Development and assessment of leaf area index algorithms for the Sentinel-2 multispectral imager

Richard Fernandes¹, Marie Weiss², Fernando Camacho³, Beatrice Berthelot⁴, Fred Baret², Riccardo Duca⁵
1: CCRS, Government of Canada; 2: INRA, France; 3: EOLAB, Spain; 4: Magelllium, France; 5: ESTEC, European Space Agency
Objectives

- Description of Validation Sentinel 2 (VALSE2) experiment - focus on LAI algorithm validation.

- Description of two LAI algorithms applicable to S2 MSI
  - INRA Neural Network inversion of PROSAILH
  - CCRS Red-Edge analytical solution
## Sentinel 2 Mission Requirements

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Name</th>
<th>Description</th>
<th>Goal Accuracy</th>
<th>Product Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>POA</td>
<td>Bottom-of-Atmosphere Reflectance</td>
<td>Atmoospherically-corrected product including cloud screening, and adjacency/slope effects correction.</td>
<td>5%</td>
<td>2A</td>
</tr>
<tr>
<td>GLC</td>
<td>Generic Land Cover</td>
<td>Land cover with a set of basic generic classes compatible with those already used for generic services such as GLC 2000 and CORINE.</td>
<td>TBD</td>
<td>2B</td>
</tr>
<tr>
<td>FAPAR</td>
<td>Fraction of Absorbed Photosynthetically Active Radiation</td>
<td>Fraction of the radiation in the photosynthetic domain (400-700nm) that is absorbed by leaves. Values range between 0 and 1. Product to provide continuity of MGVI [RD-34]. For Sentinel-2 this index would provide MGVI at high resolution.</td>
<td>RMS=0.05 S/N=21 [RD-34]</td>
<td>2B</td>
</tr>
<tr>
<td>LAI</td>
<td>Leaf Area Index</td>
<td>Map with the green leaf area per unit soil area.</td>
<td>10%</td>
<td>2B</td>
</tr>
<tr>
<td>FVC</td>
<td>Fraction of Vegetation Cover</td>
<td>% of the land surface covered by vegetation.</td>
<td>TBD</td>
<td>2B</td>
</tr>
<tr>
<td>Cab</td>
<td>Leaf Chlorophyll Content</td>
<td>The amount of chlorophyll per square centimetre. This product would provide continuity of MTCI [RD-31]. For Sentinel-2 this index would provide MTCI at high resolution. This index is directly related to the chlorophyll content of vegetation.</td>
<td>TBD</td>
<td>2B</td>
</tr>
<tr>
<td>CW</td>
<td>Leaf Water Content</td>
<td>The amount of water in weight (grams) or volume (cubic centimetres) per unit leaf</td>
<td>TBD</td>
<td>2B</td>
</tr>
</tbody>
</table>
### Table 16. Evaluation of LAI methods. Blue = semi=empirical; Green = Machine Learning; Pink = Analytical; Brown = ANN; Yellow= Convex Optimization; Grey=LUT Inversion). Accuracy statistics in italics for effective LAI.

L=low, P=Partial, F=Full satisfaction or Mission requirements.

**Fernandes et al., VALSE2 Algorithm Survey, CCRS, 2014.**
INRA NNET Algorithm

Baret et al., VALSE2 CFI Algorithm Theoretical Basis Document, INRA, 2014.
Continuous radiative transfer equation:

\[ \frac{dI(x, \Omega_0)}{dx} + \sigma(\Omega_0)I(x, \Omega_0) = \int_0^{4\pi} \sigma_S(\Omega, \Omega_0)I(x, \Omega) \, d\Omega \]

Eigenfunction decomposition:

\[ LI(x, \Omega) = SI(x, \Omega) \]
\[ \gamma Le(x, \Omega) = Se(x, \Omega) \]

The probability a photon recollides in the canopy at the infinite scattering order.

\[ \gamma_{max} = p \]
Why do we care about $p$?

- $p$ is invariant to angular or spectral variation of $I(x, \Omega)$
- $p$ is analytically related to LAI (Stenberg, 2006)

\[ a_1(\Phi) \frac{1 - e^{-\Phi LAI}}{1 - p} + a_0(\Phi) \]
Relating \( p \) to S2 MSI reflectance

\[ p = \frac{1}{\omega} \left[ 1 - \left( \frac{\partial \ln \omega}{\partial \lambda} \right) \left/ \left( \frac{\partial \ln R_{bs}}{\partial \lambda} \right) \right. \right] \]

\( p \) is a function of

1. black soil reflectance \( R_{bs} \) and
2. leaf albedo \( \omega \)

Red-edge NDVI for S2 closely related to \( N = \frac{\partial \ln R_{bs}}{\partial \lambda} \).

Fernandes et al., VALSE2 CCRS Red-Edge ATBD, CCRS, 2014.
CRS LAI Algorithm

Inputs
- Optical data ( 
- CHL, 
- reflectance

LAI Estimation

1. For each \( \omega, \Phi \) and soil reflectance
2. Estimate \( p \) and LAI
3. Is \( p \) valid?
4. Add LAI(\( p, \Phi \)) to solution

Model leaf albedo, from CHL using PROSPECT5

Estimate CHL from red-edge CHL index

Estimate soil reflectance from regions with lowest 5% NDVI

Inputs
- \( B4, B5, B6 \)
- Surface reflectance
- \( B4, B5, B6 \)
- PROSPECT parameters, \( \Phi \), soil refl.
Radiative Transfer Verification

Fernandes, R., and Gitelson, A.

