Outline

1. The TanSat satellite
2. SIF Retrieval method for TanSat
3. The results of TanSat SIF retrieval
4. Conclusions
1. The TanSat satellite

TanSat is the first Chinese satellite and the third satellite after the GOSAT of Japan and OCO-2 of the US dedicated to the monitoring and detection of carbon dioxide (CO₂) from space, which was launched on December 21, 2016.

The characters of TanSat satellite

<table>
<thead>
<tr>
<th>Name</th>
<th>Characters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit type</td>
<td>Sun-synchronous</td>
</tr>
<tr>
<td>Altitude</td>
<td>700 km</td>
</tr>
<tr>
<td>Inclination</td>
<td>98°</td>
</tr>
<tr>
<td>Local time</td>
<td>13:30</td>
</tr>
<tr>
<td>Weight</td>
<td>620 kg</td>
</tr>
<tr>
<td>Revisit period</td>
<td>16 days</td>
</tr>
</tbody>
</table>

3 observation modes

- Observation over land; Push broom; [Nadir mode]
- Observation over ocean; Sun glint track; [Sun-glint mode]
- Observation validation; Surface target track; [Target mode]
1. The TanSat satellite

- **Main payloads of TanSat:**
  - Atmospheric Carbon dioxide Grating Spectroradiometer (ACGS)
  - Cloud and Aerosol Polarimetry Imager (CAPI).

**Specification of TanSat-ACGS**

<table>
<thead>
<tr>
<th>Band</th>
<th>O$_2$-A</th>
<th>Weak CO$_2$</th>
<th>Strong CO$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral Coverage (nm)</td>
<td>758-778</td>
<td>1594-1624</td>
<td>2042-2082</td>
</tr>
<tr>
<td>Spectral Resolution (nm)</td>
<td>0.044</td>
<td>0.12</td>
<td>0.16</td>
</tr>
<tr>
<td>SNR</td>
<td>360@15.2</td>
<td>250@2.6</td>
<td>180@1.1</td>
</tr>
<tr>
<td>Spatial Resolution</td>
<td>2 km × 2 km</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Swath</td>
<td></td>
<td>20 km</td>
<td></td>
</tr>
</tbody>
</table>

**Specification of TanSat-CAPI**

<table>
<thead>
<tr>
<th>Band</th>
<th>Range</th>
<th>SNR</th>
<th>FOV</th>
<th>pixels</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>365-408</td>
<td>260</td>
<td></td>
<td>1600</td>
</tr>
<tr>
<td>2</td>
<td>660-685</td>
<td>160</td>
<td></td>
<td>1600</td>
</tr>
<tr>
<td>3</td>
<td>862-877</td>
<td>400</td>
<td>400k</td>
<td>1600</td>
</tr>
<tr>
<td>4</td>
<td>1360-1390</td>
<td>180</td>
<td></td>
<td>800</td>
</tr>
<tr>
<td>5</td>
<td>1628-1654</td>
<td>110</td>
<td></td>
<td>800</td>
</tr>
</tbody>
</table>
1. The TanSat satellite

- Fe Fraunhofer line at 758.8 nm, KI Fraunhofer line at 770.1 nm for SIF retrieval

The Fe Fraunhofer lines around 758.8 nm, KI Fraunhofer line at 770.1 nm and the atmospheric absorption band around 760 nm all have potential for use in SIF retrieval. Here, a spectral window covering several Fe Fraunhofer lines around 758.8 nm, which is marked in gray shadow, was selected for SIF retrieval.

\[
\text{Radiance} = \sum_{i=0}^{6} c_i (Dn - Dn_{dark})^i
\]

- Radiance-ACGS radiance in Level 1B data;
- \(c_i\) - Radiometric calibration gain;
- \(Dn\) - The digital number of ACGS’s response in observational model;
- \(Dn_{dark}\) - The digital number of dark signal of ACGS;

\[
\lambda = \sum_{i=0}^{5} C_i \cdot P^i
\]

- \(P\) refers to the pixel number
- \(C_i\) refers to the dispersion coefficients
1. The TanSat satellite

