A NOVEL AT-SENSOR RADIANCE HARMONIZATION METHOD

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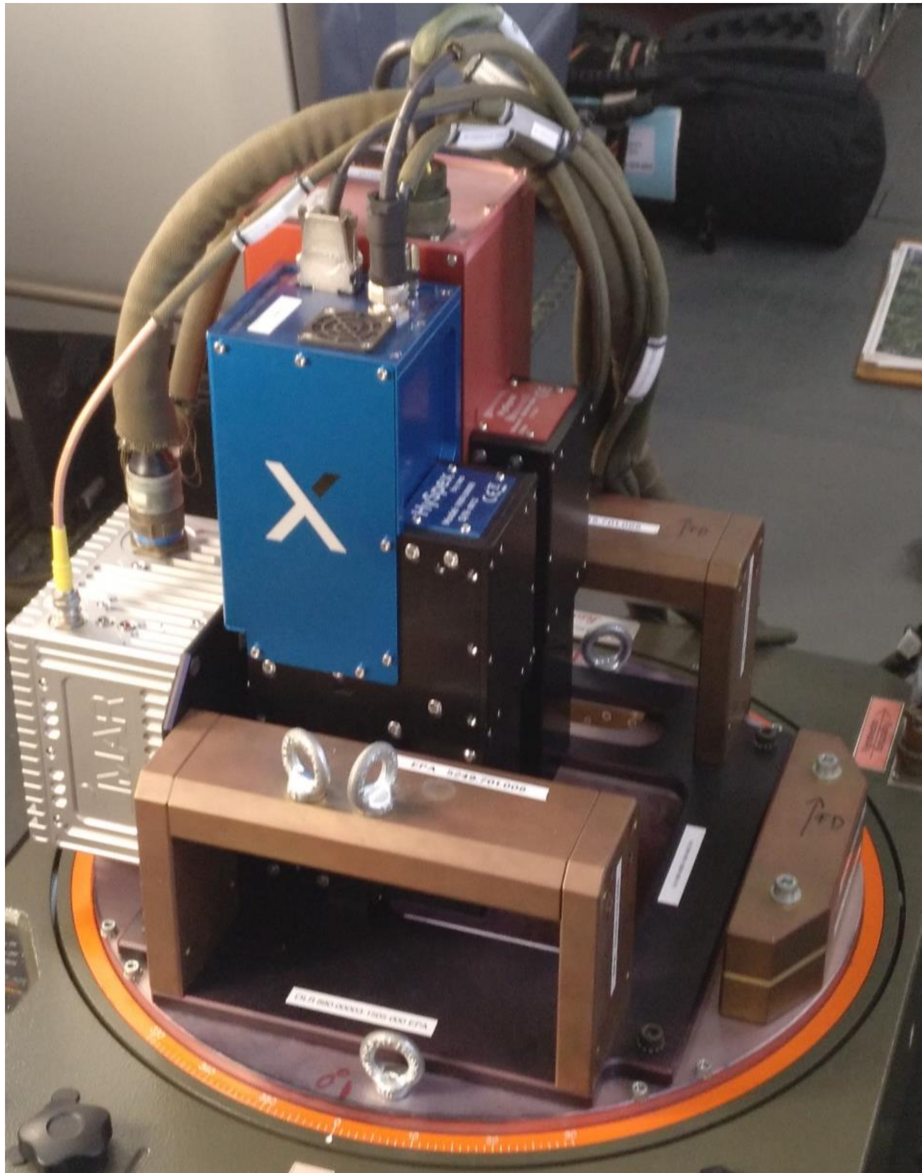
Airborne Sensor Systems

HySpex-B

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

HySpex (EnMAP demonstrator)

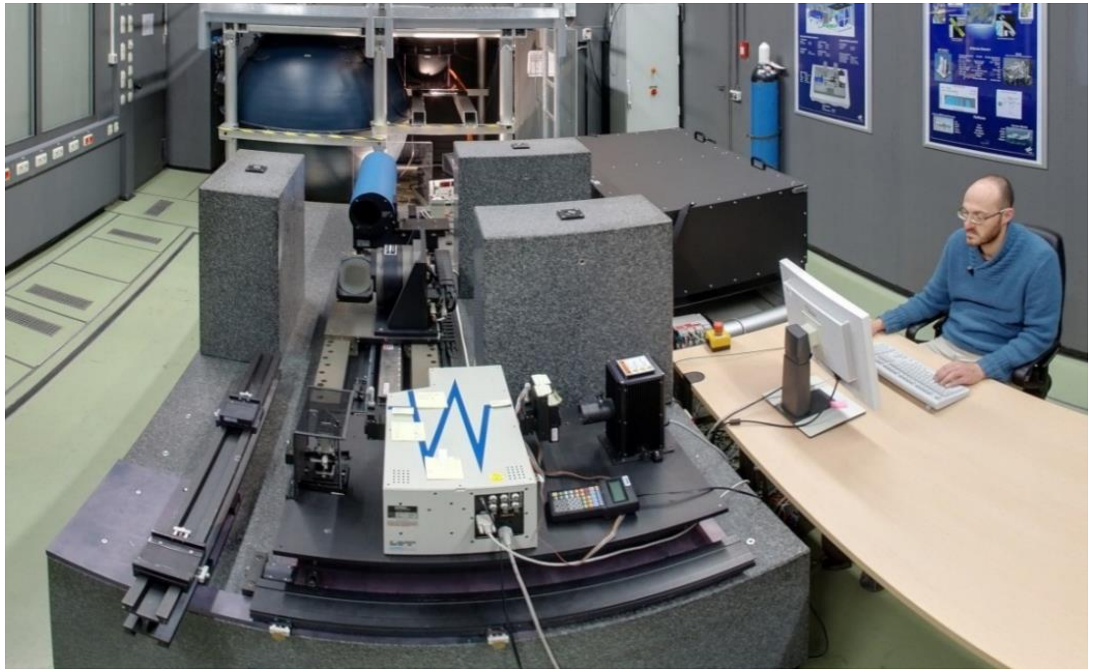
- HySpex VNIR-1600 + SWIR-320me
- Acquired for EnMAP preparation in 2011
- Extensively calibrated

