Fabry-Perot Interferometer Hyperspectral Imaging Technology Transfer to Space Applications

8th ESA Round Table on Micro and Nano Technologies for Space Applications

Session 6: Optical Sensors & Actuators

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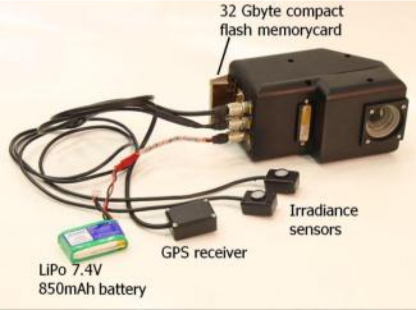
Outline

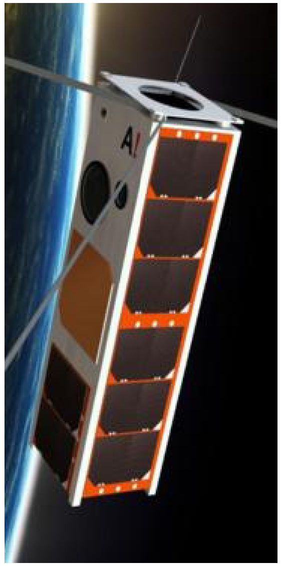
- Introduction and scope
- Classification of imaging spectrometers and Tunable filter spectral imaging concept
- Comparison of AOTF, LCTF and Fabry-Perot tunable filter technologies
- Concepts of staring imaging spectrometer for atmospheric studies (ALTIUS, SIMACC, PICASSO-VISION)
- VTT MEMS and Piezo-Actuated Fabry-Perot Interferometer (FPI) Technology overview
- Fabry-Perot Tunable Filter hyperspectral imager technologies and applications
- FPI Spectral imagers developed for light weight Unmanned Aerial Systems (UAS)
- On going development activities on FPI spectral imagers for Aalto-1 and PICASSO nanosatellites
- New MEMS Bragg mirror structures for LWIR (Long Wavelength Infrared) hyperspectral imagers
- What could FPI technology offer small and large scale earth observation satellites?
- SWIR&TIR Hyperspectral Imager based on a patterned multispectral filter integrated on an IR detector and multiple orders of Fabry-Perot Interferometer.
- Hyperspectral imager concept based on two Fabry-Perot Interferometers in series
- Conclusions

Introduction and scope 1(4)

- VTT Technical Research Centre of Finland has developed a miniaturized staring spectral imager based on Fabry-Perot Interferometer (FPI).
- Because of small size (~ 6 cm x 8 cm x 15 cm), low weight (~ 600 g) and small power consumption (~ 5 W) it is compatible with the light weight UAV platforms.
- The concept of the hyperspectral imager has been published in the SPIE Proc. 7474, 7680, 7668 and 8174. In forest and agriculture applications the recording of multispectral images at a few wavelength bands is in most cases adequate.
- The full UAS multispectral imaging system consists of a high resolution false color imager and a hyperspectral imager (λ= 400 – 1000 nm, 10…40 nm @ FWHM).
- The field of view of the hyperspectral imager is 36 x 48 degrees and ground pixel size at 150 m flying altitude varies from 5 to 25 cm.
- The UAS system has been tried in summer 2011 and 2012 in Southern Finland for the forest and agricultural areas.



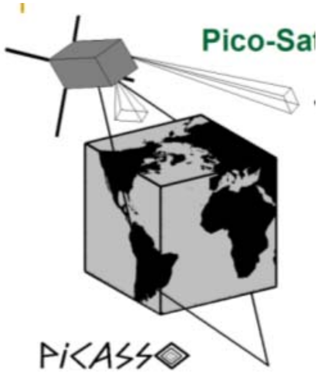
Introduction and scope 2(4)

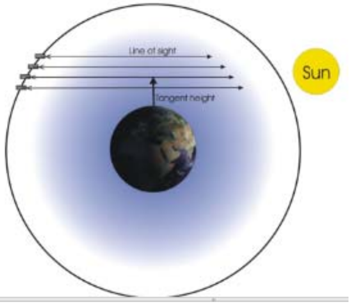


- The requirements of light weight UAV and space instruments are to large extent similar.
- Especially the new hyperspectral imaging technology suits well for the CubeSat satellites which have a volume of 34x10x10 cm3 and mass ~4 kg.
- The on-going activities to transfer the FPI hyperspectral imaging technology to space applications are the ESA activity “MEMS Fabry-Perot interferometer technology for miniaturized hyperspectral imagers and microspectrometers” (ref. ESA Contract No. 4000106267/12/NL/CP)

and

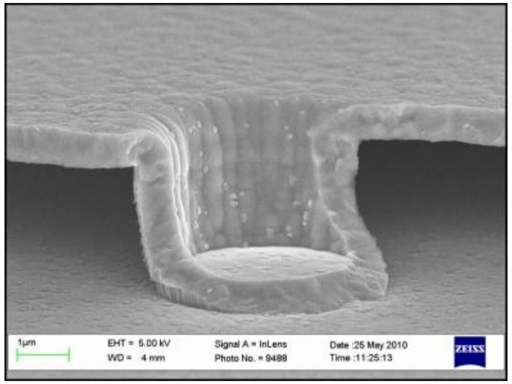
- the Belgian “Pico-Satellite for Atmospheric and Space Science Observations” PICASSO VISION Spectrometer.
- The spectral imager AaSI instrument will be developed and flown on the Aalto-1 satellite which will be described in the presentation of Näsilä et.al. in Session 11 of this conference.
- Fabry-Perot interferometer gap distribution measurement setup and results will be presented in session 11 by Akujärvi et.al.

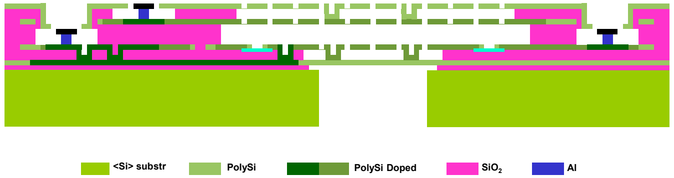


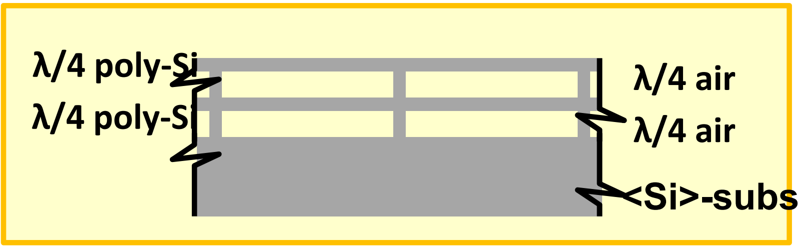


Introduction and scope 3(4)

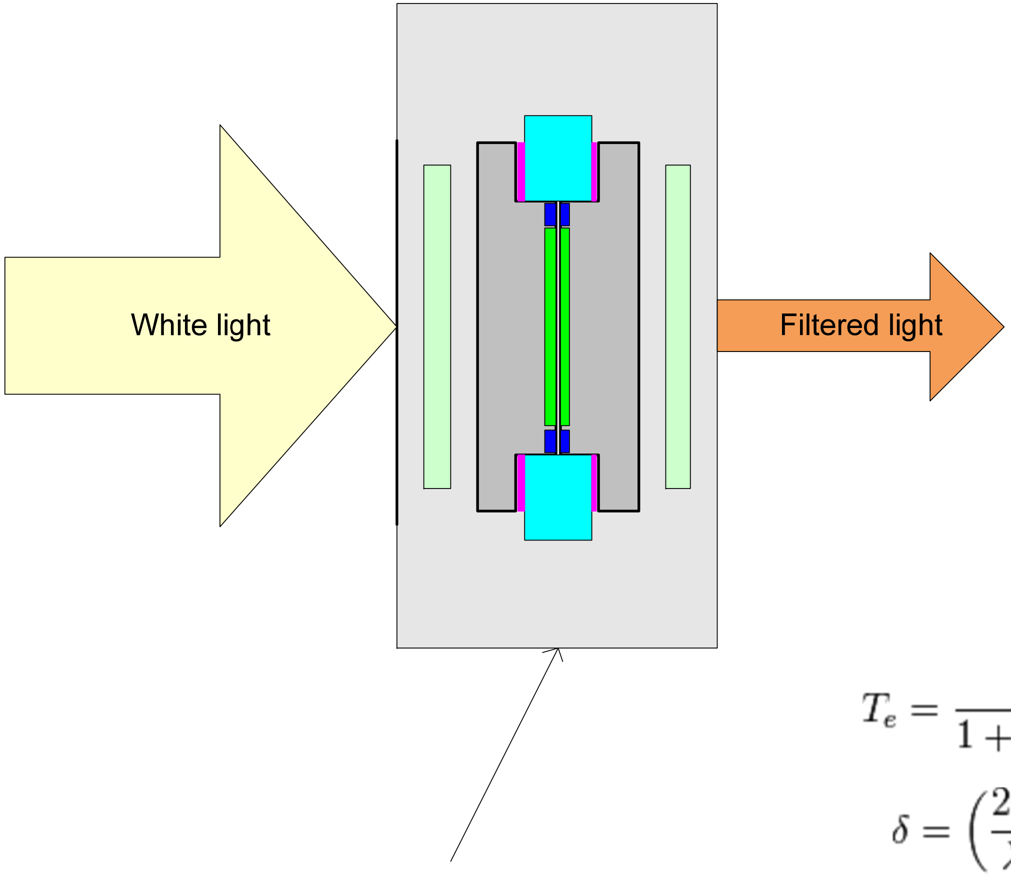
- VTT has developed new MEMS based Bragg mirror structure in which the dielectric materials are Poly-Silicon and air.
- The Poly-Si and Air dielectrics have large difference in dispersion and very low absorption making the ideal materials for Fabry-Perot Bragg Mirrors for Mid and Thermal Infrared.
- The FPI tunable filter combined with a RGB CMOS image sensor or with a customized Dichroic Filter Array (DFA) enables very compact hyperspectral imager instrument constructions.
- Using two or more Fabry-Perot interferometers in series it is possible to cover large wavelength range or achieve spectral resolution tunability using one FPI at low order (1 or 2) and the second FPI at a high order (typically 4…12).
- Fabry-Perot tunable filter hyperspectral imaging technology can be used in the detection of the target spectral signature using optical processing.
- A new “Target Specific Spectral Signature Instrument” (TASSI) concept will be described.
- Using two tunable FPI modules TASSI performs a spectral correlation operation in real time and stores only the end result
- TASSI approximates the spectral angle mapper (SAM) algorithm used in hyperspectral data processing.

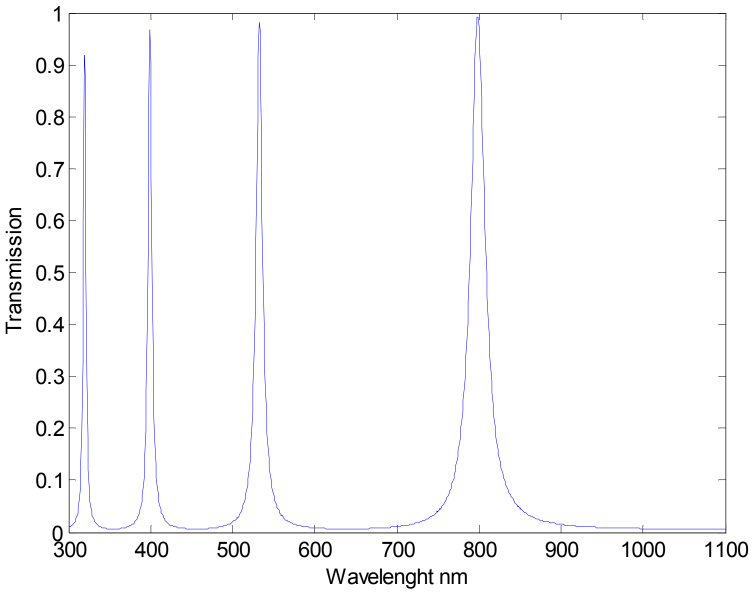






Introduction: how the FPI works 4(4)



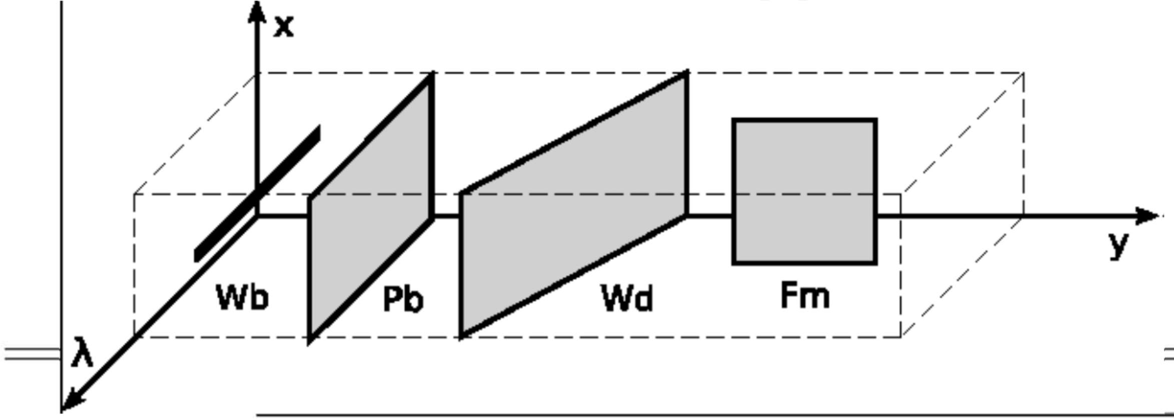


$$T_e = \frac{(1-R)^2}{1+R^2-2R\cos\delta} = \frac{1}{1+F\sin^2(\delta/2)},$$

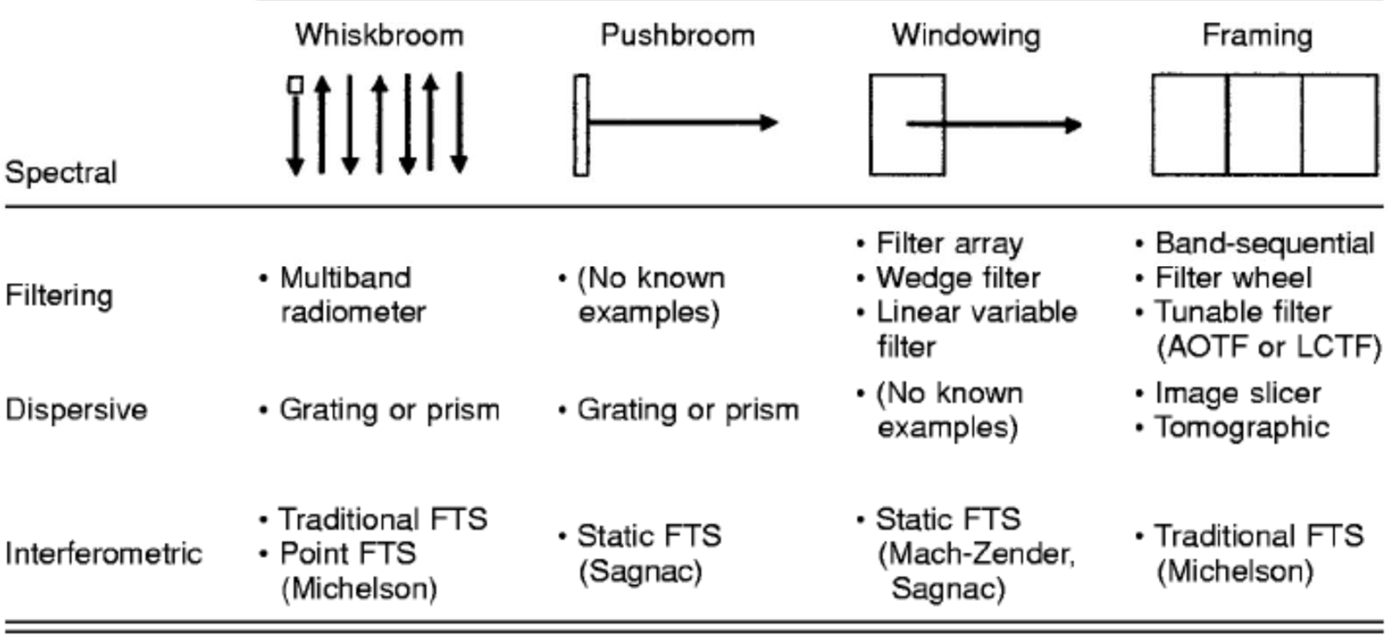
$$\delta = \left(\frac{2\pi}{\lambda}\right) 2n\ell\cos\theta.$$

Fabry-Perot
Interferometer Module

Classification of imaging spectrometers for remote sensing applications



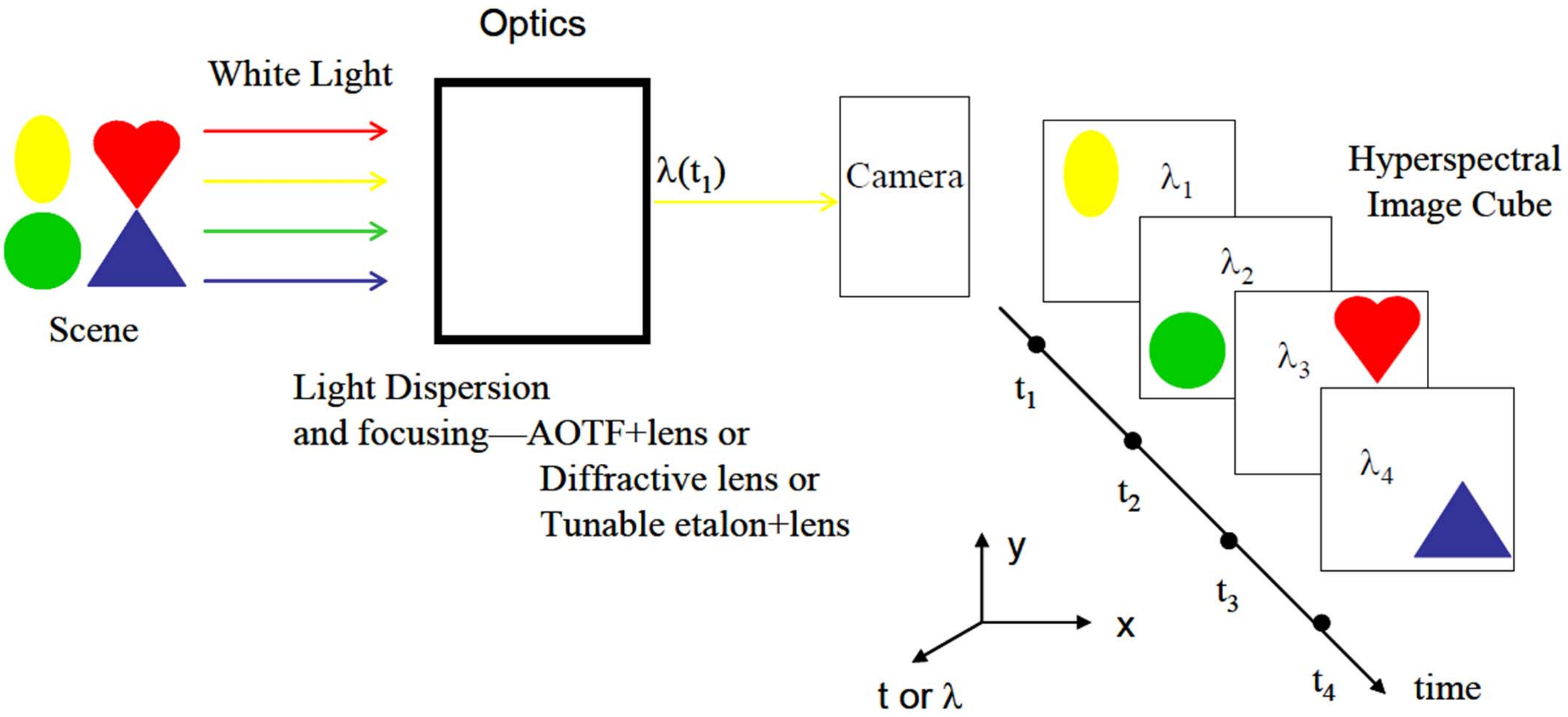
Ref. X. Prieto-Blanco, C. Montero-Orille, B. Couce, R. de la Fuente, “Optical configurations for Imaging Spectrometers, Comput. Intel. For Remote Sensing, SCI 133, pp. 1-25, 2008 Springer-Verlag, Heidelberg 2008.



Spectral	Whiskbroom	Pushbroom	Windowing	Framing
Filtering	• Multiband radiometer	• (No known examples)	• Filter array • Wedge filter • Linear variable filter	• Band-sequential • Filter wheel • Tunable filter (AOTF or LCTF)
Dispersive	• Grating or prism	• Grating or prism	• (No known examples)	• Image slicer • Tomographic
Interferometric	• Traditional FTS • Point FTS (Michelson)	• Static FTS (Sagnac)	• Static FTS (Mach-Zender, Sagnac)	• Traditional FTS (Michelson)

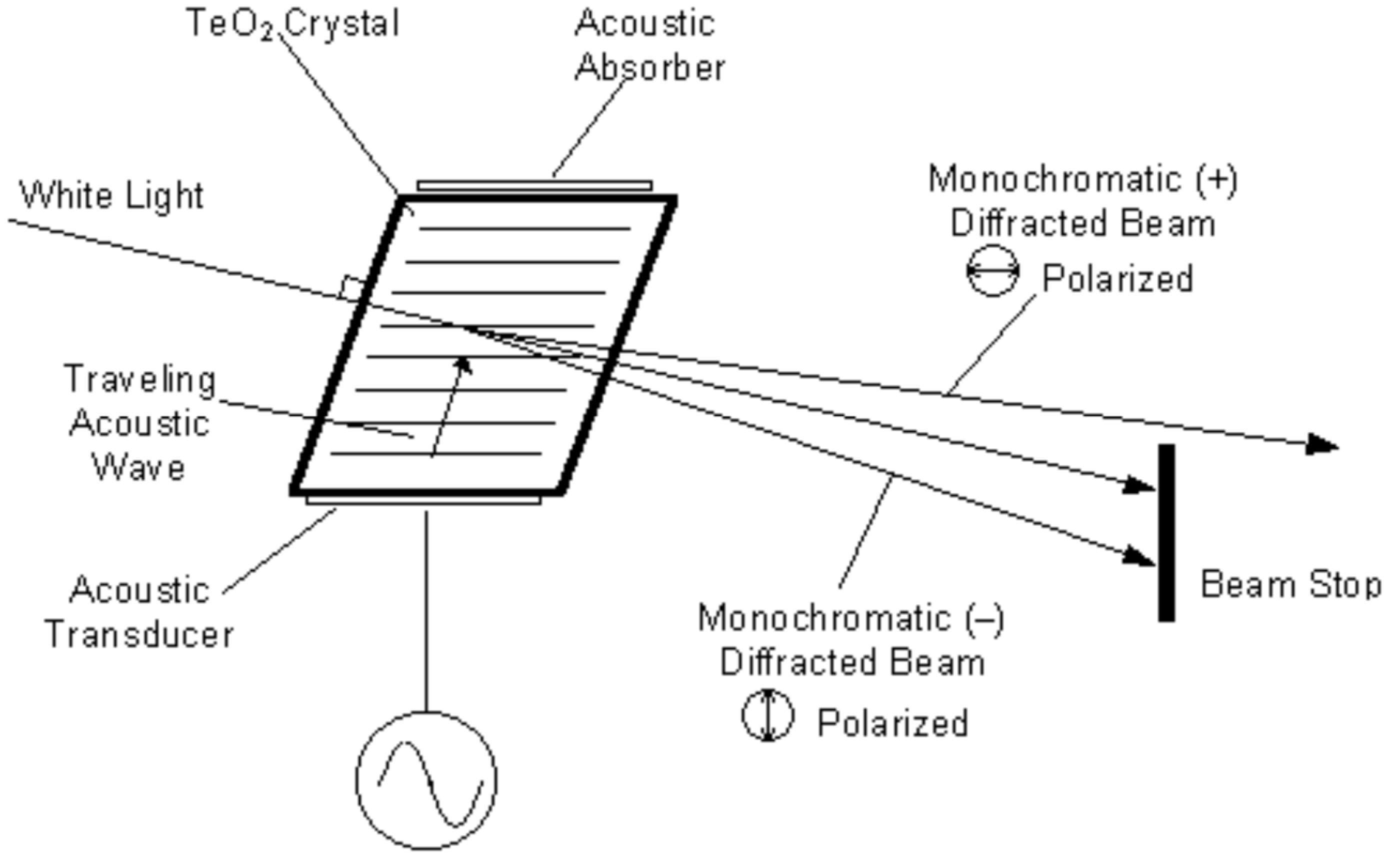
Ref. R. Sellar&G. Boreman, “Classification of imaging spectrometers for remote sensing applications“, Opt.Eng. 44(1), Jan 2005.

