Recent Improvements on the Thermal Infrared Hyperspectral Images of the SIELETERS Airborne System

O. Gazzano, Y. Ferrec, C. Coudrain and L. Rousset-Rouvière
(ONERA / DOTA)

DGA

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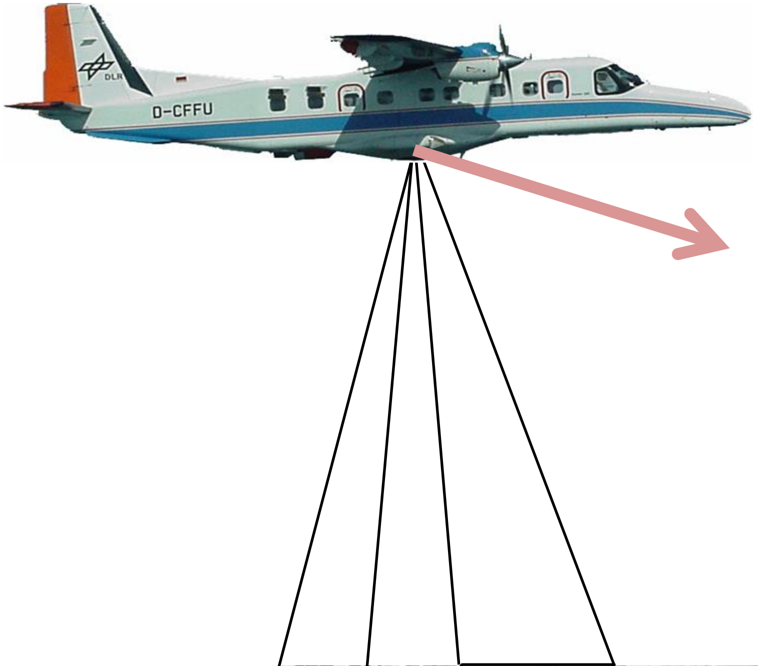
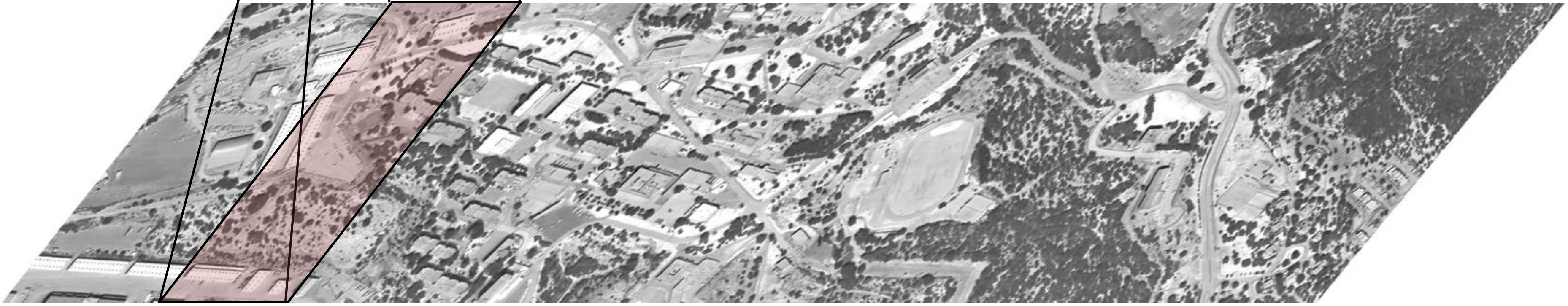
SIELETERS: an airborne hyperspectral imaging system



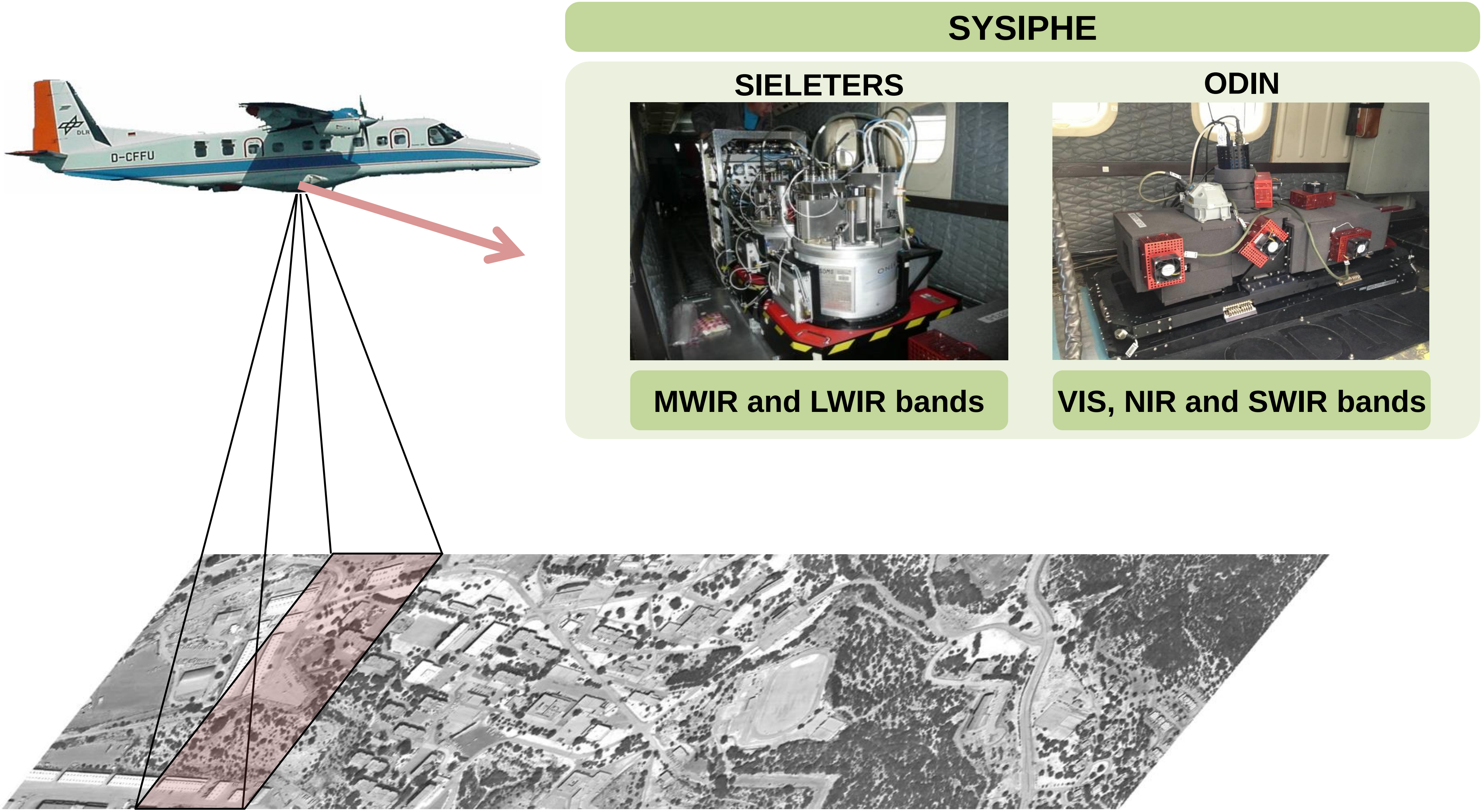
SIELETERS

MWIR and LWIR bands

➔ Hyperspectral imaging



SIELETERS: an airborne hyperspectral imaging system



SYSIPHE

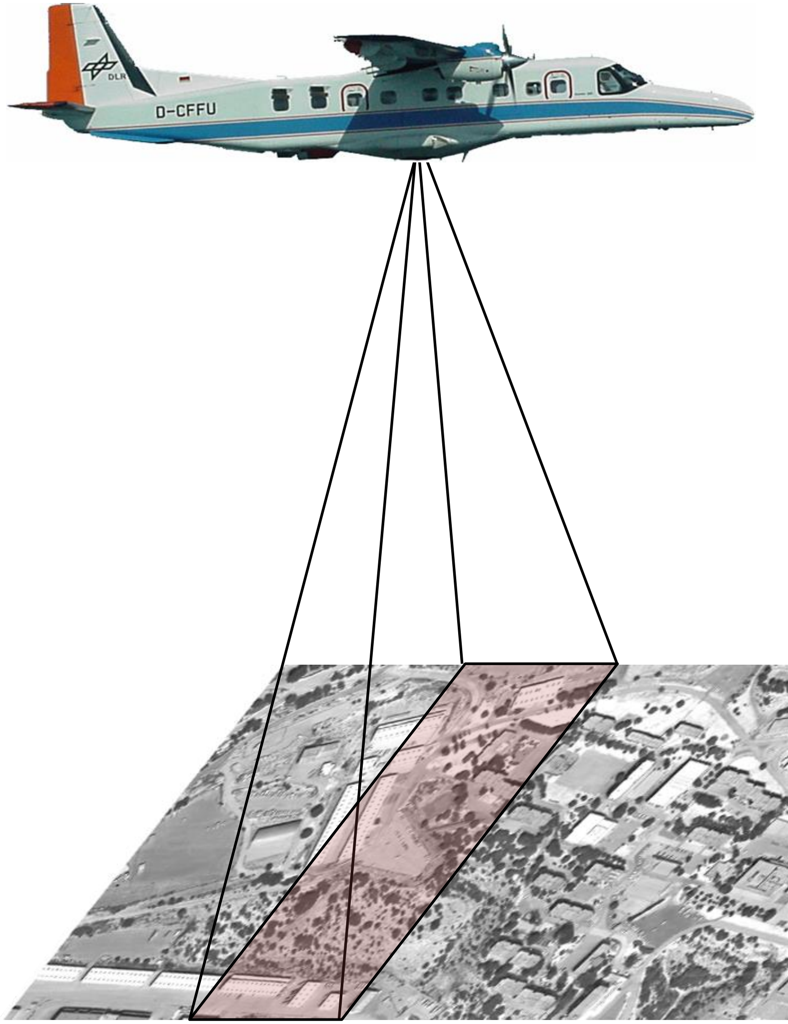
SIELETERS

MWIR and LWIR bands

ODIN

VIS, NIR and SWIR bands

SIELETERS: an airborne hyperspectral imaging system



SYSIPHE

SIELETERS

MWIR and LWIR bands

ODIN

VIS, NIR and SWIR bands

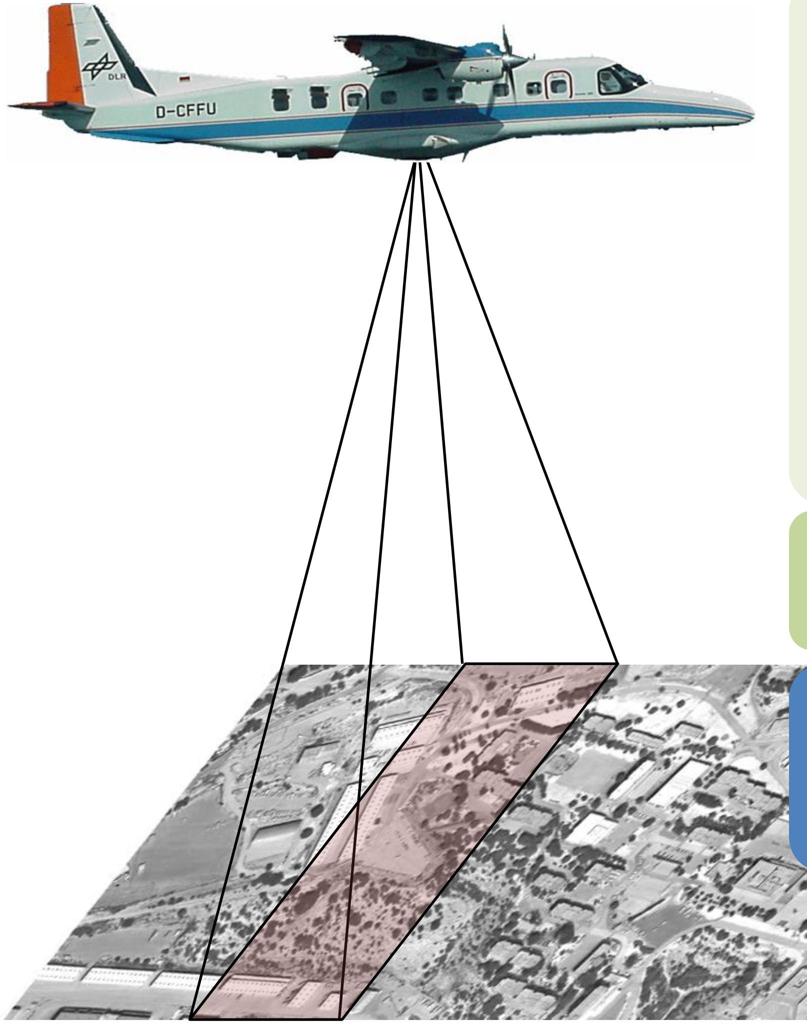
- ✓ **High spectral and spatial resolution**
  0.5 m resolution – 500 m swath – 600 spectral bands

A collaboration between France and Norway:

- ONERA, DGA
- Norsk Elektro Optikk (NEO), Forsvarets forskninginstitutt (FFI)

SIELETERS: an airborne hyperspectral imaging system

DLR
Do228 aircraft



SYSIPHE

SIELETERS

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SIELETERS: an airborne hyperspectral imaging system

DLR
Do228 aircraft

Objectives:

- To develop **skills**, **tools** and **technologies** for the design and the manufacturing of an airborne hyperspectral imaging system
- To improve **knowledge** of IR phenomenology
- To be able to **specify** an operational system

SYSIPHE

SIELETERS

MWIR and LWIR bands

ODIN

VIS, NIR and SWIR bands

- ✓ **High spectral and spatial resolution**
  0.5 m resolution – 500 m swath – 600 spectral bands

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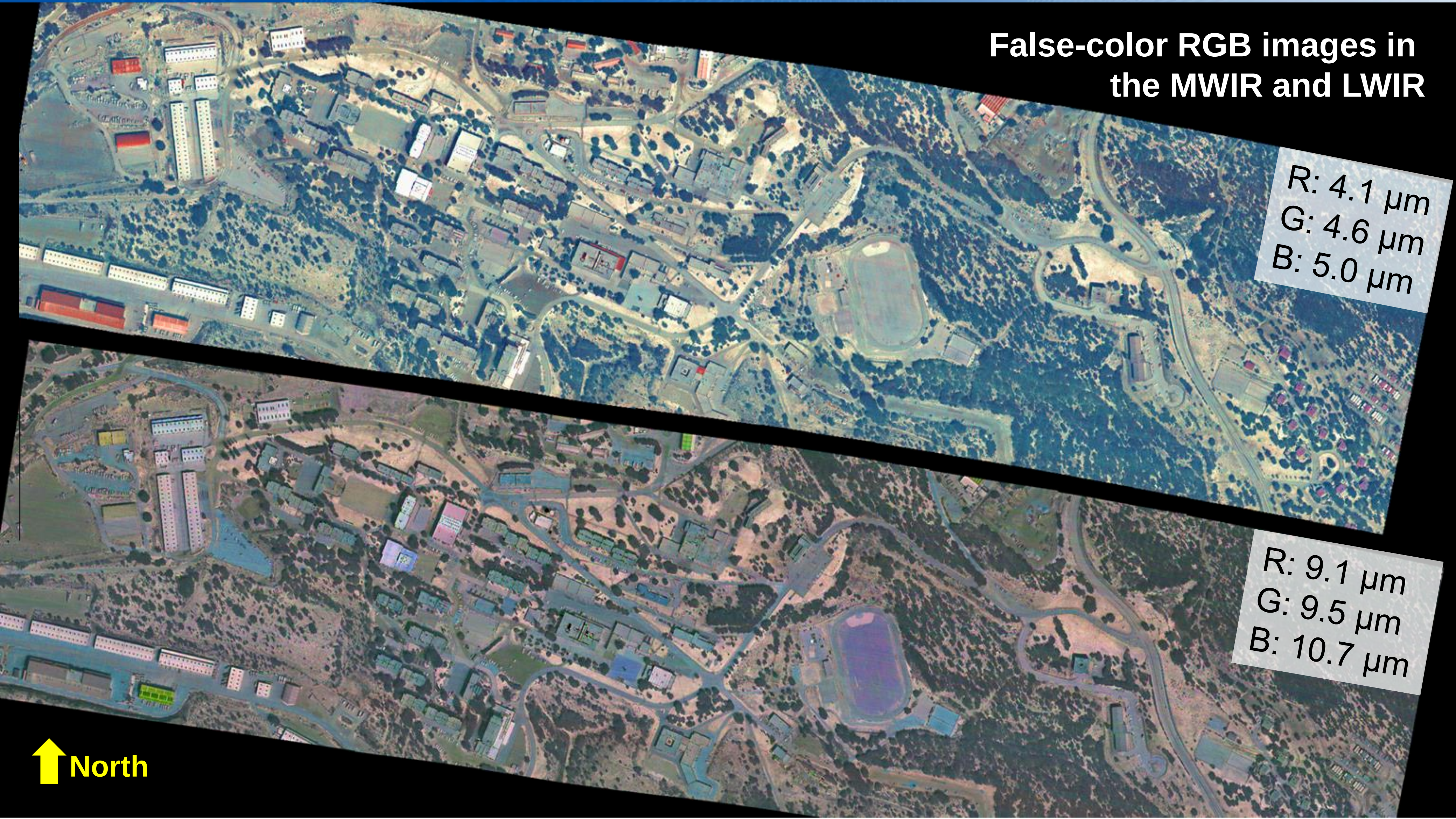
What can we get from the instrument?