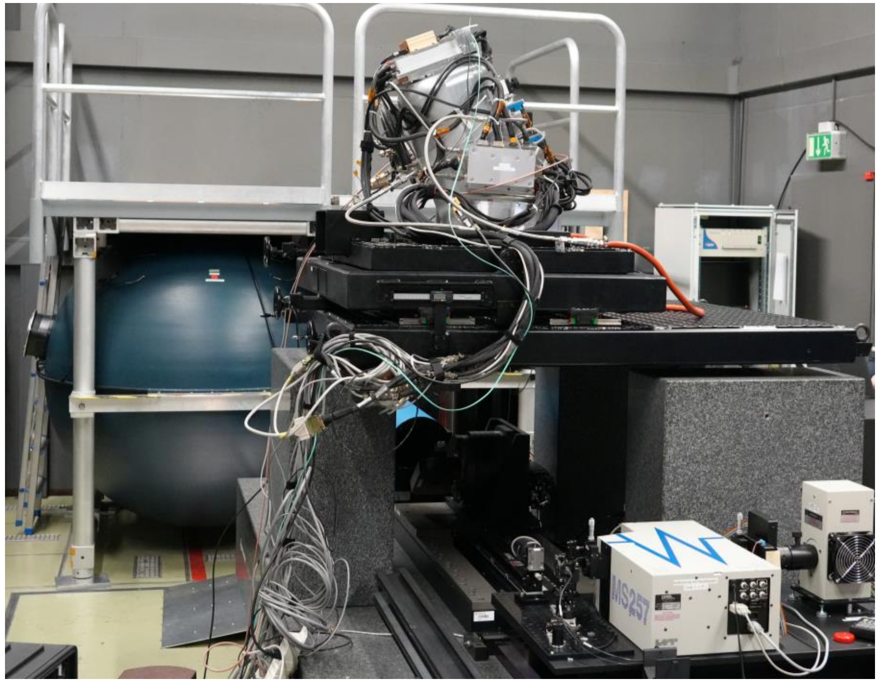


Our advantage: we can recalibrate after each campaign

Calibration Home Base (CHB)

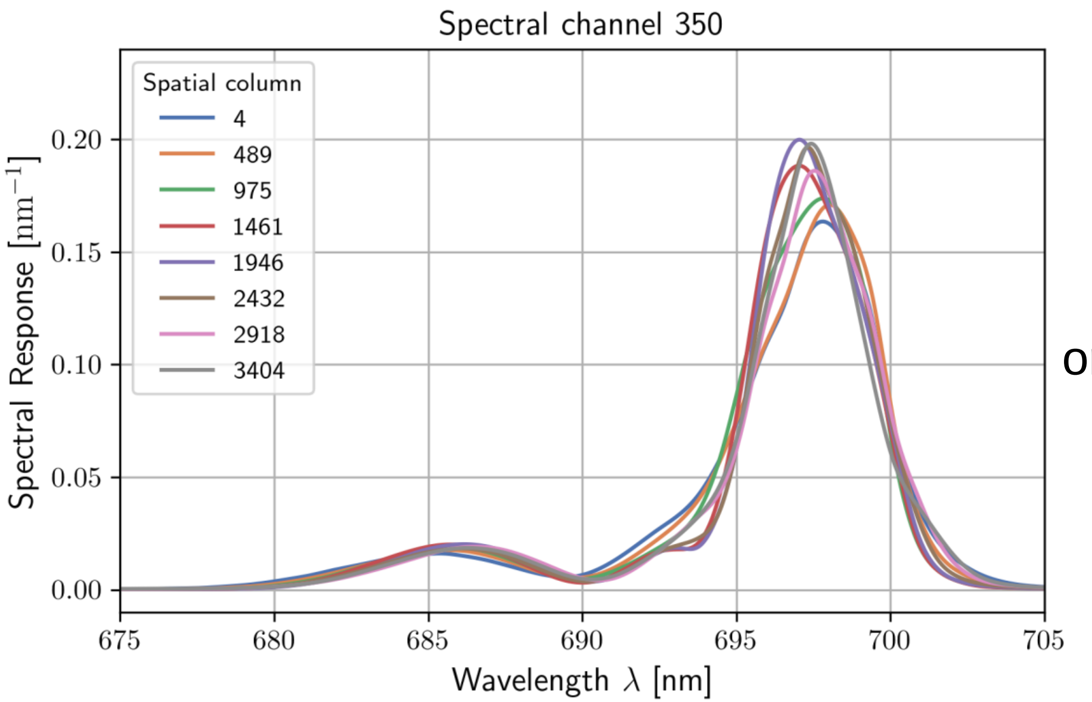
- Co-funded by ESA
- Operational since 2007
- Calibration of
  - angular response
  - spectral response
  - radiometric response
  - polarization
  - non-linearity
  - stray light
  - temperature sensitivity
  - …
- Continuous development
- Instruments: HySpex, AVIRIS-4, “EnMAP“, …