Tunable filter spectral imaging concept



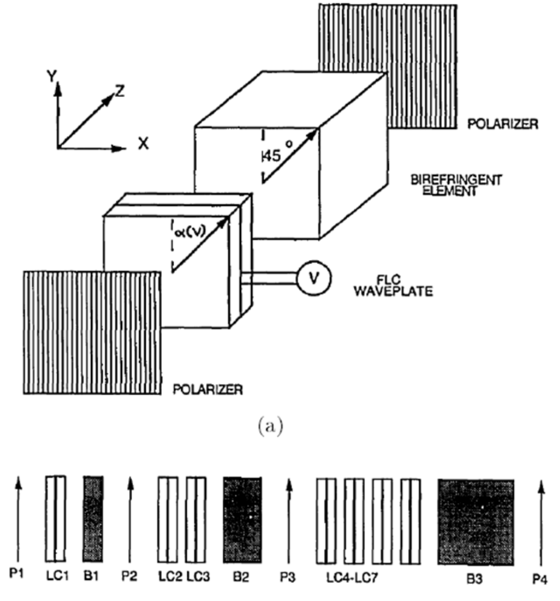
Ref. Hyperspectral imager development at Army Research Laboratory, Gupta et.al. Proc. of SPIE Vol. 6940 69401P-3, 2008. http://lib.semi.ac.cn:8080/tsh/dzzy/wsqk/SPIE/vol6940/69401P.pdf

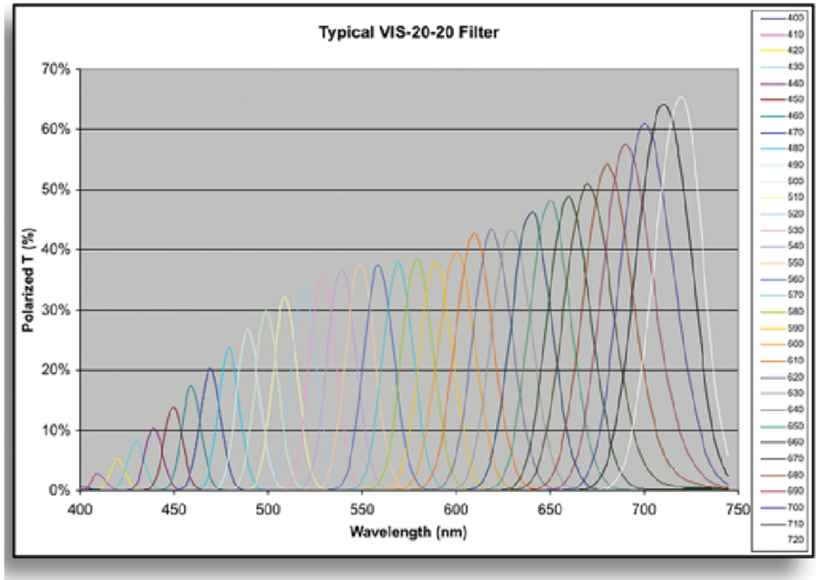
AOTF operation principle



LCTF operation principle

- The liquid crystal tunable Filter (LCTF) is based on a Lyot Filter, which is a stack of polarizers and tunable retardation liquid crystal plates.
- A typical time needed to change the pass band center wavelength in LCTF is 50 – 150 ms (ref. http://www.cri-inc.com/support/components.asp)
- Tuning range of one LCTF component is tin Visible 400—720 nm (selectable resolutions of 7-, 10-, or 20-nm @ FWHM).
- Transmission for unpolarized light is 5 – 30 %.
- The technology can be used for wavelength range 400 – 2500 nm although the transmission in Blue (400 – 500 nm) is rather limited.





Comparison of AOTF, LCTF and Fabry-Perot tunable filter technologies

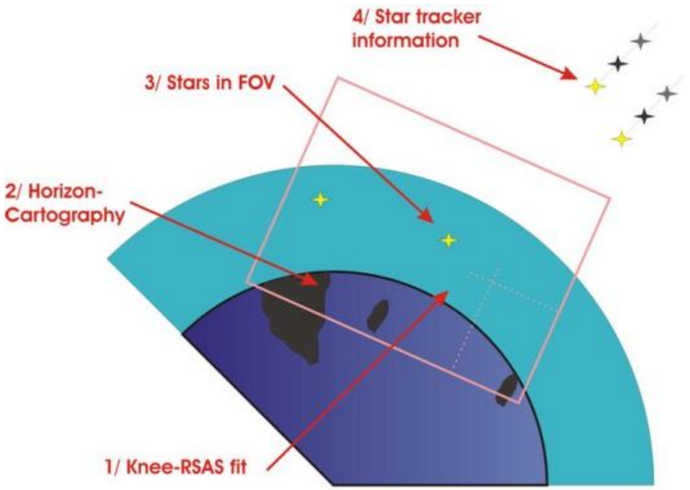
Parameter	**FPI, Fabry-Perot Interferometer**	**LCTF**	**AOTF tunable filter**	**Remarks**
Spectral ranges/resolution	[nm]	[nm]	[nm]	The spectral resolution of FPI spectrometer can be tuned with the selection of the order at which it is used.
UV	200 – 400/0.5…5	NA	200-400/0.5…2.0	
VIS-VNIR	400–1100/5…20	400–1100/5…20	400–1100/2…20	
NIR	900–2500/10…40	900–2500/10…40	900–2500/10…40	
MIR	2000–5000/20..80	NA	2000 – 4500/20…80	
LWIR	5000–15000/20…120	NA	NA	
F-number	2.0…3.0	2.0	4.0	
Transmission	>80 % diel. mirrors >25 % met. mirrors	30..75 %	70-85 %	
Polarization loss	No	50 %	50 %	
Relative light throughput	1.0 diel. mirrors 0.4 met. mirrors	0.47 @ 75 % transm. 0.19 @ 30 % transm.	0.13 @ 85 % transm. 0.11 @ 70 % transm.	
Speed	1 ms	50..150 ms	100 µs	spectral band change time
Size of spectral imager	50 mm x 50 mm x 120 mm	60 mm x 60 mm x 150 mm	50 mm x 50 mm x 200 mm	with fore optics, without camera
Image quality	G	G	M-G	

Why to use staring imaging spectrometer?

- Whisk- and Push-broom types of imaging spectrometers have been used in instruments like GOMOS, OMI and GOME.
- In these instruments the light is dispersed by means of a prism or by a diffraction grating.
- Push-broom instruments form a 2D image on a detector in which one axis represents the spectral and the other the spatial dimension, making it impossible to get an image of the atmospheric limb instantaneously.
- Originally the idea to use the entire detector as an imager of the atmospheric limb to solve the tangent altitude registration problem was proposed by ALTIUS team.
- In ALTIUS acusto-optical tunable filters (AOTF) were selected for the staring imaging spectrometer.
- In SIMACC instrument the tunable filters are proposed to be realized with MEMS or piezo-actuated FPI technology.
- The advantages of the FPI technology over AOTF are higher optical throughput and better flexibility in the wavelength range selection determined only through the mirror coating materials.

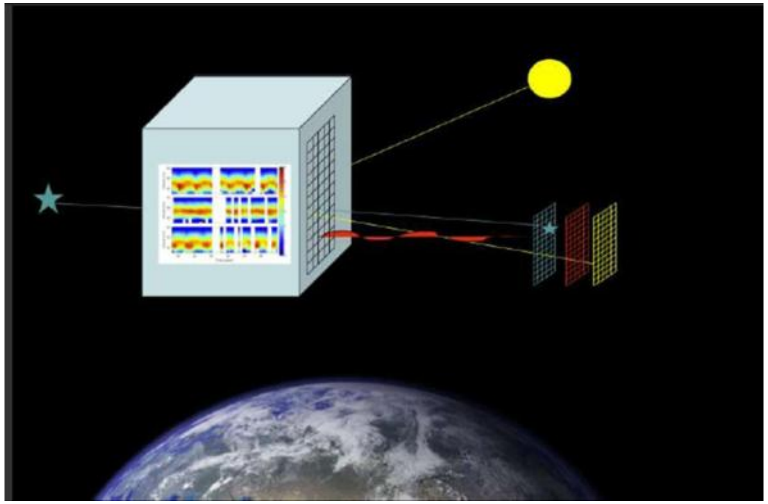
Concepts of tunable filter staring imaging spectrometer for atmospheric studies

Recently two initiatives to study atmosphere via staring imaging spectrometers has been started



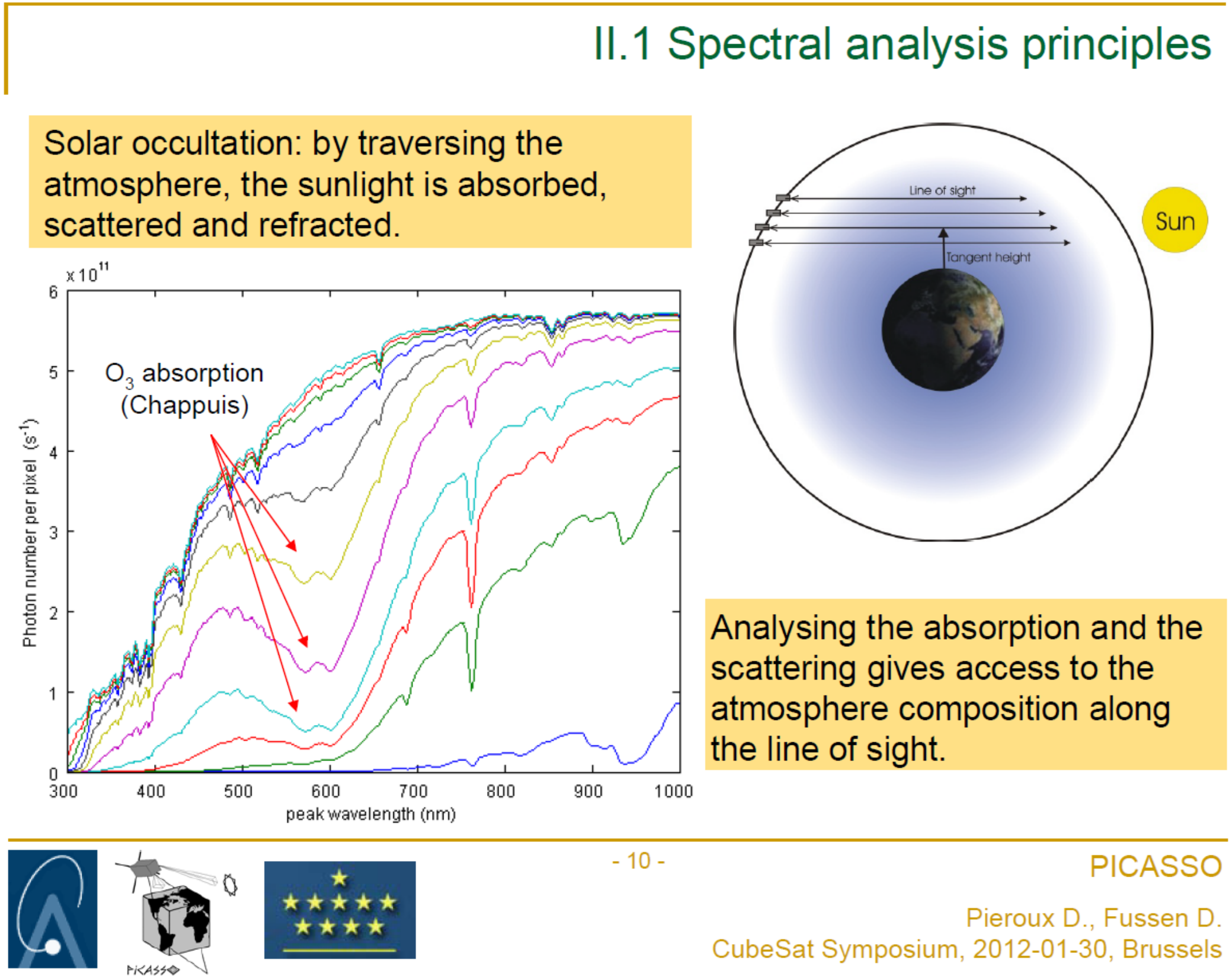
ALTIUS - Atmospheric Limb Tracker for the Investigation of the Upcoming Stratosphere, A Belgian space experiment for atmospheric sounding (PI: Dr. Didier Fussen, BISA, http://www.altius.oma.be)

and



SIMACC - Spectral Imaging of Middle Atmosphere for Climate Change. Proposal in the response of Call for Proposals for ESA Earth Explorer Opportunity Missions EE-8 (PI: Dr. Erkki Kyrölä, FMI)

PICASSO – VISION Concept



II.1 Spectral analysis principles

Solar occultation: by traversing the atmosphere, the sunlight is absorbed, scattered and refracted.

Analysing the absorption and the scattering gives access to the atmosphere composition along the line of sight.

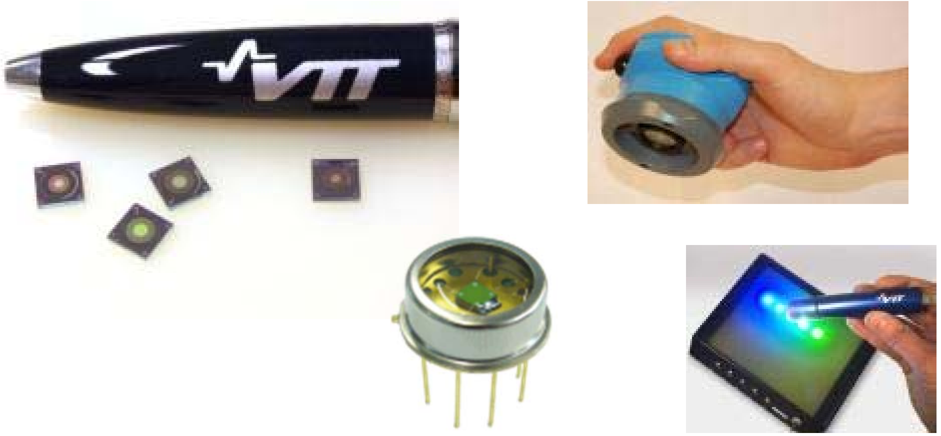
- 10 -

PICASSO

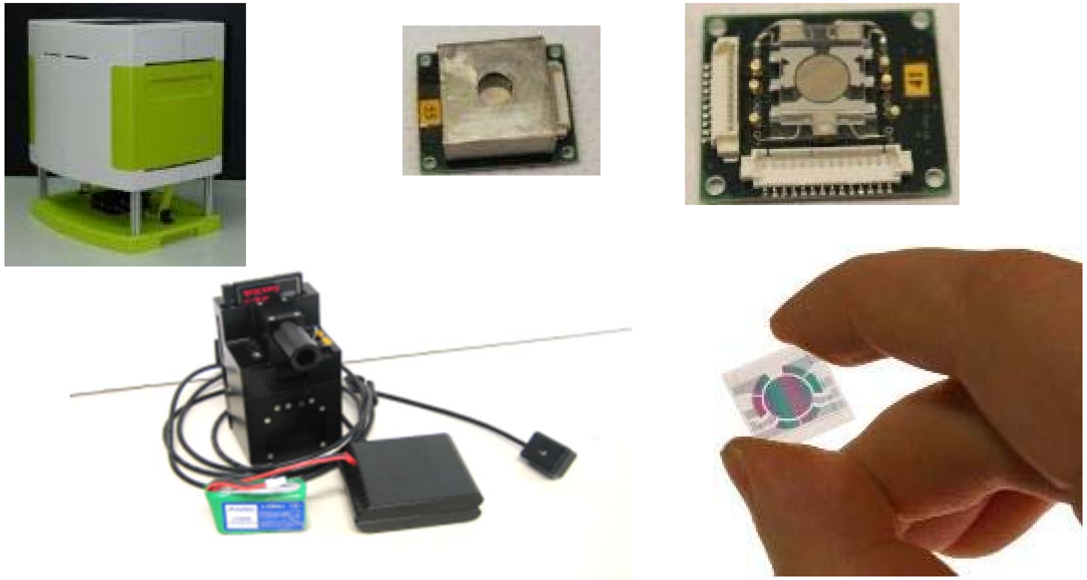
Pieroux D., Fussen D.
CubeSat Symposium, 2012-01-30, Brussels

The two VTT Fabry-Perot technologies

- **MEMS Fabry-Perot Interferometer**
    - For high volumes (>10’000/a)
    - Small, robust, inexpensive, batch-producible



- **PIEZO-actuated Fabry Perot Interferometer**
    - Especially for imaging and multipoint applications
    - Assembled ’one-by-one’
    - For small to medium volumes (10 – 1’000 /a)



General Principle of VTT's Surface Micro-Machined MEMS FPI Structure

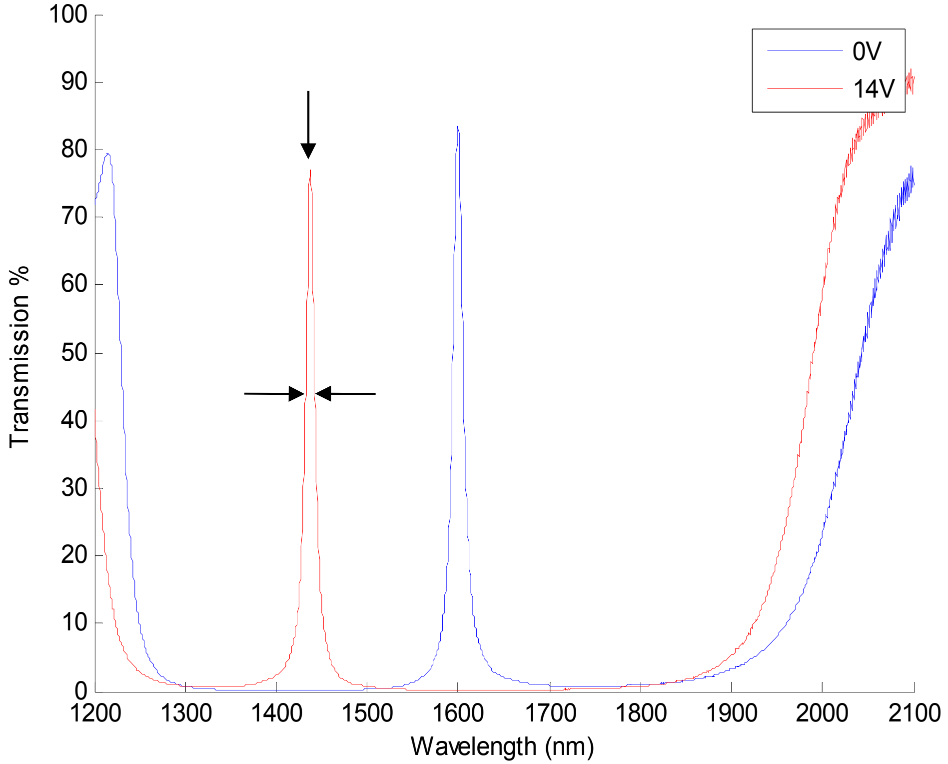
Upper mirror acts as a tensioned membrane → enables:

- Large optical apertures up to millimeters in diameter
- High level of mirror flatness
- Very high nominal frequencies, ~ 1 MHz (insensitive to vibrations)
- No gravitational effects
- Low operation voltages

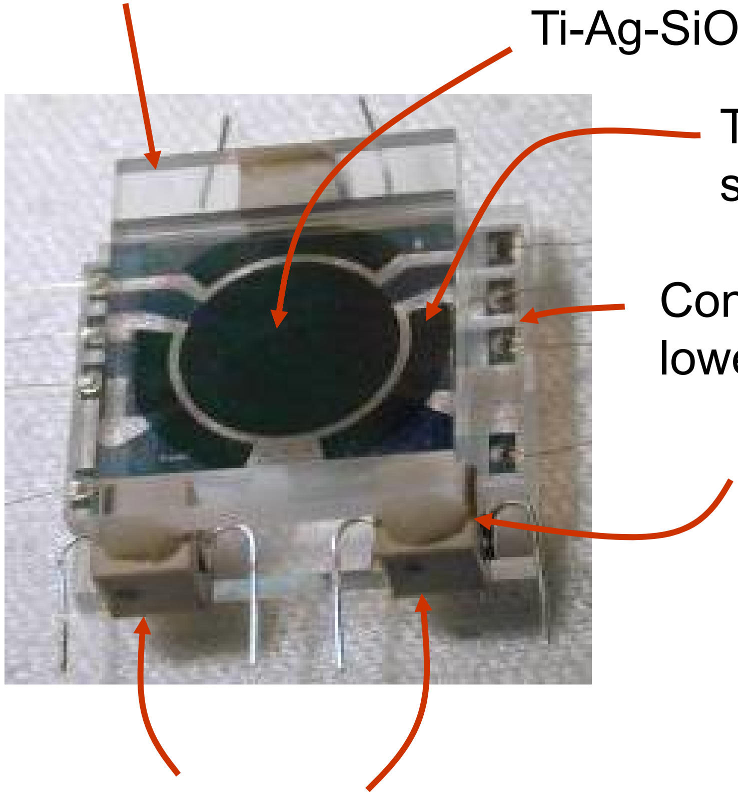
Tunability of Pass-Band

- Transmission peak can be tuned by voltage within ±10 % of the selectable center wavelength
    - Voltages typically 0 - 30V
- Maximum transmission typically > 80 %
- Width of the transmission peak depends
    - on the wavelength range,
    - order of interference and
    - mirror quality
- Typical peak widths
    - 3 - 7 nm for VIS
    - 10 - 25 nm for NIR

Example measurement



The Piezo-actuated Fabry-Perot Interferometer component and its controlling



Fused silica substrate

Ti-Ag-SiO_2 coating

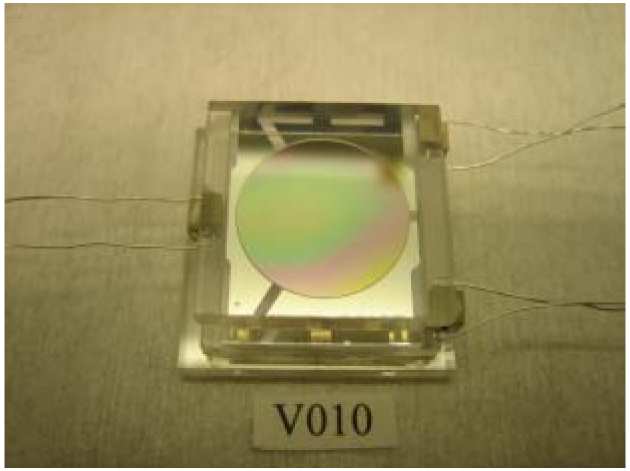
Three electrodes,
split capacitances

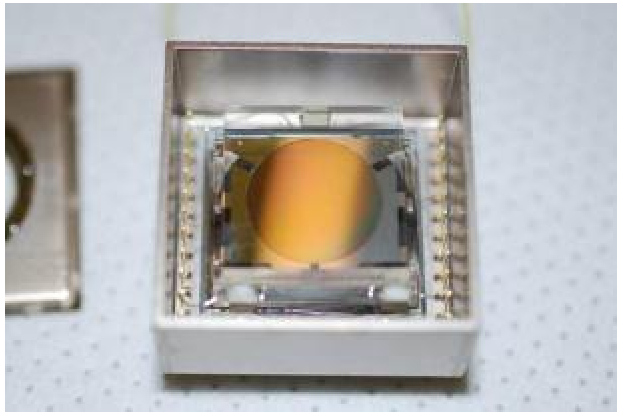
Contact pads only on
lower substrate

UV-curable glue

Commercial piezo-actuators

=> FPI cavity stays parallel

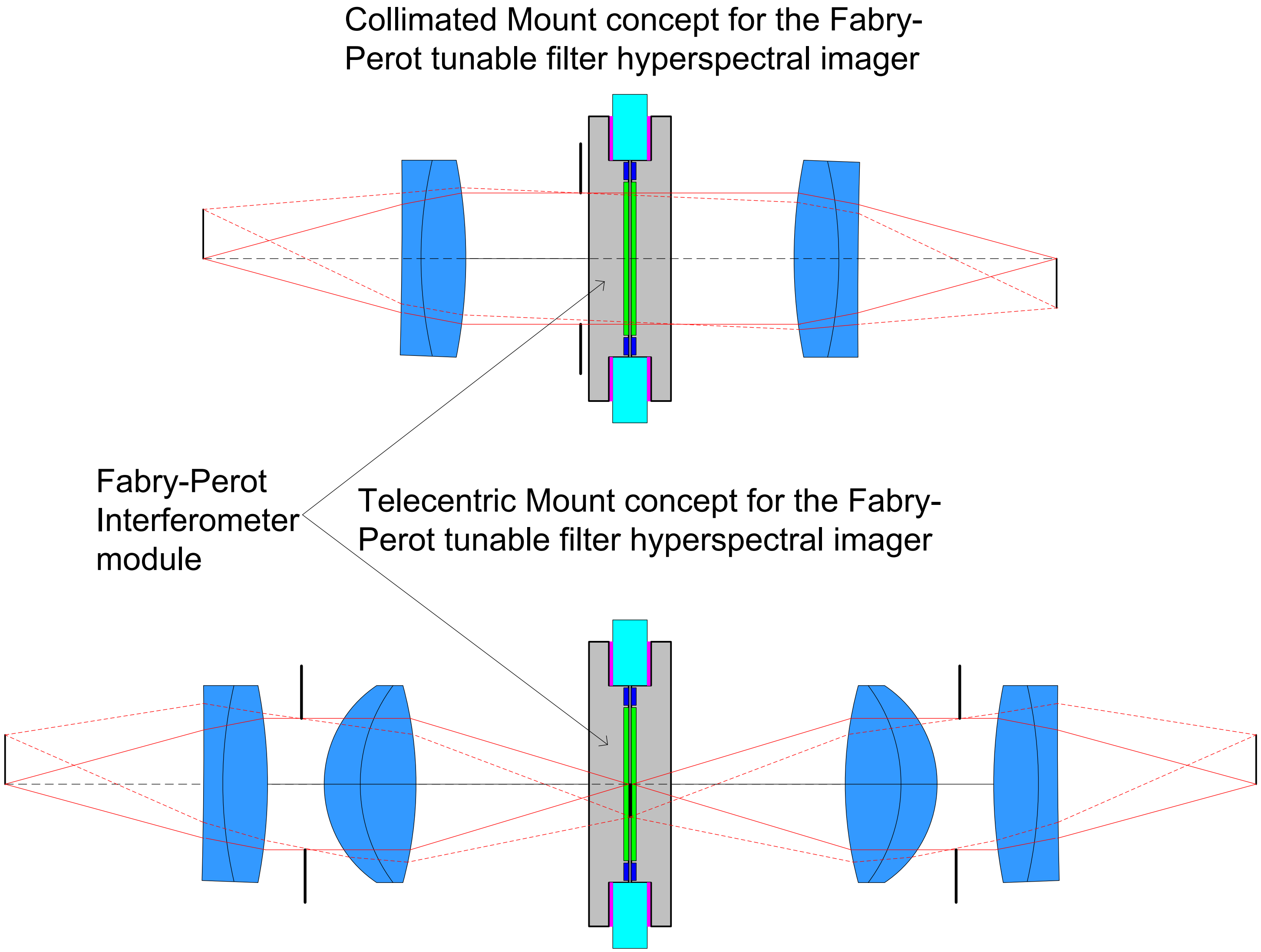




Hermetically packaged
Piezo actuated FPI

Fabry-Perot Tunable Filter hyperspectral imager concepts

- The collimated mount provides highest spectral resolution but there is a minor wavelength shift across FOV.
- The telecentric mount does not show wavelength shift across FOV but the spectral resolution is decreased because the optical beam gone angle is larger than in the collimated mount.



