THE POTENTIAL OF SENSORS WITH OVERSAMPLED RESPONSE FUNCTIONS DEMONSTRATED WITH THE HYSPEX VNIR-3000N

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- Team at DLR Earth Observation Center (EOC) Oberpfaffenhofen

- Operates and calibrates airborne and ground based earth observation spectrometers

- Builds upon more than 30 years of expertise

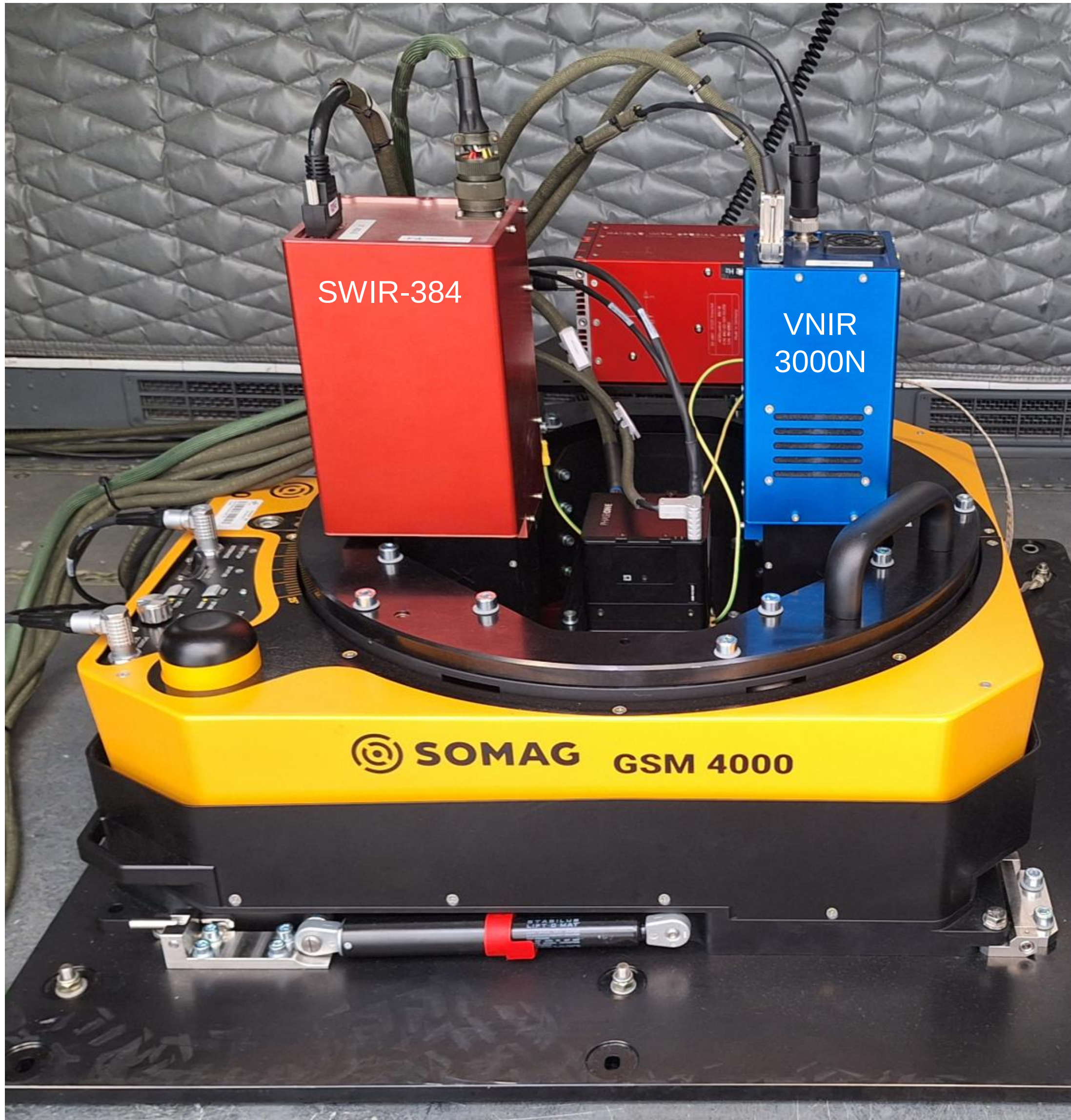
Airborne Sensor Systems

HySpex-B

- HySpex VNIR-3000**N** + SWIR-384
- *N* → **Nyquist (sampled)**
- Operational since 2023
- Typical *hyperspectral* sensor

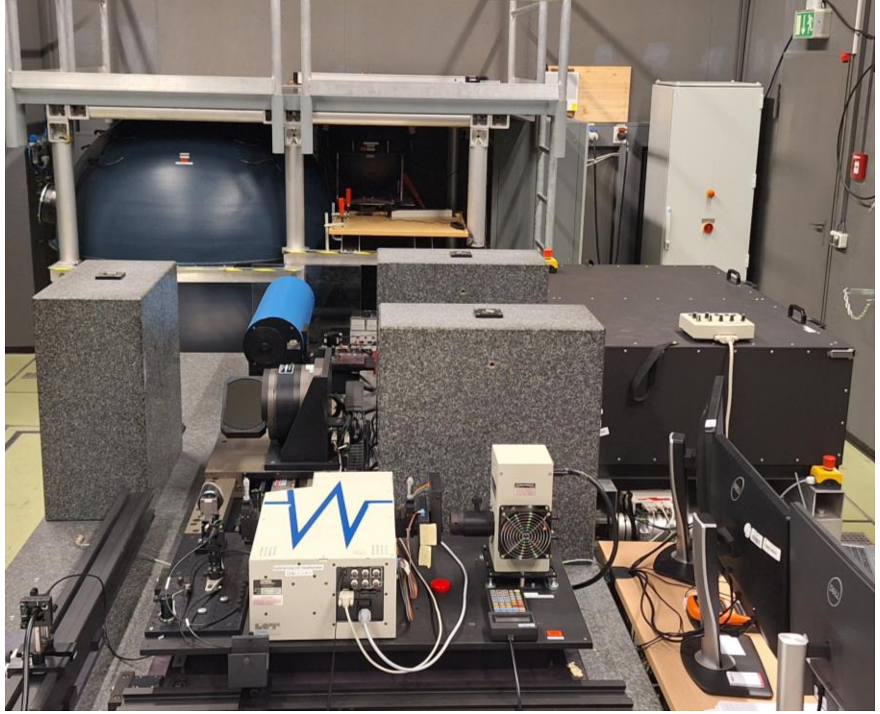
HySpex (EnMAP demonstrator)