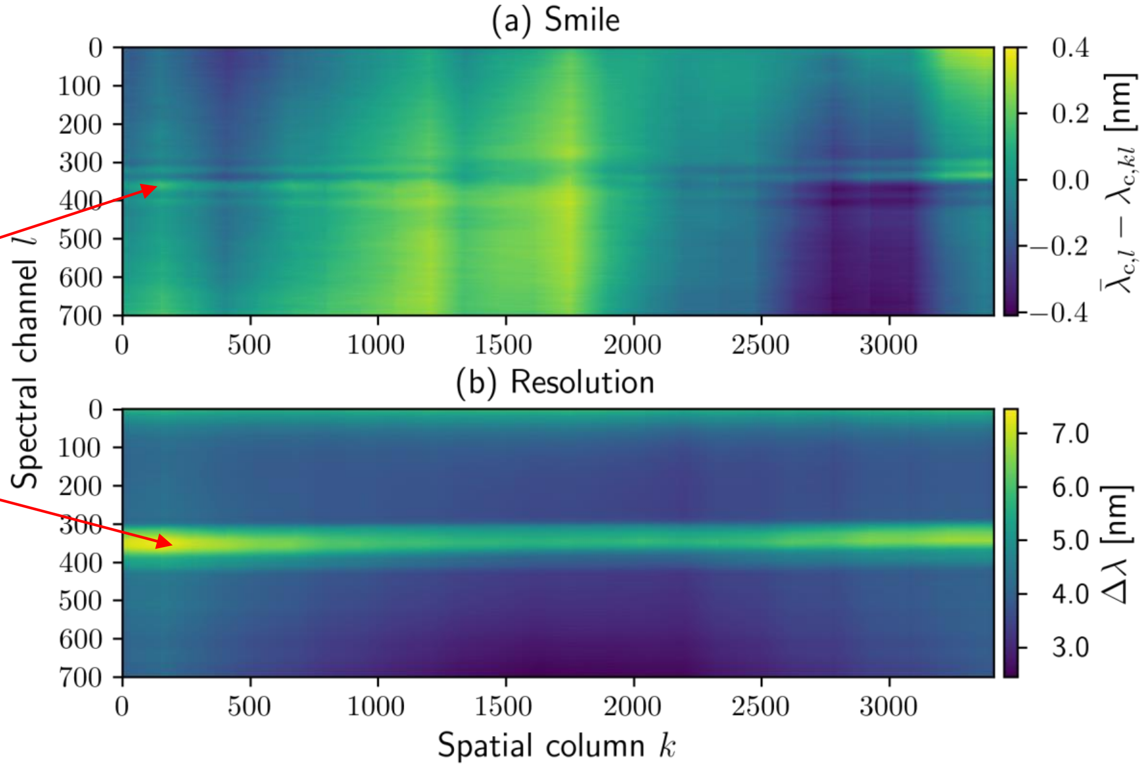


Spectral Calibration Results HySpex VNIR3400-N

- Individual SRF for each pixel (cubic spline model)
- Complicated SRF shapes → center wavelength + resolution not well defined
- Similar results for across-track response functions (ARFs)



order sorting
filter edge



Initial Situation

- We have a very good understanding (model) of the instrument

- But
  - available L1 algorithms correct only smile and keystone
  - higher level products do not make use of the full instrument model

- How can we make use of the full instrument model
  - to make data from different detector locations comparable?
  - to make data from different instruments comparable?
  - to reduce data complexity?

- Do we really need to track the response of each individual pixel in higher level products?

Imaging Equation

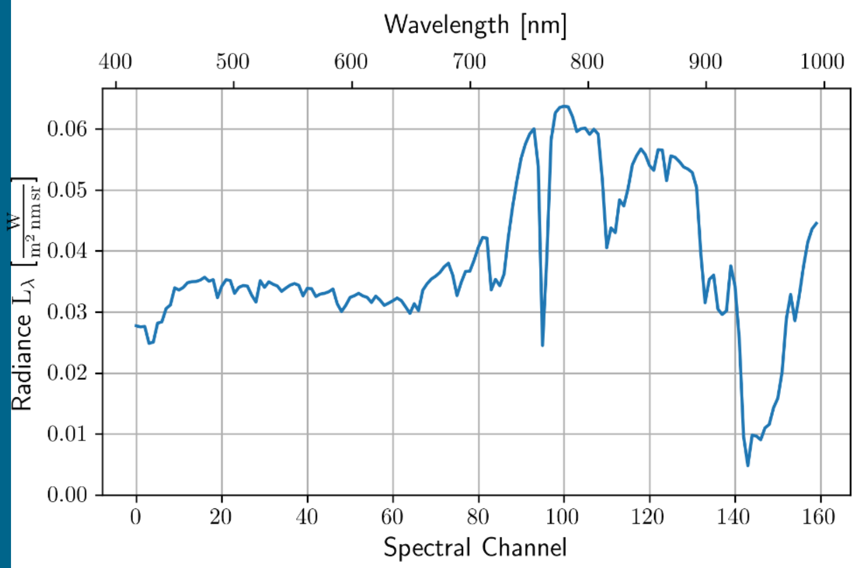
For simplicity only spectral case is shown

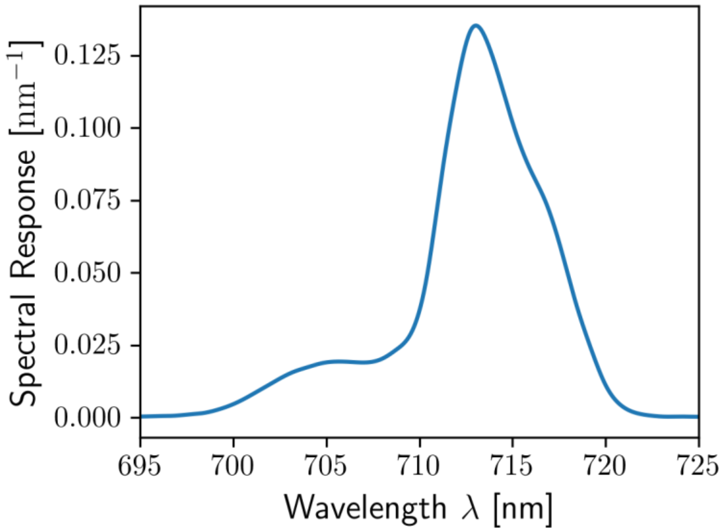
$$L_i^A = \int_0^{2\pi} \int_0^{\infty} f_i^A(\beta, \lambda) L_\lambda(\beta, \lambda) \, \mathrm{d}\lambda \, \mathrm{d}\beta$$

