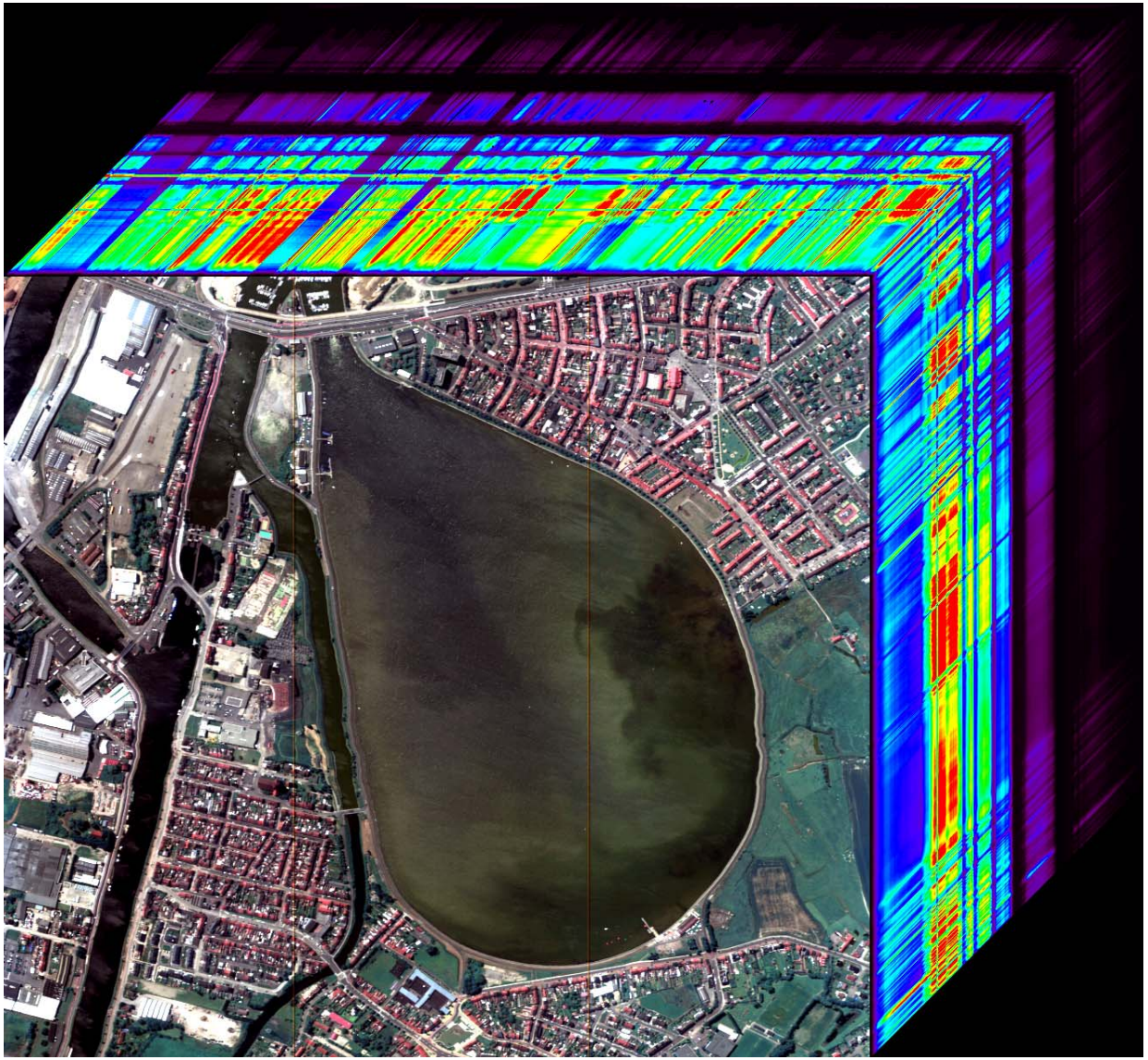


apeX

Airborne PRISM Experiment

University of Zurich
REMOTE SENSING LABORATORIES RSL
vito vision on technology
esa
RUAG
netcetera Quality Software Engineering
OIP Sensor Systems

APEX
Airborne Prism Experiment

Michael Schaepman, Edoardo Alberti, Francesco Dell'Endice, Petra D'Odorico,
Andreas Hüni, Klaus Itten (1)
Koen Meuleman, Bart Bomans (2)
Daniel Schläpfer (3)
Gerd Ulbrich (4)

(1) Remote Sensing Laboratories, University of Zurich, Switzerland
(2) VITO, Mol, Belgium
(3) ReSe Applications Schläpfer, Wil, Switzerland
(4) ESA ESTEC, Noordwijk, The Netherlands

Background

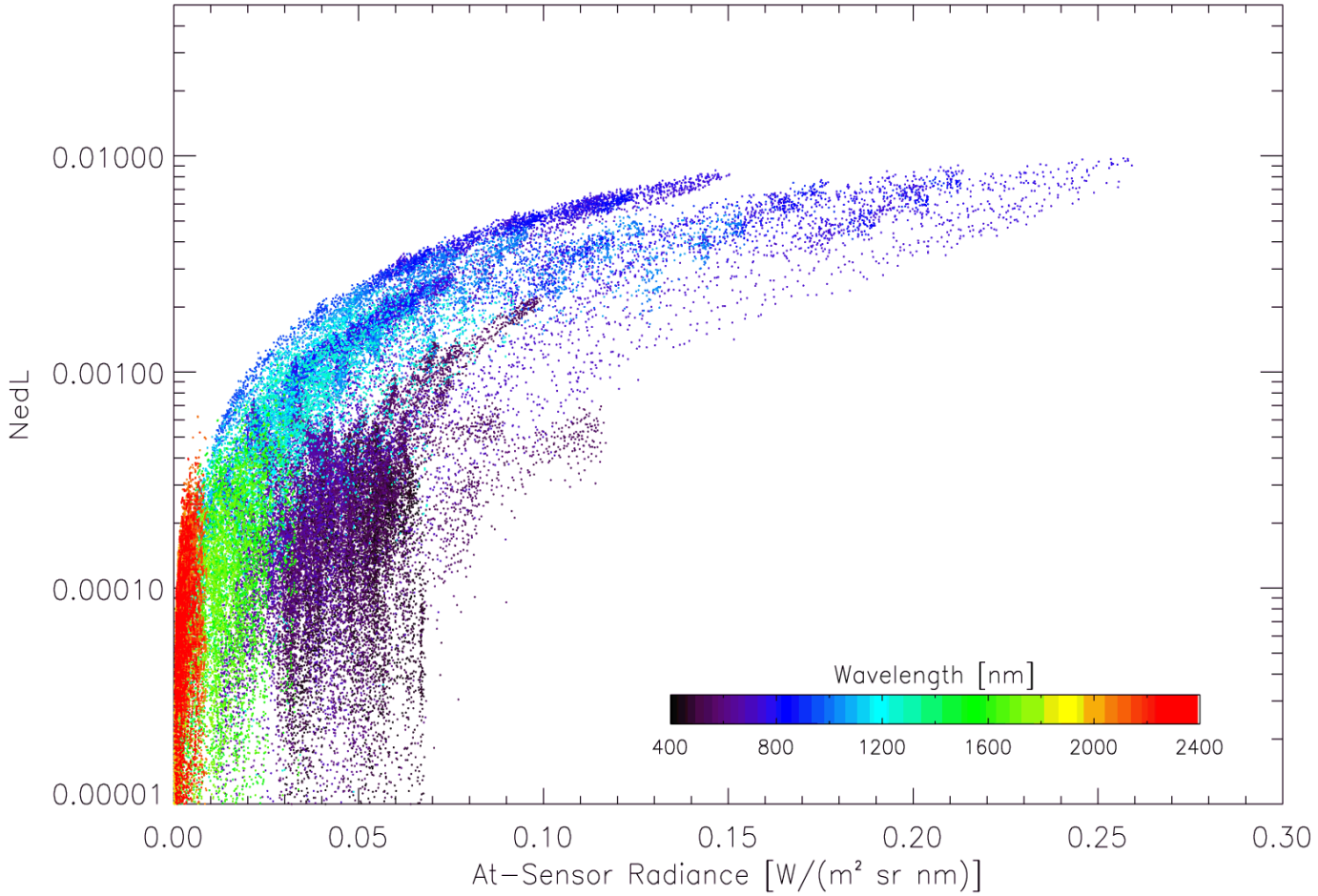
- APEX was initiated by Klaus Itten following the MacEurope campaign (1991)
- After several phases of reshaping an instrument proposal, ESA was identified as funding agency (1994)
- Belgium was asked to join in (1996)
- First instrument concept identified (1998)
- Requirements, specifications, feasibility studies (2001)
- Breadboarding activities (detectors, optical parts) (2003)
- Critical Design Review (2006)
- Acceptance flights (2009)
- Operations 2010-2015

- During realization of APEX, it has 'lost' all its spaceborne missions it was designed to simulate (PRISM, LSPIM, SPECTRA)
- Currently, APEX is foreseen to siumlate ESAs Sentinel missions, and complement the FLEX technology demonstrator

