IMPROVING L1 PRODUCT QUALITY FOR IMAGING SPECTROMETERS WITH RESPONSE FUNCTION-BASED POST-PROCESSING

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German Aerospace Center (DLR)

DLR User Service OpAiRS

- Team at DLR Earth Observation Center (EOC) Oberpfaffenhofen
- Operates and calibrates airborne and ground based earth observation spectrometers
- ISO 9001 certified entity since 2007
- Builds upon more than 30 years of expertise

Calibration Home Base (CHB)

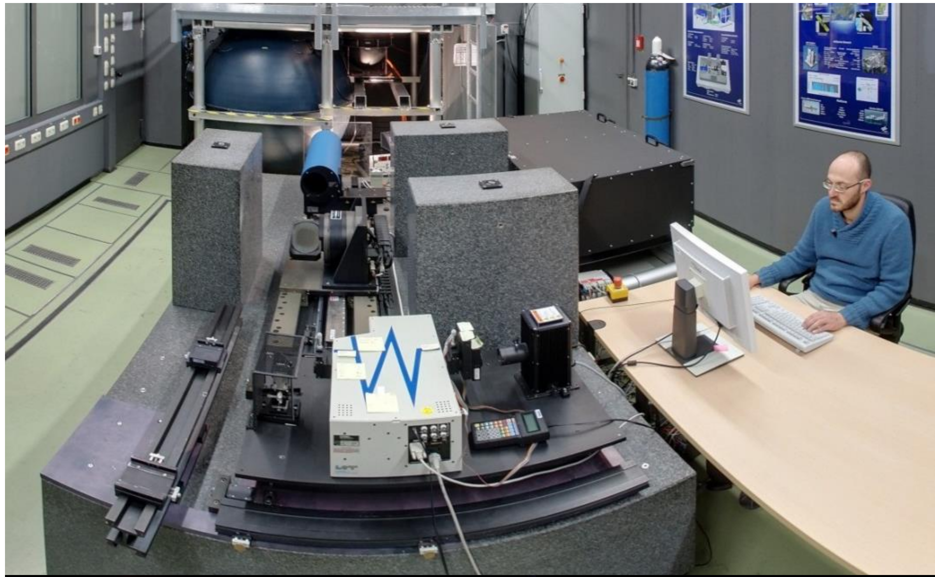
Operational Setups

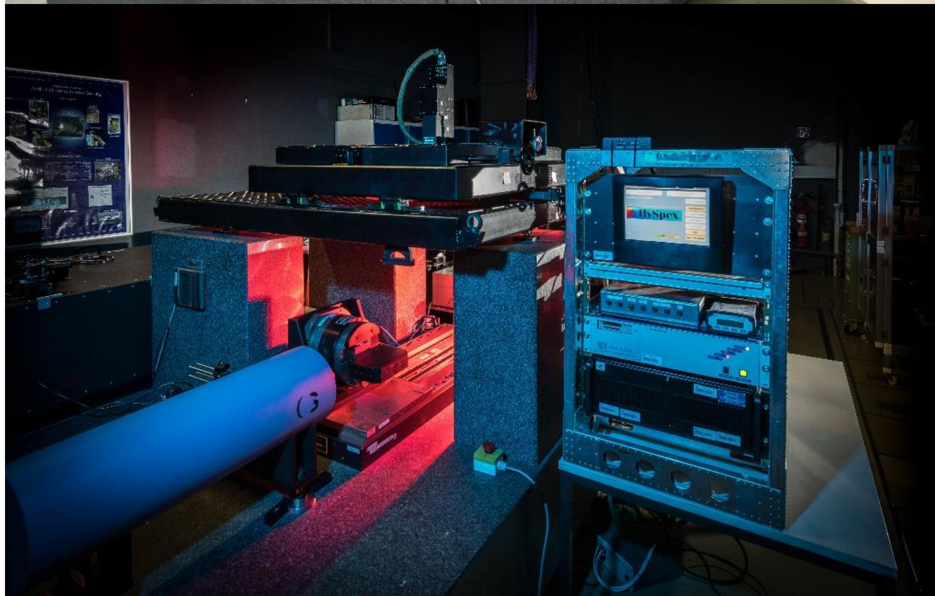
- Geometric Response Function
- Spectral Response Function
- Radiometric Response & Polarization