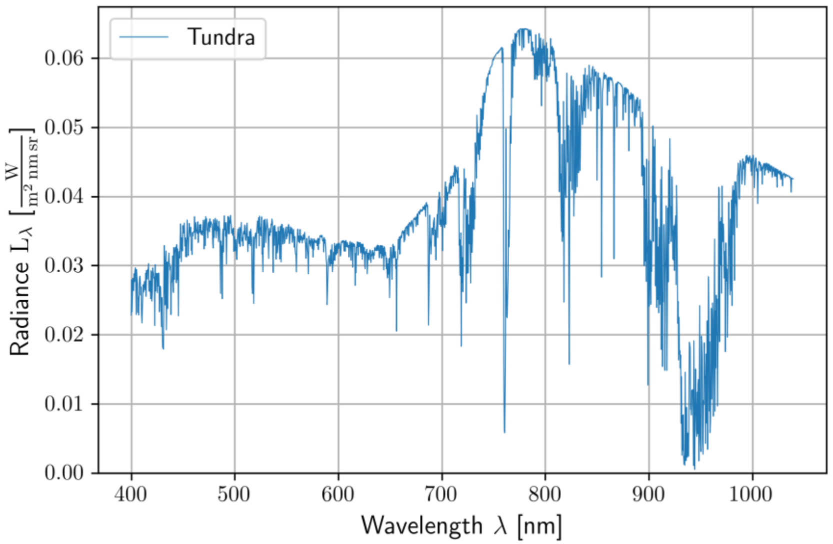
Measured radiance

Instrument responses

At sensor radiance

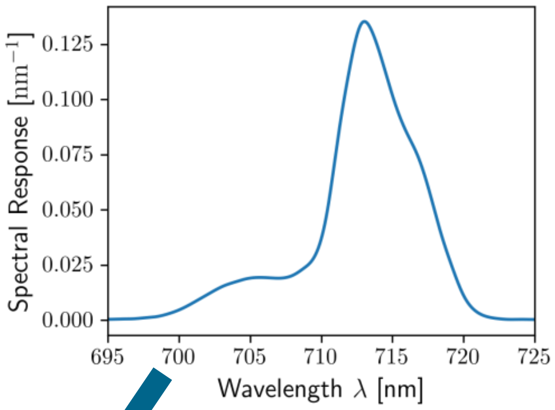




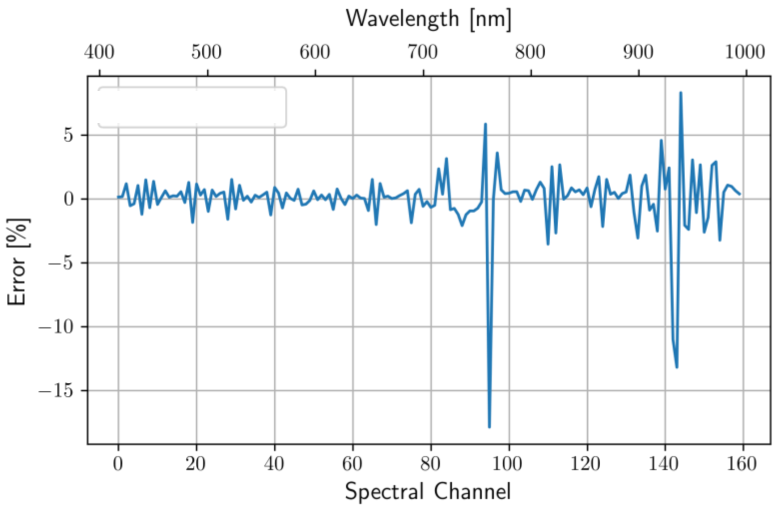


Two Systems - Two Results

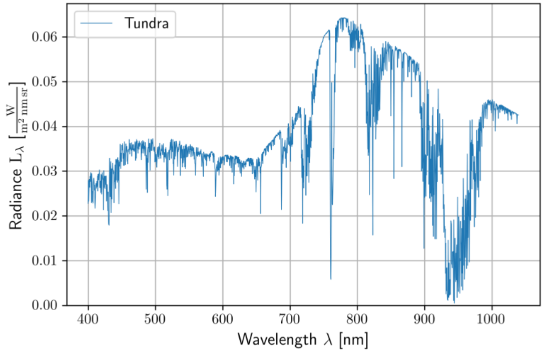
System A



Ratio System A / System B

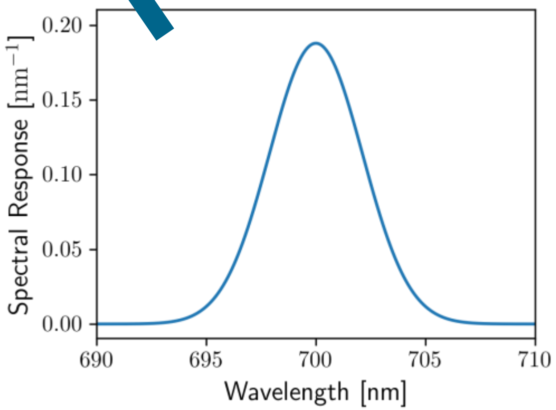


$$L_i^A = \int_0^{2\pi} \int_0^{\infty} f_i^A(\beta,\lambda) L_\lambda(\beta,\lambda)\, \mathrm{d}\lambda\, \mathrm{d}\beta$$



