IMAGE TRANSFORMATION BETWEEN (IMAGING) SPECTROMETERS

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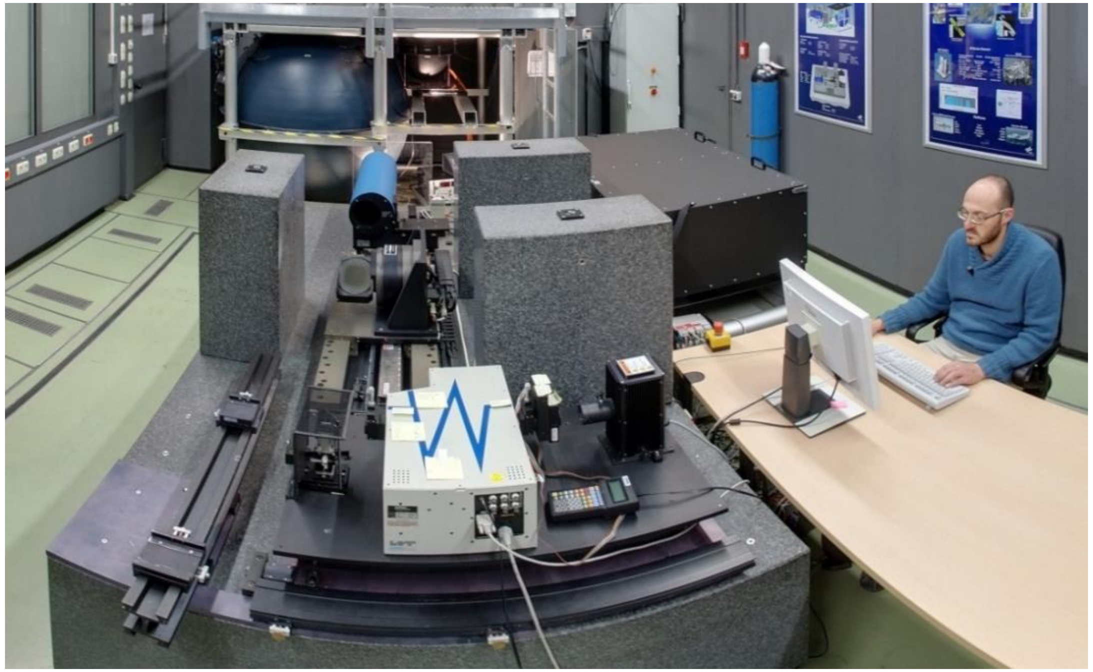
Airborne vs satellite imaging spectrometer

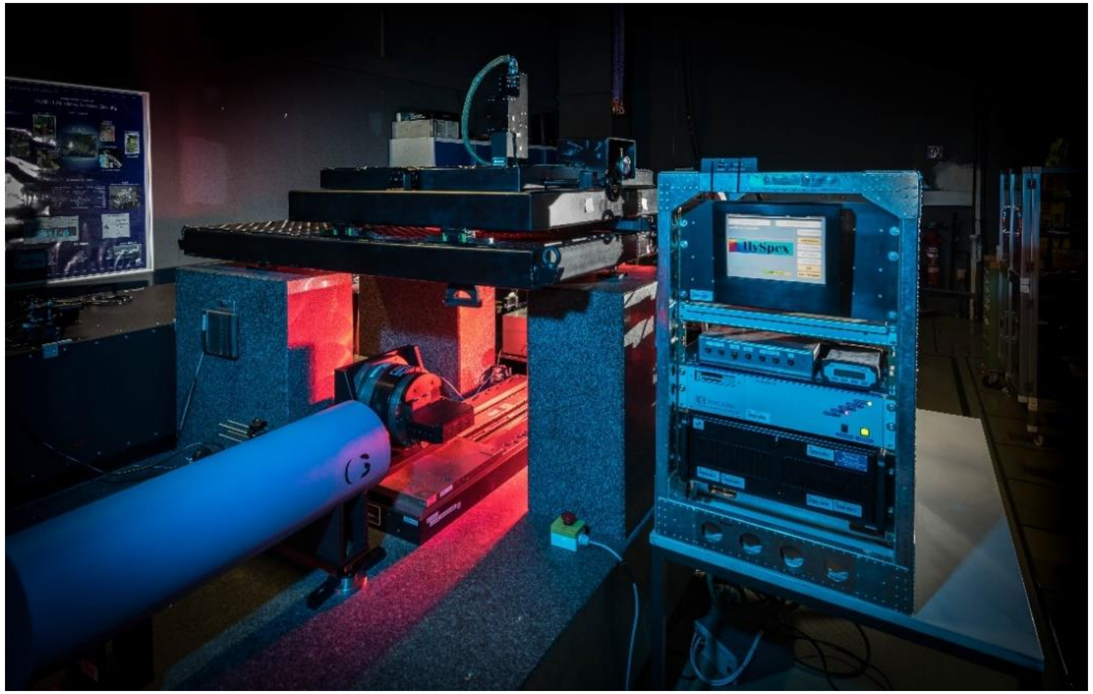
- Same working principles and similar calibration challenges
- Lab calibration of space instruments only before launch
- Airborne instruments come back to the lab

- More time to calibrate airborne instruments than for space instruments
- We can learn a lot from airborne instruments that is applicable to satellite systems

