Hyperspectral remote sensing with small satellites: systems engineering aspects

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Michael Schaepman, Devis Tuia, UniZH
Federico Belloni, ELSE SA
Edoardo Alberti, Mauro Melozzi, MICOS
SOLVE project key facts

<table>
<thead>
<tr>
<th>Name</th>
<th>Satellites Observing Lake and Vegetation Environments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mission objective</td>
<td>Understand vegetation phenology and environmental processes at hourly and daily timescales. Enable new market of products with applications in precision agriculture, water quality monitoring and forest maintenance.</td>
</tr>
<tr>
<td>Partners</td>
<td>EPFL, GAMAYA, Uni Zurich, ELSE SA, Micos</td>
</tr>
<tr>
<td>Project status</td>
<td>Phase 0, proposing for Phase A funding, launch 2019-2020</td>
</tr>
</tbody>
</table>

Compressive hyperspectral imager

<table>
<thead>
<tr>
<th>Spectral ranges, nm</th>
<th>VNIR</th>
<th>SWIR</th>
<th>PAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>400-1650</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spectral bands</td>
<td>180</td>
<td>128</td>
<td>3</td>
</tr>
<tr>
<td>Spectral resolution (FWHM)</td>
<td>5 nm</td>
<td>3 nm</td>
<td></td>
</tr>
<tr>
<td>Swath</td>
<td>108km</td>
<td>105km</td>
<td>108km</td>
</tr>
<tr>
<td>GSD (nadir)</td>
<td>35m</td>
<td>150m</td>
<td>15m</td>
</tr>
<tr>
<td>SNR</td>
<td>148:1</td>
<td>152:1</td>
<td>336:1</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>12 bit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other characteristics</td>
<td>Adaptive SNR (-30dB)</td>
<td>Compressive sensing</td>
<td></td>
</tr>
</tbody>
</table>

Constellation parameters

<table>
<thead>
<tr>
<th>Satellite bus</th>
<th>12U Cubesat</th>
<th>LEOS50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of orbital planes</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Number of satellites per plane</td>
<td>2 (more possible)</td>
<td></td>
</tr>
<tr>
<td>Data downlink capability</td>
<td>100 Mbps</td>
<td></td>
</tr>
<tr>
<td>Data volume per pass</td>
<td>8 GB</td>
<td></td>
</tr>
</tbody>
</table>

Every $\Delta T_i > (\text{Min gap time})$  \hspace{1cm} $\Sigma \Delta T_i < f(\text{SE, lat})$

<table>
<thead>
<tr>
<th>Plane #1</th>
<th>Sat #1</th>
<th>Sat #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pass</td>
<td>$1^{st}$</td>
<td>$2^{nd}$</td>
</tr>
<tr>
<td>Plane #2</td>
<td>Sat #1</td>
<td>Sat #2</td>
</tr>
<tr>
<td>Pass</td>
<td>$3^{rd}$</td>
<td>$4^{th}$</td>
</tr>
<tr>
<td>Plane #3</td>
<td>Sat #1</td>
<td>Sat #2</td>
</tr>
<tr>
<td>Pass</td>
<td>$5^{th}$</td>
<td>$6^{th}$</td>
</tr>
</tbody>
</table>
Scientific and Mission objectives

- **Key scientific objectives**
  - Understand vegetation phenology and environmental processes at hourly and daily timescales. Enable new market of products with applications in precision agriculture, water quality monitoring and forest maintenance.
  - The SOLVE mission shall allow observations of the same scene at least 3 [TBC] times per day with observations separated by at least 3 hours interval.
  - Daily global revisit time (repeat observation of the same target by all satellites in the constellation) shall be 3 (TBC) days.

- **Programmatic constraints**
  - The proposed mission can include a potential future funding contribution from the public sector of up to 30 MEUR.
Hyperspectral remote sensing will replace currently used DVI indexes.
In order to go define options and go through iterations in this project we utilised ESA’s Open Concurrent Design Tool.

Process

- co-location meeting of all engineers to discuss key trades and learn the tool
- initial iteration during co-location to get the first iteration in
- (remotely) database and model development, focusing on the mission
- weekly teleconferences to iterate. The tool is used remotely via an Excel worksheet
- co-location meeting to finalise options

This approach allowed to minimise travel time and access distributed expertise across Switzerland.
OCDT Software Design Document

Date 2013-12-10
Issue 2
Rev 1

• Communicate with other (OCDT-enabled) concurrent design centres in support of distributed concurrent design sessions.

3. The persistent data storage tier, containing the PersistentDataStore, i.e. a database management system, that provides persistent storage of study models and reference data, both during active studies and for archival of performed studies.

The rationale for this architecture is that in order to support a highly interactive concurrent design environment as a minimum two tiers are needed: GUI client tools to enable the user interact with concurrent design model as well as a common persistent data store to hold the data and ensure consistency.

As a third tier the web services layer is inserted in the middle, mainly for following reasons:

1. To provide a clean, flexible, secure and object oriented public interface to the data store for many different types of client applications.