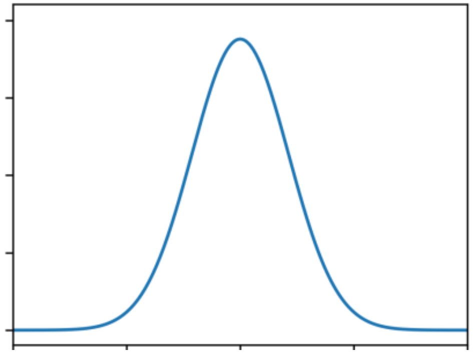
$$L_j^B = \int_0^{2\pi} \int_0^{\infty} f_j^B(\beta,\lambda) L_\lambda(\beta,\lambda)\, \mathrm{d}\lambda\, \mathrm{d}\beta$$

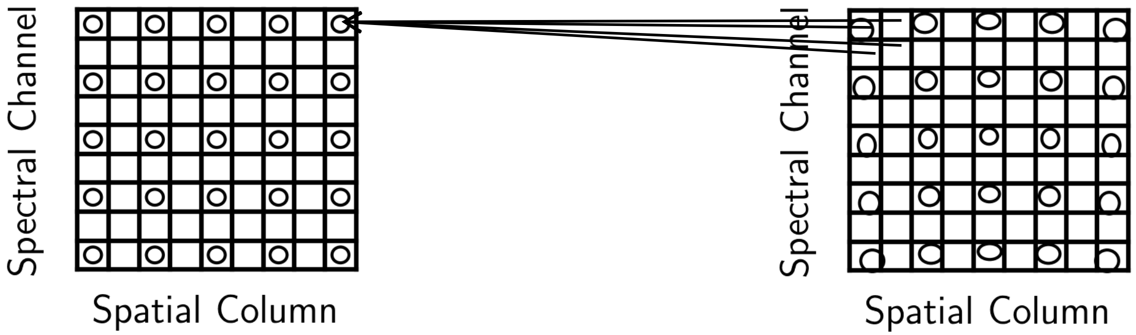
System B

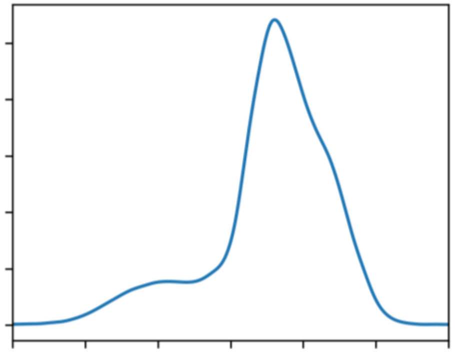


Goal: Converting Data from System A to System B

Each pixel of system B is the weight
and sum of all pixels of system A







$$\boldsymbol{L}^{B} = \boldsymbol{K} \cdot \boldsymbol{L}^{A}$$

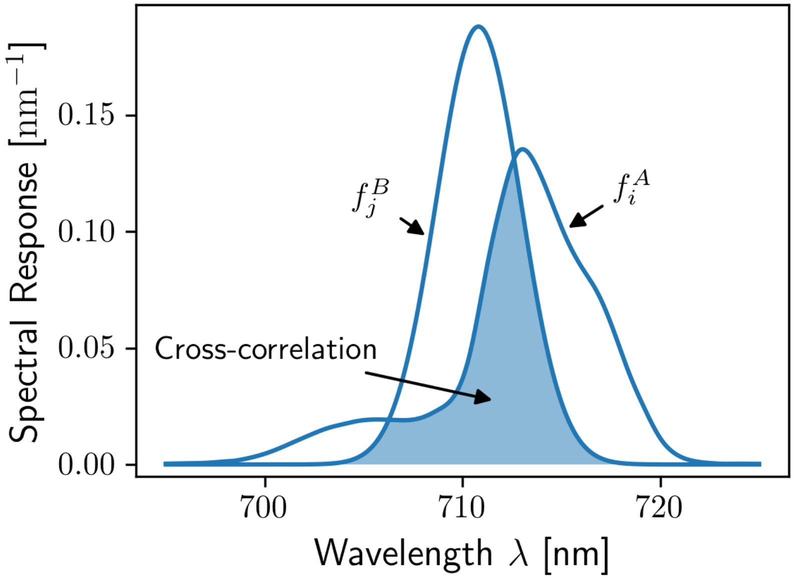
Problem: Find matrix K

Remember: Each pixel has individual spectral and geometric properties

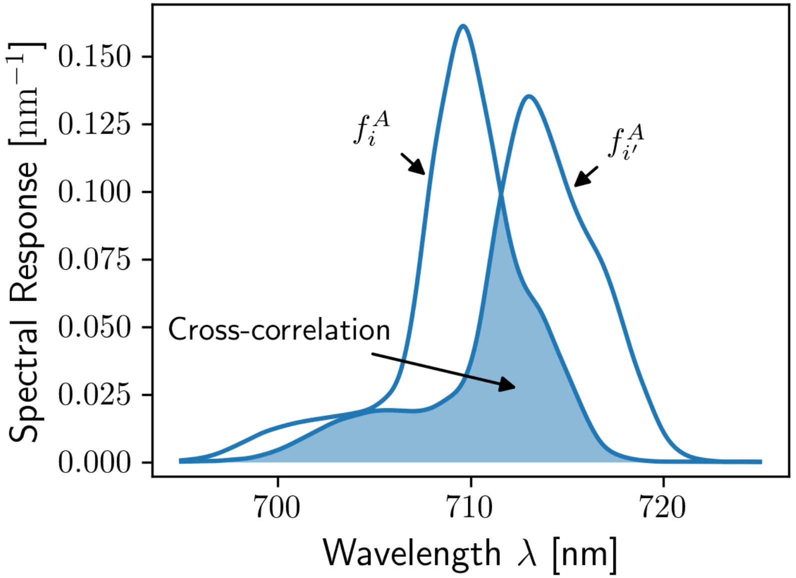
Note: K is the relation of system B to A → calculated only once
K can be applied on any spectrum of system A