Calibration Home Base (CHB)

- Operational since 2007
- Designed for typical airborne imaging spectrometers:
  - Spectral range: 350 nm – 2500 nm
  - Bandwidth: >0.5 nm
  - IFOV: >0.1 mrad
  - FOV: ±20°
- Setups for calibration of
  - Angular, spectral and radiometric response
  - Polarization
  - Non-linearity
  - Temperature sensitivity
  - Stray light
- Highly automated
- Partly funded by ESA as calibration lab for APEX
- Used with other instruments: DLR’s HySpex, LMU’s specMACS, …



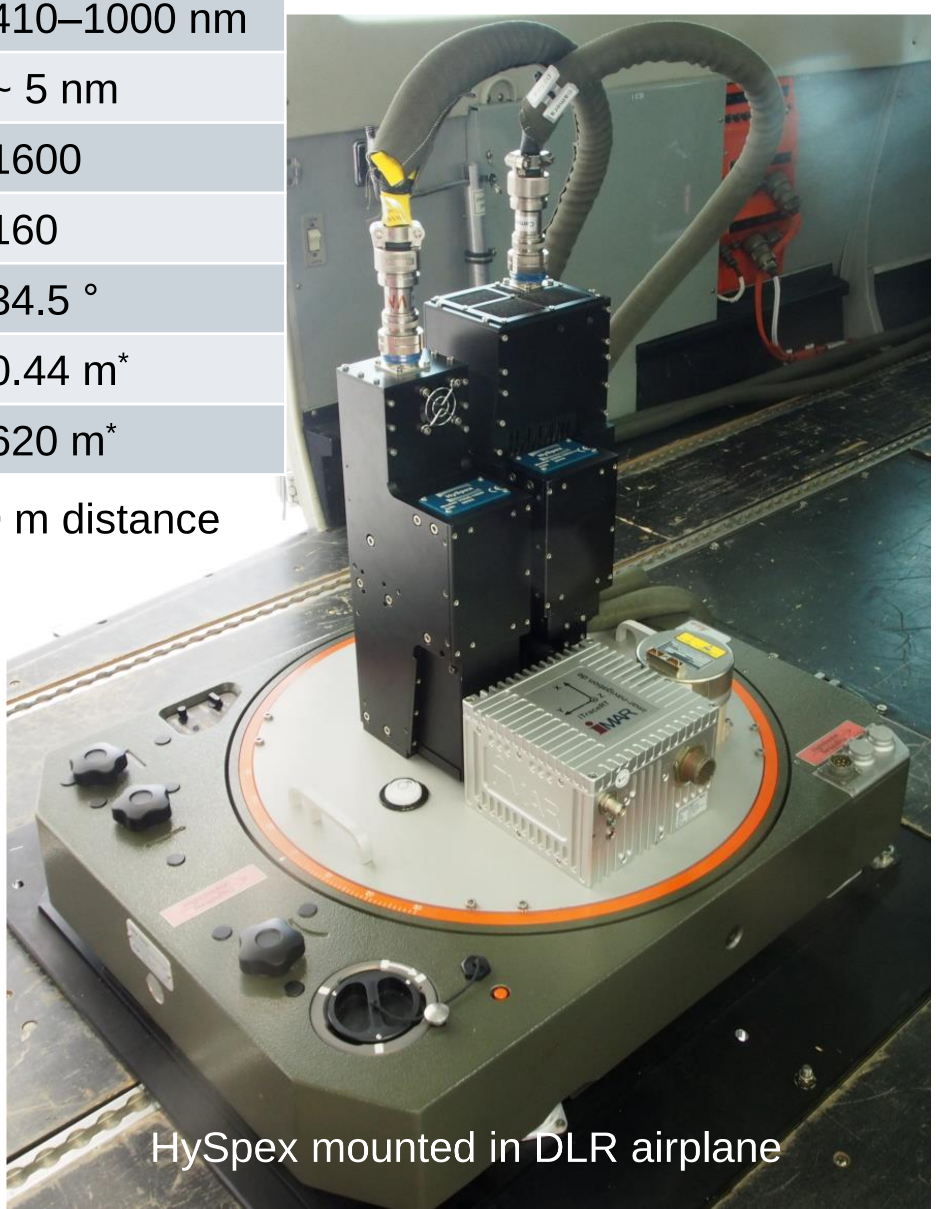


Neo HySpex VNIR-1600

- Commercially available instrument
- Used together with HySpex SWIR-320m-e
- Airborne campaigns 2012 – 2020
- 2020: replaced by new HySpex instruments

Parameter	Value
Spectral Range	410–1000 nm
Spectral Resolution	~ 5 nm
Spatial Columns	1600
Spectral Channels	160
Field of View	34.5 °
Min. GSD	0.44 m*
Swath Width	620 m*

