Integral Field Imager and Spectrometer for Planetary Exploration

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[5]Leonardo Company, Campi Bisenzio, Firenze

RSN3 Audit 27/5/2021
Piano Triennale INAF

fISPEx study status

- The fISPEx study has been selected in 2018 through the competitive call ASI-INAF *«Attività di studio per la comunità scientifica per Sistema Solare ed Eso-Pianeti»*
- Primary Study Line: RESEARCH AND DEVELOPMENT
- Primary Field: SOLAR SYSTEM
- ASI - INAF Agreement N.2018-16-HH.O
- Middle-term RA in June 2021
- Major products:
  - fISPEx flight configuration draft study report (June 2021)
  - fISPEx Optical design analysis report
  - fISPEx flight configuration final study report (June 2021)
  - fISPEx breadboard and characterization tests (December 2022)
- End of activities: December 2022
- Project funding: **652 k€**

Workpackages

7 Staff Researchers: 56 Months
3 Other Researchers: 42 Months
4 Technicians: 26 Months

fISPEX
PI G. Filacchione
(INAF-IAPS)

WP1100 Management

WP leader: Filacchione (INAF-IAPS)

- Giusti (PO)
- External Services
- RTD part-time

→ Optical Design (Leonardo, Campi Bisenzi, FI)

WP1200 System and Spectrometer Scientific Requirements

WP leader: Filacchione (INAF-IAPS)

- Piccioni,
- Ciarniello,
- Raponi

WP1300 Imager Scientific Requirements

WP leader: Mazzotta Epifani (INAF-OAR)

- Palumbo,
- AdR full time

WP1400 Breadboard AIV-AIT

WP leader: Ciarniello (INAF-IAPS)

- Bondi,
- Boccaccini,
- Nuccilli,
- Zambelli,
- Piccioni,
- Raponi
- Filacchione

WP1610 Thermo Mechanic Analysis and Design

WP leader: Tarabini (PoliMi)

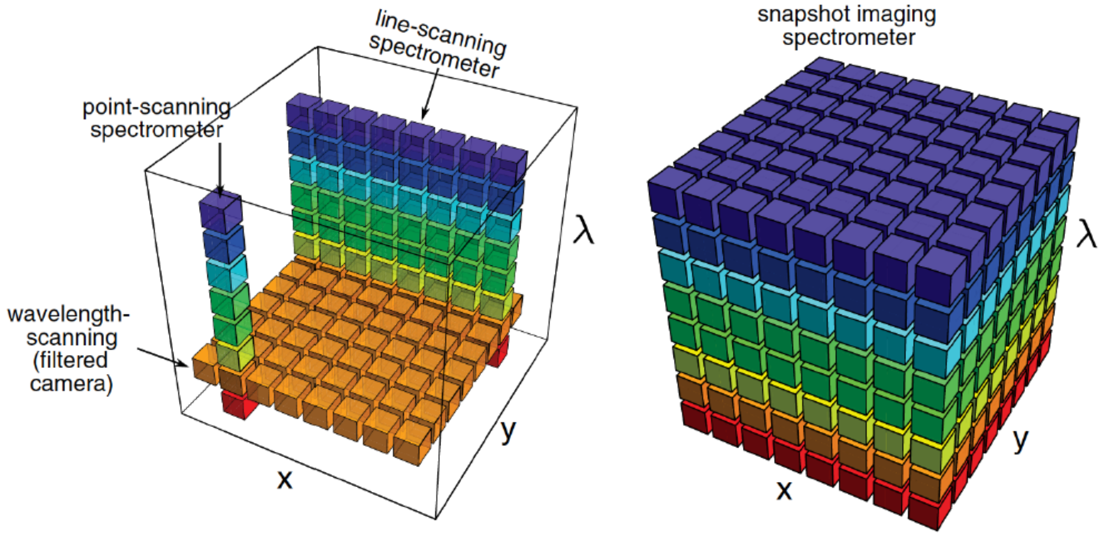
- Saggin,
- Zambelli
- RTD full time

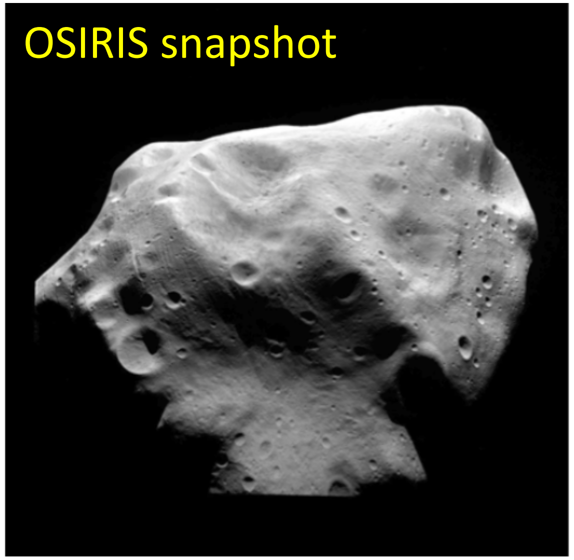
Integral-Field Imager and Spectrometer for Planetary Exploration (ƒISPEx), an highly innovative instrument in which **a single front-optics is used to feed light to a camera and imaging spectrometer**, both coaligned on the same Field of View. **The camera is capable to acquire images at different visible wavelengths by means of a Liquid Crystal Tunable Filter (LCFT)** whereas a **0.4-5 µm integral field imaging spectrometer records a hyperspectral cube with a single acquisition (snapshot mode) through a Coded-Mask Optical Reformatter (CMOR)**.

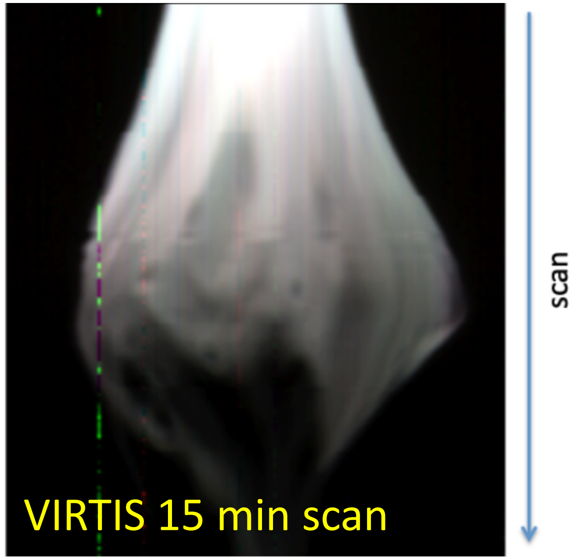
The implementation of the ƒISPEx concept will result in great advantages in terms of payload integration, instrument operations and scientific return with respect to current cameras-spectrometers configurations.

The ƒISPEx instrument is designed for the exploration of small bodies (asteroids, NEA, comets) from orbit but can be easily adapted for other targets. By operating with fast readout detectors, an Integral Field spectrometer can adequately resolve the **four dimensions** of data (2D spatial, spectral and temporal) opening the possibility to perform **time-resolved hyperspectral movies.**

Rationale





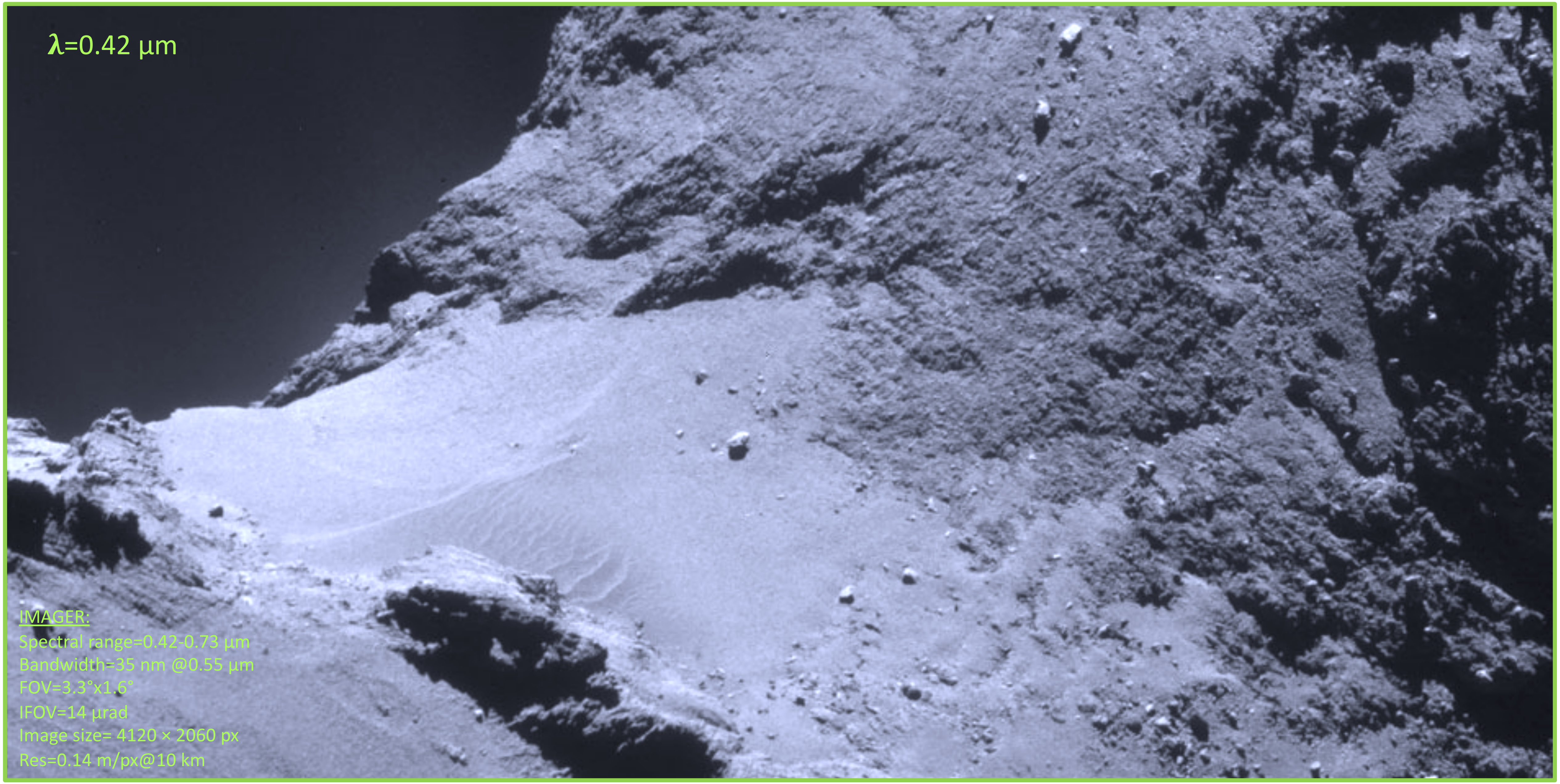


Rosetta's flyby of asteroid 21 Lutetia on July 10th 2010 (minimum distance 3162 km, fly-by velocity 15 km/s) evidences the limitations of pushbroom spectrometers like VIRTIS.

