Miniaturized hyperspectral imagers for VNIR and SWIR small satellite missions


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Research Team Leader, VTT Microspectrometers
Outline

- Introduction
- FPI technology
- Hyperspectral imaging for small satellites
VTT Microspectrometers team in brief

Team expertise:
- MEMS process design
- Optics, electronics and mechanics design
- Assembly, testing & characterization
- Software and UI development

Key research topics
- Space CubeSat instruments
- Environmental sensing
- Stand-off detection
- Medical and diagnostics
- MEMS sensors for automotive, mobile and process industry
- Gas sensors
- Optical readers

Our offering
- Contract R&D
- Product prototyping
- Pilot MEMS production
- IPR out-licensing and sales
Team motivation

- Miniaturizing spectrometers - opportunity for novel sensing applications

From bench-top to handheld

- Space & environmental
- Mobile & consumer
- Stand-off detection
- Diagnostics & health
- Industrial IoT
Fabry-Perot (FPI) technology for miniaturizing optical sensors

✓ FPI is a tunable optical filter – electrical actuation changes the passband wavelength

✓ VTT develops miniaturized spectrometers based on tunable FPIs, for both imaging and non-imaging application

✓ FPI-based microspectrometers and hyperspectral imagers can be scaled to volume production

Basic equation: \( m\lambda = 2d \)
where \( m \) is operation order and \( d \) is air gap width
FPI tunable pass-band filter in spectroscopy

Single-point spectroscopy
- FPI combined with IR detector
- No array detector needed -> reduced sensor cost
- Examples: NDIR sensors, portable NIR analyzers, selective gas sensors

Hyperspectral imaging
- FPI combined with imaging detector
- Both spectral and spatial data
- Example: Visualization of gas distribution in stand-off detection

Comparison to pixel array-HSIs:
- **Smaller** size than pixel-based spectral imagers
- **Hundreds** of spectral bands
- **Does not require bulky and expensive telemetric lenses**
- Compatible with **low-cost mobile optics**!
VTT’s complementary FPI technologies

- **MEMS FPIs** for mass-producible microspectrometers in large-volume applications
  - Monolithic cleanroom fabrication processes
    - Hyperspectral imaging, gas sensing, IR sensors
    - Automotive, mobile, IoT
- **Piezo-actuated FPI** for small-to-medium volume applications
  - Separately assembled filter structure
  - Large optical apertures enable enhanced light throughput for high-performance applications
    - CubeSats, drones, medical, defense

- Wavelengths available from **UV to thermal IR**
FPI platforms and examples of realized filters

MEMS process platforms:
- ALD MFPI
- PolySi-SiN/SiO2 MFPI
- Si-air MFPI
- Metal MFPI

Material science
- Biology
- Pharma, Food, Agriculture
- Forestry
- Minerals

Gases, Plastics
- Minerals

Visible
- UV
- NIR
- SWIR
- MWIR
- LWIR
FPI technology applications – examples and demonstrators

**Mobile and hand-held**
- Spectral Engines NIR sensor (2016)
- MEMS-based hyperspectral imager demo (2012)
- Mobile CO2 sensor demo (2014)

**Health and diagnostics**
- Fundus camera: Detection of glaucoma and diabetes, oxygen saturation (hypoxia, apnea)
- Brain surgery spectral imaging integrated to the Zeiss Pentero brain surgery microscope

**Space and environmental sensing**
- Drone hyperspectral imagers: for forestry, precision agriculture, gas sensing and UV-Raman

**Stand-off - and and chemical detection**
- Thermal IR hyperspectral imager (2014)
- UV-FPI Raman stand-off trace detection (2014)

**Health and diagnostics**
- Hyperspectral microscope: Imaging of cells, micro well arrays & fluorescence imaging (2016)

**Mobile hyperspectral iPhone demo (2016)**

**Hyperspectral imagers for space instruments**
- NASA OMI (2006)
- PICASSO Vision (2015-2018)*
- Hello World 2017-2018

**SO₂/NOₓ ship emissions imaging (2016)**

**Chemical imager** for 1-2.5 µm
Distribution of active ingredients
Impact

- Customization of FPI technology to novel applications in research- and contract projects
- Several successfully commercialized sensing technologies
- Space R&D activities have also generated first commercial CubeSat mission with Reaktor Space Labs
Hyperspectral imaging for small satellites

