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 SENTINEL-2 MISSION

- Optical mission for land and coastal region monitoring and emergency services
- Constellation of 2 satellites S2A and S2B (June 2015 & Mars 2017)
- Polar, Sun-synchronous orbit:
  - Swath of 290km
- Global coverage with 5 days or less revisit period with both satellites

13 spectral bands
Spatial resolution
10 m, 20 m, 60 m.
LEVEL-2A PROCESSING STEPS

- Two main modules: Scene Classification (SCL) and Atmospheric Correction (AC)
- Set of Look-Up Tables (LUTs) generated with libRadtran
- AOT derived at 550nm based on the DDV (Dense Dark Vegetation) algorithm
- WV retrieval based on the Atmospheric Pre-corrected Differential Absorption Algorithm (APDA)
L2A PROCESSOR OUTPUTS

Sentinel-2A product
Four tiles
North of Italy
22 April 2018

+ Cloud & Snow Confidence QI
L2A PROCESSOR OUTPUTS

Sentinel-2A product
Four tiles
North of Italy
22 April 2018
LEVEL-2A PROCESSING BASELINES

- RAM consumption less than 4GB
- L2A OLQC reports included

Level-1C evolutions
(L1C PB 02.07)

- OpenJPEG 2.3 faster reading time
- Topographic correction extended

PB 02.08
(Sen2Cor v.02.06.03)
23 May 2018

PB 02.09
(Sen2Cor v.02.06.06)
8 Oct 2018

PB 02.10
(Sen2Cor v.02.06.06)
6 Nov 2018

PB 02.11
(Sen2Cor v.02.07.01)
21 Nov 2018

PB 02.12
(Sen2Cor v.02.08.00)
6 May 2019

- Single retrieval of atmospheric parameters (AOD & WVP) at 20 m
- Resampling of 20 m to 60 m
- Scene Classification using ESA CCI Data package
- Spatial homogeneity improved: blue path radiance rescaling -> OFF

- Topographic correction under clouds disabled
- PDGS Optimizations (dual databases)

Worldwide L2A production since 14 December 2018
Sen2Cor versions

- General User’s version:
  - Version 2.5.5 released on March 19, 2018 (publicly available)
    (For L1C with PSD older than 14.2 and not reprocessed by ESA)
  - Version 2.8 released on May 10, 2019 (publicly available)

- S2 PDGS versions:
  - Version 2.8.0 in operations since May 9, 2019


L2A Validation Results: Cloud Screening and Scene Classification

Accuracy assessment for SCL product with 11 classes, and for clear pixels vs clouds separation

<table>
<thead>
<tr>
<th>Site</th>
<th>OA</th>
<th>OA clear pixels</th>
<th>OA clouds</th>
<th>Pixel validated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antarctic</td>
<td>94.7</td>
<td>96.8</td>
<td>98.8</td>
<td>527803</td>
</tr>
<tr>
<td>Barrax (Spain) - 1</td>
<td>64.6</td>
<td>96.9</td>
<td>98.7</td>
<td>141546</td>
</tr>
<tr>
<td>Barrax (Spain) - 2</td>
<td>90.5</td>
<td>98.7</td>
<td>99.5</td>
<td>104799</td>
</tr>
<tr>
<td>Berlin (Germany)</td>
<td>93.4</td>
<td>96.5</td>
<td>no clouds</td>
<td>51964</td>
</tr>
<tr>
<td>Casteo (Argentina)</td>
<td>63.8</td>
<td>86.1</td>
<td>98.1</td>
<td>186238</td>
</tr>
<tr>
<td>Dunhuang (China)</td>
<td>57.3</td>
<td>66.2</td>
<td>no clouds</td>
<td>105454</td>
</tr>
<tr>
<td>Manila (Philippines)</td>
<td>82.1</td>
<td>90.0</td>
<td>91.6</td>
<td>106263</td>
</tr>
<tr>
<td>Rimrock (USA)</td>
<td>90.2</td>
<td>98.2</td>
<td>99.2</td>
<td>103394</td>
</tr>
<tr>
<td>Yakutsk (Russia)</td>
<td>69.9</td>
<td>93.8</td>
<td>92.9</td>
<td>177983</td>
</tr>
<tr>
<td>Etna Volcano (Italy)</td>
<td>95.8</td>
<td>97.9</td>
<td>99.4</td>
<td>132340</td>
</tr>
<tr>
<td>Kilauea Volc. (Hawaii, U)</td>
<td>60.4</td>
<td>75.4</td>
<td>74.2</td>
<td>118357</td>
</tr>
<tr>
<td>Lagos (Portugal)</td>
<td>96.8</td>
<td>97.3</td>
<td>no clouds</td>
<td>69753</td>
</tr>
<tr>
<td>Buenos Aires (Argentina)</td>
<td>91.8</td>
<td>97.3</td>
<td>no clouds</td>
<td>31841</td>
</tr>
<tr>
<td>Tallin (Estonia)</td>
<td>84.3</td>
<td>90.4</td>
<td>95.6</td>
<td>71773</td>
</tr>
<tr>
<td></td>
<td>Total:</td>
<td></td>
<td></td>
<td>1929508</td>
</tr>
<tr>
<td>Average</td>
<td>81.1</td>
<td>91.5</td>
<td>94.8</td>
<td>137822</td>
</tr>
<tr>
<td>Stdev</td>
<td>14.6</td>
<td>9.7</td>
<td>7.8</td>
<td></td>
</tr>
</tbody>
</table>