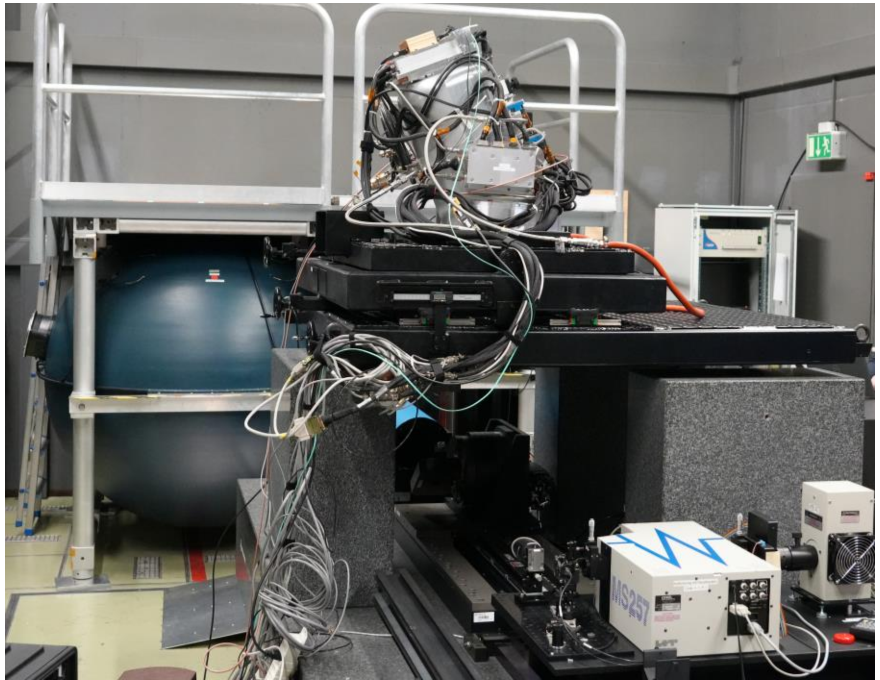
- HySpex VNIR-1600 + SWIR-320me
- Acquired for EnMAP preparation in 2011
- Extensively calibrated



Calibration Home Base (CHB)

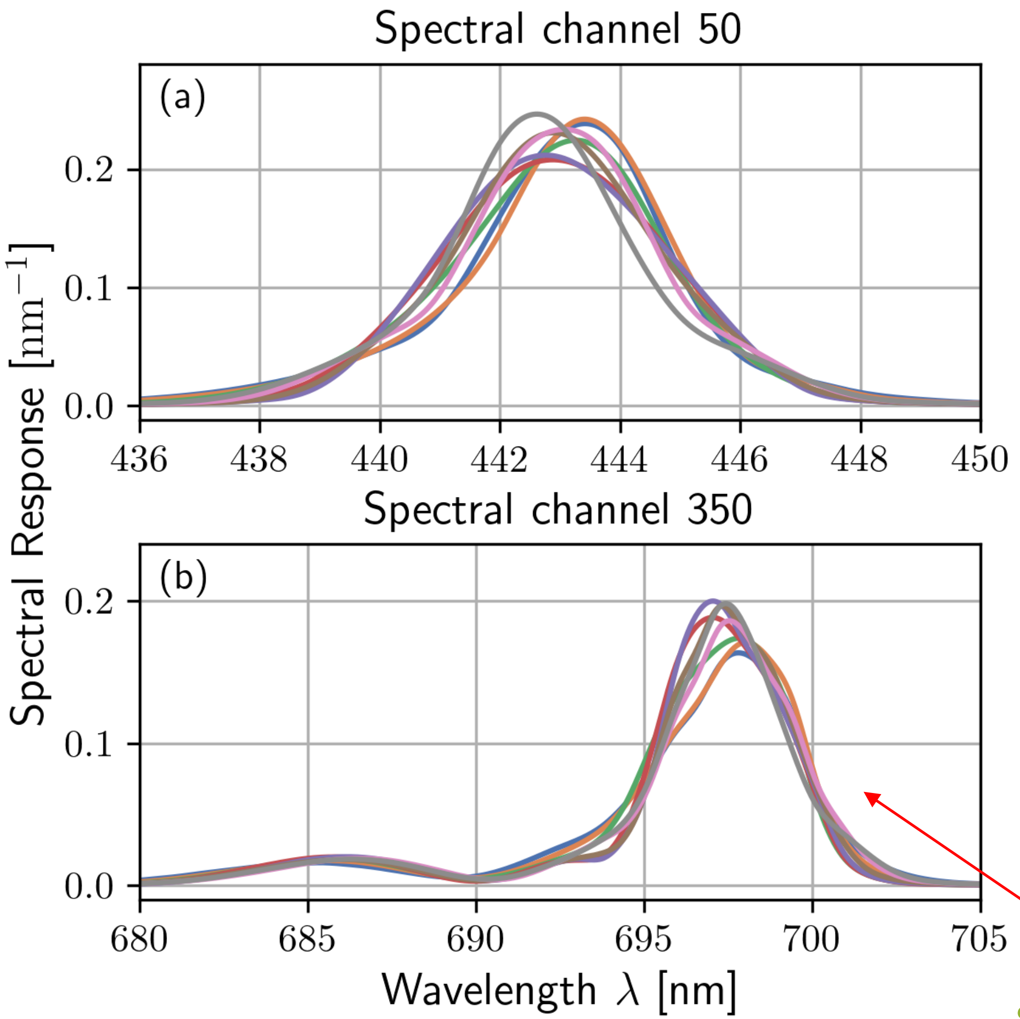
- Operational since 2007
- Calibration of
  - angular response
  - spectral response
  - radiometric response
  - polarization
  - non-linearity
  - stray light
  - temperature sensitivity
  - …
- Continuous development
- Instruments: HySpex, AVIRIS-4, “EnMAP“, …