- Traditional optical remote sensing from nanosatellites can be challenging due to the limited size and capabilities of nanosatellite platforms.
- Larger optical apertures are hard or even impossible to realize within a 3U CubeSat platform.
- Tunable FPI spectral filter offers high throughput which enables instrument miniaturization.
- Currently three nanosatellite missions with VTT’s miniaturized spectral imagers are planned to be flown in 2017-2018.
CubeSat missions

1. Aalto -1 imager will image land and ocean targets at wavelengths 500 - 900 nm to demonstrate the technology at low Earth orbit environment.

2. VISION-instrument on-board the Belgian PICASSO nanosatellite will look at the Sun through the Earth’s atmosphere and record the atmospheric transmission spectrum between 430 - 800 nm at different altitudes.

3. Reaktor Hello World – satellite will image in the infrared region (1000 - 1600 nm). These wavelengths will be used for vegetation monitoring, but it is also possible to use this range for mineral detection.
Classification of imaging spectrometers for remote sensing applications

- Spectral imagers have traditionally been realized as push-broom instruments, where the movement of the spacecraft provides the other spatial dimension for the images.
  - Requires a stable and precise attitude control, which can be difficult to achieve with a nanosatellite

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Classification of imaging spectrometers.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Along-track scanning</td>
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<tr>
<td></td>
<td>Whiskbroom</td>
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<tr>
<td>Spectral</td>
<td></td>
</tr>
<tr>
<td>Filtering</td>
<td>Multiband</td>
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<tr>
<td></td>
<td>radiometer</td>
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<tr>
<td>Dispersive</td>
<td>Grating or prism</td>
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<tr>
<td></td>
<td></td>
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<tr>
<td>Interferometric</td>
<td>Traditional FTS</td>
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<td></td>
<td>(Michelson)</td>
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</tbody>
</table>


Spectral imaging with tunable filters

- Tunable filter imagers acquire 2D images at a given wavelength.
- Spectral data cube is constructed by taking multiple images of the same target at different wavelengths.
- This method is more robust spatially, as the whole 2D scene is imaged at once, which makes the technology suitable for more unstable platforms, such as UAVS or nanosatellites.

![Spectral imager with vegetation reflectance](image)

![Typical instrument spectral response function](image)

- Selectable wavelengths reduce downlink data.
- Programmable software configuration - Customization of operation wavelengths enables a large variety of applications with same hardware.
- Good spatial resolution.
Piezo FPI assembly concept for space environment
Mission 1 – Aalto-1 technology demonstrator

- Launched 23.6.2017
- Two cameras: the spectral imager (SPE) and a normal RGB camera (VIS)
- Size: 0.5U, weight < 600g
- 3 operational modes: 6, 25 and 75 wavelengths
- Built-in temperature compensation
- Operation temperature: +10 °C to +55 °C
- On-board calibration possibility
Aalto-1 Spectral Imager – AaSI

**Spectral camera Module (SPE)**
- Field of View: 10 deg x 10 deg
- Focal length 32 mm
- F-number 3.4
- Image size 512x512 pixels
- Ground pixel size ca. 200 m from 600 km orbit
- Selectable wavelength bands between 500 and 900 nm

**Visible RGB-camera (VIS)**
- Commercial micro-objective (Kokagu AVR40)
- Field of view 15 deg x 10 deg
- Focal length 40 mm
- F-number 3.2
- Image size: 2048 x 1280 pixels
- Ground pixel size ca. 100 m from 600 km orbit

![Graph showing wavelength bands](graph.png)

- Minimal (3 gaps, 6 wavelengths)
- Nominal (14 gaps, 25 wavelengths)
- Extended (49 gaps, 75 wavelengths)
Ground imaging tests
First images from AaSI