False-color RGB images in the MWIR and LWIR

What can we get from the instrument?

	MWIR	**LWIR**
Spectral range	**3.0 - 5.2 µm**	**8.1 – 11.5 µm**
Spectral resolution	**11 cm^{-1}** **17 nm at 4 µm**	**5 cm^{-1}** **50 nm at 10 µm**
# spectral bands	~ 130	~ 75
Pixel FOV	0.25 mrad	
Total FOV	15°	
Spatial resolution	50 cm at 2 000 m	
F-number	F4.0	F3.0
Calibration	Spectral radiance, Emissivity/temperature	
Georeferencing	✔	

- MCT IR from Lynred (1016 x 440 px)
- Entirely cryogenic (liquid nitrogen, 77K)
- Stabilized

SIELETERS / SYSIPHE airborne campaigns

4 airborne campaigns

2013 **2015** **2016** **2019**


DGA Essais en vol/photo site de Cazaux


DGA Essais en vol/photo site de Cazaux


DGA Essais en vol/photo site de Cazaux

4 airborne campaigns

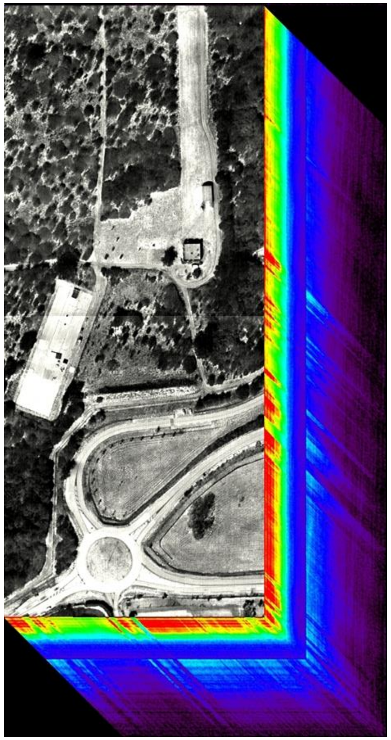
2013

2015

2016

2019

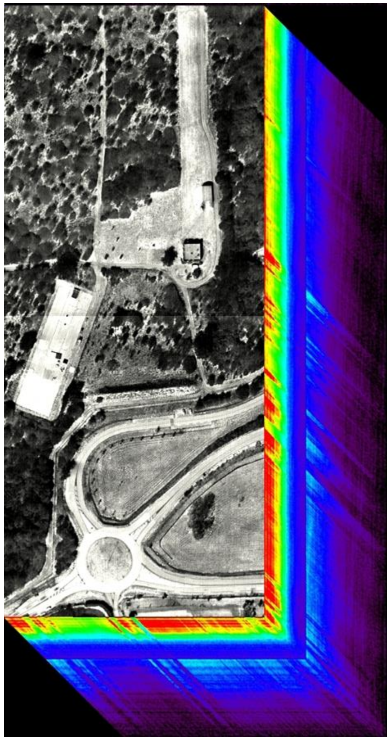
First flight,
First images



DLR
Dornier
Do228 aircraft

4 airborne campaigns

**First flight,
First images**

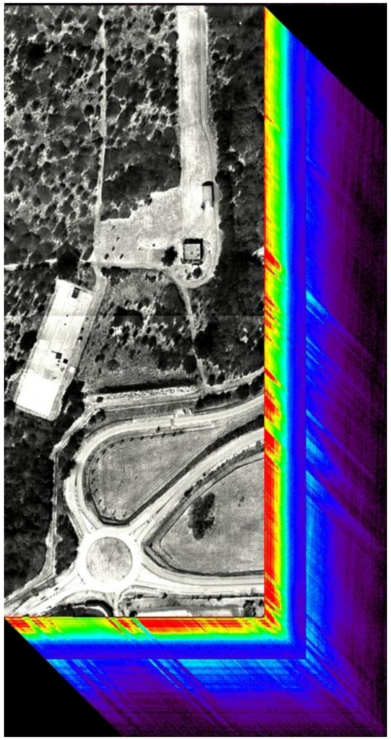


**Civilian and military
ground truths**

4 airborne campaigns

2013

First flight,
First images



2015

Civilian and military
ground truths

2016

Different aircraft,
different scenarios

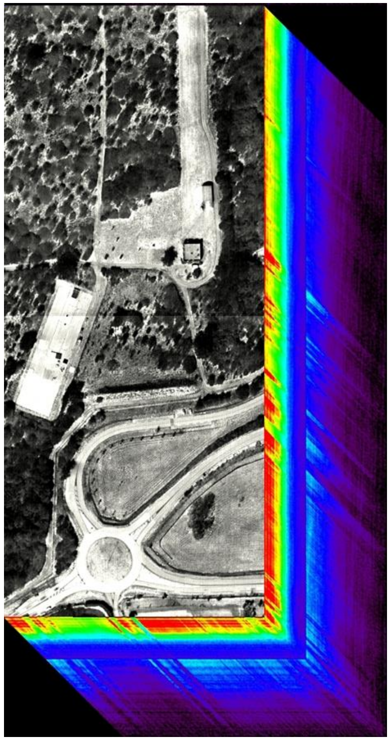
IMAO's aircraft

2019

4 airborne campaigns

2013

First flight,
First images



2015

Civilian and military
ground truths

2016

Different aircraft,
different scenarios

IMAO's aircraft

2019

More civilian and
military ground truths ;
Winter scenarios

4 airborne campaigns

2013

First flight,
First images

2015

Civilian and military ground truths

2016

Different aircraft, different scenarios

2019

More civilian and military ground truths ; Winter scenarios

4 airborne campaigns

2 different aircrafts (from DLR and from IMAO)

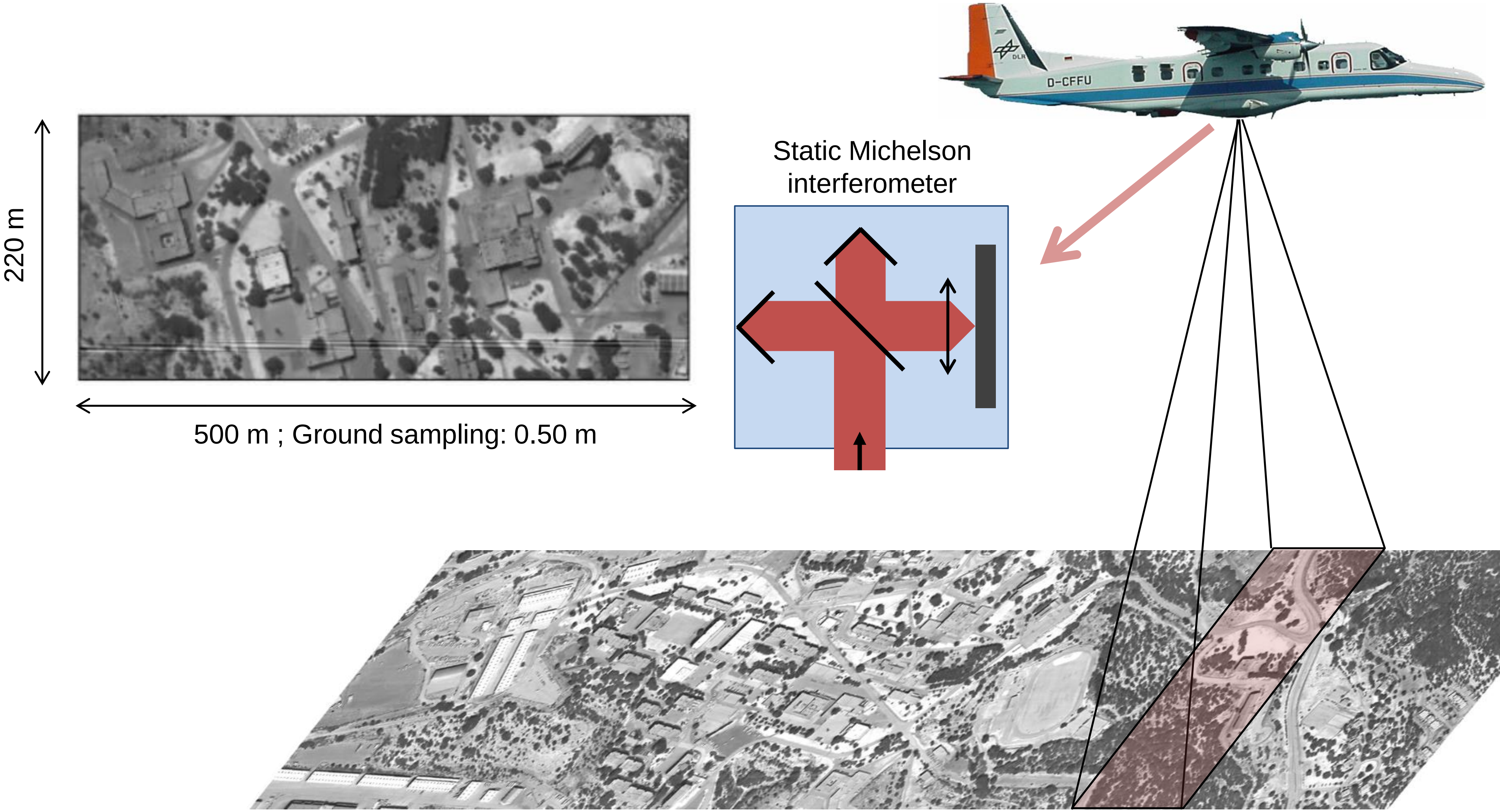
19 flights

2 night flights

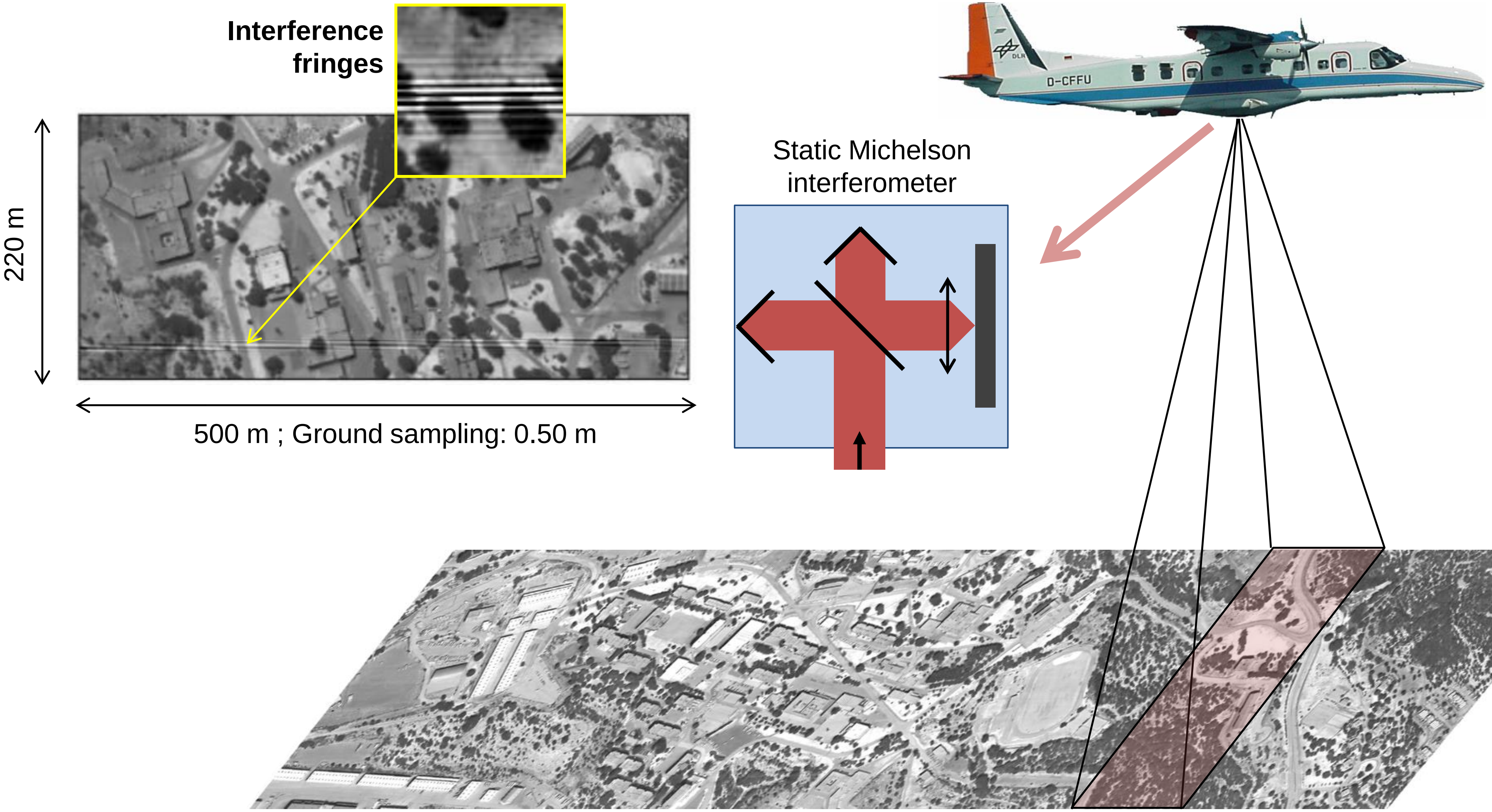
50+ people involved

How does the system work?