APEX – Performance Requirements

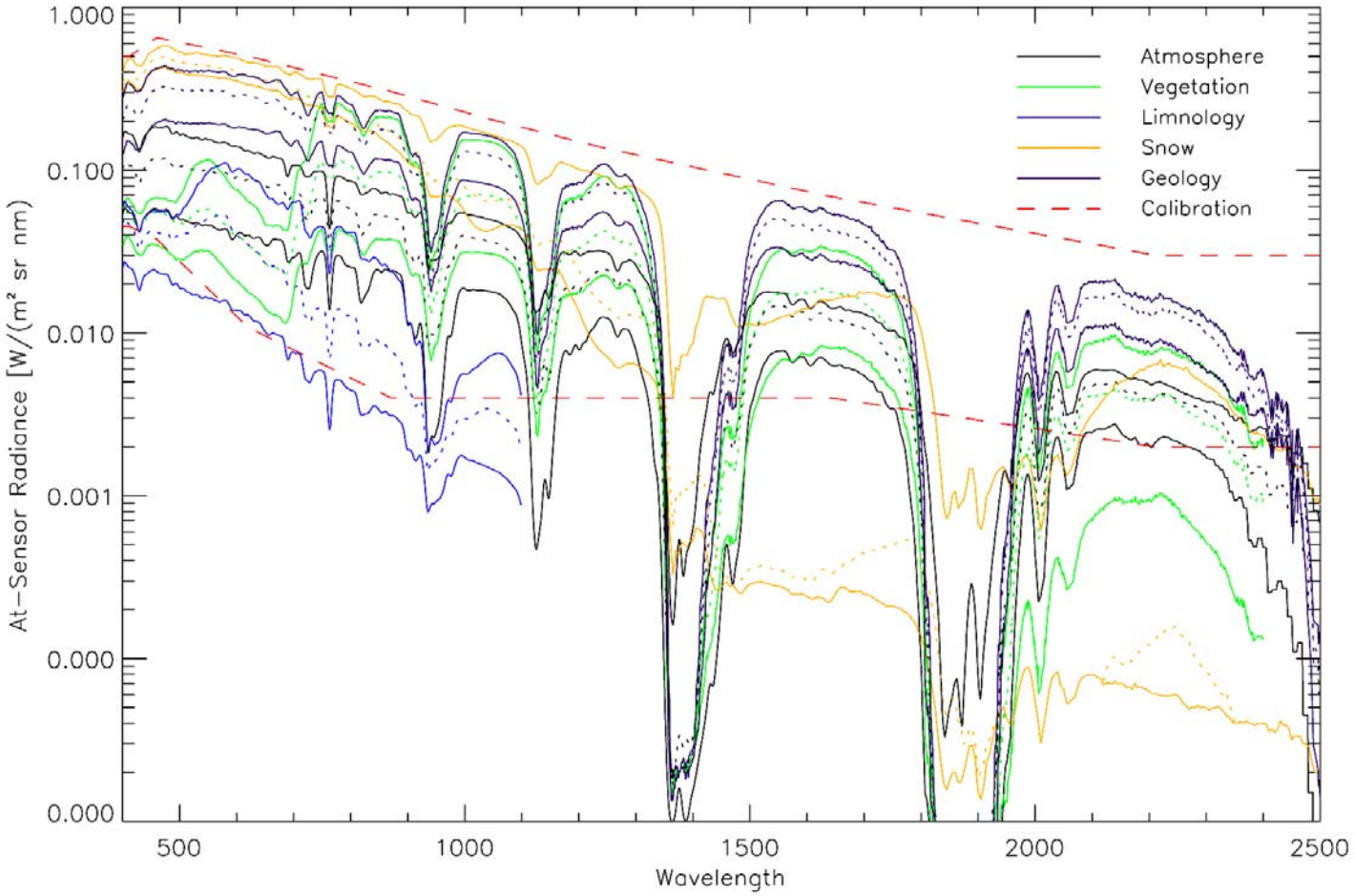
- One magic number: SNR = 1000

APEX Performance Definition

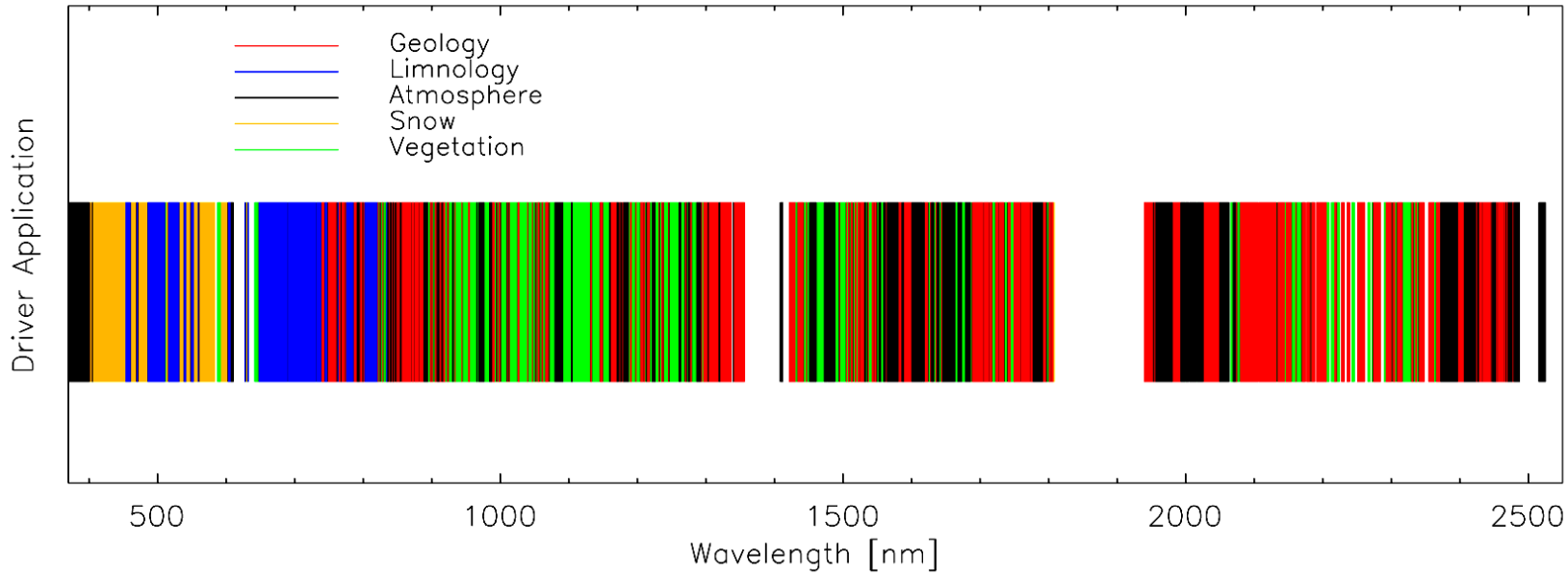


Schaepman, M.E., Schläpfer, D., & Müller, A. (2002). Performance requirements for airborne imaging spectrometers. In M.R. Descour & S.S. Shen (Eds.), *Imaging Spectrometry VII (pp. 23-31). San Diego: SPIE*

APEX Performance Definition



APEX Performance Definition



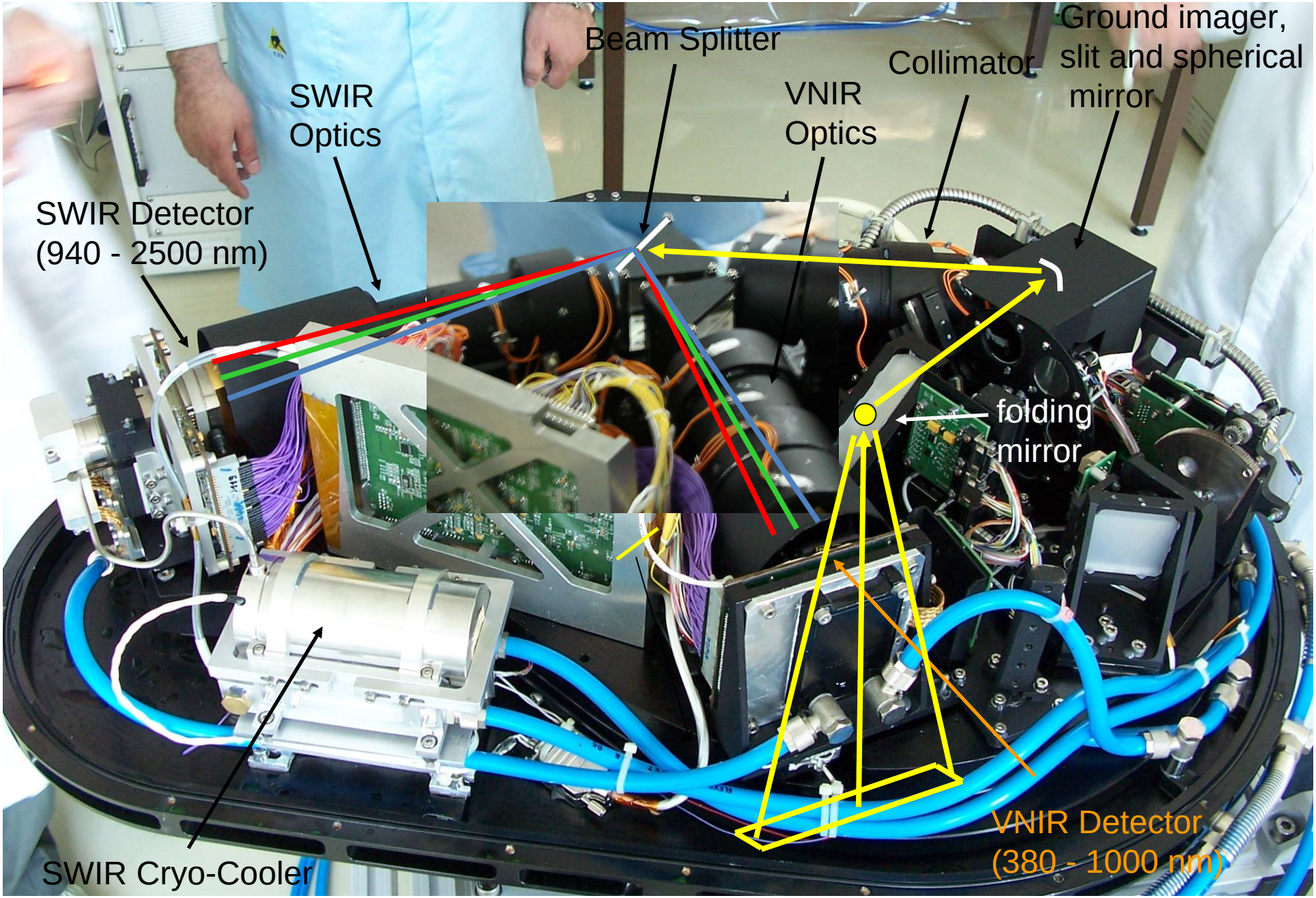
Schläpfer, D., & Schaepman, M.E. (2002). Modeling the noise equivalent radiance requirements of imaging spectrometers based on scientific applications. *Applied Optics, 41, 5691-5701*

APEX Performance

Spectral Performance	**VNIR**	**SWIR**
Spectral Range	380 – 970 nm	940 – 2500 nm
Spectral Bands	Up to 334 (default: 114)	199
	(number of VNIR spectral rows programmable via binning pattern upload)	
Spectral Sampling Interval	0.5 - 8 nm (default: 11 - 8 nm)	10 - 6 nm
Spectral Resolution (FWHM)	0.6 - 6.3 nm	13.5 - 7 nm
Spatial Performance		
Spatial Pixels (acrosstrack)	1024	dito
FOV	28°	
IFOV	0.028° (ca 0.5 mrad)	
Spatial Sampling Interval (across track)	1.75 m @3500 m AGL	
Sensor Characteristics		
Dynamic Range	CCD, 14 bit encoding	CMOS, 13 bit encoding
Pixel Size	22.5 µm x 22.5 µm	30 µm x 30 µm
Smile		0.2 pixel
Keystone (Frown)	Average, less than	0.2 pixel
Co-Registration		< 0.2 pixel nominal, 0.6 max.
Other Information		
Data Capacity	500 GB on SSD	
Data Transfer	Spectral frames	30 MB/s via Optical Link
	Housekeeping Data	20 kB/s via SR
Flight mission in default configuration	0.4 GB/km (1250 km over target, max)	