ƒISPEx

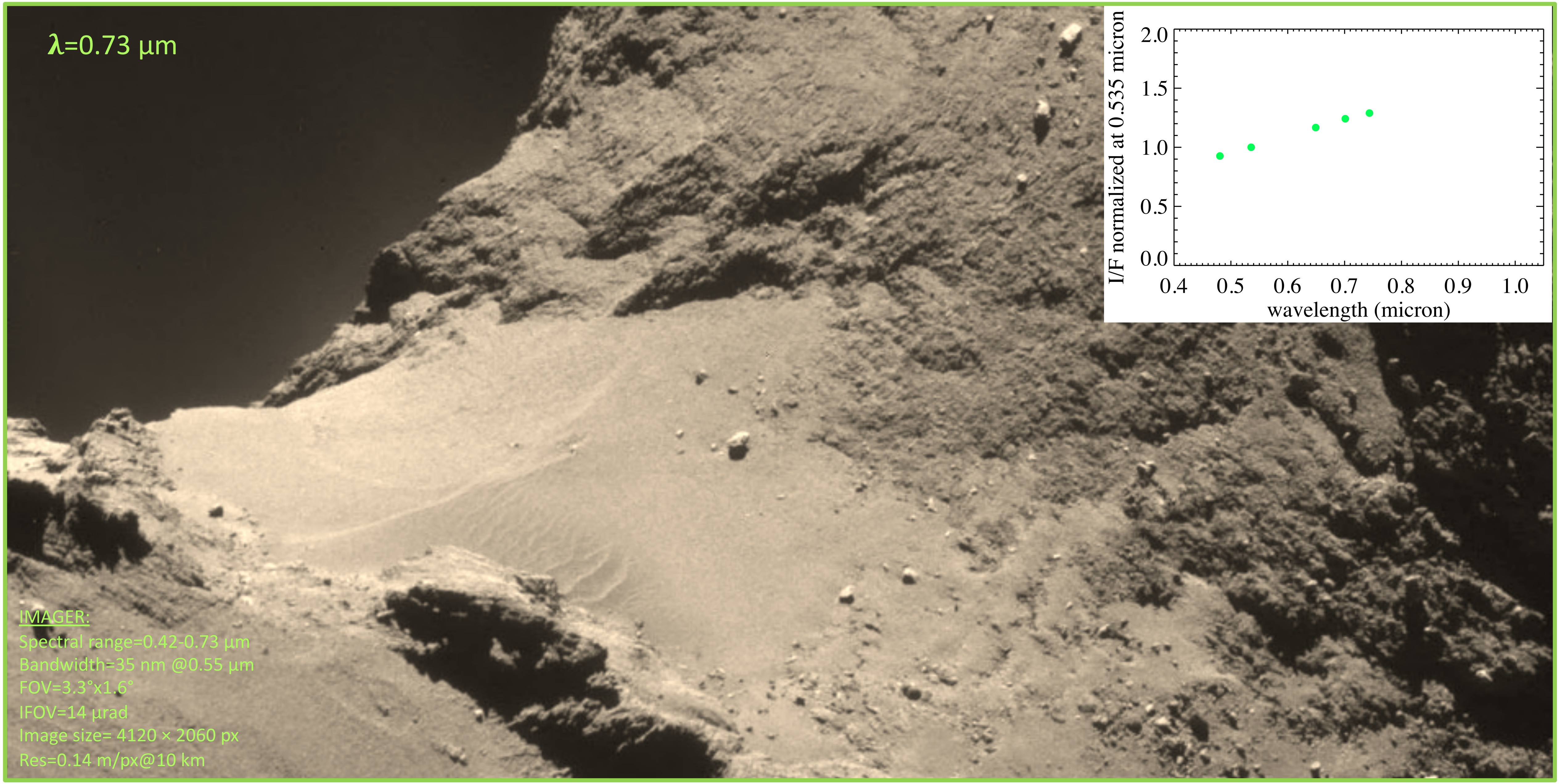
How ƒISPEx works: Imager spectral scan

ƒISPEx 4a

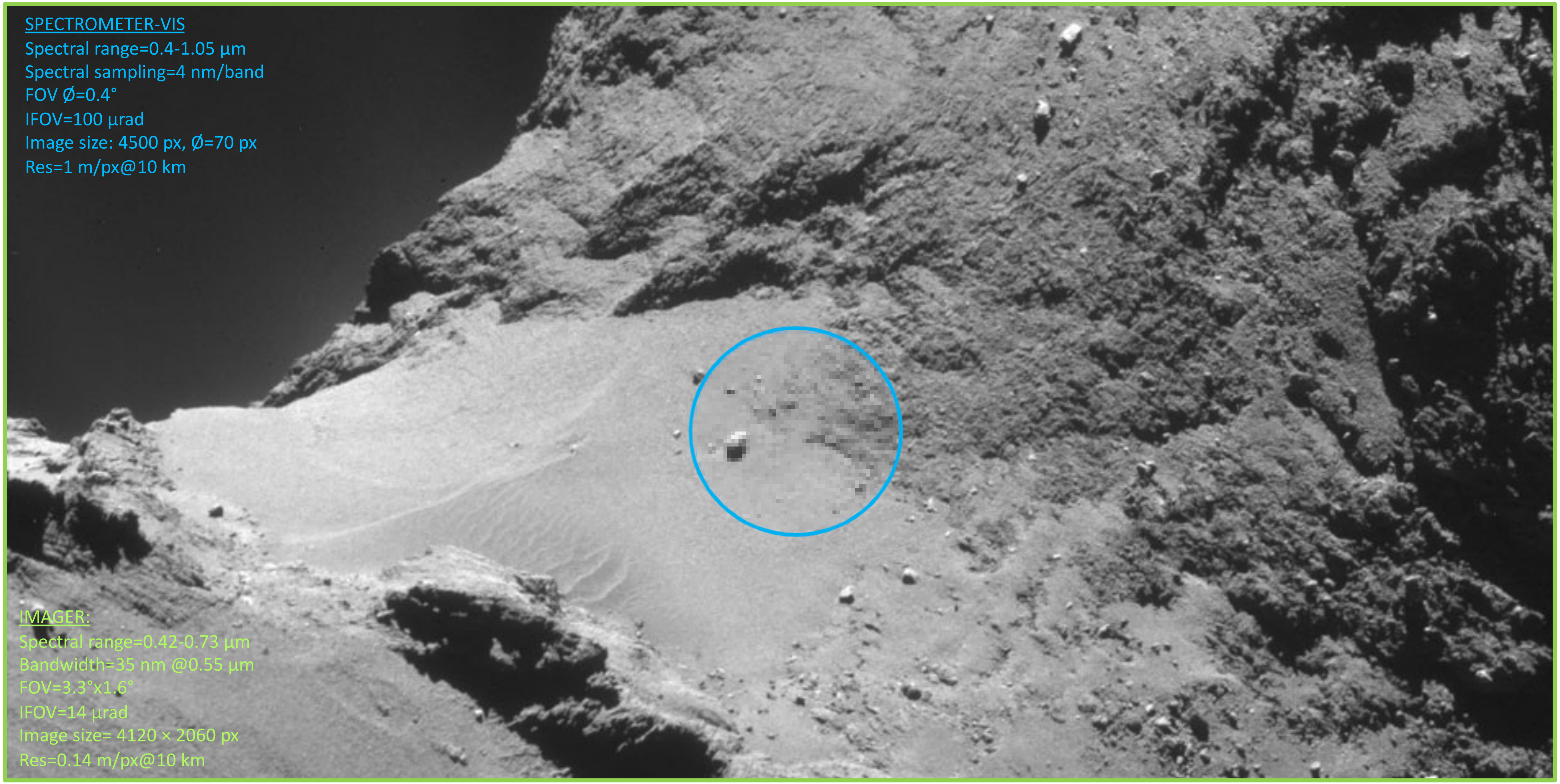


How fISPEx works: Imager spectral scan

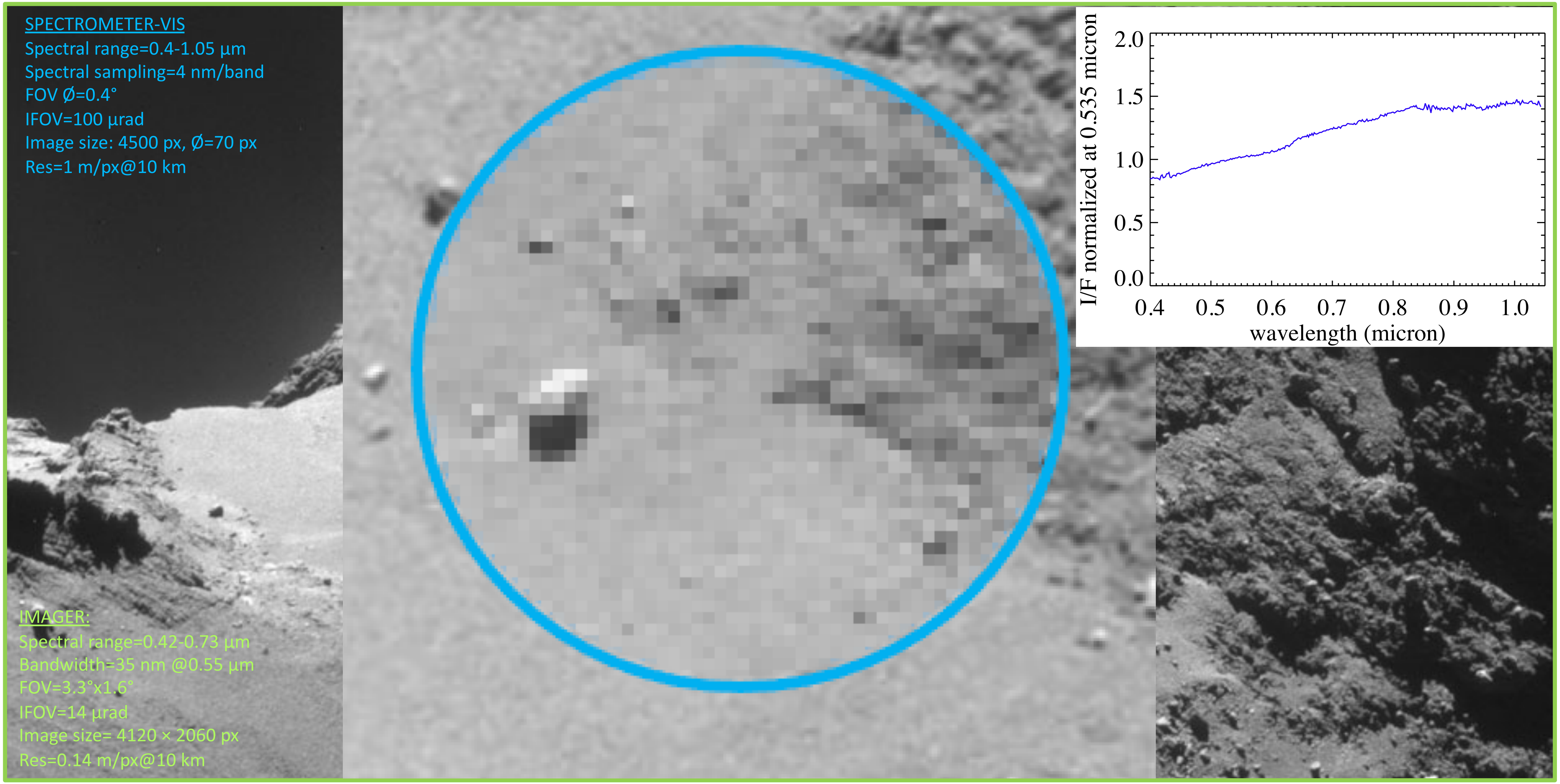