SIELETERS instrument: an imaging static Fourier transform spectrometer



SIELETERS instrument: an imaging static Fourier transform spectrometer



Interference fringes

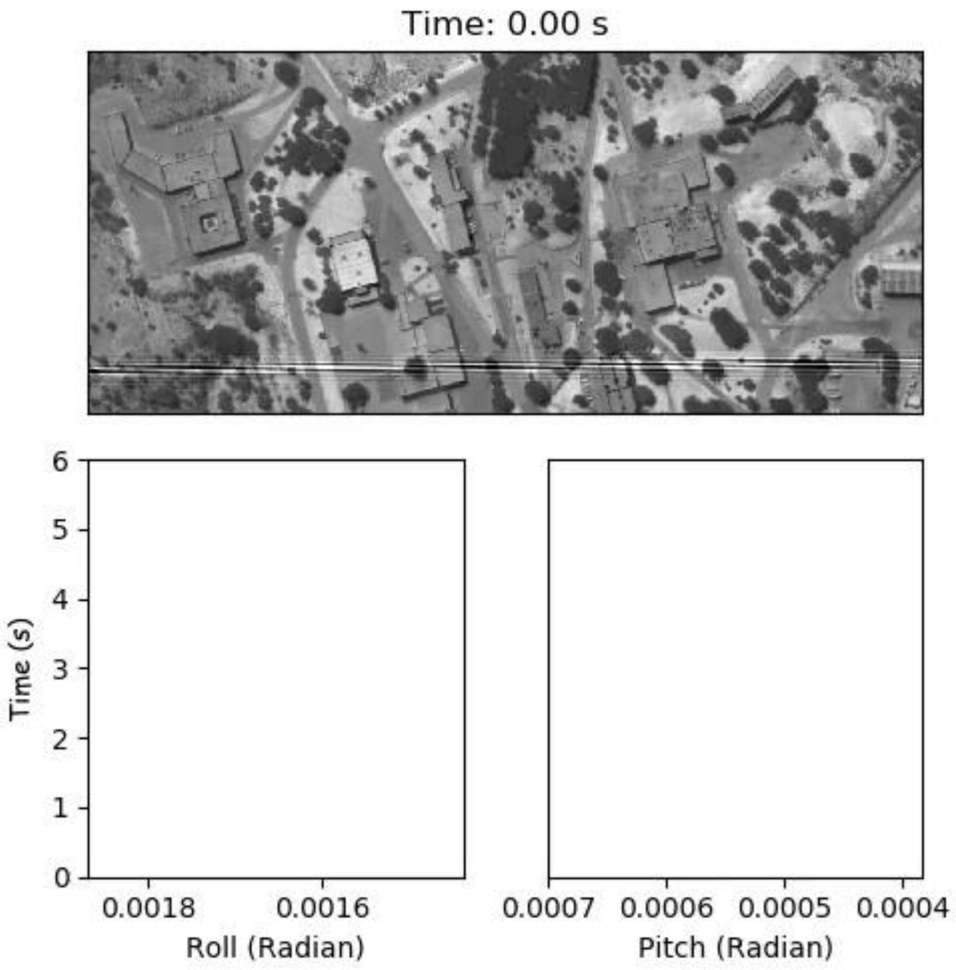
220 m

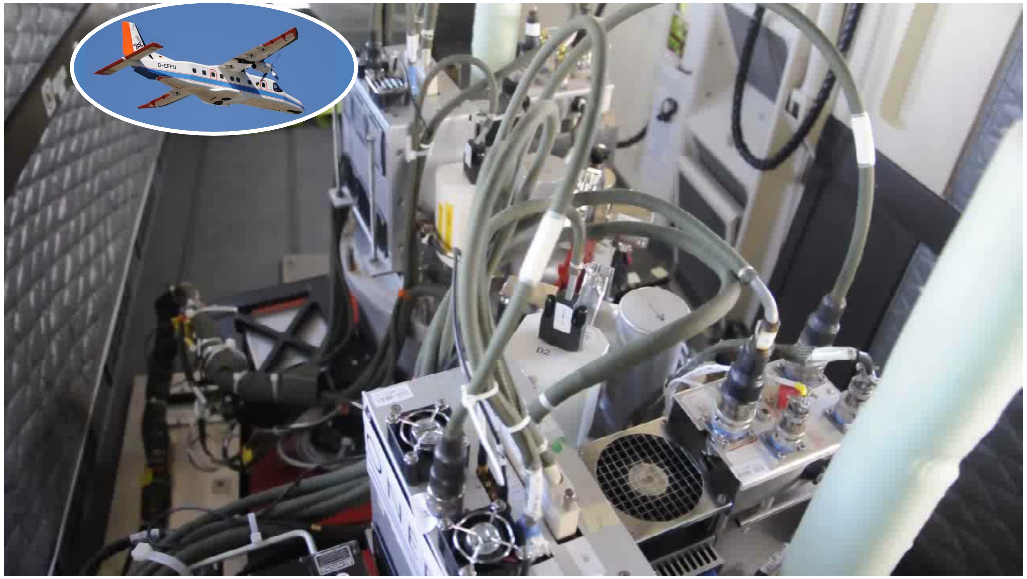
500 m ; Ground sampling: 0.50 m

Static Michelson interferometer

SIELETERS instrument: an imaging static Fourier transform spectrometer

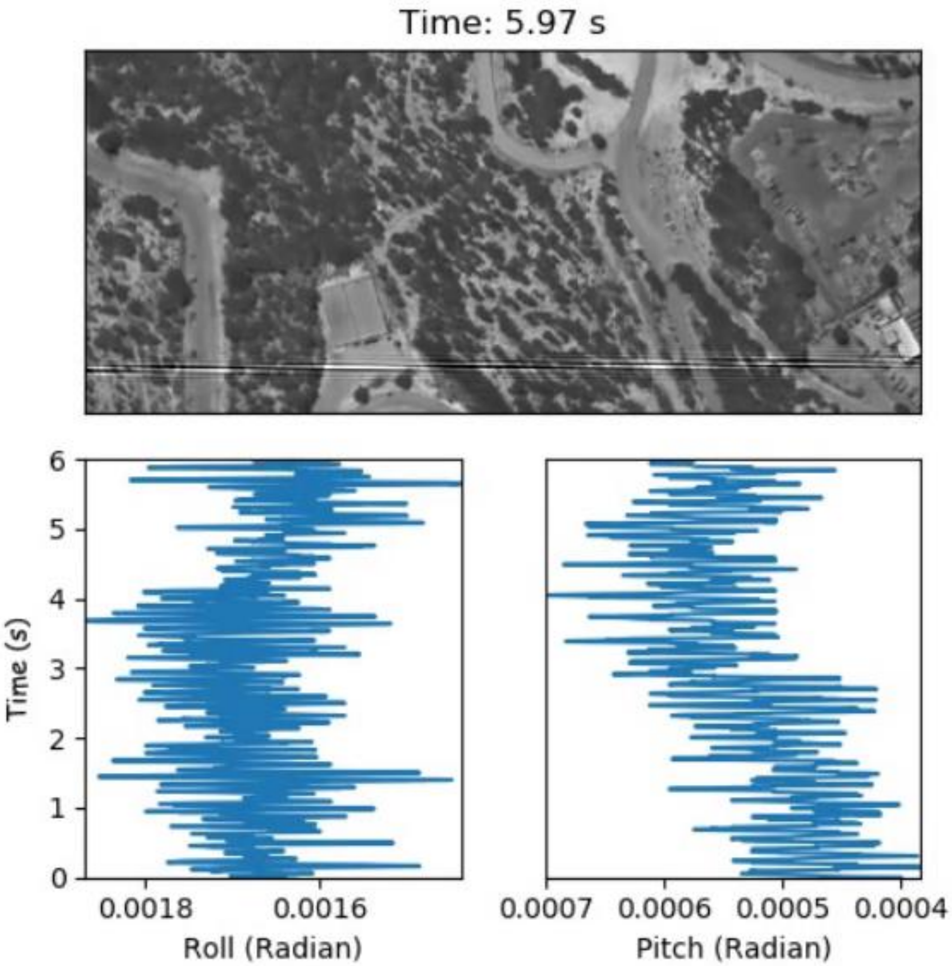
Airborne measurement (150 Hz)



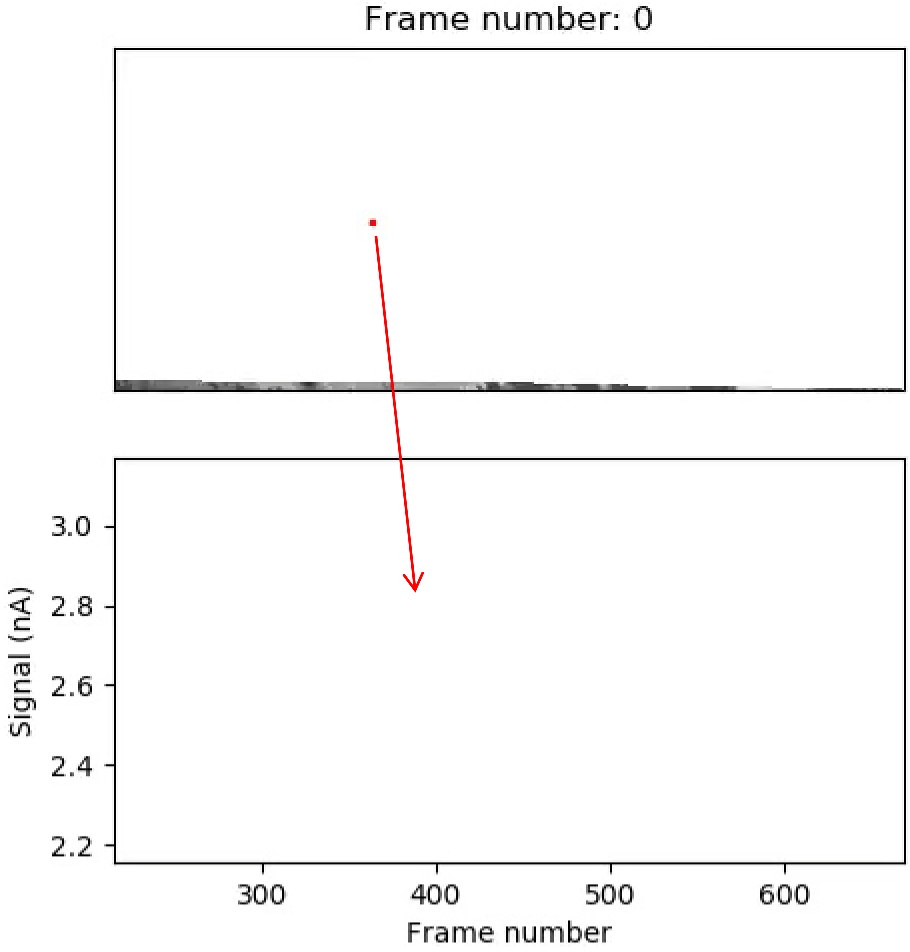


SIELETERS instrument: an imaging static Fourier transform spectrometer

Airborne measurement (150 Hz)



REGISTRATION



SIELETERS instrument: an imaging static Fourier transform spectrometer

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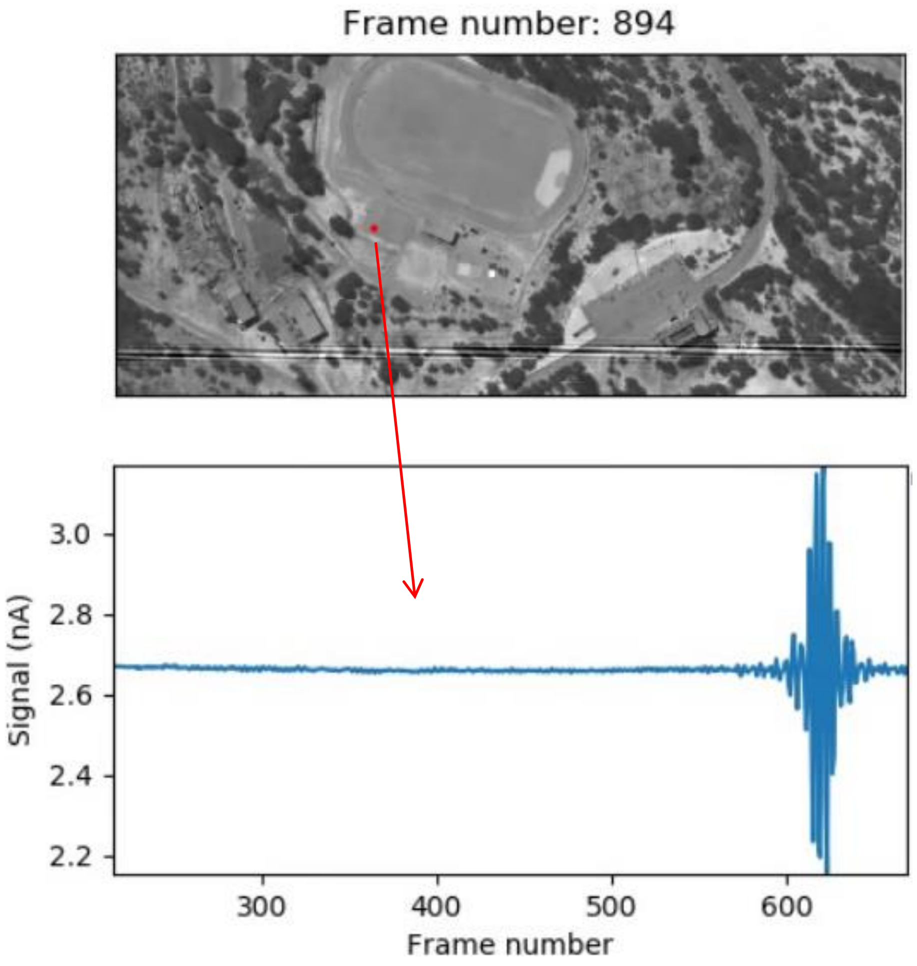
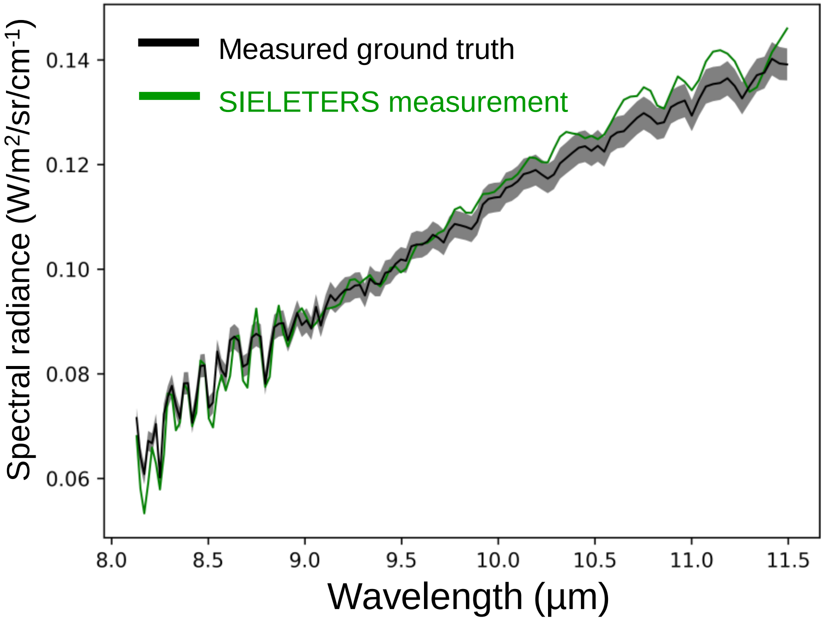
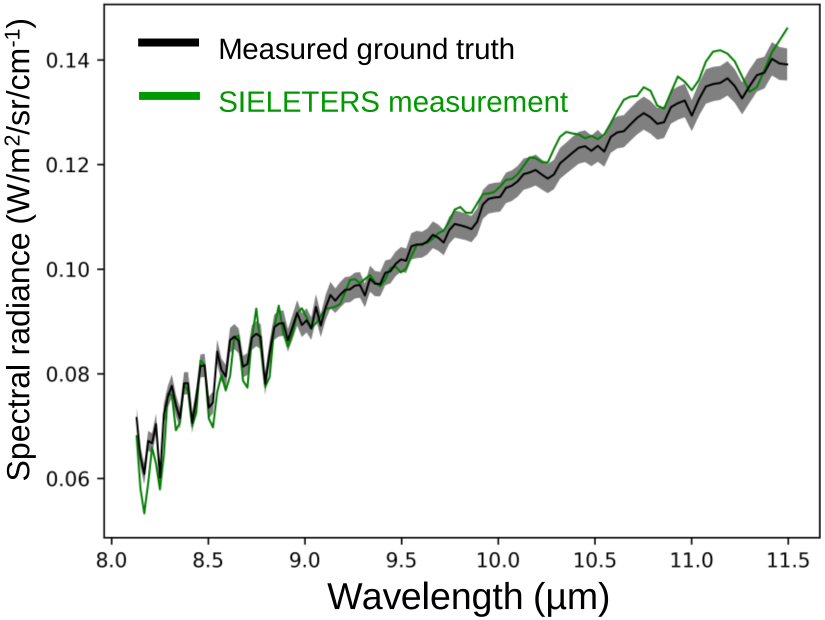




SIELETERS instrument: an imaging static Fourier transform spectrometer

Example : False-color RGB image
R = 9.12 µm, G = 9.52 µm, B = 10.75 µm)



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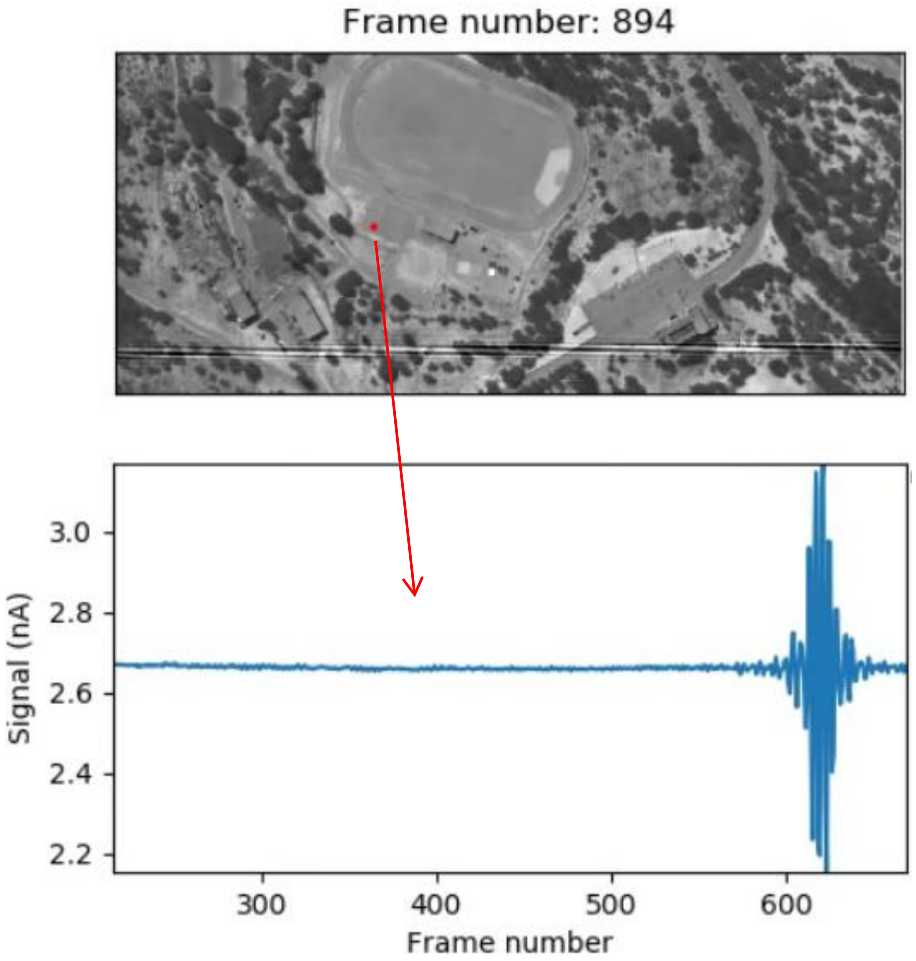