- Comparison of characters for TanSat and OCO-2

<table>
<thead>
<tr>
<th>Character of O₂-A</th>
<th>TanSat</th>
<th>OCO-2</th>
<th>SNR&lt;sub&gt;oco2&lt;/sub&gt; = \frac{100N^2}{\sqrt{C_{\text{background}}^2 \frac{\text{MaxMS}}{100} + \text{MaxMS} \times (C_{\text{photon}}^2 N)}}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral range</td>
<td>758-778</td>
<td>757-775</td>
<td></td>
</tr>
<tr>
<td>Spectral resolution (nm)</td>
<td>0.044</td>
<td>0.042</td>
<td></td>
</tr>
<tr>
<td>Spatial resolution (km²)</td>
<td>2 × 2</td>
<td>1.3 × 2.25</td>
<td></td>
</tr>
<tr>
<td>Number of F</td>
<td>9</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Signal to noise (SNR)</td>
<td>360@15mW</td>
<td>~200@10mW</td>
<td></td>
</tr>
<tr>
<td>Swath (km)</td>
<td>20</td>
<td>10.3</td>
<td></td>
</tr>
<tr>
<td>(day)</td>
<td>16</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Equator crossing time</td>
<td>1:30pm</td>
<td>1:30pm</td>
<td></td>
</tr>
<tr>
<td>Date time</td>
<td>02/2017</td>
<td>08/2014</td>
<td></td>
</tr>
<tr>
<td>Sampling mode</td>
<td>Sparse</td>
<td>Sparse</td>
<td></td>
</tr>
</tbody>
</table>

\[
\text{SNR}_{\text{TanSat}} = \frac{\text{Rad}}{\sqrt{\text{Rad} \times C_1^2 + C_2^2}}
\]

2. SIF Retrieval method for Tansat

• Fraunhofer Line Discrimination

\[
\begin{align*}
L_{in} &= I_{in} \cdot R_{in} + F_{S_{in}} \\
L_{out} &= I_{out} \cdot R_{out} + F_{S_{out}}
\end{align*}
\]

\[
F_{S_{in}} = \frac{\alpha_R I_{out} L_{in} - I_{in} L_{out}}{\alpha_R I_{out} - \alpha_F I_{in}}
\]


2. SIF Retrieval method for Tansat

The relative contribution of TOC/TOA SIF

space-based SIF retrieval

- full-physics approach
- data-driven approach
2. SIF Retrieval method for Tansat

\[ L_{TOA} = L_0 + \frac{[(E_{dir} \mu_s + E_{dif}) \rho_s / \pi + F_s]T_{\uparrow}}{1 - S \rho_s} \]

where \( L_0 \) is the atmospheric path radiance, \( E_{dir} \) and \( E_{dif} \) are the direct and diffuse fluxes of solar irradiance arriving at the surface, \( \mu_s \) is the cosine of the solar zenith angle, \( \rho_s \) is the surface reflectance, \( S \) is the atmospheric spherical albedo and \( T_{\uparrow} \) is the total transmittance of the atmosphere.

\[
\begin{align*}
Y &= \frac{L_{TOA} - L_0}{T_{\uparrow}} \\
X &= \frac{1}{\pi} (E_{dir} \mu_s + E_{dif}) + YS \\
Y &= X \rho_s + F_s
\end{align*}
\]

\[ F_s = \frac{X_{\text{out}} Y_{\text{in}} - X_{\text{in}} Y_{\text{out}}}{X_{\text{out}} - X_{\text{in}}} \]

\( Y \) is the upward radiance at the TOC and \( X \) is the downward radiance that reaches the TOC.
2. SIF Retrieval method for Tansat

\[ \text{par}_{\text{norm}} = \frac{\text{par}}{\text{par}_{\text{max}} - \text{par}_{\text{min}}} \]

\[ \delta \text{SIF}_{\text{rel}} = \frac{\text{SIF}_{\text{pert}} - \text{SIF}_{\text{exp}}}{\text{SIF}_{\text{exp}}} \]

\[ \mathbf{J} = \left[ j_k \right]_{1 \leq k \leq m}, \quad j_k = \frac{\delta \text{SIF}_{\text{rel}}}{\delta \text{par}_{\text{norm}, k}} \]

(a) AOD550

(b) SZA

(c) VZA

The atmospheric correction accuracy is too limited for SIF retrieval from satellite data; Fraunhofer Lines are more reliable for retrieval from satellite data.

《Liu XJ * Liu LY RS 2014》
2. SIF Retrieval method for Tansat

   data-driven approach

- Evaluation of the in-filling of solar Fraunhofer lines by SIF
  - not affected by atmospheric scattering, simple modelling.
    - GOSAT, OCO-2, TanSat, FWHM~0.04 nm – narrow fitting window (single lines)
    - GOME-2 & SCIAMACHY, FWHM~0.5nm – wide fitting window (red-edge)

From Guanter L, 2016, Presentation at RADI, CAS
2. SIF Retrieval method for Tansat

SIF retrieval from space: in-filling of solar Fraunhofer lines

Radiative transfer eq.

\[ L_{TOA} = L_0 + \frac{\frac{1}{\pi} \cdot \rho_s \cdot T_{\downarrow} \cdot \mu_s \cdot I_{sc} T_{\uparrow} + F_s \cdot T_{\uparrow}}{1 - S \cdot \rho_s} \]

