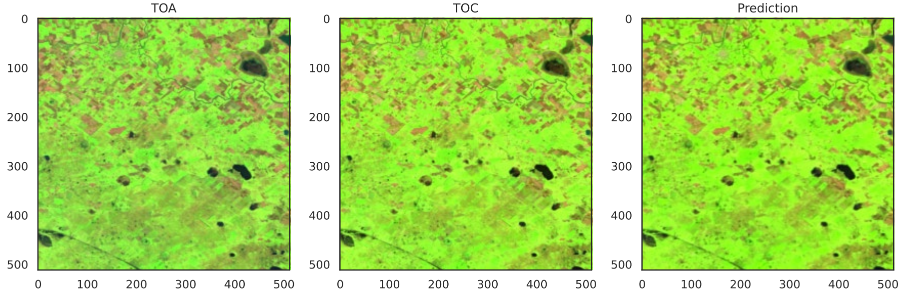
- Ratio of predicted values (PV FCNN TOC) vs. reference values (SMAC AC)

False color: NIR-Red-Blue

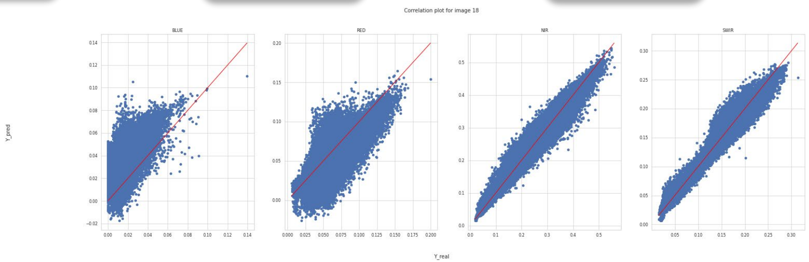


TOA Proba-V | TOC SMAC | TOC PVFCNN

False color: SWIR-NIR-Red



TOA Proba-V | TOC SMAC | TOC PVFCNN



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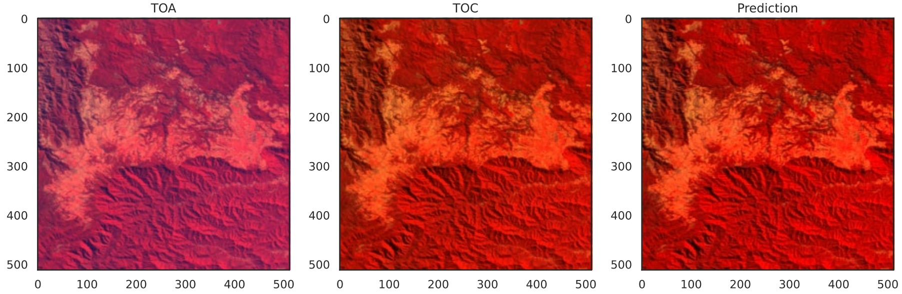
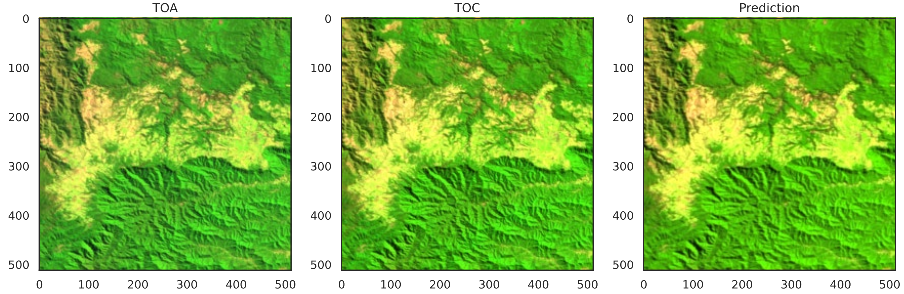
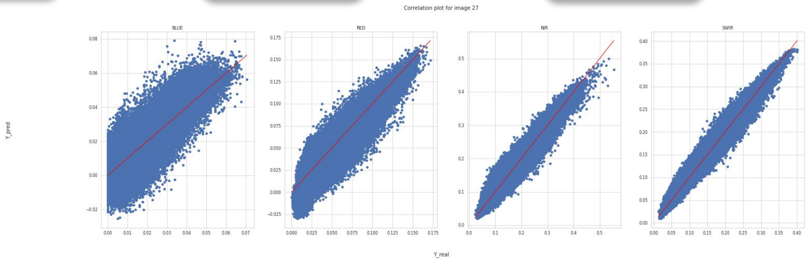