New Approach: Using Cross-Correlations to Find Matrix K

$$C_{ji}^{BA} = \int_0^{2\pi}\int_0^{\infty} f_j^B(\beta,\lambda) f_i^A(\beta,\lambda)\,\mathrm{d}\lambda\,\mathrm{d}\beta$$



$$C_{ii'}^{AA} = \int_0^{2\pi}\int_0^{\infty} f_i^A(\beta,\lambda) f_{i'}^A(\beta,\lambda)\,\mathrm{d}\lambda\,\mathrm{d}\beta$$



Instrument properties

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

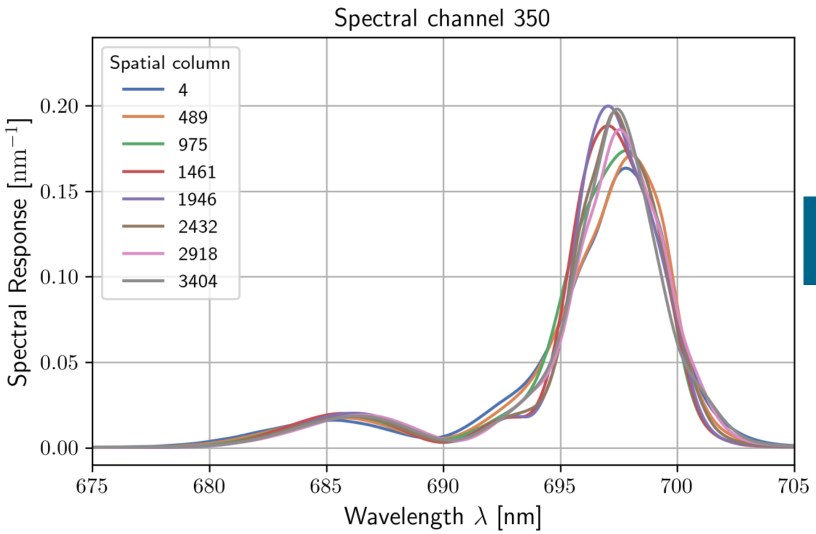
Transformation matrix can be computed from cross-correlation matrices

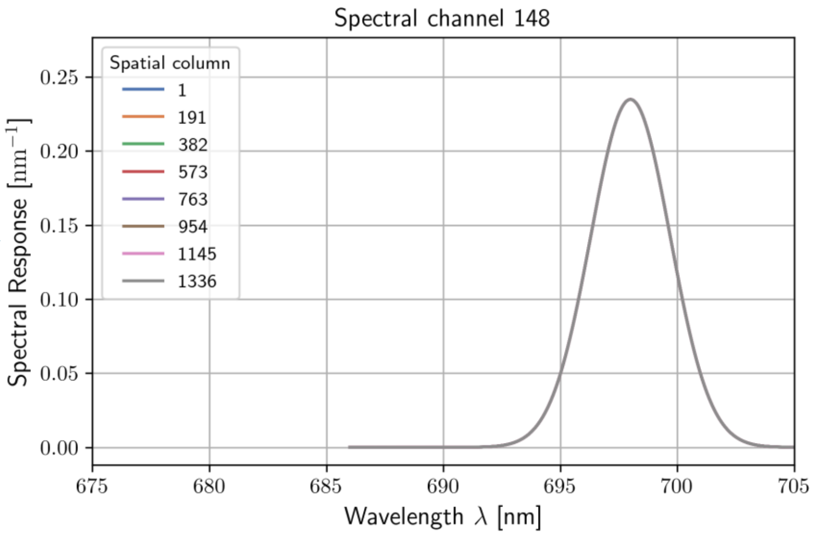
Mathematical background in

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

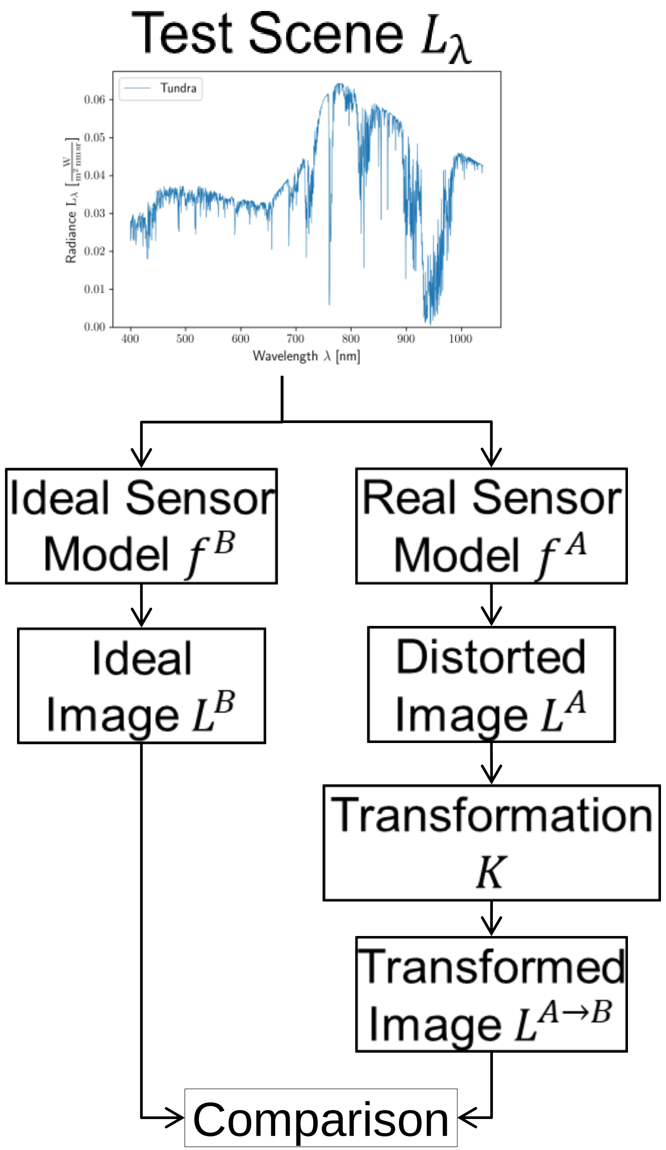
Current HySpex VNIR-3400N Processing Settings