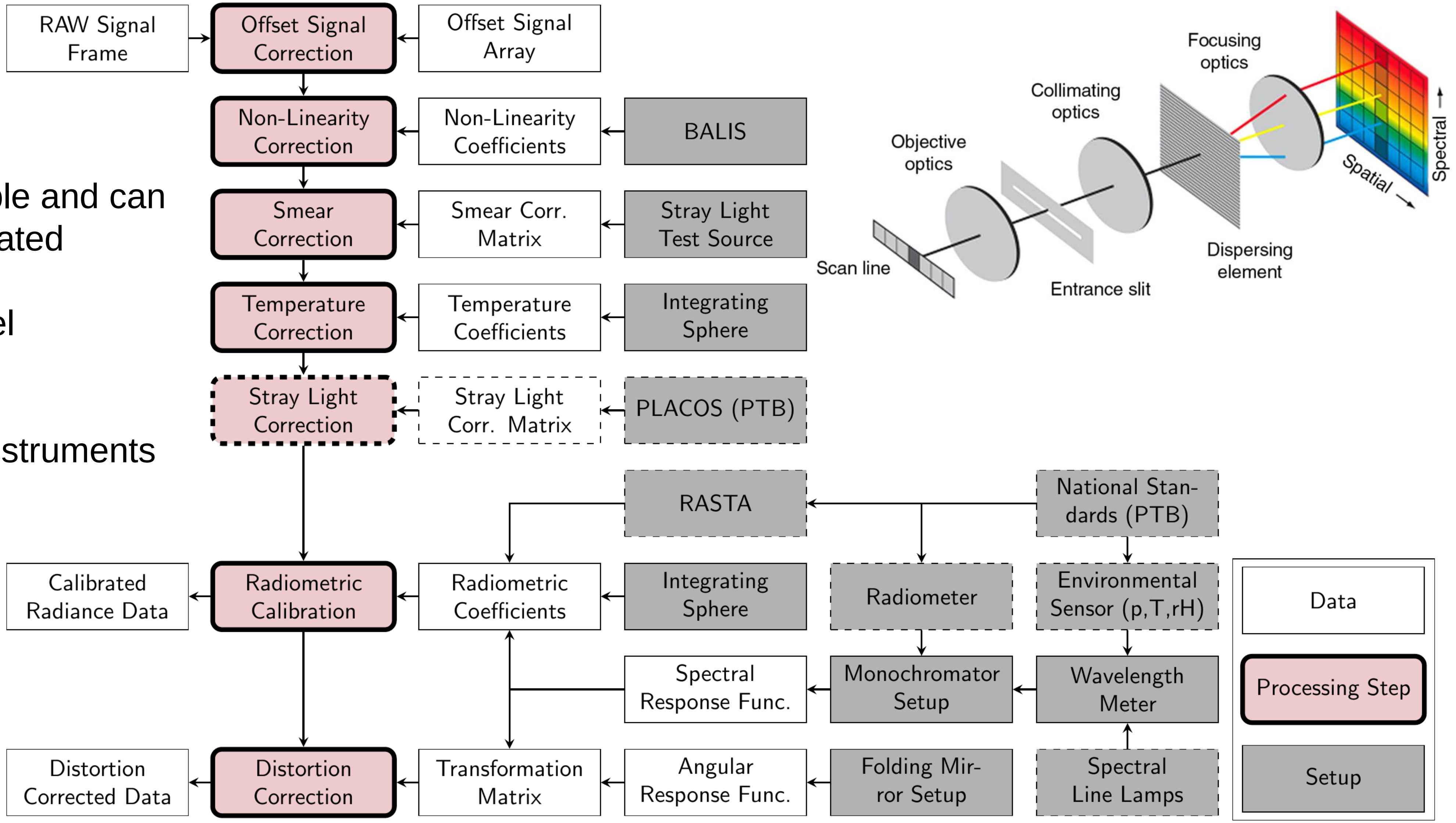
* @ 1000 m distance


HySpex mounted in DLR airplane

HySpex VNIR-1600 Level-1 Calibration Chain

L1 processor:

- Modules are reusable and can be individually activated
- Propagates per pixel uncertainties
- Usable with other instruments