RGB image

509 nm

671 nm

False color image: red pixels show 671 nm, blue pixels 509 nm (green pixels are average).
Mission 2 - PICASSO VISION

- **Picasso**: Picosatellite for Atmospheric and Space Science Observations
- **VISION**: Visible Spectral Imager for Occultation and Nightglow
- 2 scientific experiments for Earth observation
  - **VISION**: retrieving vertical profiles of ozone and temperature via Sun occultation
  - **SLP**: studying the ionosphere (Langmuir probe)

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Belgian Institute for Space Aeronomy (BEL), prime: management, mission definition & scientific aspects (incl. data analysis), whole development of SLP & software of VISION

Clyde Space: platform development & payload items integration, tests, ground-station & operations

VTT: VISION hardware
Solar occultation and mission scientific goals

- Observation of sunsets and sunrises through the Earth’s atmosphere
- Occultation technique is self-calibrating (dividing by out-of-atmosphere signal)
- Vertical distribution retrieved by onion peeling method

Scientific goal 1: Polar and mid-latitudes stratospheric ozone vertical profiles
Absorption increases when looking deeper in the atmosphere (lower tangent heights). Ozone retrieved from the Chappuis band (~600 nm)

Scientific goal 2: Mesosphere and stratosphere temperature profiles
Methods: 1) shape of the sun, 2) sunlight dilution
# VISION instrument parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field of View</td>
<td>2.5° x 2.5°</td>
<td>f = 244 mm</td>
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<tr>
<td>Image size</td>
<td>2048 x 2048 RGB pixels</td>
<td>1024 x 1024 spectral pixels</td>
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<tr>
<td>Spectral range</td>
<td>430 – 800 nm</td>
<td></td>
</tr>
<tr>
<td>Spectral resolution (FWHM)</td>
<td>&lt; 10 nm</td>
<td></td>
</tr>
<tr>
<td>Mass</td>
<td>526 g</td>
<td></td>
</tr>
<tr>
<td>Power</td>
<td>&lt; 3W</td>
<td></td>
</tr>
<tr>
<td>Operation temperature</td>
<td>-35 °C to +55 °C</td>
<td></td>
</tr>
</tbody>
</table>
Ground based measurements

Measurement time: noon to sunset

Comparison to simulation

187 wavelengths between 440 nm – 770 nm at elevations from 30 deg to 2 deg

Good correlation at 600 nm – 770 nm.
Mission 3 - Hello World

- In-orbit demonstration mission
- NIR spectral imager payload
  - 1000 – 1600 nm
  - 512 x 512 pixels
- RSL reusable CubeSat platform, 2-6U
- Reconfigurable software
- Linux application processor
- S-band user communications
- Launch: Q2/2018
Ground measurements for Hello World NIR/SWIR payload

SWIR hyperspectral imaging example - detecting person on a roof based on reflectance spectra:
Future plans
Asteroid Spectral Imager mission (ASPECT)

- 3U CubeSat capable of measuring from 500 nm to 2500 nm (can be extended to 3000 nm)
- Aims for measuring asteroid composition
- Instrument envelope: 1U
- 2 spectral imagers, VIS and NIR
- 1 SWIR spectrometer
- Includes the AOCS navigation camera

**VIS channel**
Based on Aalto-1 Spectral Imager
Spectral range: 500 – 900 nm
Image size: 614 x 614
Spectral bands: ca. 14

**NIR channel**
Spectral range: 900 – 1600 nm
Image size: 256 x 256 / 512 x 512
Spectral bands: ca. 24

**SWIR channel**
Spectral range: 1600 – 2500 nm
Image size: N/A (1 pixel)
Spectral bands: ca. 30
Summary and conclusions

▪ VTT has developed spectral imager solutions for UV, visible and infrared regions

▪ FPI-based technology enables small payload miniature hyperspectral imaging with CubeSats

▪ The technology is easily tailored for different mission needs

▪ Three missions to be flown in 2017 - 2018

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