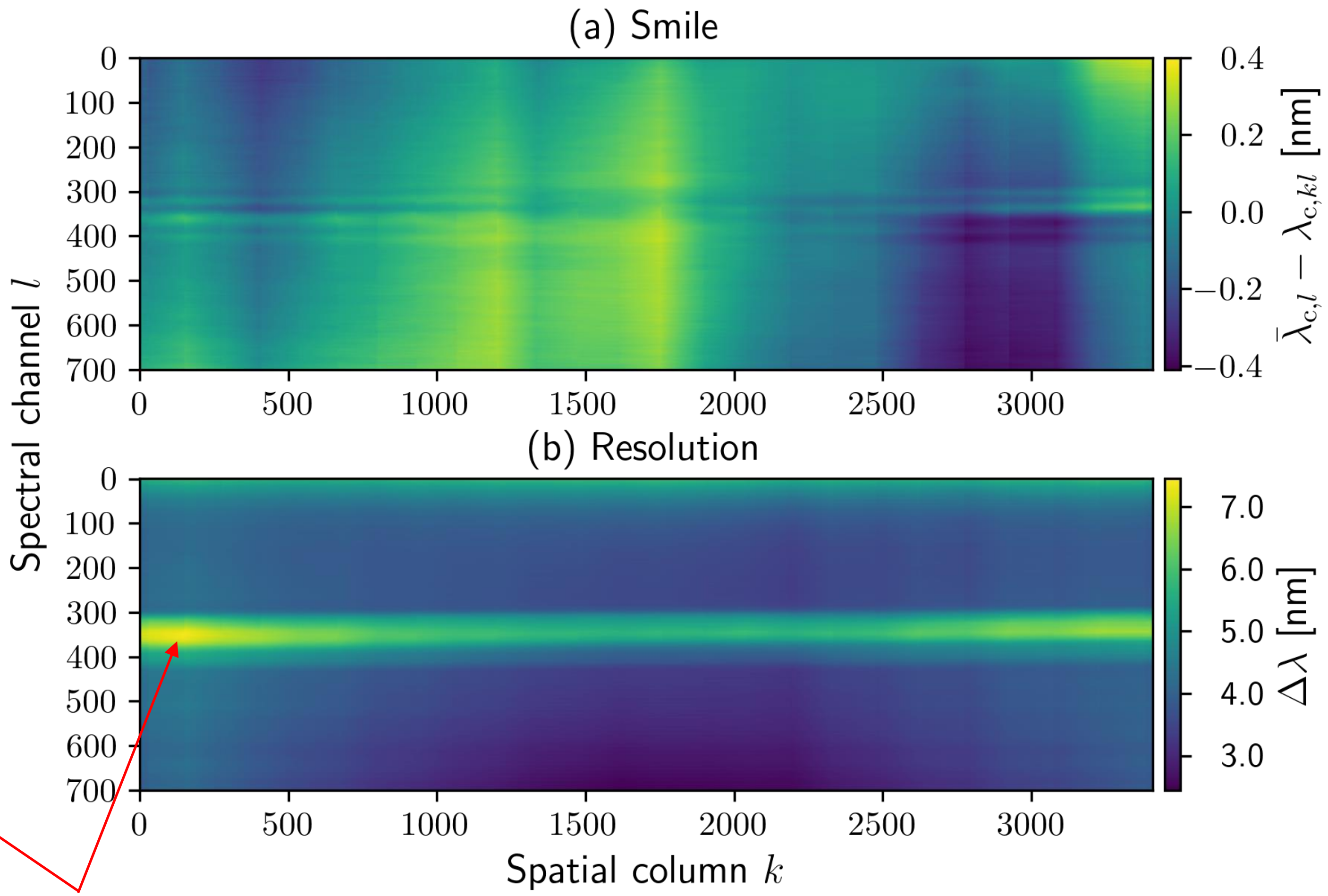




Spectral Calibration Results for VNIR-3000N

Similar information is available since 2012 for the original HySpex System





spectral order filter

We were quite optimistic in 2013 …

- State-of-the-art sensor system
- Extensive knowledge about key calibration data
- Expected to see significant improvements in surface reflectance and derived EO products
- This hope never materialized

What was going on?

What we learned

- Atmospheric Correction assumes Gaussian SRFs (free-form not supported)
- FWHM and shape are assumed to be constant within one band. Center wavelengths (smile/keystone) are allowed to change, though.
- VNIR and SWIR spectra are interpolated to common spatial grid before Atmospheric Correction (to enable combined VNIR/SWIR treatment)

A lot of measurements did not find their way into derived products!

Question

Is it possible to create a at aperture radiance product, which …

- …enables users to profit from **all** our calibration measurements (e.g. full SRF instead of just center wavelength & FWHM)
- …fosters incorporation of high-quality sensor characterization into higher level products
- …simplifies working with L1 data for non-experts by reducing complexity

Imaging Equation – True for Every Camera System

For simplicity only spectral case is shown

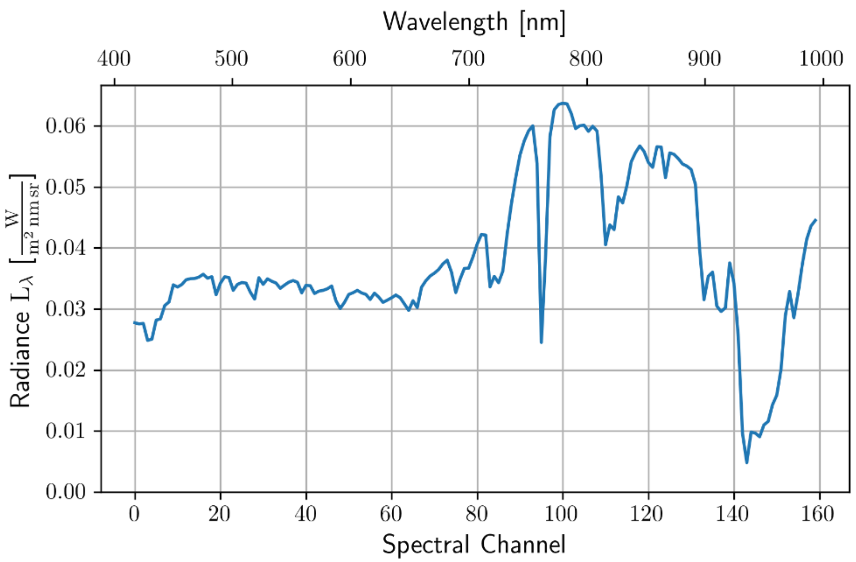
f_i: Instrument Pixel Response Function (IPRF) can also have two-dimension geometric information

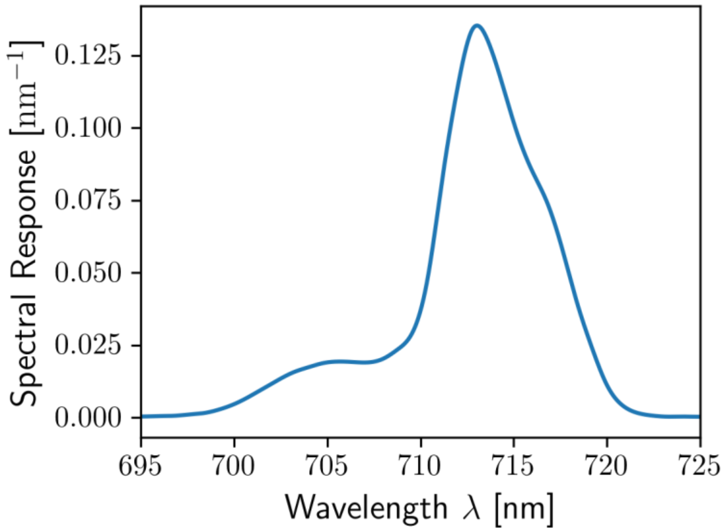
$$s_i = \int_0^\infty f_i(\lambda)\, L_\lambda(\lambda)\, d\lambda$$

