CO and CH$_4$ from TROPOMI on Sentinel-5 Precursor

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2) SRON Netherlands Institute for Space Research, Utrecht, The Netherlands
Copernicus
The European contribution to GEOSS

Services Component – led by EC
- Produces information services in response to European policy priorities in environment and security
- Relies on data from in-situ and space component

In-situ Component – led by EEA
- Observations mostly within national responsibility, with coordination at European level

Space Component – led by ESA
- Sentinels - EO missions developed specifically for Copernicus

Plus Contributing Missions - EO missions built for purposes other than Copernicus but offering part of their capacity to Copernicus
The Copernicus Mission
Sentinel-5 Precursor

- Pre-operational, precursor to Sentinel-5
- Daily global observations of atmospheric composition
- Loose formation with Suomi-NPP/JPSS
- For air quality and climate services
- Payload = TROPOspheric Monitoring Instrument (TROPOMI)
- Jointly developed by Airbus Defense and Space Netherlands, KNMI, SRON and TNO, on behalf of the NSO and ESA.
- Planned launch date 2017
- 7 year design lifetime
TROPOMI on S5P

- 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
**S5P Level-2 Products (operational)**

<table>
<thead>
<tr>
<th>Species</th>
<th>Characteristics</th>
<th>expected accuracies</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ozone - O₃</strong></td>
<td>vertical profile</td>
<td>10-30 % (6 km res.)</td>
</tr>
<tr>
<td></td>
<td>total column</td>
<td>3.5 – 5 %</td>
</tr>
<tr>
<td></td>
<td>tropospheric column</td>
<td>25%</td>
</tr>
<tr>
<td><strong>Nitrogen dioxide - NO₂</strong></td>
<td>total column</td>
<td>&lt;10%</td>
</tr>
<tr>
<td></td>
<td>tropospheric column</td>
<td>25-50%</td>
</tr>
<tr>
<td><strong>Sulphur dioxide - SO₂</strong></td>
<td>SO₂ enhanced</td>
<td>30 %</td>
</tr>
<tr>
<td></td>
<td>total column</td>
<td>30 – 50 %</td>
</tr>
<tr>
<td><strong>Formaldehyde - HCHO</strong></td>
<td>total column</td>
<td>40 – 80 %</td>
</tr>
<tr>
<td><strong>Methane - CH₄</strong></td>
<td>total column</td>
<td>1.5 %</td>
</tr>
<tr>
<td><strong>Carbon monoxide - CO</strong></td>
<td>total column</td>
<td>&lt; 15 %</td>
</tr>
<tr>
<td><strong>Cloud</strong></td>
<td>optical depth, fraction, height</td>
<td>&lt;20 % (all parameters)</td>
</tr>
<tr>
<td><strong>Aerosol</strong></td>
<td>UV absorption index</td>
<td>~1 AAI</td>
</tr>
<tr>
<td></td>
<td>layer height</td>
<td>&lt; 100 hPa</td>
</tr>
<tr>
<td><strong>Surface UV</strong></td>
<td>spectral irradiance, UV index</td>
<td>TBD</td>
</tr>
</tbody>
</table>

+ Cloud data from VIIRS imager on Suomi-NPP
## S5P Level-2 Products (research)

<table>
<thead>
<tr>
<th>Species</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerosol</td>
<td>fine mode optical depth</td>
</tr>
<tr>
<td>Glyoxal - CHOCHO</td>
<td>total column</td>
</tr>
<tr>
<td>Surface</td>
<td>effective reflectance</td>
</tr>
<tr>
<td>Water vapour - H$_2$O</td>
<td>total column</td>
</tr>
<tr>
<td>Bromine oxide - BrO</td>
<td>total column</td>
</tr>
<tr>
<td>Chlorine dioxide - OCIO</td>
<td>total column</td>
</tr>
<tr>
<td>Iodine oxide - IO</td>
<td>total column</td>
</tr>
<tr>
<td>Semiheavy water - HDO</td>
<td>total column</td>
</tr>
</tbody>
</table>

...and potentially many others including e.g. SIF (solar induced fluorescence)
The 2.3 μm spectral range

Spectral range contains information on:
• Water
• HDO
• Methane
• Carbon monoxide

Quality requirement for operational data product:

CO: 10 % precision / 15 % accuracy

CH₄: 1 % precision / 1 % bias
Operational CH$_4$ algorithm: RemoTeC

- Cloud filtering using co-located VIIRS measurement
- Remaining scattering by aerosols and thin cirrus is accounted by the retrieval (O$_2$ A band in the NIR, and strong CH$_4$ bands in the SWIR)
- Height of a scattering layer, size and number of scattering particle, H$_2$O, CH$_4$, CO, surface albedo, spectral calibration, SIF
- 10 seconds per ground pixel

References:
Butz et al., 2009; 2010; 2011;
Schepers et al., 2012; 2016
Guerlet et al., 2013; Hu et al., 2016
CH$_4$ bias estimate for four-day ensemble of simulated clear sky measurements

For 94% of all cases bias < 1%, rms error 0.55%
Operational CO algorithm: SICOR

**Band 1: 2315-2324 nm**
Non-scattering retrieval, difference between retrieved CH$_4$ and a priori knowledge used to filter on high and optically thick clouds

**Band 2: 2324-2338 nm**
Physics-based retrieval:
Fit parameters: CO, H$_2$O, scattering optical depth and scattering layer height, using a priori CH$_4$. Retrieval uses a two-stream RTM.

→ Processing time: 0.15 seconds per ground pixel

Reference:
Gloudemans et al., 2009 / Vidot et al., 2012, Borsdorff et al., 2014, 2015 Landgraf et al., 2016
TROPOMI orbit ensemble (1)

simulated measurements with resampled MODIS cloud data to TROPOMI pixel size

Slide: J. Landgraf, SRON

cloud fraction
cloud optical depth
cloud top height
TROPOMI orbit ensemble – CO column

Biomass burning event central Africa

Overall very good precision

Small biases with some outliers <8% due to simple cloud model

Slide: J. Landgraf, SRON
## Status of Sentinel-5P

<table>
<thead>
<tr>
<th>Activity</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>TROPOMI on-ground calibration and characterisation from Dec 2014 until Apr 2015</td>
<td>✔️</td>
</tr>
<tr>
<td>Instrument into S5P satellite integration in May 2015</td>
<td>✔️</td>
</tr>
<tr>
<td>Assembly, integration and testing (AIT) until early 2016</td>
<td>✔️</td>
</tr>
<tr>
<td>Flight acceptance review (FAR) – Mar 2016</td>
<td>✔️</td>
</tr>
<tr>
<td>Delivery to launch site (Plesetsk/Russia) – early 2017</td>
<td>❎</td>
</tr>
<tr>
<td>Launch window opens end March 2017</td>
<td>❎</td>
</tr>
</tbody>
</table>
S5P CalVal - Some Key Findings

- Ozone profile and total column well covered, except for the required measurement spatial representativity and specific environmental conditions.
- Tropospheric ozone, NO₂ and formaldehyde well covered but lacking global validation and in particular for the tropics.
- SO₂ lacks redundancies and validation capabilities for high SO₂ pollution.
- CO and methane validation at risk, in particular as a result of funding issues for validation, e.g. TCCON.
- Clouds and aerosol layer height well covered.
- AAI validation only against other satellites.
- Level 1b lack any redundancy and covering only UV/VIS.
Conclusion

Sentinels-5P

- Embarks the UVNS instrument TROPOMI on a dedicated satellite
- Will provide global daily atmospheric composition observations incl. CO and CH₄
  - for the Copernicus Atmosphere Monitoring Service (CAMS)
  - for the Copernicus Climate Change Service (C3S)
  - for the future Emergency Management Service
- Is part of the CEOS AQ Constellation
  - acts as a “travelling standard” between the GEOs (TEMPO, S4, GEMS)
  - target common formats and static aux data, coordinated cal/val activities, reviews, ...
- Bridges the gap between OMI on Aura and Sentinel-5
- Will fly in “loose formation” with Suomi NPP to use VIIRS for cloud clearing
- Is ready for launch, wait for launcher availability, launch scheduled in 1st Q 2017
Thank You

Any Questions?