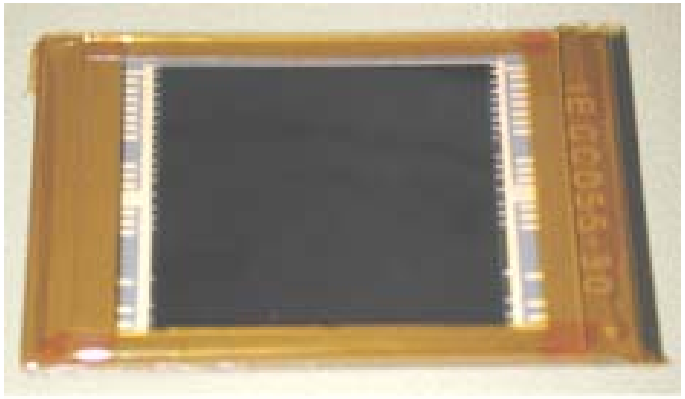
APEX Aircraft Integration

APEX Optical Sub-Unit



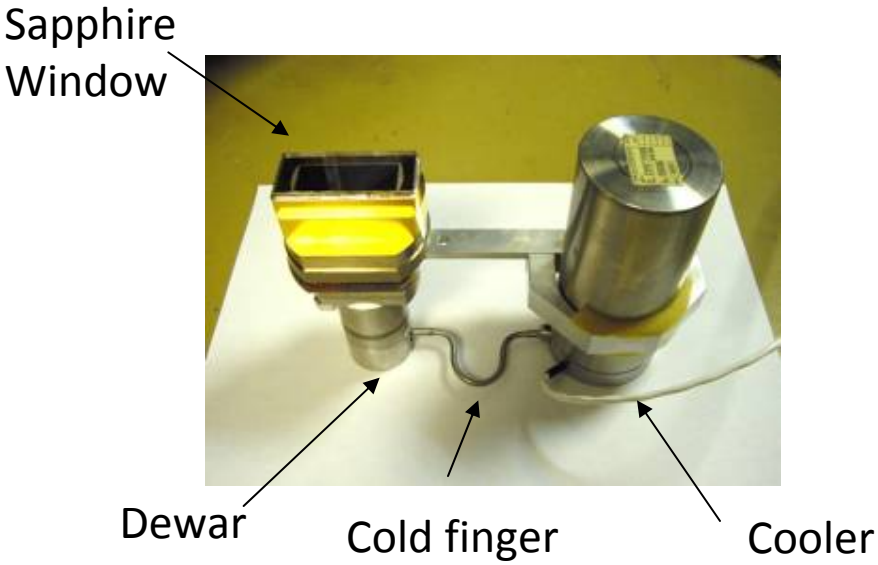
VNIR and SWIR Detectors

- CCD 55-30 from E2V Technologies (GB)
  - Frame transfer mode
  - 1252 x 1152 pixel (eff. 1000 x 334)
  - Pixel pitch 22.5 µm x 22.5 µm
  - Fill factor 100%
  - Back illuminated
  - Read out frequency 7 MB/s
  - 14 bit encoding



Overall datastream: 30 MB/s!

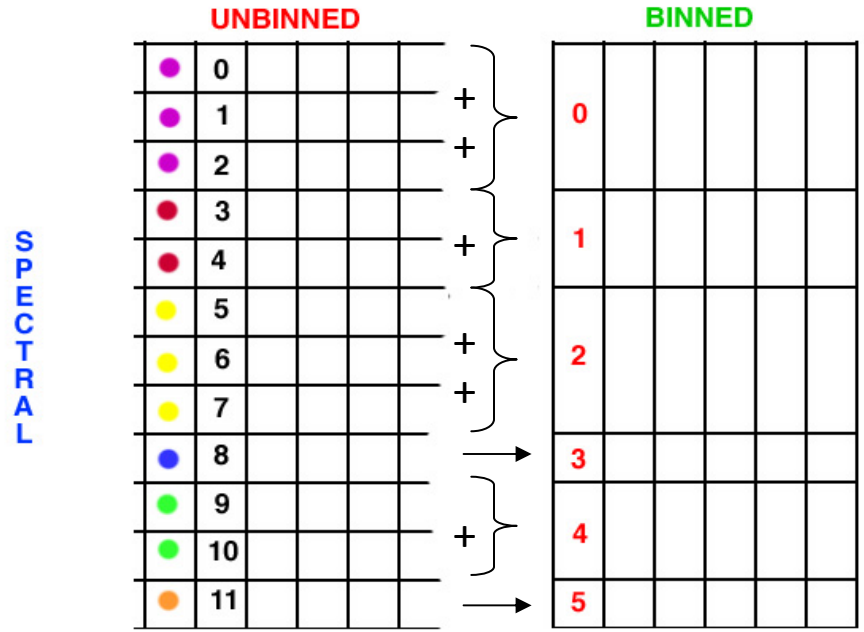
- HgCdTe CMOS from SOFRADIR (F)*
  - Hybridized on multiplexer
  - 1024 x 256 square pixels (eff. 1000 x 199)
  - Pixel pitch 30 µm x 30 µm
  - Addressable readout, fast operation
  - Integrated in cryostat cooler assembly
  - Wavelength range: 0.94 – 2.50 µm
  - QE: > 70 % average, $T_{op.}$: 150 K
  - 13 bit encoding



Detector with Cryostat/Dewar Assembly

*custom developed under ESA-EOP contract

Spectral Binning Patterns: BinGO

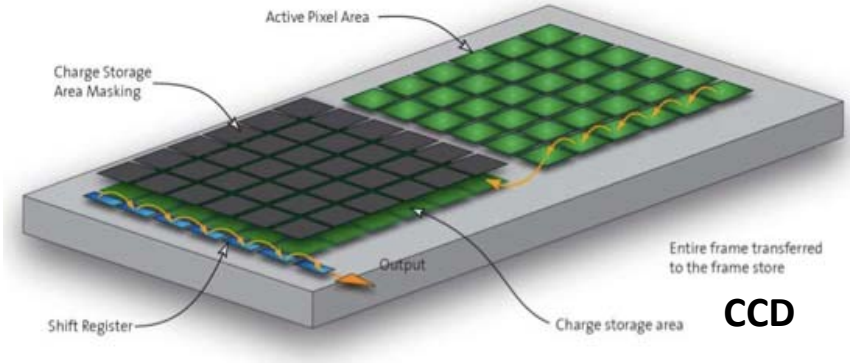


Binning spectral bands

- increases/optimizes SNR
- adds application flexibility
- increases FWHM

Optimization based on SNR

$$SNR = \frac{S}{N} \propto \frac{\frac{L * A * S^2 * \tau * \eta * \lambda * \Delta\lambda * t}{h * c}}{\sqrt{N_{dark}^2 + N_{amp}^2 + N_{read}^2 + N_{ADC}^2 + N_{phot}^2 + N_{other}^2}}$$



APEX unbinned bands:

o334 VNIR (on-chip binning, adjustable gain)

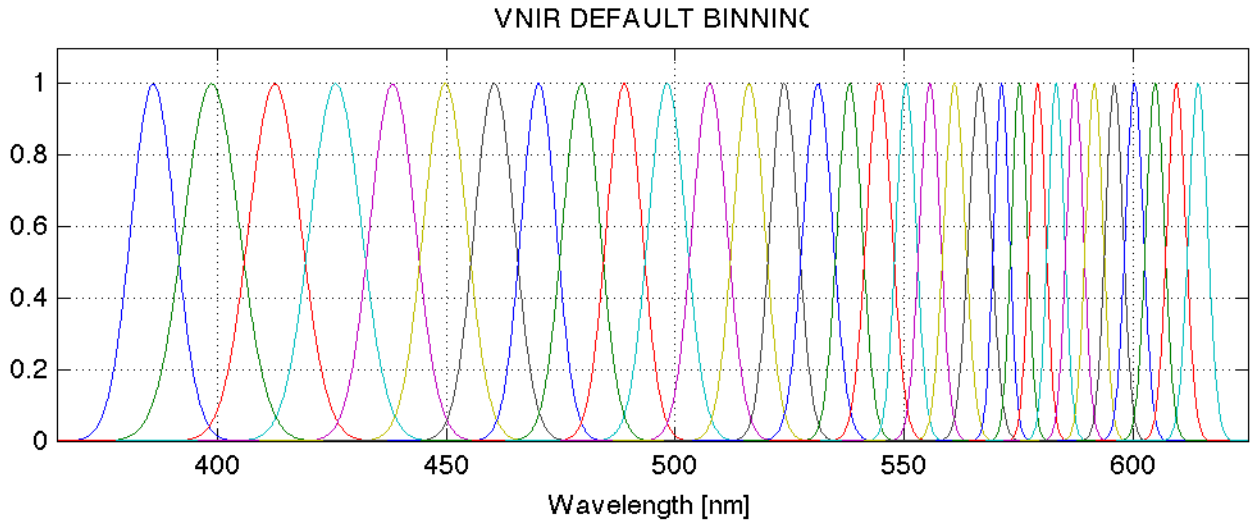
o199 SWIR (SW binning possible, adjustable gain)

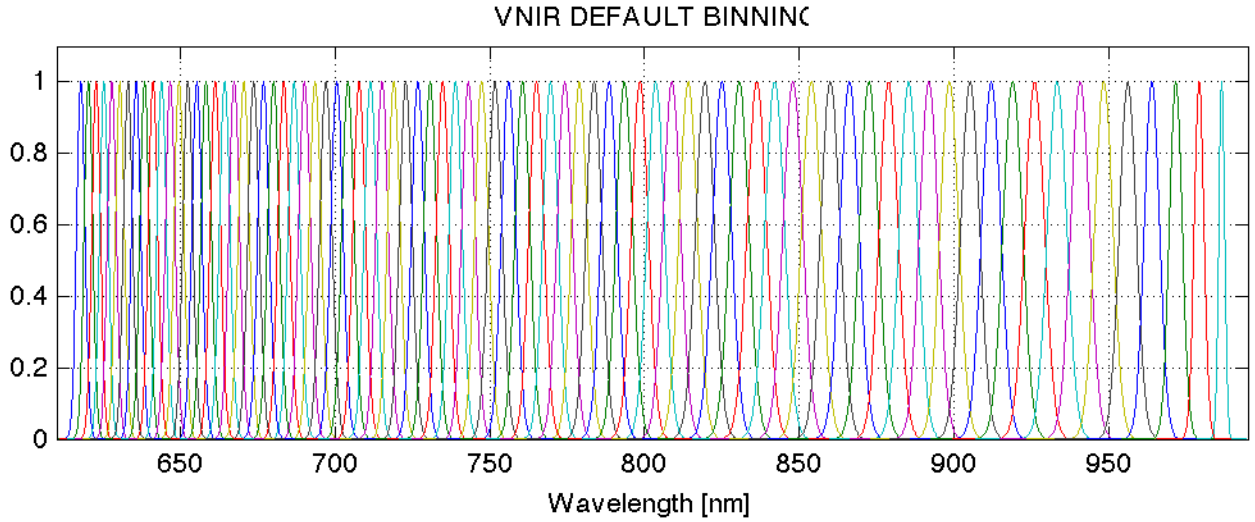
Variables:

- Spectral FWHM
- Integration Time
- SNR
- Ne Δ L
- Uncertainty estimates
- Spatial Resolution