Co-funded by ESA for APEX calibration

Research & Development

- Non-linearity correction
- Straylight correction
- Temperature dependence





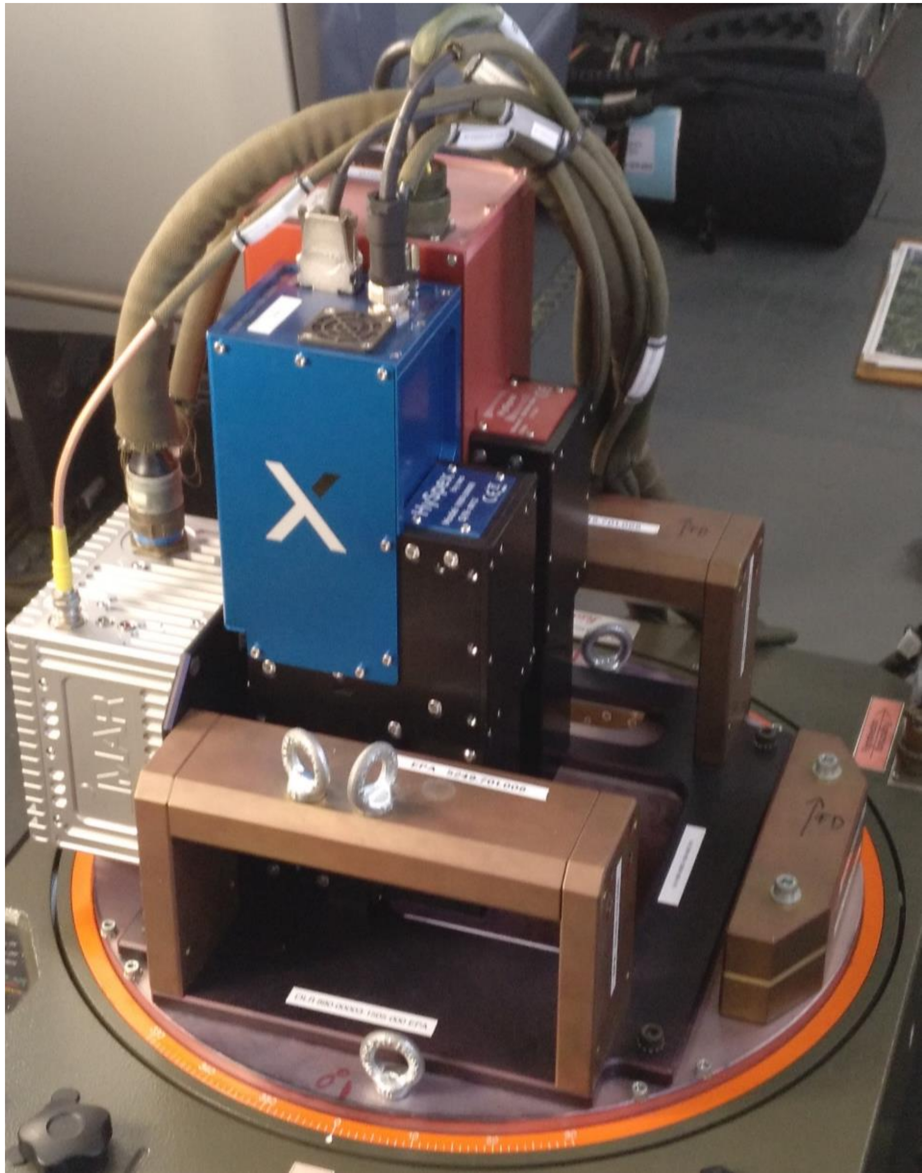
Airborne Sensor Systems

HySpex-B

- HySpex VNIR-3400**N** + SWIR-384
- *N* → **Nyquist (sampled)**
- Operational since 2023
- Typical *hyperspectral* sensor

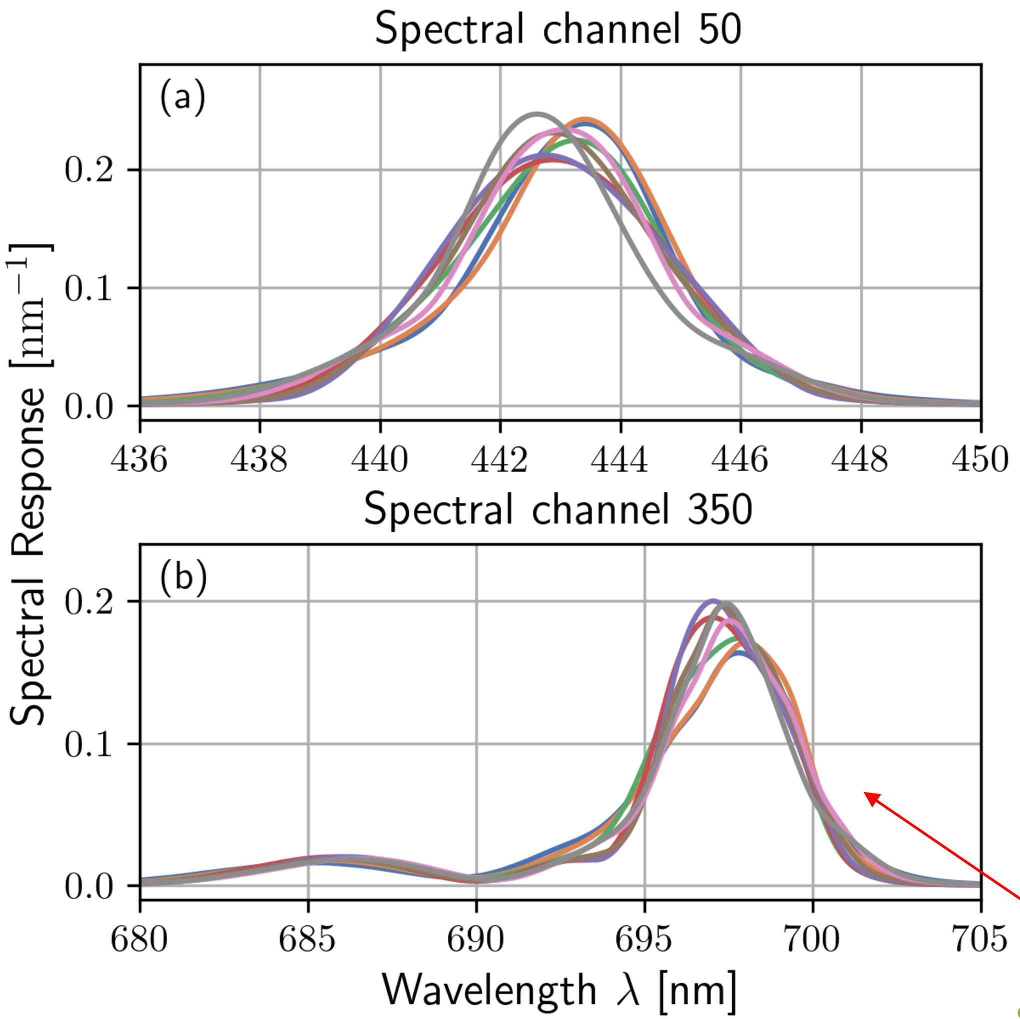
HySpex (EnMAP demonstrator)