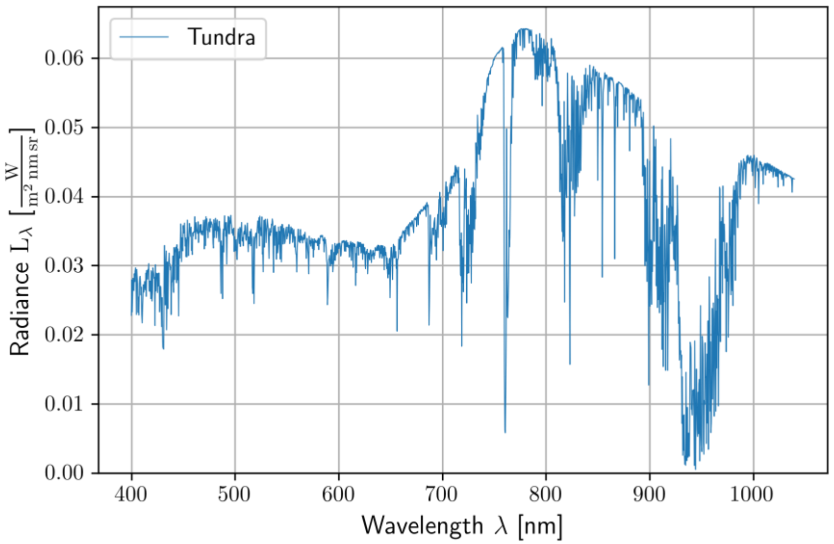
measured signal of pixel i

SRF of pixel i

at-sensor radiance

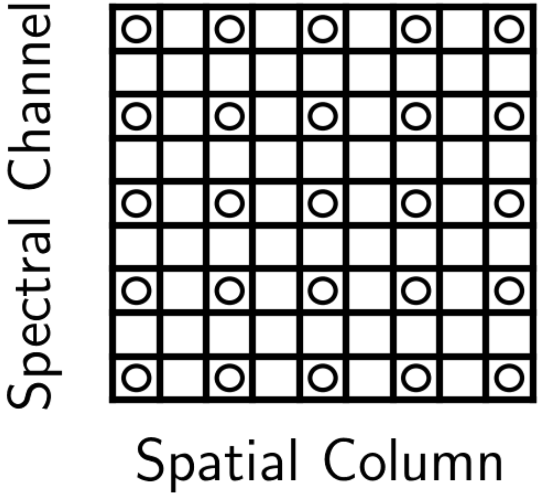




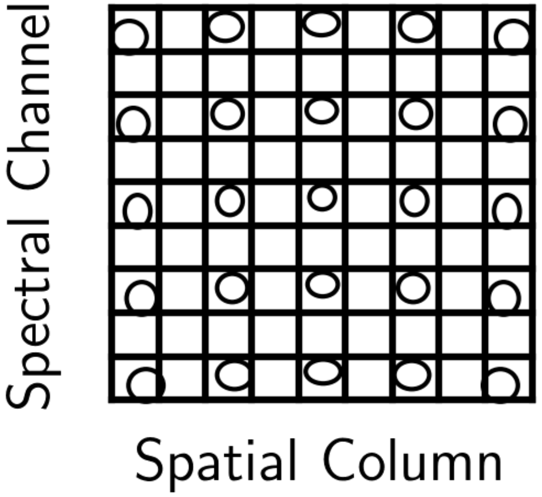


Converting Data from one Sensor to Another

ideal sensor B



real sensor A



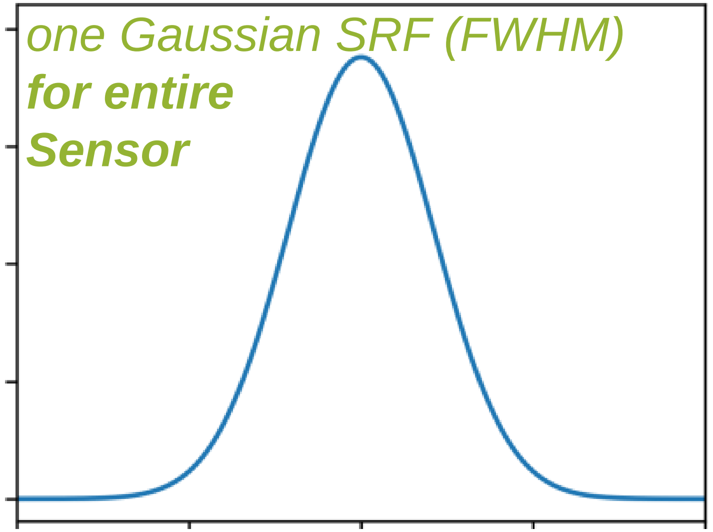
sensor B signal vector (b_rows · b_cols elements)

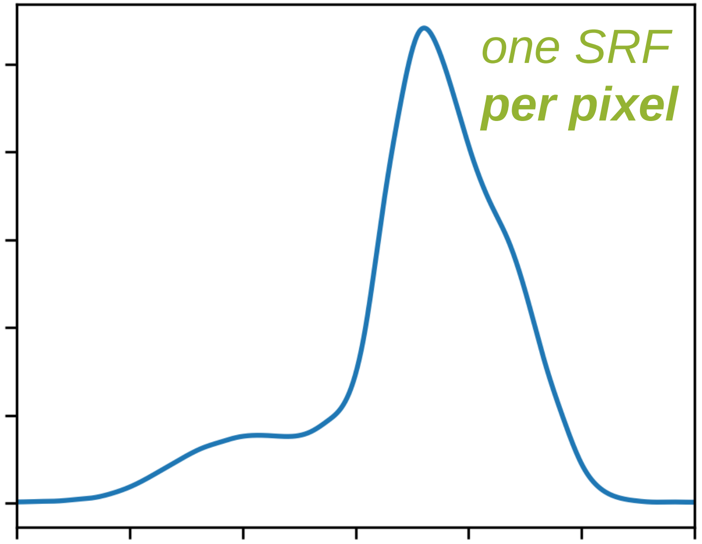
sensor A signal vector (a_rows · a_cols elements)

$$\boldsymbol{s}_B = \boldsymbol{K} \cdot \boldsymbol{s}_A$$

Transformation Matrix (len $\boldsymbol{s}_B$ *x len* $\boldsymbol{s}_A$*)*

→ Calculated only once
→ Can be applied on every spectrum of sensor A



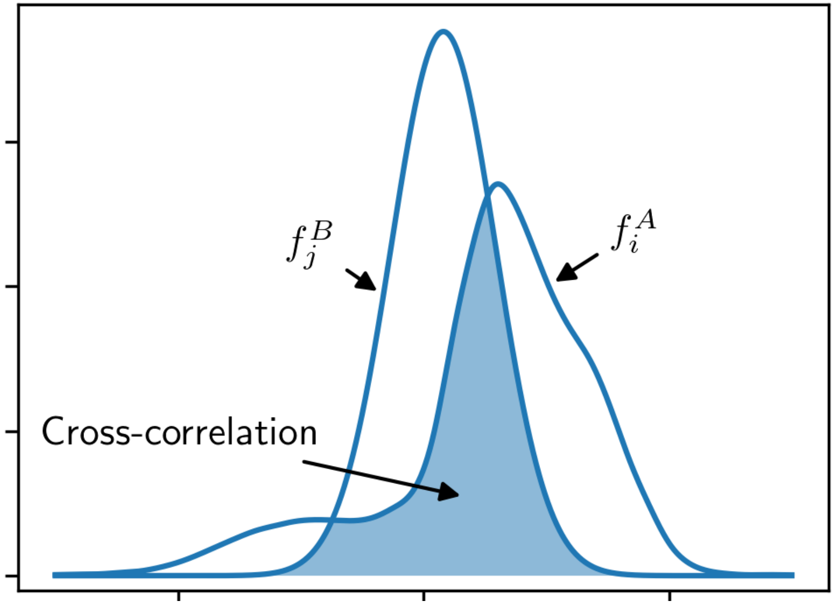


How to Find the Transformation Matrix *K*

Question: How to find $\boldsymbol{K}$ from response functions?