Transparent Atmosphere

Linear forward model

\[ L_{TOA}(F_s, a_i) = \langle I_{sc} \rangle \cdot (a_0 + a_1 \cdot \lambda) + F_s \]

SIF retrieval, GOSAT, OCO-2, Tansat

Single Fraunhofer lines, no atmospheric modelling needed

Retrieval straightforward

From Guanter L, 2016, Presentation at RADI, CAS
2. SIF Retrieval method for Tansat

- Current satellite-based SIF products

<table>
<thead>
<tr>
<th>Instrument</th>
<th>SR (nm)</th>
<th>Equator crossing time</th>
<th>Spatial resolution (km)</th>
<th>Sampling method</th>
<th>Spatial resolution of SIF product</th>
<th>Date</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCIAMACHY</td>
<td>0.48</td>
<td>10:00</td>
<td>30 × 240</td>
<td>Cont.</td>
<td>1.5° × 1.5°</td>
<td>2002-2012</td>
<td>Köhler, et al., 2015</td>
</tr>
<tr>
<td>OCO-2</td>
<td>0.042</td>
<td>13:30</td>
<td>1.3 × 2.25</td>
<td>Sparse</td>
<td>1° × 1°</td>
<td>2014-</td>
<td>Joiner et al., 2013, Frankenberg et al., 2014</td>
</tr>
<tr>
<td>GOME-2</td>
<td>0.5</td>
<td>9:30</td>
<td>40 × 80</td>
<td>Cont.</td>
<td>0.5° × 0.5°</td>
<td>2007-</td>
<td>Köhler, et al., 2015, Joiner et al., 2013</td>
</tr>
<tr>
<td>TROPOMI</td>
<td>0.38</td>
<td>13:30</td>
<td>7 × 3.5-15</td>
<td>Cont.</td>
<td>0.2° × 0.2°</td>
<td>2017.10-</td>
<td>Köhler et al., 2018</td>
</tr>
</tbody>
</table>

TROPOMI  ftp://fluo.gps.caltech.edu/data/tropomi/
2. SIF Retrieval method for Tansat

- **SVD data-driven algorithm for SIF retrieval**

The Singular Value Decomposition (SVD) data-driven algorithm, which was firstly used for global SIF retrieval by Guanter et al. (2012), was employed to retrieve SIF from the TanSat–ACGS data.

\[
L_{TOA} = I_0^\lambda \mu [\rho_0^\lambda + \frac{\rho_s^\lambda \cdot T_{\uparrow \downarrow}^\lambda}{\pi}] + SIF_{TOA} \\
M = U \Sigma V^T \\
R_{TOA} = \sum_{i=1}^{n_v} \omega_i v_i + F_s^{TOA} \cdot I \\
A = [V, I] \quad x = [\omega_i, SIF_{TOA}]^T \\
A x = L_{TOA}
\]

The following rules were designed for the selection of the training samples:

1. Non-vegetated surface (bare soil or snow)
2. Normalized and averaged at-sensor radiance at O₂-A band within the range 25 to 200 mW m⁻² sr⁻¹ nm⁻¹
3. Uniform distribution with latitude to guarantee the representativeness of the sun zenith angle (SZA) for the training samples
2. SIF Retrieval method for Tansat

- The selection of training data

The spatial distribution of the training samples for July, 2017

- MODIS nadir BRDF-adjusted reflectance product - MCD43C4

**Bare soil:**
- \( R_{NIR} < R_{SWIR} \)
- \( R_{SWIR} > 0.2 \)
- \( \text{NDVI} < 0.1 \)

**Snow:**
- \( \text{NDSI} > 0.4 \)
- \( R_{green} \in [0.1, 0.4] \)
2. SIF Retrieval method for Tansat

- SVD data-driven algorithm for SIF retrieval

This figure gives the First 4 singular vectors derived from the training dataset. P is the explained variance, given as a percentage of the total. The 98% of the variance of the spectral variance was captured by the first singular vector and that the first 4 singular vectors can explain about 99% of the variance.
3. The results of TanSat SIF retrieval

- SVD data-driven algorithm for SIF retrieval

This figure gives an example of simulated TanSat–ACGS TOA radiance in the spectral window of 757–759 nm spectral window obtained using the first four singular vectors and retrieved fluorescence values.