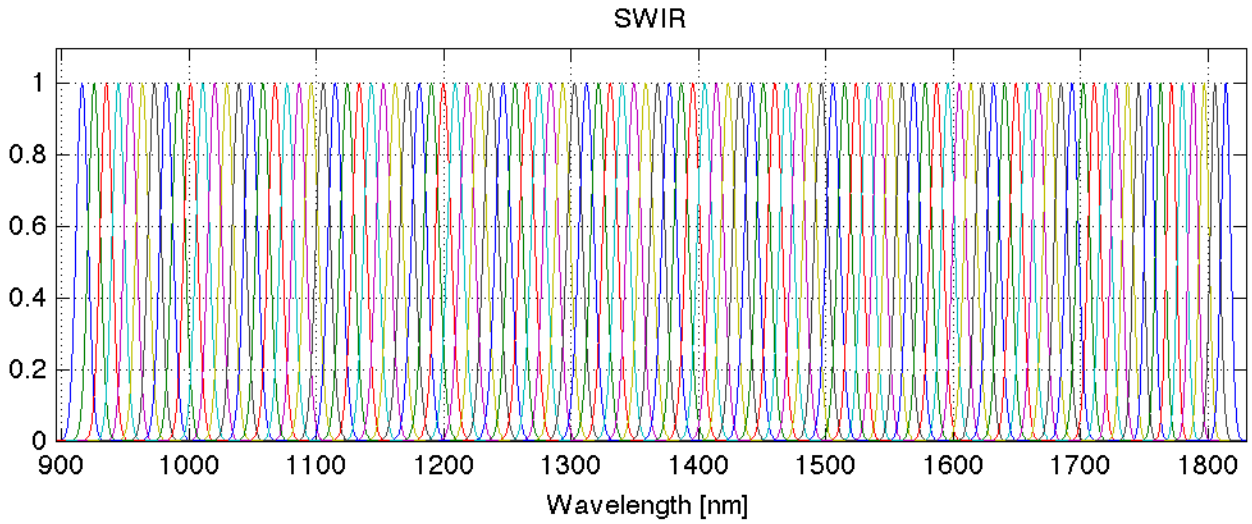
Dell'Endice, F., Nieke, J., Koetz, B., Schaepman, M.E., & Itten, K. (2009). Improving radiometry of imaging spectrometers by using programmable spectral regions of interest. *ISPRS Journal of Photogrammetry and Remote Sensing, In Press*

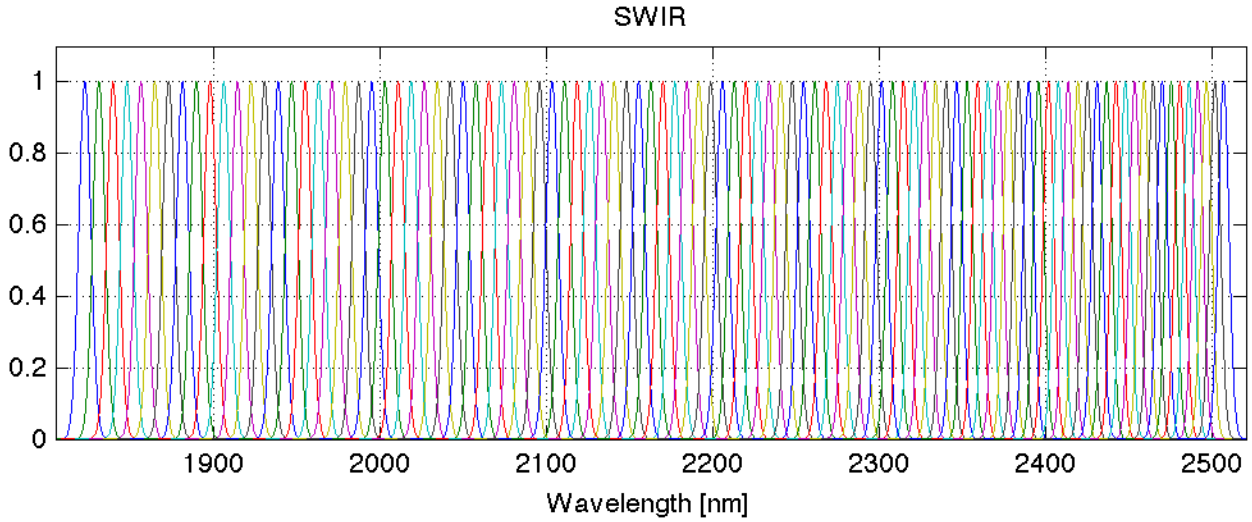
VNIR FWHM and Binning





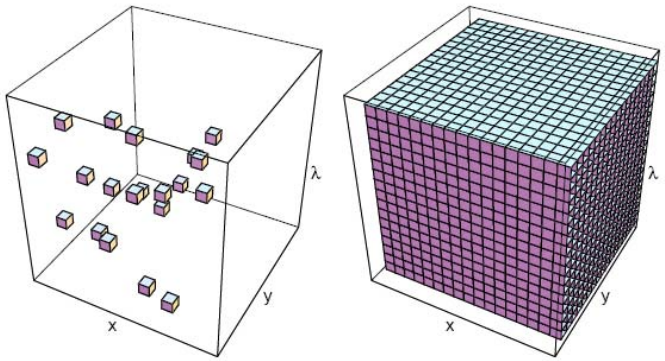
SWIR FWHM


SWIR
1
0.8
0.6
0.4
0.2
0
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
Wavelength [nm]

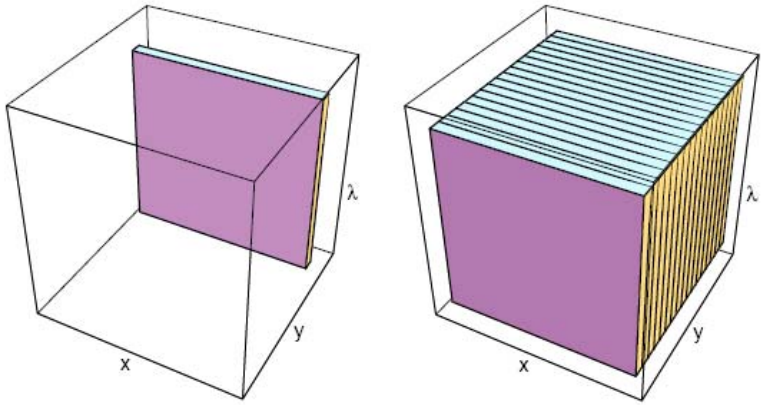

SWIR
1
0.8
0.6
0.4
0.2
0
1900
2000
2100
2200
2300
2400
2500
Wavelength [nm]

APEX – Calibration Concept

- Provision of well calibrated remote measurements incl. uncertainty estimates
- Calibration of all individual ‘radiometers’ of APEX as a function of time (1024*(334+199)*(scan lines),t)
- Downscaling the amount of calibration data (pushbroom, interpolation, symmetry)



Generic IS



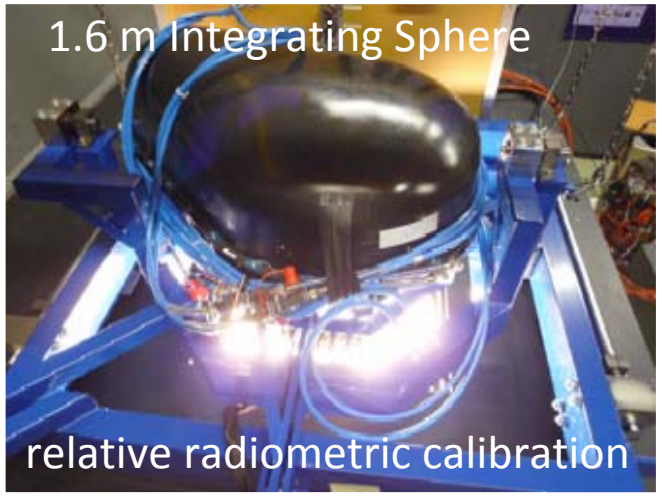
Pushbroom IS

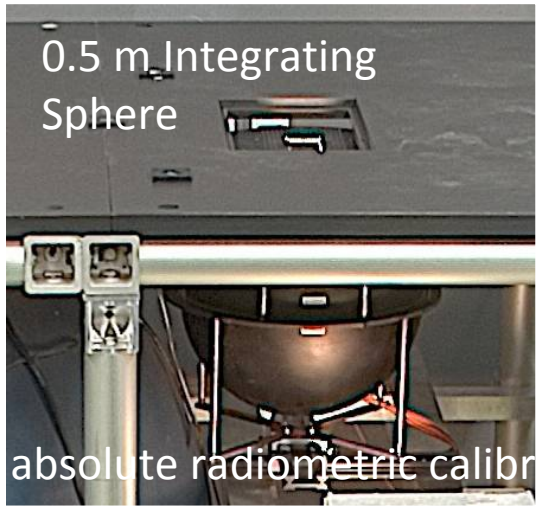
APEX – Calibration Concept

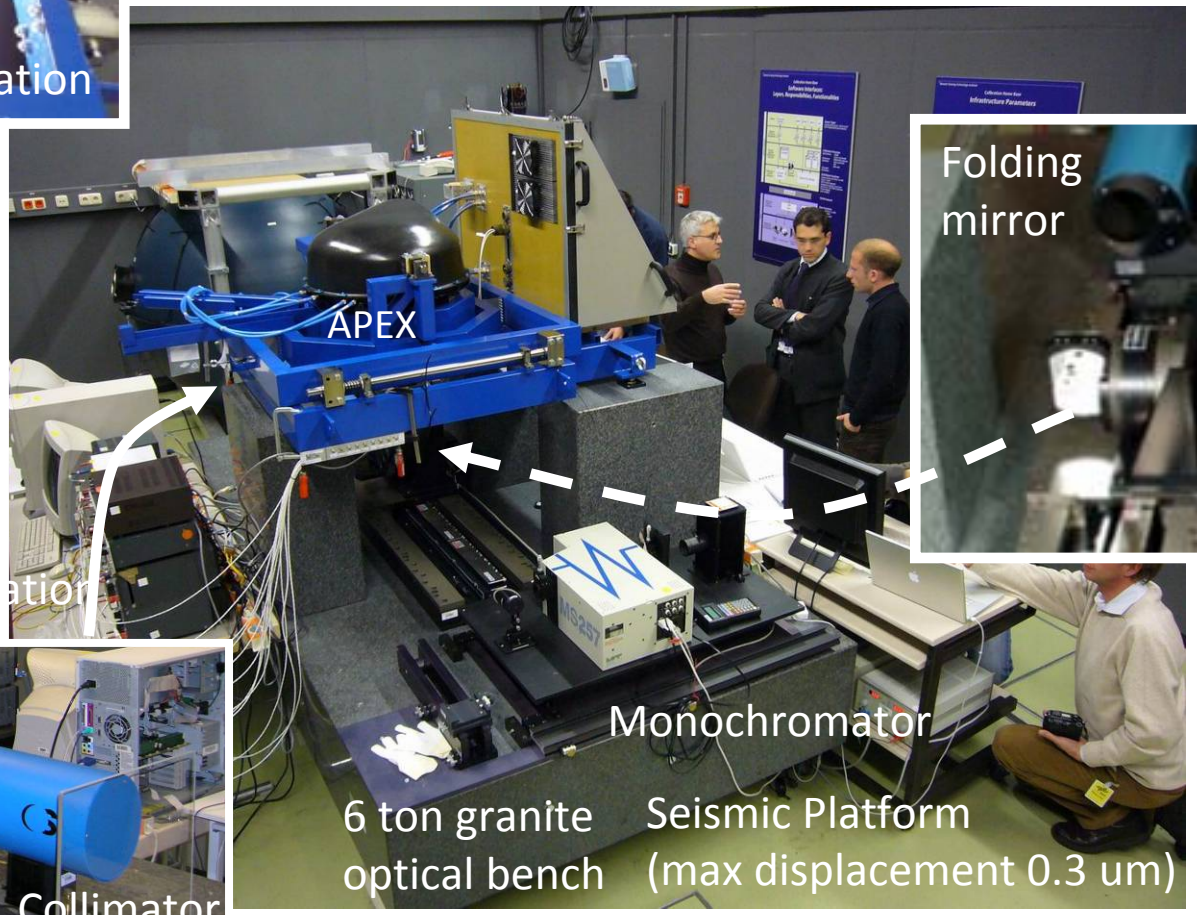
- CHB – Calibration Home Base (installed at DLR Oberpfaffenhofen (GER)
- IFC – In-flight calibration, allowing reference measurements before and after each data take
- Vicarious calibration activities
- PAF/CTM – Processing and Archiving Facility and Calibration Test Master

