A new SIF (solar-induced chlorophyll fluorescence) product derived from TROPOMI onboard Sentinel-5 Precursor

ESA TROPOSIF project

Consortium:

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• Chlorophyll fluorescence is an electromagnetic signal emitted by the photosynthetic machinery of green plants that can be linked to instantaneous photosynthesis.

• First global measurements of SIF over land achieved in late 2011 from GOSAT spectra (Frankenberg et al., Joiner et al.).

• It has been proven to be a better indicator of terrestrial photosynthesis activity and gross primary production (GPP) than reflectance-based vegetation indices.
• SIF can be retrieved in the solar and atmospheric absorption lines, which facilitates the retrieval of the weak SIF signal from the surface reflectance.

• Atmospheric spectrometers provide the required spectral and radiometric resolutions.

<table>
<thead>
<tr>
<th></th>
<th>GOME-2</th>
<th>SCIAMACHY</th>
<th>GOSAT</th>
<th>OCO-2</th>
<th>TROPOMI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spatial resolution</strong></td>
<td>40x40 km²</td>
<td>30x60 km²</td>
<td>0.5x0.5 km²</td>
<td>1.3x2.25 km²</td>
<td>3 km x 7 km²</td>
</tr>
<tr>
<td><strong>Revisit frequency</strong></td>
<td>3 days</td>
<td>6 days</td>
<td>3 days</td>
<td>16 days</td>
<td>~ 1 day</td>
</tr>
<tr>
<td><strong>Overpass time</strong></td>
<td>9:30</td>
<td>10:00</td>
<td>13:00</td>
<td>13:30</td>
<td>13:30</td>
</tr>
<tr>
<td><strong>Spectral range</strong></td>
<td>650–790 nm</td>
<td>650–790 nm</td>
<td>755–775 nm</td>
<td>Micro windows at 757 nm and 770 nm</td>
<td>675–775 nm</td>
</tr>
<tr>
<td>SIF@685 nm</td>
<td></td>
<td>SIF@740 nm</td>
<td></td>
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<tr>
<td>SIF@740 nm</td>
<td></td>
<td></td>
<td></td>
<td>SIF@683nm</td>
<td></td>
</tr>
<tr>
<td><strong>Spectral resolution</strong></td>
<td>~ 0.5 nm</td>
<td>~ 0.5 nm</td>
<td>~ 0.025 nm</td>
<td>~ 0.05 nm</td>
<td>0.38 nm</td>
</tr>
</tbody>
</table>

• Challenge: to decouple SIF from the solar radiation reflected by the surface and the atmosphere.

• Evaluation of the fractional depth of solar Fraunhofer lines → not affected by atmospheric scattering, simple modelling.
TROPOMI SIF retrieval scheme

- Data-driven retrieval implemented for far-red fitting windows (743-758 nm and 735-758 nm) based on Guanter et al. (2015)
- Linear Forward model based on Singular Vectors derived from vegetation-free areas
- Easy implementation and fast processing (~5 min/orbit in a desktop computer)
- Input data: only L1B_RAD and cloud fraction (L2_Cloud) products

\[
L_{\text{TOA}} = \frac{\mu_s I_{sc}}{\pi} \left[ \rho_0 + \frac{\rho_s T_{\uparrow \uparrow}}{1 - S \rho_s} \right] + \frac{F_s T_{\uparrow}}{1 - S \rho_s} 
\]

\[
F(a, \alpha, F_s) = \left( \sum_{i=0}^{n_p} a_i \lambda_i \right) \cdot \left( \sum_{j=1}^{n_v} \alpha_j v_j \right) + F_s h_F \cdot T^c_{\uparrow}
\]

\[
F'(a, \alpha, F_s) = v_1 \sum_{i=0}^{n_p} a_i \lambda_i + \sum_{j=2}^{n_v} \alpha_j v_j + F_s h_F \cdot T^c_{\uparrow}
\]

Number of eigenvectors \( n_v \):
- 743-758 nm fitting window: 4
- 735-758 nm fitting window: 7

Singular vectors
• Measurement noise is the main error source: variations in atmospheric conditions (cloud aside), angles or surface reflectance are negligible for the two fitting windows
• Width of the fitting window drives 1-sigma errors
• SIF (esp. from 743-758 nm) is much less sensitive to clouds than reflectance-based indices.

Fitting window selection:
• Compromise between random error (favours 735-758 nm) and sensitivity to clouds (favours 743-758 nm)
• Retrievals from the 743-758 nm window is the primary SIF product

• The calculation of 1-sigma retrieval errors based on empirical SIFerr - TOA Radiance curves
Input data summary
- L1B_RA_BD6 (dynamic)
- L2__CLOUD (dynamic)
- Land Cover Map (static)
- SIF spectrum (static)
- TOA irradiance spectrum (static)

Processing workflow

L1B_RA_BD6 & _BD5 Products
Filter L1B product data:
- No water
- Cloud fraction < 0.8
- SZA < 75
- Quality_level > 80

L2__CLOUD Product
TOA Radiance @ [665, 680, ..., 773, 781] nm
TOA reflectance retrieval
Reflectance data