fISPEx



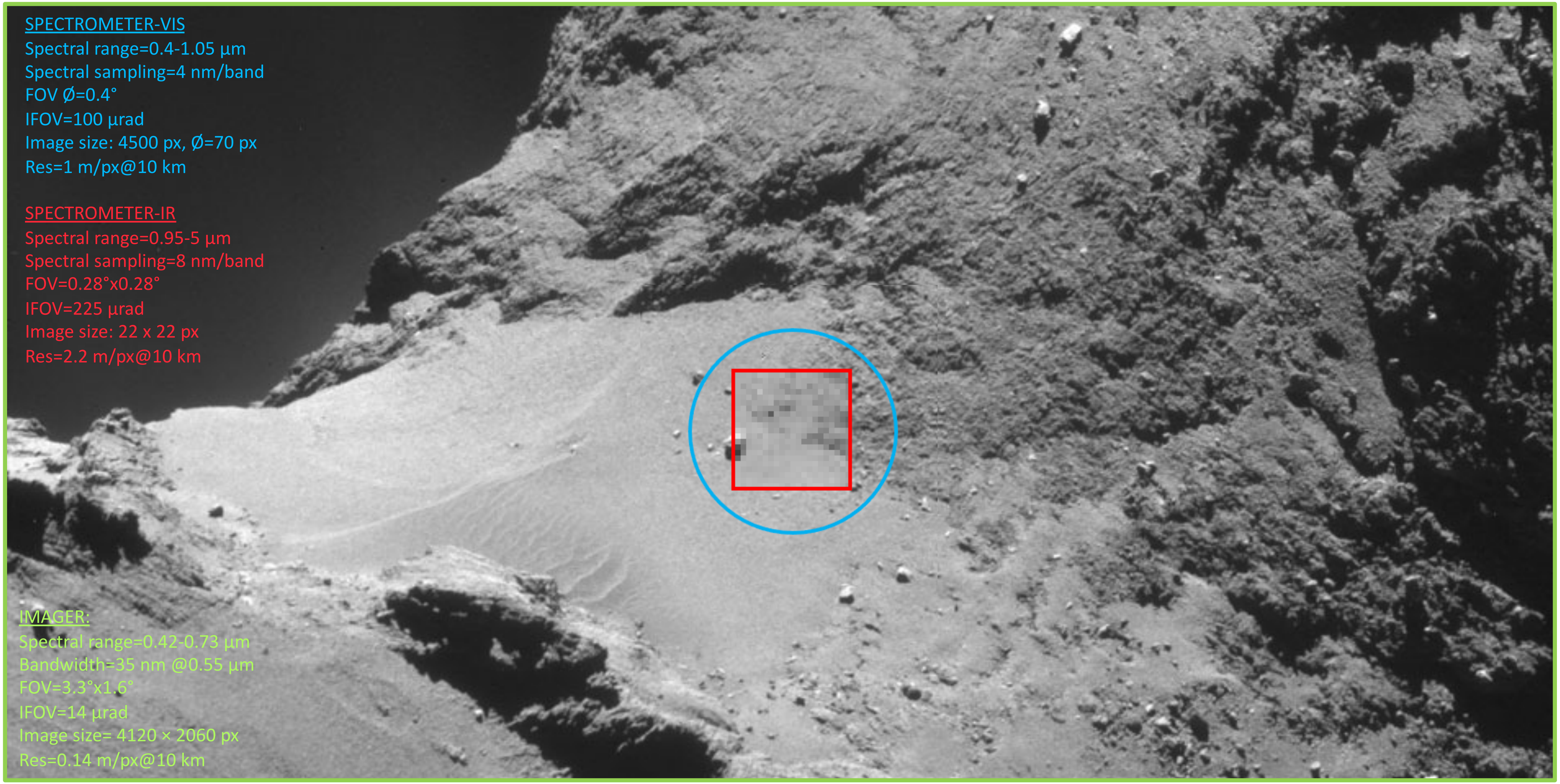
How fISPEx works: 4c Imager spectral scan



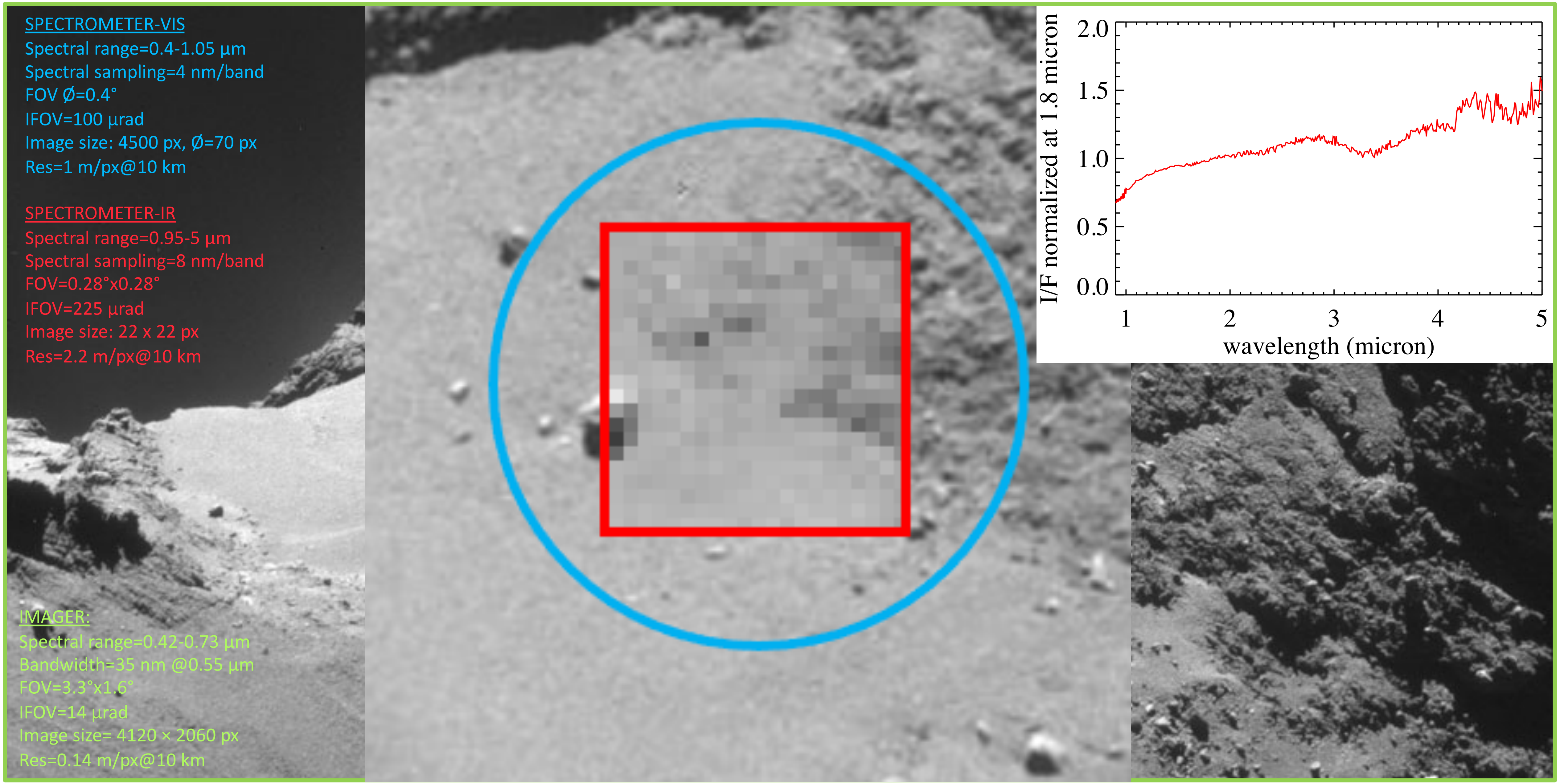
How fISPEx works: VIS spectrometer snapshot