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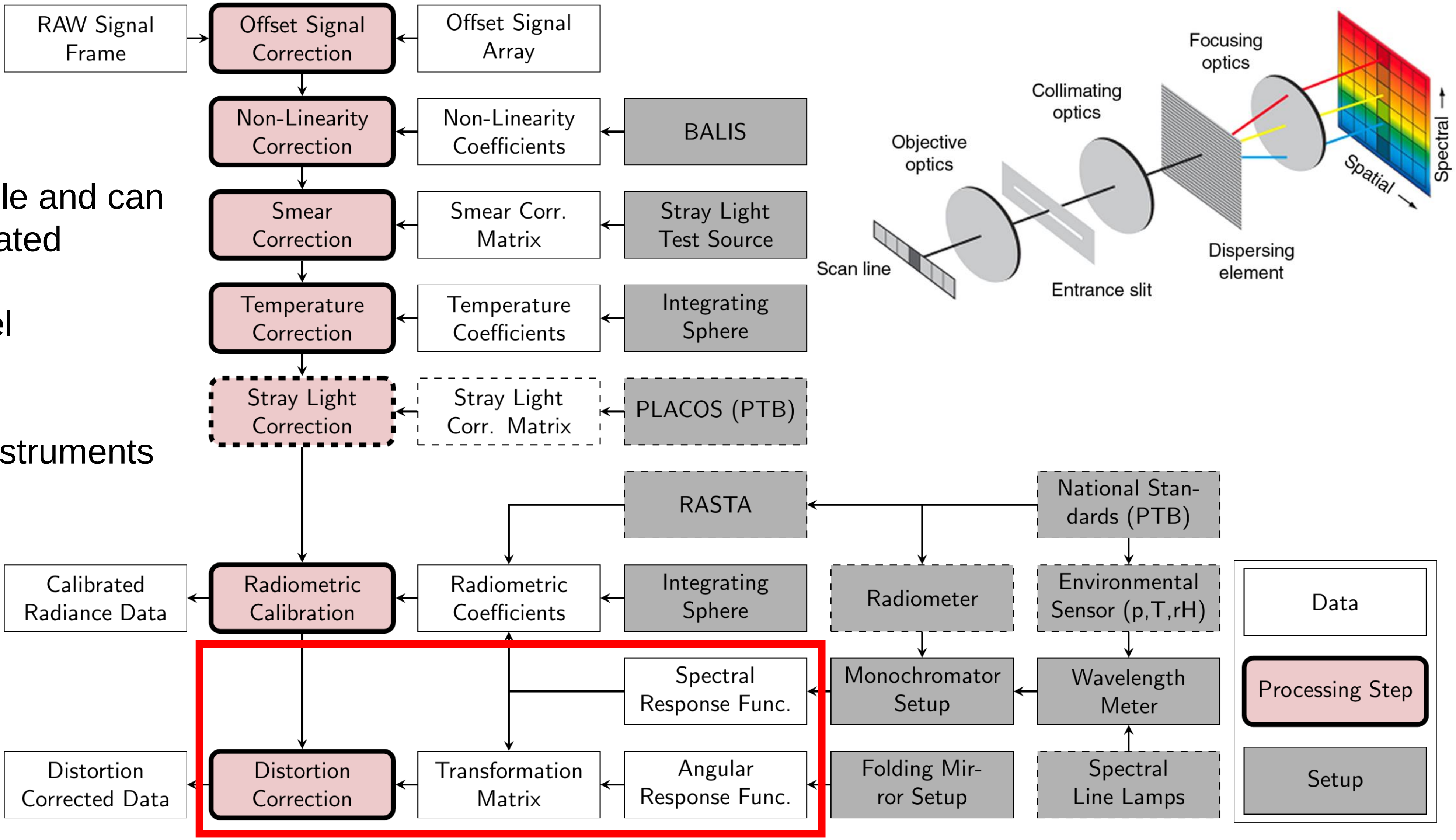
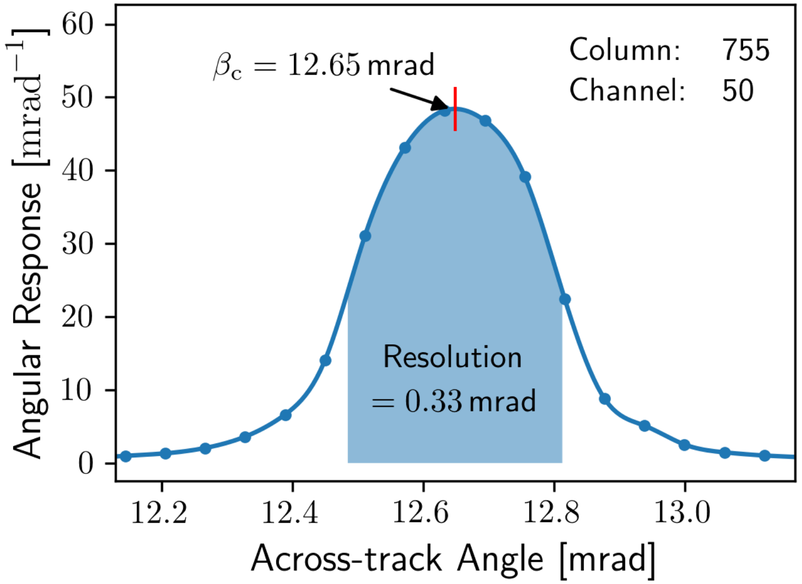
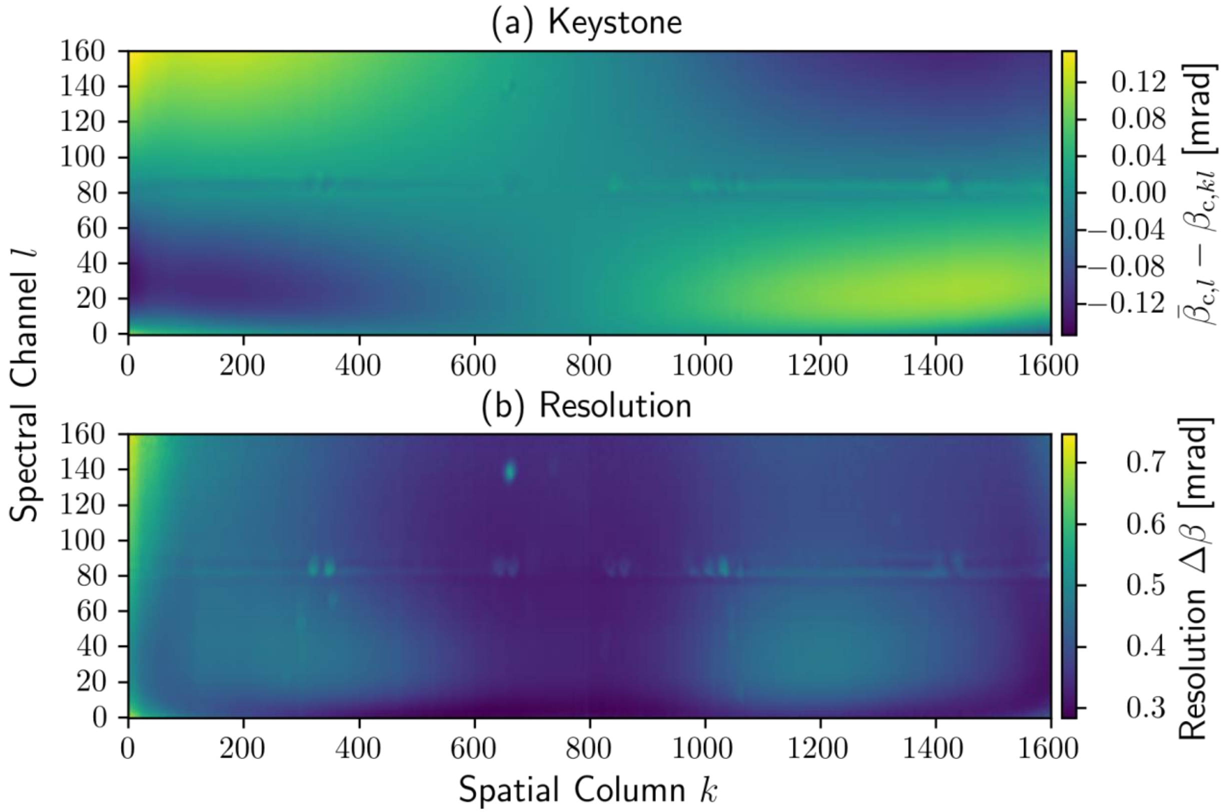