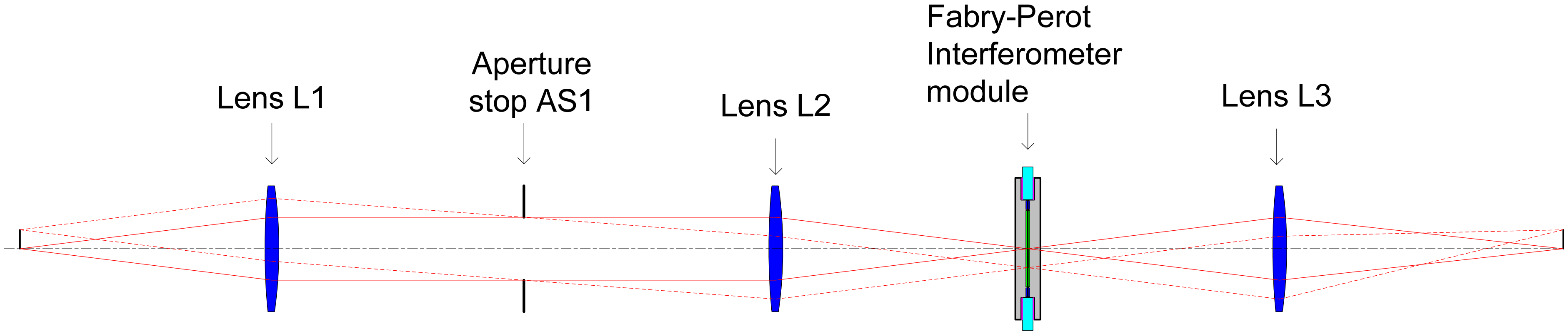
Collimated Mount concept for the Fabry-Perot tunable filter hyperspectral imager

Fabry-Perot Interferometer module

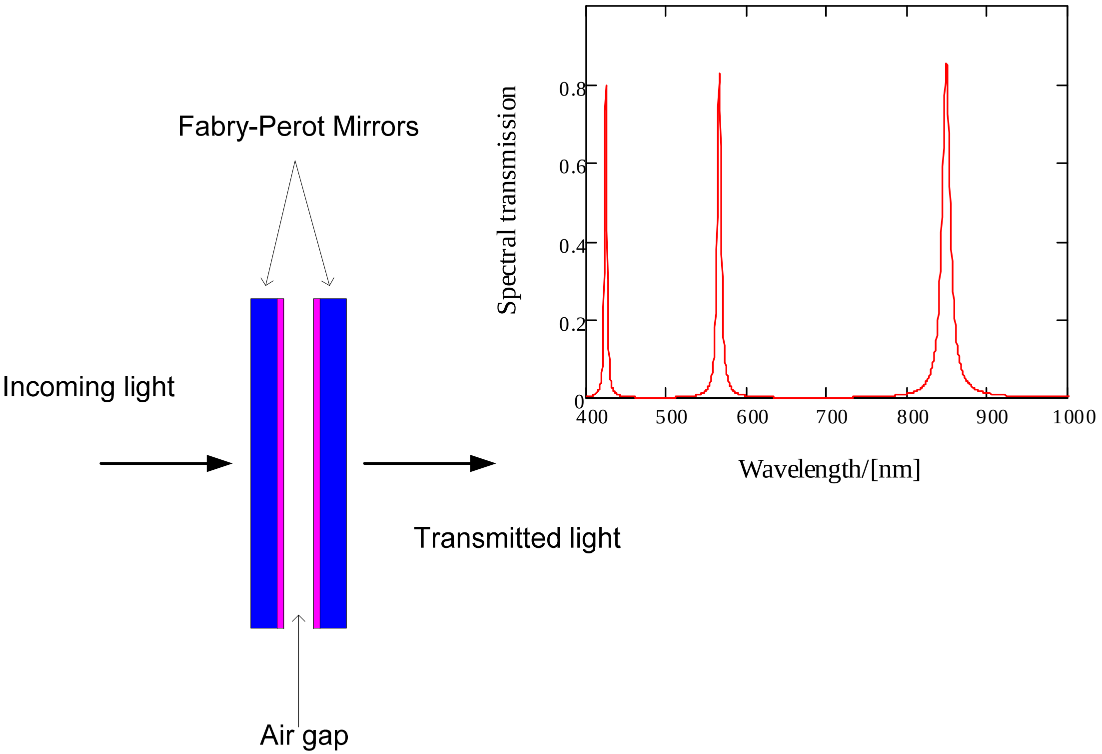
Telecentric Mount concept for the Fabry-Perot tunable filter hyperspectral imager

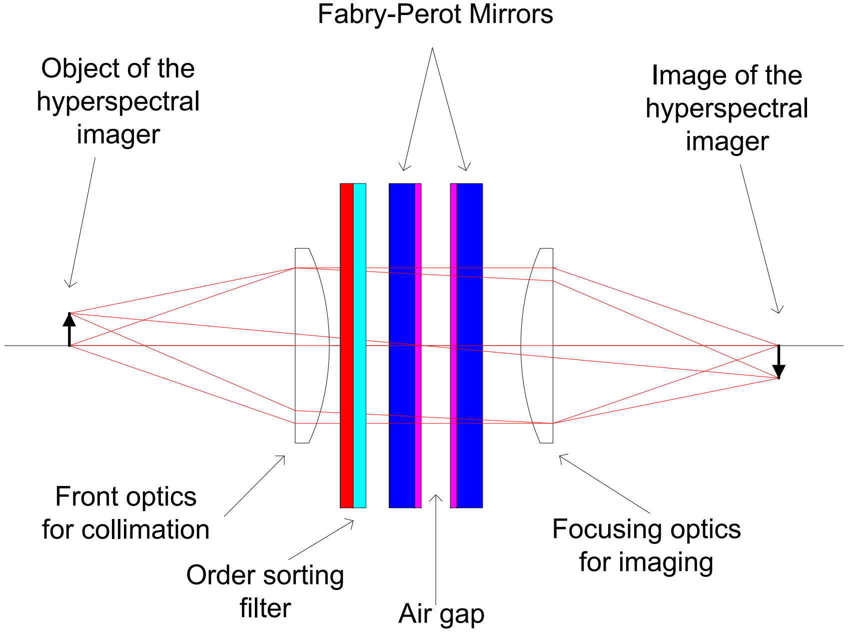
Telecentric configuration of the Fabry-Perot Tunable filter hyperspectral imager

- The optics is designed in such a way that the rays go through the FPI as a focused beam the same gone angle for each pixel in the image.
- So there is no wavelength shift across the Field-of-View assuming the air gap does not have variation over the FPI aperture.
- The telecentric optics requires more space and mass budget that the collimated beam concept.



Fabry-Perot Interferometer principle and its typical spectral transmission for orders 2, 3 and 4 with an air gap of 0.85 µm





The Fabry-Perot Interferometer based spectral imager concept.

AaSI Instrument Concept: Fabry-Pérot interferometer (FPI) combined with a RGB CMOS image sensor

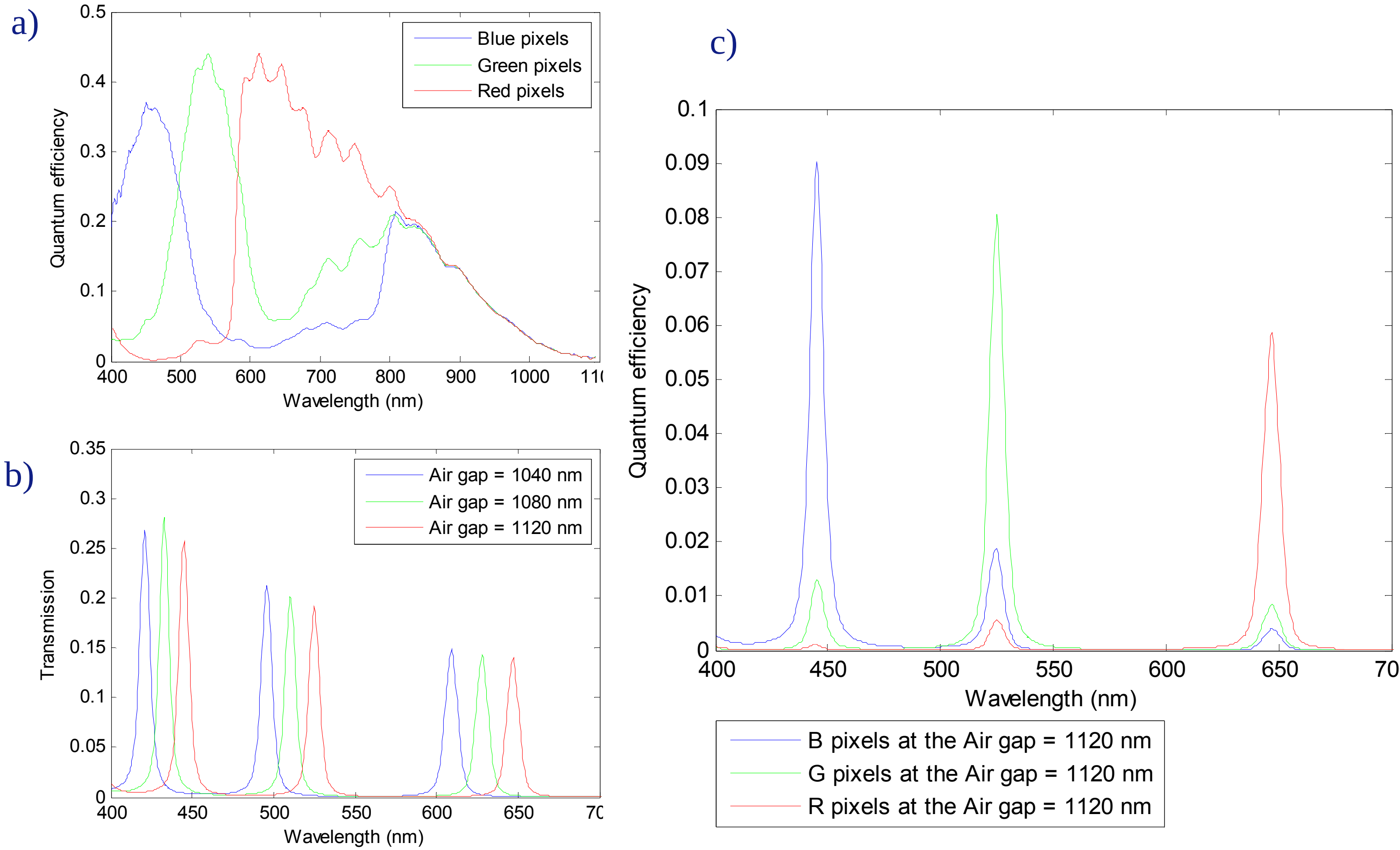


Figure 2. The quantum efficiency of the CMV4000 sensor, the FPI transmission and the total quantum efficiency of CMV4000 – FPI combination.

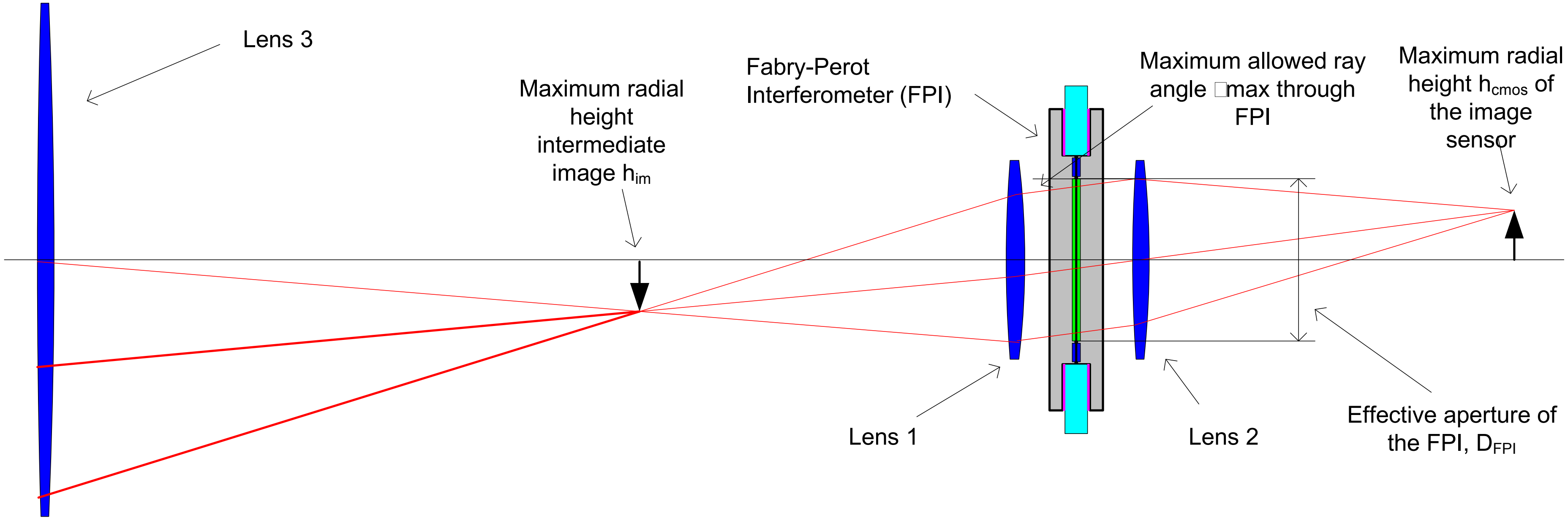
Collimated mount FPI based spectral camera F-number and throughput 1(4)

An ideal lens with focal length of f_{lens1} collimates the rays coming from an object with a height h_{im} and the angle of the collimated beam is θ_{max}. In the case of relay optics at magnification of 1 the $h_{im} = h_{cmos}$ which is the maximum radial height of the image sensor. It is now possible to calculate the focal length of the Lens 1

$$f_{Lens1} = \frac{h_{cmos}}{\tan(\theta_{\max})} \qquad \text{Eq. 1}$$

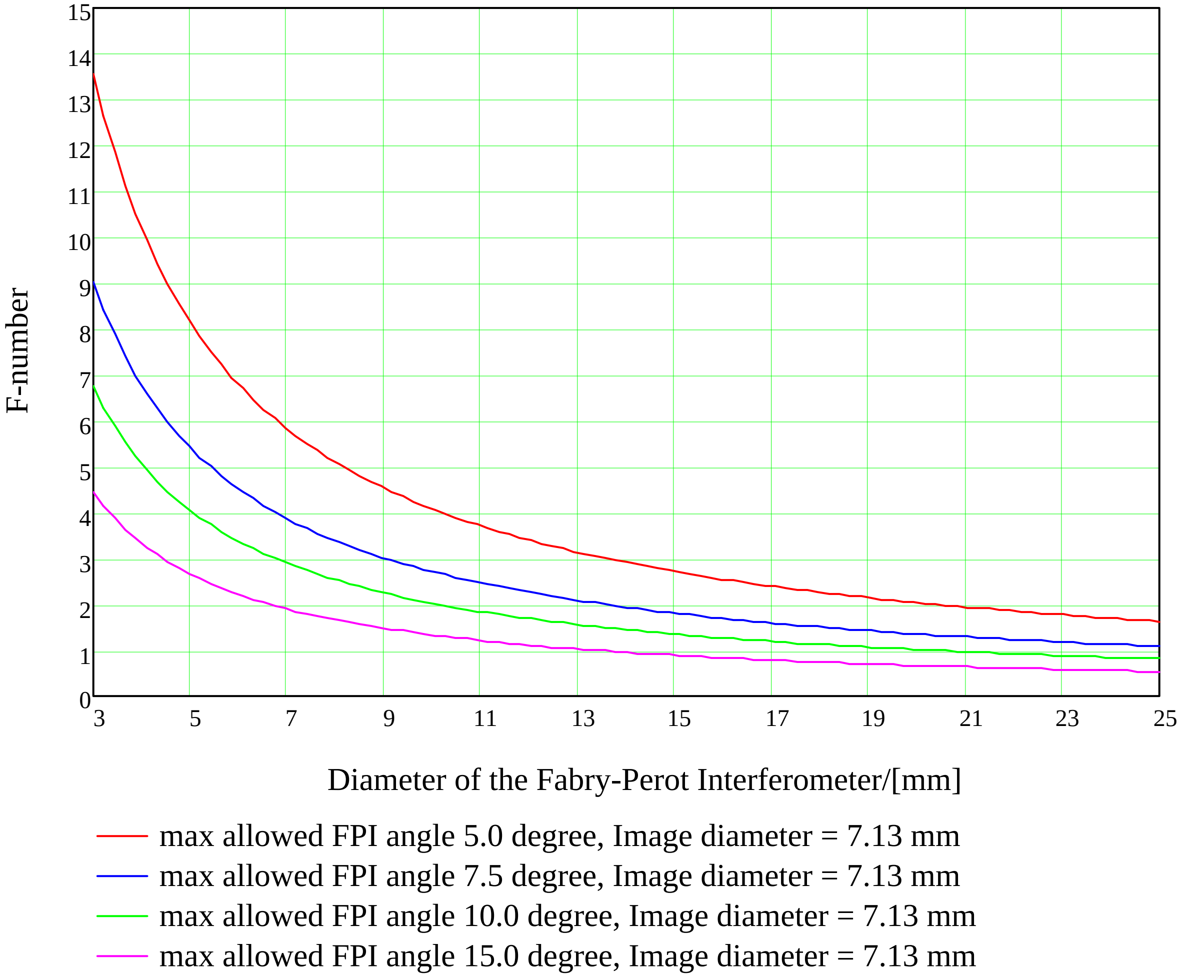
The maximum effective aperture of the lens 1 can be approximated by the effective diameter of the FPI module D_{FPI}. The F-Number of the FPI spectral camera Fn_{sys1} is given by

$$Fn_{sys1} = \frac{h_{cmos}}{D_{FPI} \cdot \tan(\theta_{\max})} \qquad \text{Eq. 2}$$



FPI based spectral camera F-number and throughput 2(4)

- It is possible to lower the F-number by using a larger FPI diameter and by increasing the max allowed FPI ray angle.
- The F-number as low as 1.0 can be achieved with 15 mm FPI diameter and 10 degree max FPI angle.
- This makes it possible to manufacture Hyperspectral imager with weight < 400 g for Vis-VNIR with F-number 1.0 and spectral resolution < 10 nm @ FWHM

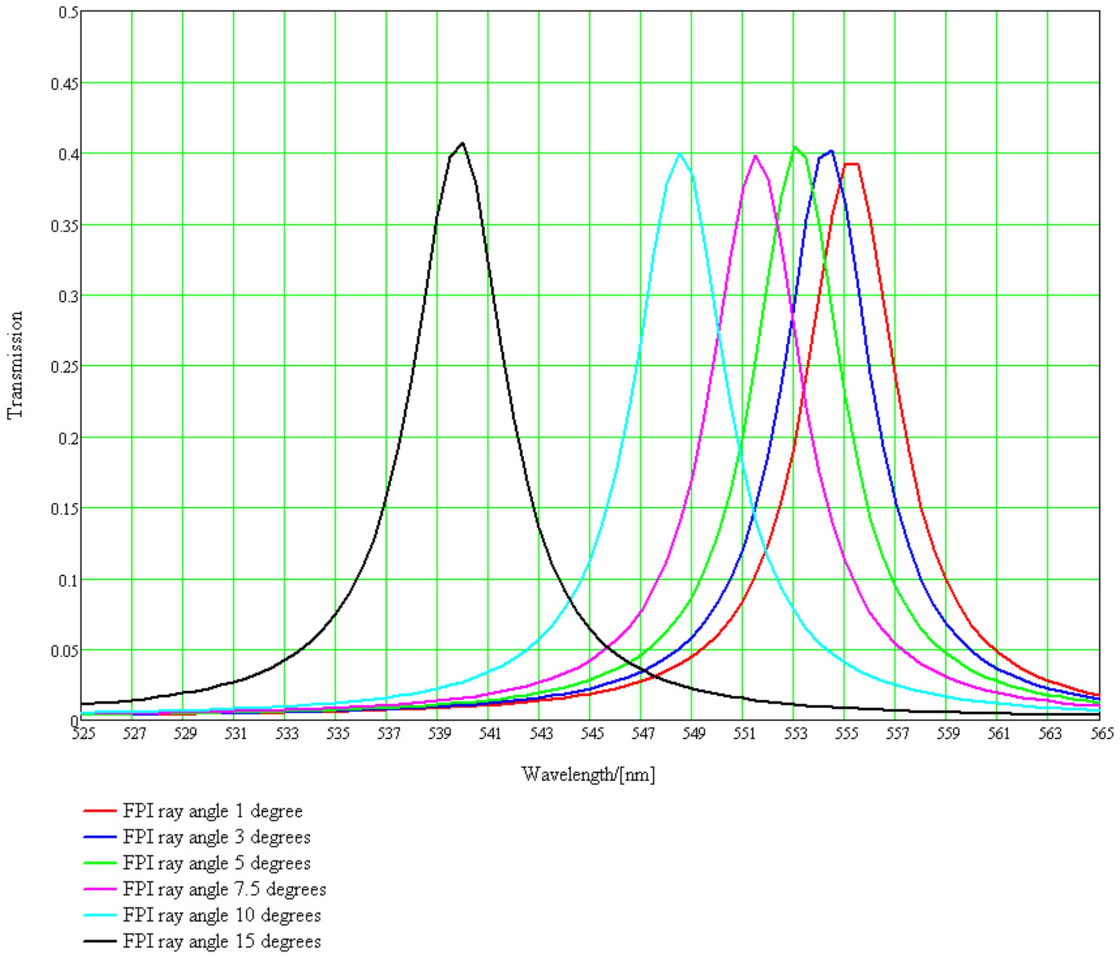


FPI based spectral camera F-number and throughput 3(4)

- The FPI ray angle affects the center wavelength of the FPI spectral peak. In the first approximation the peak wavelength is linearly dependent on the cosine of the ray angle.

$$\lambda_0 = \frac{m \cdot d \cdot \cos(\theta)}{2} \quad , \ m=1,2\ldots.$$

- The optics can be designed in such a way that the rays go through the FPI as a collimated beam for a specific pixel of the image.
- So for the measurement of continuous spectrum the large FPI ray angles can be used because the spectral resolution is not affected by the FPI ray angle



Transmission through Fabry-Perot Interferometer at 1,3, 5, 7.5, 10 and 15 degree entrance angle.

FPI based spectral camera F-number and throughput conclusions 4(4)

- The lowest F-numbers for existing push broom instruments are in the range 2.0….2.8 and the average transmission of the spectrograph is around 50% with peak transmission 70..80%.
- The FPI spectral imager average transmission with metal mirrors is around 25 % and 80 % with dielectric mirrors and lowest F-number in the range 1.0…1.8.

The throughput of FPI spectral imager can be higher than the throughput of push broom instruments if continuous spectrum is to be measured.