How fISPEx works: VIS spectrometer snapshot



How fISPEx works: IR spectrometer snapshot

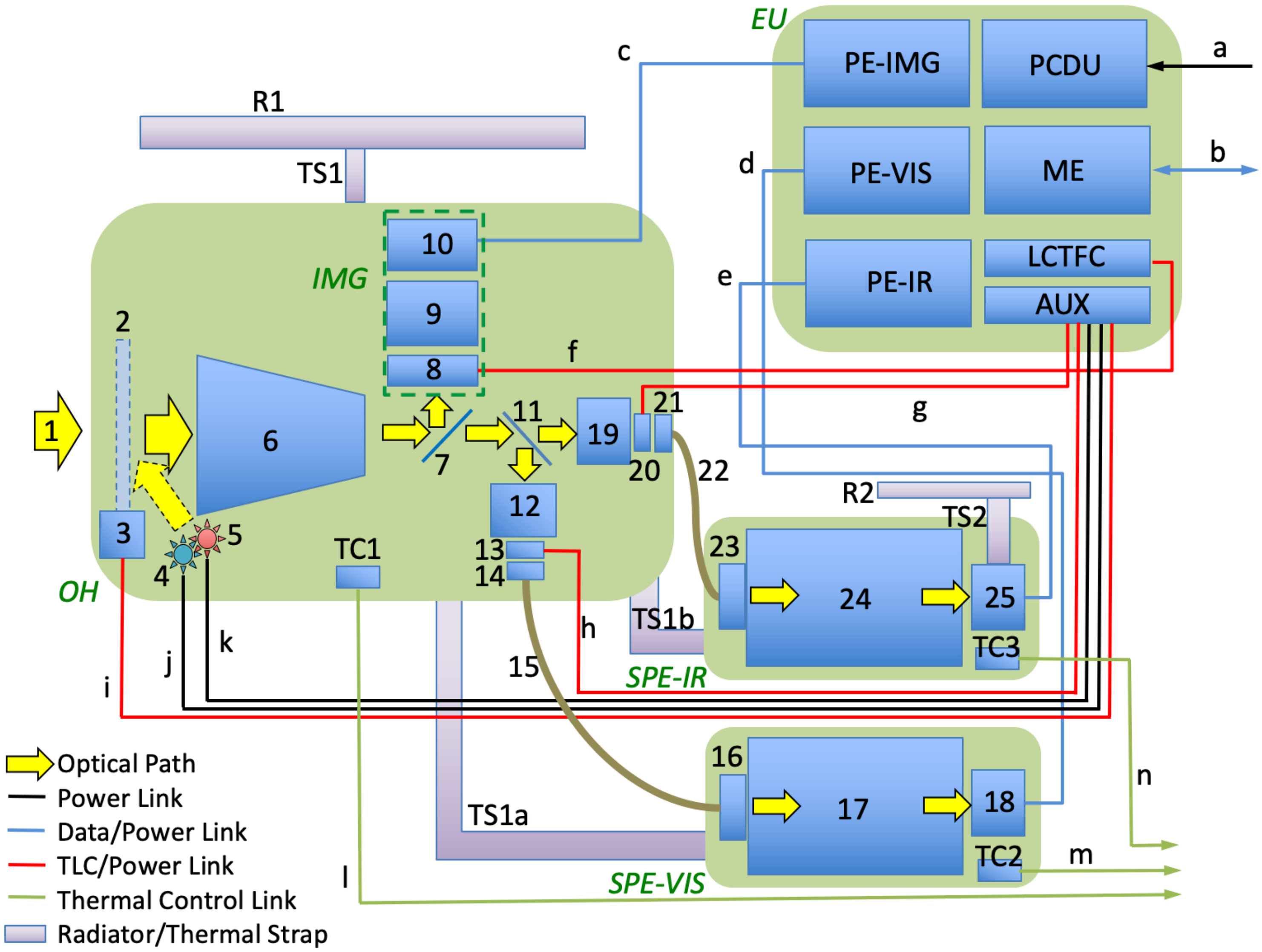


How fISPEx works: IR spectrometer snapshot

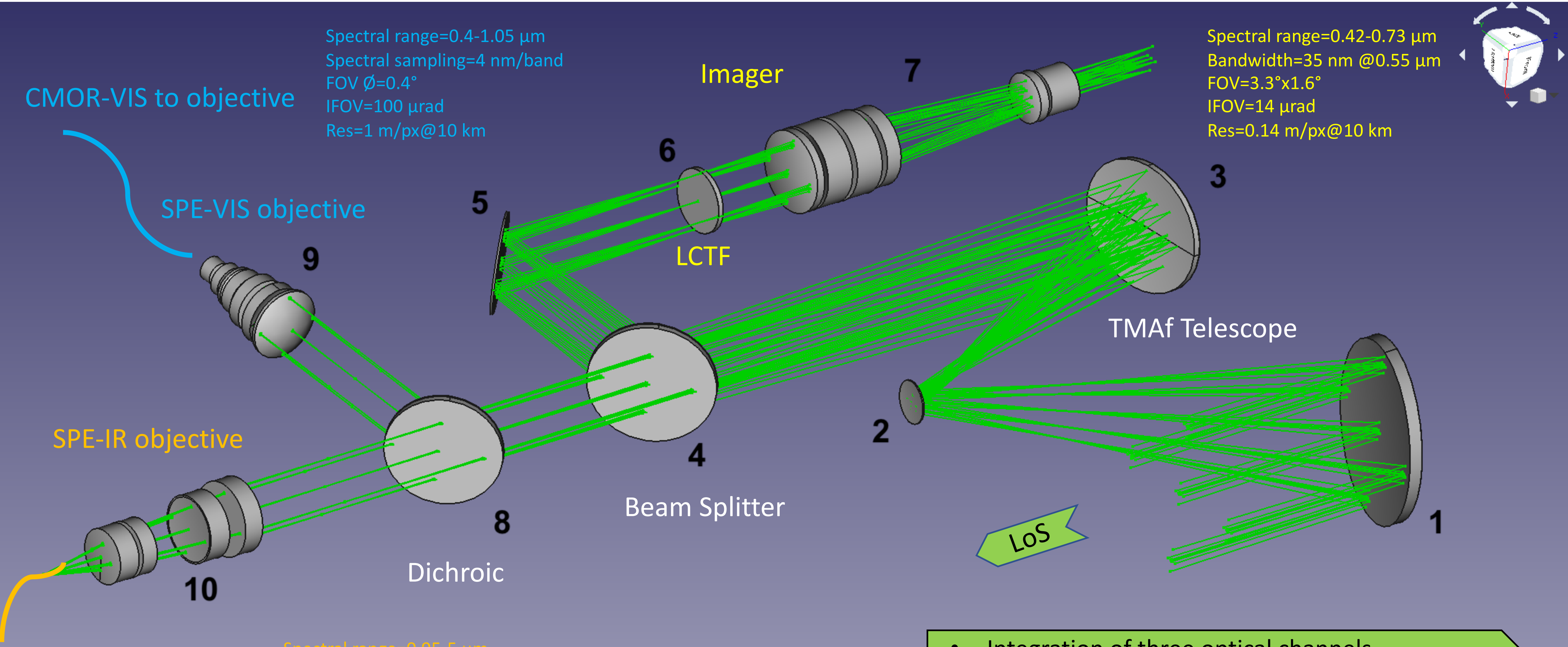
fISPEx 4h

Block Diagram/Flight Configuration

Units: OH Optical Head, including the Imager (IMG) channel; SPE-VIS Visible channel spectrometer; SPE-IR Infrared channel spectrometer; EU Electronics Unit. Subsystems: 1) Input optical beam (boresight); 2) Telescope entrance cover, including calibration target on the internal wall; 3) Cover movement mechanism and motor; 4) Internal calibration unit VIS lamp; 5) Internal calibration unit IR emitter; 6) Three mirror afocal telecope; 7) Beam splitter (50-50); 8) LVTF; 9) IMG objective; 10) IMG focal plane; 11) Dichroic filter; 12) SPE-VIS objective; 13) SPE-VIS shutter mechanism and motor; 14) SPE-VIS CMOR 2D input terminal; 15) SPE-VIS CMOR bundle; 16) SPE-VIS CMOR 1D output terminal; 17) SPE-VIS Dyson spectrometer; 18) SPE-VIS detector; 19) SPE-IR objective; 20) SPE-IR shutter mechanism and motor; 21) SPE-IR CMOR 2D input terminal; 22) SPE-IR CMOR bundle; 23) SPE-IR CMOR 1D output terminal; 24) SPE-IR Offner spectrometer; 25) SPE-IR detector; R1) Passive radiator for OH SPE-VIS and SPE-IR; TS1) thermal strap from R1 to OH; TS1a) thermal connection between OH and SPE-VIS; TS1b) thermal connection between OH and SPE-IR; R2) Passive radiator for IR detector; TS2) thermal strap from R2 to SPE-IR detector; PE-IMG) Proximity Electronics for IMG channel; PE-VIS) Proximity Electronics for SPE-VIS channel; PE-IR) Proximity Electronics for SPE-IR channel; PCDU) Power Conditioning and Distribution Unit; ME) Main Electronics; LCTFC) LCTF Controller; AUX) Auxiliary Board; TC1) OH thermal control; TC2) SPE-VIS thermal control; TC3) SPE-IR thermal control. Harness: a) Power link to S/C; b) TLC/Data link to S/C; c) PE-IMG to IMG detector link; d) PE-VIS to SPE-VIS detector link; e) PE-IR to SPE-IR detector link; f) LCTFC to LCTF link; g) AUX to SPE-IR shutter motor link; h) AUX to SPE-VIS shutter motor link; i) AUX to cover motor; j) AUX to internal calibration unit VIS lamp; k) AUX to internal calibration unit IR emitter; l) TC1 to S/C bus; m) TC2 to S/C bus; n) TC3 to S/C bus. Lines functionalities are color coded in black for power links, blue for data/power links, red for TLC/power links, green for thermal control links. Optical paths are shown in yellow. Radiators and thermal straps in violet.



ʃISPEx optical architecture



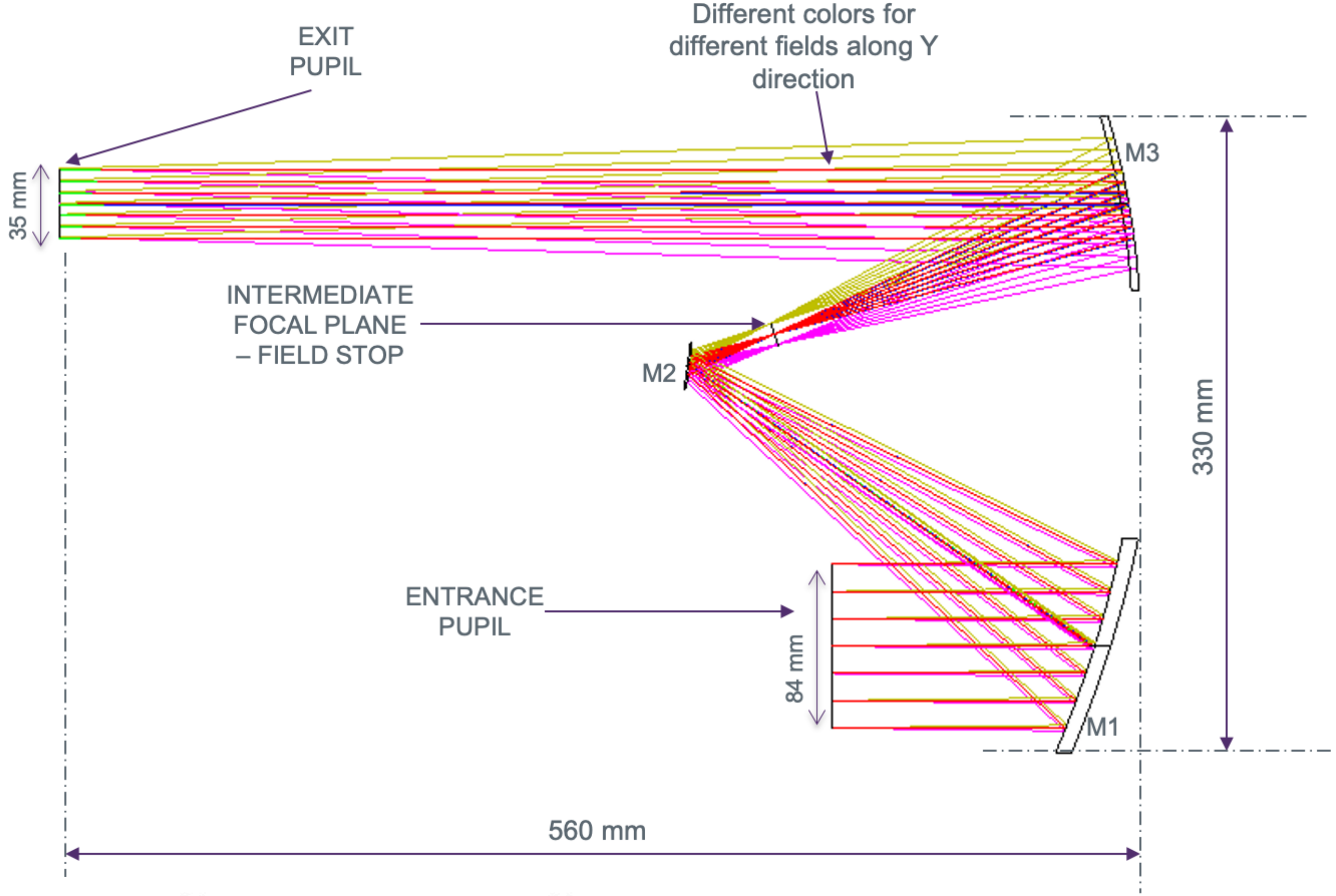
CMOR-IR to SPE-IR

Spectral range=0.95-5 µm
Spectral sampling=8 nm/band
FOV=0.28°x0.28°
IFOV=225 µrad
Res=2.2 m/px@10 km

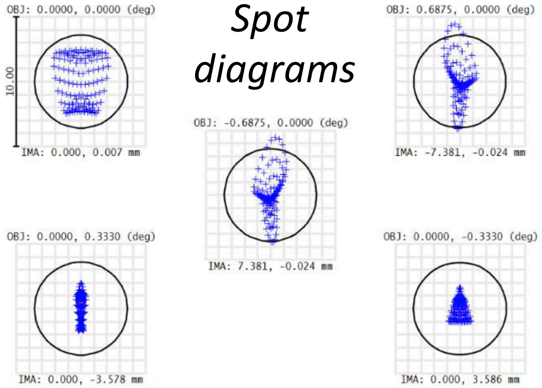
- Integration of three optical channels
- Innovative design
- Modularity
- Removal of mechanisms (scanner, filters wheel)

ʃISPEx

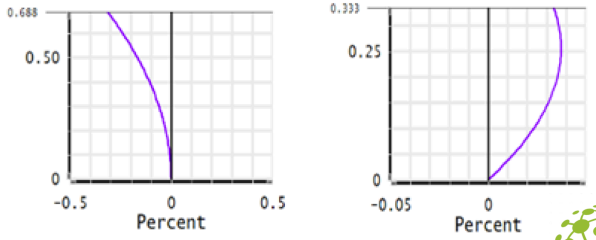
Three Mirror Afocal Telescope



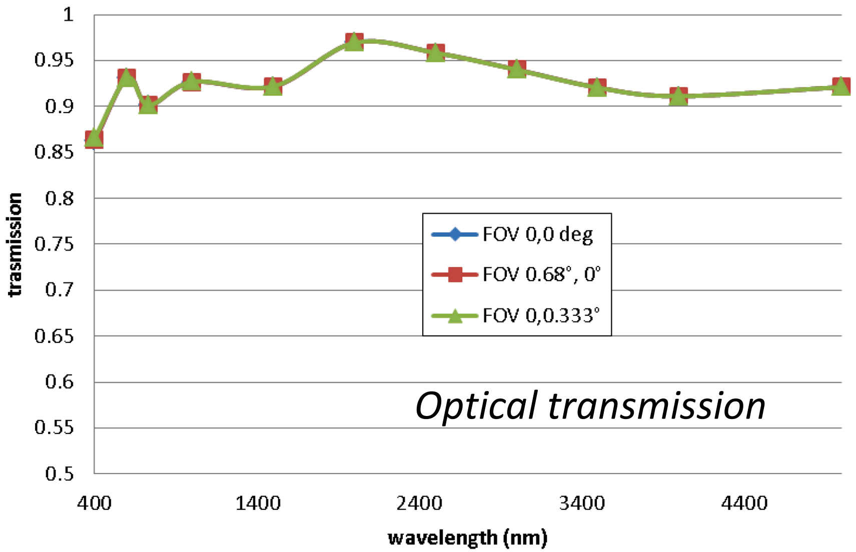
- Innovative concept, unobstructed design, diffraction limited, spherical mirrors
- Input pupil ø=84 mm, output=ø 35 mm (2.4X)
- FOV_x=±0.6875°, FOV_y=±0.333°
- Allows optimal optical coupling with LCTF through collimated beam at exit pupil
- Possibility to mount an internal baffle on the intermediate field-stop position to reduce straylight
- High VIS-IR optical transmission achieved through silver-enhanced coating on mirrors