SIELETERS instrument: an imaging static Fourier transform spectrometer

Raw
images

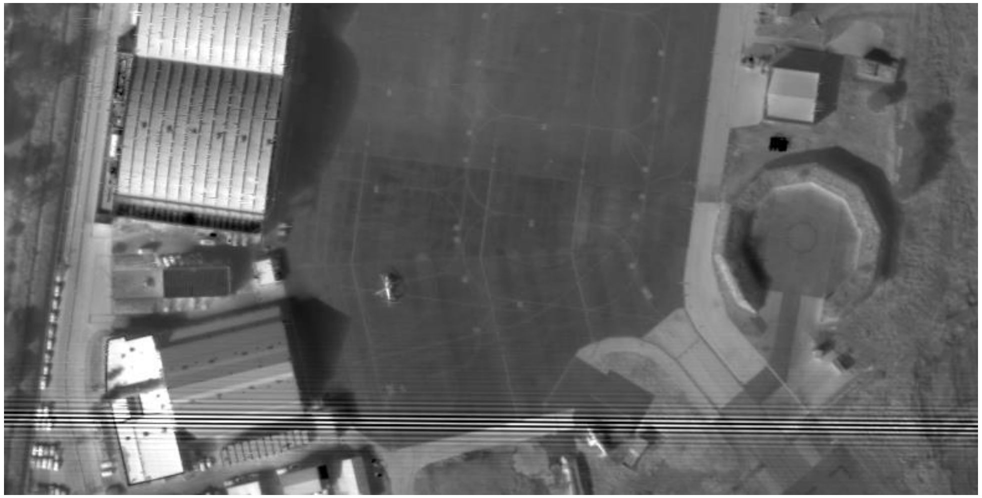
Raw image in the LWIR

SIELETERS instrument: an imaging static Fourier transform spectrometer

Raw images

Non-uniformity correction

Raw image in the LWIR

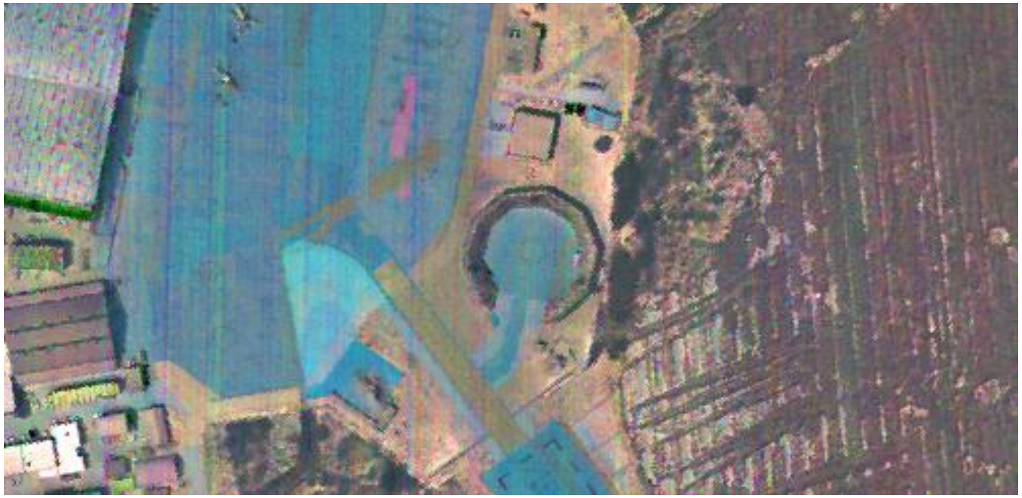


Same image in the LWIR
with the non-uniformity correction

SIELETERS instrument: an imaging static Fourier transform spectrometer

Raw images → **Non-uniformity correction** → **Registration** → **Phase estimation** → **Fourier transform** → Georeferenced hyperspectral images

Raw image in the LWIR



False-color RGB image in the LWIR

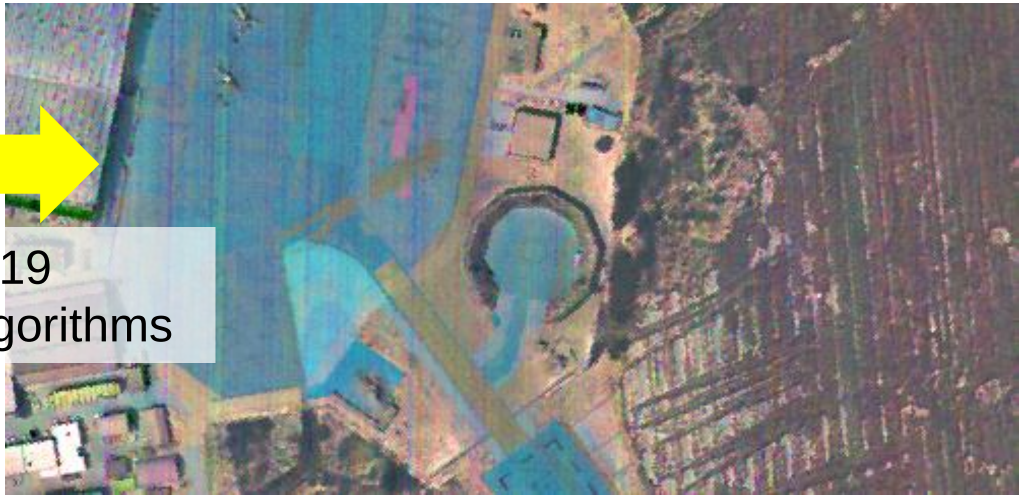
R: 9.1 µm
V: 9.5 µm
B: 10.7 µm

SIELETERS instrument: an imaging static Fourier transform spectrometer

Raw images → **Non-uniformity correction** → **Registration** → **Phase estimation** → **Fourier transform** → Georeferenced hyperspectral images

Raw image in the LWIR

2019
latest algorithms



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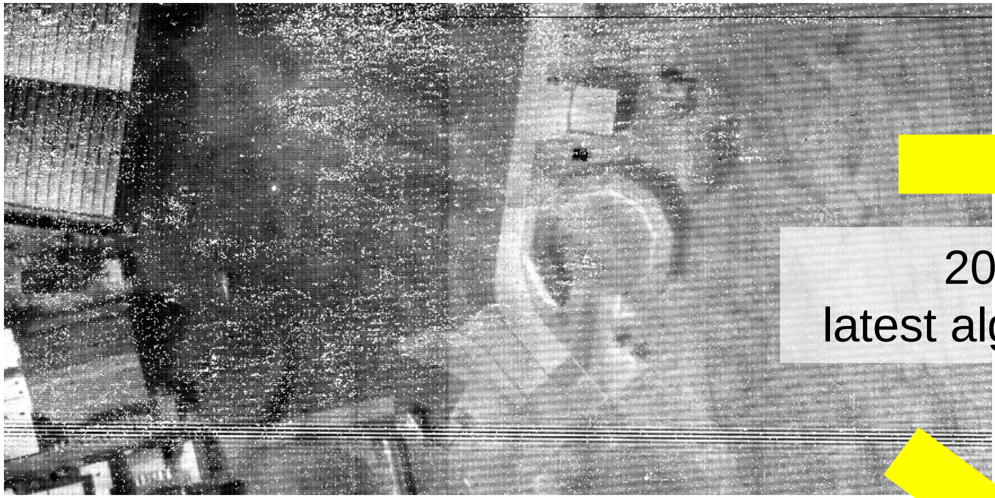
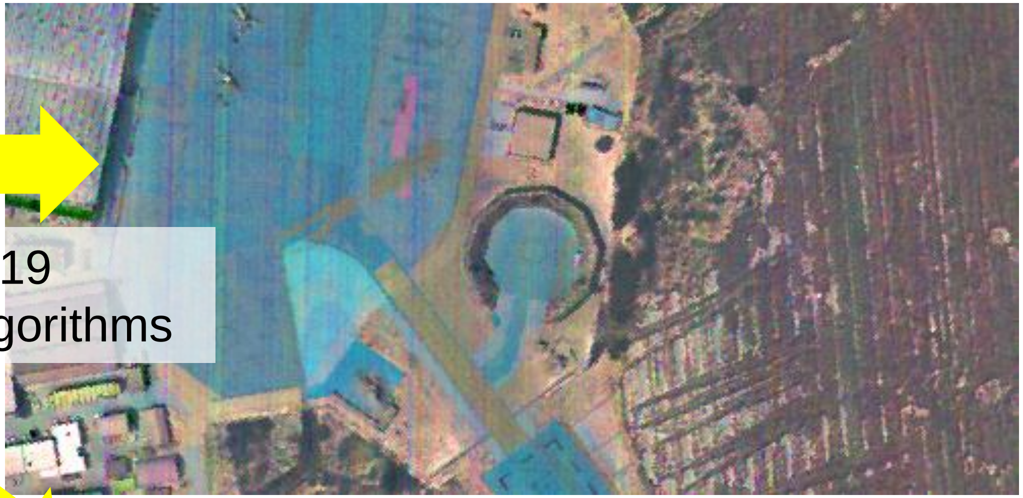


Raw image in the LWIR

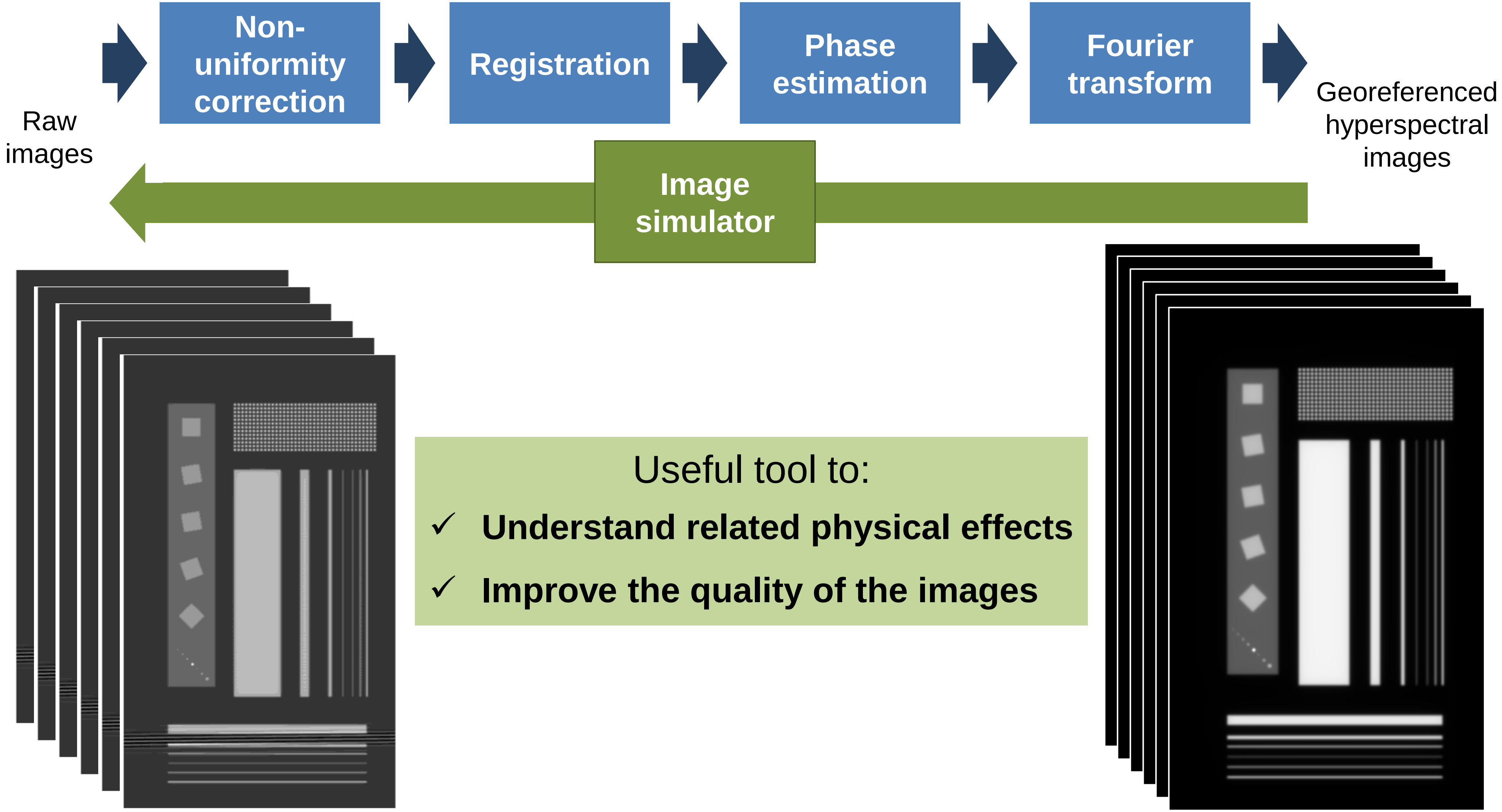


2019
latest algorithms

2017
algorithms

How did we improve the data processing programs?

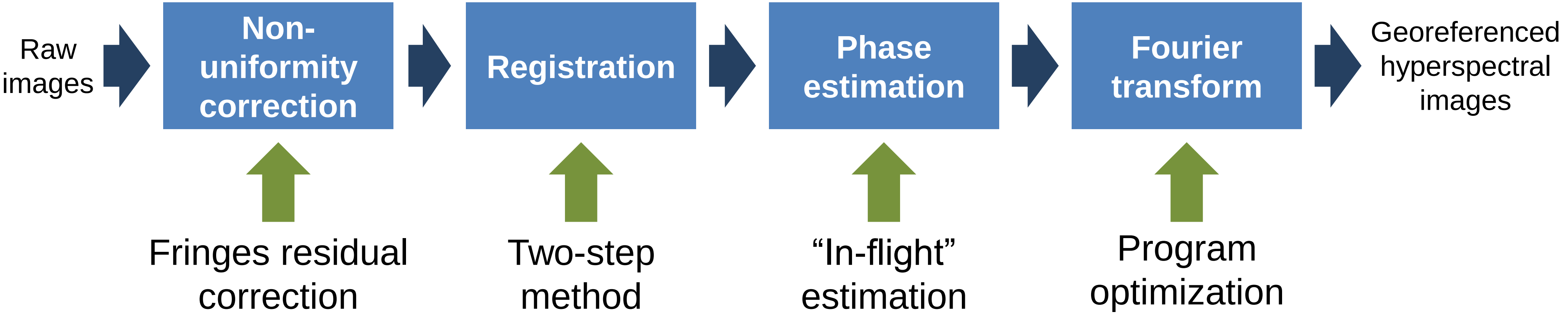
Simulator of the SIELETERS raw airborne images



Useful tool to:

- ✓ **Understand related physical effects**
- ✓ **Improve the quality of the images**

How did we improve the data processing programs?