TOA Proba-V | TOC SMAC | TOC PVFCNN

False color: SWIR-NIR-Red



TOA Proba-V | TOC SMAC | TOC PVFCNN



Proba-V FCNN results (model trained with Proba-V)

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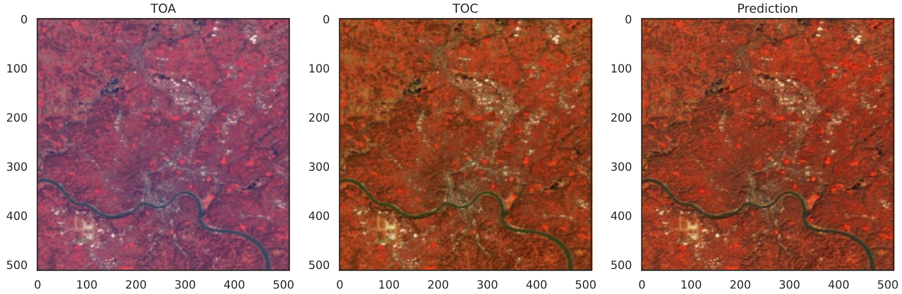
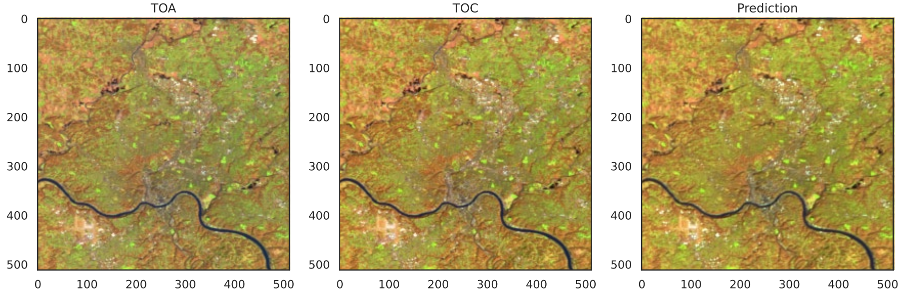
False color: NIR-Red-Blue