Validation data set with different:

- atmospheric conditions (e.g. cloud cover)
- latitudes (various solar angles and seasons)
- topography (flat, rough and mountainous terrain)
- land cover types (agricultural area, forests, water bodies, arid area, urban area, deserts, permanent ice, and active volcanos).

- The average OA for 14 classification products reached 81.1 ± 14.1%.

- Overall Accuracy (OA) of clear pixels aggregates results for the Sen2Cor classes “vegetation”, “non-vegetated” and “water”.

- OA of clouds aggregates results for Sen2Cor classes “cloud medium probability”, “cloud high probability” and “thin cirrus”.

- The recognition of clear pixels reached an OA of 91.5% and a consolidated OA for clouds recognition is 94.8%.
Sen2Cor 2.8 public version

L2A VALIDATION RESULTS: AOT550 RETRIEVAL PERFORMANCE

- DDV processing: underestimation of high AOT values and overestimation of low AOT
- Results for the noDDV granules show the need for releasing a better fall-back solution based on CAMS-AOT data

**AOT statistics**

<table>
<thead>
<tr>
<th></th>
<th>Sen2Cor2.8 Complete set</th>
<th>DDV subset</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total no. of products</td>
<td>702</td>
<td>337</td>
</tr>
<tr>
<td>Products within specification</td>
<td>36%</td>
<td>48%</td>
</tr>
<tr>
<td>$R^2$ (Coefficient of variation)</td>
<td>0.21</td>
<td>0.63</td>
</tr>
<tr>
<td>$r$ (Pearson’s correlation coeff.)</td>
<td>0.45</td>
<td>0.80</td>
</tr>
<tr>
<td>MD (Median deviation)</td>
<td>0.06</td>
<td>0.04</td>
</tr>
<tr>
<td>MA (Median Accuracy value)</td>
<td>0.004</td>
<td>-0.007</td>
</tr>
<tr>
<td>MP (Median Precision value)</td>
<td>0.23</td>
<td>0.10</td>
</tr>
<tr>
<td>$U$ (Uncertainty)</td>
<td>0.24</td>
<td>0.11</td>
</tr>
<tr>
<td>Max AOT$_{550}$ difference</td>
<td>1.65</td>
<td>0.60</td>
</tr>
</tbody>
</table>

- solid lines: Accuracy requirement $|\Delta \text{AOT}_{550}| \leq 0.1 \times \text{AOT}_{550,\text{ref}} + 0.03$
- Dashed line: Sen2Cor_output = Reference
- Green triangles: Results for DDV-algorithm
- Orange triangles: fall-back processing
- Linear trend lines for DDV and fall-back
L2A Validation Results: WV Retrieval Performance

Sen2Cor 2.8 public version

- **Very accurate WV retrieval**
- **Trend**: light underestimation of WV
- **Larger differences occur for cloudier situations** (may be linked to the influence of cloud borders)

### WV statistics

<table>
<thead>
<tr>
<th>Sen2Cor2.8</th>
<th>Complete set</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total no. of products</td>
<td>702</td>
</tr>
<tr>
<td>Products within specification</td>
<td>94%</td>
</tr>
<tr>
<td>$R^2$ (Coefficient of variation)</td>
<td>0.98</td>
</tr>
<tr>
<td>$r$ (Pearson’s correlation coeff.)</td>
<td>0.99</td>
</tr>
<tr>
<td>MD (Median deviation)</td>
<td>0.12 cm</td>
</tr>
<tr>
<td>MA (Median Accuracy value)</td>
<td>-0.11 cm</td>
</tr>
<tr>
<td>MP (Median Precision value)</td>
<td>0.19 cm</td>
</tr>
<tr>
<td>U (Uncertainty)</td>
<td>0.24 cm</td>
</tr>
<tr>
<td>Max AOT$_{550}$ difference</td>
<td>1.39 cm</td>
</tr>
</tbody>
</table>
L2A Validation Results: Surface Reflectance (Campaign Lake Stechlin)

