TROPOMI on the Copernicus Sentinel 5 Precursor
instrument performance, the L0-1B processor
and on-ground calibration results

Pepijn Veefkind, Quintus Kleipool, Antje Ludewig, Ilse Aben,
Johan de Vries, Pieternel Levelt
The ESA Sentinel-5 Precursor (S-5P) is a pre-operational mission focusing on global observations of the atmospheric composition for air quality and climate.

The TROPOspheric Monitoring Instrument (TROPOMI) is the payload of the S-5P mission and is jointly developed by The Netherlands and ESA.

The planned launch date for S-5P is 2016 with a 7 year design lifetime.

- **TROPOMI**
  - UV-VIS-NIR-SWIR nadir view grating spectrometer.
  - Spectral range: 270-500, 675-775, 2305-2385 nm
  - Spectral Resolution: 0.25-1.1 nm
  - Spatial Resolution: 7x7km²
  - Global daily coverage at 13:30 local solar time.

- **Contribution to Copernicus**
  - Total column: O₃, NO₂, CO, SO₂, CH₄, CH₂O, H₂O, BrO
  - Tropospheric column: O₃, NO₂
  - O₃ profile
  - Aerosol absorbing index & layer height
• Organization
• Instrument
• Level 0-1B Development
• On-ground Calibration

Picture: Airbus DS NL
International Co-operation

- TROPOMI/S5P is part of the CEOS AQ Constellation
  - TROPOMI provides the global coverage
  - Act as a “travelling standard” between the GEOs

- S5P will fly in “loose formation” with Suomi NPP
  - Primary objective is to use the VIIRS data for cloud clearing
<table>
<thead>
<tr>
<th></th>
<th>UV</th>
<th>UVIS</th>
<th>NIR</th>
<th>SWIR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Band</strong></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td><strong>Spectral coverage [nm]</strong></td>
<td>270 – 320</td>
<td>320 – 495</td>
<td>675 - 775</td>
<td>2305 – 2385</td>
</tr>
<tr>
<td><strong>Full spectral coverage [nm]</strong></td>
<td>267 - 332</td>
<td>303 - 499</td>
<td>660 - 784</td>
<td>2299 - 2390</td>
</tr>
<tr>
<td><strong>Spectral resolution [nm]</strong></td>
<td>0.49</td>
<td>0.54</td>
<td>0.38</td>
<td>0.25</td>
</tr>
<tr>
<td><strong>Spectral sampling ratio</strong></td>
<td>6.7</td>
<td>2.5</td>
<td>2.8</td>
<td>2.5</td>
</tr>
<tr>
<td><strong>Spatial sampling [km²]</strong></td>
<td>7 x 28</td>
<td>7 x 7</td>
<td>7x3.5</td>
<td>7 x7</td>
</tr>
</tbody>
</table>
EOL SNR for 2% albedo scene

Figure: Johan de Vries, Airbus DS NL

UV: 21 x 28 km², 7 x 7 km²

UVIS

NIR

SWIR
### Dark Current

Dark currents in Bands 1-6 lower than 2 e/s

<table>
<thead>
<tr>
<th>band</th>
<th>dc e/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.622</td>
</tr>
<tr>
<td>2</td>
<td>1.477</td>
</tr>
<tr>
<td>3</td>
<td>1.593</td>
</tr>
<tr>
<td>4</td>
<td>1.579</td>
</tr>
<tr>
<td>5</td>
<td>1.759</td>
</tr>
<tr>
<td>6</td>
<td>1.849</td>
</tr>
</tbody>
</table>

![Graph of dark current average per column](image)

**Legend:**
- band1
- band2
- band3
- band4
- band5
- band6

**Y-axis:** Dark current [e^- s^-1]

**X-axis:** Ccd column
From OMI to TROPOMI

- 6x higher spatial resolution
  7x7 km² vs. 13x24 km²
- 1-5x higher signal-to-noise per ground pixel
- Much lower dark current
  detector temperatures much lower
- Better cloud information
  oxygen A band added
- CO and CH₄ observations
  SWIR band added
- Many lessons learned from 11 years of OMI data
Level 0-1B Processor

- Multi-threading
- Multi-pass
- Algorithms are pluggable at run-time
- Full error propagation (noise + systematic errors)
- L1B product ~35 Gbyte / 100 min
- S/W design can be re-used
On-ground Calibration

• All measurements done in vacuum.
• Automated processing system for quick-look and key data analysis, using L0-1B processor.
• Calibration period of 127 days of continuous measurements.
• Strong involvement of KNMI/SRON:
  – On-site science support team
  – Data analysis team
<table>
<thead>
<tr>
<th>Optical Stimulus</th>
<th>Calibration Key Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Star stimulus</td>
<td>Geolocation</td>
</tr>
<tr>
<td>Lasers (UVN/SWIR)</td>
<td>ISRF, Stray light</td>
</tr>
<tr>
<td>Echelle grating stimulus</td>
<td>UVN ISRF</td>
</tr>
<tr>
<td>Spectral filters</td>
<td>Stray light</td>
</tr>
<tr>
<td>Spectral Line Lamps</td>
<td>Spectral calibration</td>
</tr>
<tr>
<td>FEL lamp + diffuser</td>
<td>Absolute radiometric calibration</td>
</tr>
<tr>
<td>Black bodies</td>
<td>Absolute radiometric calibration</td>
</tr>
<tr>
<td>CO, CH₄ gas cells</td>
<td>Spectral calibration SWIR</td>
</tr>
<tr>
<td>Integrating Sphere</td>
<td>Relative radiometry, BSDF</td>
</tr>
<tr>
<td>Sun simulator</td>
<td>Relative radiometry, BSDF</td>
</tr>
<tr>
<td>Internal LEDs</td>
<td>Detector parameters</td>
</tr>
<tr>
<td>Internal WLS</td>
<td>Relative radiometry</td>
</tr>
<tr>
<td>Internal laser diodes</td>
<td>ISRF</td>
</tr>
</tbody>
</table>
Use of L01b processor for on-ground calibration