Raw images

Non-uniformity correction

Registration

Phase estimation

Fourier transform

Georeferenced hyperspectral images

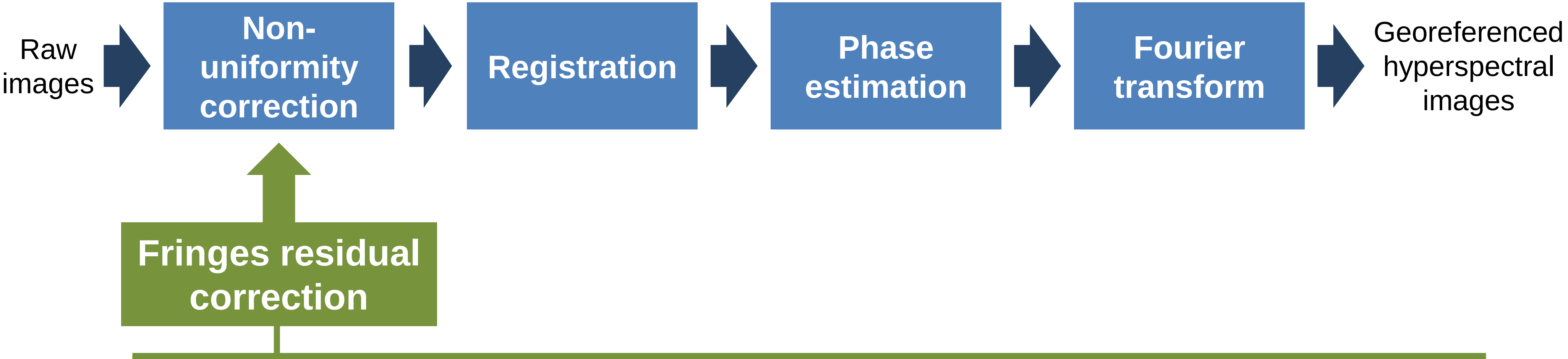
Fringes residual correction

Two-step method

“In-flight” estimation

Program optimization

Data processing programs improvements



Raw images

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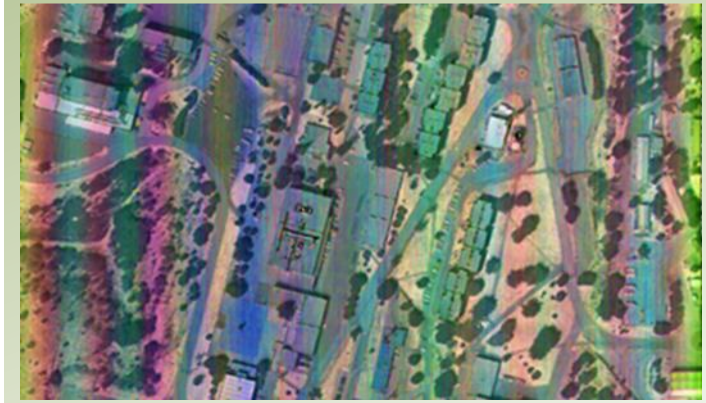
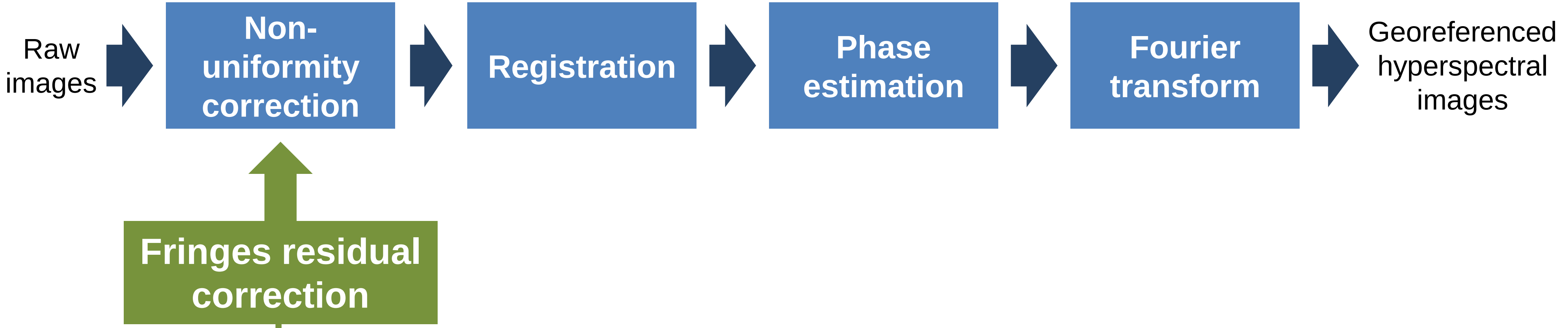
Fringes residual correction



False-color RGB image (LWIR)

1. Temporal instability of the IR sensor
2. Non-uniformity correction using in-flight images
3. Need to filter interference fringes
4. Introduce fringes residuals on the corrected images
5. Vertical oscillations on the spectral images

Data processing programs improvements



Raw images

Non-uniformity correction

Registration

Phase estimation

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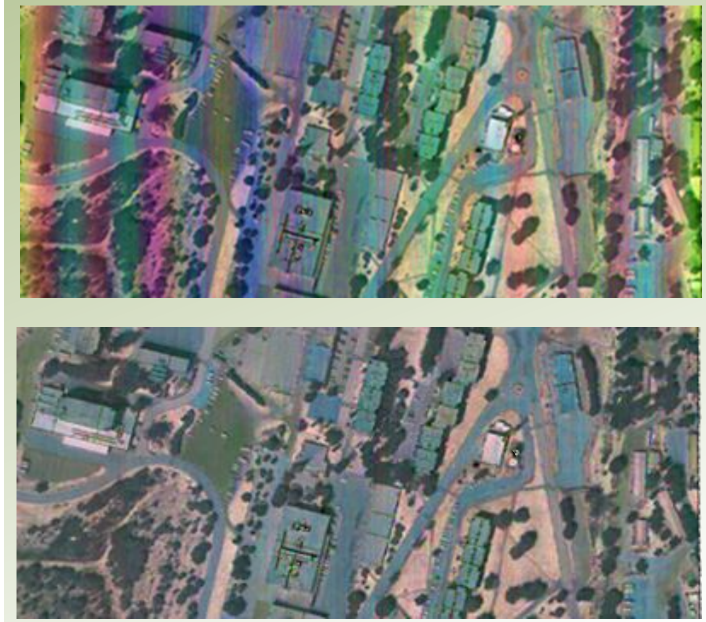
Georeferenced hyperspectral images

Fringes residual correction

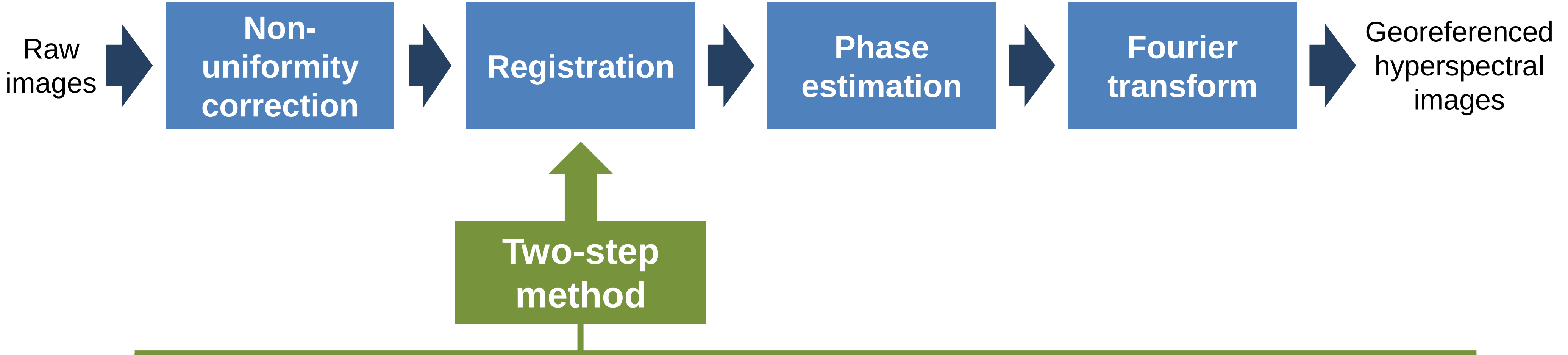


1. Temporal instability of the IR sensor
2. Non-uniformity correction using in-flight images
3. Need to filter interference fringes
4. Introduce fringes residuals on the corrected images
5. Vertical oscillations on the spectral images

Solution :

- **Detect** the fringes residuals
- **Remove** the residuals

Data processing programs improvements



Raw images → **Non-uniformity correction** → **Registration** → **Phase estimation** → **Fourier transform** → Georeferenced hyperspectral images

Two-step method

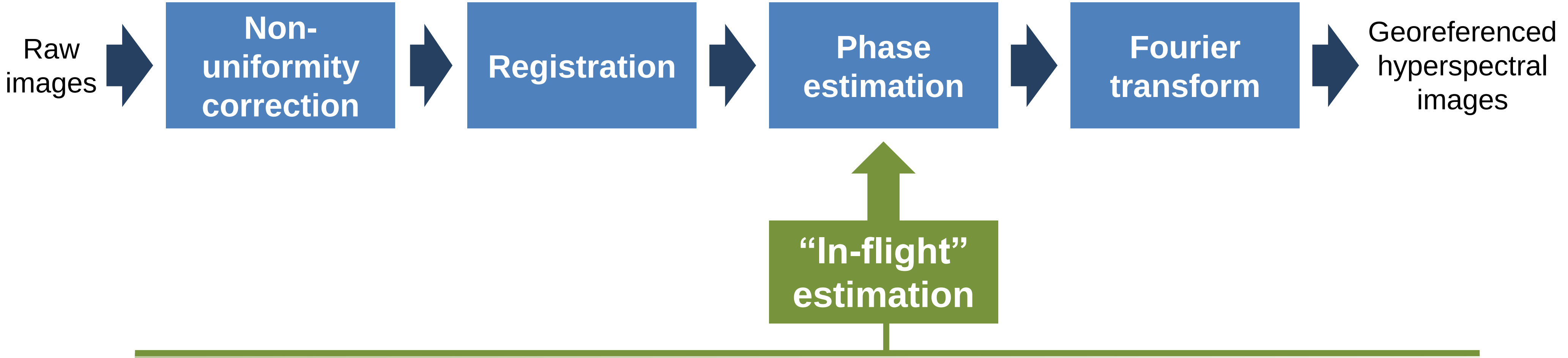
Perfect registration (simulation)

Noisy registration (simulation)

- ❖ **Step 1 :** **Line of sight** recorded during the flight
  \+
  Digital elevation model
- ❖ **Step 2 :** image **correlation**

- **Step 1 ➔ ~ 0.1 pixel resolution**
- **Step 1 + Step 2 ➔ << 0.1 pixel resolution**
  << 5 cm on the ground!

Data processing programs improvements



Raw images

Non-uniformity correction

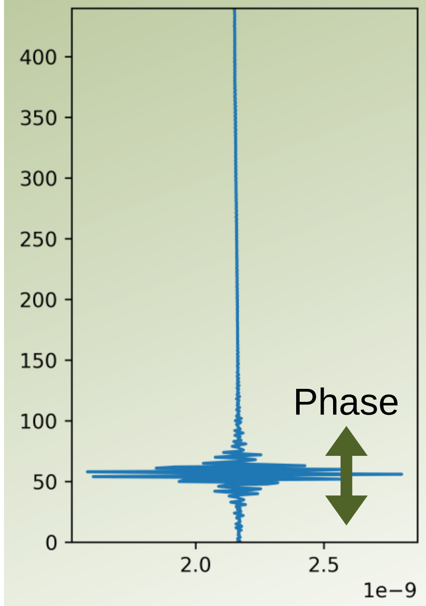
Registration

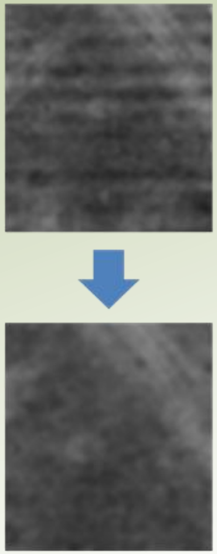
Phase estimation

Fourier transform

Georeferenced hyperspectral images

“In-flight” estimation





- **Phase ➔ critical parameter for the Fourier transform step**

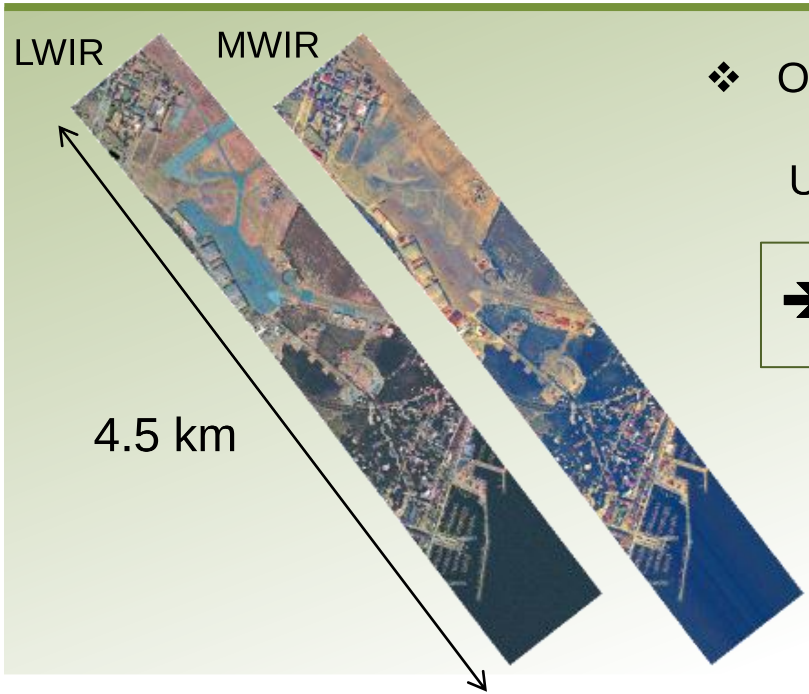
Algorithm improvements:

- **Account for the wavelength dependence of the phase**
- **Updated with the in-flight images**

Data processing programs improvements

Raw images → **Non-uniformity correction** → **Registration** → **Phase estimation** → **Fourier transform** → Georeferenced hyperspectral images

Program optimization ↑ (Fourier transform)



❖ Optimization of the IDL programs
\+
Use of some Python functions

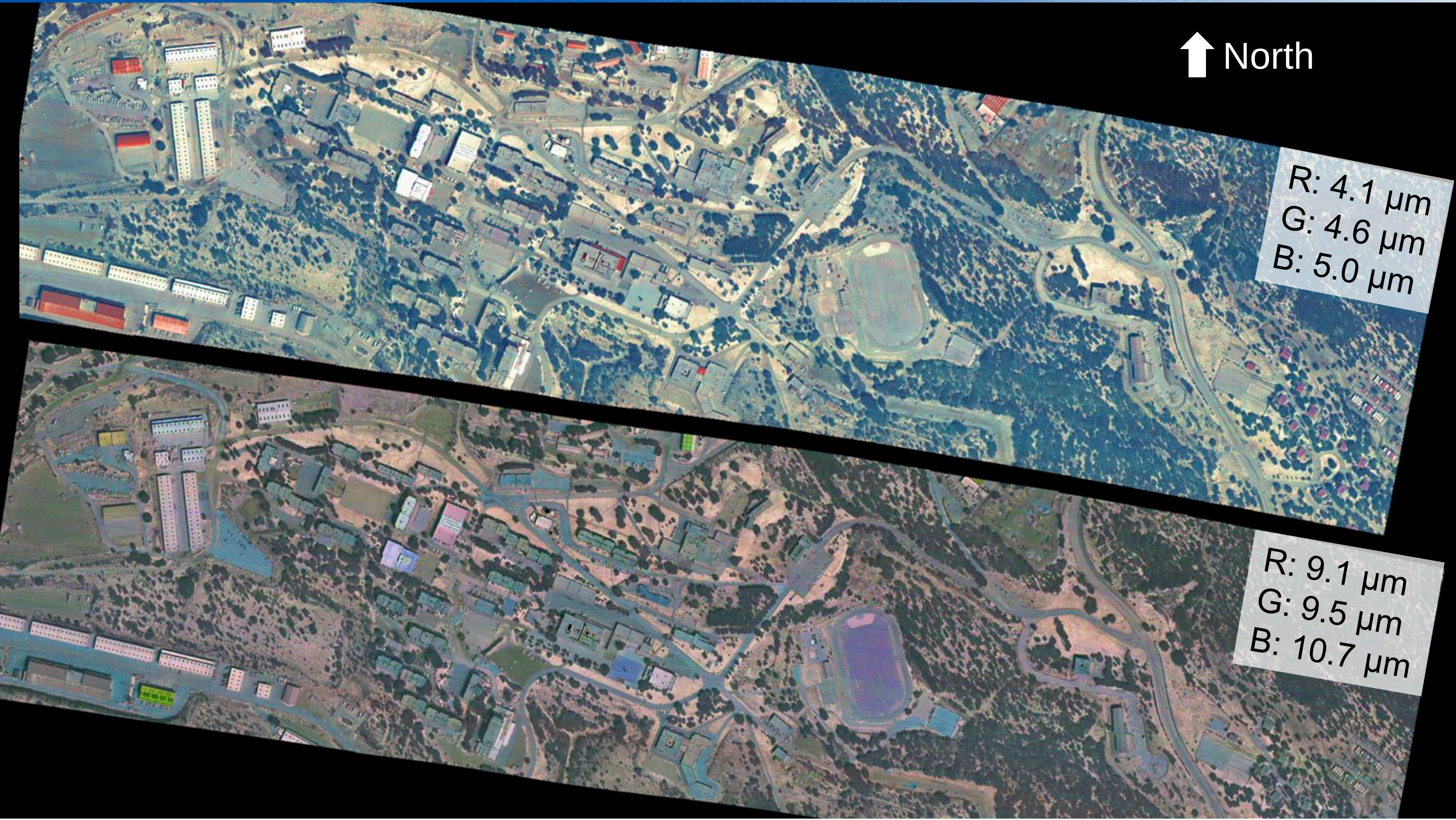
➔ Fourier transform step 3 times faster

Time to convert 4.5 km of raw images into spectral images :