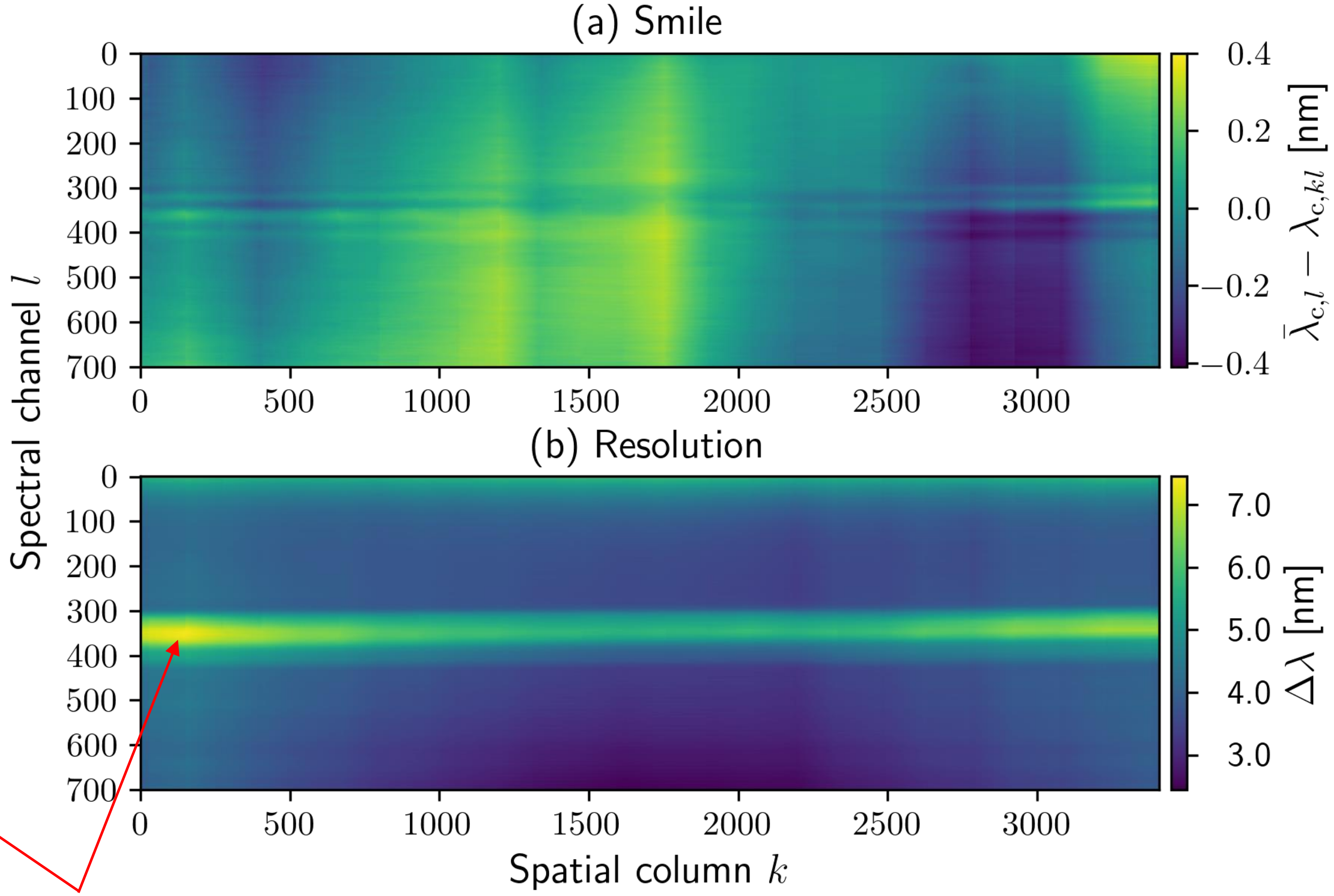
- HySpex VNIR-1600 + SWIR-320me
- Acquired for EnMAP preparation in 2011
- Extensively calibrated



Exemplary Results for VNIR-3400N

Similar information is available since 2013 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)

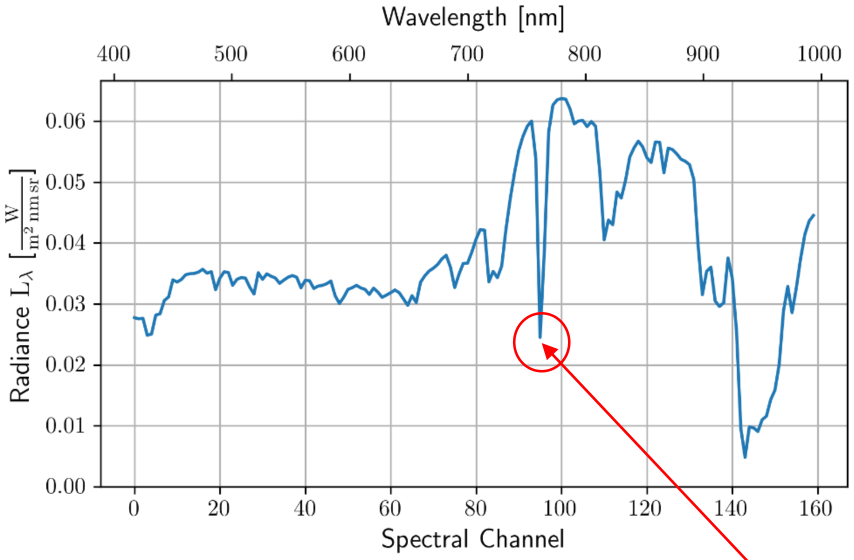
A lot of measurements did not find their way into derived products!