Spot diagrams

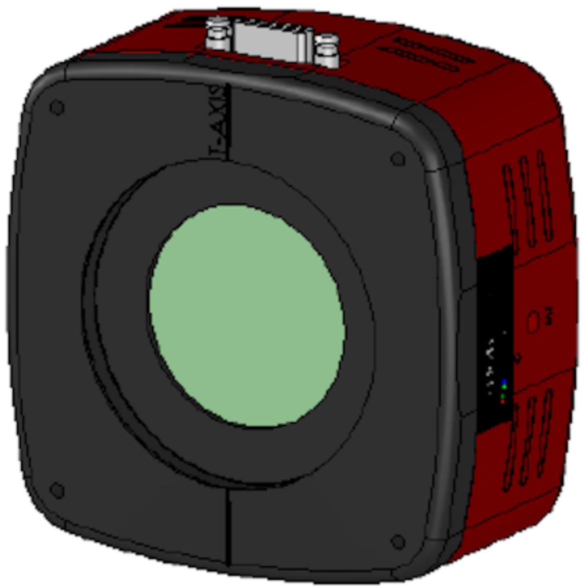


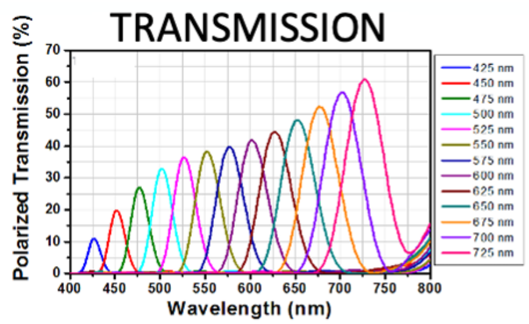
Radial distortions

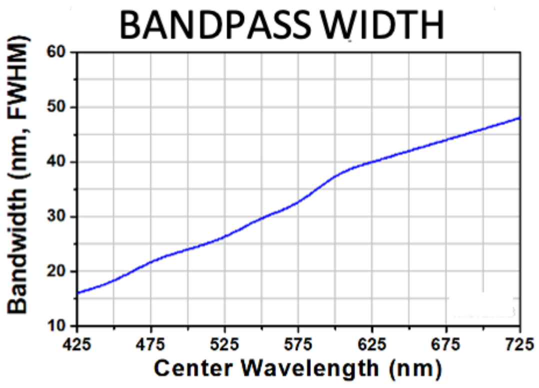


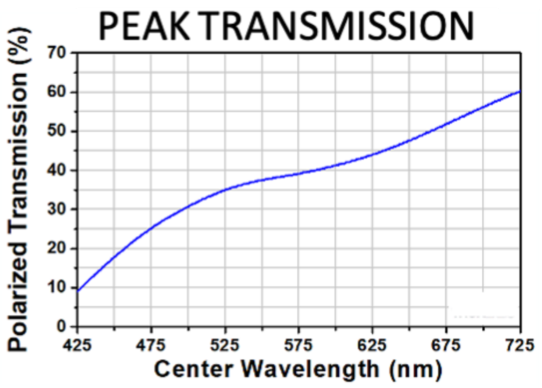
Optical transmission

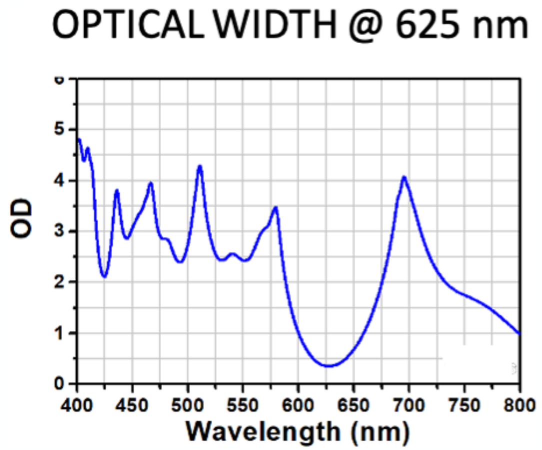
Imager: Liquid Crystal Tunable Filter

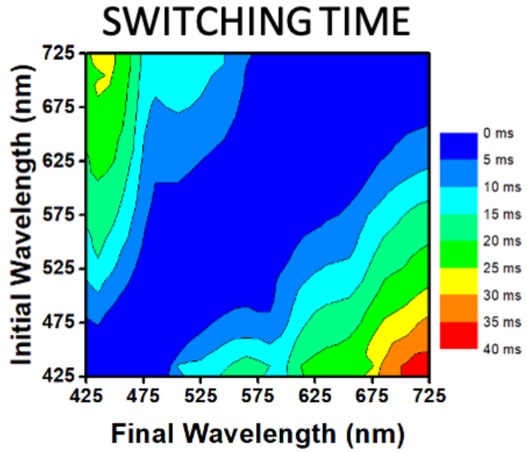


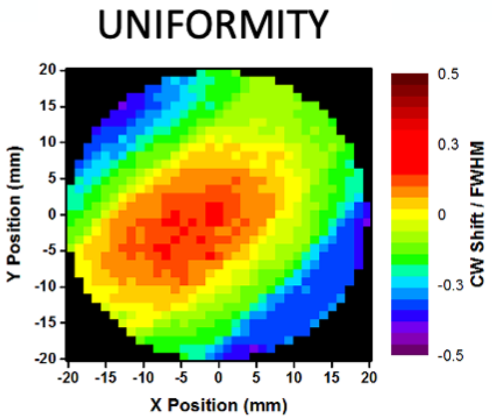


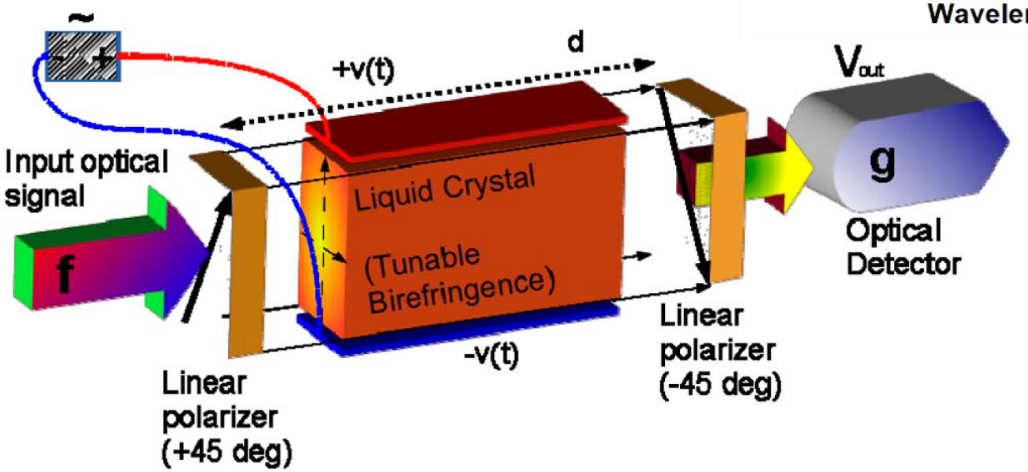










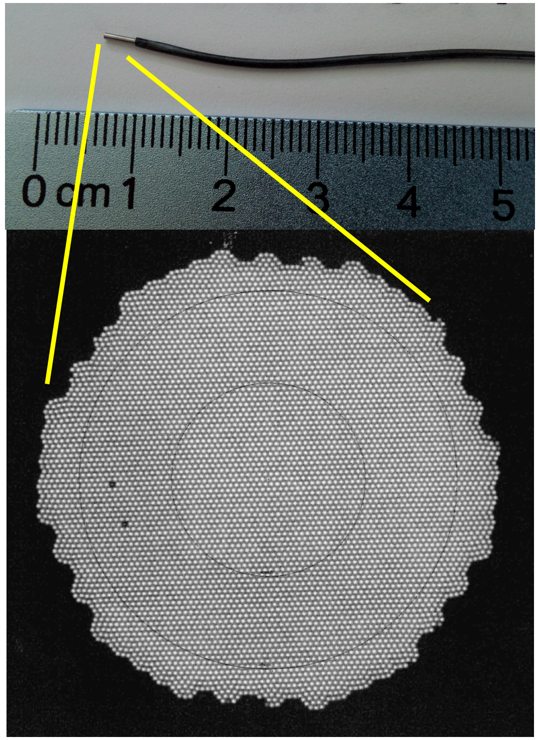


- High flexibility in wavelength selection (1 nm resolution)
- Short switching time (<40 ms)
- Removal of filter wheel mechanism/mass saving
- Many possible Nematic LC/Polarizer/Lyot Filter combinations

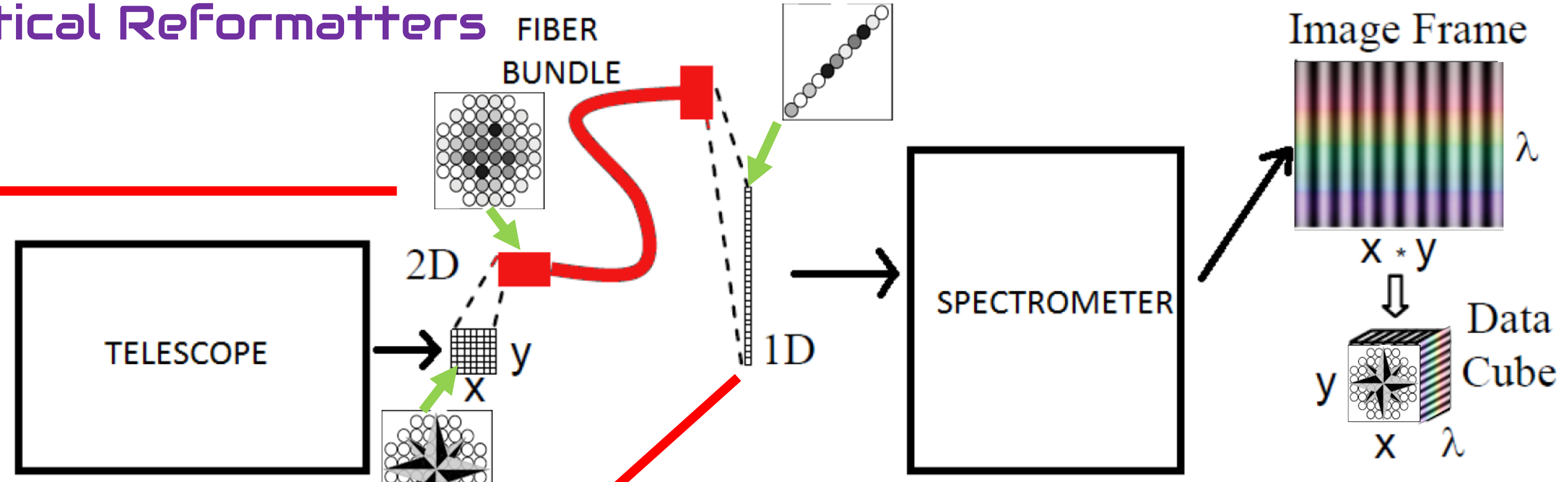
- Space Qualification: Thermal Control (operative T_{min}=0°C)
  Cell Sealing under vacuum/Outgassing