- Available measurements for Surface Reflectance:
  - SVC spectrometer (HR-1024i)

- AOD$_{550\text{nm}}$:
  - Microtops Sunphotometer: 0.07 ±0.04

- WV [cm or g.cm$^{-2}$]:
  - Microtops ozonometer: 0.59 ±0.12
**L2A Validation Results: Surface Reflectance (Campaign Lake Stechlin)**

Surface reflectance Reference: Average of SVC measurements on ground for one S2-pixel

- Sen2cor 2.8 surface reflectance spectrum agrees well with Surface reflectance Reference
- Bands 11, 12 and 5 agree with reference

### Processor relative to SR reference

<table>
<thead>
<tr>
<th></th>
<th>SR (20 m)</th>
<th>RMSD</th>
<th>corr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sen2Cor public</td>
<td>0.022</td>
<td>0.973</td>
<td></td>
</tr>
</tbody>
</table>

Corr = coefficient of determination

Level 1C product: S2B_MSIL1C_20180504T101029_N0206_R022_T33UUU_20180504T122043.SAFE
Casted Shadow Algorithm

- Current version is based on gdaldem – hillshade algorithm limited to sun incidence angle comparison with terrain slope without casted shadow propagation
- → not possible to find a topographic shadow on a flat area (e.g. lakes or plain)
Casted Shadow Algorithm

Plan to use Corripio, J.G. 2002 routines
(activated only on S2 tiles with particular illumination conditions)

EVOLUTION OF SCL ALGORITHM: FALSE SNOW DETECTION IN CLOUDS

- Limiting false snow detection in clouds
  - Post-processing of ESA CCI 52 Weekly Snow Condition files
    - Aggregation into 12 Monthly Snow Condition files
    - E.g. February Snow Condition file contains information on January, February, March

RGB: B12, B11, B8A
PB.02.12
Prototype
SCL map dilation strategy (on-going)

- + 80 m cloud mask
- + 40 m cloud shadow mask
- Careful dilation to avoid false cloud dilation leading to higher commission error

RGB: B04, B03, B02
PB.02.12
Prototype
Fall back solution when Dark Dense Vegetation (DDV) pixels are missing in the image.

- ECMWF-CAMS Total AOD at 550 nm short term forecast (< 12 hours)
- Data available on Operational FTP with short-term rolling archive (~ 3 days)
- CAMS data is collected daily
- CAMS data quality is controlled above L2A calibration test sites.

Sen2Cor CAMS prototype developed by TPZ F

First validation performed by DLR on ACIX dataset

Copernicus Atmosphere Monitoring Service (CAMS) website: https://atmosphere.copernicus.eu/
Example of CAMS product retrieved from operational FTP

Projection and Resolution: Geographic projection (lat-lon grid) @ 0.4 x 0.4 deg resolution
**EVOLUTION OF AC ALGORITHM: ECMWF-CAMS AOD AT 550 NM FALLBACK**

- **Nsamples:** 1442 (over 21 aeronet sites)
- **Pearson’s corr. Coeff**
  - $R(\text{all})$: 0.80
- **Bias:** ~ 0.03
- **Slope:** ~ 1.06
- **Slight overestimation for lower aerosol loads < 0.25**
L2A VALIDATION RESULTS SEN2COR 2.5 CAMS: AOD PRODUCT

- Correlation plot of Sen2Cor AOD550 retrieval at 20 m resolution versus AOD550 reference from AERONET (25 AERONET sites).

- Using CAMS data as fallback solution in case there are no DDV-pixels in the image show a better distribution of AOD values vs AOD reference values.
CONCLUSION AND OUTLOOK

- Sentinel-2 Level-2A products (surface reflectance) generated worldwide operationally since December 2018.

- L2A Validation results:
  - AOD retrieval with DDV pixels: about half of the products within requirements
    \[ |\Delta \text{AOD}_{550}| \leq 0.1 \times \text{AOD}_{550}^{\text{ref}} + 0.03 \]
  - Very accurate Water Vapour retrieval
  - Accurate surface reflectance retrieval for moderate atmospheric conditions

- On-going developments to improve the quality of the cloud screening

- In case DDV pixels are missing in the image a new fallback solution has been developed using meteorological aerosol estimates (CAMS)

- Sen2Cor participates to ACIX-2 and CMIX inter-comparison exercises
ACKNOWLEDGEMENTS
The authors thank the PI investigators and their staff for establishing and maintaining the AERONET sites used in this investigation.