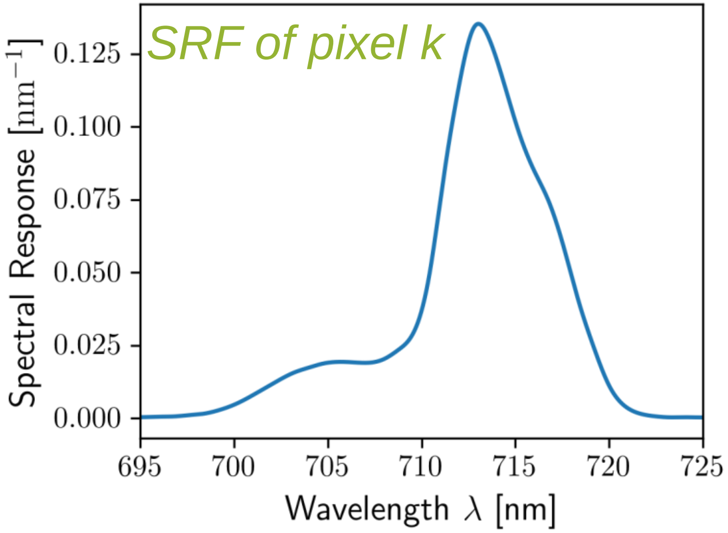
Question

Is it possible to create a L1C product, which …

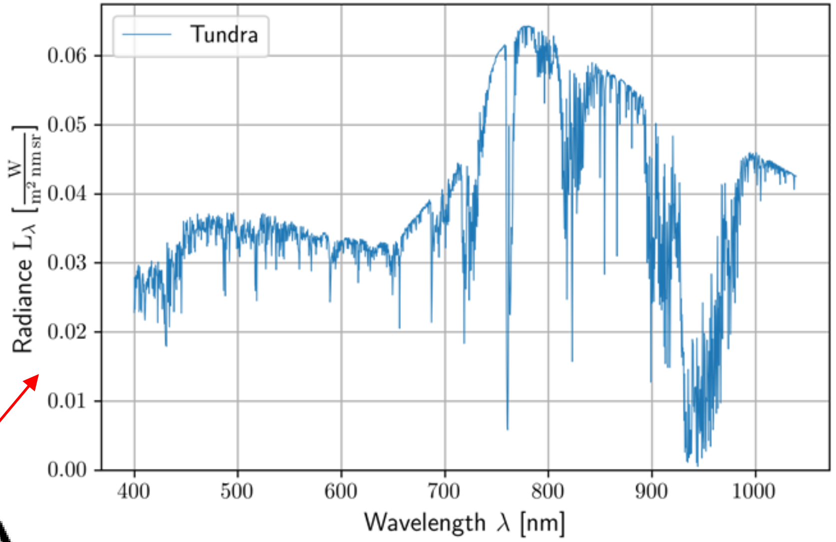
- …enables users to profit from **all** our calibration measurements (e.g. full SRF instead of just center wavelength & FWHM)
- …fosters incorporation of high-quality sensor characterization into higher level products
- …simplifies working with L1 data for non-experts by reducing complexity

Physical Model





at-sensor radiance



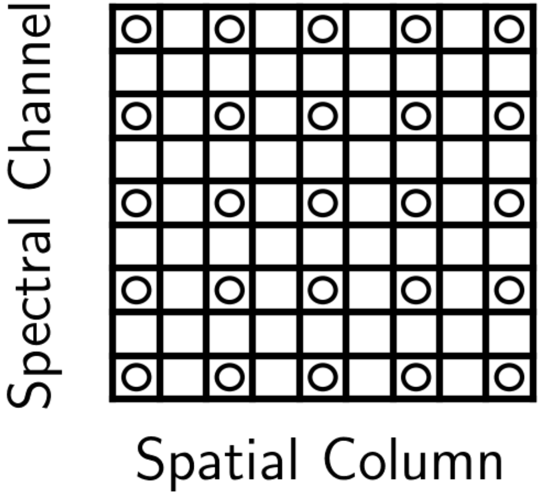
$$s_k = \langle f_k, \; L_s \rangle$$

signal measured by pixel k (a number)

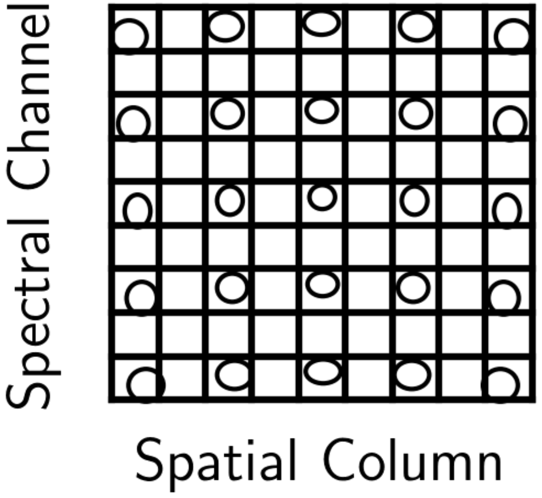
scalar product (integral)

Idea

ideal sensor B



real sensor A

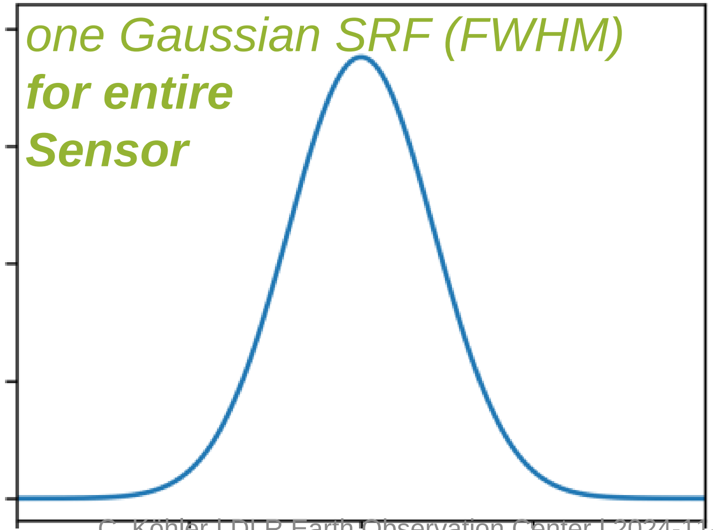


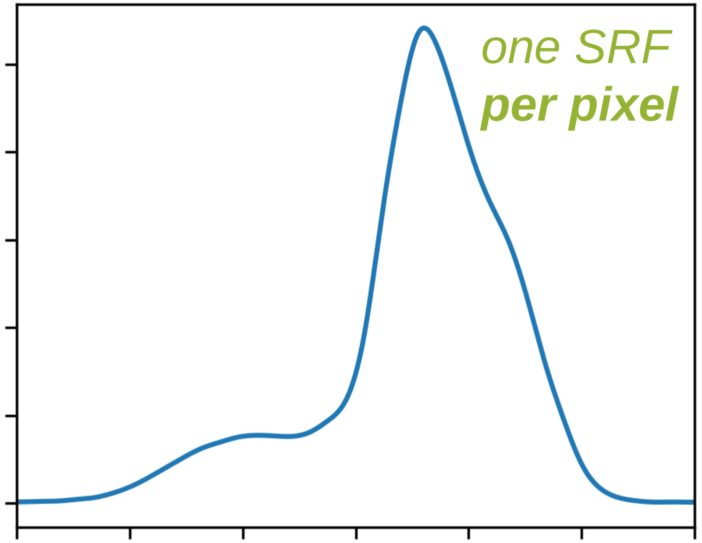
sensor B signal vector
(nrows · ncols elements)

sensor A signal vector
(nrows · ncols elements)