INRA NNET

CCRS Red-Edge

RMSE = 0.86485  0.85948

LAI Actual

LAI Estimated

1:1 line

CHL μg/cm²
10
20
30
40
50
60
70
80
Producer Validation

INRA NNET
(maize)

CCRS Red-Edge
(maize, soybean)

Estimated LAI vs Actual LAI

N=300, MAE=0.45

Fernandes, R., and Gitelson, A.
Validation of Sentinel 2: VALSE2
# ALSE2 Imagery

|                  | CAIS | AHS | HYMAP | ROSIS | AHS | AHS | HYPER | AHS | CASI | AHS | CASI | AHS | CASI | AHS | CASI | AHS | CASI | AHS | CASI | AHS | CASI | AHS | CASI | AHS | CASI | AHS | CASI | AHS | CASI | AHS | CASI |
|------------------|------|-----|-------|-------|-----|-----|-------|-----|------|-----|------|-----|------|-----|------|-----|------|-----|------|-----|------|-----|------|-----|------|-----|------|-----|------|-----|------|-----|------|
| Orthometry       | No L2| Yes | No    | No    | No  | Yes | yes   | Yes | Yes  | Yes | Yes  | Yes | Yes  | Yes | No   | Yes | Yes  | Yes | Yes  | Yes | Yes  | Yes | Yes  | Yes | Yes  | Yes | Yes  | Yes | Yes  |
| Co-registration  | No   | No  | No    | No    | No  |      |       | No  | No   | Yes | Yes  | Yes | Yes  | Yes | No   | Yes | Yes  | Yes | Yes  | Yes | Yes  | Yes | Yes  | Yes | Yes  | Yes | Yes  | Yes | Yes  |
| Temporal         | Yes  | No  | No    | No    | No  |      |       | No  | No   | Yes | Yes  | Yes | Yes  | Yes | No   | Yes | Yes  | Yes | Yes  | Yes | Yes  | Yes | Yes  | Yes | Yes  | Yes | Yes  | Yes | Yes  |
| Radiometry       | Cloud| yes | *     | *     | *   | *   | *     | *   | *    | *   | *    | *   | *    | *   | *    | *   | *    | *   | *    | *   | *    | *   | *    | *   | *    | *   | *    |
| Spectral (*)     | 3    | 3   | 2     | 2     | 1   | 1   | 1     | 1   | 1    | 1   | 1    | 1   | 1    | 1   | 1    | 1   | 1    | 1   | 1    | 1   | 1    | 1   | 1    | 1   | 1    | 1   | 1    |
| ESU              | yes  | yes | Yes   | yes   | Yes | Yes | Yes   | Yes | Yes  | Yes | Yes  | Yes | Yes  | Yes | No   | Yes | Yes  | Yes | Yes  | Yes | Yes  | Yes | Yes  | Yes | Yes  | Yes | Yes  | Yes | Yes  |

*No L2 available*

**ESU**: Yes (Barrax), No San Rossore

**Priority in the processing**: San Rossore, Barrax
**ALSE2 Ground Reference Data**

<table>
<thead>
<tr>
<th>LAI</th>
<th>WC</th>
<th>CHL</th>
</tr>
</thead>
<tbody>
<tr>
<td>DHP</td>
<td>LICOR</td>
<td>AccuPAR</td>
</tr>
<tr>
<td>✓</td>
<td>✓</td>
<td>×</td>
</tr>
<tr>
<td>✓</td>
<td>✓</td>
<td>×</td>
</tr>
<tr>
<td>✓</td>
<td>✓</td>
<td>×</td>
</tr>
<tr>
<td>✓</td>
<td>✓</td>
<td>×</td>
</tr>
</tbody>
</table>

Several methodologies, often poor documentation
Need for guidelines!!

Mostly crops were sampled
Need for other experiments!

![Graph showing data distribution and comparison]

Only few data available for some variables.
CHL significantly overestimated (>>60ug/cm²)

Saturation in retrieval due to saturation of input bands
ALSE2 LAI Validation V2

ANNET

SEN3EXP AHS

$y = 0.56 + 0.41x$

Mean($y$) = 1.30

N flights = 8

N = 50  $R^2=0.55$  RMSE = 1.40  $B=-0.46$  $S=1.32$

SEN3EXP CASI

$y = 0.56 + 0.41x$

Mean($y$) = 1.30

N = 45  $R^2=-0.53$  RMSE = 1.76  $B=-0.58$  $S=1.61$

et al., VALSE2 Validation Report, EOLAB, 2014.
Conclusions

Better co-ordination and careful processing of reference datasets so radiometry and in-situ measurements meet product specifications

Need to perform forest validation (BOREAS, Harz)

Sentinel Level 2P implementing NNET and CCRS algorithms but users must have patience: MODIS LAI had ~1 version/2 years.
2 MSI and S3 OLCI Red-Edge
How did we estimate leaf CHL?
Why does CCRS Red-Edge sometimes underestimate LAI?