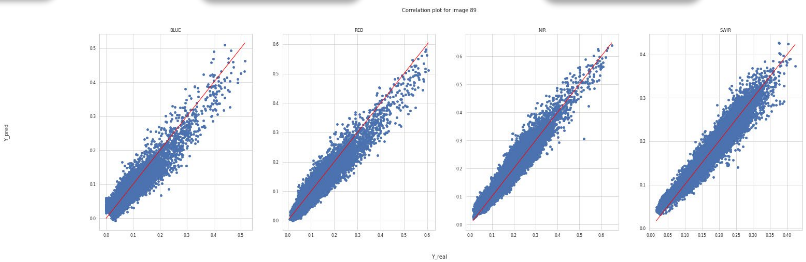


TOA Proba-V | TOC SMAC | TOC PVFCNN

False color: SWIR-NIR-Red



TOA Proba-V | TOC SMAC | TOC PVFCNN



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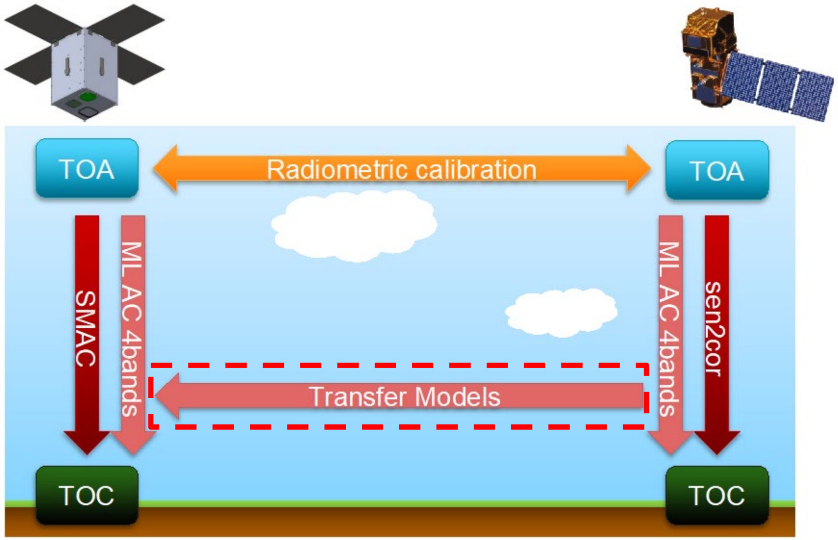
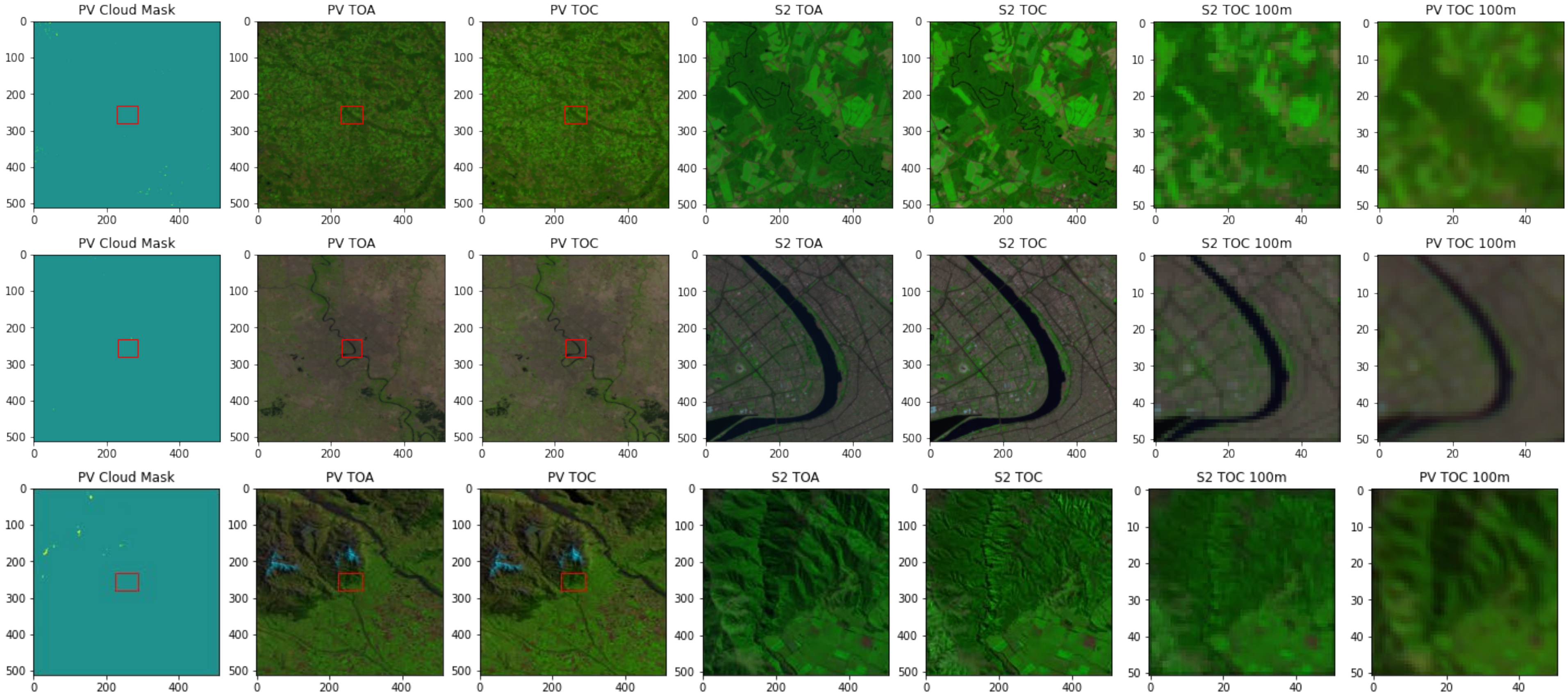
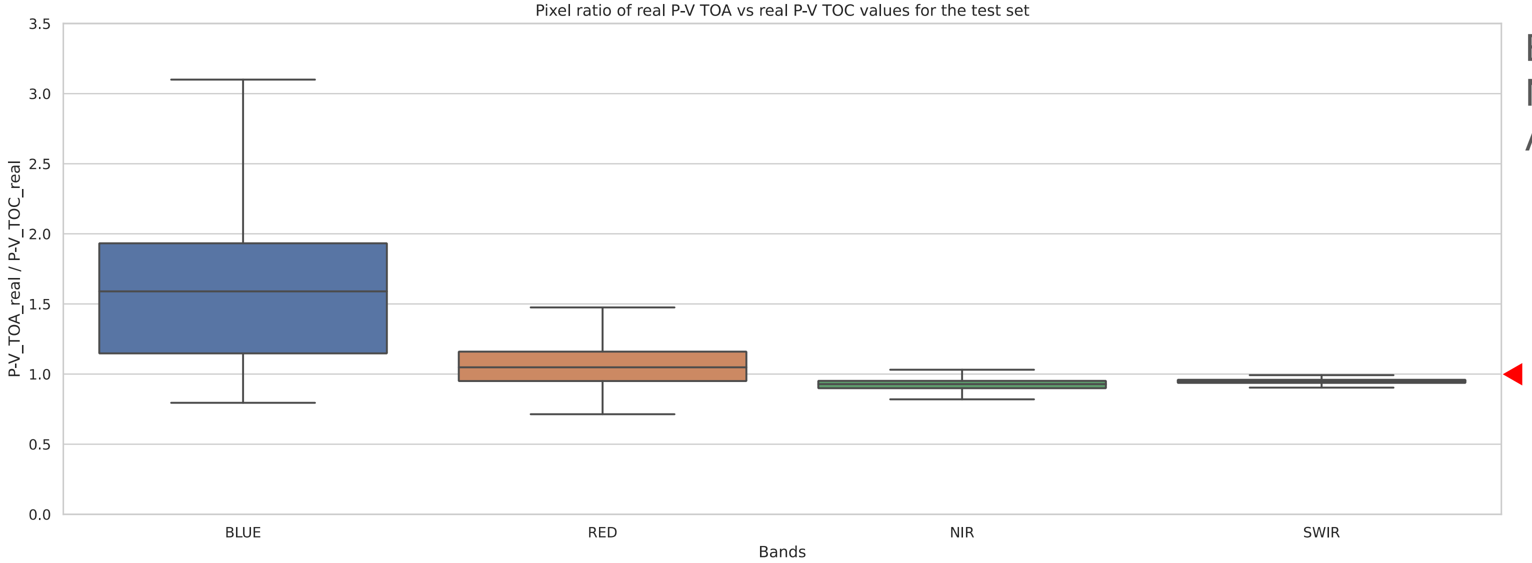