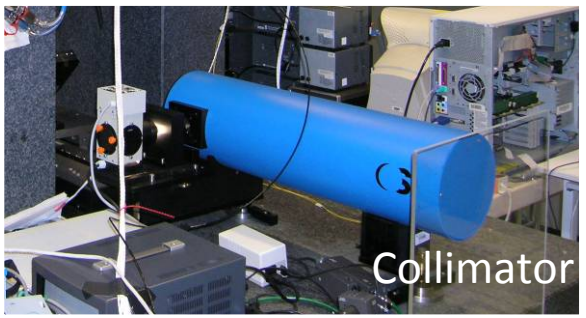
Calibration Home Base

Designed and realised to meet APEX instrument requirements (e.g. Instrument alignment has to be performed within 0.005° in roll, pitch and yaw)



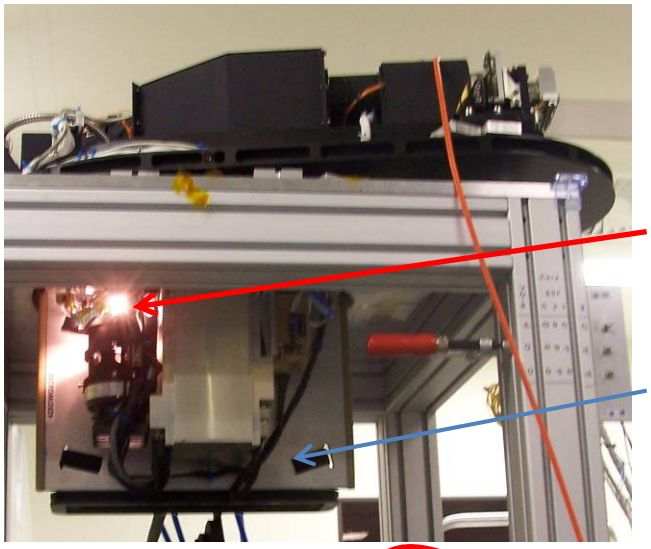






CHB at DLR (Oberpfaffenhofen, GER)
ESA funded facility, enabled through APEX requirements

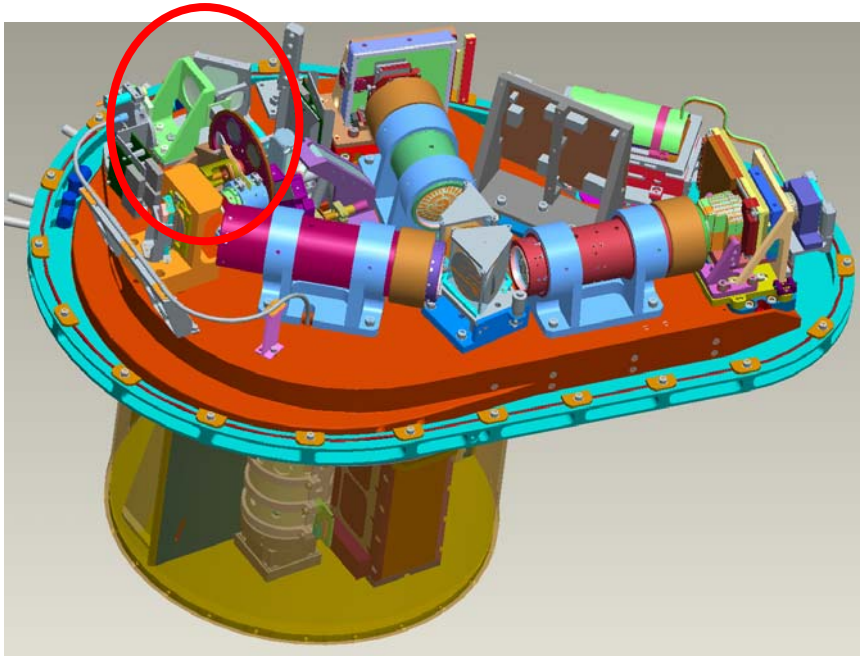
In-Flight Characterization Facility

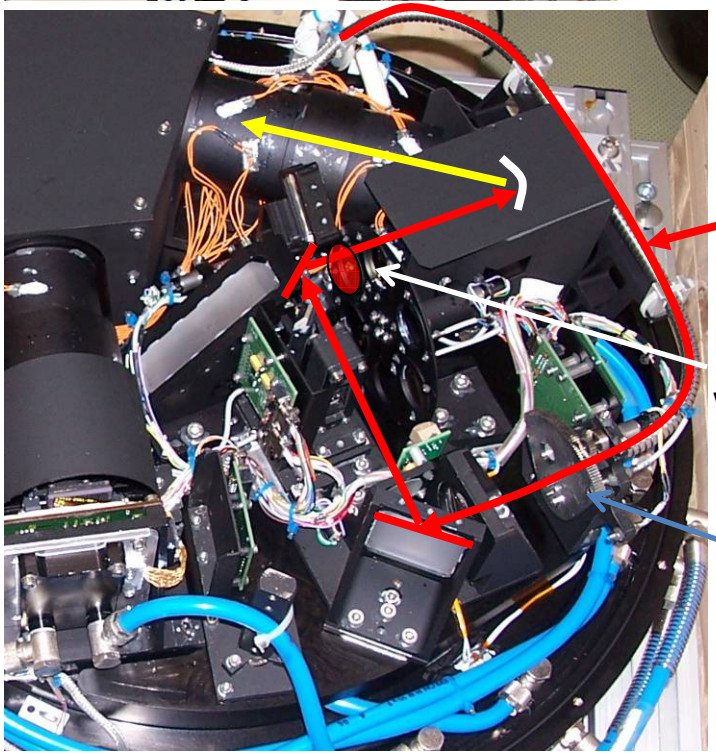


Stabilised IFC QTH lamp

Entrance Baffle

The IFC is a tool designed to investigate the overall instrument (radiometric, spectral, geometric) stability in-flight





IFC light path (glass fiber)

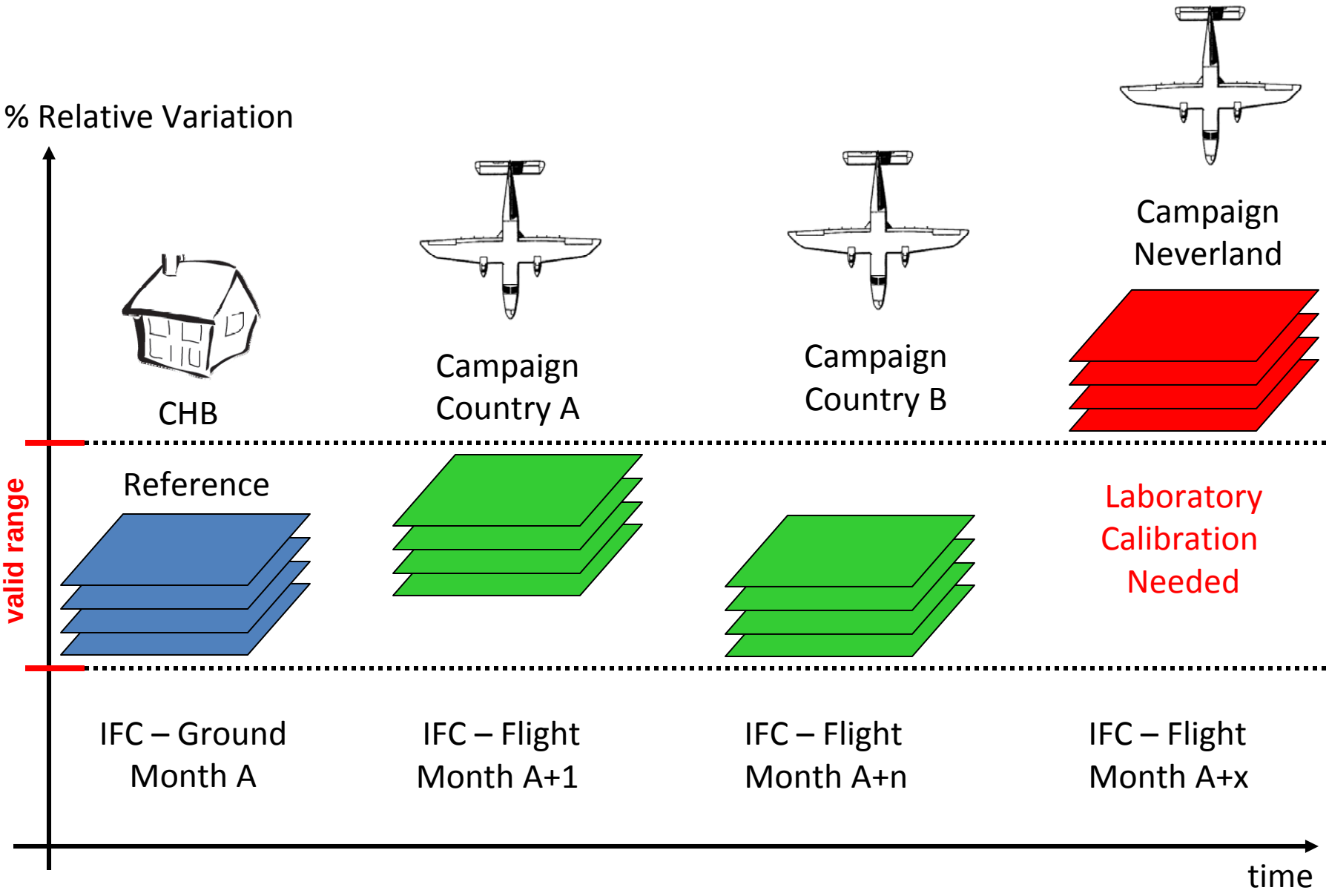
Filter wheel

Shutter for standard imaging operations

Installed Filters:

- 3 Bandpass (color) Filters
- 1 Rare Earth Material (NIST) filter
- 1 Neutral Density (gray) filter