Idea: Using overlapping pixel properties

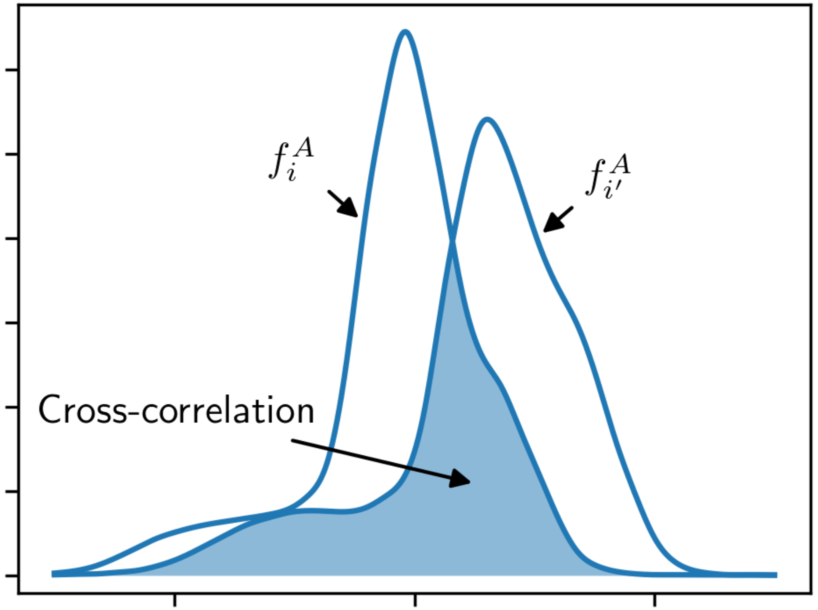
$$\boldsymbol{C}_{ij}^{BA} := \left\langle f_i^B, f_j^A \right\rangle$$



$$\boldsymbol{C}^{BA} = \boldsymbol{K}\,\boldsymbol{C}^{AA}$$

$\boldsymbol{K}$ can be computed from cross-correlation matrices

$$\boldsymbol{C}_{ij}^{AA} := \left\langle f_i^A, f_j^A \right\rangle$$



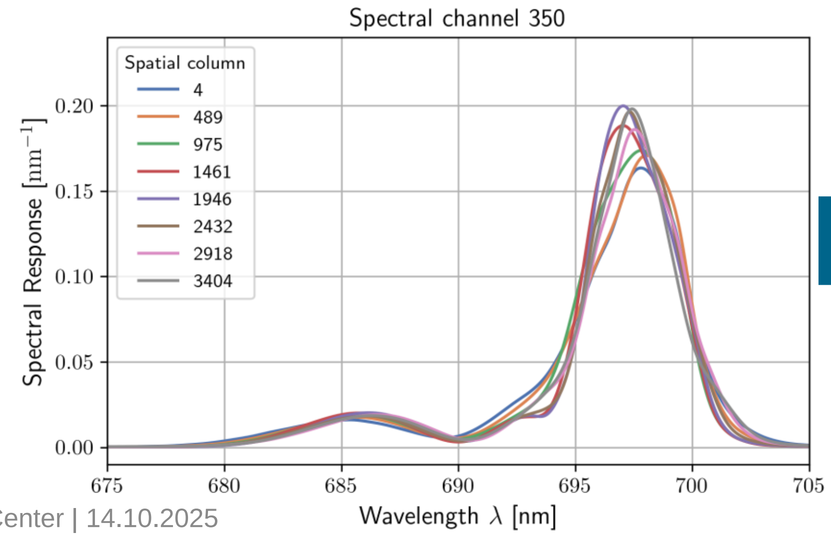
$$\hat{\boldsymbol{K}} = \arg\min_{\boldsymbol{K}} \left\{ \left\| \boldsymbol{K}\,\boldsymbol{C}^{AA} - \boldsymbol{C}^{BA} \right\|_2^2 + \gamma^2 \left\| \boldsymbol{K}\boldsymbol{\Gamma} \right\|_2^2 \right\}$$