BEFORE : ~ 48 hours
NOW : ~ 24 hours

Some results

Georeferenced images: thermal infrared bands (MWIR and LWIR)

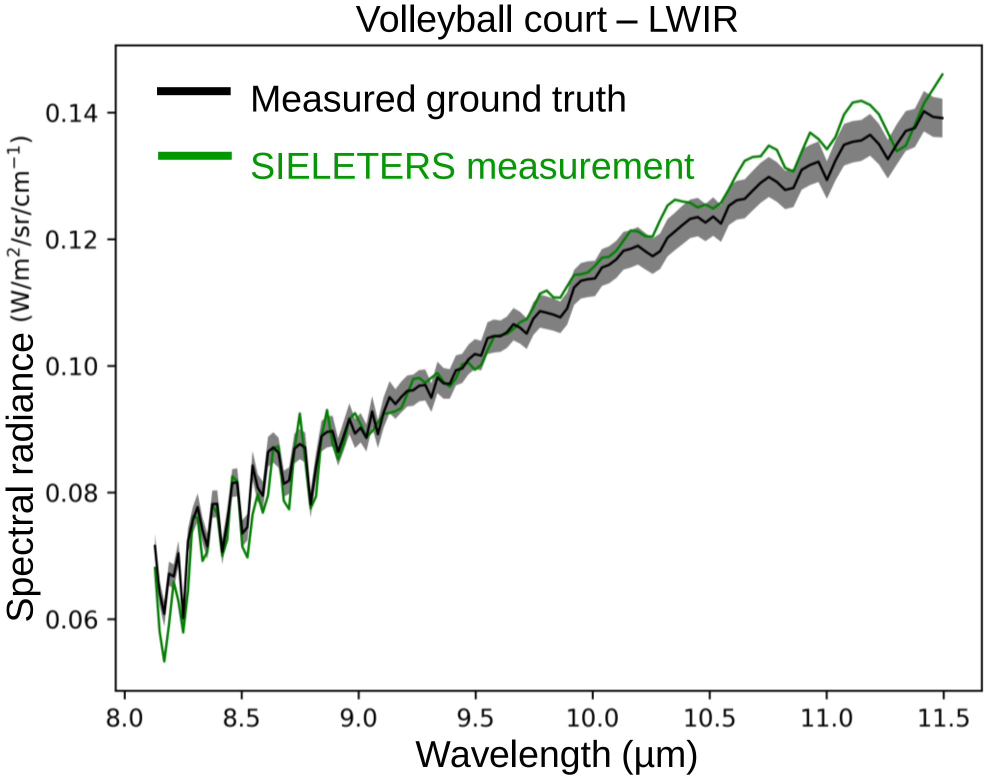


North

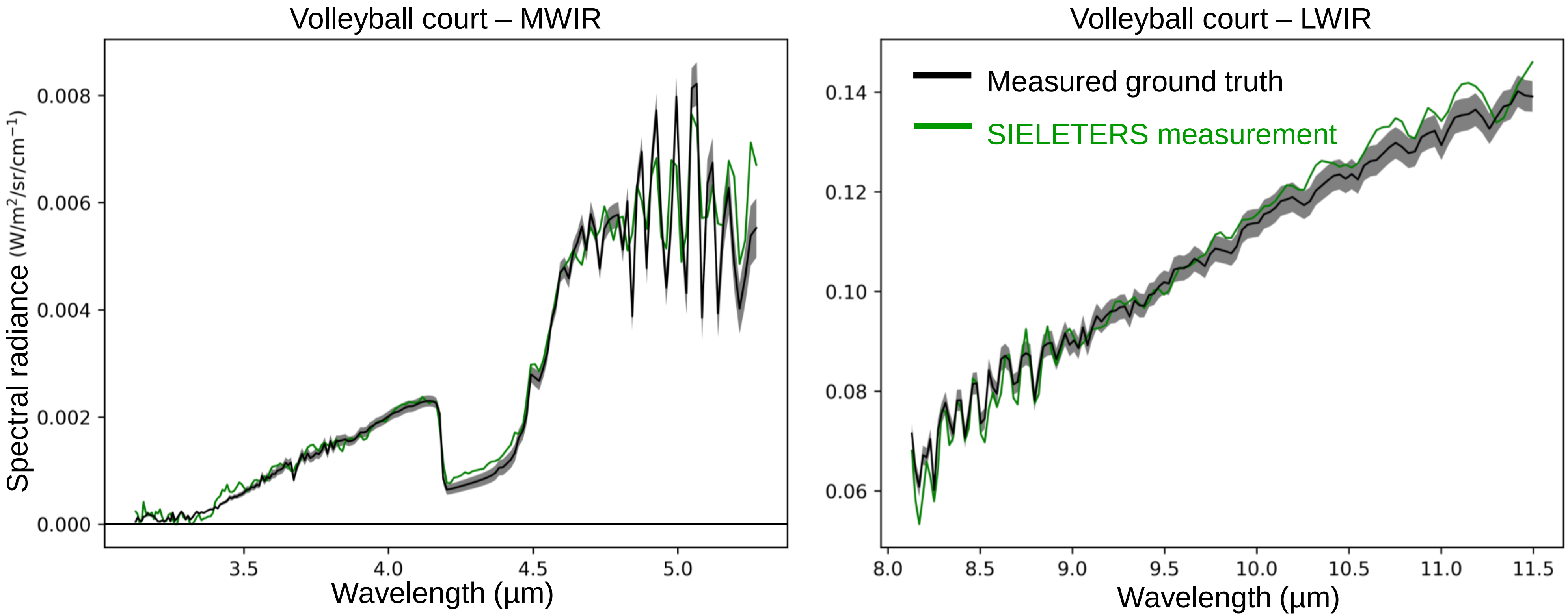
R: 4.1 µm
G: 4.6 µm
B: 5.0 µm

R: 9.1 µm
G: 9.5 µm
B: 10.7 µm

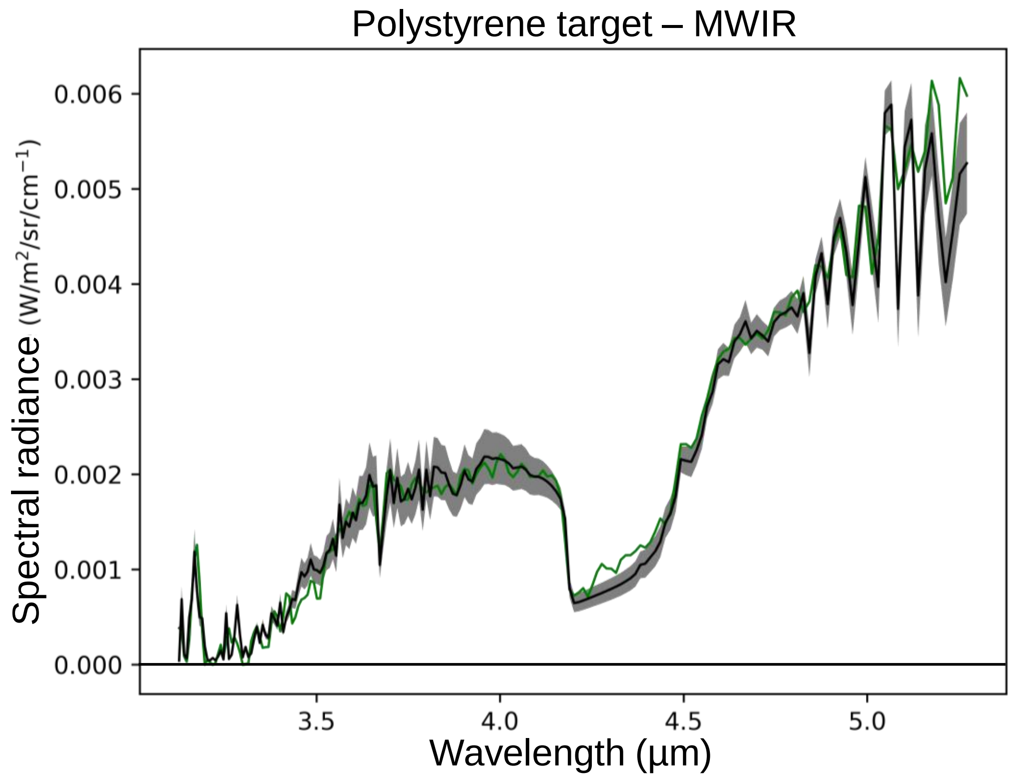
Spectrum from the 2015 campaign

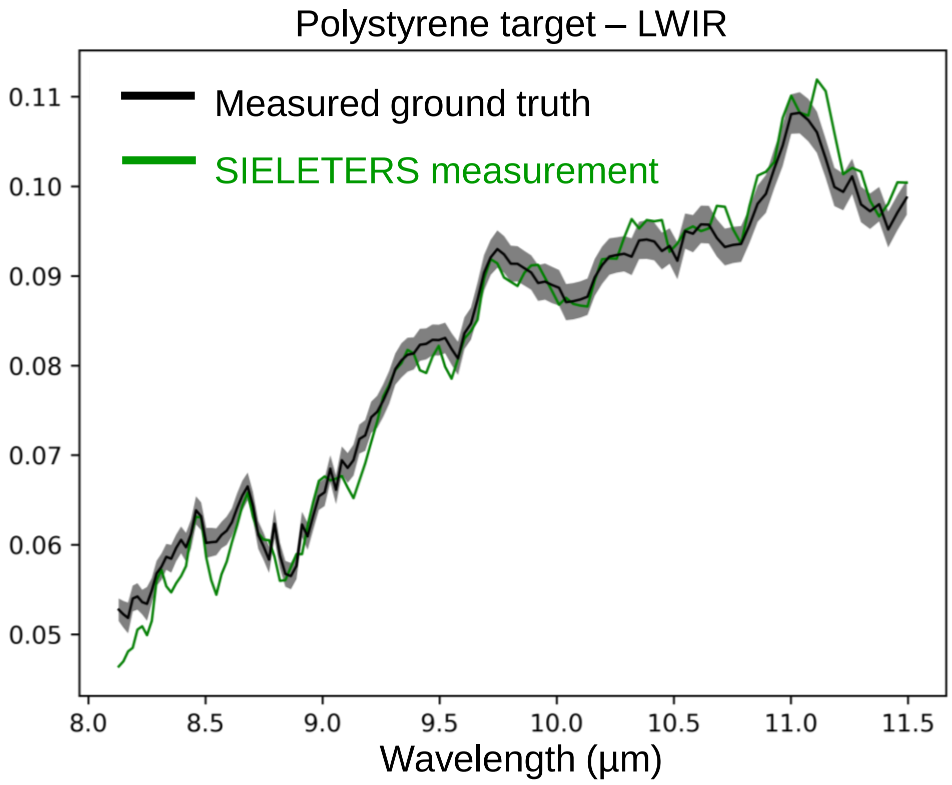

Volleyball court – LWIR

Spectrum from the 2015 campaign

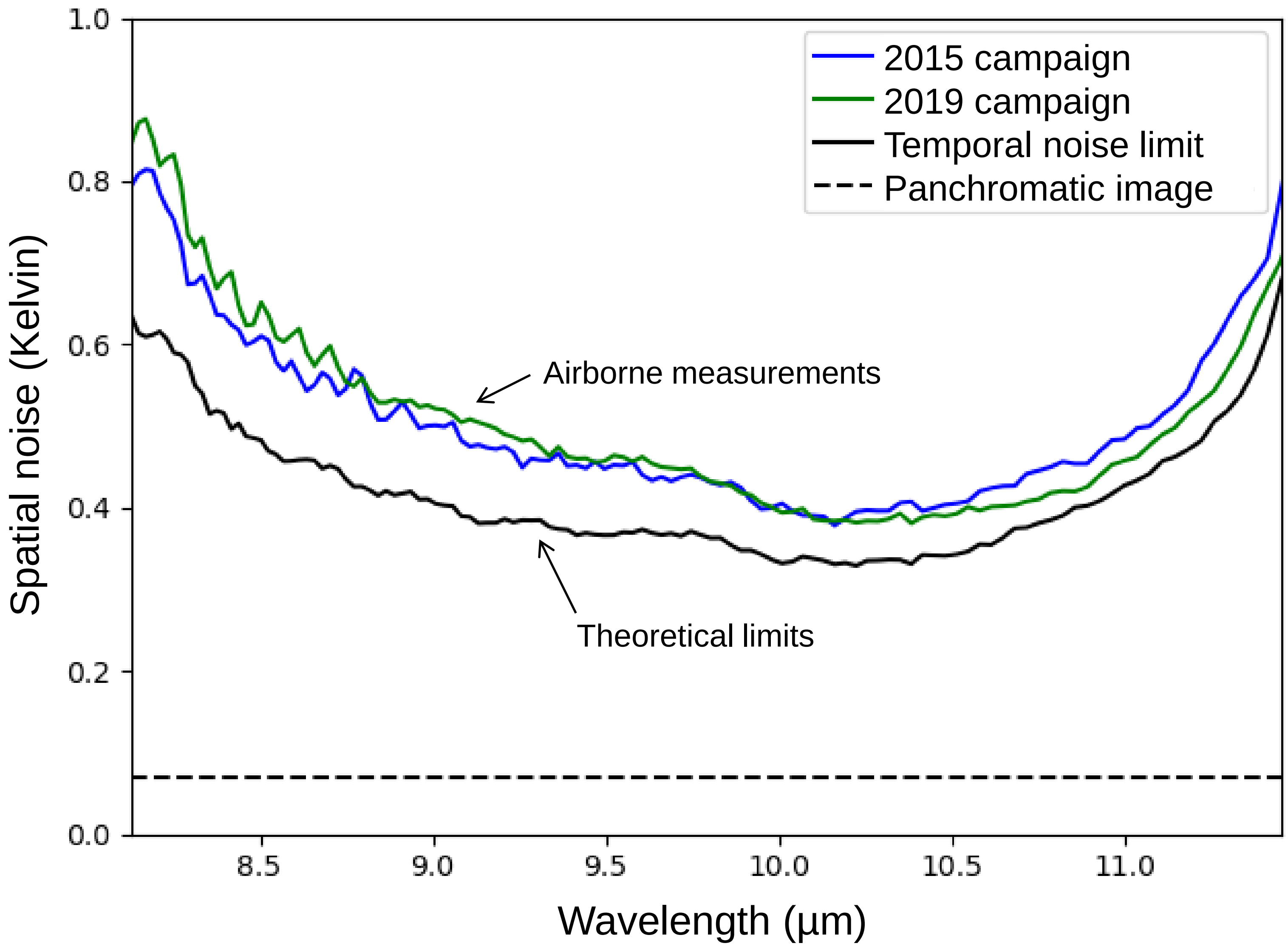


Spectrum from the 2015 campaign

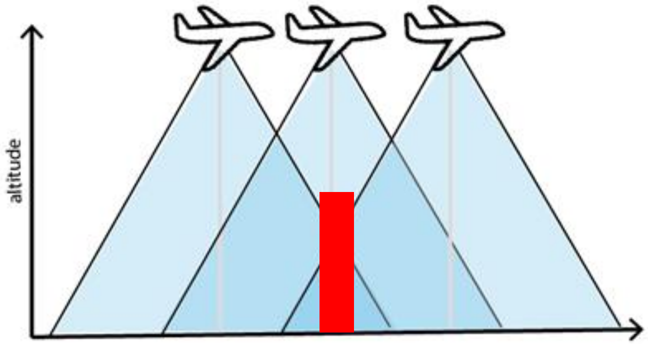

Polystyrene target – MWIR

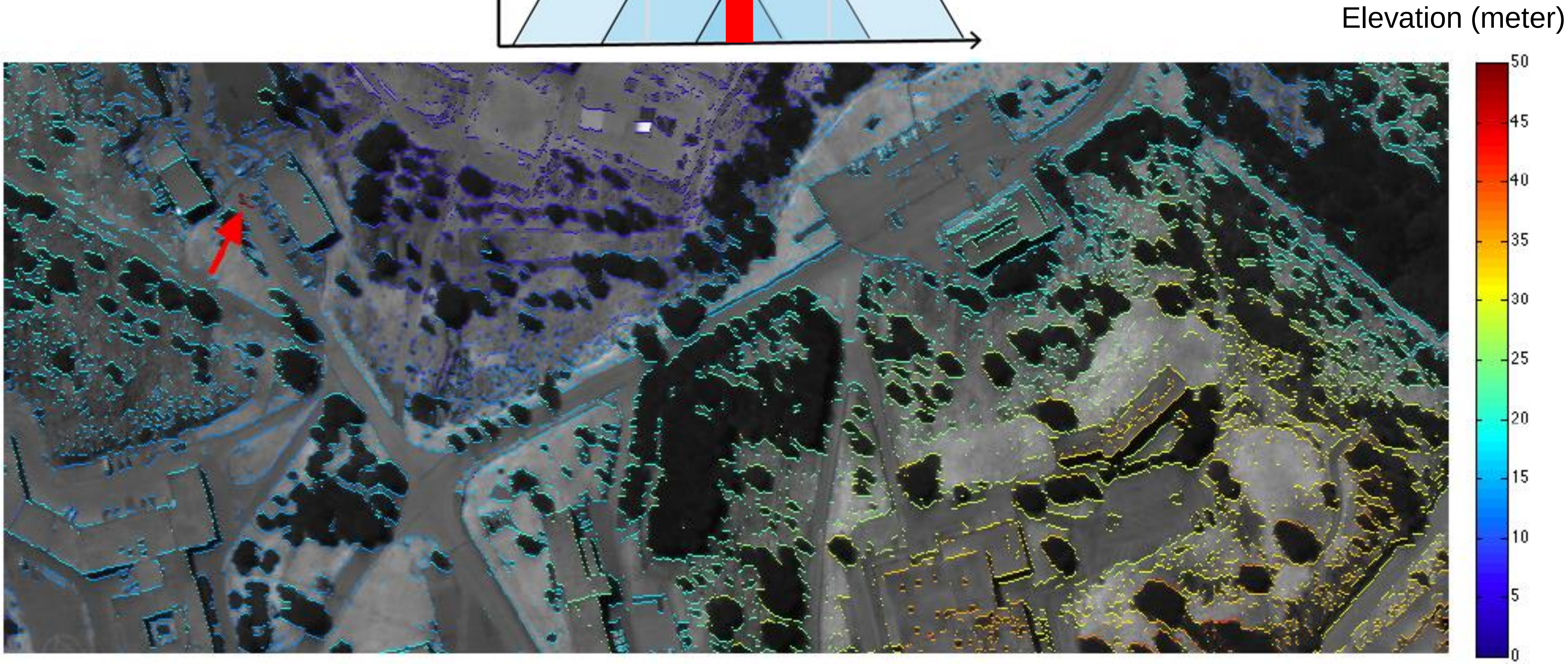

Polystyrene target – LWIR

Spatial noise over a uniform area (sea)



Side product:
Digital surface model from the SIELETERS images





Conclusions

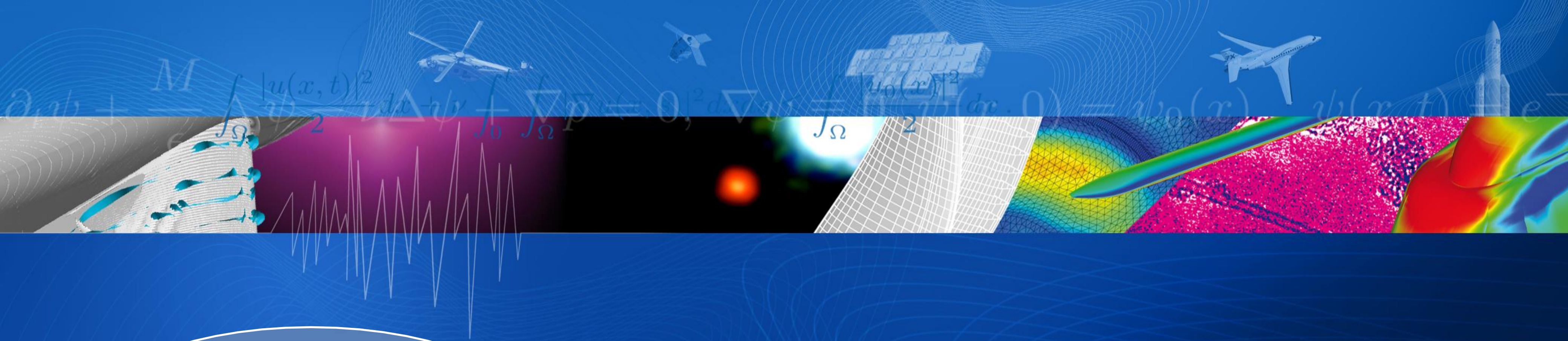
- ✓ Very good results from past 4 campaigns
- ✓ Recent improvements on the quality of the hyperspectral images

Some applications: Atmosphere compensations ; Temperature – emissivity separation ; Data classification ; Anomaly detection

Ground version of SIELETERS under development:

➔ Gas detection ; high spatial and spectral resolution imaging

- ✓ SIELETERS / SYSIPHE is opened to external users:
  - NATO, EDA or bi-lateral arrangement
  - EUFAR, European Facility for Airborne Research (SIELETERS)
  - National and international community:
    scientific, industrial or institutional



Thank you for your attention

THE FRENCH AEROSPACE LAB

HySpex ODIN-1024 main characteritics

Parameter	VNIR	SWIR
Spectral range	400 – 1000 nm	950 – 2500 nm
Spectral resolution	3.0 nm	6.1 nm
Pixel FOV	0.25 mrad / 0.125 mrad	0.25 mrad
Total across track FOV	15°	15°
Spatial resolution	1024 px / 2048 px	1024 px
F-number	F1.64	F2.0

- Common fore-optics design
- On-board calibration system

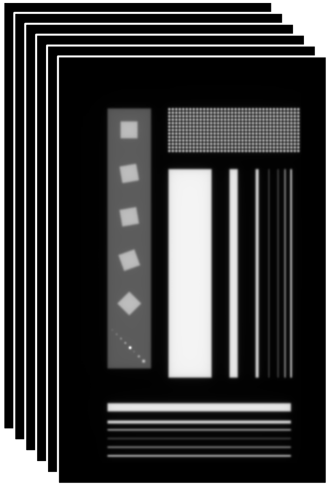
Sieleters main characteristics

Parameter	MWIR	LWIR
Spectral range	3.0 - 5.2 µm	8.1 – 11.5 µm
Spectral resolution	11 cm^{-1}	5 cm^{-1}
Pixel FOV	0.25 mrad	0.25 mrad