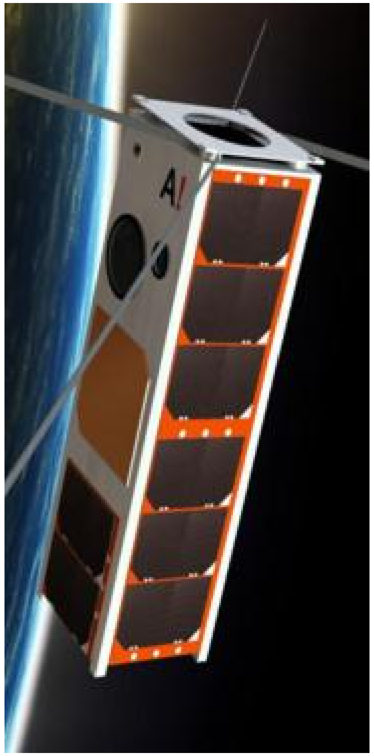
Overview of VTT Hyperspectral imaging technologies and applications

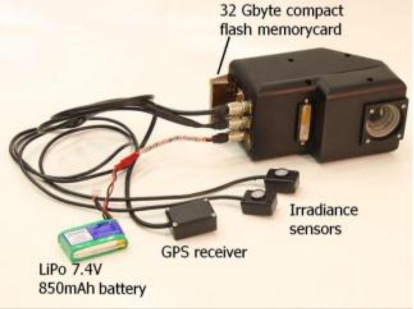
Technology :

- Fabry-Perot Interferometer tunable filter spectral imager offers fast way to acquire target images at multiple spectral bands adapted to the application.
- The size, mass and power consumption of the spectral imager are low.
- Spectral imager is compatible with light weight UAVs

Wide application areas :

- Medical Imaging
- Crop monitoring for fertilizer and pesticide optimization
- Forest inventory with UAVs and standard aircraft.
- Environmental monitoring with UAVs for natural water resources, deforestation etc.
- Remote sensing of atmosphere, sea and ground from Nanosatellites





Why use UAV?

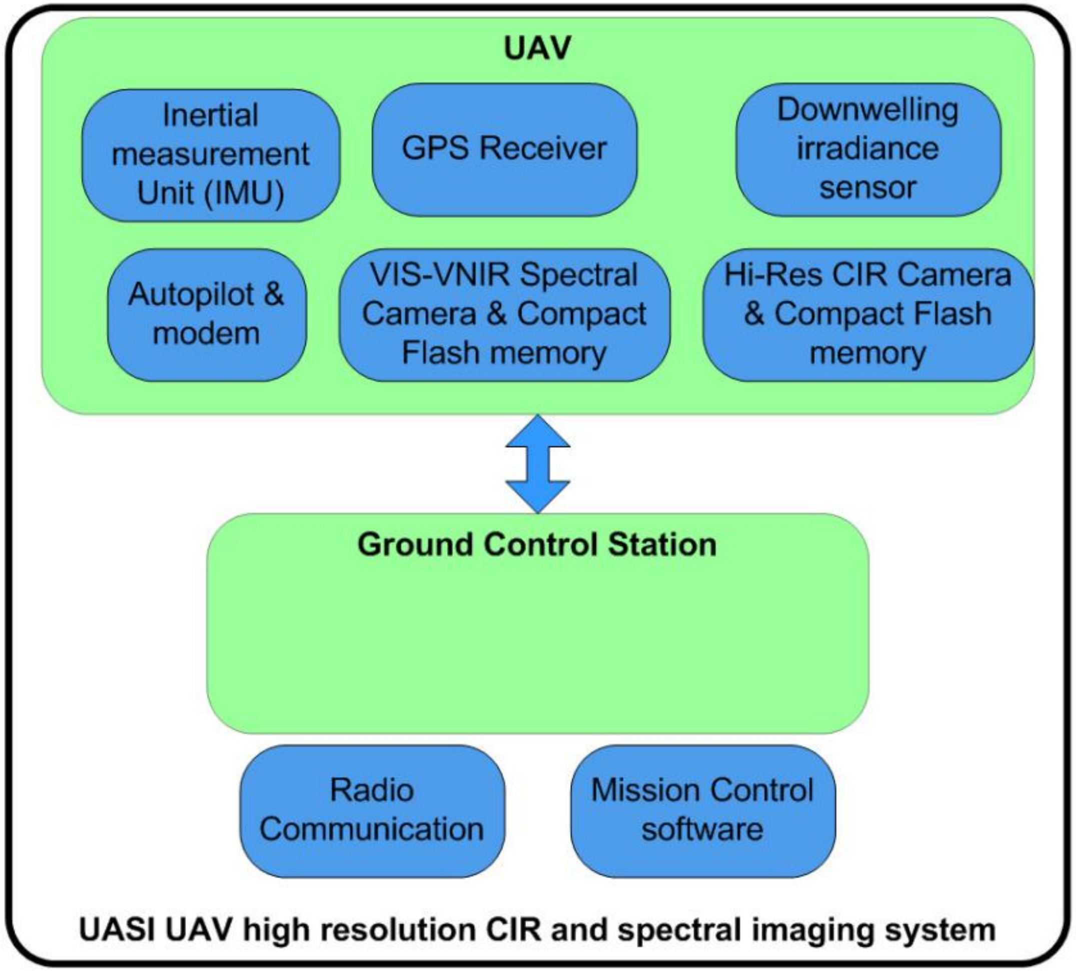
From aircraft to UAV

- High spatial resolution 2..5 cm
- Easy access to imagery
- Temporal resolution few days
- Lower cost

From Push-broom imager to new tunable filter device

- Weight from 20 kg to 1 kg
- No need for stabilized mount
- Several imagers on same flight (Thermal imager+Hyperspectral or CIR+Hyperspectral)
- Lower cost

VTT UASI imaging system used in forest and agriculture UAV flight campaigns in 2011 and 2012



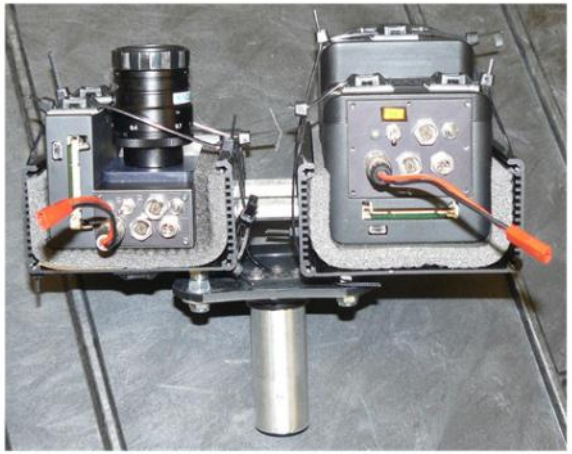
UAV

- Inertial measurement Unit (IMU)
- GPS Receiver
- Downwelling irradiance sensor
- Autopilot & modem
- VIS-VNIR Spectral Camera & Compact Flash memory
- Hi-Res CIR Camera & Compact Flash memory

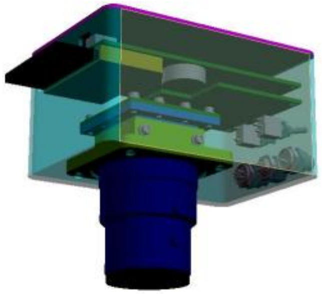
Ground Control Station

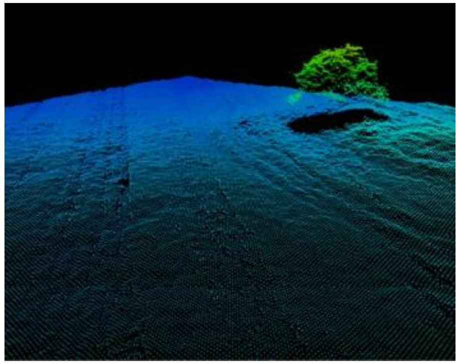
- Radio Communication
- Mission Control software

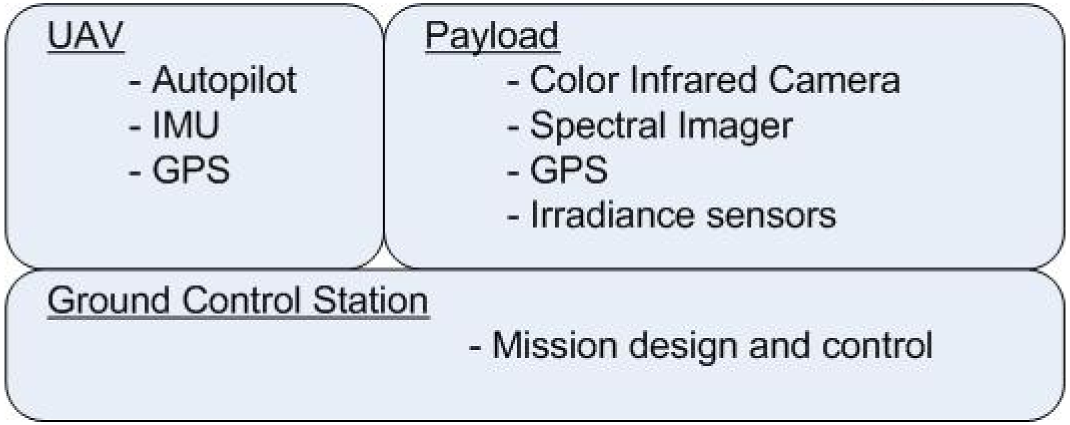
UASI UAV high resolution CIR and spectral imaging system



UASI 2012 imaging system



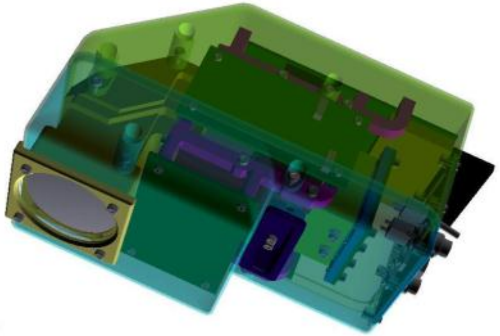


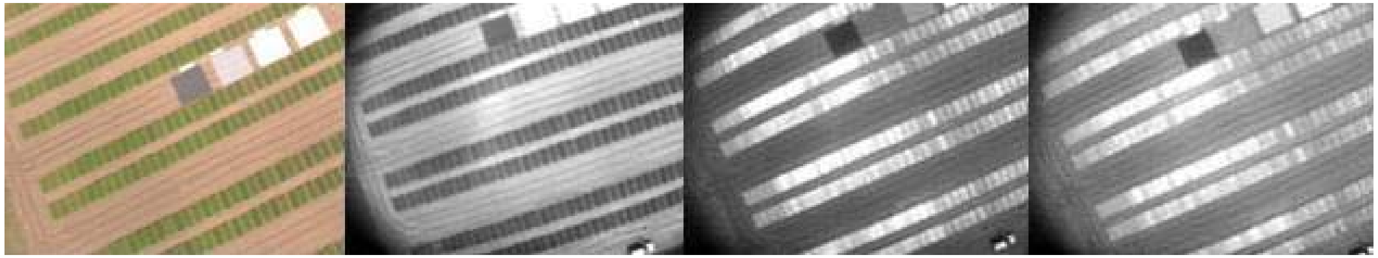


UAV
- Autopilot
- IMU
- GPS

Payload
- Color Infrared Camera
- Spectral Imager
- GPS
- Irradiance sensors

Ground Control Station
- Mission design and control





UAV imaging system used for Crop monitoring in Summer 2012

- Mikrokopter UAV, > 1000 g payload
- Hyperspectral imaging: Updated Fabry-Perot interferometer based camera prototype by the VTT Technical Research Finland: UASI=Unmanned Aerial System Innovations
  - 1024 x 648 pixels, Pixel size: 11 µm, F=11 mm, FoV: 54º, 34º, fstop < 2.7
  - Desired spectral channels by changing the FPI interferometer air gap during a short time interval (50 channels in 1.5 s)
- High spatial resolution imaging: VTT developed CIR (Color Infared) Camera
  - 2048x2048 pixels, Pixel size 5.5 µm, F=16 mm, FOV: 39º, 39º
  - 4 different exposure times used for higher dynamic range

UASI Hyperspectral Imager 2012 prototype

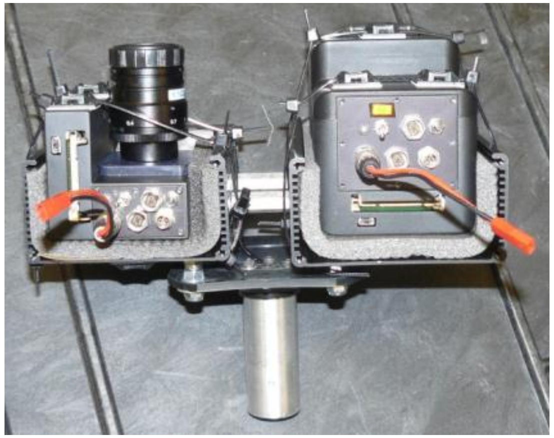
UASI CMV4000 CIR Camera, GPS receiver batteries, etc.

Mikrokopter UAV with UASI imagers

UAV imaging system used for forest monitoring in Summer 2012 1(2)

- Infotron IT180 UAV, > 5000 g payload
- Hyperspectral imaging: Updated Fabry-Perot interferometer based camera prototype by the VTT Technical Research Finland: UASI=Unmanned Aerial System Innovations
  - 1024 x 648 pixels, Pixel size: 11 µm, F=11 mm, FoV: 54º, 34º, fstop < 2.7
  - Desired spectral channels by changing the FPI interferometer air gap during a short time interval (50 channels in 1.5 s)
- High spatial resolution imaging: VTT developed CIR (Color Infared) Camera
  - 2048x2048 pixels, Pixel size 5.5 µm, F=16 mm, FOV: 39º, 39º
  - 4 different exposure times used for higher dynamic range

UASI Hyperspectral Imager 2012 prototype

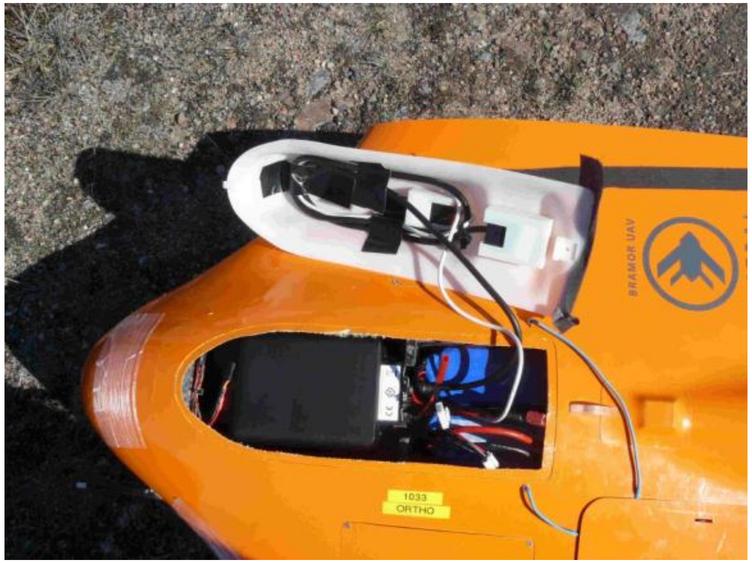


UASI Proto-2B Hyperspectral imager and CMV4000 CIR camera

Infotron IT180 with UASI imagers 22.5.2012

UAV imaging system used for forest monitoring in Summer 2012 2(2)

- Bramor Ortho, > 600 g payload
- Hyperspectral imaging: Updated Fabry-Perot interferometer based camera prototype by the VTT Technical Research Finland: UASI=Unmanned Aerial System Innovations
  - 1024 x 648 pixels, Pixel size: 11 µm, F=11 mm, FoV: 54º, 34º, fstop < 2.7
  - Desired spectral channels by changing the FPI interferometer air gap during a short time interval (50 channels in 1.5 s)
- High spatial resolution imaging: Olympus E-420 in CIR mode, 3648 x 2736 pixels, Pixel size 4.7 µm, F=25 mm, FOV: 38º, 29º

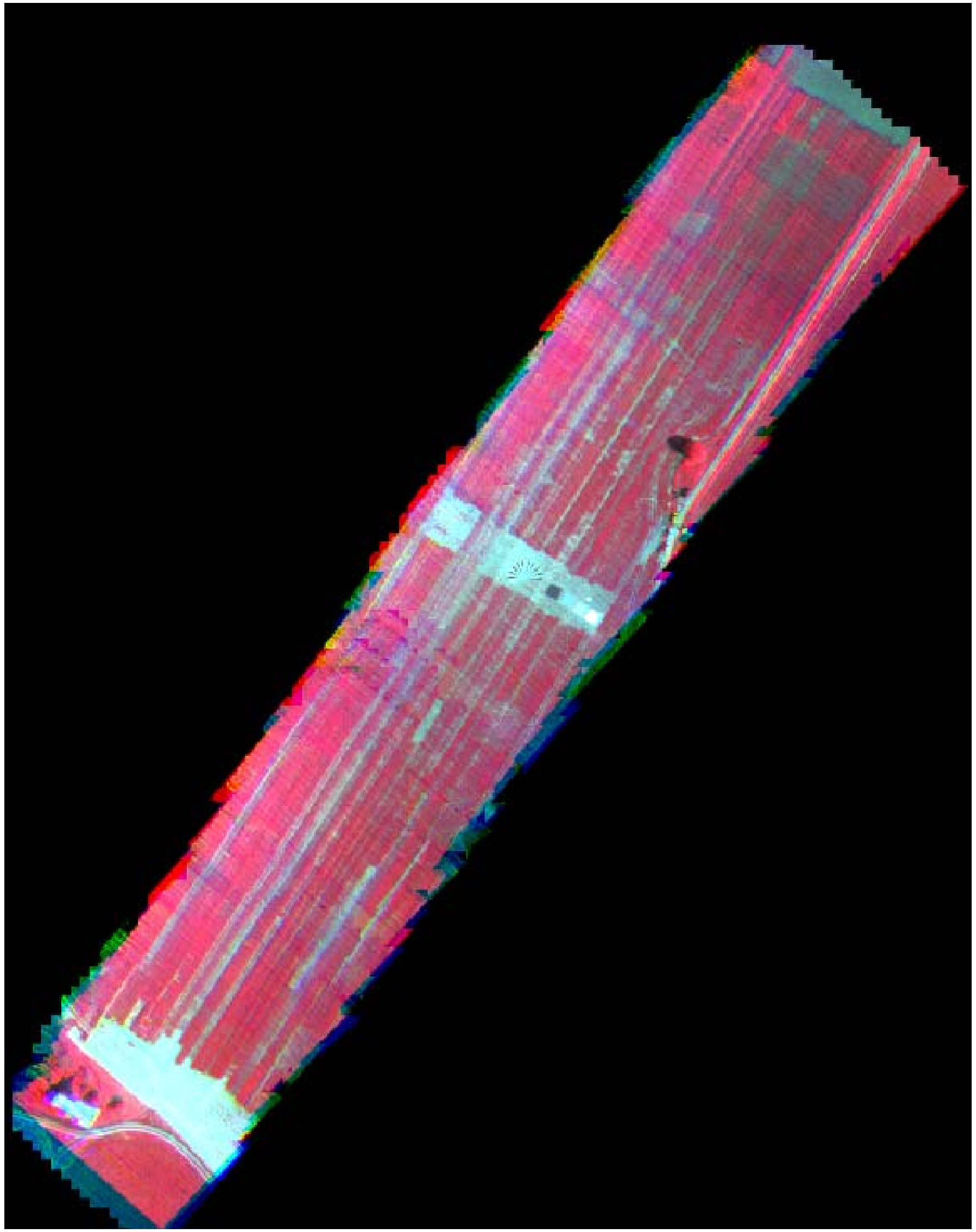


Bramor Ortho with UASI Proto-2B hyperspectral Camera 23.5.2012

Bramor Ortho with Olympus E-420 Camera 23.5.2012

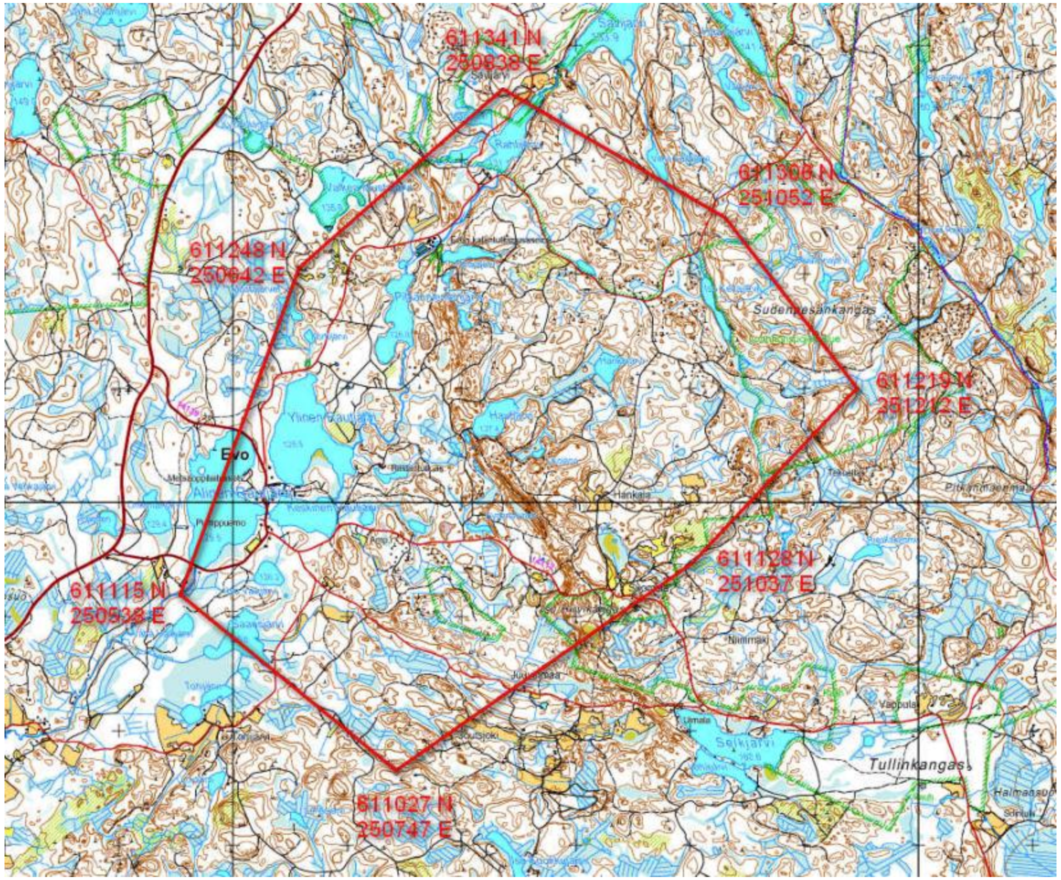
False color mosaic of Vihti test area consisting of wavelength channels centered at 569 nm, 658 nm and 739 nm

Dr. Eija Honkavaara from FGI has created a georeferenced mosaic from the UASI hyperspectral imager data for 5 wavelength bands.
As an example a three channel false color image for 569 nm, 658 nm and 739 nm is shown on the right.



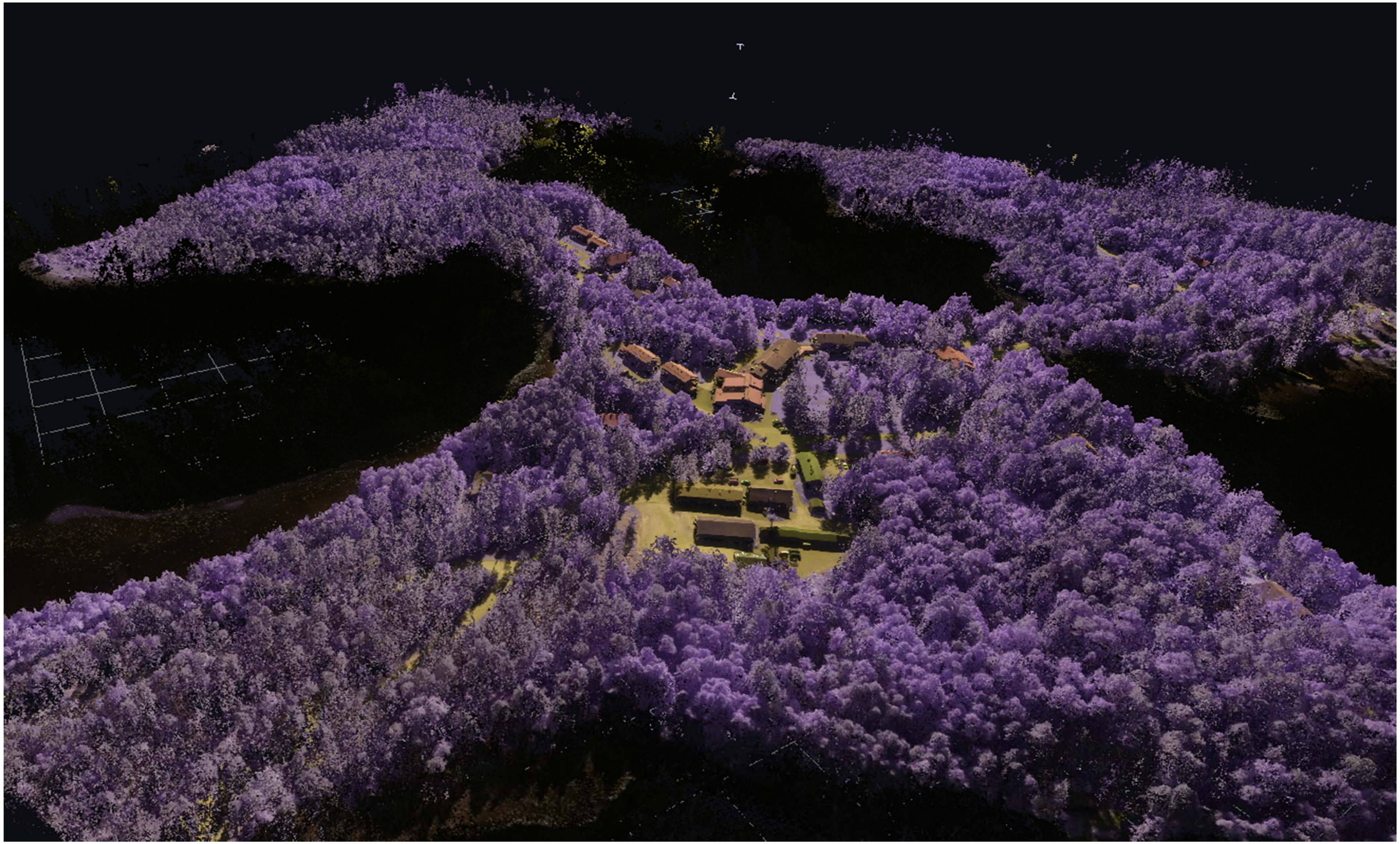
False color imaging of the EVO forest area in June 2012

- The test sites selected for the forest application studies were four areas covering in total approximately 600 hectares of boreal forest.
- The forest area is located in state owned forest in Hämeenlinna, Southern Finland.
- The main tree species in the test areas were pine, spruce and birch, and the stand volumes varies from 0 to approximately 550 m^3/ha.
- The test areas imaged with C-Astral Bramor-Otrho fixed wing UAV using Olympus E-420 Color Infrared camera.