Cross-sensor results (transfer from S2 to PV)



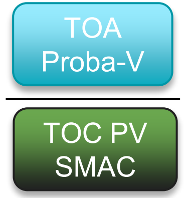
Cross-sensor results (transfer from S2 to PV)

- **Input:** TOA Proba-V
- **Model:** No correction / SMAC AC / PV-FCNN / S2-FCNN
- **Reference:** TOC PV (SMAC AC) / TOC S2 (sen2corr @100m)



Baseline:
No correction
AOT @blue

Ratio =



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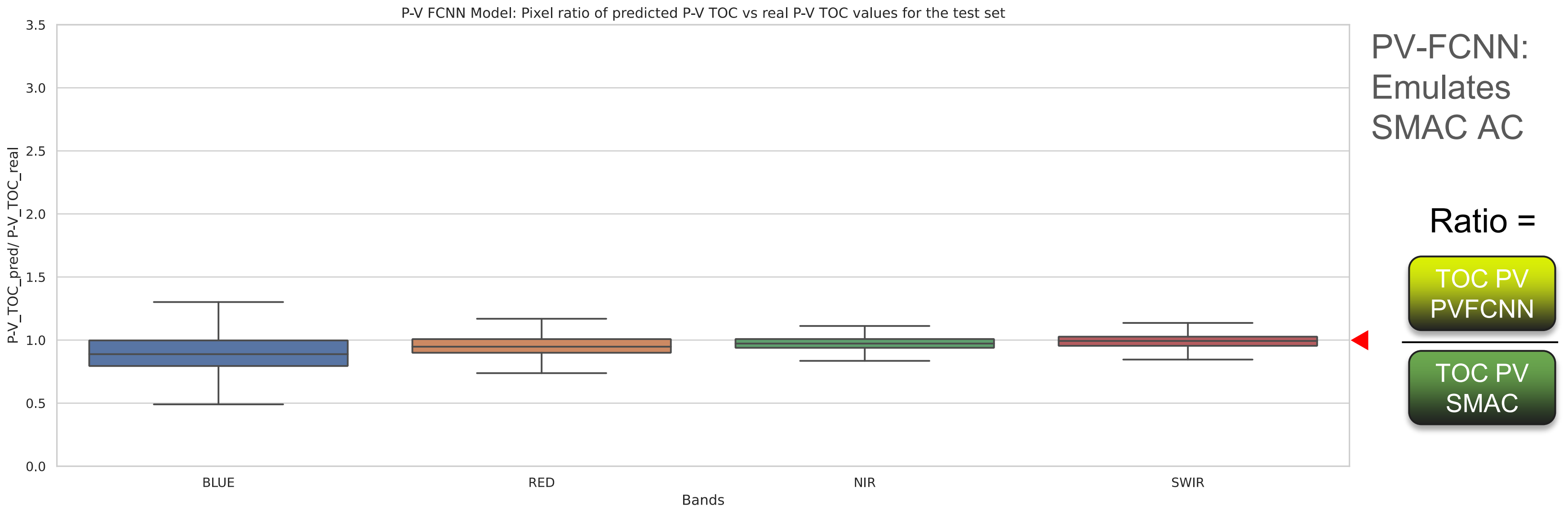