Total across track FOV	15°	15°
Spatial resolution	1016 px	1016 px
F-number	F4.0	F3.0

- Two separate static Fourier transform spectral imagers
- MCT IR-FPAs from Sofradir, 1016x440 pixels
- Entirely cryogenic (liquid nitrogen, 77K)
- Stabilized

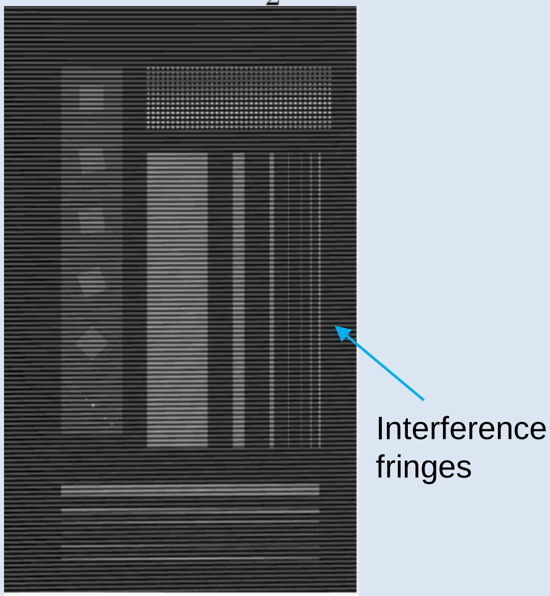
Simulator of the SIELETERS raw airborne images

1- Cube of oversampled images at many wavenumbers σ



2 – Apply the interference fringes on the images for each wavenumbers σ

$$A \cdot \frac{1 + C(x,\sigma) \cdot \cos\left(2\pi\delta(x,y)\sigma - \phi(x,\sigma)\right)}{2}$$

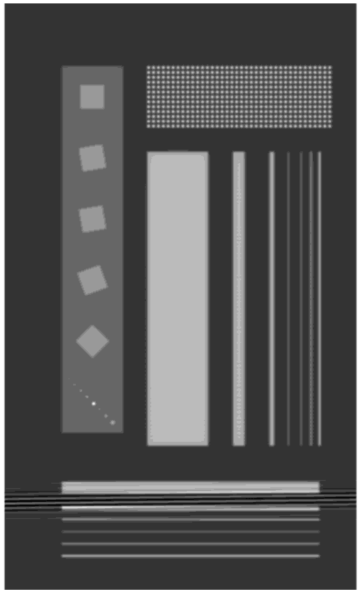


3 – Convolution by :

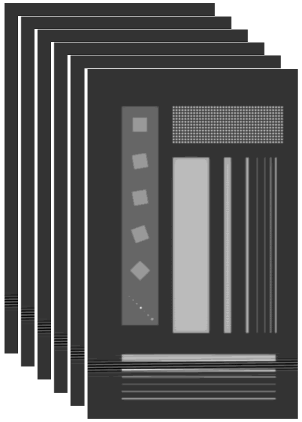
- **The pixel spatial response**
- **The system optical transfer function (OTF)**

4 – Sun over the wavenumbers σ

$$\sum_{\sigma_0 \ldots \sigma_{N-1}}$$



5- Shift of the images to generate the whole sequence



Simulated in flight images (in current)

Useful tool to:

- ✓ **Understand related physical effects**
- ✓ **Improve the quality of the images**

Sieleters images registration

Method 1

Image correlation (2013 campaign)

✓ << 0.1 pixel registration possible

Conditions:
- ☐ Flat ground
- ☐ No bright or moving objects

Method 2

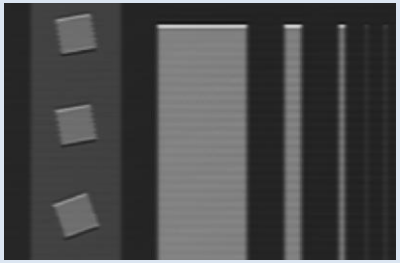
Line of sight (2015 campaign)

Using:
- Metadata recorded during the flight
- Digital elevation model

✓ Produce georeferenced images

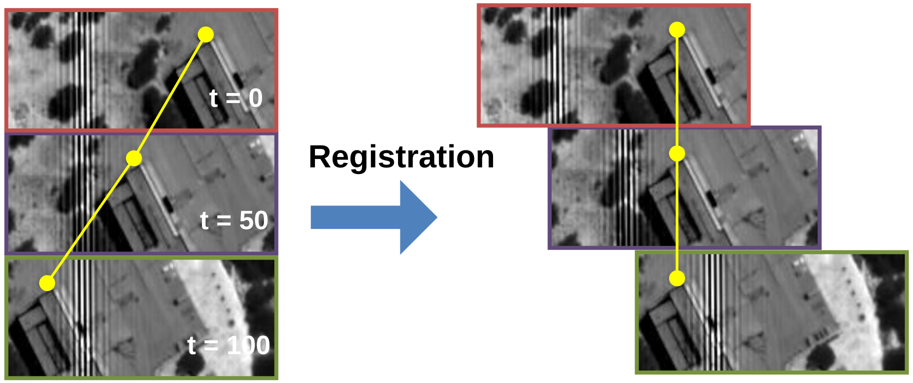
✓ Ground independent

Resolution: ~ 0.1 pixel (*ie* 5 cm on the ground)



Perfect registration (simulation)

Noise registration (simulation)



Raw images

Registration

Registered images

New method

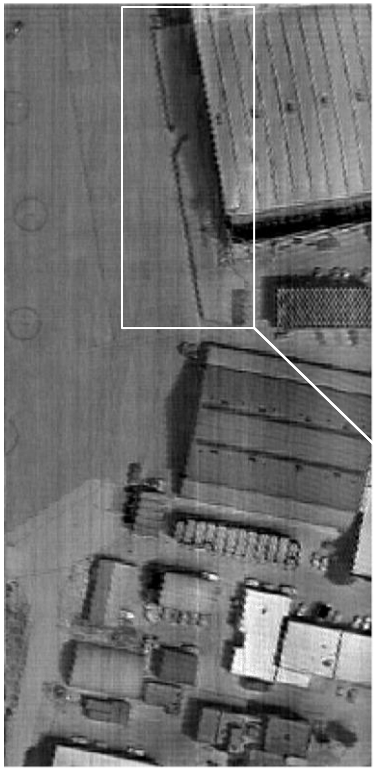
Line of sight

+

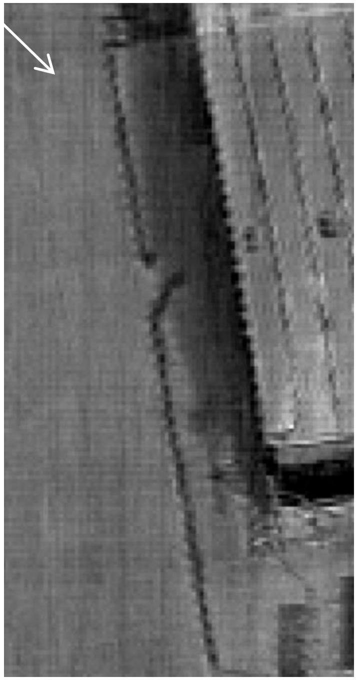
Image correlation of the images preregistered by the line of sight

Sieleters images registration: results on the spectral images

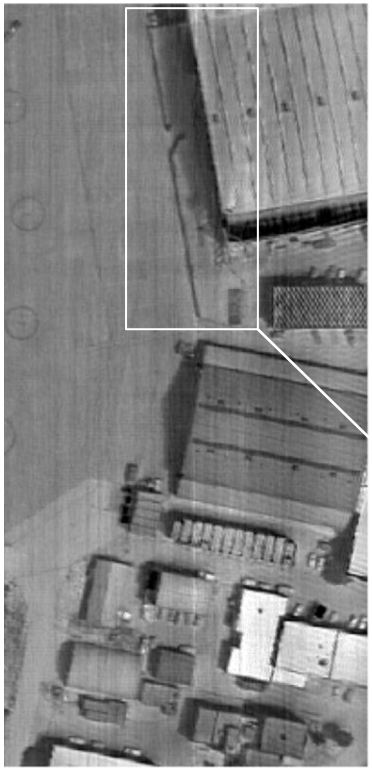
Spectral images in the LWIR



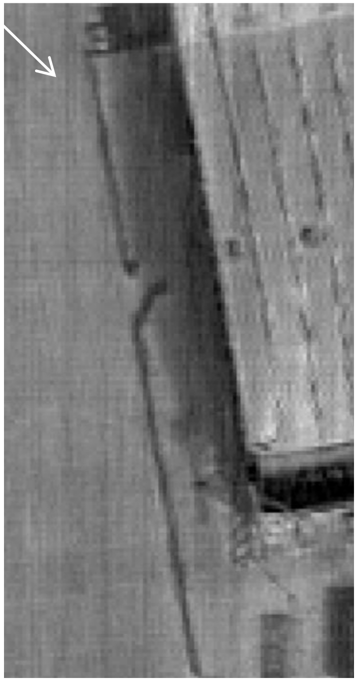
Using only the line of sight (method 2)