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

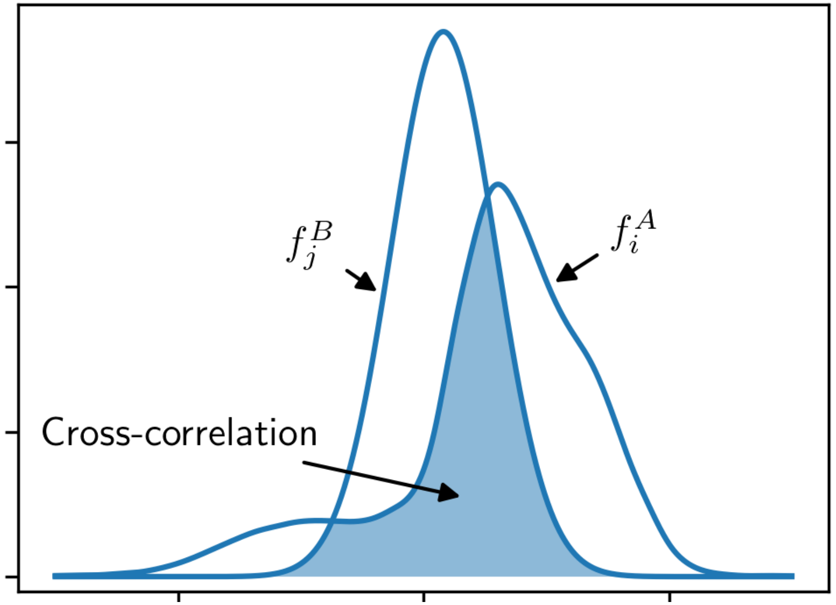
Transformation Kernel
(len $\mathbf{s}_B$ x len $\mathbf{s}_A$)



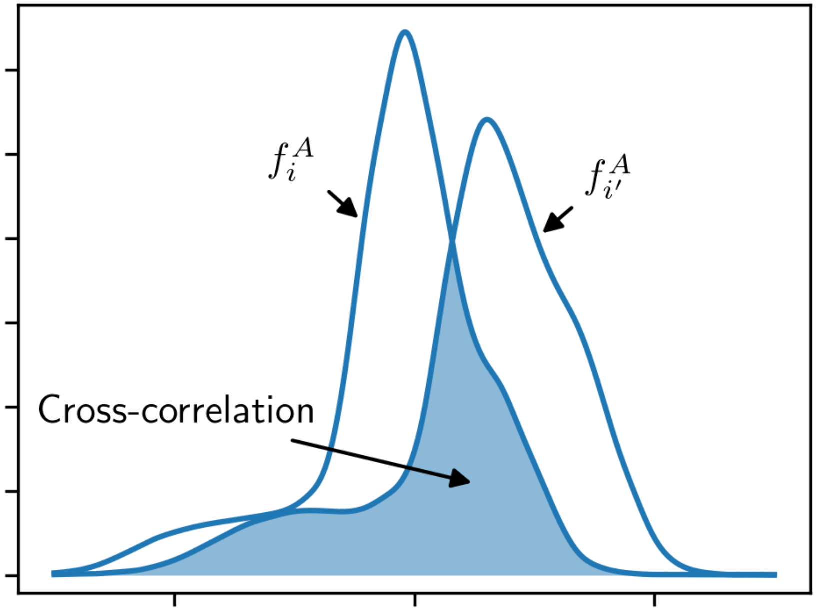


The Convolution Kernel

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



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



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

Kernel can be computed from Cross-correlation matrices

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

Tikhonov solution

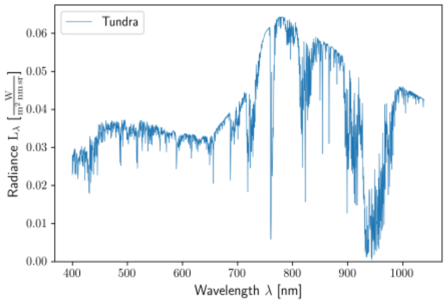
Baumgartner et al. (2020)
doi : 10.1364/oe.409626

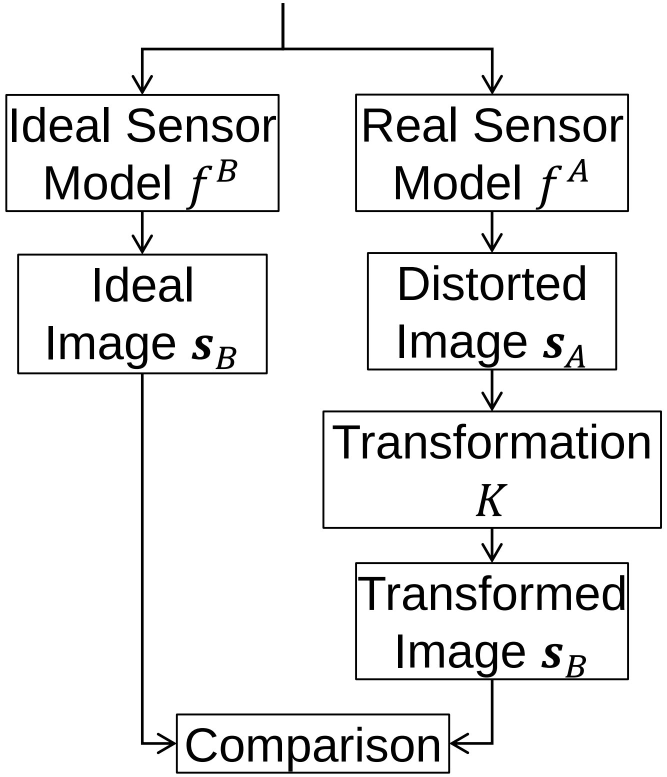
Applications

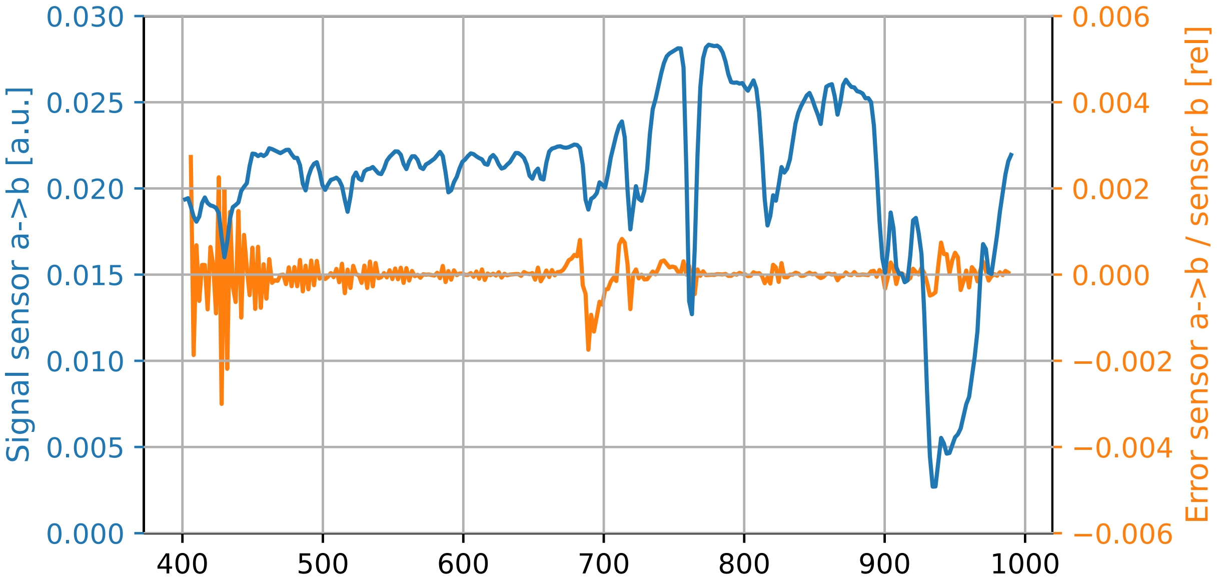
Sensor A	Sensor B	Application
HySpex	“**B**etter” HySpex	*homogeneous L1C product* *smart binning*
HySpex	CHIME	*CHIME validation*
CHIME	Sentinel-2	*cross-validation*
~~CHIME~~	~~Sentinel-5p~~	*wishful thinking!*