Land Cover map (MODIS MCD12C1)
SZA, Lat, Lon
Calculation day-length factor
DL Factor

TOA Radiance [~740-758] nm
SIF retrieval
SIF@740 nm data

Output NetCDF4 writing

Data
Operations

L2 SIF product
Single retrievals
Data format and availability

Data Format

- **netCDF-4**
- **L2 product:**
  - Ungridded data available for each TROPOSIF orbit
  - SIF estimates at 740 nm from the two fitting windows and associated retrieval error
    - 743-748 nm: baseline product
    - 735-748 nm: more «experimental»
  - Daily corrected SIF in the two fitting windows
  - Surface reflectance at 665, 680, 712, 741, 755, 773 and 781 nm
  - Solar and view angles, TOA radiance, Cloud fraction
  - Quality flag

- **L2B product:**
  - Ungridded daily files (similar to the Caltech product Köhler et al. (2018))
  - Contains only the valid retrievals

- Covered time period: **May 2018 to December 2020**

Data availability

- project web site: [https://s5p-troposif.noveltis.fr/](https://s5p-troposif.noveltis.fr/)

- The TROPOSIF product will be generated and distributed to users by S5P-PAL in an operational manner in the near-future.
Characterization of the mean error and bias over Sahara

• Comparison against Caltech and OCO-2 SIF products
  – estimates aggregated at 0.1° / daily, CF < 0.05
  – \( SIF(OCO2) = 1.56 \times (SIF@757nm + 1.8 \times SIF@771nm)/2 \). (Köhler et al. (2018))

Mean bias (mW.m\(^{-2}\).sr\(^{-1}\).nm\(^{-1}\))

<table>
<thead>
<tr>
<th></th>
<th>OCO-2 @740nm</th>
<th>Caltech</th>
<th>TROPOSIF - 743nm</th>
<th>TROPOSIF - 735nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sahara</td>
<td>0.0098</td>
<td>-0.0357</td>
<td>-0.0277</td>
<td>-0.0059</td>
</tr>
<tr>
<td></td>
<td>(0.0308)</td>
<td>(-0.1047)</td>
<td>(-0.0805)</td>
<td>(-0.0173)</td>
</tr>
</tbody>
</table>

Mean random error (mW.m\(^{-2}\).sr\(^{-1}\).nm\(^{-1}\))

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<tbody>
<tr>
<td>Sahara</td>
<td>0.61</td>
<td>0.52</td>
<td>0.42</td>
</tr>
</tbody>
</table>

- Distribution of the daily SIF estimates from Caltech and TROPOSIF products over 10 Pseudo-Invariant Calibration Sites (Bacour et al., 2019)
- The slope of the temporal variation of the SIF data over 2018–2020 is close to 0; no temporal drift was detected for any of the sites
Global scale evaluation

- Cross-comparison between TROPOSIF (743 nm), Caltech and OCO-2
- Daily data / 0.1° resolution, Cloud Fraction (CF) < 0.2
- Daily corrected SIF

August 2019

We generally observe that:
- SIF(TROPOSIF) > SIF(Caltech)
- SIF(OCO2) > SIF(Caltech)
- SIF(OCO2) ~ SIF(TROPOSIF)
Biome scale evaluation

- Time series comparison for an ensemble of “homogeneous” pixels - biome representative (Bacour et al., 2019)
- Several clusters for each biome (14 Plant functional Types)
- Weekly / 0.5 °aggregation ; CF < 0.2 ; VZA < 40°

Illustration of compared SIF seasonal variations for 3 PFTs

- Tropical Evergreen Broadleaf Forest
- Temperate Deciduous Broadleaf Forest
- C4 Crops

Temporal correlation

- higher agreement between the 2 TROPOMI products than with OCO-2 (similar sampling for the TROPOMI products and higher number of observations within the 0.5° pixels that reduces the retrieval error)
- OCO-2 in closer agreement with TROPOSIF than with Caltech
Yearly SIF average (2019) / daily / 0.1°, Cloud Fraction < 0.2

Number of daily SIF estimates at 0.1°, CF < 0.2

- The difference between Caltech and TROPOSIF are largely explained by the different Cloud Fraction products used:
  - Caltech: VIIRS
  - TROPOSIF: TROPOMI L2_Cloud
Overview of the TROPOSIF products

Comparison between TROPOSIF-743nm and TROPOSIF-735nm at sites

- Cheryan - South Korea - Crop (rice paddy)
- Heidala - Finland - Evergreen Broadleaf Forest
- Leinfell - Germany - Deciduous Broadleaf Forest
- Majadas de Tietar North - Spain - Savannah
- Ozark - USA - Deciduous Broadleaf Forest
- Niwot Ridge - USA - Evergreen Broadleaf Forest
Overview of the TROPOSIF products

NDVI and NIRv
8-15 July 2019

Relationships between SIF(743nm), NDVI and NIRv, and with FluxSat-GPP

Boreal Evergreen Needleleaf Forests
Temperate Deciduous Broadleaf Forests
Tropical Deciduous Broadleaf Forests

FluxSat-GPP from Joiner et al. (2018)