PV-FCNN: Emulates SMAC AC

Cross-sensor results (transfer from S2 to PV)

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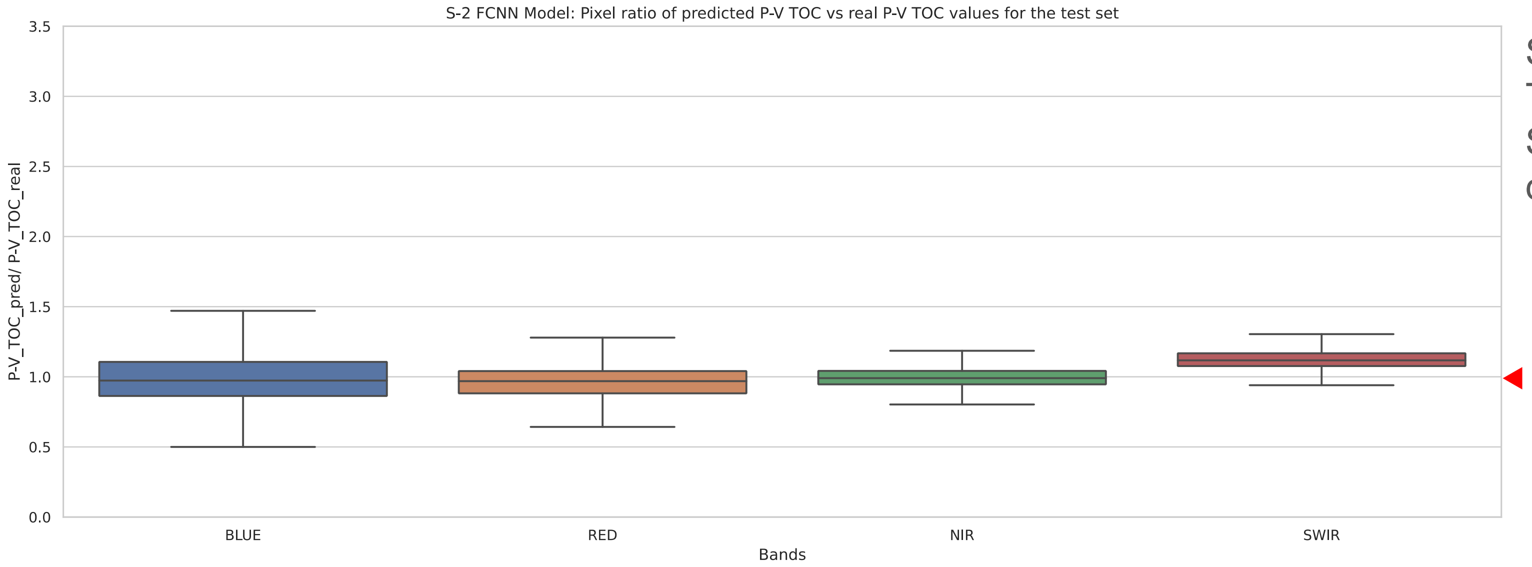

S2-FCNN:
Transfer AC
S2 → PV
diff. SWIR

Ratio = TOC PV S2FCNN / TOC PV SMAC

Cross-sensor results (transfer from S2 to PV)