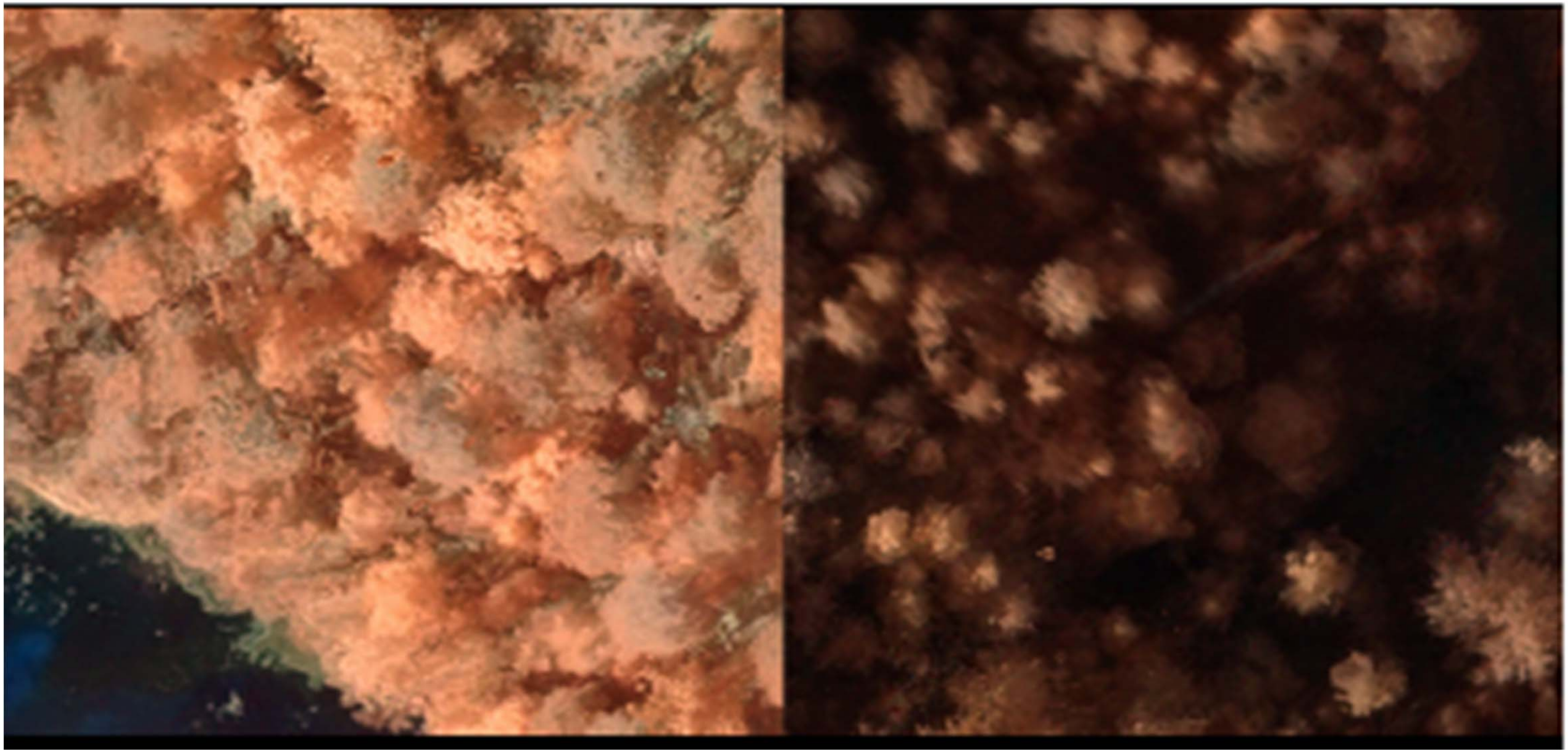


UASI forest application test area at Evo, near the city of Hämeenlinna in Southern Finland.

Digital Surface model of generated from UAS CIR imagery



Details of Forest DSM



Comparison table of Framing and Pushbroom Hyperspectral Imagers in UAV applications

Parameter	New multispectral 2D sensor and Fabry-Perot Interferometer based Hyperspectral Framing Imager	Hyperspectral Pushbroom Imager	Remarks
Mass	350 g	10 kg[1] (AisaEAGLET) 6.4 kg[2] (HyperUAV) 0.7 – 1.1 kg (MicroSpec Hyperspec)	The AisaEAGLET and HyperUAV are designed for medium weight UAVs (20..50 kg)
Mounting Requirements	no mount required because 2D image is recorded	3-axis gimbaled camera mount required because 1D spatial image is recorded.	Framing camera does not need 3-axis mount
Power consumption	< 3 W	< 100 W[1] < 110 W[2]	Including data storage and batteries
Optical throughput	good to excellent	good to excellent	
Spectral resolution in Vis-VNIR (400 – 1100 nm)	5..20	2.5…7 nm	
Time required to record 500 x 750 spatial pixel, 100 spectral band data cube	0.5..1.0 s	5..10 s[1] 9...18 s[2]	Binning of 8 pixels in spectral dimension assumed for pushbroom imagers

[1] http://www.specim.fi/media/pdf/aisa-datasheets/aisaeaglet_datasheet-ver1-2009.pdf

[2] http://www.isssr.com/2008/Post-conf/Downloads/Foes-Post.pdf

[3] http://www.headwallphotonics.com/Portals/145999/docs/Micro-Hyperspec%20Datasheet_comm_UAV_2012.pdf

Aalto-1 overview (ref. Näsilä et. al., The Aalto-1 Spectral Imager (AaSI) Mission, Session 11: MOEMS based Instruments & Missions)

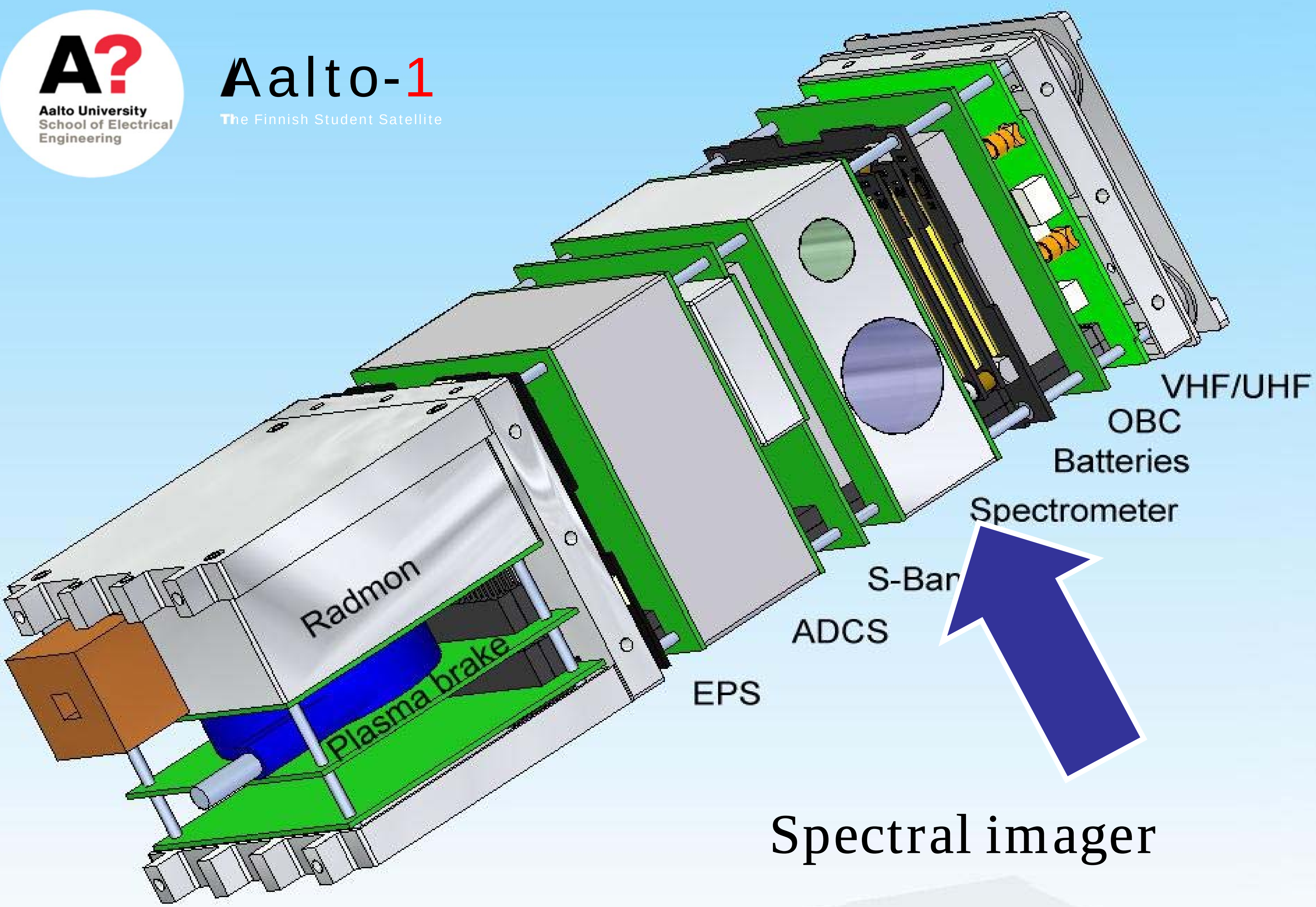
Aalto-1 system design
CubeSat 3U compatible
Dimensions: 34×10×10 cm
Mass: 4 kg
Orbit: Sun-synchronous mid-day LEO
Attitude control: 3 axis stabilized
Communication: VHF-UHF telecommand
S-band data transfer
Lifetime: 2 years
Solar powered: max power 8 W

Payloads: Spectral Imager (VTT)
Radiation detector (Univ. of Helsinki, Univ. of Turku, FMI)
Electrostatic Plasma Brake (FMI)

Aalto University
School of Electrical Engineering

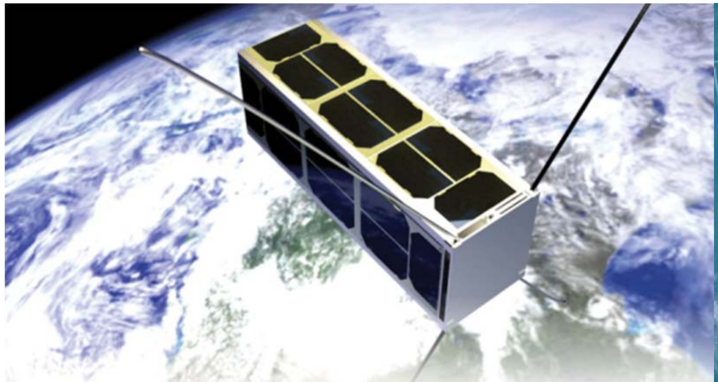
Aalto-1

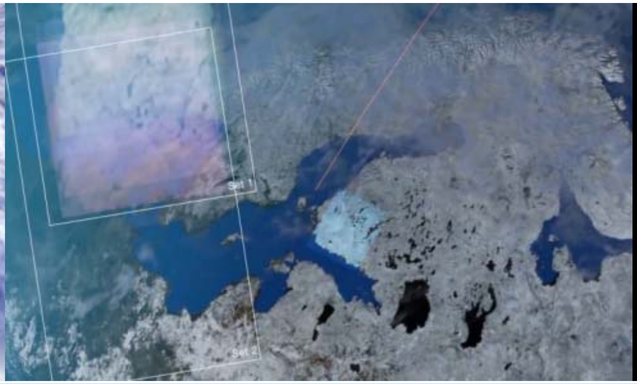
The Finnish Student Satellite

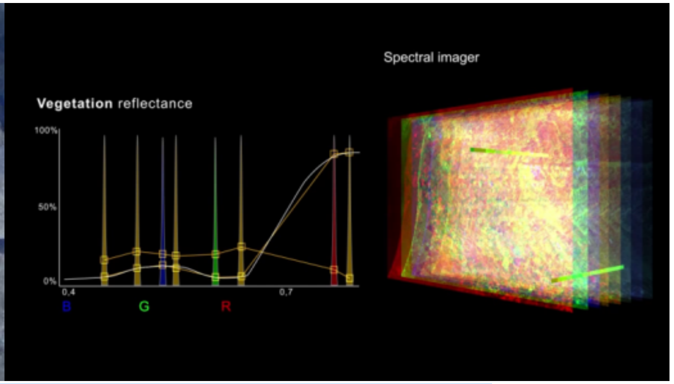


Spectral imager

Aalto-1 Spectral Imager







Main Parameters of AaSI:

- Wavelength range: 500-900 nm
- Spectral resolution: 10 – 30 nm (FWHM)
- Field of View: 10° x 10°
- Spectral image size: 512 x 512 pixels (2x2 binning)
- VIS image size: 1680 x 1120 pixels
- Amount of spectral bands: >20
- Volume: 90 x 96 x 48 mm^3
- Mass: 500 g

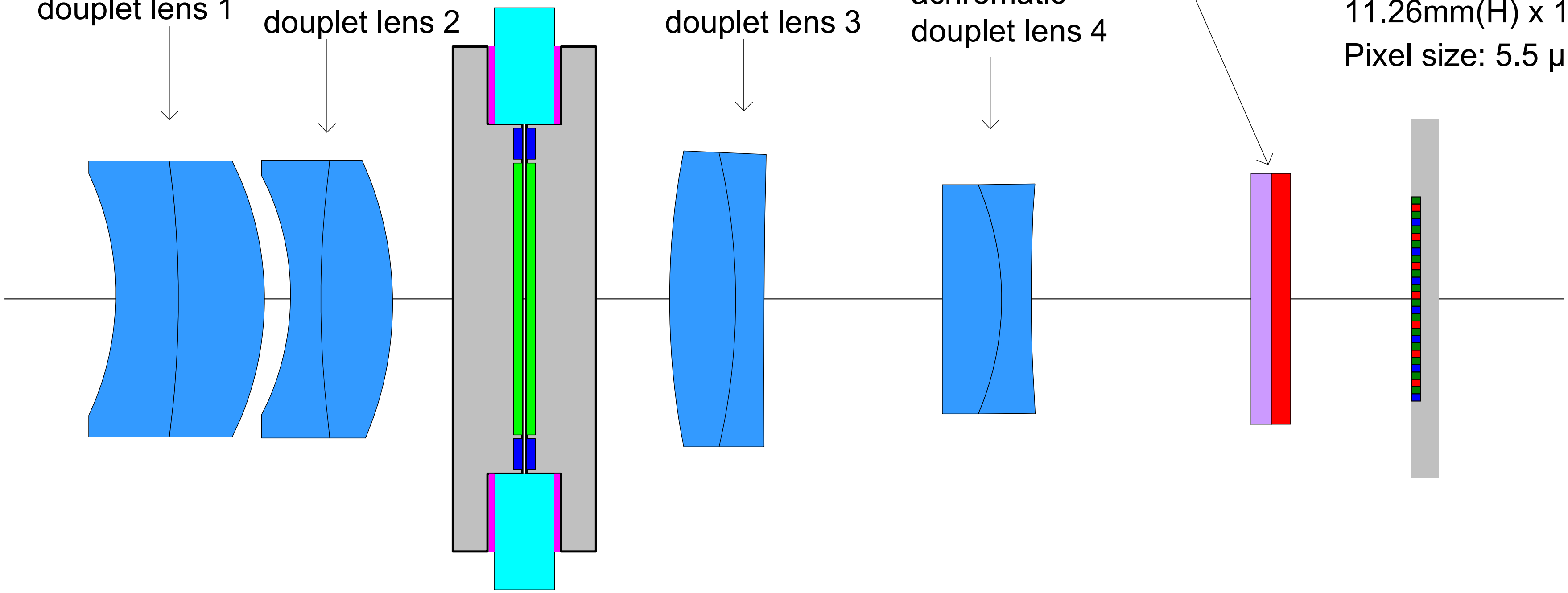
AaSI Mission

The major scientific and technological objective is to demonstrate the operation of the novel staring spectral imager in a nanosatellite.

Parameter	**Specified value**	**Remarks**
Across the flight FOV	10° (0.174 rad)	120 km swath width @ 700 km altitude.
Along the flight FOV	10°	
Instantaneous FOV	0.02° (0.34 mrad)	FOV/512 pixels, ground pixel 240 m at nadir @ 700 km
Wavelength range	500 – 900 nm	The wavelength range can be selected within the spectral response of a silicon image sensor
Spectral resolution	10..30 nm @ FWHM	The target applications require medium spectral resolution. Center wavelength and resolution is programmable.
Number of spectral bands	10..30	Number limited by buffer memory and downlink capacity.
Spectral step	< 1 nm	Adjustable by controlling the air gap of the Fabry-Perot interferometer (FPI)
SNR @ 20 ms integration time & 20 nm FWHM	> 50	SNR requirement is defined for June and latitude of Helsinki (60) and for albedo 30%.
Volume	50x100x100 mm^3	
Mass	500 g	

VTT plans in-orbit tests to verify spectral, spatial and radiometric performance.

Aalto-1 Spectral Imager Optics



Custom achromatic doublet lens 1

Custom achromatic doublet lens 2

Fabry-Perot Interferometer module
Fused silica mirrors: 2 x 4.5 mm glass thickness, Aperture 15.5 mm

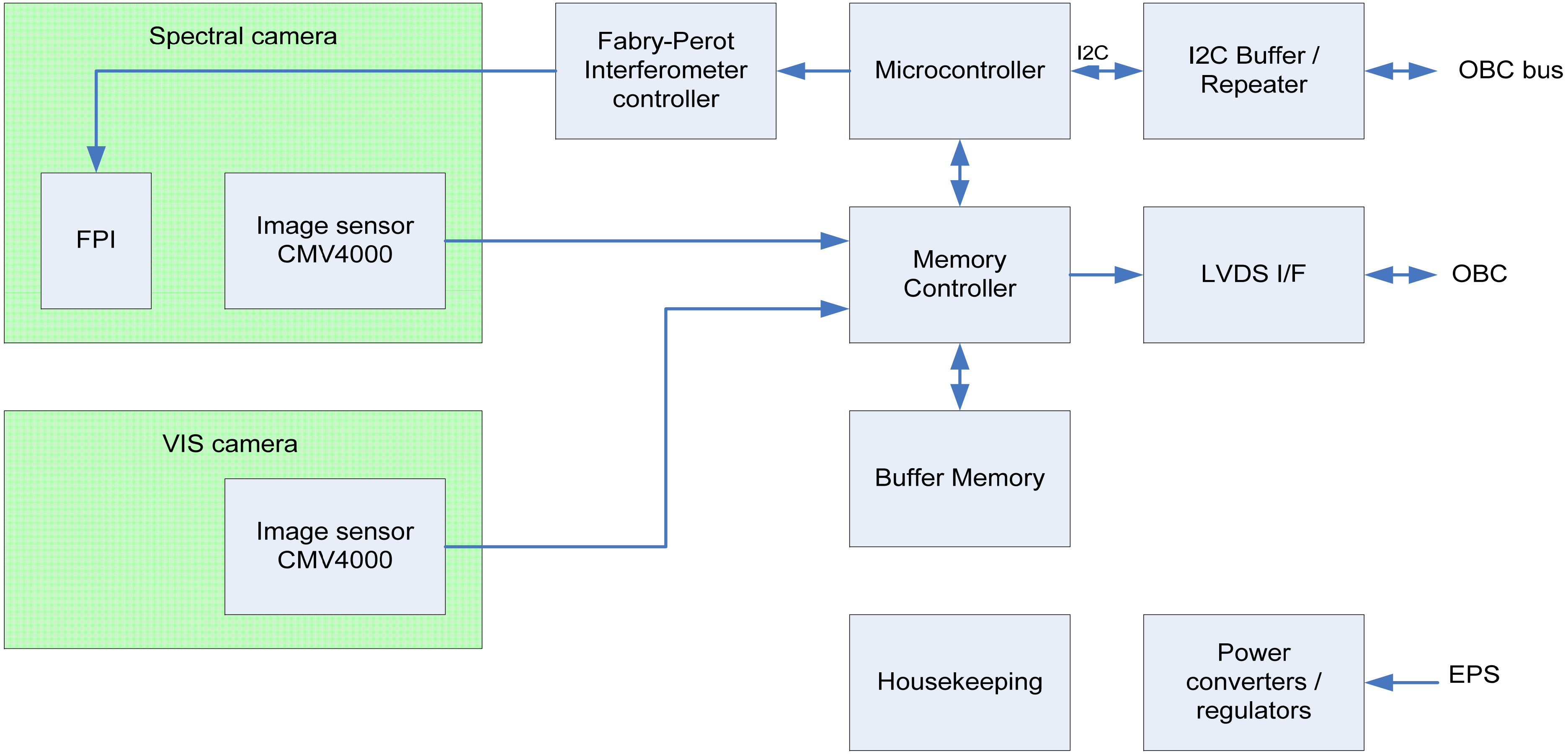
Custom achromatic doublet lens 3

Custom achromatic doublet lens 4

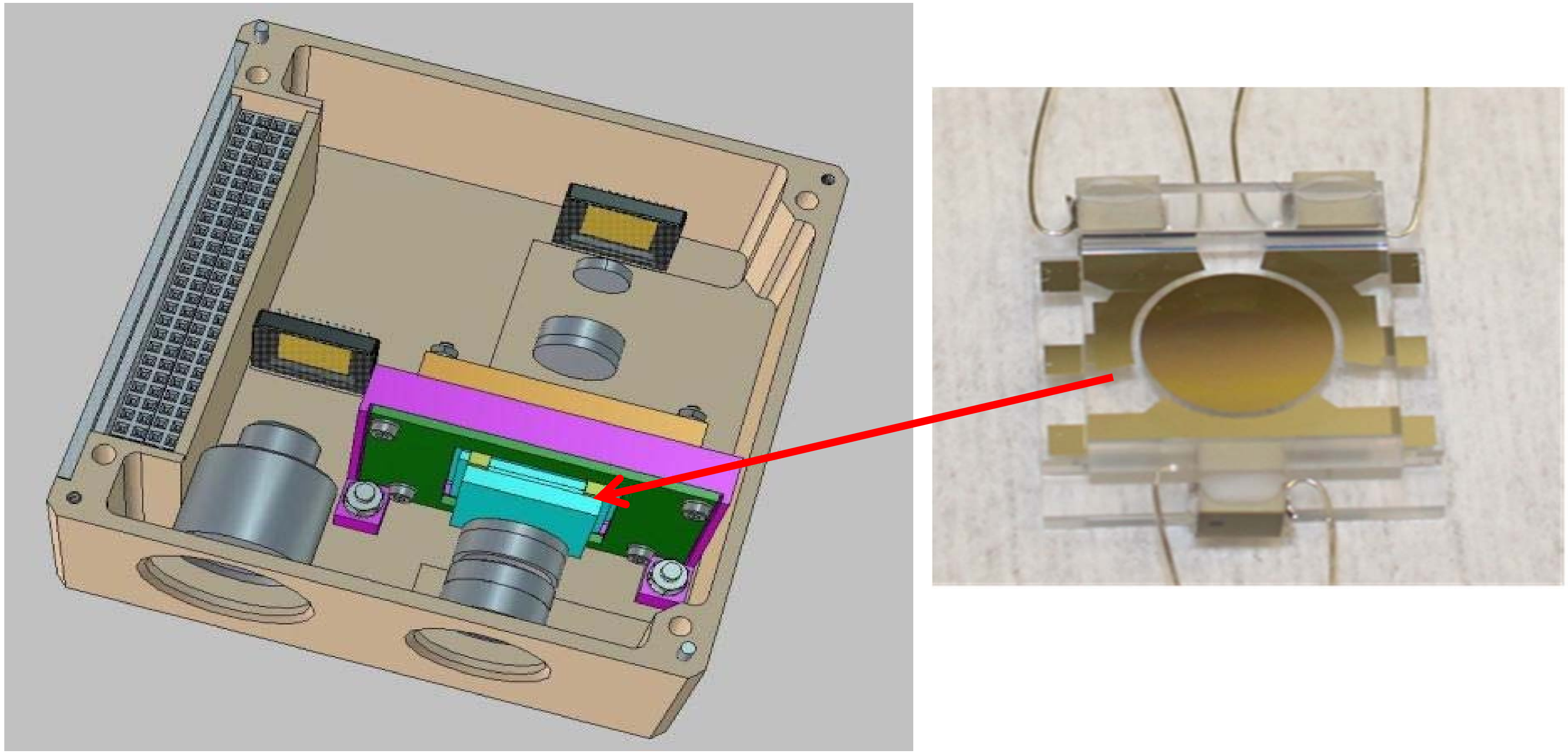
Shortpass Filter
pass band: < 900 nm
Longpass filter
pass band: > 500 nm