2. To ensure robustness for future technology changes by separating the public interface between end-user applications and the "server" from the specific API that comes with the selected third-party database management system that implements the persistent data store.

3. To enable robust and secure distributed concurrent design sessions involving multiple centres without relying too deeply on the federation/distribution capabilities of the database management system itself.

Figure 1, Figure 2 and Figure 3 below show the architectural design and the main interface connections in UML deployment diagrams.

Schematic representation of the Open Concurrent Design Tool infrastructure. OCDT server is maintained by the systems engineering organization. Users have simple access to parameters, options and iterations via simple Excel plugin.
Mission architecture

- **Multi Platform Integration**
- Satellites can cover large territories, several times a day, depending on cloud cover (10000ha in one scene).
- UAV platforms can cover smaller (~1000ha) territories, without problems with cloud cover.
- UAVs can be fitted with the same sensor and additional instrumentation to allow vicarious calibration (radiance based calibration, Slater et al (1996)) of satellite data.
Mission design

Table 5.3: Different sets of requirements for the case studies

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
<th>Case 5</th>
<th>Case 6</th>
<th>Case 7</th>
<th>Case 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSD/focal length ratio</td>
<td>3.6e-5</td>
<td>3.6e-5</td>
<td>3.6e-5</td>
<td>3.6e-5</td>
<td>3.6e-5</td>
<td>3.6e-5</td>
<td>3.6e-5</td>
<td>3.6e-5</td>
</tr>
<tr>
<td>Min No of obs per day</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Min gap time [min]</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Revisits</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Min sun angle [deg]</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Max GSD [m]</td>
<td>35</td>
<td>35</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>35</td>
<td>35</td>
<td>35</td>
</tr>
</tbody>
</table>

Table 5.4: Results for the case studies derived from the requirement sets

<table>
<thead>
<tr>
<th>Performance Results</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
<th>Case 5</th>
<th>Case 6</th>
<th>Case 7</th>
<th>Case 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude [km]</td>
<td>561</td>
<td>411</td>
<td>561</td>
<td>411</td>
<td>561</td>
<td>561</td>
<td>411</td>
<td>460</td>
</tr>
<tr>
<td>Total swath [km]</td>
<td>888</td>
<td>898</td>
<td>511</td>
<td>645</td>
<td>511</td>
<td>888</td>
<td>898</td>
<td>904</td>
</tr>
<tr>
<td>No. orbital planes</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>No. satellites per plane</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>No. satellites</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>10</td>
<td>6</td>
<td>6</td>
<td>6</td>
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Mission design

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<td>60</td>
<td>30</td>
<td>30</td>
</tr>
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<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Min sun angle [deg]</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
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<td>10</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>No. satellites per plane</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>No. satellites</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>10</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>

All the different orbits should have the same repeating ground track cycles. The overall coverage will then be the intersection of all the repeating ground tracks.

5.3 Analysis of Launch options, Orbital Debris mitigation

5.3.1 Launch

There is a number of launch opportunities for shared launch of small satellites. Due to explosive growth of the small satellite market in the last decade, hundreds of small satellites were launched into Low Earth Orbits. We realize that our design constraints, described above will be an issue to find a suitable share ride. More studies will be necessary to understand effects of constrained launch on the SOLVE constellation capability.

Launch vehicle availability has been identified as a risk and will be investigated in further studies.

Ref: SOLVE-0-MissionDefinition
Payload design (compressive sensing)

Characteristics of IMEC detectors

<table>
<thead>
<tr>
<th>Designation</th>
<th>VNIR</th>
<th>SWIR</th>
<th>PAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation mode</td>
<td>Snapshot</td>
<td>Snapshot</td>
<td>Snapshot</td>
</tr>
<tr>
<td>Type</td>
<td>CMOS, Silicon</td>
<td>CMOS, InGaAs</td>
<td>CMOS, Silicon</td>
</tr>
<tr>
<td>Size</td>
<td>2048 x 1088 px</td>
<td>640 x 480 px</td>
<td>5632 x 2992 px</td>
</tr>
<tr>
<td>Pixel size</td>
<td>5.5 µm</td>
<td>23 µm</td>
<td>2 µm</td>
</tr>
<tr>
<td>Focal length</td>
<td>8 cm</td>
<td>8 cm</td>
<td>8 cm</td>
</tr>
<tr>
<td>Lens diameter</td>
<td>3.5 cm</td>
<td>3.5 cm</td>
<td>3.5 cm</td>
</tr>
<tr>
<td>Frame rate</td>
<td>120 i/s</td>
<td>120 i/s</td>
<td>120 i/s</td>
</tr>
<tr>
<td>Power consumption</td>
<td>2 W</td>
<td>2 W</td>
<td>2 W</td>
</tr>
<tr>
<td>Single image size</td>
<td>3.2 MB</td>
<td>0.4 MB</td>
<td>24.1 MB</td>
</tr>
</tbody>
</table>

Table 6.4: Radiometric performances of the SOLVE payload.