Geometric Calibration Results

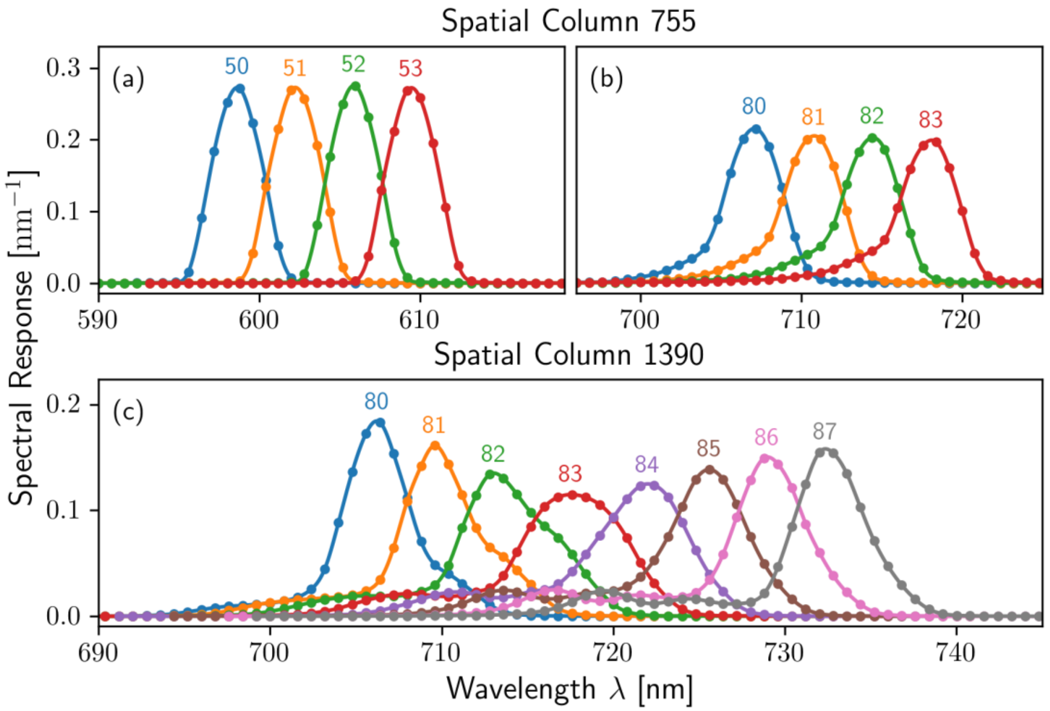
- > 10,000 individual collimator measurements (~16 h)
- Determination of Angular Response Function (ARF) of each pixel
- In contrast to existing methods no analytical function is fitted:
  - Cubic spline interpolation
  - Center angle: Median
  - Resolution: Width of area containing 75 % of total collected energy