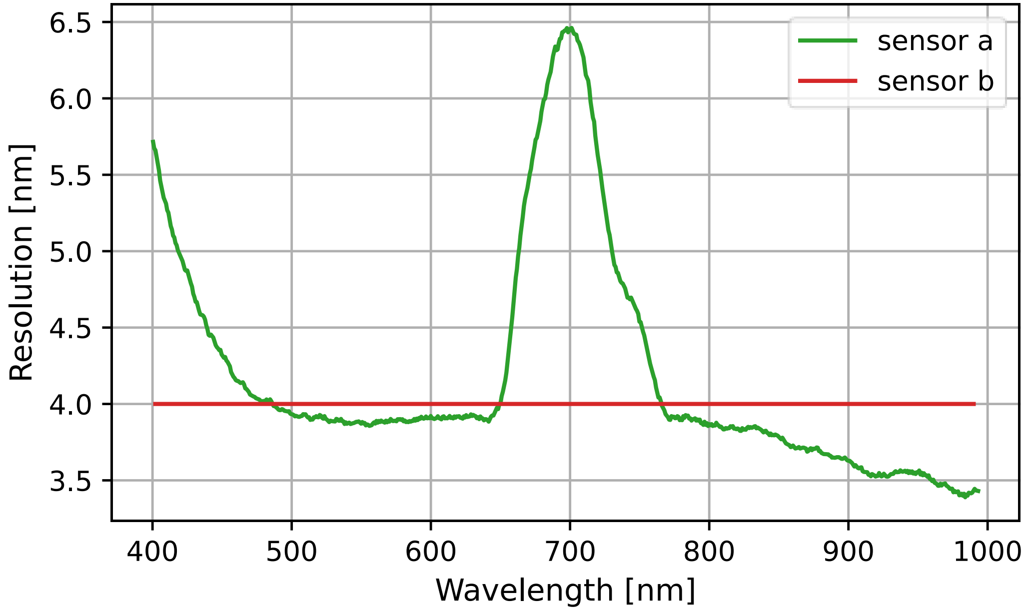
Simulation Study VNIR-3400N

Test Scene L_λ



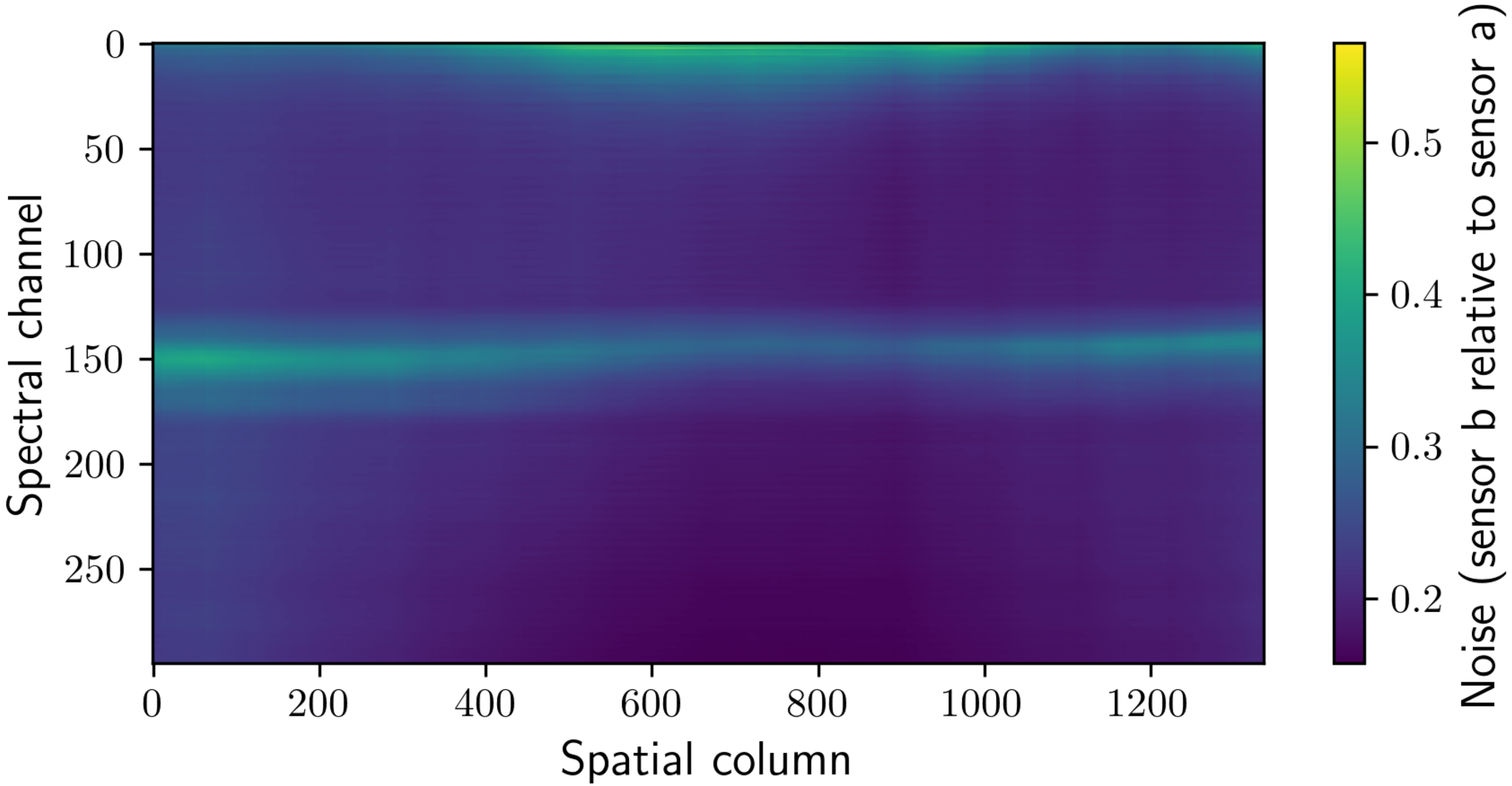






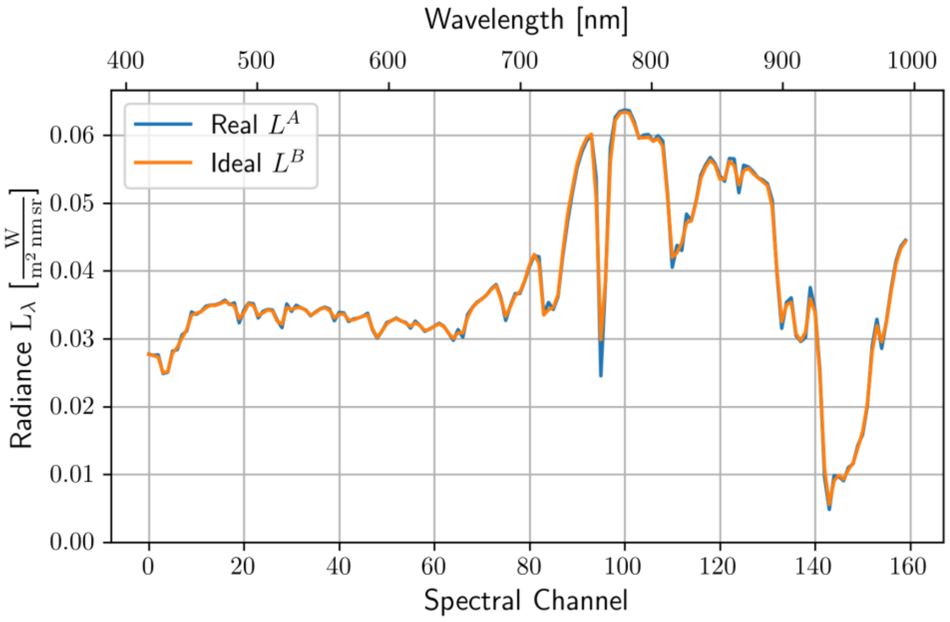