Monitoring Stability: An Example

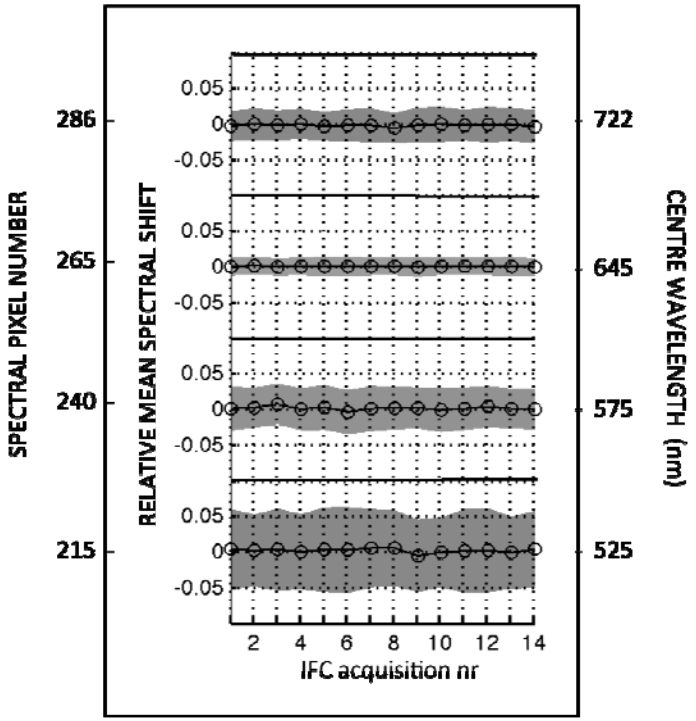


Spectral Stability Monitoring

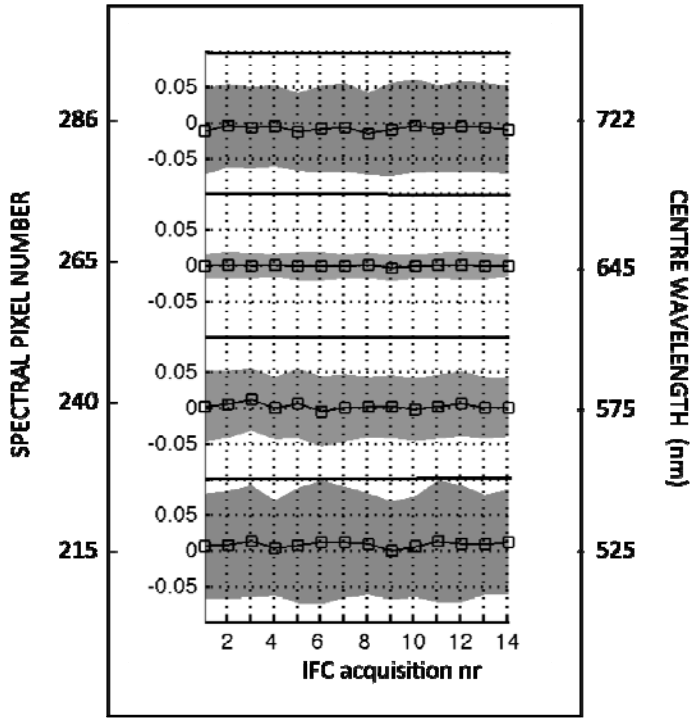
Spectral features used for shift retrieval:

BP700 655-808 nm
SRM-NIST 626-672 nm
SRM-NIST 555-598 nm
SRM-NIST 516-539 nm

EF: CORRELATION COEFFICIENT



EF: CENTER OF GRAVITY DELTA



Calibration Test Master (CTM)

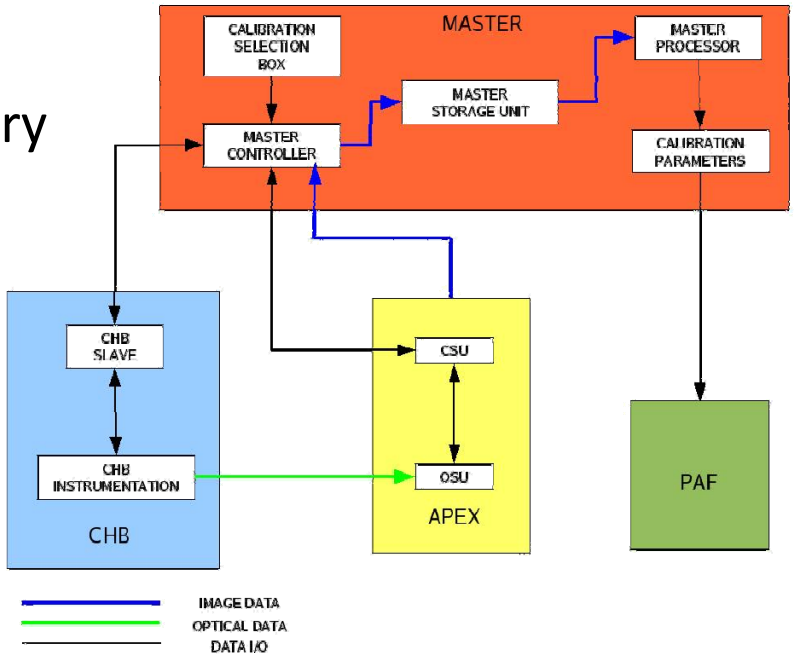
Calibration and characterisation activities are time consuming:

Spectral calibration for each pixel: **110 measurements,** each measurement requiring parameter modifications (overall matrix: 1000 x 534 pixels + temporal component)

The CTM software has been developed to automatically perform the laboratory calibration steps with minimal manual intervention.

Main components are:

1. Master Controller
2. Master Processor



Advantages:

- Automated (runs at night)
- Characterization of all radiometers
- Fully adaptable
- High accuracy of products

Spectral Calibration for 1 pixel: 2'30"

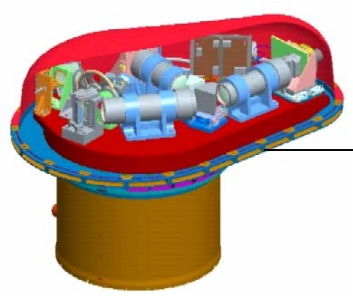
Processing and Archiving

- Operational processor and archive at VITO (B)
- Scientific processor with ‘sandbox’ access at RSL (CH)
- Mitigation of scientific products on operational processor for the user community following internal testing

Processing and Archiving

- Processing and Archiving Facility
  - PAF (SPOT Vegetation archive at VITO) – data distribution for all standard users
  - Science PAF development at RSL
- μ PAF
  - Mobile PAF following ground crew, pontentially also for advanced users
- Sandbox
  - API (Application Programmers Interface) for own development (currently in Tcl/TK and Python, partly JAVA, IDL/ENVI)
- Support Tools
  - Spectral database (www.specchio.ch) for ground measurements
  - Field/Laborartory goniometer system (incl. 2 ASDs & sunphotometer; thermal spectrometer and multispectral LIDAR to come)
- Distributed computing approach (today), cloud computing approach envisaged (Google)

Processing and Archiving Facility



SSD Data Transfer

APEX PAF
Level 0 - 1C
Processor

Level 1C Product

Calibrated image cube (HCRF)

APEX PAF
Level 2A – 2C
Processor

APEX PAF
Level 3A – 3B
Processors
(Operational & 'Sandbox')

Level 3A-3B Products

Higher order products

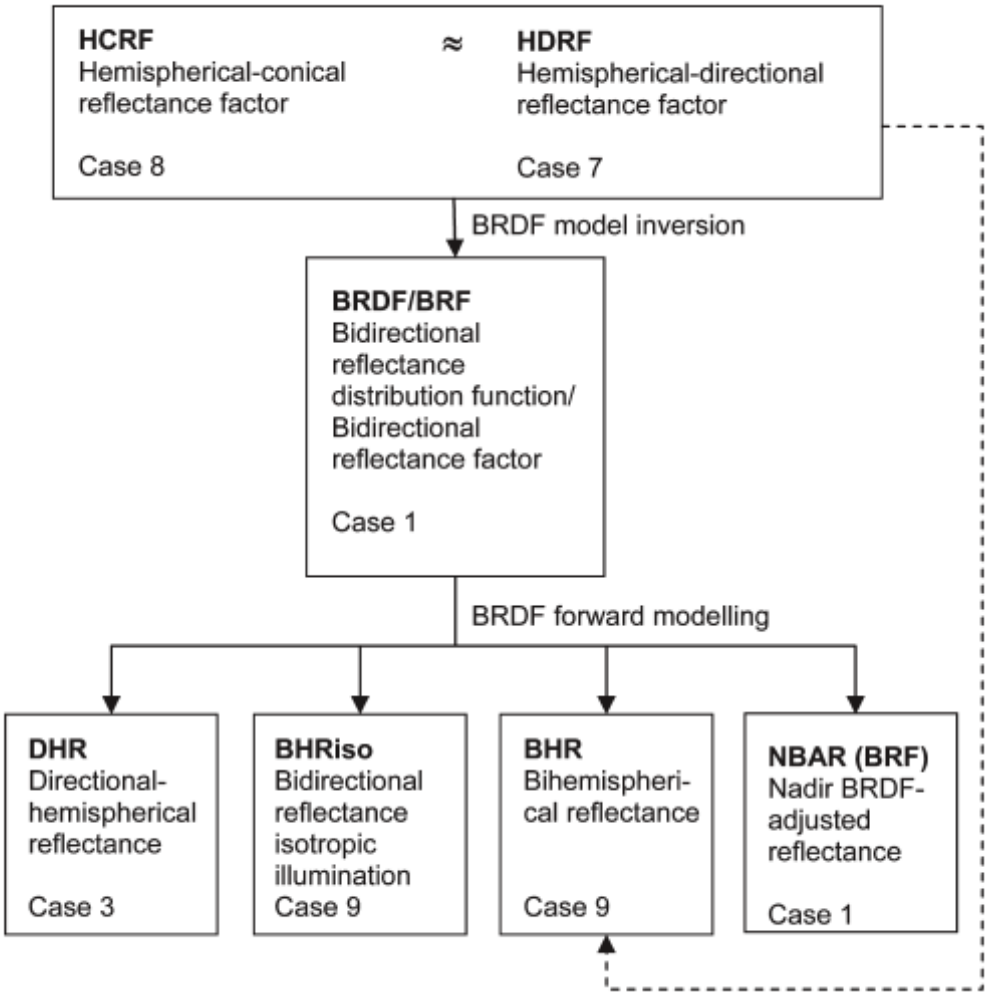
Geolocated spectral Albedo

Level 2A-2C Products

PAF Version Evolution
HCRF-BRDF-BHR
1 empirical BRDF
2 NBAR
3 DHR/BHR/BHRiso

PAF HW hosted @ VITO (Mol, B)

Reflectance & Albedo Challenge



Schaepman-Strub, G., Schaepman, M.E., Martonchik, J.V., Painter, T.H., & Dangel, S. (2009). Radiometry and Reflectance: From Terminology Concepts to Measured Quantities. In T.A. Warner, M. Duane Nellis & G. Foody (Eds.), *The SAGE Handbook of Remote Sensing (pp. 215-228): SAGE*

Target Product Challenge

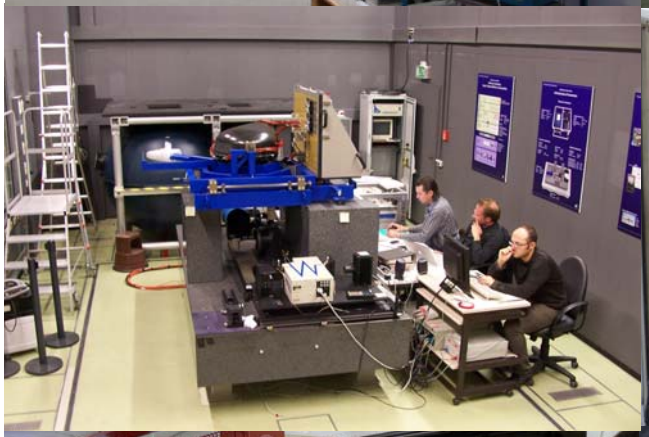
- Calibrated radiances (at-sensor, hemispherical-conical case)
- Spectral Albedo (incl. BRDF parameters)
  - DHR, BHR, BHRiso, BRF (or NBAR)
  - Conversion of spectral Albedo to Broadband, Narrowband, NIR, SWIR, etc. Albedo provided
- However (!)
  - HDRF ≈ HCRF (in satellite case)
  - Field measurements are mostly HCRF ('ASD measurements')
  - MODTRAN relies on BHR (and not on HCRF)
  - Goniometers exhibit difficulties in measuring elevated canopies (most instruments provide measurements, where x,y >> z)
  - Parametrizations of inverted atmospheric RTC (ATCOR, etc.) must be recomputed for increased spectral resolution and geographical operation
  - Albedo of partially clouded atmospheres is not yet a standard product
- Potential uncertainties in reflectance arising due to the above facts may exceed 20%!