YOKOHAMA, JAPAN
13/04/2019
L2A
THANK YOU FOR YOUR ATTENTION!

Jérôme Louis
Vincent Debaecker
Uwe Müller-Wilm

Bringfried Pflug
Magdalena Main-Knorn

jerome.louis@telespazio.com
CAMS geopotential used to calculate elevation

\[ \text{elevation} = \frac{\text{surface geopotential}}{9.80665} \]

Resolution 0.4 x 0.4 deg
Sen2Cor CAMS prototype now based on 2.8 (public version)

- AOD inputs from CAMS NEAR_REALTIME (FTP) or MACC data from API server
- CAMS AOD data used in AC processing only **when not enough DDV are present**
- CAMS AOD converted to **visibility** (km) using the altitude of the CAMS DEM.
- Visibility spatially and temporally interpolated to S2 geometry and S2 acquisition time.
- Visibility parameter then used in the radiative transfer equations together with Sen2Cor Digital Elevation Model information (PlanetDEM for operational L2A)
- Iterative negative reflectance check performed afterwards:
  - If too many negative surface reflectance pixels -> visibility slightly increased
    (⇌ AOD decrease) to reduce the amount of negative reflectance pixels.
### AOT statistics

<table>
<thead>
<tr>
<th>AOT statistics</th>
<th>noDDV set 2.5 public</th>
<th>noDDV set 2.5 CAMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total no. of products</td>
<td>30</td>
<td>28</td>
</tr>
<tr>
<td>Products within requ.</td>
<td>27%</td>
<td>36%</td>
</tr>
<tr>
<td>$R^2$ (Coefficient of variation)</td>
<td>0.19</td>
<td>0.60</td>
</tr>
<tr>
<td>$r$ (Pearson's correlation coeff.)</td>
<td>0.43</td>
<td>0.77</td>
</tr>
<tr>
<td>MA (Median Accuracy value)</td>
<td>-0.08</td>
<td>0.04</td>
</tr>
<tr>
<td>MD (Median deviation)</td>
<td>0.08</td>
<td>0.05</td>
</tr>
<tr>
<td>MP (Median Precision value)</td>
<td>0.25</td>
<td>0.16</td>
</tr>
<tr>
<td>U (Uncertainty)</td>
<td>0.25</td>
<td>0.17</td>
</tr>
<tr>
<td>Max AOT$_{550}$ difference</td>
<td>0.77</td>
<td>0.48</td>
</tr>
<tr>
<td>95.4% Quantile</td>
<td>0.14</td>
<td>0.26</td>
</tr>
<tr>
<td>68.3% Quantile</td>
<td>0.07</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Median Deviation = median ( |Sen2Cor - reference|)

- Much higher correlations, remarkable lower MP, U and Max AOT550 difference, lower A
- More products within requirement
No direct correlation between cloud coverage and CAMS AOD uncertainty.

Qualitative analysis of outliers shows that these are often related to a large weather front approaching the aeronet site.
VALIDATION PROCEDURE

- AOT & WV validation procedure:
  - direct comparison with AERONET as reference
  - AERONET: satellite overpass time ±30 min
  - Sentinel-2: average over
    - 9km x 9km area around sunphotometer of all vegetated and not-vegetated pixels

- SR validation procedure:
  - Pixel-by-pixel comparison with AERONET corrected (surface reflection) data as reference
  - SR reference computed from [Eric Vermote]
    - Sentinel-2 L1C (TOA) data with
    - 6S radiation transport model using
    - aerosol parameters from AERONET as input
  - AERONET: satellite overpass time ±30 min
  - Sentinel-2:
    - 9km x 9km area around sunphotometer with
    - only non-saturated, non-cloudy and non-missing pixels considered
VALIDATION PROCEDURE

• Statistical metrics:
  - $X_i = SR_{i\lambda}, AOT^{550}_{i\lambda}, WV_i$ (i:= pixel; $\lambda$: Band)
  - $\Delta X_i = X_i, SEN2COR - X_i$, reference
  - Median Accuracy value (median difference to reference value)
    $$MA = \text{Median}_{i=1}^{n} (\Delta X_i)$$
  - Median absolute Deviation:
    $$MD = \text{Median}_{i=1}^{n} (|\Delta X_i|)$$
  - Median Precision value (rms around MA)
    $$MP = \sqrt{\frac{1}{(n-1)} \cdot \sum_{i=1}^{n}(\Delta X_i - MA)^2}$$
  - Uncertainty U (rms around reference value)
    $$U = \sqrt{\frac{1}{n} \sum_{i=1}^{n}(\Delta X_i)^2}$$
  - SR per band:
    - MA, MP and U are computed per 0.02-SR-bins and
    - overall values for entire SR range