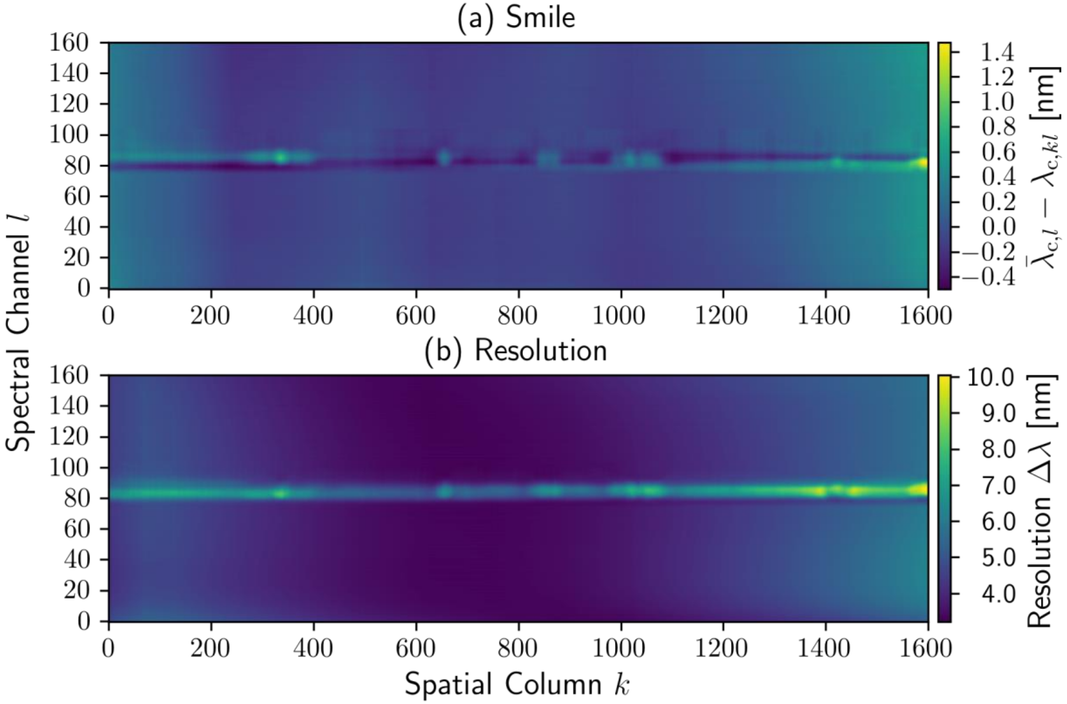




Spectral Calibration Results

- Derived from >31,000 individual monochromator measurements (~2 days)
- Determination of Spectral Response Function (SRF) of each pixel
- Lower spectral resolution at the right detector edge
- Distortion of SRFs at center channels caused by spectral long pass filter mounted on upper detector half
- Simulations show that assuming Gaussian responses can introduce significant uncertainties





Non-uniformity Correction

- We have a very good understanding of the spatial and spectral properties (3D instrument pixel response function)
- But individual pixel information
  - is lost after orthorectification
  - would be cumbersome to deal with in higher level products

  -> Pixel properties are often assumed to be constant

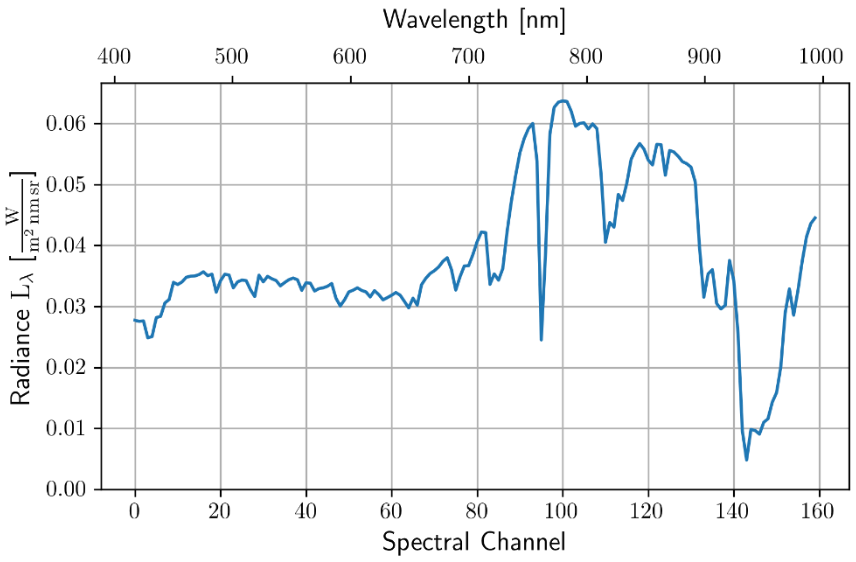
- A method is needed to homogenize not only SRF and ARF centers but also their shape

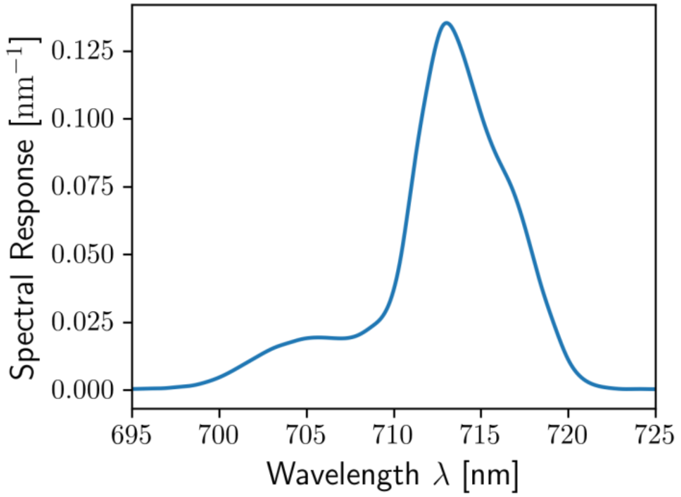
Baumgartner, Andreas and Köhler, Claas Henning (2020) **Transformation of point spread functions on an individual pixel scale.** Optics Express, 28 (26), pp. 38682-38697. Optical Society of America. DOI : 10.1364/oe.409626