VNIR-3400N Uncertainty after Smart Binning

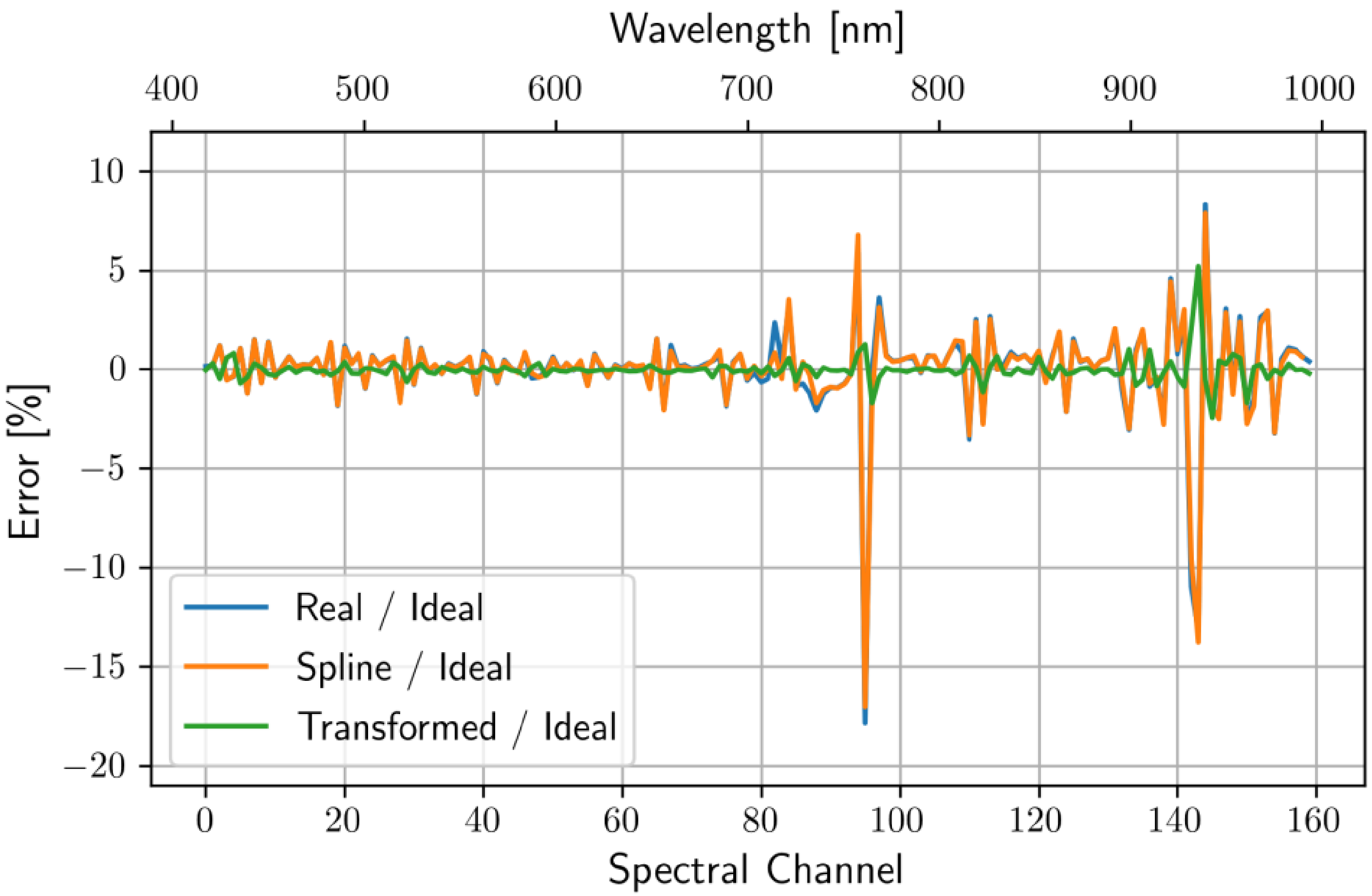
$$\Sigma^{\mathrm{B}} = K\Sigma^{\mathrm{A}}K^{\mathrm{T}}$$ *uncertainty propagation*