CMOSIS 1-inch CMV4000
CMOS RGB color sensor
2048H x 2048V pixels
11.26mm(H) x 11.26 mm (V)
Pixel size: 5.5 µm x 5.5 µm

Block diagram of the Imaging Spectrometer electronics

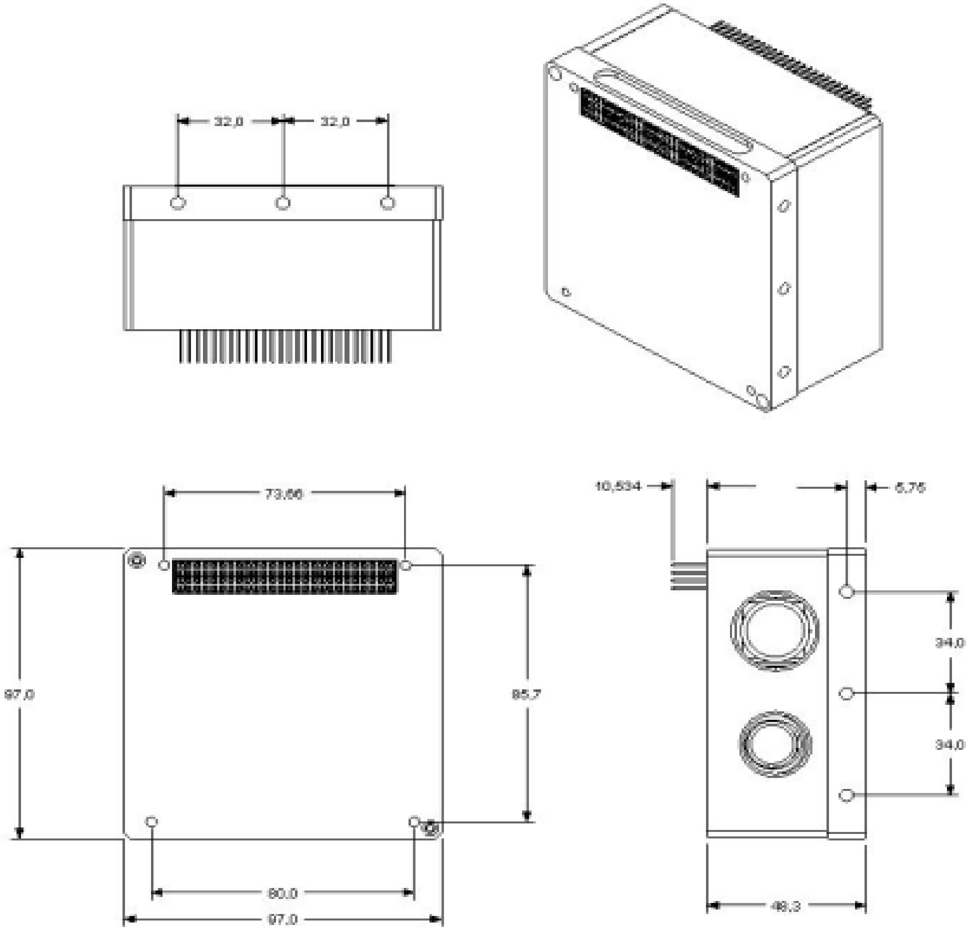


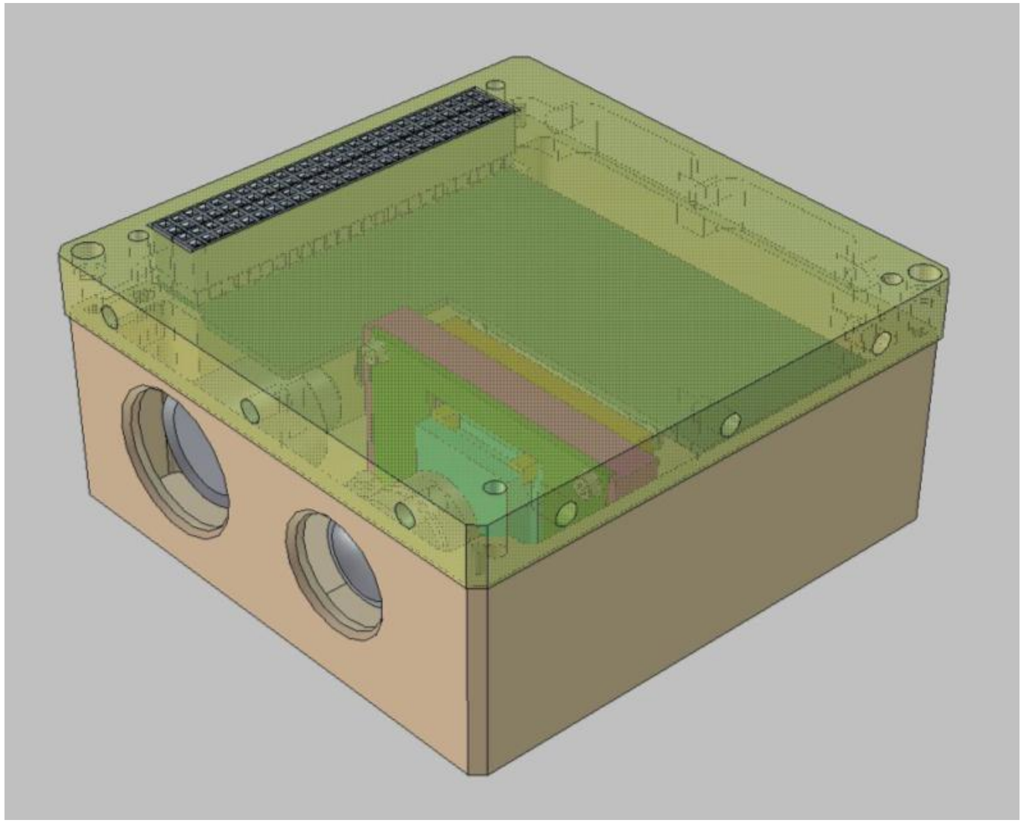
The Aalto-1 Spectral Imager and a piezo-actuated FPI



The Aalto-1 Spectral Imager and a piezo-actuated FPI

Spectral Imager Preliminary Design

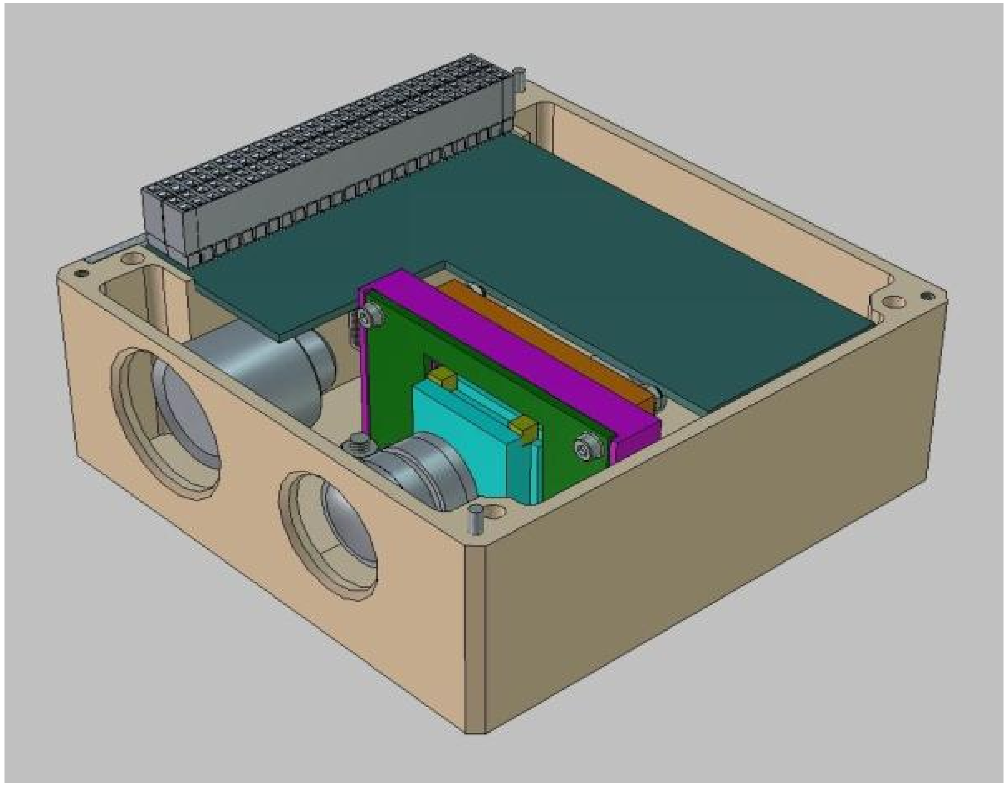


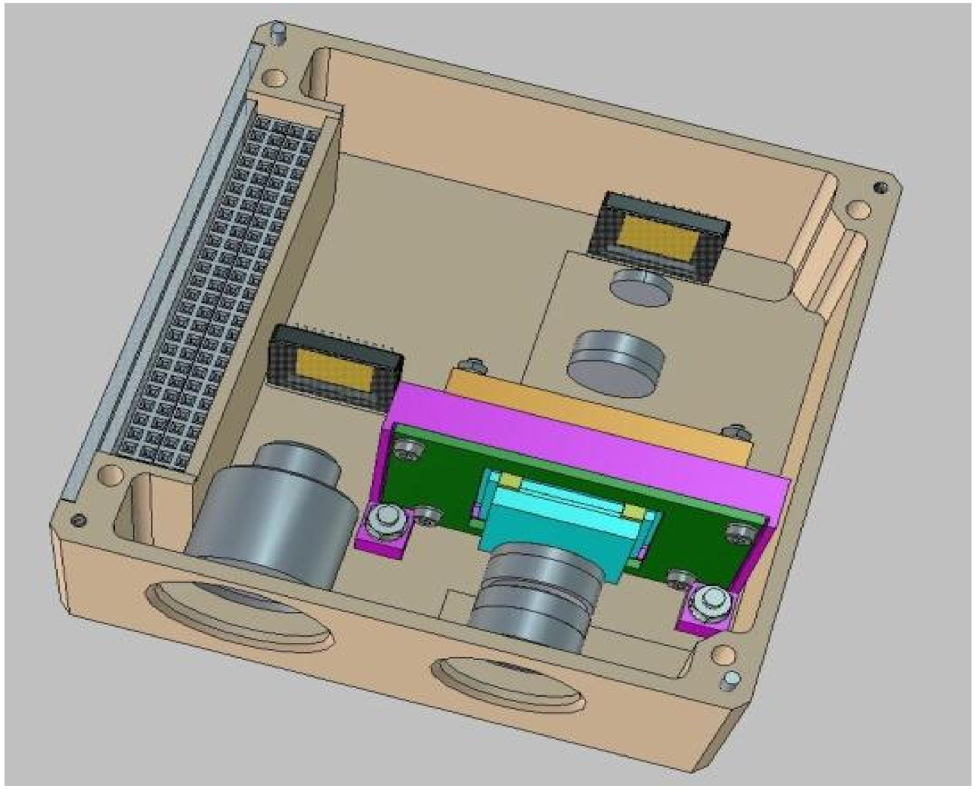


Mass: ~500 g

Size: ~50 mm x ~50 mm x ~100 mm

Spectral Imager Preliminary Design





VTT MEMS Fabry-Perot Interferometer for Thermal Infrared

- *VTT has developed a surface-micromachined tunable Fabry–Perot interferometer for the thermal infrared spectral range of wavelengths 7–12 μm.*
- *The dielectric mirror layers consists of Poly-Silicon and air*
- *The optical transmission over the wavelengths from 3 to 20 μm.*

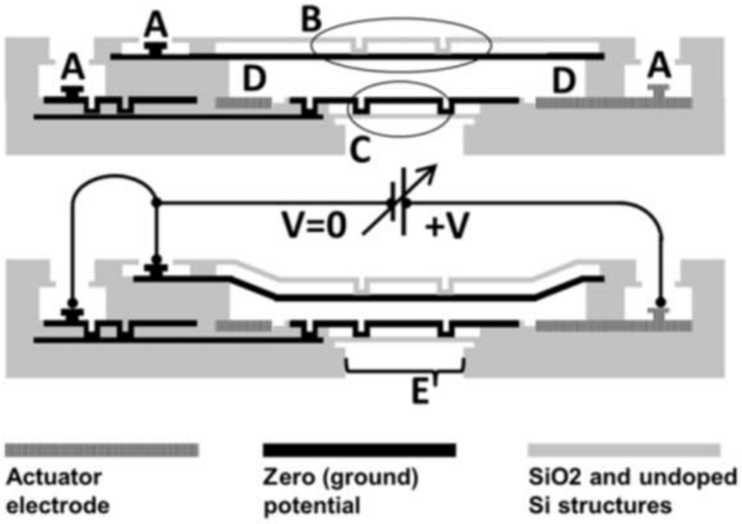
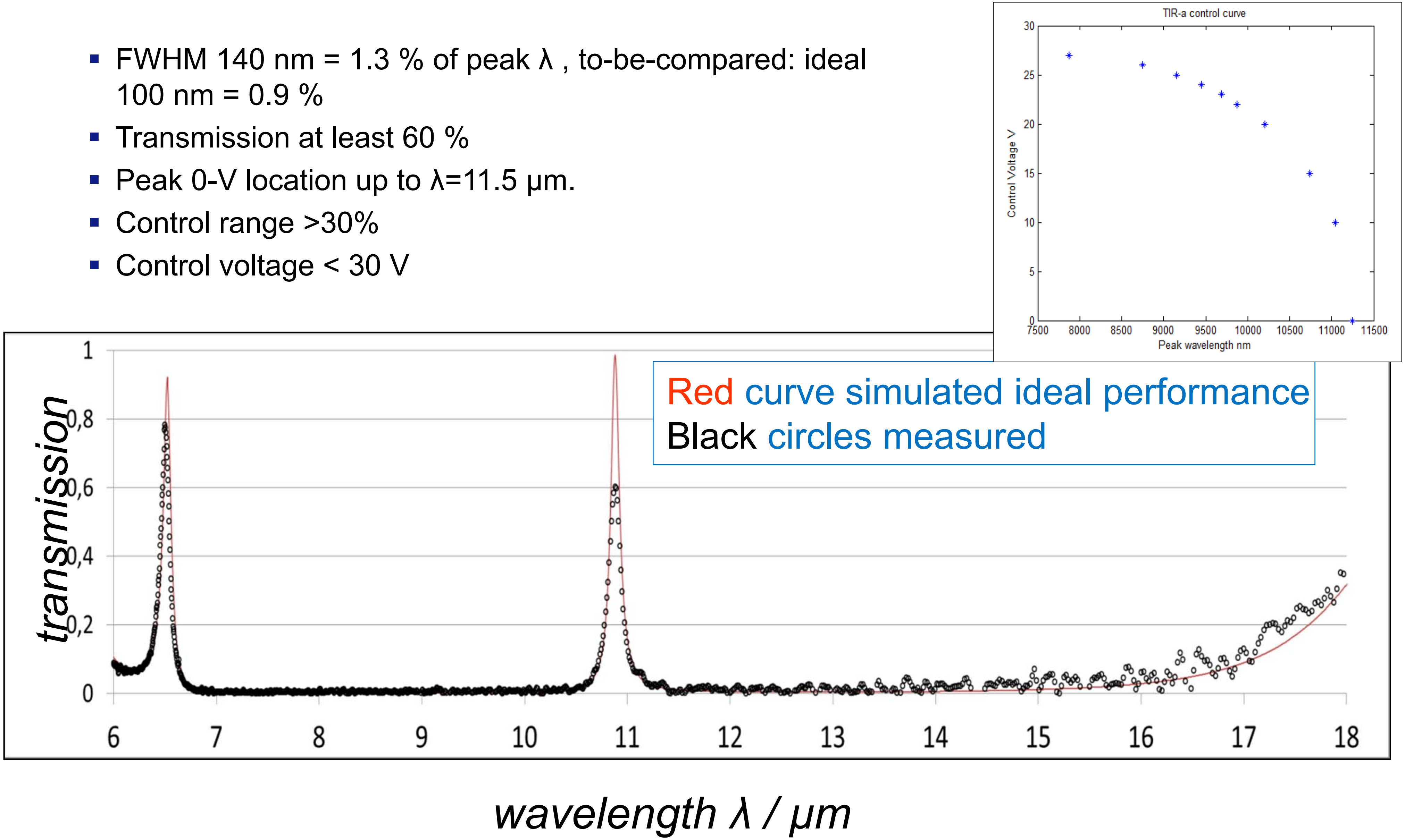


Figure 1. TIR-FPI design. A schematic cross section of the structure and of the tuning concept by means of an electrostatic actuator. Several functional structures are indicated: A, contact pads ; B, upper mirror; C, lower mirror ; D, actuator electrode and E, optical path and the aperture.

ref. Tuohiniemi et.al. Optical transmission performance of a surface-micromachined Fabry–Perot interferometer for thermal infrared, J. Micromech. Microeng. 22 (2012).

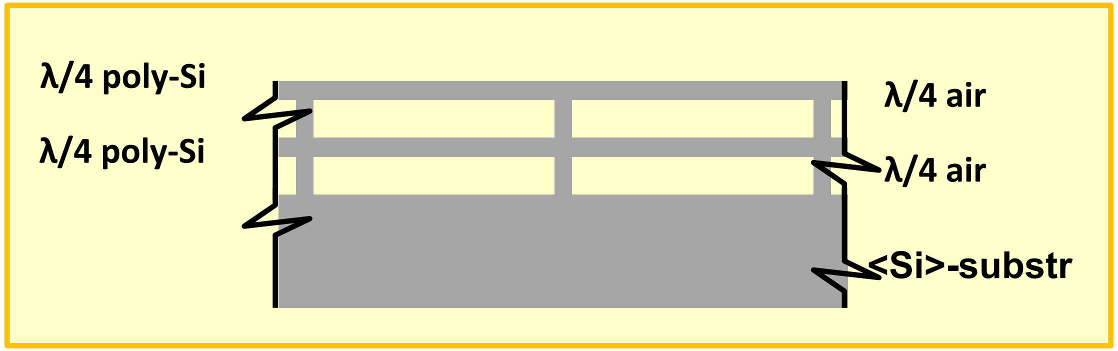
MEMS TIR-FPI Characterization results

- FWHM 140 nm = 1.3 % of peak λ , to-be-compared: ideal 100 nm = 0.9 %
- Transmission at least 60 %
- Peak 0-V location up to λ=11.5 μm.
- Control range >30%
- Control voltage < 30 V



Red curve simulated ideal performance
Black circles measured

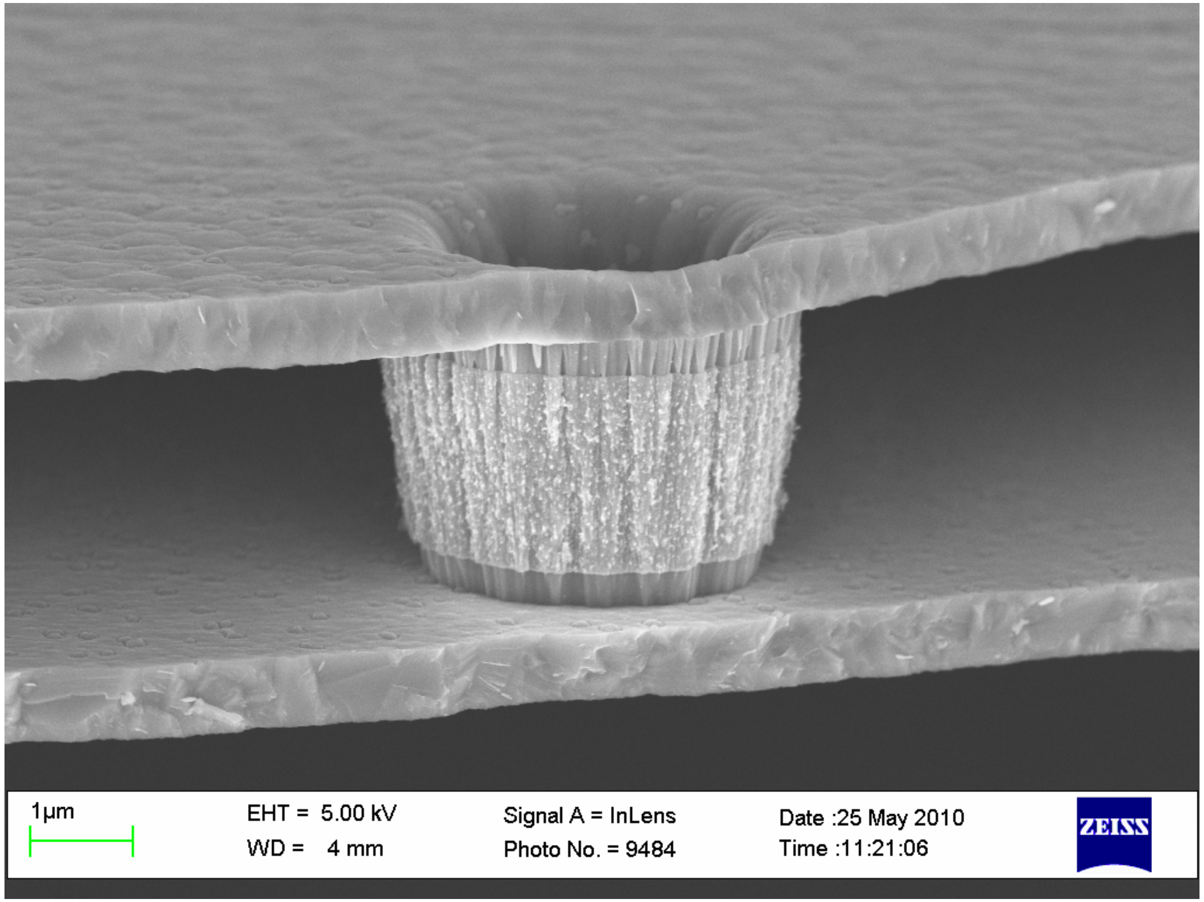
Concept of MEMS dielectric Bragg mirrors based on two suspended λ/4 poly-Si layers separated by λ/4 air layers



- Piezo-actuated FPI for MWIR (2 – 5 μm) and LWIR (5-16 μm) spectral ranges
  - Tuneable ca. 30-50 % down from rest wavelength
- Two suspended λ/4 poly-Si layers separated by λ/4 air layers
- Complete mirror structure: substr-<Si> / air / poly-Si / air / poly-Si
- Air-layers (gaps) fixed at constant and controlled thickness by anchor structures
- Very wide aperture (> 25 mm) expected to be feasible
  - Concepts for even wider up to the 150-mm full wafer worth studying
- High-resistivity Si substrate is transparent up to 16 μm

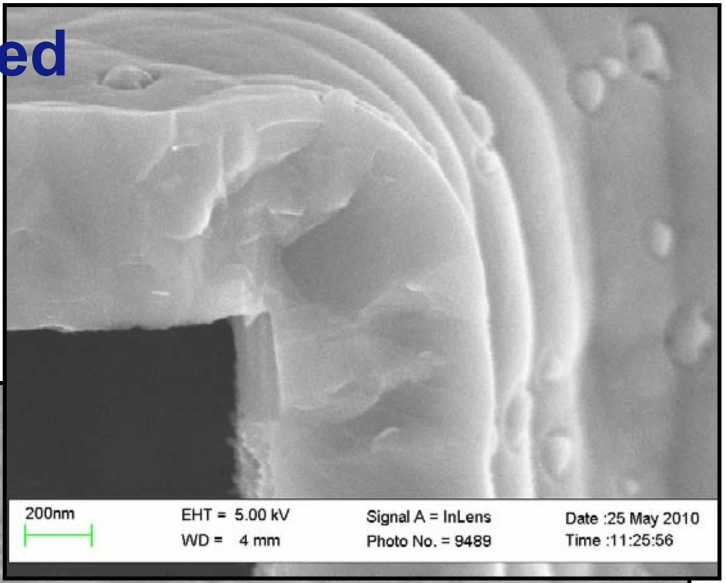
SEM images of poly-silicon layers supported with the barrel-like structures 1(2)

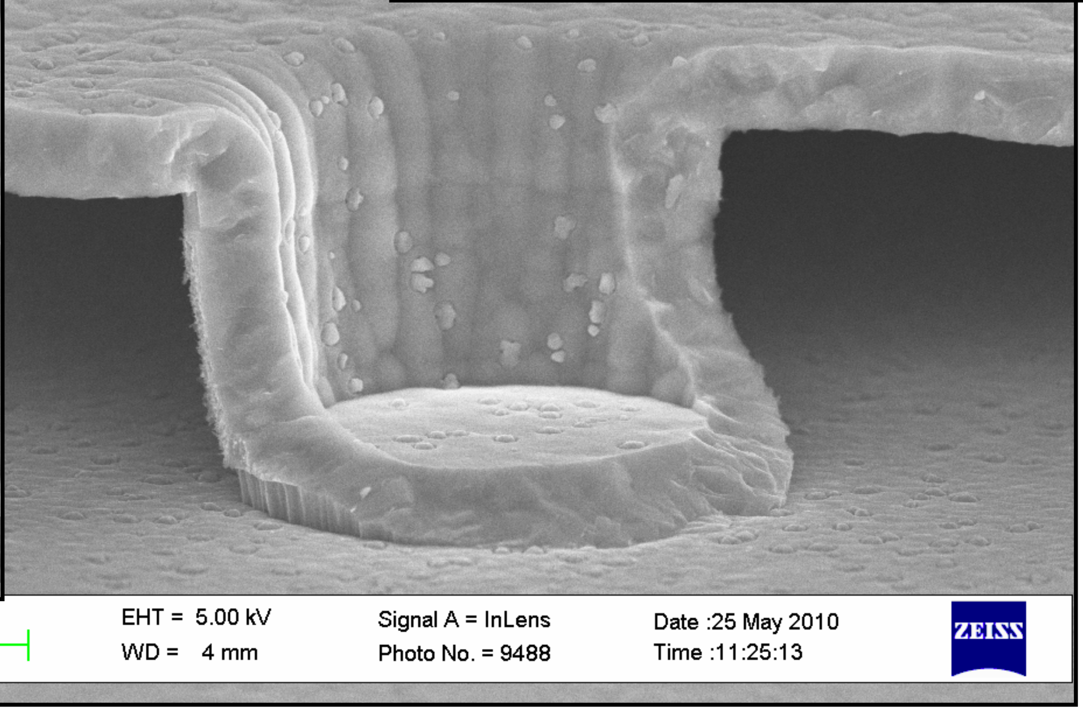
- The thin layers of solid material are the poly-silicon layers of an air-gap Bragg mirror
- The space between the layers is the middle-layer of the mirror: the air gap.
- The barrel-like structure is an anchor for keeping the poly-silicon layers at constant distance.
- Empty space below the structure is also essential. 3-mm diameter mirrors were demonstrated releasing them free from the underlying Si-wafer substrate. The substrate surface lies outside the image, 5 µm downwards below the released structures.