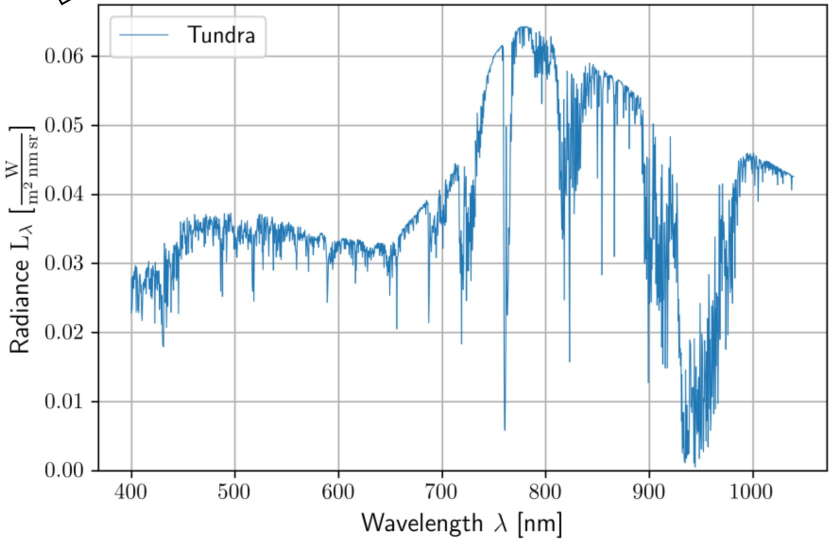
Imaging Equation

Image L_i^A = radiance field L_λ is weighted by spectral and angular response function of each pixel f_i^A

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



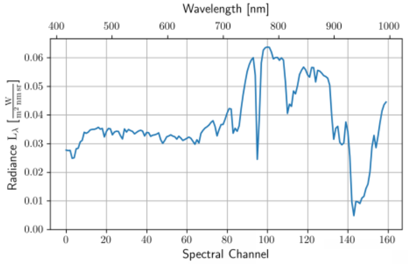


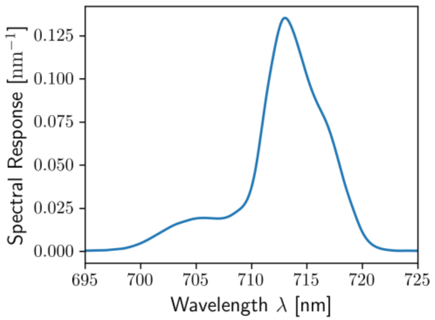


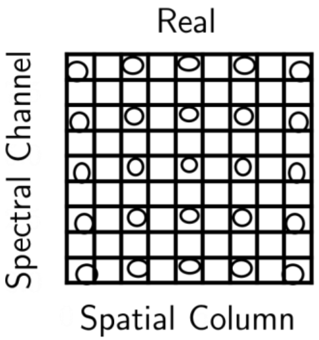
For simplicity only spectral case is shown

Real vs Ideal System

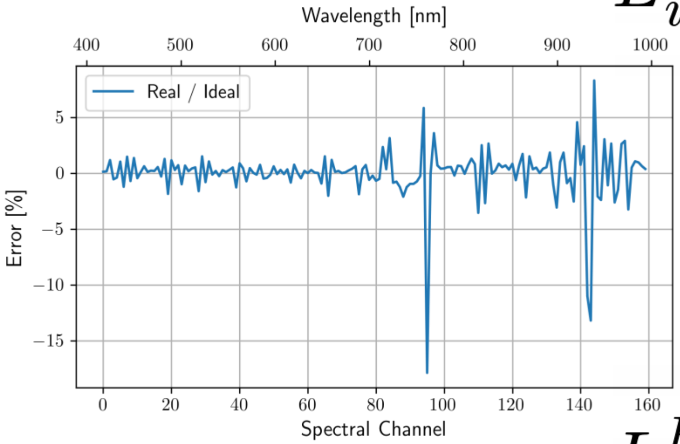
Real System

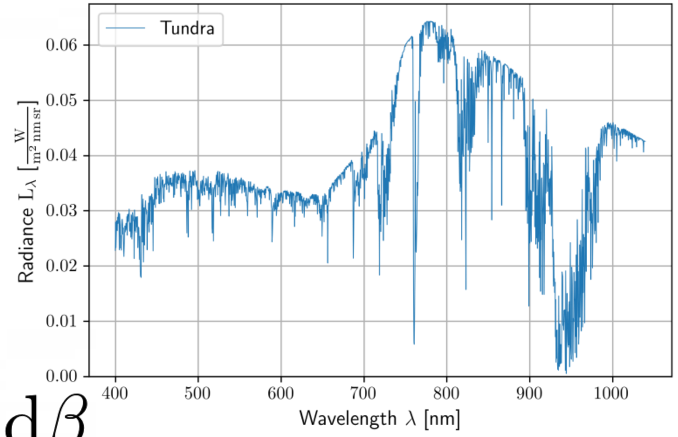






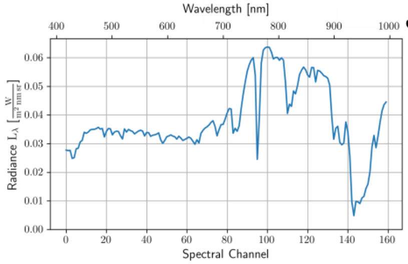
$$L_i^A = \int_0^{2\pi}\int_0^{\infty} f_i^A(\beta,\lambda)\,L_\lambda(\beta,\lambda)\,\mathrm{d}\lambda\,\mathrm{d}\beta$$