Simulation Study VNIR-1600

- ~1.4 channels / FWHM
- Larger errors compared to oversampled sensor
- Smaller errors compared to conventional methods



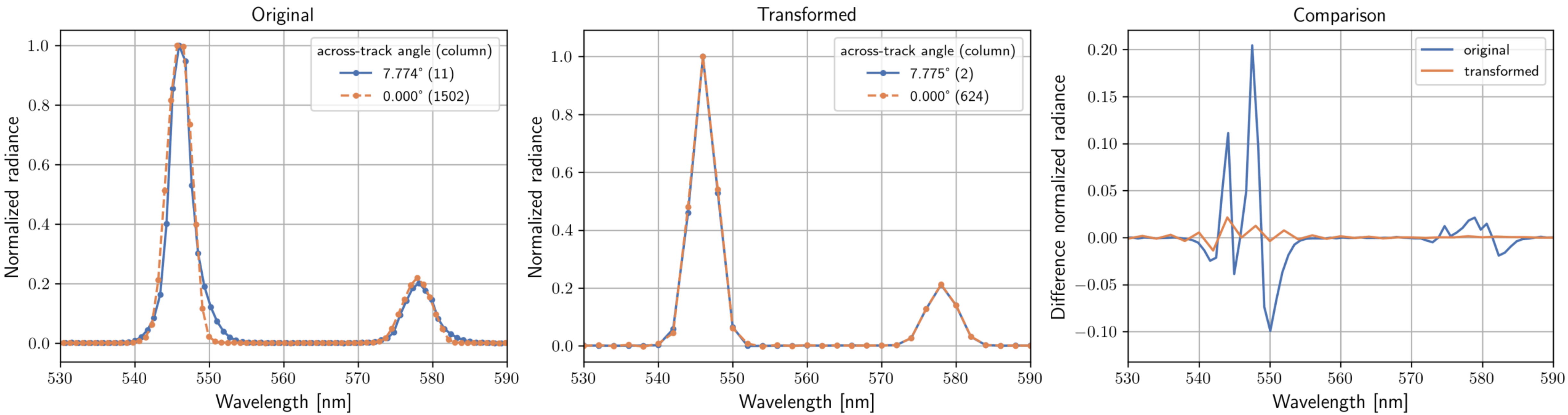


Current HySpex 3400N Processing Settings

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	

Experimental Validation of VNIR3400N Resampling

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



Implications on L1 Processing

- Convolution Kernel is *big data*
  - ~ 941 billion elements for HySpex VNIR
  - 7.5 TB at full resolution
  - 5.5 GB in practice (sparse matrix)

- Processing Time
  - Moderately optimized python code
  - VM with 16 CPUs @ 2.5 GHz, 128 GB RAM
  - 3-4 frames per second HySpex VNIR
  - ~50 frames per second HySpex SWIR

- 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 for optical design imperfections
- Effectively reduces smile / keystone
- Denser sampling (Nyquist) required compared to typical hyperspectral sensors
- Response Functions have to be available (and stable)

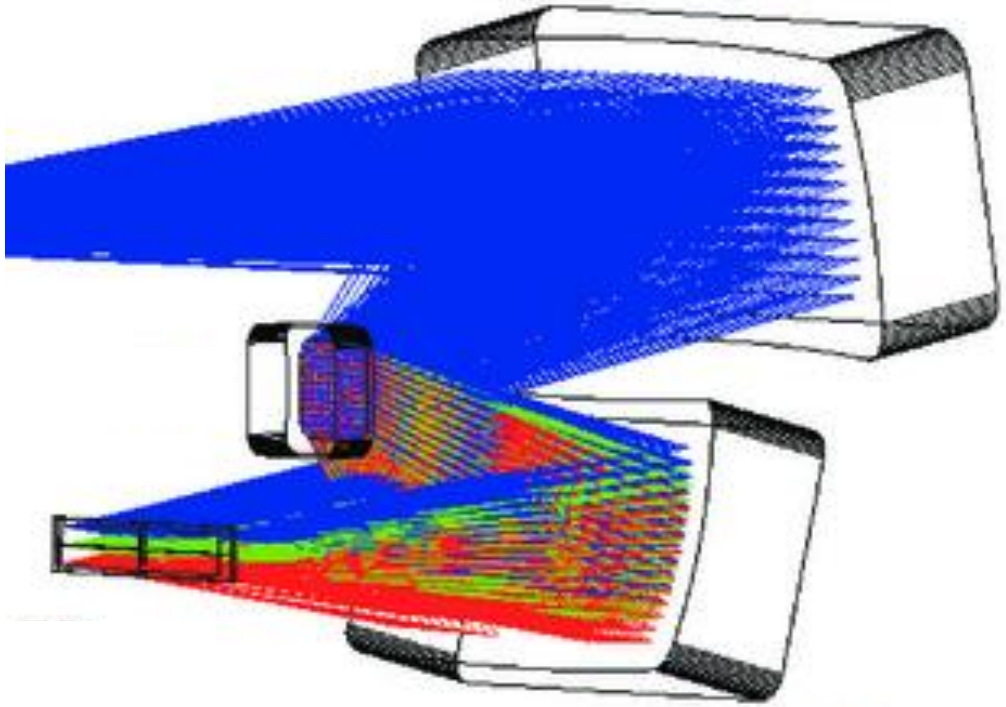


IMAGE: Buschkamp et al. 2021, doi:10.1117/12.2599428

Conclusions

- Kernel-based response function homogenization
  - corrects several optical artifacts
  - reduces data size by smart binning
  - reduces complexity of down-stream processing
  - delivers L1C products which are easier to adopt by the community

- Our findings have implications regarding 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 in-orbit changes) is of paramount importance

- We should also take a closer look at along-track oversampling (scene inhomogeneity)

Imprint

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Institute: Remote Sensing Technology Institute, Oberpfaffenhofen

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Venue: ESA Workshop on Pre-Flight Calibration & Characterisation of Optical Satellite Instruments for EO

19 – 22 November 2024, Nordwijk, The Netherlands