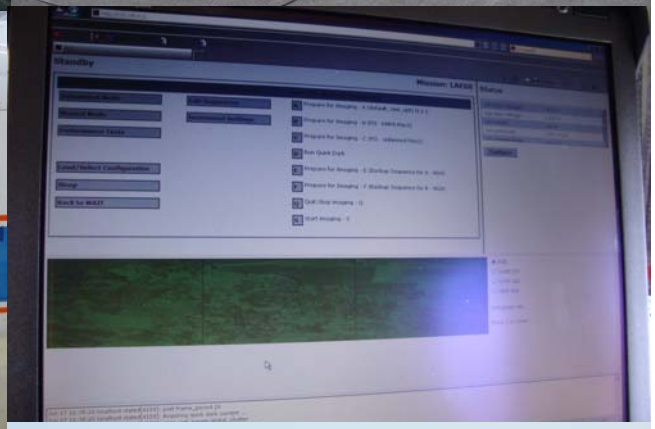
First APEX Experiments

- Scaling (FLUXNET tower representativeness) using various binning patterns
- Fluorescence proxies in homogenous canopies
- Pigment based plant functional groups
- Combined atmospheric composition and urban climate
- Ecotones of alpine species
- Biodiversity measures of dominant alpine species (stratification using PNV)
- Radiative transfer model experiements (scattering component separation (sunlit/shaded canopy; PV vs. NPV, woody elements scattering))
- Minnaert-*k* retrieval (canopy heterogeneity; snow on trees, snow under trees, understorey separation)
- Experiments related to defence & security applications (no clearance for more details ☺)
- Upcoming
  - Large scale methane emissions in Siberia (4 year vegetation removal, methane tower, and field sampling experiment (Indigirka lowlands))
  - Automatic updating of snow and ice properties within the WGMS (World Glacier Monitoring System)
  - Alpine and arctic species mapping (niche/dispersal modelling)
  - Wet/dry N deposition using atmospheric columnar nitrogen (SCIAMACHY) measures, rainfall (MSG, TRMM), atmospheric transport model (TM4/TM5), and plant functional groups
  - Spectral Albedo (goniometer measurements & multiangular APEX flights for BHR/DHR generation)