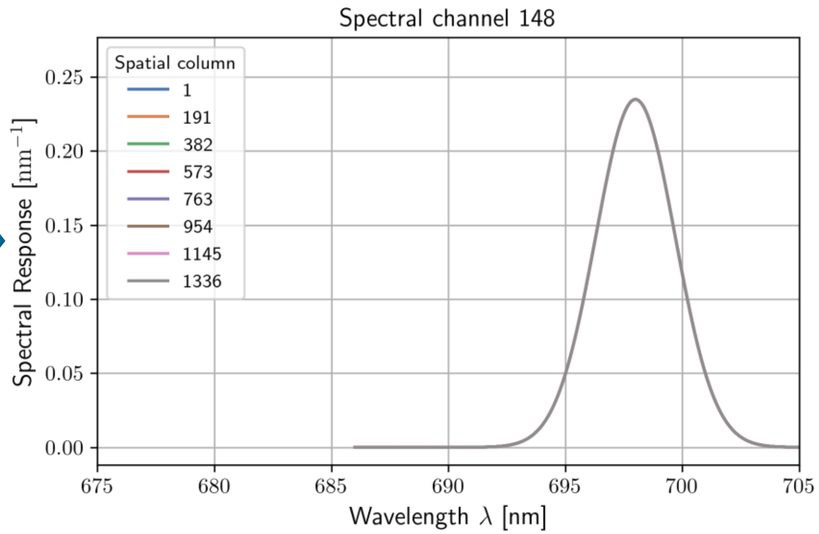
Tikhonov solution

Baumgartner et al. (2020)
doi : 10.1364/oe.409626

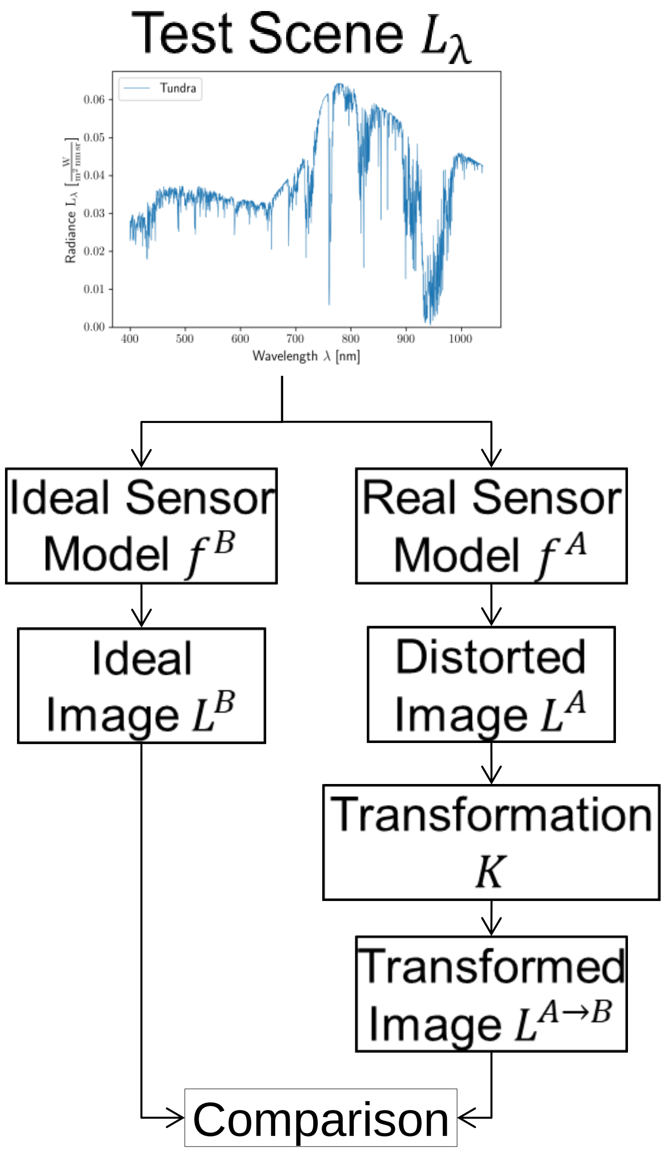
Current HySpex VNIR-3000N Processing Settings

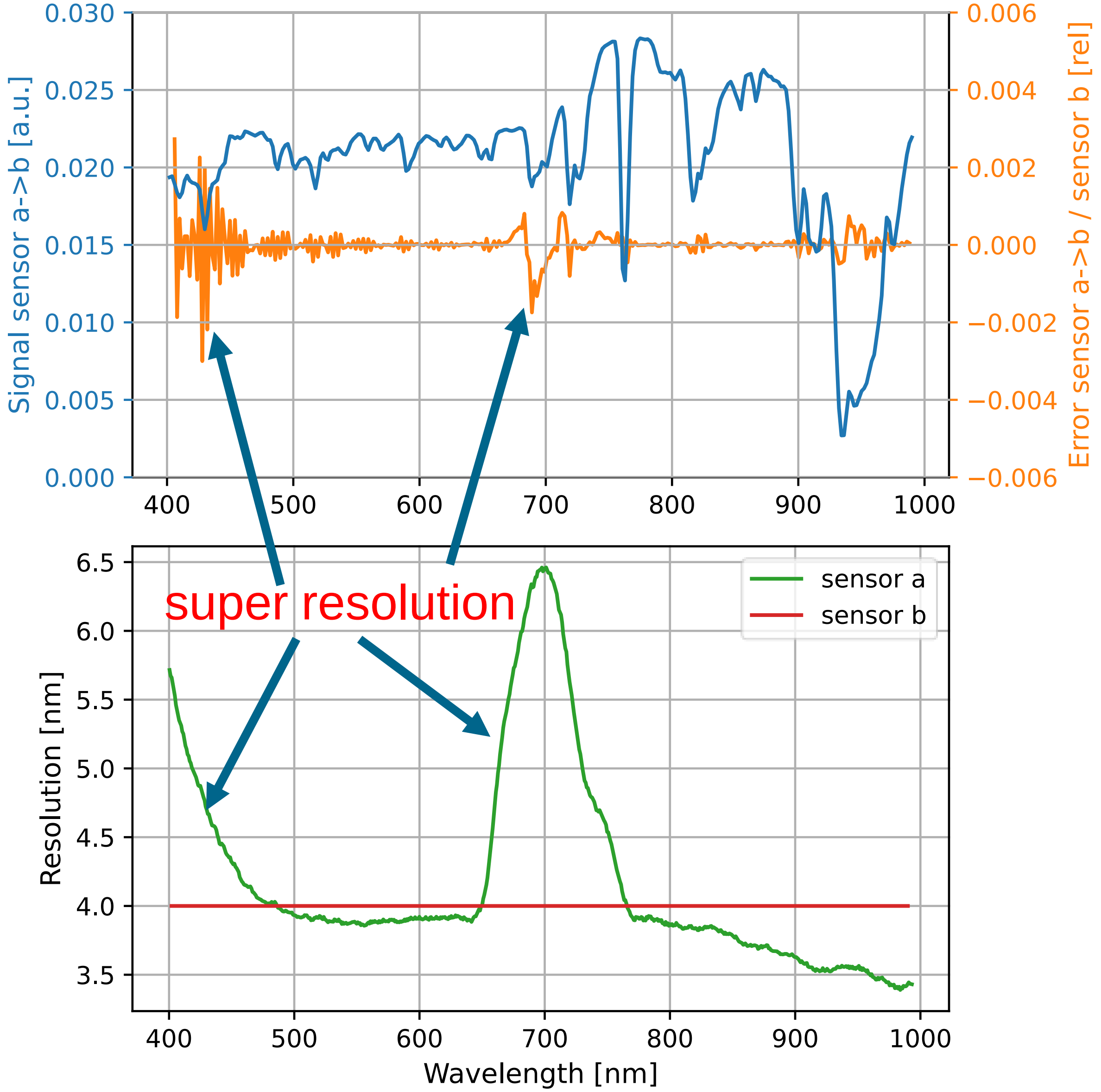
Parameter	Sensor A	Sensor B	
Spatial columns	3408	1337	*smart binning*
Spectral channels	700	295	*smart binning*
Smile [nm]	<0.8	0	
Keystone [mrad]	<0.14	0	
Angular resolution [mrad]	0.09 – 0.43	0.44	
Spectral resolution [nm]	2.5 – 7.5	4	*super resolution*
SRF and ARF shape	Spline model (complicated)	Gaussian	