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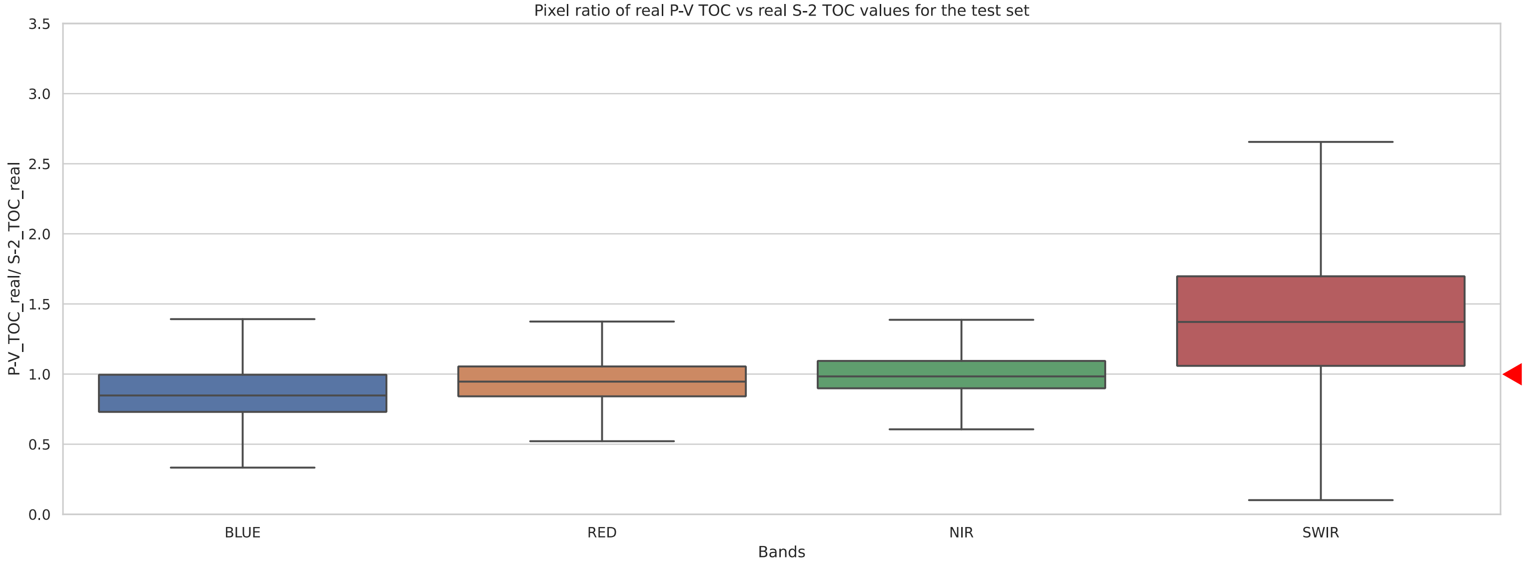

Baseline:
Differences
SMAC~sen2corr
diff. SWIR

Ratio = TOC PV SMAC / TOC S2 sen2corr

Cross-sensor results (transfer from S2 to PV)

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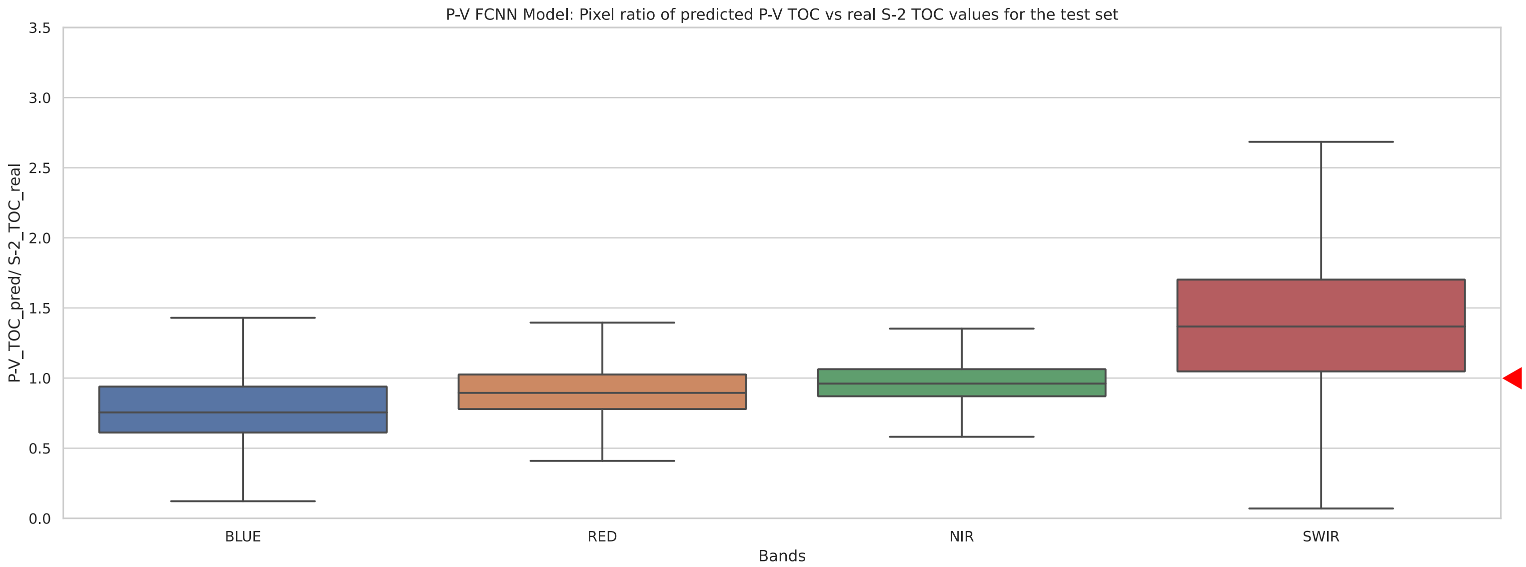
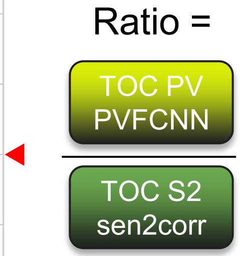