<table>
<thead>
<tr>
<th>Designation</th>
<th>VNIR</th>
<th>SWIR</th>
<th>PAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNR</td>
<td>148:1</td>
<td>152:1</td>
<td>336:1</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>12 bits</td>
<td>16 bits</td>
<td>12 bits</td>
</tr>
<tr>
<td>abs. radiometric accuracy</td>
<td>5%</td>
<td>5%</td>
<td>5%</td>
</tr>
<tr>
<td>rel. radiometric accuracy</td>
<td>5%</td>
<td>5%</td>
<td>5%</td>
</tr>
<tr>
<td>Polarisation sensitivity</td>
<td>2%</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>Polarisation sensitivity stability</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>Straylight sensitivity inside FOV</td>
<td>2%</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>Straylight sensitivity outside FOV</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>Straylight sensitivity / pixel</td>
<td>1e-5</td>
<td>1e-5</td>
<td>1e-5</td>
</tr>
</tbody>
</table>
Payload design (overview)
Spacecraft design (budgets)

**Smalle Satellite Option : BST LEOS-50 (DE)**
- Satellite mass 60 kg
- Payload mass up to 15 kg
- Payload power 20 W (140 W peak)
- 3 axis stabilized (0.016° pointing)
- 100 Mbps downlink
- **Multiple** payloads
  - TRL > 6

Multiple similar alternatives available in: UK, FR, SW, BE, IT, ES, US

Platform cost: ~2.5 MEuro (TBC)
Extra satellite cost 1.5 MEuro (TBC)

**CubeSat option: 6U / 12U (Baseline)**
- Satellite mass 8/16 kg
- Payload mass up to 4/8 kg
- Payload power up to 10/15 W
- 3 axis stabilized (<0.2° pointing)
- 100 Mbps downlink
- **Single** payload
  - TRL > 4 (depends on Subsystem)

System available in: UK, NL, DK, FR, HU, US, CH
Platform cost: ~2.5 MEuro (TBC)
Extra satellite cost 0.7/1 MEuro (TBC)
Spacecraft design

ADCS budgets for 500 km orbit
Ground segment design

ESTRACK ground stations network
(Credits: ESA)
# Program risks

<table>
<thead>
<tr>
<th>ID</th>
<th>Title</th>
<th>Description</th>
<th>Subsys sub</th>
</tr>
</thead>
<tbody>
<tr>
<td>MGMT.1</td>
<td>Overall mission cost</td>
<td>Presented analysis shows considerable margin. However, the exact funding instrument have not been identified yet.</td>
<td>MGM 1</td>
</tr>
<tr>
<td>SYS.1</td>
<td>Launch opportunities</td>
<td>Launch opportunities may constrain the range and sampling of local times available.</td>
<td>SYS 1</td>
</tr>
<tr>
<td>INS.1</td>
<td>Instrument development.</td>
<td>The instrument concept is at TRL 1 at the moment. Development program necessary to create concept hardware and verify performance on a UAV platform.</td>
<td>INS 1</td>
</tr>
<tr>
<td>SYS.2</td>
<td>Technology availability for the mission</td>
<td>All necessary technologies exist: sensors, small spacecraft bus, data processing algorithms, communication capabilities, attitude determination and control system.</td>
<td>SYS 2</td>
</tr>
<tr>
<td>INS.2</td>
<td>Sensor thermal control</td>
<td>Thermal stability requirements may increase cost and complexity of the instrument design</td>
<td>INS 2</td>
</tr>
<tr>
<td>INS.3</td>
<td>Degradation due to radiation</td>
<td>Additional testing is required to analysis impact of radiation on detectors</td>
<td>INS 3</td>
</tr>
<tr>
<td>SYS.3</td>
<td>Attitude Control increasing costs of the mission</td>
<td></td>
<td>SYS 3</td>
</tr>
<tr>
<td>SYS.4</td>
<td>Computational facilities</td>
<td>Data center needs to be established for automatic image processing</td>
<td>SYS 4</td>
</tr>
</tbody>
</table>

![Impact vs Likelihood Matrix](image-url)

**SWISSED'16**
Summary

- Systems engineering problem:
  - expertise is scattered across Switzerland across different organisations
  - very limited funding available for initial phase design and trade-offs

- Solution
  - distributed infrastructure for domain specific models
  - extremely structured schedule to discuss design iterations with minimum travel
  - result: shorten time for design and options, while using 1/3 budget nominally available at the European Space Agency.

- Mission summary
  - Science goals
    ‣ there is a strong need for hyperspectral observations at hourly frequencies to complement larger, high resolution high SNR missions
  - Key driving requirements
    ‣ hyperspectral bands to match most interesting phenomena in vegetation and water processes.
    ‣ surface resolution comparable with those of big missions
    ‣ 24 hours data availability
  - Two main options and a number of cases for mission design have been identified
Images acquired by the CHRIS instrument on PROBA 1
(2005-10-09) 13x13km, 17m/pixel

Original image, RGB

Simulation of compressive sensing; result of image restoration
(50% compression)