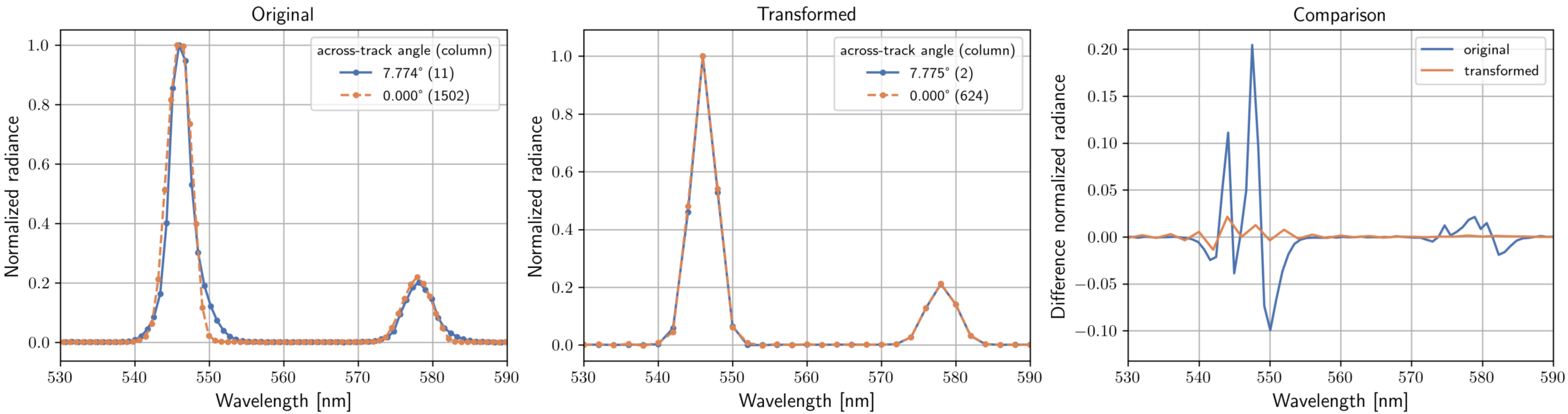
Simulation Study VNIR-3000N



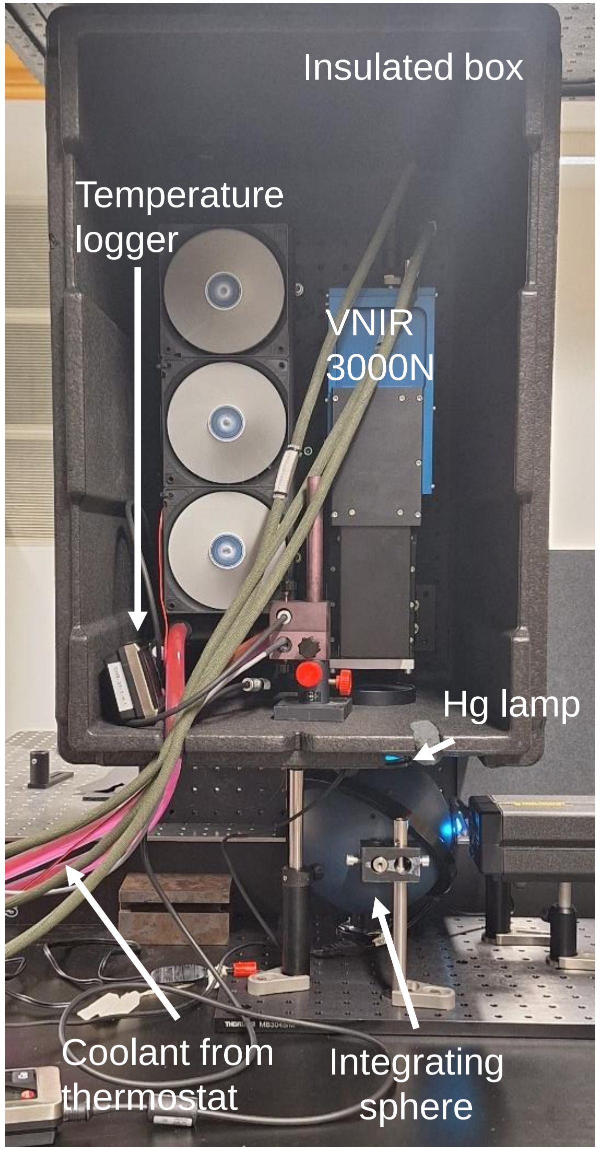


Experimental Validation of VNIR-3000N

- Mercury lamp coupled into integrating sphere
- Isolated spectral emission lines → high frequency stress test
- Comparison of two spatial columns (across-track angles)



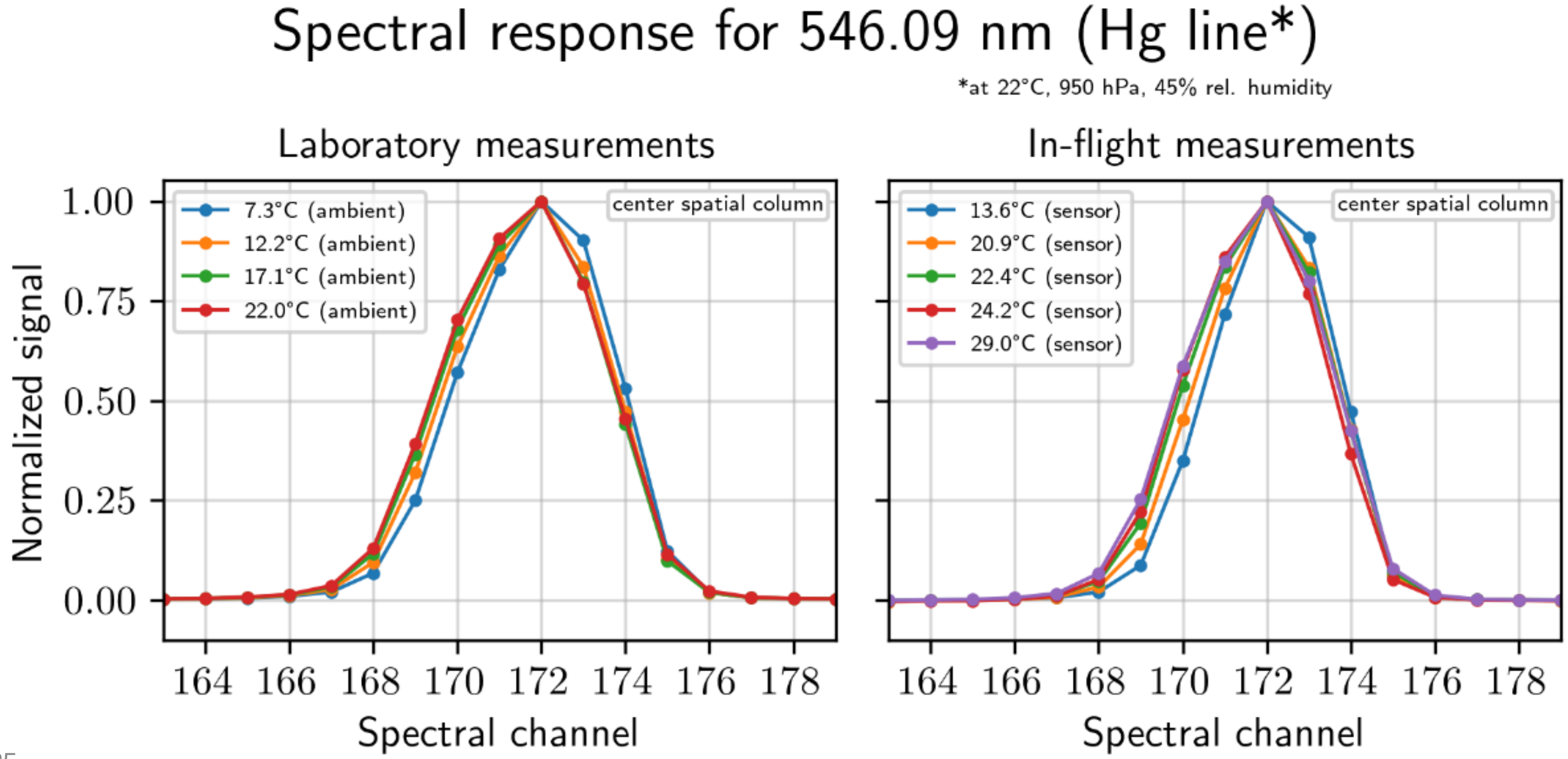
HysSpex VNIR-3000N Temperature Sensitivity