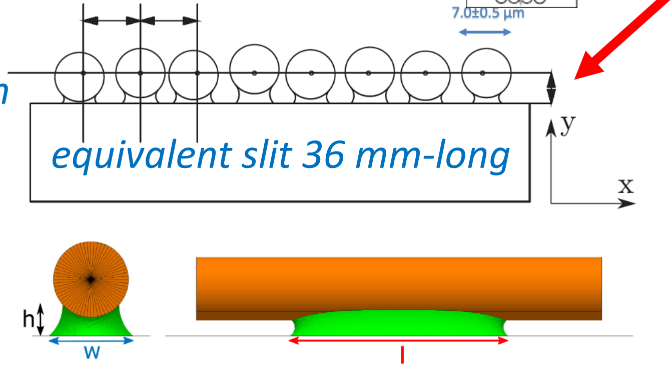
fISPEx

VIS Spectrometer: Coded-Mask Optical Reformatters



VIS channel:
4500 fibers
fiber Ø=8.6 µm
bundle Ø=0.56 mm
(circular)

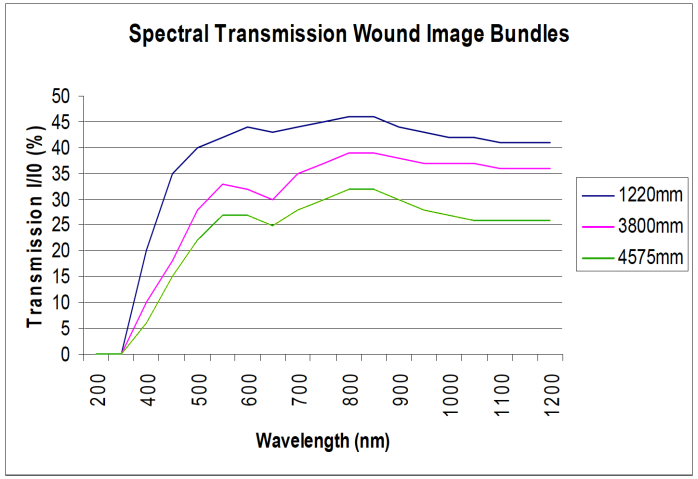




fiber's positioning and glueing

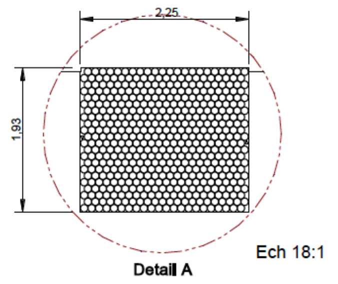
- Innovative design, integral field spectroscopy allows to acquire 4500 spectra with a single acquisition
- Coded mask configuration allows to reconstruct 2D image
- Similar concept applied to VIS (0.4-1.05 µm) and IR (1-5 µm) spectrometers

- 1D terminal manufacturing and cost (contacts ongoing with national and foreign firms)
- Fibers - optics f/# coupling (=1.28 VIS, 2.5 IR)
- Optical matching between fibers diameter and detector pixel pitch
- CMOR space qualification process



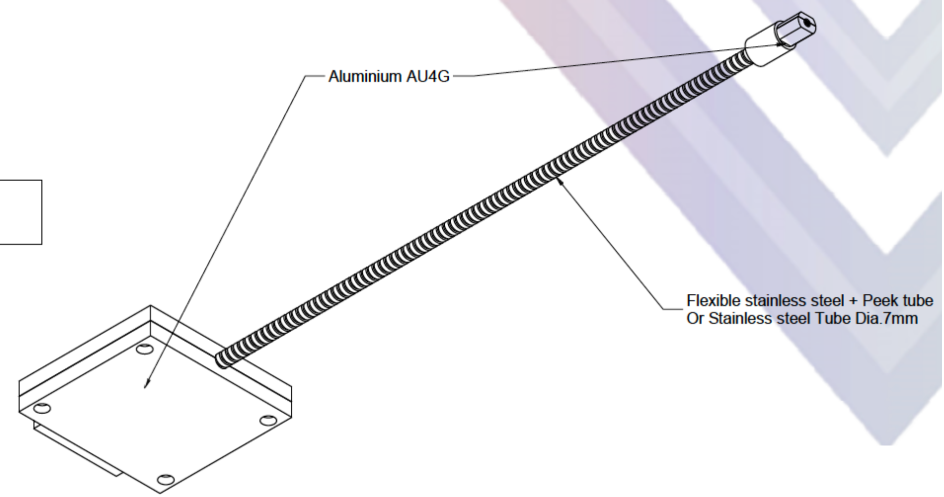
IR Spectrometer: Coded-Mask Optical Reformatter

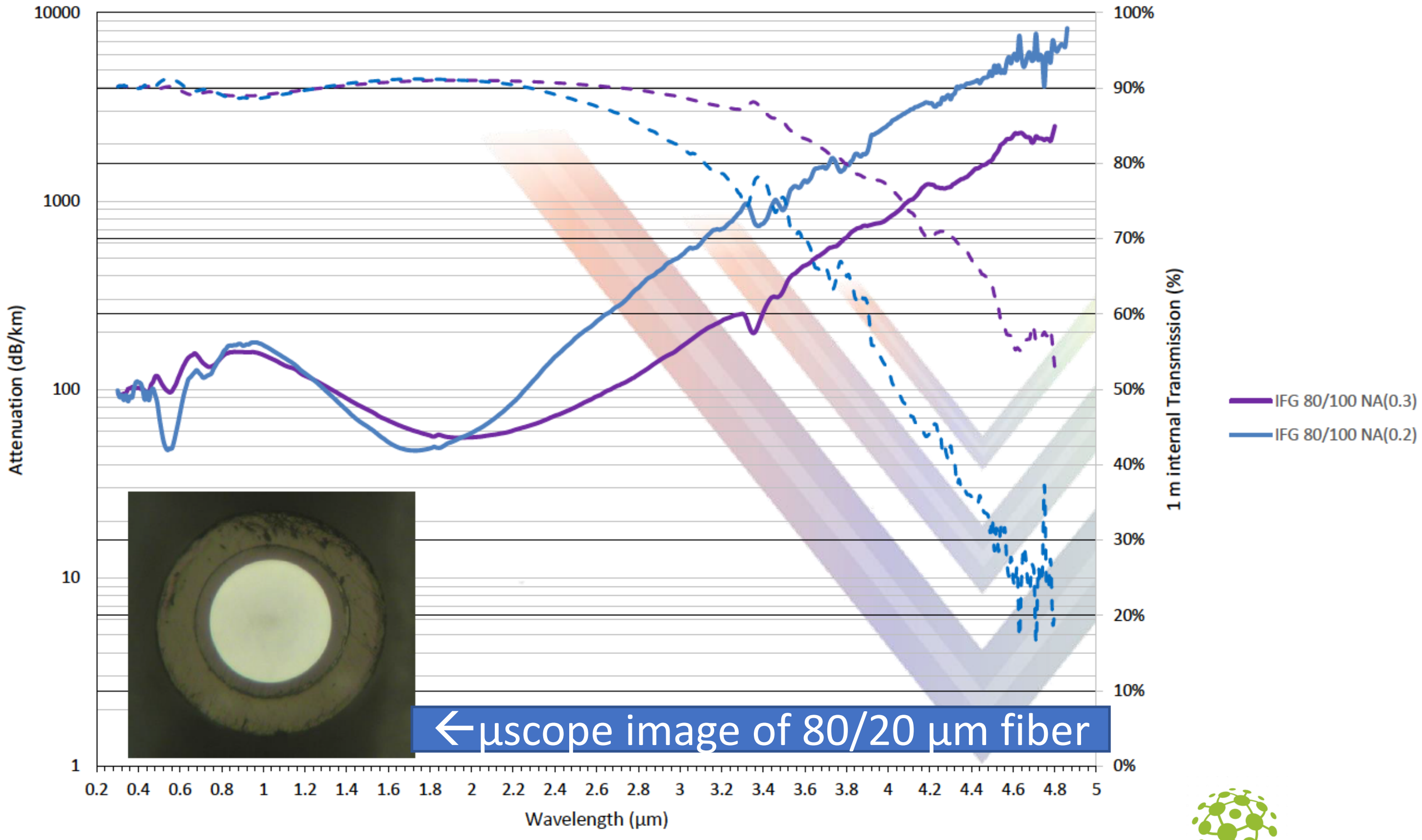
IR channel:
484 fibers
fiber core Ø=80 μm
fiber core+cladding Ø=100 μm
Terminal A: 22x22 fibers (square)

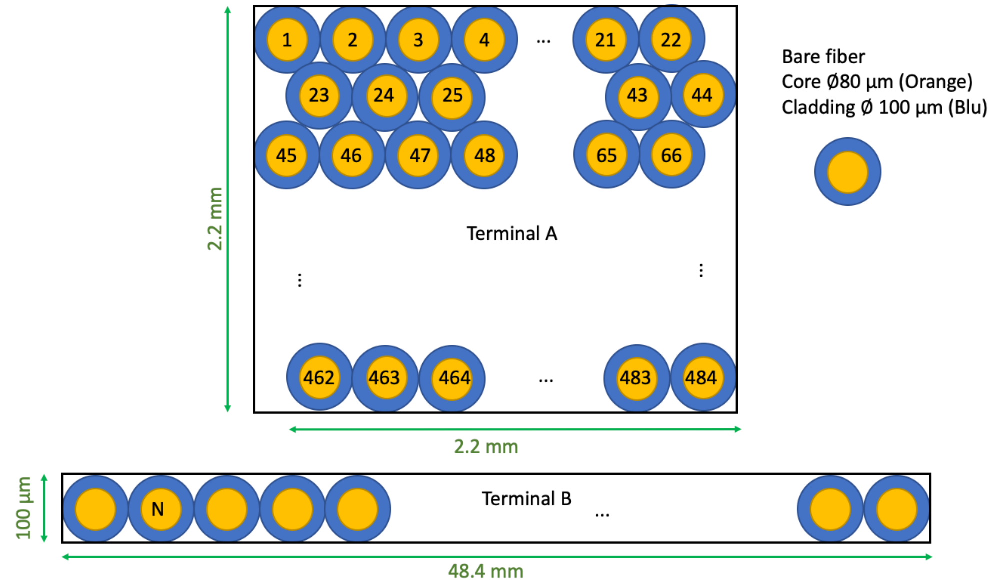


Max error on the external envelope position is < 20 μm
Max error on the position of each fiber center wrt to its own regular "hexagon" grid position is <10μm

Maximum angle wrt optical axis direction <0.5° for terminal B,
Maximum angle wrt optical axis direction <1° for terminal A,
Maximum displacement wrt to nominal surface level is < 1μm instead 0.1μm asked