KLIMA - KAMMER

APEX



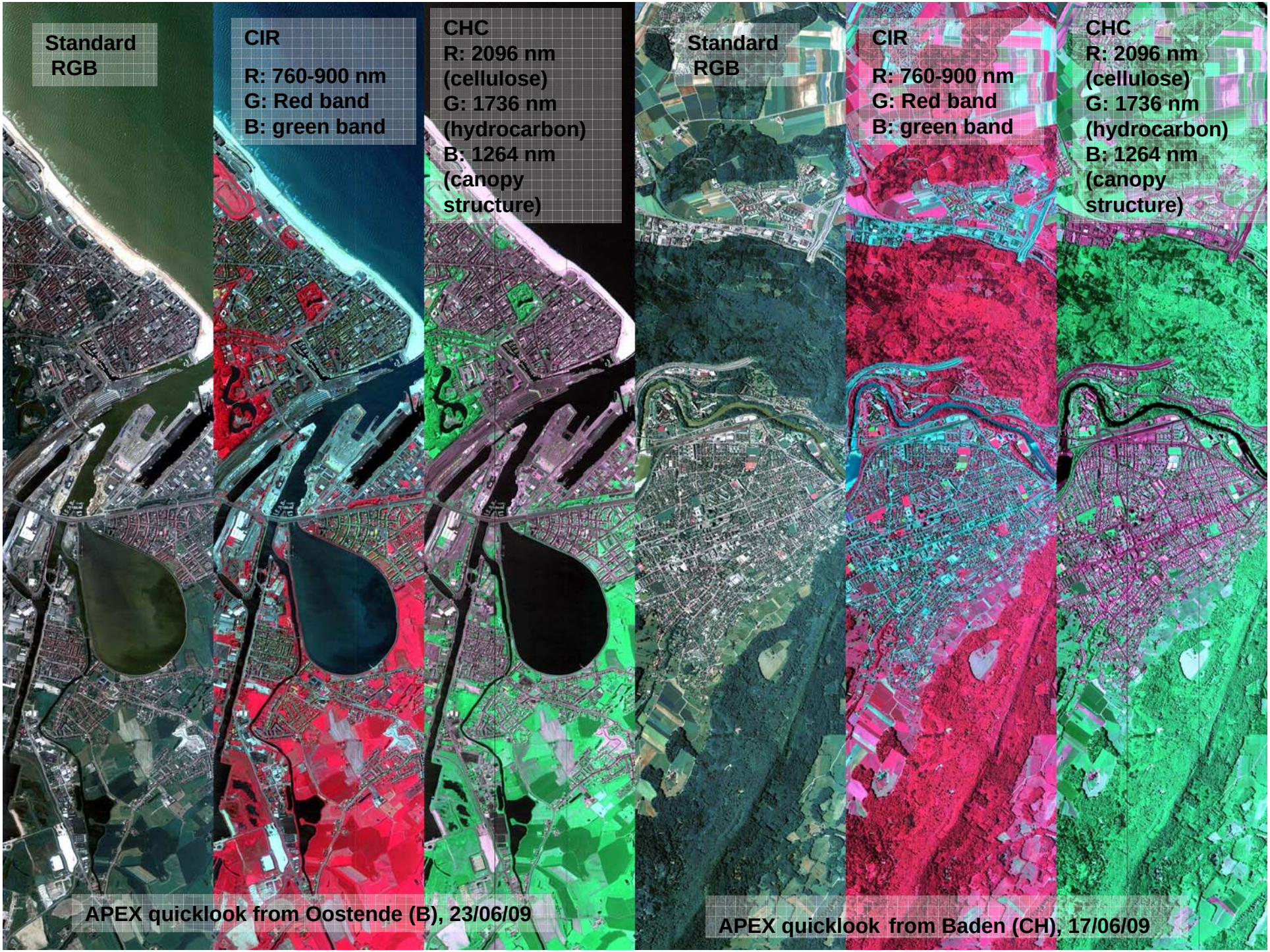
apex
apex
esa


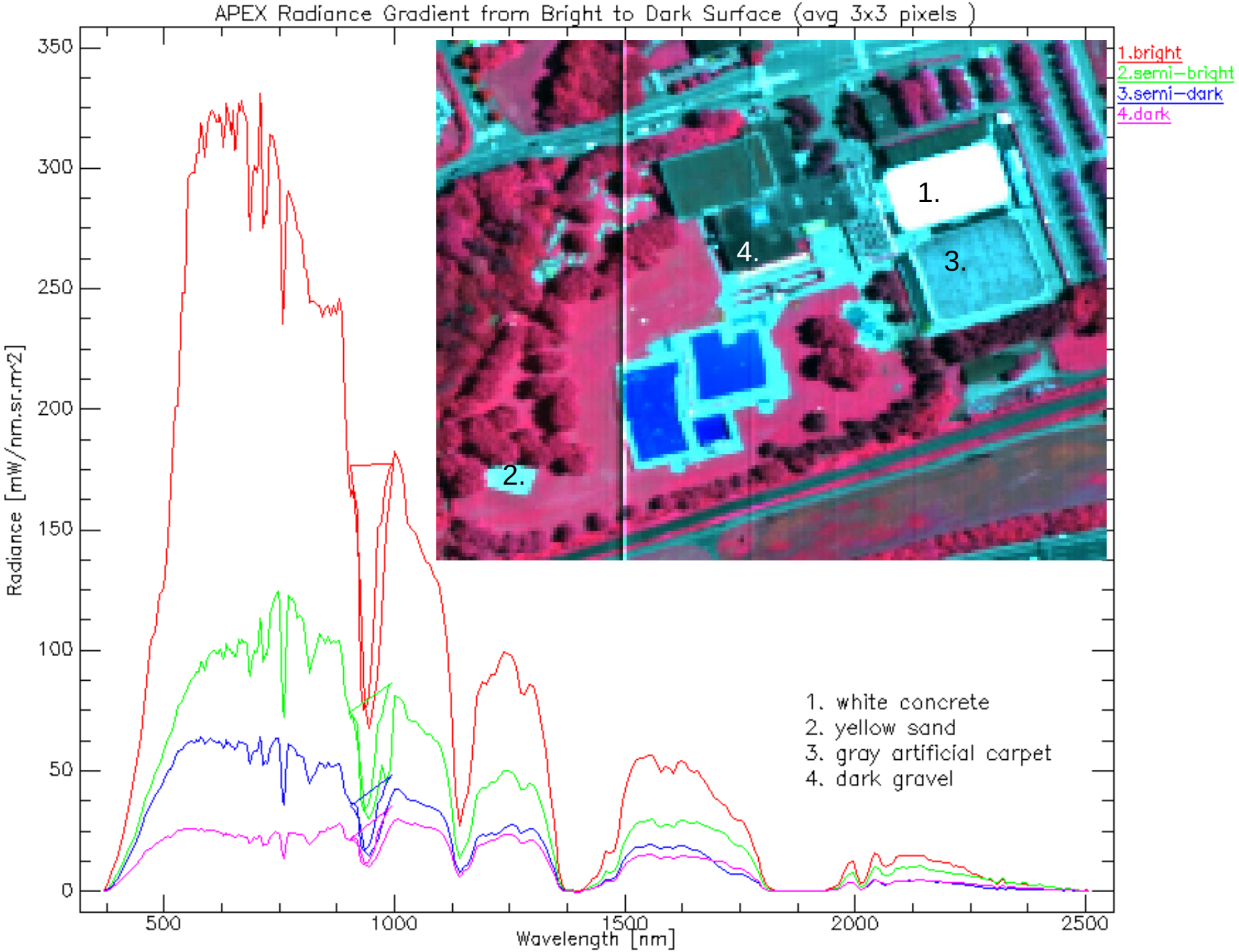


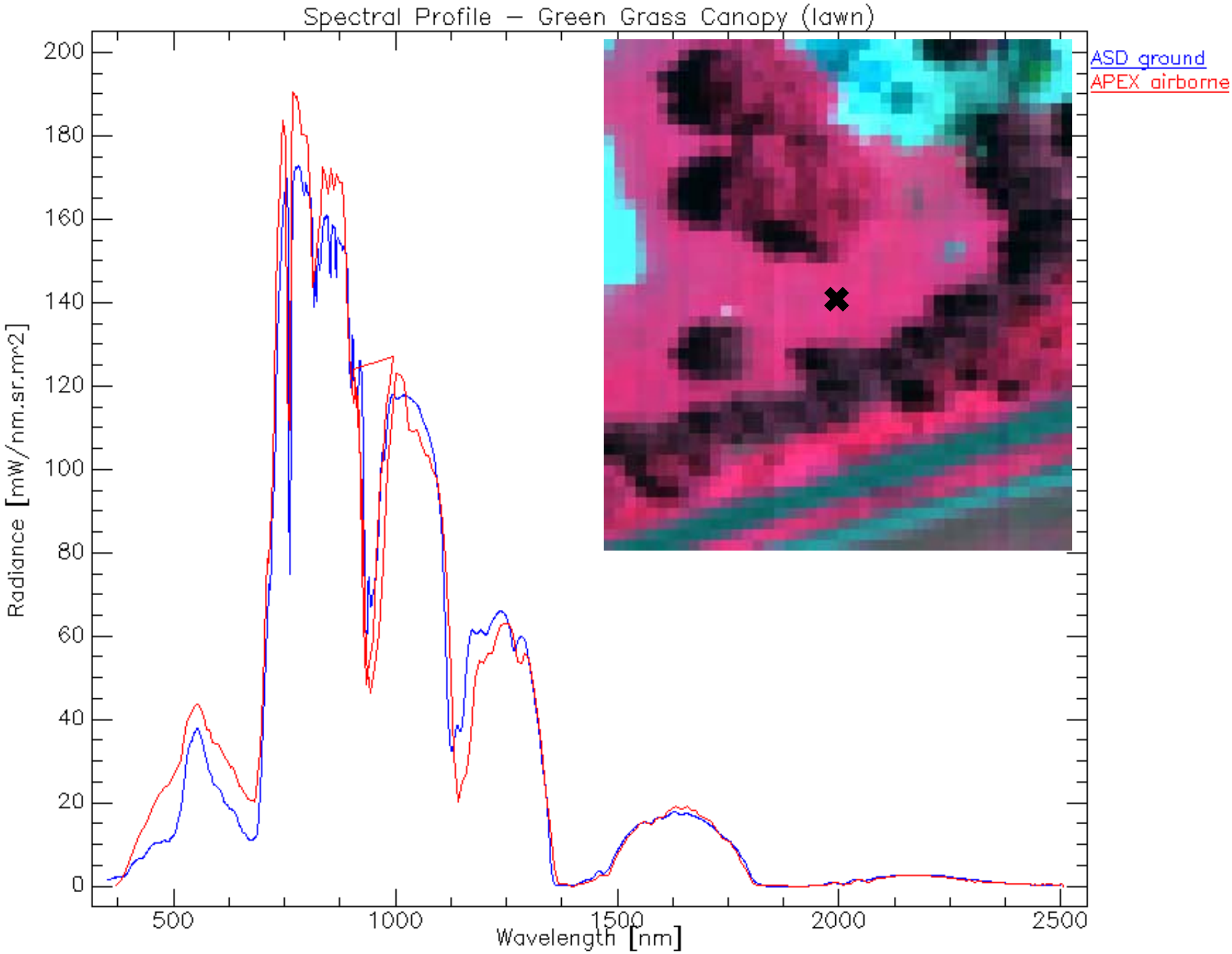


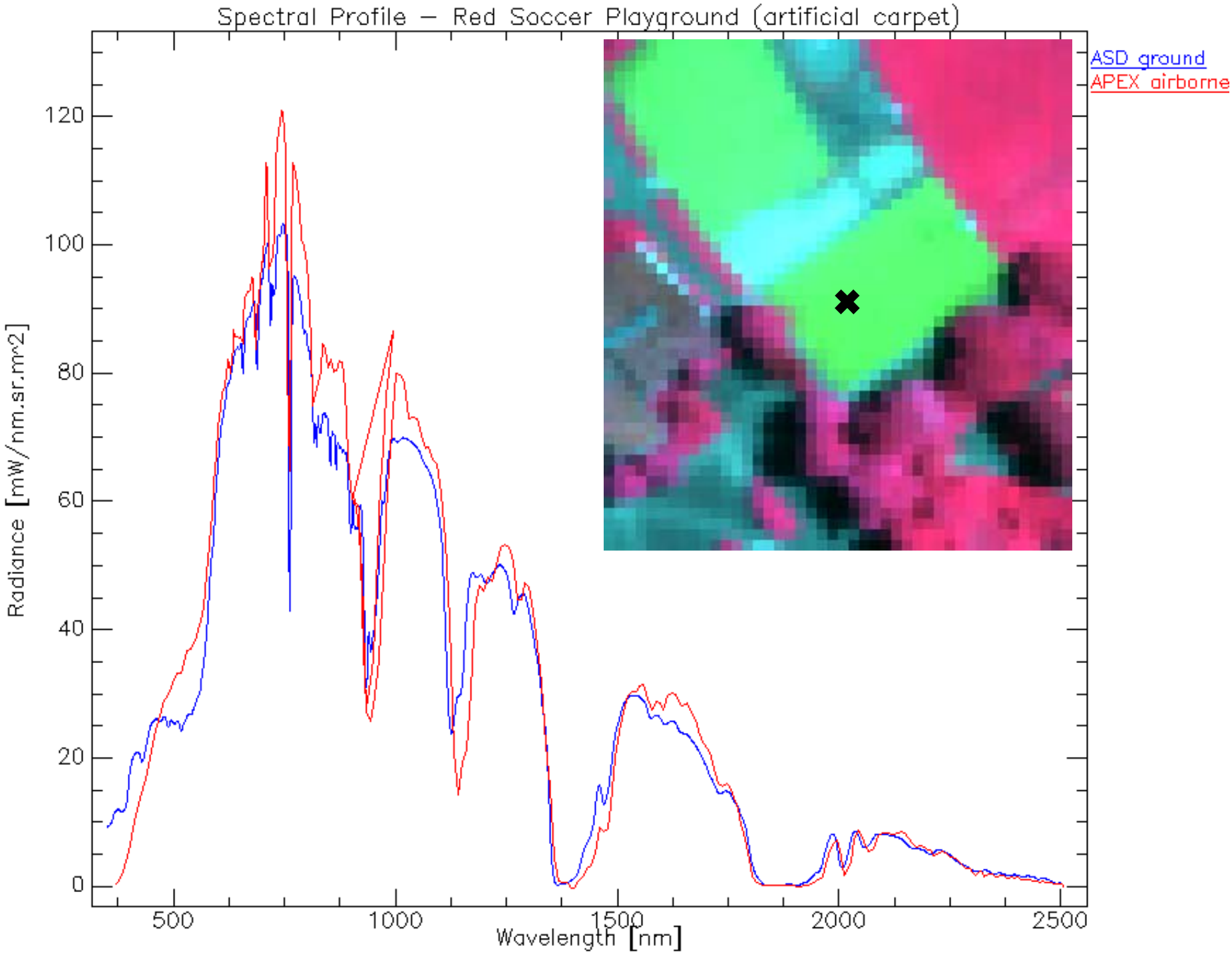






Standard RGB
CIR
R: 760-900 nm
G: Red band
B: green band
CHC
R: 2096 nm (cellulose)
G: 1736 nm (hydrocarbon)
B: 1264 nm (canopy structure)
APEX quicklook from Oostende (B), 23/06/09
Standard RGB
CIR
R: 760-900 nm
G: Red band
B: green band
CHC
R: 2096 nm (cellulose)
G: 1736 nm (hydrocarbon)
B: 1264 nm (canopy structure)
APEX quicklook from Baden (CH), 17/06/09


APEX Radiance Gradient from Bright to Dark Surface (avg 3x3 pixels)
Radiance [mW/nm.sr.m^2]
Wavelength [nm]
350
300
250
200
150
100
50
0
500
1000
1500
2000
2500
1.bright
2.semi-bright
3.semi-dark
4.dark
1.
2.
3.
4.
1. white concrete
2. yellow sand
3. gray artificial carpet
4. dark gravel


Spectral Profile – Green Grass Canopy (lawn)
ASD ground
APEX airborne
Radiance [mW/nm.sr.m^2]
Wavelength [nm]
0
20
40
60
80
100
120
140
160
180
200
500
1000
1500
2000
2500


Spectral Profile – Red Soccer Playground (artificial carpet)
ASD ground
APEX airborne
Radiance [mW/nm.sr.m^2]
Wavelength [nm]
0
20
40
60
80
100
120
500
1000
1500
2000
2500

Opportunities

- APEX announcements of opportunity (through VITO) starting 2010
- APEX on HALO (Gulfstream G550)
  - Stratospheric operation (15 km asl) with > 10'000 km endurance (or 10 flight hours) - http://www.halo.dlr.de/
- Envisaged to achieve airworthiness certification of APEX for 4-6 carriers (Dornier, Gulfstream, King Air, Cessna, etc.)
- Cooperation possibilities
  - HyspIRI validation in different ecosystems/ecotones
  - ESSP Venture-class Science Investigations: Earth Venture-1: RSL can support bidders with instrumentation, methods and/or products
  - RSL is mandated by ESA to operate APEX for 5 years

Conclusions

- APEX has performed first acceptance flights with success (it's an *imaging spectrometer*!)
- Currently the system is further improved (Version 1.0, reliability, realingment, certain hardware upgrades)
- Data will be available as of 2010
- Inquiries and cooperation welcome!

Personal HyspIRI Observations

- Mature concept based on state-of-the-art science
  - may rephrase certain wording, reducing its vulnerability of being down-prioritized
- Link to intl. agenda (IPCC, GEO, etc.)
  - Scaling (contribution to a complete observational system, a GEOSS argument)
  - Unknown feedbacks (vegetation-atmosphere: wet/dry N deposition) and largest uncertainties on small scale processess (an IPCC argument)
- Relevance of products
  - Definition of typical length scales of processes
  - National, intl. relevance of a product (complementing traceability matrix with one column on relevance (or impact))
  - Spectral Albedo would be desirable as baseline product (surface reflectance remains an ambiguous term and does not include directional effects)
  - Focus on ecotones (transitional zones) and largest pressure areas (eg delta regions (red-blue conflict), urbanization (red-green), coastal zones (red-green-blue), etc.)
- Additional arguments
  - (Closing) Energy balance, Albedo (partially clouded atmospheres, cryosphere, biosphere, etc.)
  - Earth System Science approach (holistic view, **simultaneous *and* independent** retreival of various variables)
  - Process modelling support (ecology: niche/dispersal modelling; data assimilation; scaling up/down using RT models)
  - All these spectral bands are an asset and not a problem!
- ... and ...
  - why not ImspIRI (Nyquist ☺)?
- Acknowledgements
  - Woody Turner and the HyspIRI Team for funding the long awaited special issue on imaging spectroscopy in RSE (edited by Susan and myself)
  - Reprints, PDFs of the RSE special issue and presentations from IGARSS 2006 can be made available


apex
Airborne PRISM Experiment
University of Zurich
REMOTE SENSING LABORATORIES RSL
vito
vision on technology
esa
RUAG
Aerospace Defence Technology
netcetera
Quality Software Engineering
OIP Sensor Systems