New approach



Registration with the line of sight
+
Images correlation

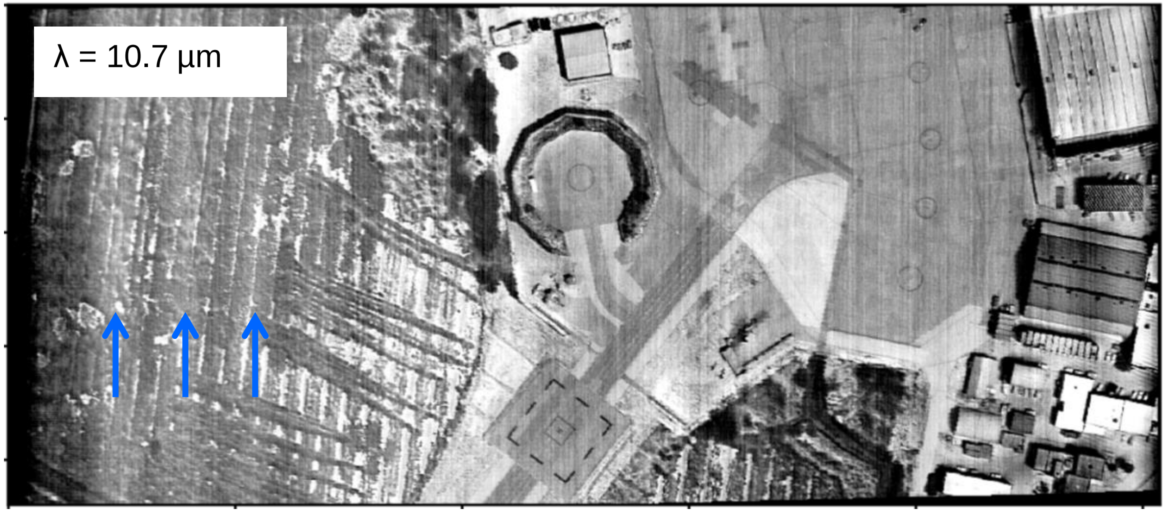


Geometrical improvements of the spectral images

Vertical oscillations on the spectral images

Oscillations on the spectral images:

- Vertical
- Period depends on:
  - The wavelength
  - Dependents on the method used to correct non uniformities of the IR sensor



Vertical oscillations on the spectral images

Temporal instability of the IR sensor

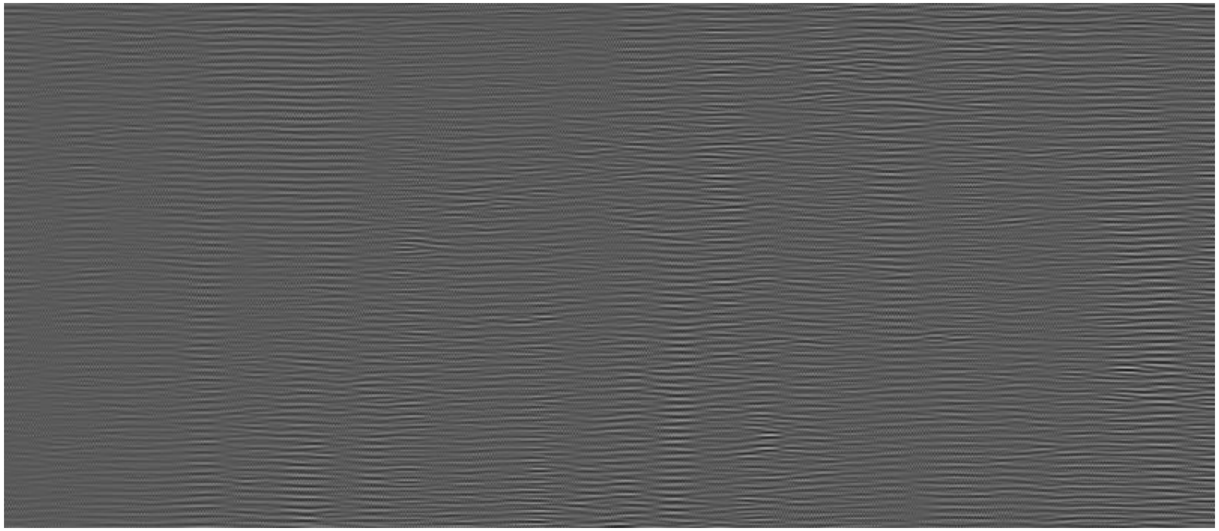
Estimation of gain and offset using in-flight images

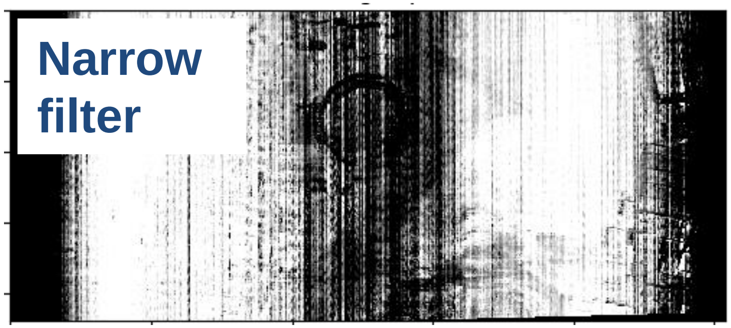
Need to filter interference fringes

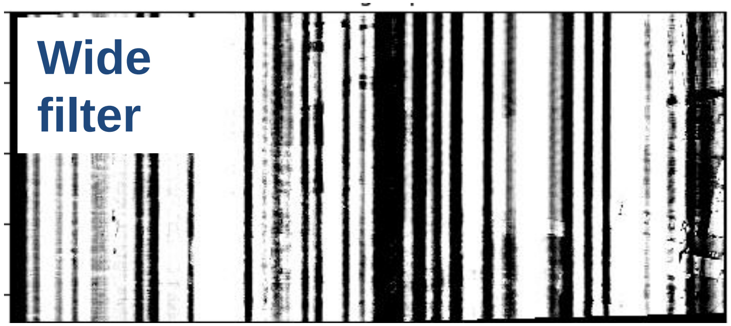
Leeds to fringes residuals on the gain/offset and on the images

Introduce vertical oscillations on the spectral images

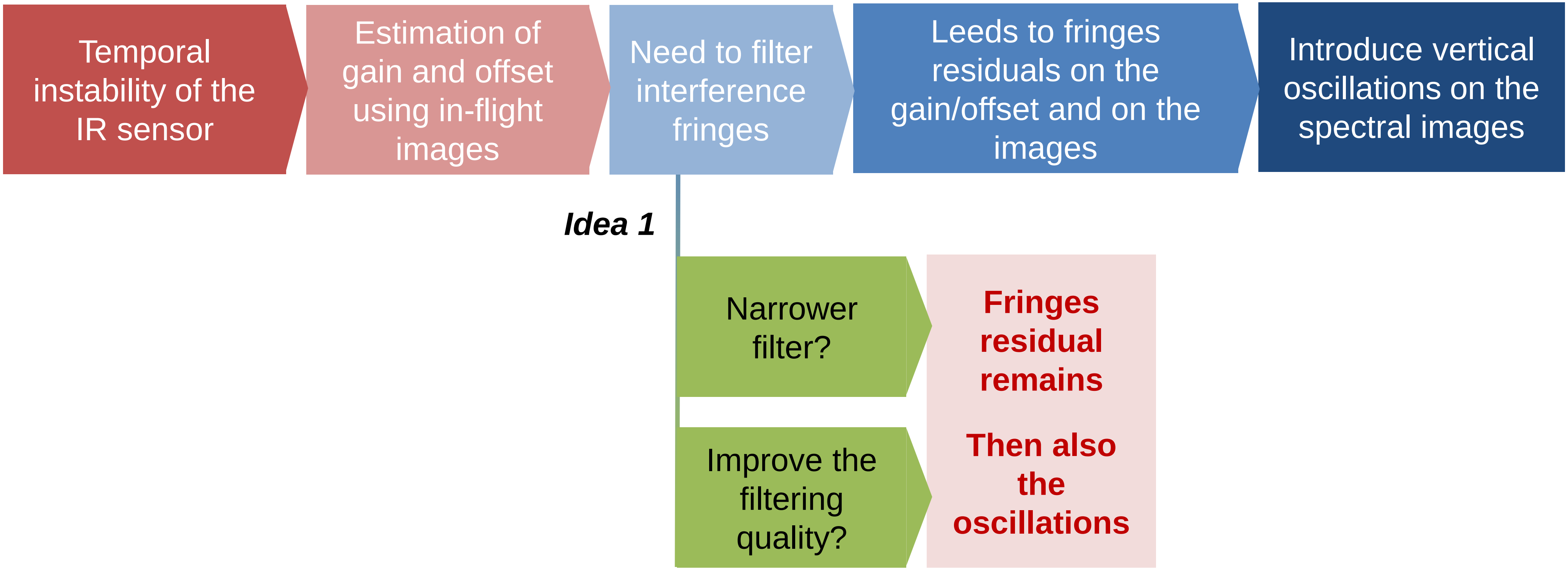
Fringes filtering in the Fourier space ➔ fringes residuals







Vertical oscillations on the spectral images



Temporal instability of the IR sensor

Estimation of gain and offset using in-flight images

Need to filter interference fringes

Leeds to fringes residuals on the gain/offset and on the images

Introduce vertical oscillations on the spectral images

Idea 1

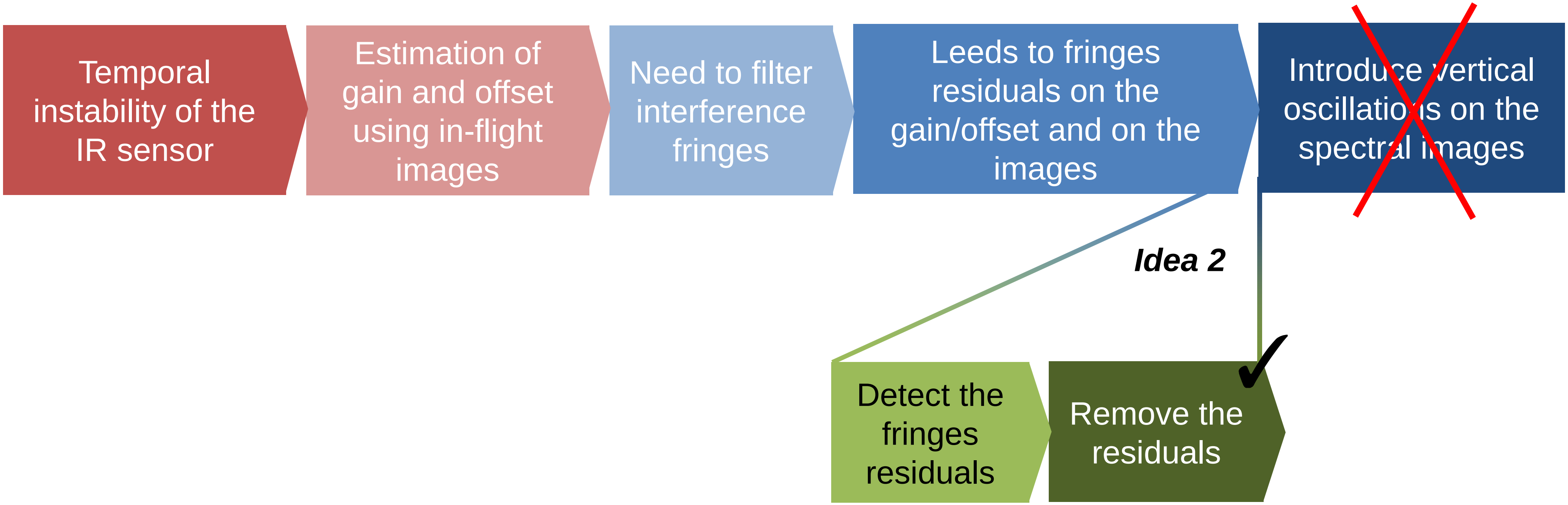
Narrower filter?

Improve the filtering quality?

Fringes residual remains

Then also the oscillations

Vertical oscillations on the spectral images



Temporal instability of the IR sensor

Estimation of gain and offset using in-flight images

Need to filter interference fringes

Leeds to fringes residuals on the gain/offset and on the images

~~Introduce vertical oscillations on the spectral images~~

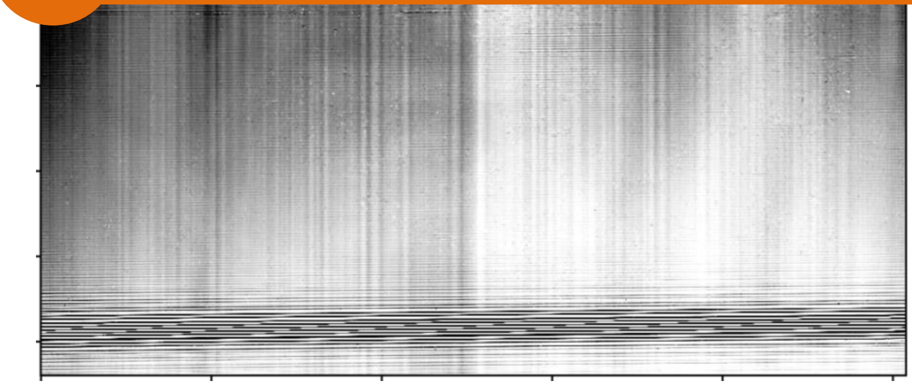
Idea 2

Detect the fringes residuals

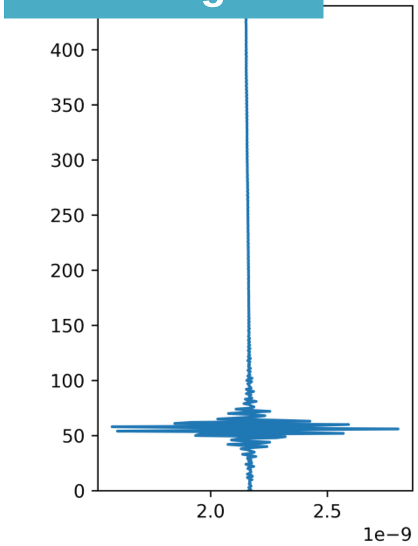
Remove the residuals ✓

Fringes removal in the non-uniformity correction

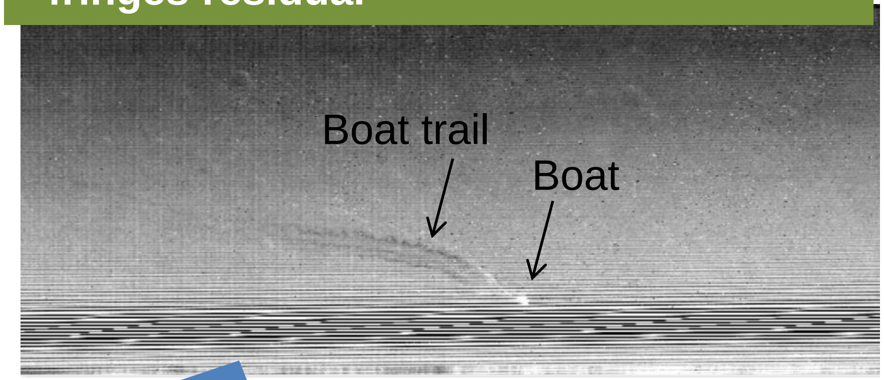
1 Input: Uniform image (average on the sea)



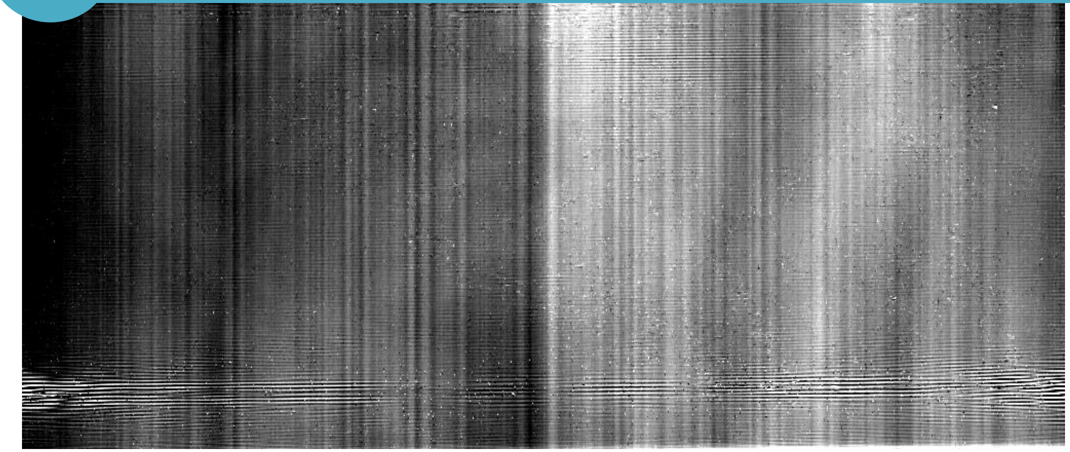
Mean interferogram



3 Output: corrected image without the fringes residual



2 Difference to the mean interferogram ➔ map of the fringes residuals



Fringes removal in the non-uniformity correction

Spectral image at 9.2 µm

Without the correction

Spectral image at 10.7 µm

With the correction