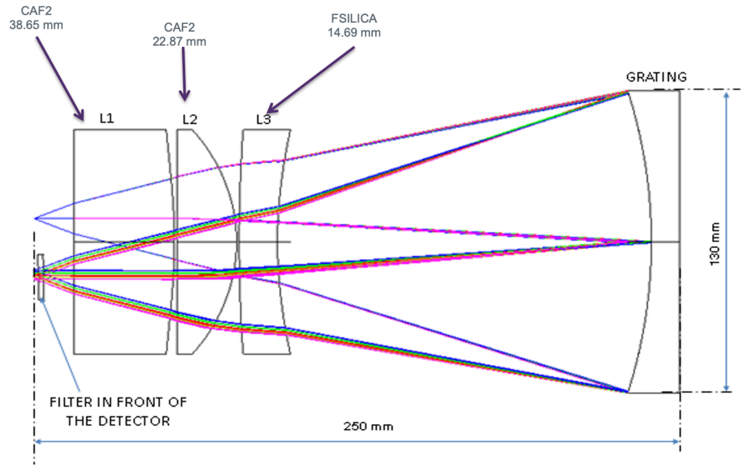


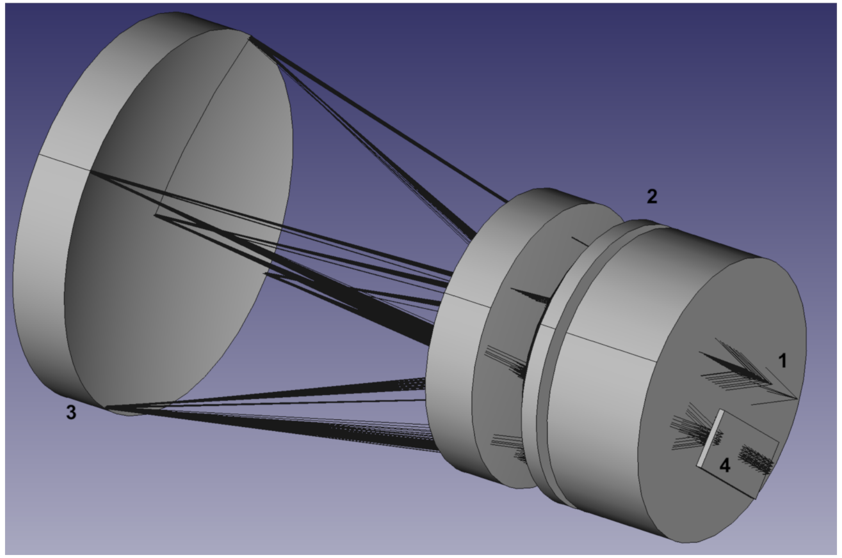


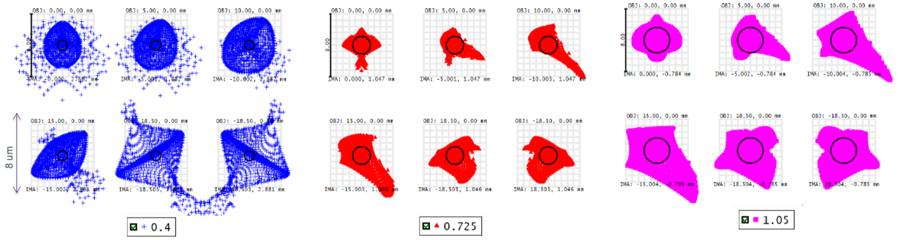


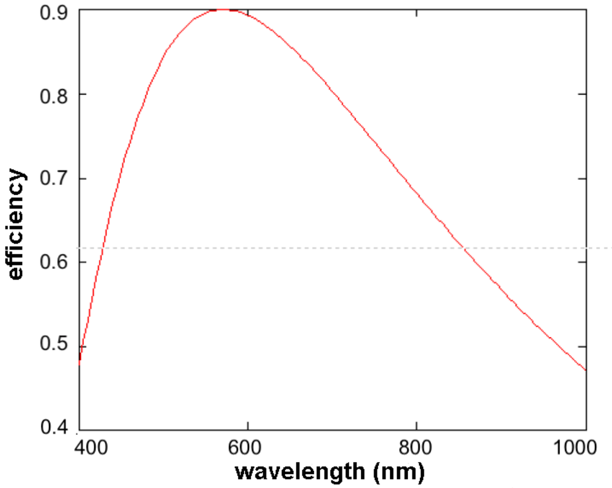
Spectrometers design

VIS/Dyson

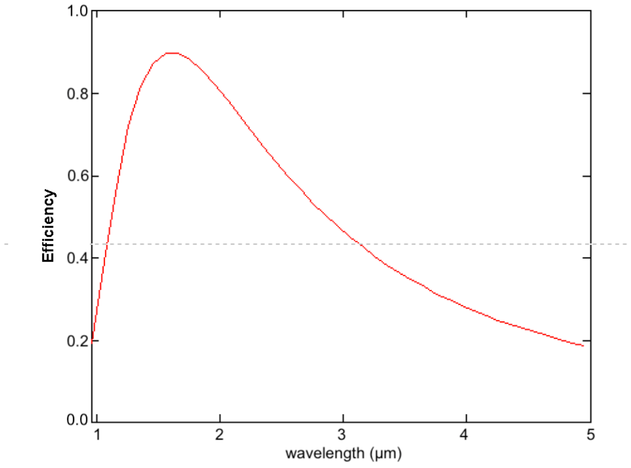






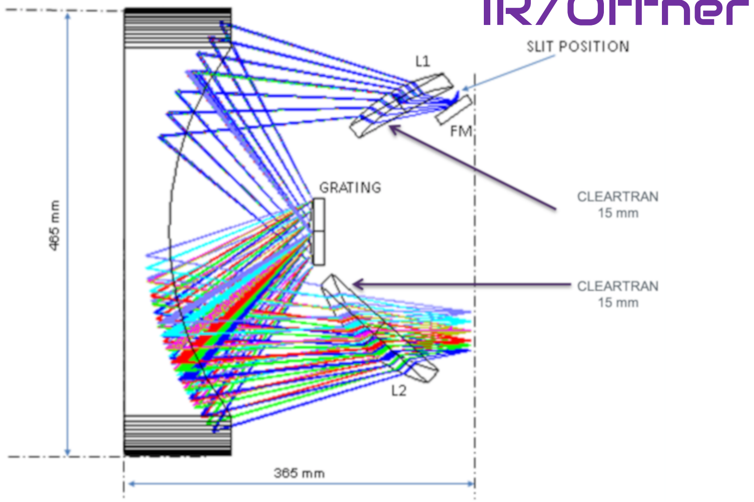


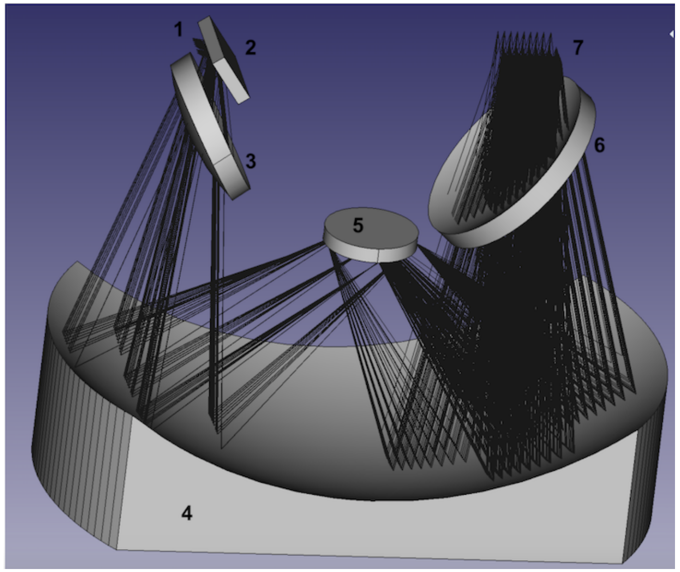
Th. Gratings efficiency

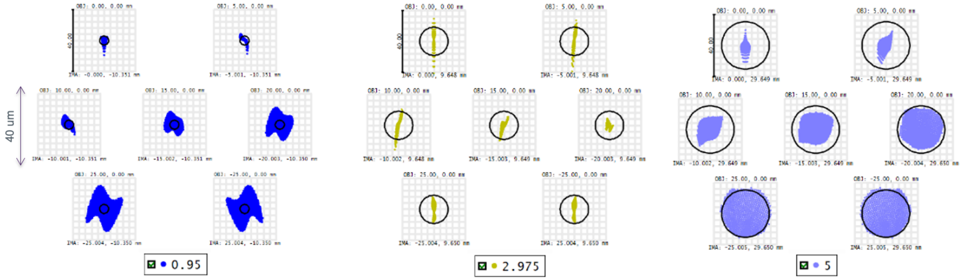


← Spot Diagrams →

IR/Offner

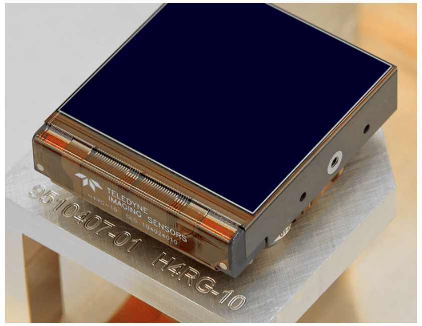






Detectors

- Coupling fiber core size, spectrometer's slit aperture and detector pixel size
- Coupling slit length with detector size
- IR detector buttable configuration



SPE-IR

Teledyne HAWAII H4RG-10

Specification	Value
Detector Format	4096×4096
Pixel Pitch	10 μm
Sensor area	41 × 41 mm
Total Pixels	16.8 MP
Cutoff	5.3 μm
Substrate removal	Yes
Common-mode Noise removal	reference rows and columns
Interleaved readout	programmable window up to 5 MHz
Selectable number of outputs	1, 4, 16, 32, 64
Full frame readout rate	74 Hz
Pixel readout rate	500 KHz (slow mode), 10 MHz (fast mode)
Dark current	<100 e/s/px for T=90 K
Readout Noise	$< 10e^-$ slow mode, $< 40e^-$ (fast mode)
Full well capacity	100-150 ke^-
Buttable design	4 sides option
TIS Sidecar ASIC compatible	Yes
Packaging materials	molybdenum or invar