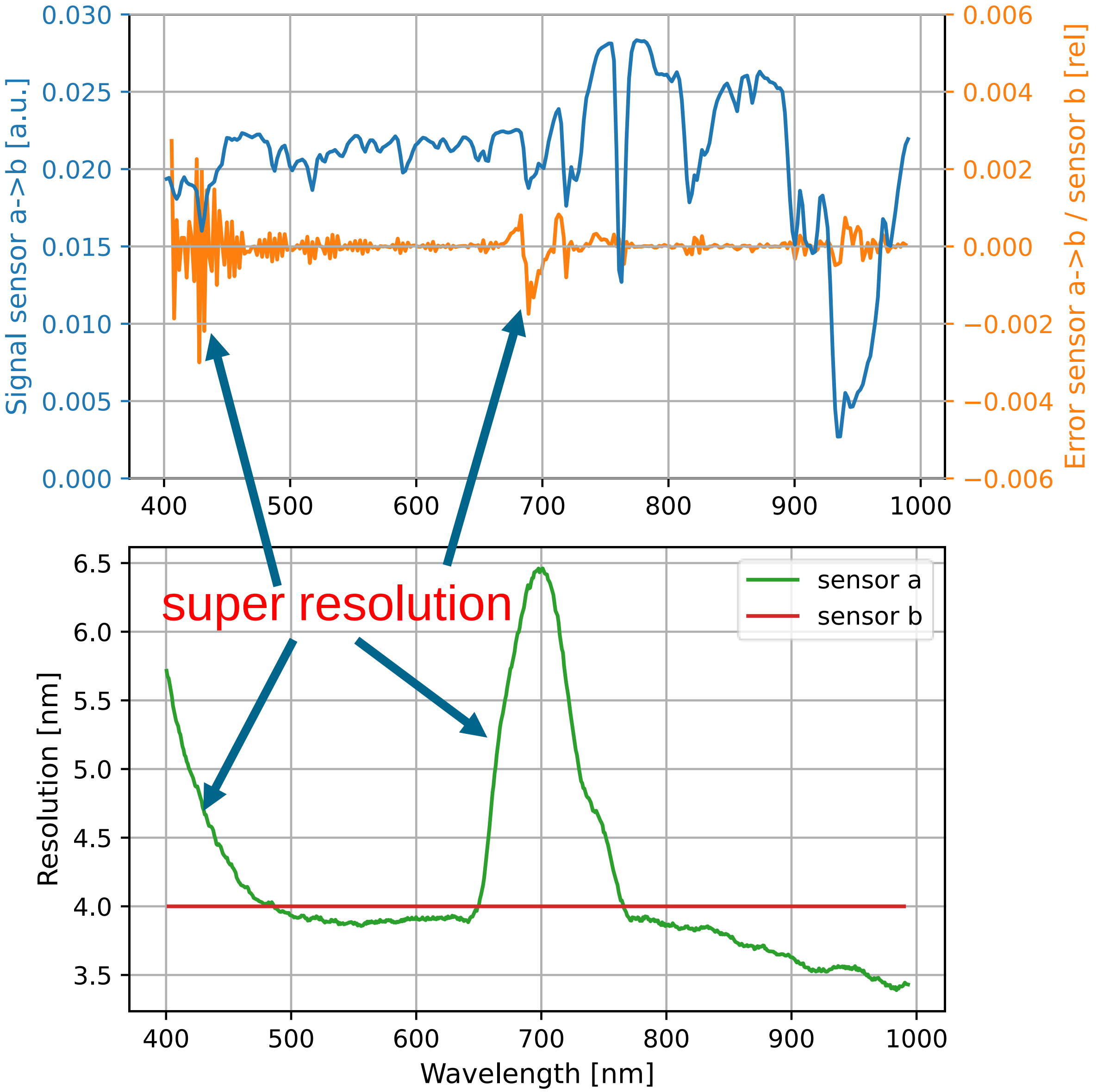
Parameter	Sensor A	Sensor B	
Spatial columns	3408	1337	*smart binning*
Spectral channels	700	295	*smart binning*
Smile [nm]	<0.8	0	
Keystone [mrad]	<0.14	0	
Angular resolution [mrad]	0.09 – 0.43	0.44	
Spectral resolution [nm]	2.5 – 7.5	4	*super resolution*
SRF and ARF shape	Spline model (complicated)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