PV-FCNN: Consistent results



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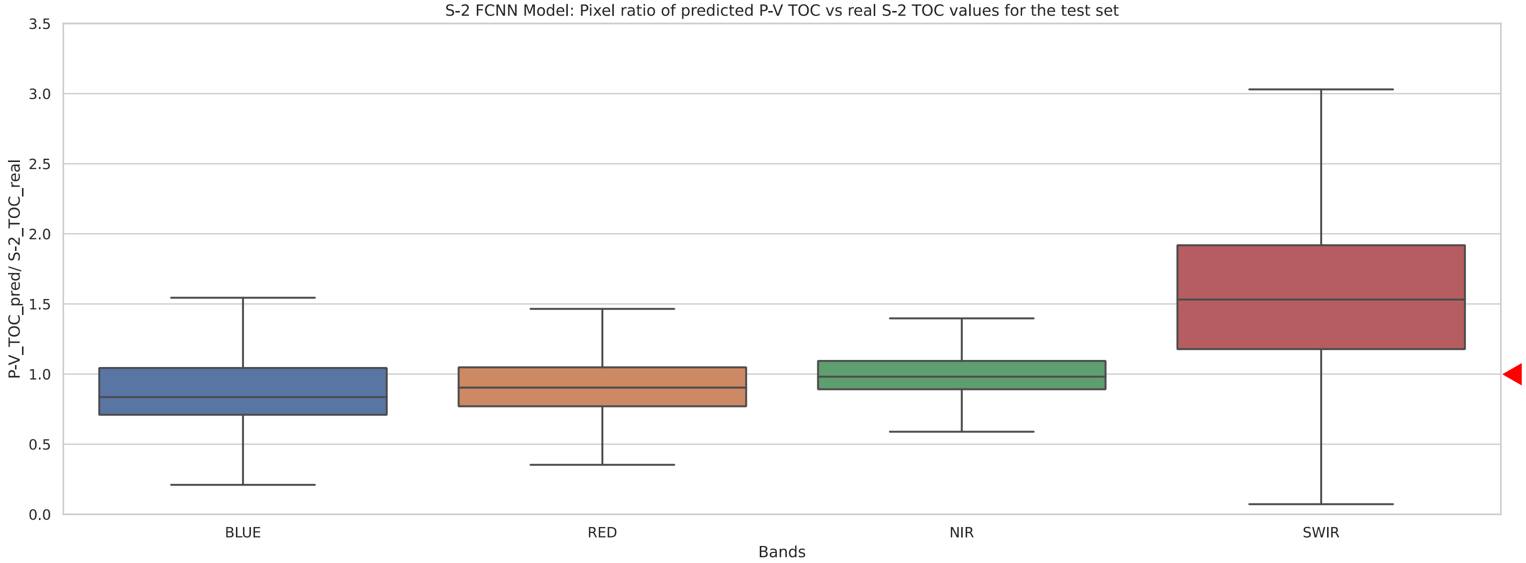
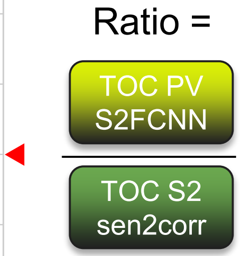


S2-FCNN: Consistent results



Cross-sensor results (transfer from S2 to PV)