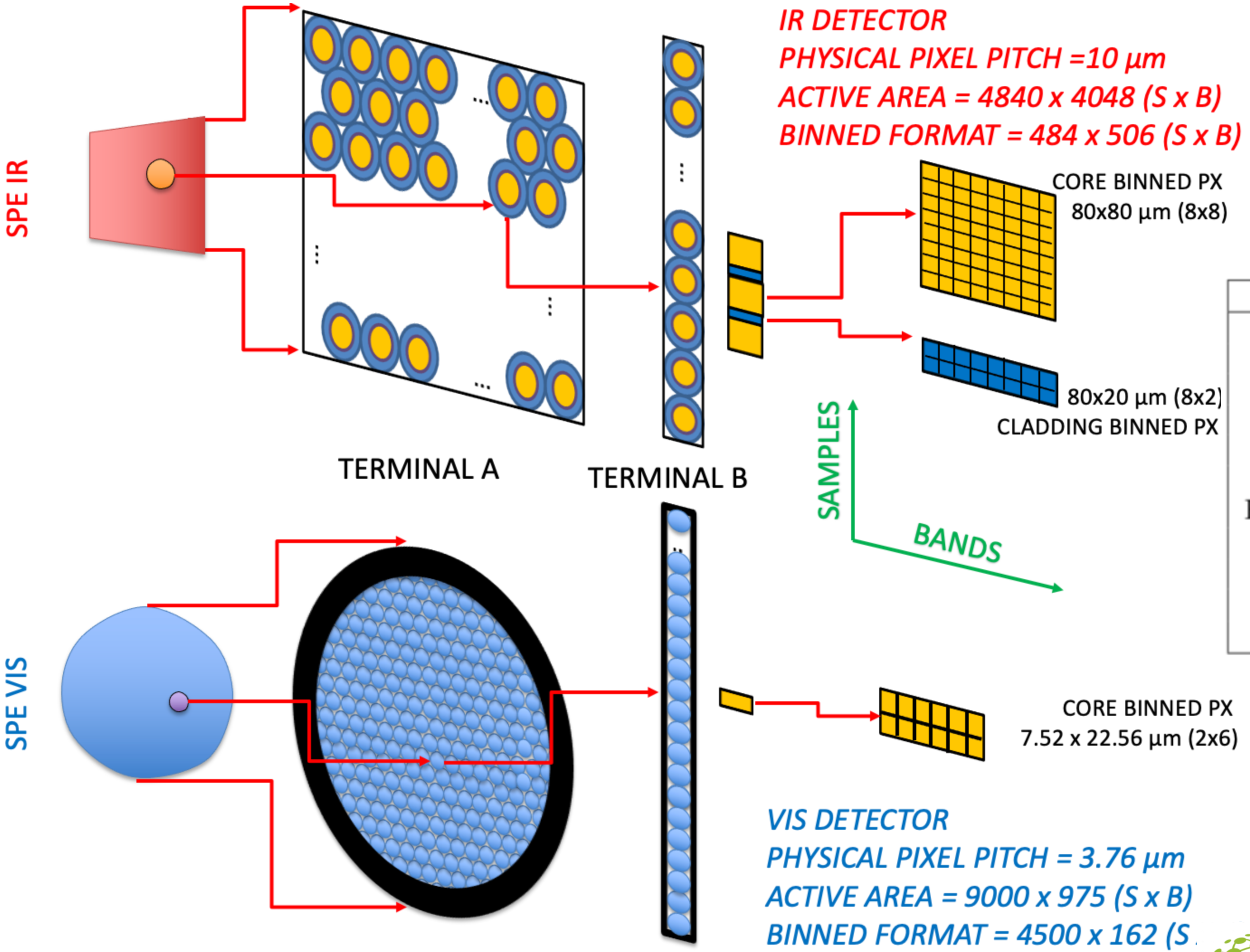
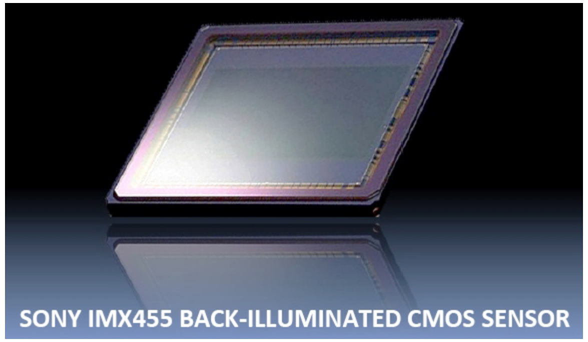


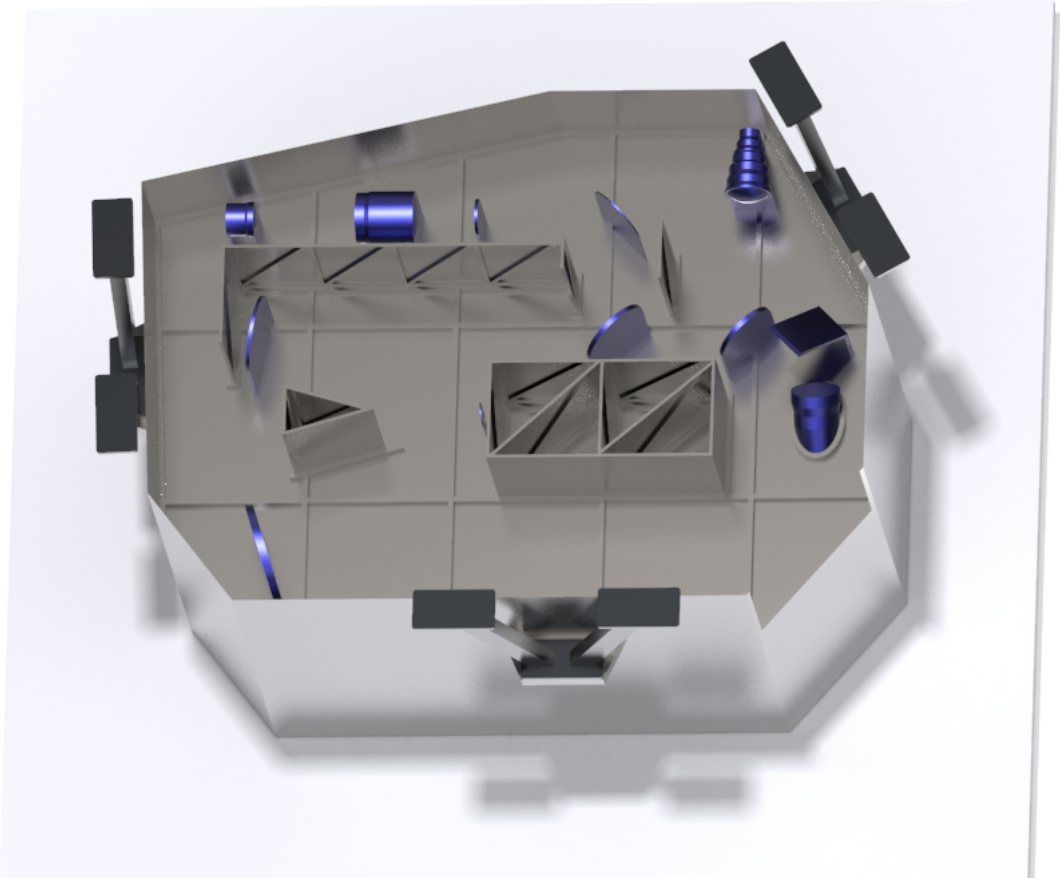
Image sensor	SONY IMX455ALK-K	SONY IMX571
Sensor Technology	Full Frame CMOS	APS-C CMOS
Sensor Type	Back Illuminated	Back Illuminated
Pixel Pitch	3.76 × 3.76 μm	3.76 × 3.76 μm
Sensor surface window	AR+AR Multi-Coated	AR+AR Multi-Coated
Effective pixels	9576 × 6388	6284 × 4210
Effective image area	36 × 24 mm	23.6 × 15.8 mm
Full well capacity in ke^- (standard; extended)	51; 80	51; 75
A/D converter	16 bit	16 bit
Full frame rate	2.5 FPS (USB3)	6 FPS (USB3)
Readout Noise in $^-$ (high; low gain)	1.0; 3.7	1.1; 3.5
Dark current in $e^-/px/s$ (at -20°C; -10°C)	0.0022; 0.0046	0.0005; 0.001

SPE-VIS IMG

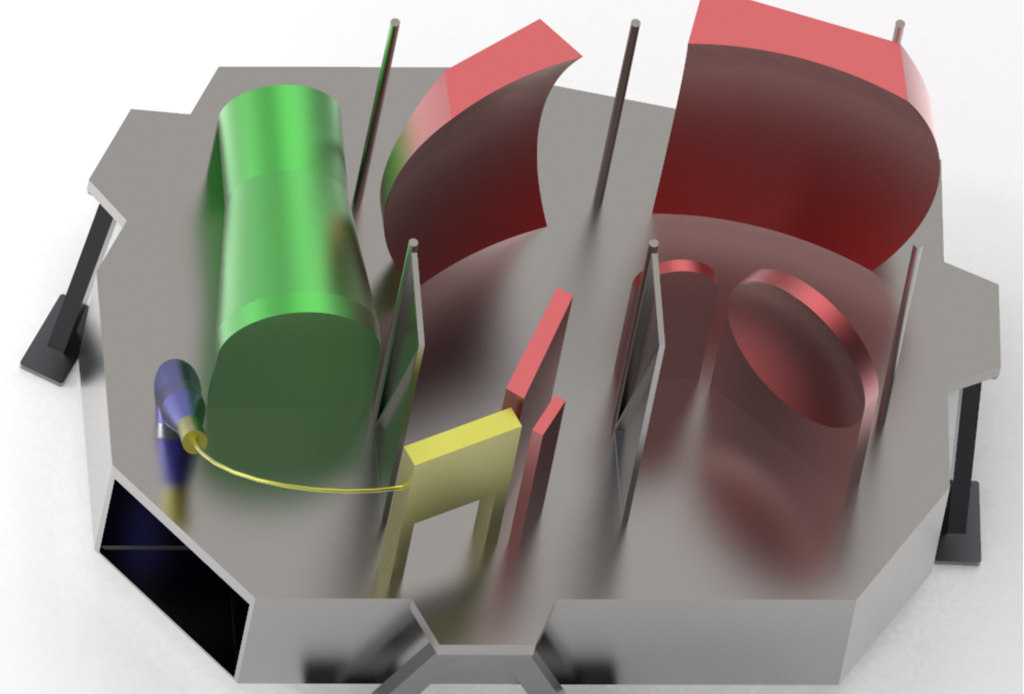


Thermomechanical Structure

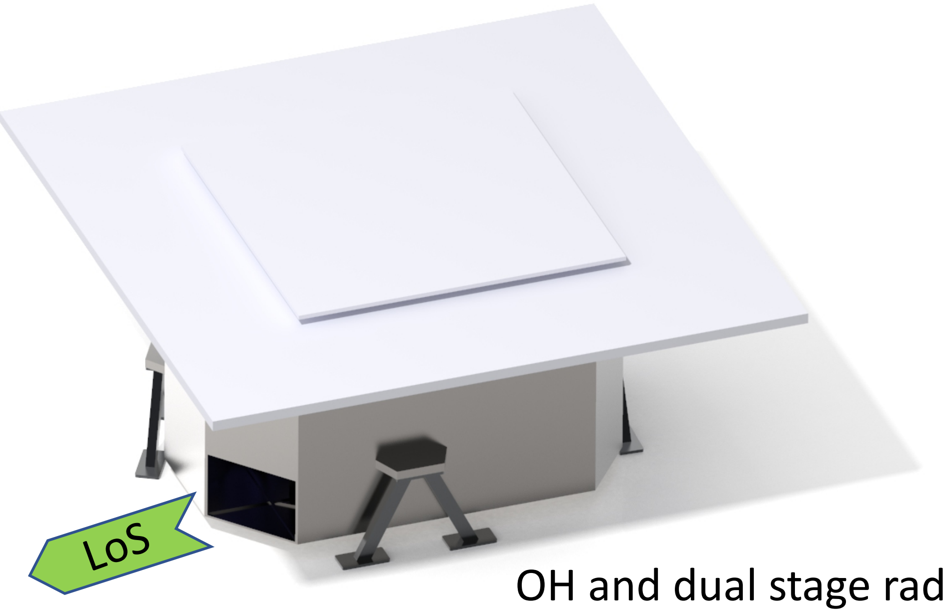
Optical Head mass =28 kg
ME unit mass = 6 kg
Total Mass = 34 kg (plus harness)
(20% margin not included)



Telescope and Imager optical bench (bottom side)



VIS and IR spectrometers (top side)



OH and dual stage radiators

Conclusions

- ƒISPEx has been proposed starting from the lessons learned from 20^{+} years of technical/scientific experiences on imaging spectrometers and cameras.
- Collaboration among INAF, University and Industry.
- Acquisition of new expertise in the field of photonic research (LCTF, CMOR).
- Optimization of the scientific return from VIS-IR imaging spectrometers and color cameras through data fusion and integration of science/operation teams.
- Thanks to modularity, it is possible to adapt the $\int_{0.4}^{5.0\,\mu m}$ISPEx design to other optical architectures (µscopes) and mission scenarios (landers, rovers, Earth Observation).

- Next steps: realization of $\int_{0.4}^{1.0\,\mu m}$ISPEx breadboard model aiming to optimize optical layout, to verify enabling technologies (CMOR, LCTF) performances and to increase overall TRL.
- Organization of a new optical lab space in IAPS for breadboard integration and tests. Synergies with other ongoing programs (Juice, Dora...)
- Consolidate radiometric models
- Consolidate system architecture and resources
- Open a new AdR position in IAPS shared with Dora program
- Preliminary results will be presented at next EPSC conference

ƒISPEx