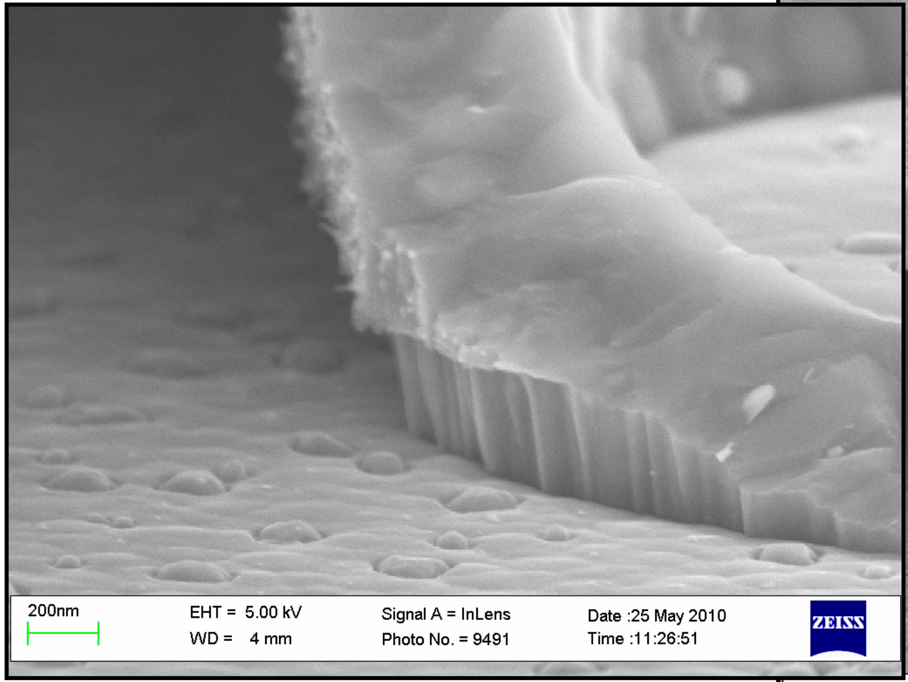


SEM images of poly-silicon layers supported with the barrel-like structures 2(2)

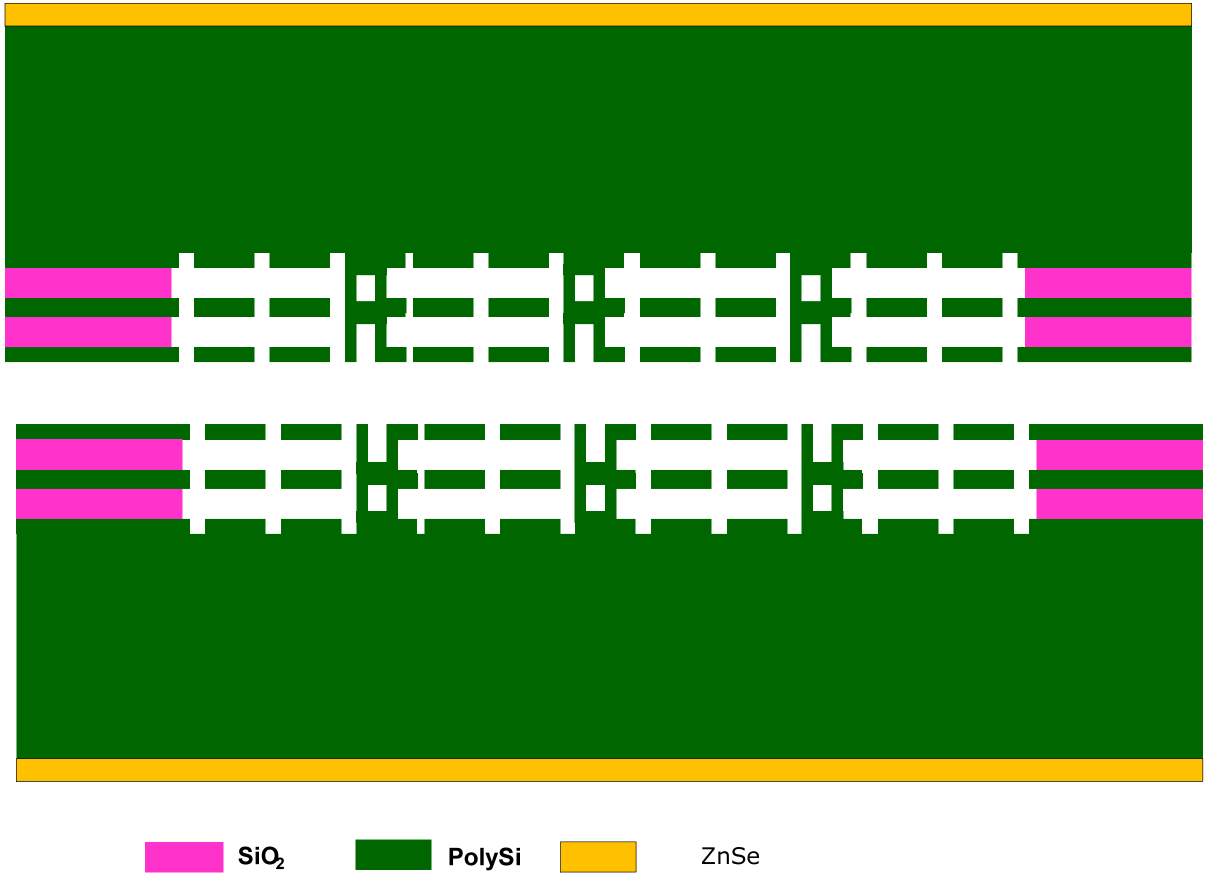
- An anchor cut half at the middle for illustrating the structure.
- The lower poly-silicon layer cleaving line is not shown.



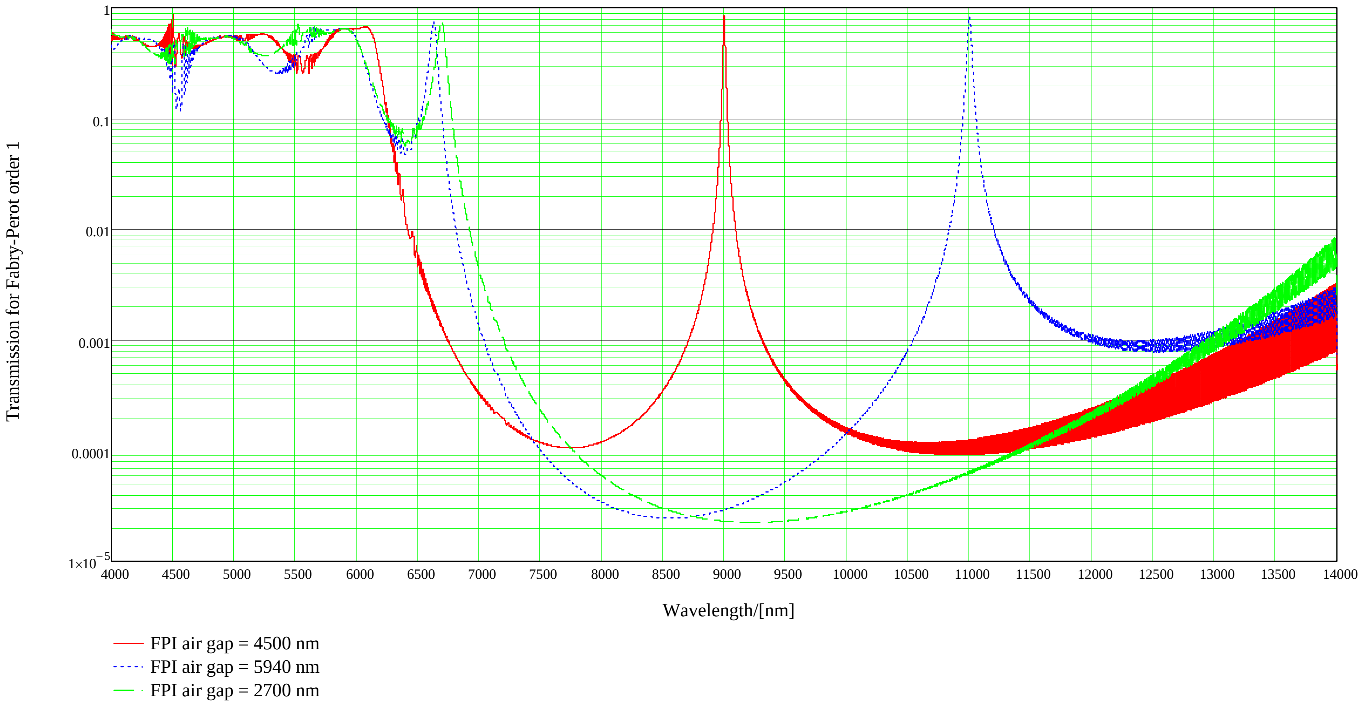


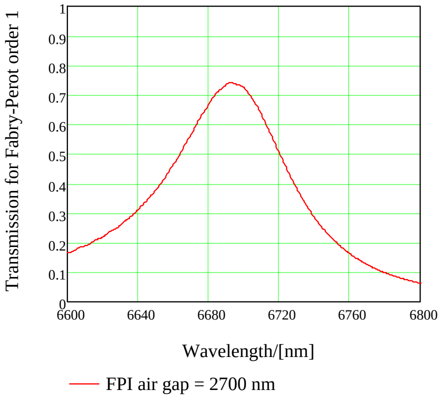


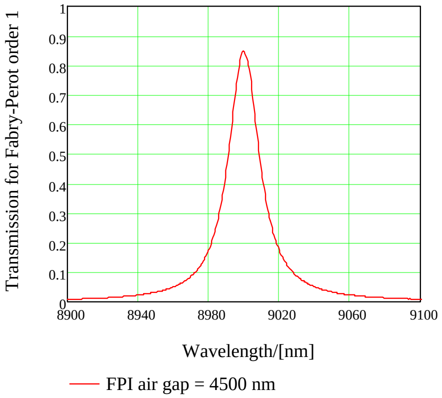
Concept of Fabry-Perot Interferometer constructed of the MEMS dielectric Bragg mirrors based on two suspended λ/4 poly-Si layers separated by λ/4 air layers

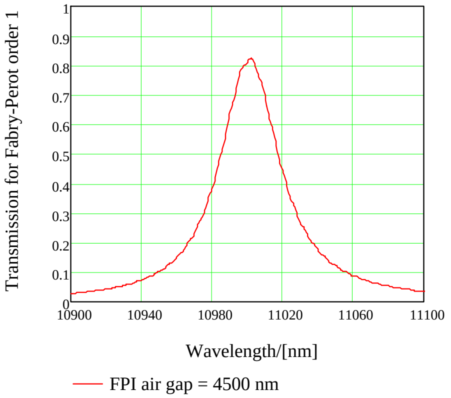


Simulations of the 4 layer Poly-Si-Air Bragg mirror FPI optimized for 9000 nm at FPI order 1

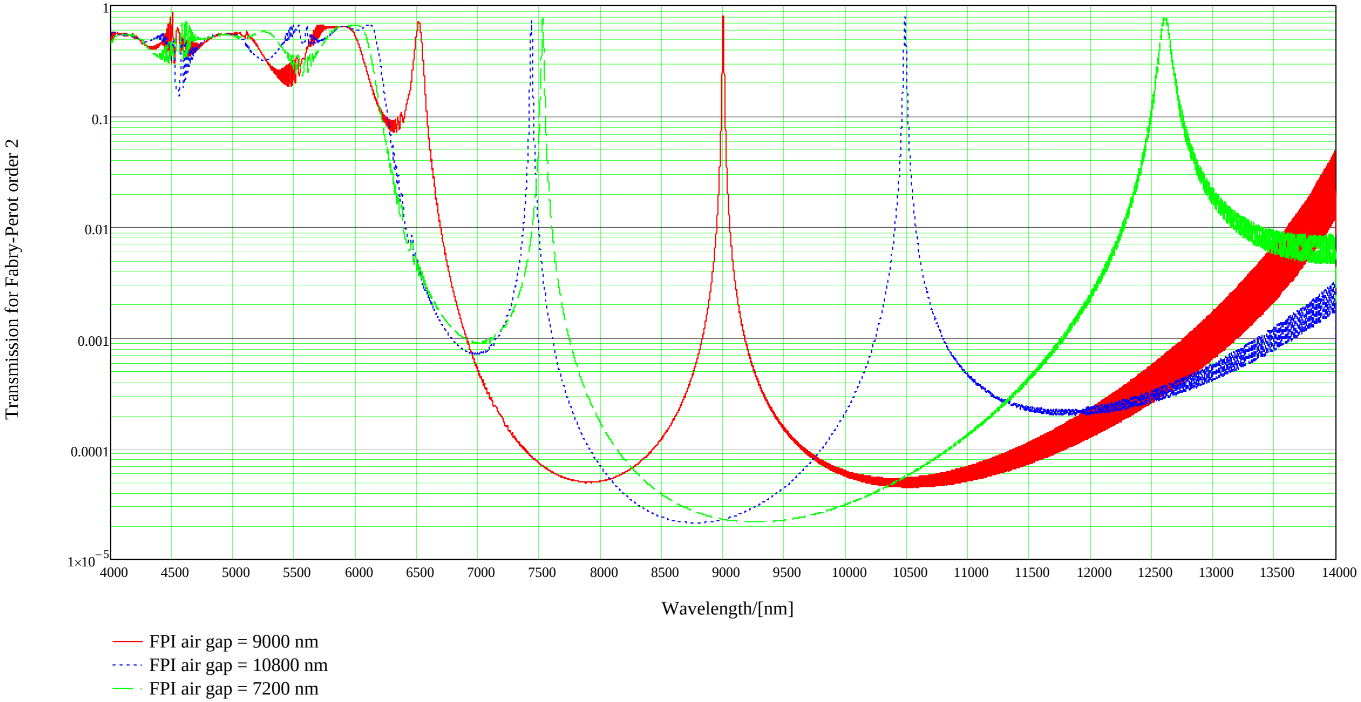


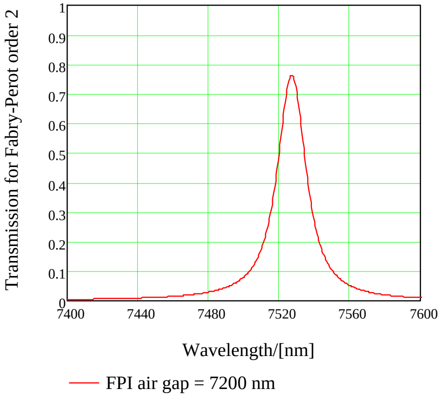


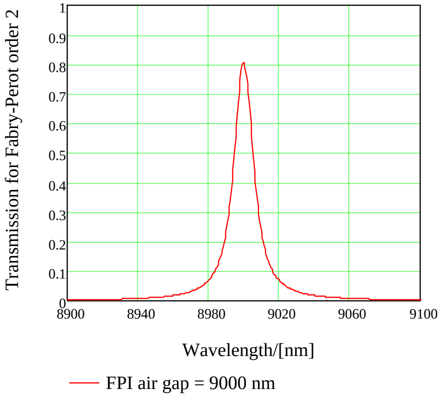


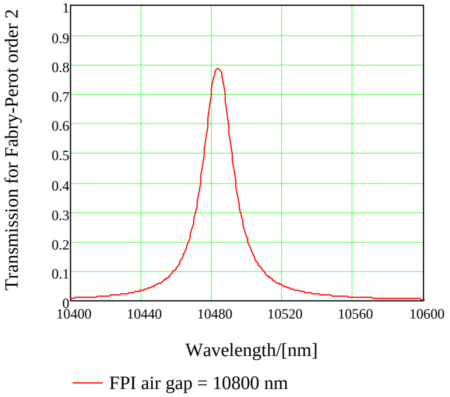


Simulations of the 4 layer Poly-Si-Air Bragg mirror FPI optimized for 9000 nm at the FPI order 2







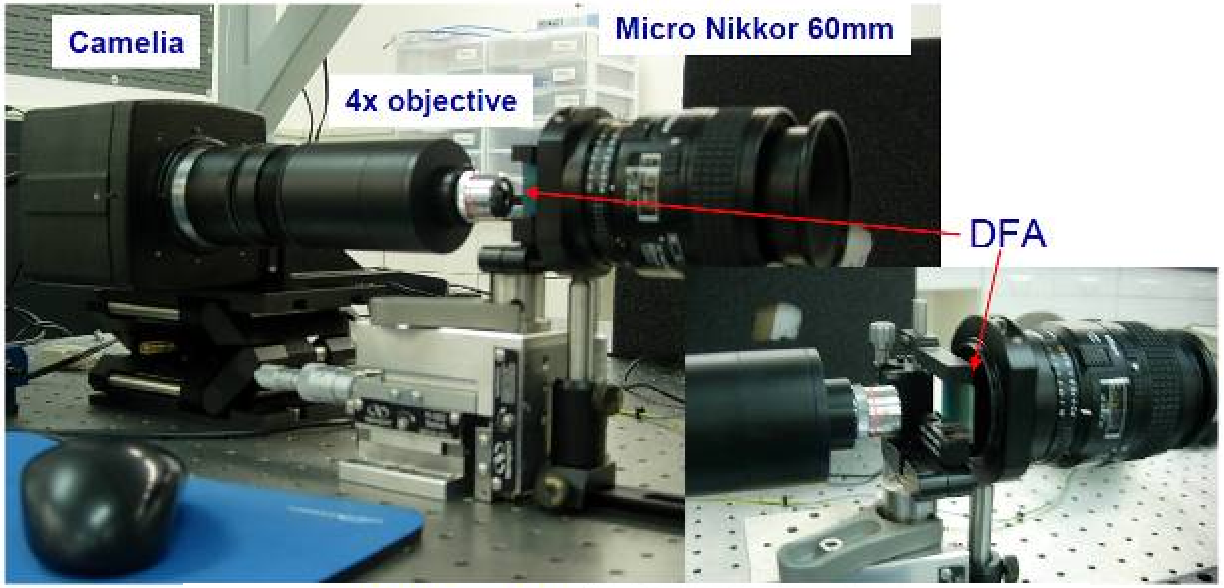


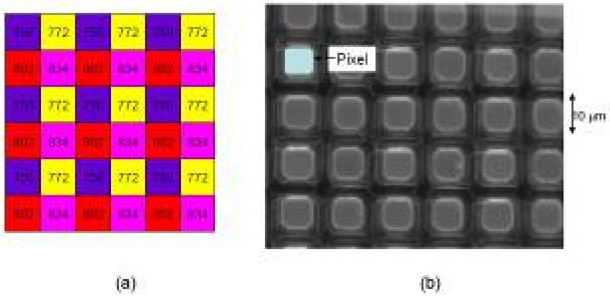
What could FPI technology offer small and large scale earth observation satellites?

- The FPI tunable filter combined with a RGB CMOS image sensor or with a customized Dichroic Filter Array (DFA) enables very compact hyperspectral imager instrument constructions (AaSI&PICASSO-VISION Spectral Imagers).
- With new MEMS Poly-Silicon-Air dielectric material Bragg Mirror structure it is possible cover large wavelength range with a single FPI (±20…±25% around center wavelength).
- Using two or more Fabry-Perot interferometers in series it is possible to cover even larger wavelength range or achieve spectral resolution tunability using one FPI at low order (1 or 2) and the second FPI at a high order (typically 4…12).

Dichroic Filter Array (DFA) Multispectral Camera

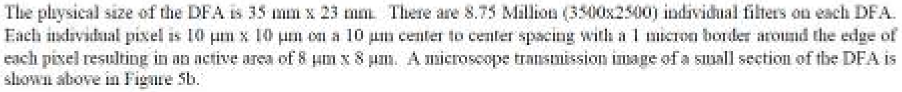
- The physical size of the DFA is 35 mm x 23 mm and there are 3500x2500 individual filters on the DFA. The pixel pitch is 10 µm x 10 µm.
- The image of a target is formed on the DFA surface and the Microscope objective forms an image of the DFA on the Camera sensor.
- The advantages of DFA camera are
  - The spectral bands are registered simultaneously
  - No moving parts
- The disadvantages of the DFA concept are
  - Tuning of the spectral bands is not possible
  - The miniaturization is challenging because of relay optics required for imaging the DFA to the image sensor.





(a) (b)

Figure 5. (a) Bayer like pattern and (b) microscope image of the dichroic filter array.

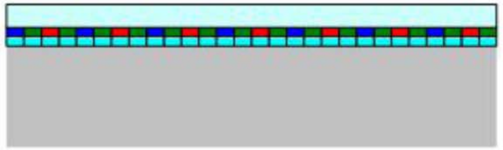


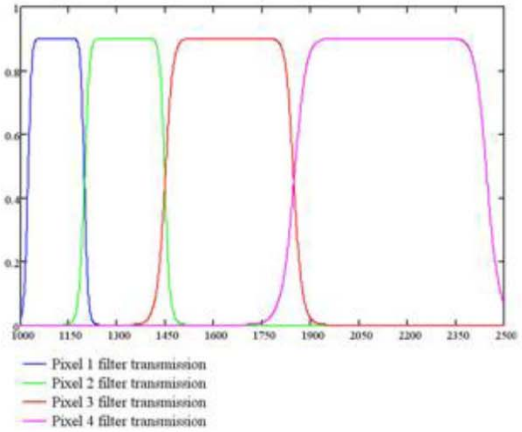
The physical size of the DFA is 35 mm x 23 mm. There are 8.75 Million (3500x2500) individual filters on each DFA. Each individual pixel is 10 µm x 10 µm on a 10 µm center to center spacing with a 1 micron border around the edge of each pixel resulting in an active area of 8 µm x 8 µm. A microscope transmission image of a small section of the DFA is shown above in Figure 5b.

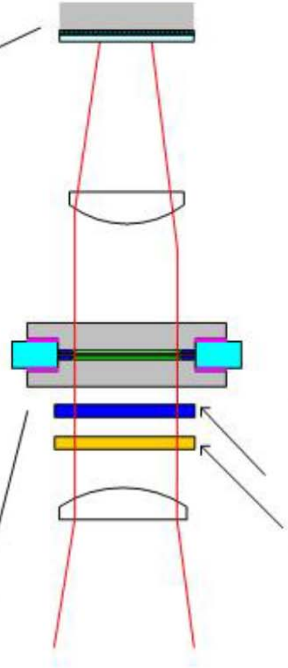
Ref. Eichenholz, J.M., et.al., "Real time Megapixel Multispectral Bioimaging", Proc. SPIE 7568 (2010).

Hyperspectral imager concept based on combining a Dichroic Filter Array with Fabry-Perot Interferometer

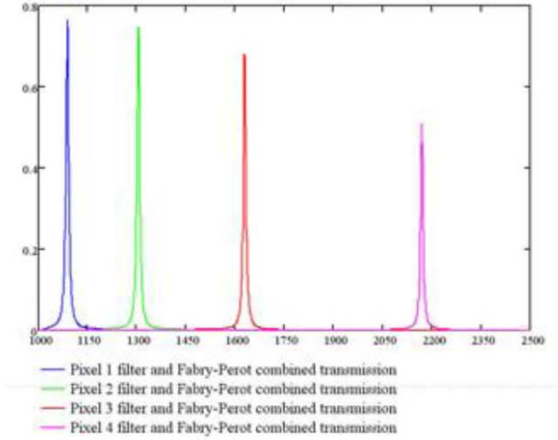
Patterned dielectric multispectral filter array integrated with a IR detector





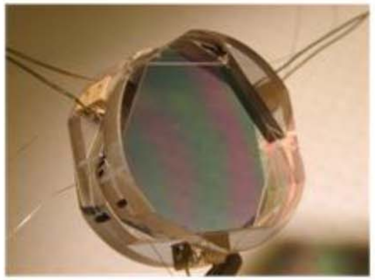


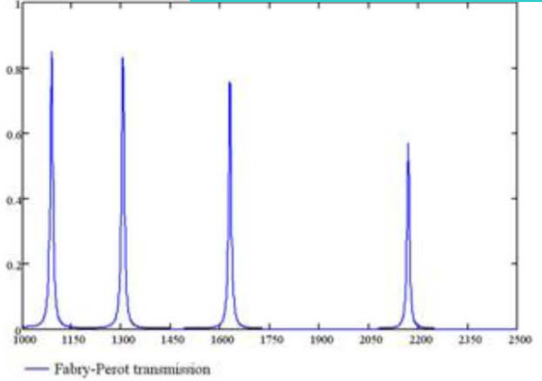
Combined spectral transmission of Patterned dielectric multispectral filter array and Fabry-Perot Interferometer used at 4 orders



One can separate the multiple order peaks by using special pixel filter arrays!