- **Input:** TOA Proba-V

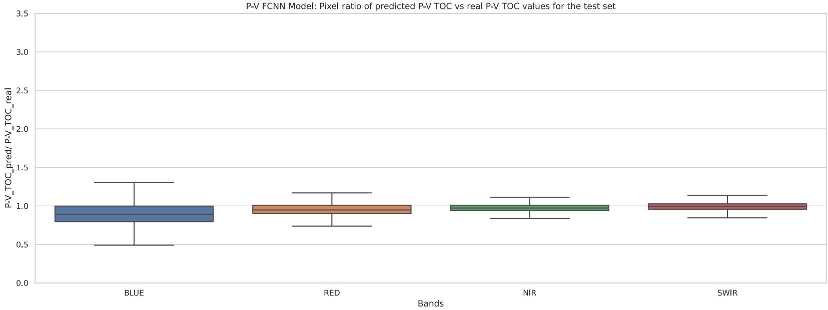
TOC Validation References

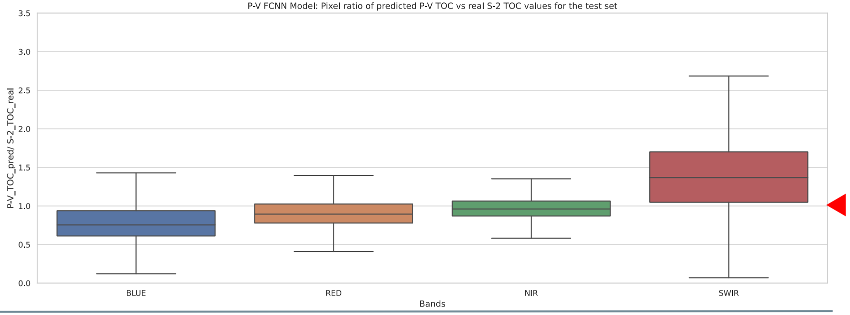
TOC PV SMAC

TOC S2 sen2corr

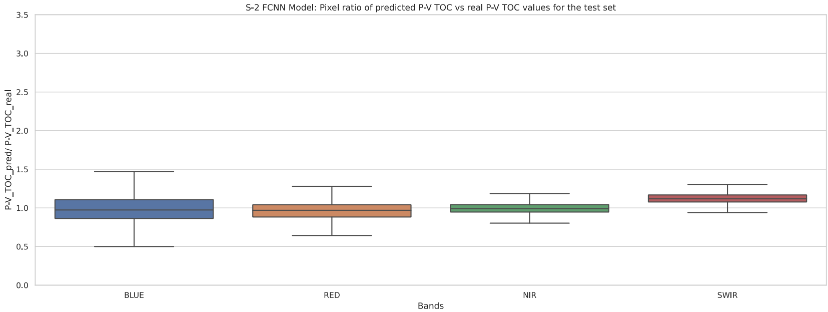
ML Models

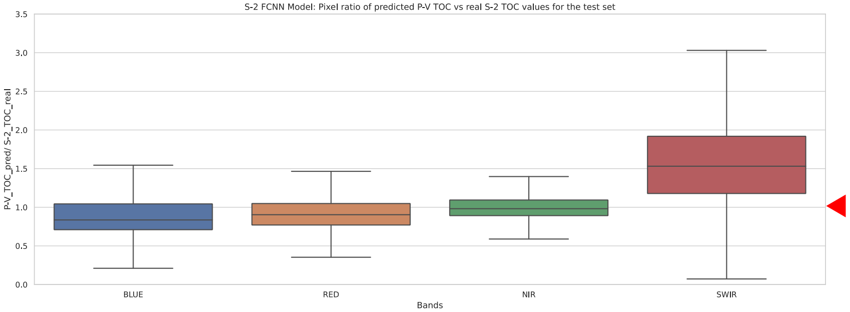
TOC PV PVFCNN





TOC PV S2FCNN





Summary & Conclusions

IT IS NOT an atmospheric correction method (very preliminary results)

"Excusatio non petita, accusatio manifesta"

IT IS a ML-based emulator of SMAC/Sen2Cor processors

- Learns how to (atmospherically) correct PV by reducing statistical differences between PV TOA and AC TOC images
- Data-driven transformation model from TOA to TOC: $TOC = f(TOA)$
    - Trained over cloud-free images
    - Proba-V can be used as proxy of PV-CC data
- Exploits the (superior) atmospheric correction from Sentinel-2 (12 bands) using the spectral bands in common with Proba-V (4 corrected bands)

Some operational advantages

- Allows **transfer learning** from robust AC of operational missions to medium/low-cost missions (PV-CC)
- **Validation of atmospheric correction** for small satellites (PV-CC)
    - Differences with physically-based AC (per-pixel uncertainty)
- **Simple and fast** computation without ancillary atmospheric data
- **Operational applications** for other missions:
    - Consistent time series of veg. products mitigating atmospheric effects
    - On-board implementation to improve real-time applications

Future research directions …

- **Increase the training set** to train more complex models (UNET)
- **Validation** against real TOC reflectance data
- Include **metrics** to consider both spectral & spatial distortion (SSIM)
- **Hybrid models**:
  - Including SMAC & ancillary atmospheric data as inputs/outputs
- **Physics-aware ML**:
  - Including RT equation constraints into the model training
- Generative Adversarial Domain Adaptation using **GANs**
  - Unpaired images (⟶ no co-registered/simultaneous)

Synergistic exploitation of PV-CC in combination with Sentinel-2 towards a ML based AC

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[1] University of Valencia, IPL-ISP Spain
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