It is obvious that the TOA radiance can be accurately modelled using the SVD data-driven algorithm, with a spectral residual of $<\pm 0.03$ mW m$^{-2}$ sr$^{-1}$ nm$^{-1}$, and a spectral RMSE of $<0.12$ mW m$^{-2}$ sr$^{-1}$ nm$^{-1}$.
3. The results of TanSat SIF retrieval

- Global SIF retrieved from TanSat and comparison with OCO-2
3. The results of TanSat SIF retrieval

- **Comparison between TanSat with OCO-2 SIF**

  - The SIF difference is less than 0.3 mW m\(^{-2}\) sr\(^{-1}\) nm\(^{-1}\) for 80% pixels. The overall distribution of TanSat SIF values closely corresponds to those for OCO-2.
  - For both SIF products, the distribution of the SIF is Gaussian-like with the mean value of 0.44 and 0.38 mW m\(^{-2}\) sr\(^{-1}\) nm\(^{-1}\), the mode value of 0.01 and 0.05 mW m\(^{-2}\) sr\(^{-1}\) nm\(^{-1}\) and the median value of 0.33 and 0.34 mW m\(^{2}\) sr\(^{-1}\) nm\(^{-1}\) for TanSat and OCO-2 SIF, respectively.
3. The results of TanSat SIF retrieval

- Comparison between TanSat with OCO-2 SIF

506 TanSat soundings which can match with the OCO-2 soundings with a buffer of 0.01° were found out. It is obviously that the two SIF retrievals closely follow the 1:1 line, which indicates a good agreement between TanSat and OCO-2 SIF datasets.
3. The results of TanSat SIF retrieval

- Temporal patterns of TanSat SIF and other remote sensing products

TanSat SIF has an overall consistent temporal variation with OCO-2 SIF, VIs and GPP in the six regions. Especially in the three regions of the northern hemisphere (the above row), all datasets capture the seasonal variation of the phenology of vegetation. Compared to VIs, both TanSat SIF and OCO-2 SIF are closer to GPP. The relative bad comparisons between two SIF products and GPP are found in the three regions of the southern hemisphere which covers mainly the tropical vegetation in these regions.
3. The results of TanSat SIF retrieval

- Quantitative comparison of TanSat SIF with OCO-2 and MODIS Vegetation indices

The high consistency between TanSat and OCO-2 SIF products ($R^2=0.86$) and the consistency between the spatial patterns in the TanSat SIF and MODIS vegetation indices increase the confidence in the potential and feasibility of TanSat data for SIF retrieval.
3. The results of TanSat SIF retrieval

- Temporal global TanSat SIF at 758 and 771 nm

<table>
<thead>
<tr>
<th>Variables</th>
<th>Comments</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude:</td>
<td>Surface altitude of the observed footprint</td>
<td>meters</td>
</tr>
<tr>
<td>Latitude:</td>
<td>Geodetic latitude of the TanSat footprint</td>
<td>degrees</td>
</tr>
<tr>
<td>SIF_758nm:</td>
<td>Solar SIF at 758</td>
<td>mw/m²/sr/nm</td>
</tr>
<tr>
<td>SIF_771nm:</td>
<td>Solar SIF at 771</td>
<td>mw/m²/sr/nm</td>
</tr>
<tr>
<td>Id:</td>
<td>(YYYYMMDDHHMMSS).</td>
<td>-</td>
</tr>
<tr>
<td>SZA:</td>
<td>Solar zenith angle (degrees)-angle</td>
<td>degrees</td>
</tr>
<tr>
<td>Time:</td>
<td>Time in seconds since 2012-1-1 00:00:00.</td>
<td>seconds</td>
</tr>
<tr>
<td>VAZ:</td>
<td>View zenith angle (degrees)-angle</td>
<td>degrees</td>
</tr>
<tr>
<td>VZA:</td>
<td>View zenith angle (degrees)-angle</td>
<td>degrees</td>
</tr>
</tbody>
</table>
4. Conclusions

- A singular vector decomposition (SVD) statistical method was successfully employed to retrieve SIF using radiance over micro spectral windows (2 nm) around the Fe and KI Fraunhofer lines.
- The global SIF at 758.8 nm was successfully retrieved with a low residual error of 0.03 mW m\(^{-1}\) sr\(^{-1}\) nm\(^{-1}\).
- The overall consistency between TanSat and OCO-2 SIF products \((R^2=0.86)\) between the TanSat SIF and MODIS vegetation indices and GPP enhance our confidence in the potential and feasibility of TanSat data for SIF retrieval.

TanSat, therefore, provides a new opportunity for global sampling of SIF at fine spatial resolution (2 km $\times$ 2 km), thus improving photosynthesis observations from space.

All TanSat radiance data and SIF products will be online soon at
http://www.chinageoss.org/tansat/index.html
http://www.geodata.cn
- TanSat Global SIF dataset-2017 is available at
https://pan.baidu.com/s/1XXdUUkjFnDdPXHXMR90yxA
Password: nl45

Thanks!

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