Piezoactuated Fabry-Perot Interferometer module

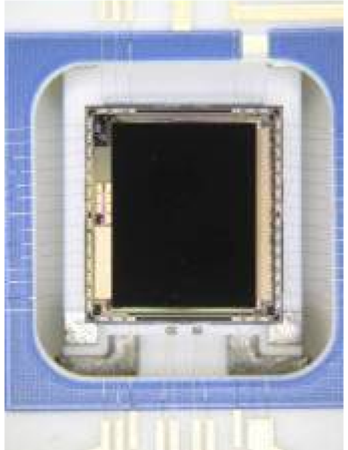


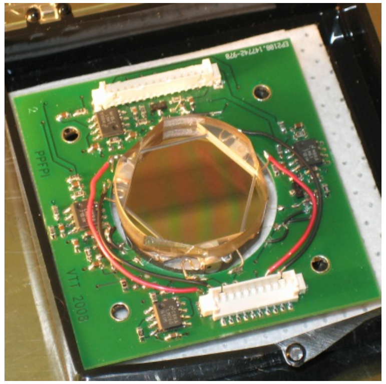


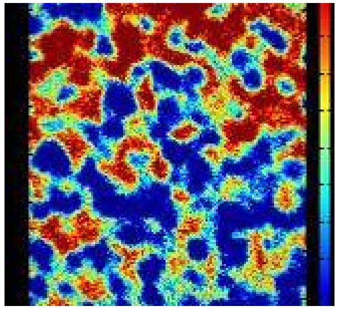
SWIR&TIR Hyperspectral Imager based on a patterned multispectral filter integrated on an IR detector and multiple orders of Fabry-Perot Interferometer

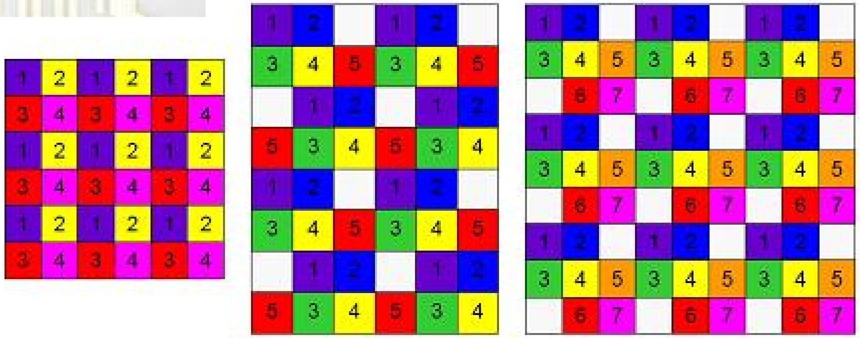
Technology:

- Modified IR technology with integrated patterned dielectric filter array for high speed order sorting; 1- 5 μm or 8-12 μm wavelength range
- High speed piezo-actuated Fabry-Perot interferometer to provide spectral resolution and tuning.









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3	4	3	4	3	4
1	2	1	2	1	2
3	4	3	4	3	4

1	2		1	2	
3	4	5	3	4	5
	1	2		1	2
5	3	4	5	3	4
1	2		1	2	
3	4	5	3	4	5
	1	2		1	2
5	3	4	5	3	4

1	2		1	2		1	2	
3	4	5	3	4	5	3	4	5
	6	7		6	7		6	7
1	2		1	2		1	2	
3	4	5	3	4	5	3	4	5
	6	7		6	7		6	7
1	2		1	2		1	2	
3	4	5	3	4	5	3	4	5
	6	7		6	7		6	7

Figure 4. Examples of three different Bayer type dichroic filter arrays for multispectral imaging

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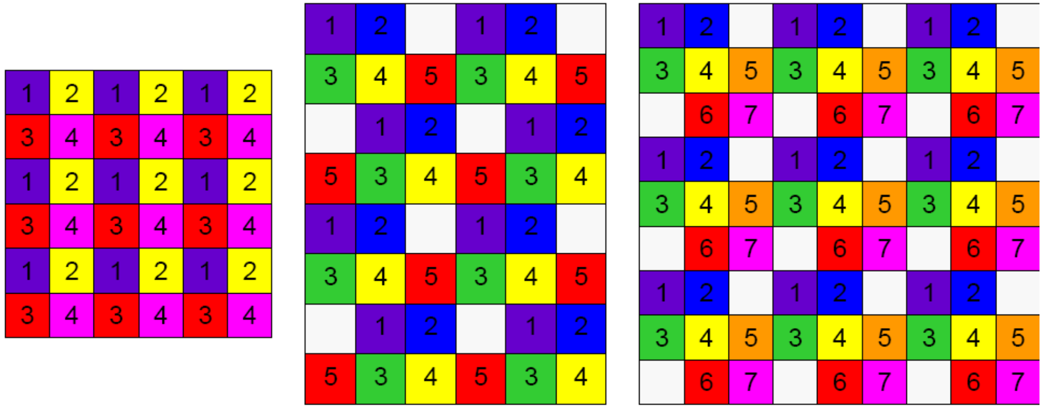
Examples of Bayer type dichroic filter arrays for IR detector arrays (ref. Ocean Thin Films Inc.)



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3	4	3	4	3	4
1	2	1	2	1	2
3	4	3	4	3	4

1	2		1	2	
3	4	5	3	4	5
	1	2		1	2
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3	4	5	3	4	5
	1	2		1	2
5	3	4	5	3	4

1	2		1	2		1	2	
3	4	5	3	4	5	3	4	5
	6	7		6	7		6	7
1	2		1	2		1	2	
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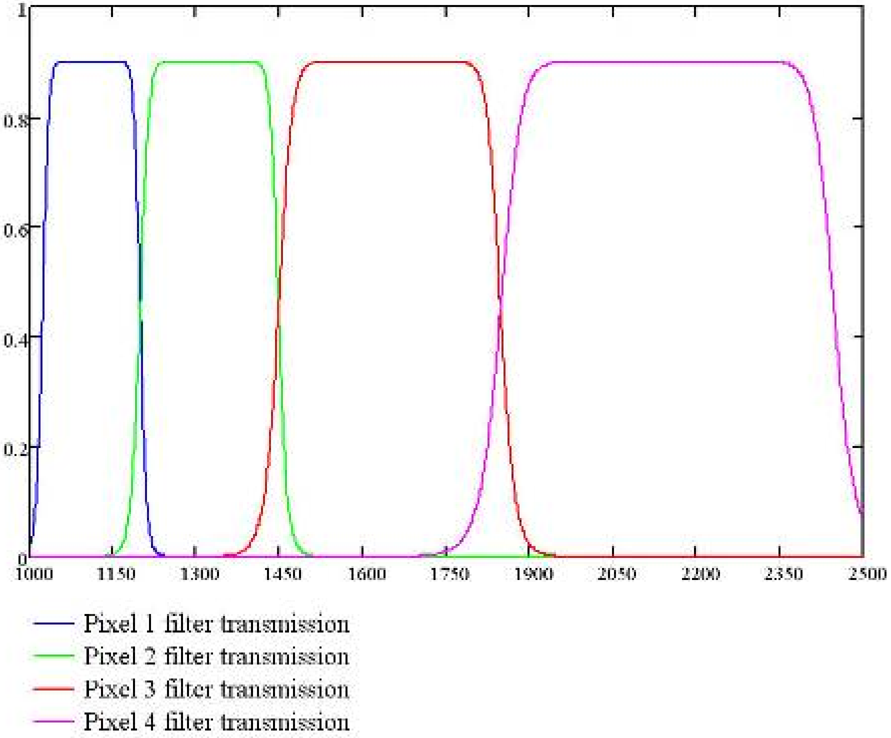
	6	7		6	7		6	7
1	2		1	2		1	2	
3	4	5	3	4	5	3	4	5
	6	7		6	7		6	7

Figure 4. Examples of three different Bayer type dichroic filter arrays for multispectral imaging



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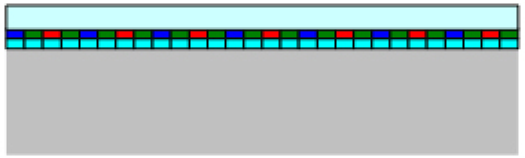
SWIR/TIR Hyperspectral Imager Concept

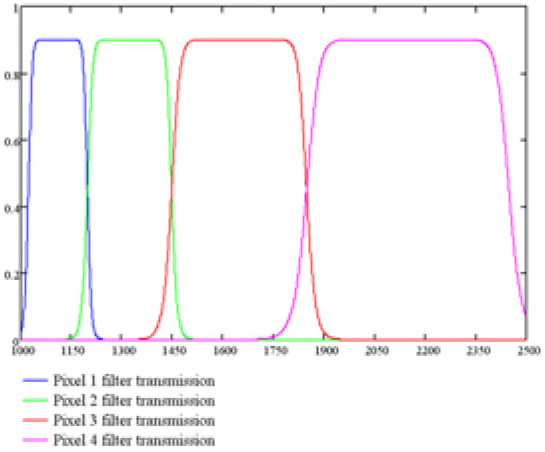
The fast hyperspectral imaging is enabled with Fabry-Perot Interferometer (FPI) used at multiple orders and a patterned multispectral filter integrated with an IR detector.

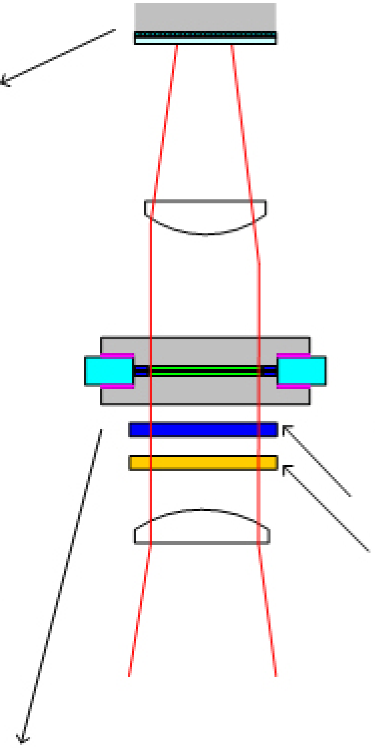
Each FPI order is dedicated to a pixel filter enabling the recording of 4 narrow spectral band images simultaneously.

Piezo actuated wide aperture FPIs provide high optical throughput.

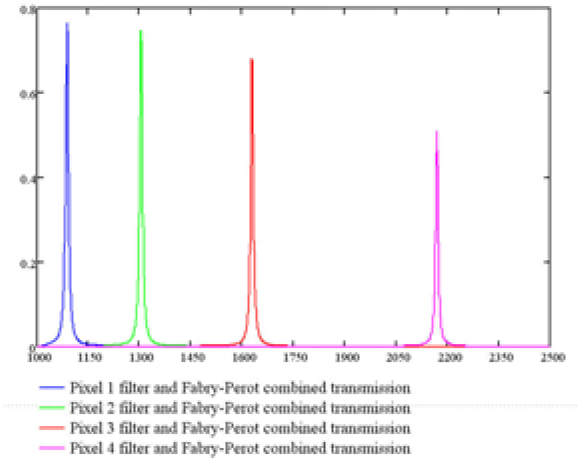
Patterned dielectric multispectral filter array integrated with a IR detector



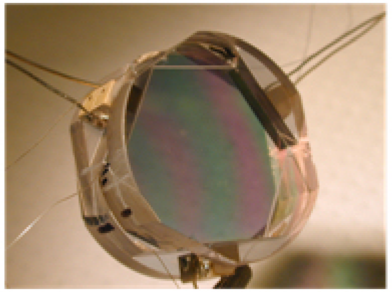


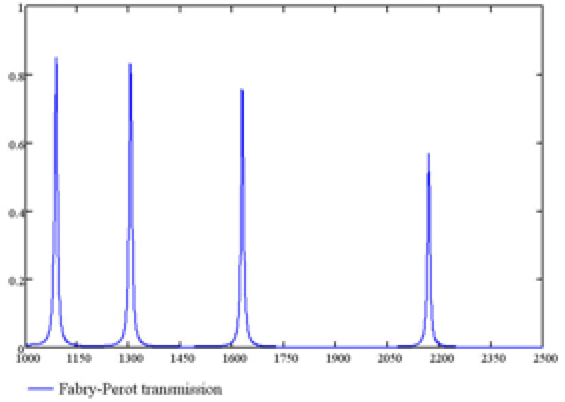


Combined spectral transmission of Patterned dielectric multispectral filter array and Fabry-Perot Interferometer used at 4 orders



Piezoactuated Fabry-Perot Interferometer module

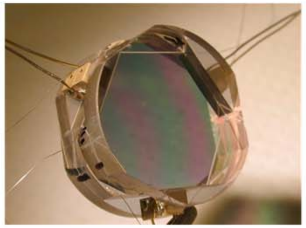


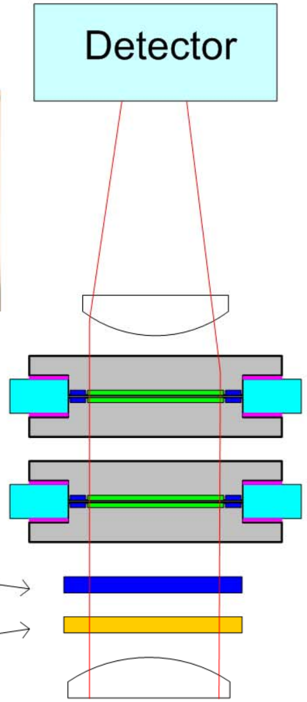


Hyperspectral imager concept based on two Fabry-Perot Interferometers in series 1(2)

- The concept has been used, for example, in the TESOS instrument (A double Fabry-Perot instrument for solar spectroscopy, ref. Kentischer et al., 1998).
- The instrument concept is based on the use of two Fabry-Perot Interferometers (FPI) in series.
- The first one is at low order and the second one at high order.
- The first FPI acts like a broad band pass filter and the second FPI is used at a high order to provide the required high spectral resolution.

Hyperspectral imager concept based on two Fabry-Perot Interferometers 2(2)

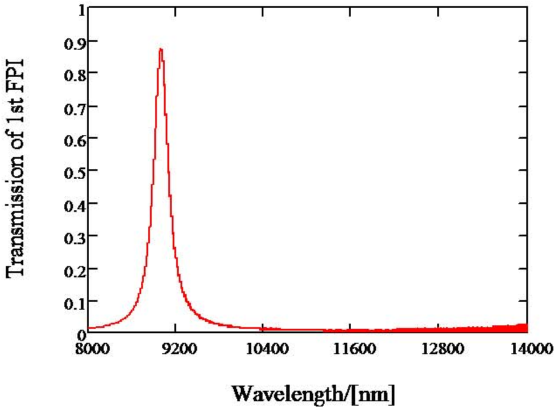




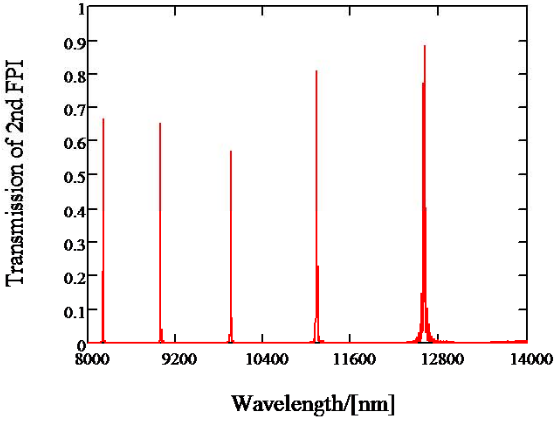
FPI1 and FPI2
Fabry-Perot
Interferometers

High Pass Filter

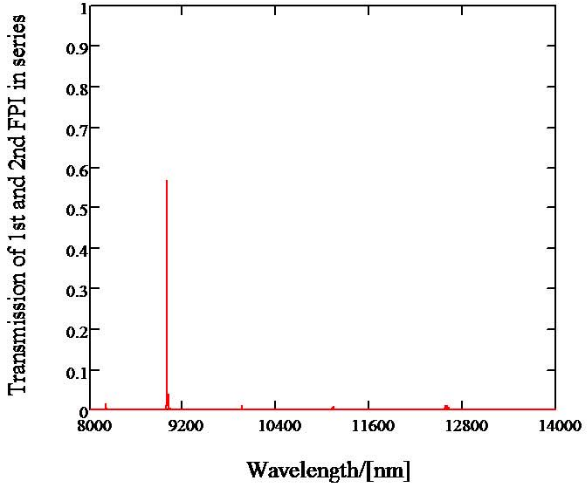
Low Pass Filter



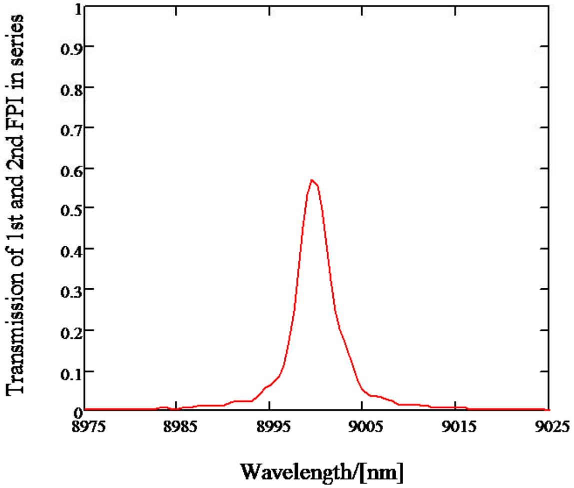
1st FPI order 1, air gap = 4500 nm



2nd FPI order 10, air gap = 45000 nm



1st FPI at order 1 and 2nd FPI at order 10



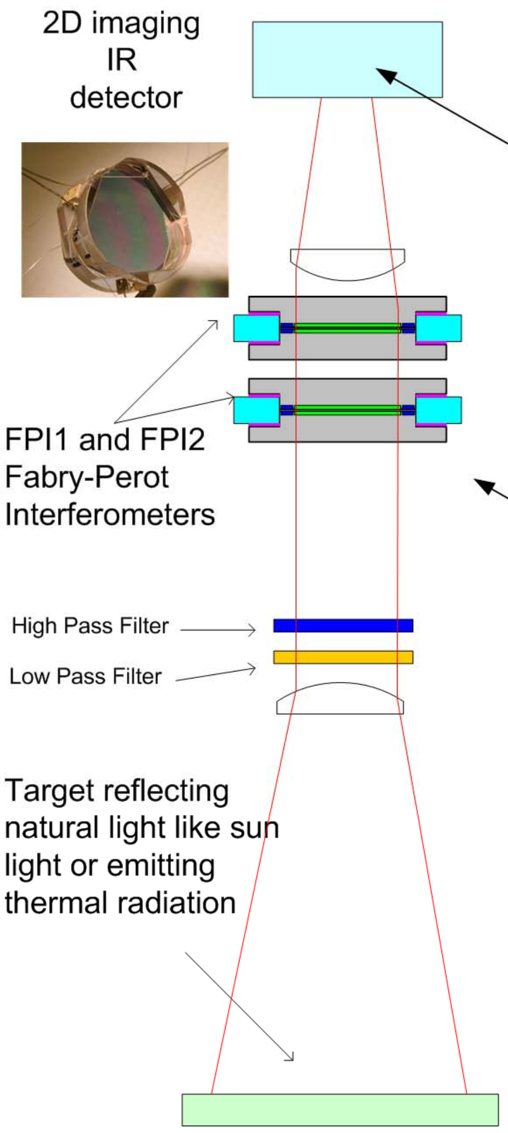
1st FPI at order 1 and 2nd FPI at order 10

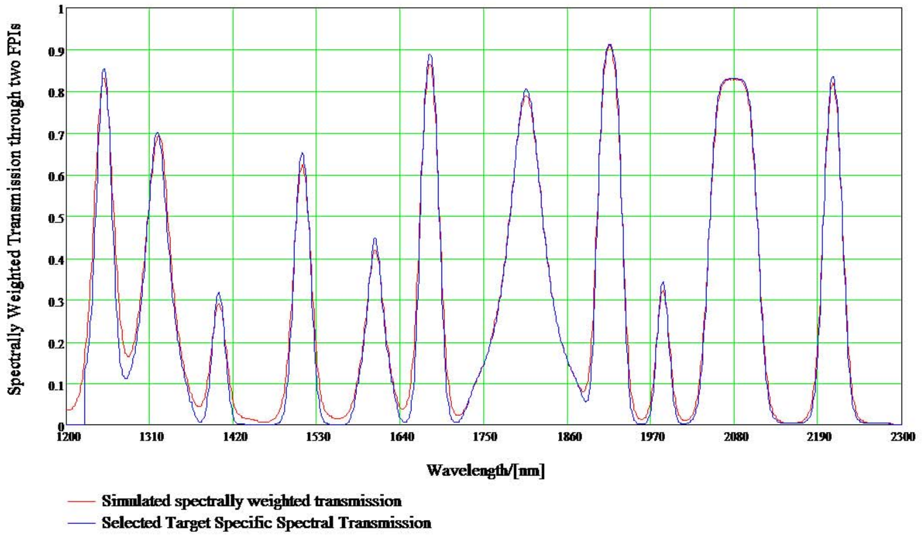
Target Specific Spectral Imaging concept based on two Fabry-Perot Interferometers 1(2)

- In many applications the spectral signature of a target is known and the target is desired to be recognized by means of this signature in real-time.
- Imaging Spectral Signature Instrument (ISSI) concept provides capability to construct 1D target specific spectral image in real time
- VTT has introduced a novel concept (Pat. pending PCT/FI/2010/050258) based on using two Fabry-Perot Interferometers to provide the spectral weighting of a 2D image during the exposure.
- Contribution of each spectral band to the total signal of the exposed image can be controlled by adjusting the orders of the two FPIs and the effective integration time of each set of FPI orders.

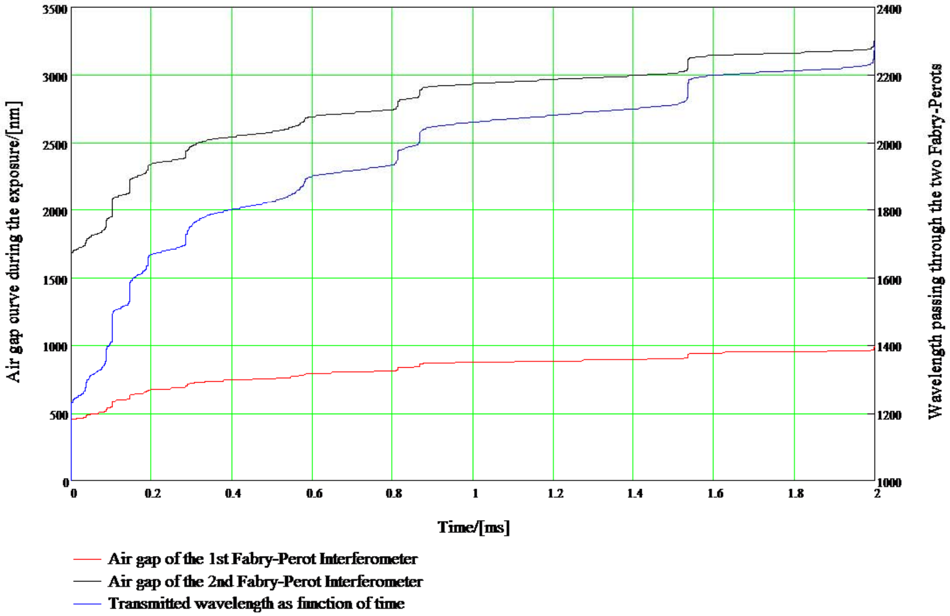
Target Specific Spectral Imaging concept based on two Fabry-Perot Interferometers 2(2)

- Example for realizing a target specific spectral imaging in the range 1200 – 2300 nm
- The air gaps 2 FPIs are changed continuously during the 2 ms exposure (500 – 1000 nm and 1700 – 3100 nm).
- With the selected air gap curves the targetted spectral transmission can achieved.





Changing the air gaps of the two Fabry-Perot Interferometers during the image exposure it is possible to implement a target specific weighted spectral transmission



Conclusions

- The possibilities to apply Fabry-Perot Interferometer Hyperspectral Imaging technology in Space Applications were discussed.
- Comparison of AOTF, LCTF and Fabry-Perot tunable filter technologies shows that the FPI technology provides advantages when highly compact hyperspectral imagers are required.
- VTT MEMS and Piezo-Actuated Fabry-Perot Interferometer (FPI) Technology is suitable for space instruments and it can be tailored to wavelength ranges from UV to LWIR.
- On going development activities on FPI spectral imagers for Aalto-1 and PICASSO nanosatellites were shortly discussed.
- New hyperspectral imager concepts based on dichroic filter arrays and 2 or more cascaded Fabry-Perot interferometers were presented.

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