Setup for simulating different ambient temperatures

→ Determination of thermal stability

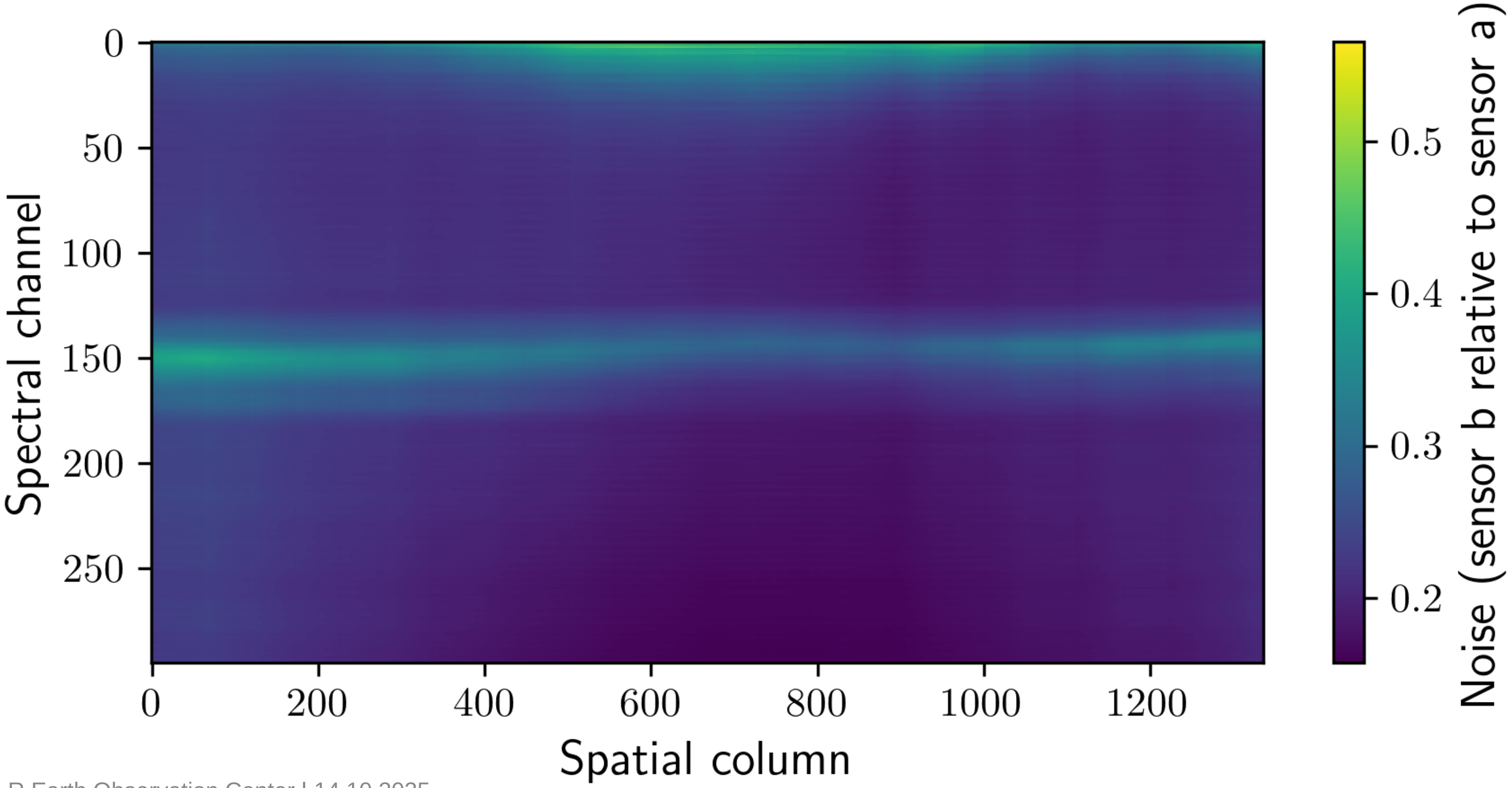
HySpex VNIR-3000N temperature dependent spectral shift



Uncertainty Estimation

Covariance propagation: $\Sigma^{\mathrm{B}} = K\Sigma^{\mathrm{A}}K^{\mathrm{T}}$

HySpex VNIR-3000N: Relative noise level change after transformation:



Applications

Sensor A	Sensor B	Application
HySpex	ideal HySpex	*homogenized at-sensor radiance* *smart binning*
HySpex	CHIME	*CHIME validation*
CHIME	Sentinel-2	*cross-validation*
~~CHIME~~	~~Sentinel-5p~~	*wishful thinking!*

Implications on L1-Processing

- Transformation Matrix is big data
  - ~ 941 billion elements for HySpex VNIR
  - 7.5 TB at full resolution
  - 5.5 GB in practice (sparse matrix)
- Processing Time
  - Python JIT compiled code (Numba)
  - VM with 16 CPUs @ 2.5 GHz, 128 GB RAM
  - 3-4 frames per second HySpex VNIR
  - ~50 frames per second HySpex SWIR
  - Great potential for further improvements using graphic cards
- Reduces complexity of all following processing steps
- Only 16 % of HySpex VNIR data points remain after smart binning

IMAGE: M. Verch (www.ccnull.de)

Implications on Future Sensor Design

- L1 post-processing can compensate optical design imperfections
  - Effectively reduces / eliminates smile / keystone
  - Homogenizes response functions

- Denser sampling (Nyquist) required compared to typical hyperspectral sensors

- Response functions have to be available
  - Accurate calibration of each pixel is required
  - Instrument instabilities can be corrected, if known and correctly modelled

Conclusions

- Matrix based response function homogenization is an efficient tool
  - Correct several optical artifacts
  - Reduce data size by smart binning
  - Reduce complexity of down-stream processing
  - Deliver at-aperture radiance products which are easier to adopt by the community

- Our finding have implications of the design of future sensors
  - Oversampling (spectral & across-track) improves data quality
  - Smile and keystone should not drive the optical design
  - Knowledge of the response functions (including stability) is of paramount importance

Discussion

- Where do you see hyperspectral imaging in the next 5–10 years?
  - Increasing similarity between atmospheric trace-gas-sensing and hyperspectral sensors

- What features or improvements would you most like to see in future instruments (portability, calibration, spectral range, real-time analysis, sensor fusion, scale)?
  - Spectral and spatial oversampling
  - Creating data tailored for certain applications from one instrument

- What emerging applications could drive adoption?
  - Not my field of expertise
- How can academia, government, and industry collaborate to accelerate the adoption of hyperspectral methods?
  - Not my field of expertise