Simulation Results

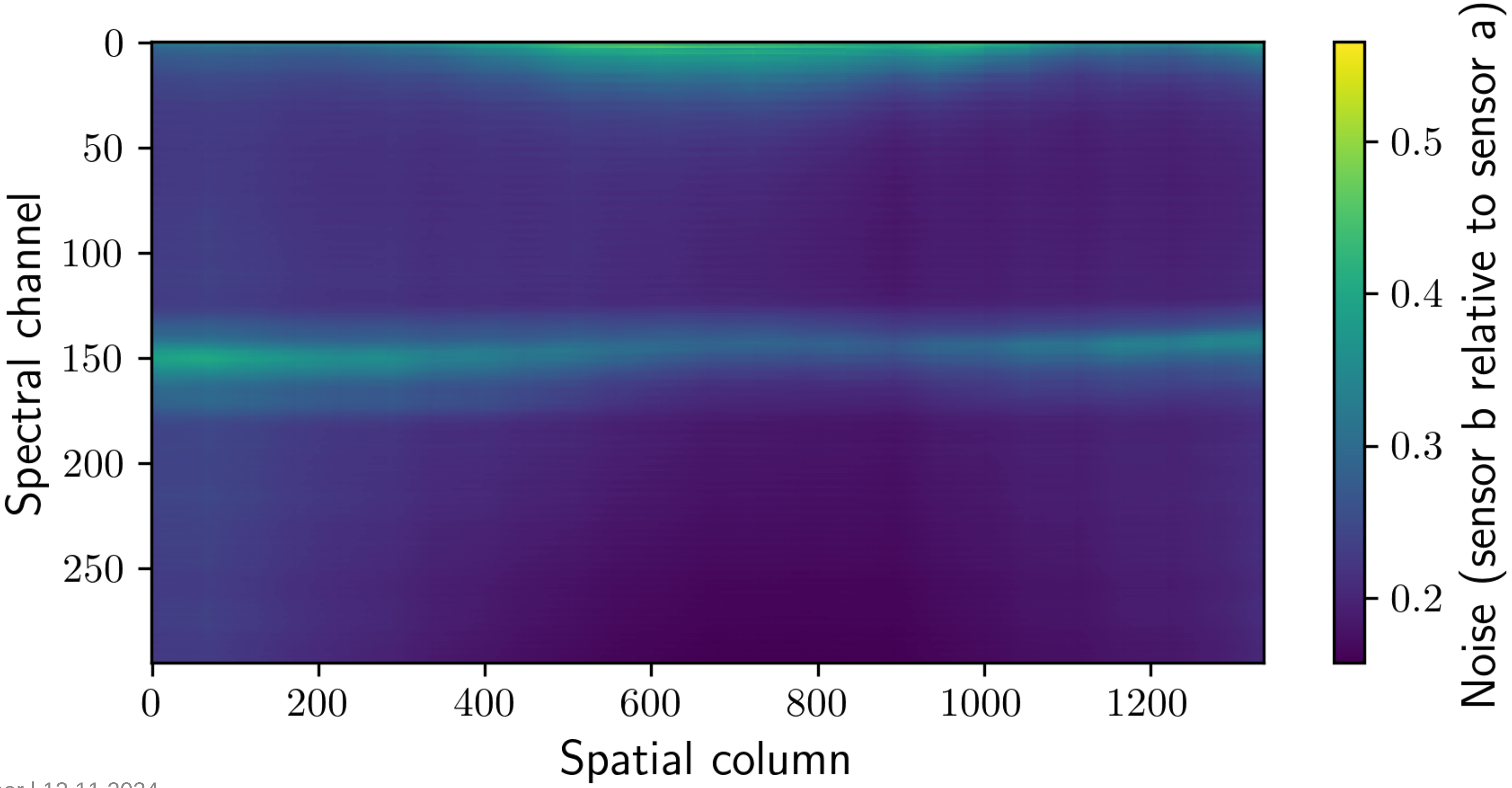




Uncertainties

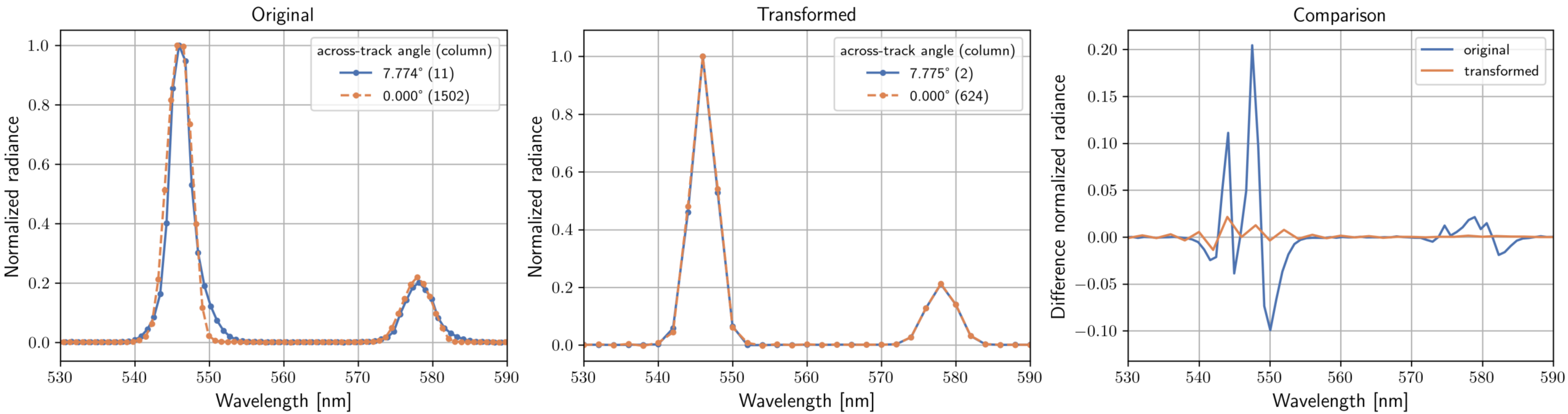
Covariance propagation: $\Sigma^{\mathrm{B}} = K\Sigma^{\mathrm{A}}K^{\mathrm{T}}$

HySpex VNIR-3400N: Relative noise level change after transformation:



Experimental Validation of HySpex VNIR-3400N

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



Applications

Sensor A	Sensor B	Application
HySpex	ideal HySpex	*harmonized L1 product* *smart binning*
HySpex	CHIME	*CHIME validation*
CHIME	Sentinel-2	*cross-validation*
~~CHIME~~	~~Sentinel-5p~~	*wishful thinking!*

Conclusion

- Matrix based response function harmonization is an efficient tool
  - Correct several optical artifacts
  - Reduce data size by smart binning
  - Reduce complexity of down-stream processing
  - Deliver L1 products that are easier to adopt by the community
  - Works also with undersampled instruments!

- Our finding have implications on 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