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http: www.esa.int/copernicus

CEOS-ACC-12 | 13-14 Oct 2016 | NIER, Seoul, Korea | Slide 16
Joint Operation of S5P with S-NPP

- TROPOMI SWIR channel L2 processing (CH₄) relies on accurate, high resolution cloud mask data
- phased operation with NASA’s Suomi-NPP envisaged
- routine delivery of S-NPP/VIIRS products to PDGS

**Suomi-NPP:** Launched Oct. 2011
S5P - Swath
Campaigns

Sep 2016 (presently on-going)

CINDI-2 Cabauw/NL - intercalibration of reference ground-based systems planned for NO₂, O₃, HCHO, O₄ → NDACC intercomparison, network setup
  - Full suite of PANDORA, (MAX-)DOAS, Lidar, sunphotometer systems
  - NO₂/O₃ sondes, in-situ systems, ...

2018

(1) Deployment of suite of airborne and ground-based mobile/imaging systems for small scale variability analysis and TROPOMI validation in urban environment (NO₂, SO₂, HCHO, aerosol) → Romania, summer clear-sky
  - AirMap, NO₂ sonde, SWING UAV, mobile DOAS, fast azimuth scan MAXDOAS, PANDORA, ground-based imaging DOAS, aerosol ... 

(2) Cloud impact campaign, instrumentation TBD → Cabauw/NL, Spring/summer/autumn
## Launch Schedule of Atmospheric Sentinels

<table>
<thead>
<tr>
<th>Year</th>
<th>Sentinel-5P</th>
<th>Sentinel-4 - 1</th>
<th>Sentinel-5 - 1</th>
<th>Sentinel-4 - 2</th>
<th>Sentinel-5 - 2</th>
<th>Sentinel-5 - 3</th>
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<td>2030</td>
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S5P and S5 = LEO  
S4 = GEO
Overview: ESA’s CAMS Related Missions

**MTG-S**
- IRS
- Sentinel-4 UVN

**MTG-I**
- FCI
- LI

**MetOp-SG B**
- SCA
- MWI
- RO
- ICI
- Argos-4

**Sentinel-5P**
- TROPOMI

**MetOp-SG A**
- METimage
- IASI-NG
- MWS
- RO
- Sentinel-5 UVNS
- 3MI

Graphics: ESA
S5P L-2 Algorithm Development

KnMI
DLR
IUP-Bremen
BIRA
SRON
MPIC
RAL

Ready for commissioning phase

GOME(-2)-SCIAMACHY-OMI

PROTOTYPE
VERIFICATION
OPERATIONAL S/W
S5P Spatial Resolution

- **Scia CO**: 120x30 km²
- **Scia NO₂**: 60x30 km²
- **GOME-2 NO₂**: 80x40 km²
- **OMI**: 13x24 km²
- **TROPOMI**: 7x7 km²

Credit: KNMI
Sentinel-5 Precursor Data Dissemination

- Data Volume:

<table>
<thead>
<tr>
<th>Product type</th>
<th>GB per Orbit</th>
<th>GB per day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1b Radiance NRT/OFL</td>
<td>(2 x) 35.6</td>
<td>(2 x) 504</td>
</tr>
<tr>
<td>Level 1b Irradiances OFL</td>
<td>0.03</td>
<td>0.42</td>
</tr>
<tr>
<td>Level 2 NRT</td>
<td>4.27</td>
<td>60.6</td>
</tr>
<tr>
<td>Level 2 OFL</td>
<td>5.24</td>
<td>74.3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>45.1</strong></td>
<td><strong>639</strong></td>
</tr>
</tbody>
</table>

- Data Organisation
  - Level 1b radiance is provided as separate files for each of the 8 bands
    - Plus UV-UVIS-NIR and SWIR solar irradiance product
  - Each geophysical Level 2 parameter is provided in a dedicated product
  - Data format is netCDF-4 using Climate and Forecasting Metadata Standards
  - Data format harmonisation with heritage and future Sentinels
Sentinel-5 Precursor Data Access

- The Sentinel-5P core products list agreed with the Commission currently includes **Level-1** and **Level-2 products**

- Systematically provided on-line to ALL users in both Near-Real-Time (NRT, within 3 hrs from sensing, TBC) and Non-Time-Critical (NTC, within 14 days after sensing)
  
  - The relevant Copernicus Services will access the core products via the dedicated access point with strict guaranteed quality of service and associated Key Performance Indicators
  
  - Other users will access the core products via the Sentinels Scientific Data Hub. This will be provided without strict timeliness guaranteed albeit with expected nominal performances

*Note:*

expert users supporting the S5P commissioning and Cal/Val tasks will have access to the products (NRT and NTC) via specific mechanisms (e.g. open access data hub, dedicated data access points)