- Implemented latest knowledge in processor during campaign
- Processing to different correction steps possible
- Quality check of measurements possible within minutes

- For all derived keydata:
  - Self consistency check
  - Traceability
Calibration framework and quicklook

Basic measurement analysis of the L01b converted files (netcdf) using python:

- Averaging of frames with identical settings
- SNR estimate
- Background subtraction

Custom made netcdf viewer for:

- Frame by frame inspection
- Instrument and ground support equipment settings
Electronic non-linearity

- Relative nonlinearity is less than 1.5%, while remaining relative residual < 0.1%
- Calibration key data is a fitted curve, defined by polynomial coefficients and domain interval
Pixel response non-uniformity (PRNU) before correction:

- **Rows** = swath direction
- **Columns** = spectral direction

![Image of PRNU before correction](image)
Pixel response non-uniformity (PRNU)

after correction:

Rows = swath direction

Columns = spectral direction
Geolocation: spatial smile

- 2 week long measurement
- Fast analysis vital for further calibration
- Using a weighted mean method
- 6th order polynomials result in smallest residuals.
Geolocation: pixel response function

UV

SWIR

[Graphs and data visualizations related to geolocation and pixel response function]
Stray light for UV, VIS, NIR spectrometers

Three methods:
• external white light source
• bandpass filter
• laser

White light source:
• near-to-mid-field ghost.
• scrambler ghosts
• scattering
Stray light: result from filter measurements

- Far-field stray light buried in noise.
- Near-field stray light above noise.
- Near-field stray light dominates over the far-field stray light.
Stray light correction possible with laser data

Stray light correction of an EWLS measurement at an azimuth of 39.79 degrees. Used stray light response function was measured at an azimuth of 0 deg.

- before
- after first step

Signal [e/s]

Rows (not sure what row 0 is)
ISRF Measurements

- UV: FWHM ~0.45 - 0.48 nm
- UVIS FWHM ~0.48-0.54 nm
- VIS: FWHM ~0.33 nm
- NIR: FWHM ~0.38 nm

Inhomogeneous slit filling
UV: laser measurements

UVIS: laser measurements

NIR: SFS measurements
Summary & Outlook

• TROPOMI will be a major step forward for atmospheric composition observations due to improved spatial resolution & sensitivity.

• The on-ground calibration has been finalised; calibration analysis is ongoing.

• L0-1B development is on-track and the processor was an essential part of the on-ground calibration campaign.

• We are counting down for a launch in 2016!

veefkind@knmi.nl
www.tropomi.nl
www.tropomi.eu
www.temis.nl
www.knmi.nl/omi
sentinel.esa.int/s5p
<table>
<thead>
<tr>
<th>Antje Ludewig</th>
<th>Judith van Bruggen van Putten</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arjen Oostdijk</td>
<td>Ljubisa Babic</td>
</tr>
<tr>
<td>Bouwe Andela</td>
<td>Nico Rozemeijer</td>
</tr>
<tr>
<td>Chris Kruszynski</td>
<td>Oscar Brinkhof</td>
</tr>
<tr>
<td>Daniel Schiavini</td>
<td>Pepijn Kenter</td>
</tr>
<tr>
<td>Dinand Schepers</td>
<td>Pepijn Veefkind</td>
</tr>
<tr>
<td>Edwin van de Sluis</td>
<td>Peter Meijering</td>
</tr>
<tr>
<td>Emiel van der Plas</td>
<td>Pieter-Jan Dewitte</td>
</tr>
<tr>
<td>Erik Schenkeveld</td>
<td>Quintus Kleipool</td>
</tr>
<tr>
<td>Erwin Loots</td>
<td>Remco Braak (†)</td>
</tr>
<tr>
<td>Frank Vonk</td>
<td>Rob van Swol</td>
</tr>
<tr>
<td>Giuseppe Vacanti</td>
<td>Robert van Versendaal</td>
</tr>
<tr>
<td>Henri Nijkamp</td>
<td>Rolf Bartstra</td>
</tr>
<tr>
<td>Jacqueline Baas</td>
<td>Rudy Ujzanovitch</td>
</tr>
<tr>
<td>John Kissi-Ameyaw</td>
<td>Werner Dierssen</td>
</tr>
<tr>
<td>Jonatan Leloux</td>
<td></td>
</tr>
<tr>
<td>Joost Smeets</td>
<td></td>
</tr>
</tbody>
</table>
UVN module

SWIR module