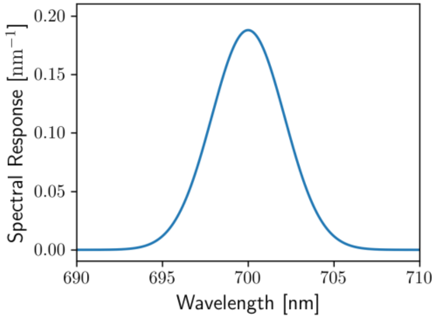


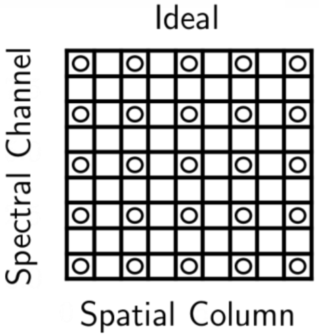


$$L_j^B = \int_0^{2\pi}\int_0^{\infty} f_j^B(\beta,\lambda)\,L_\lambda(\beta,\lambda)\,\mathrm{d}\lambda\,\mathrm{d}\beta$$

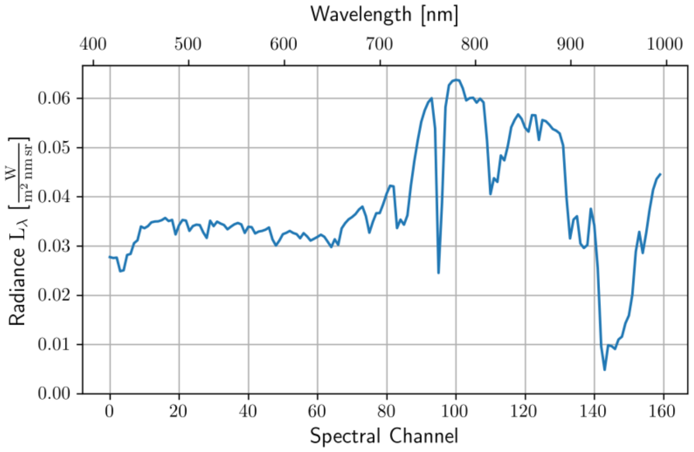
Ideal System
(can be „any“ system with overlapping properties)

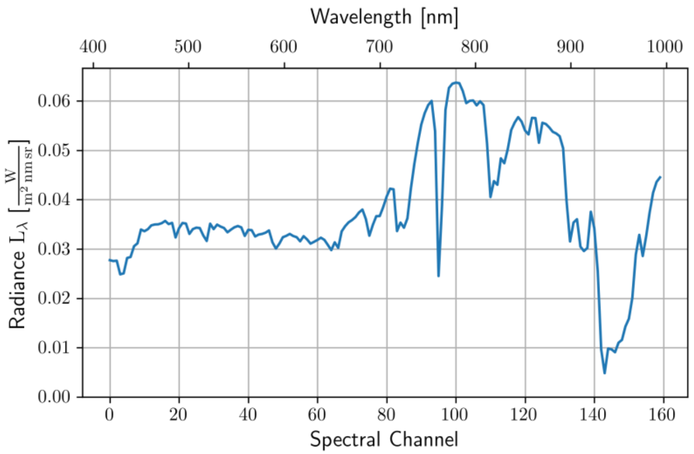






Goal: Converting Data from System A to System B





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

Problem: Find a matrix K that maps each pixel in column vector L^A to all pixels of column vector L^B
(a row of K maps all pixels of L^A to a pixel of column vector L^B)

Remember: Each pixel has individual spectral and geometric properties

New Approach: Using Cross-Correlations to Find Transformation Matrix K

Converting vector L^A to L^B is same operation as converting matrix C^{AA} to C^{BA}

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

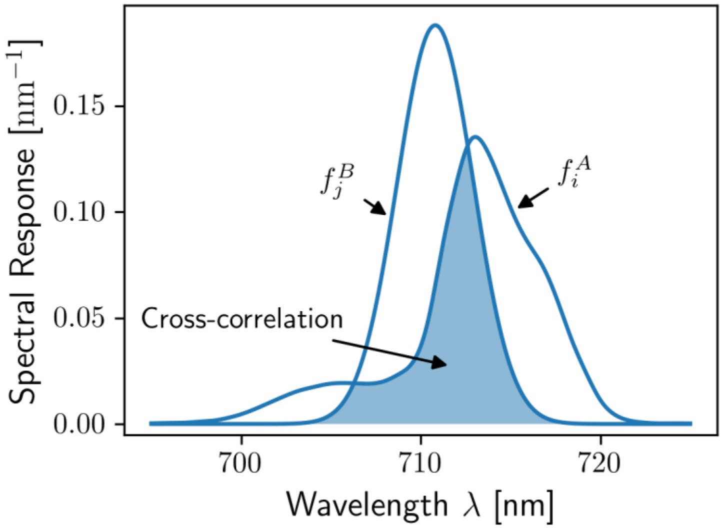
$$\boldsymbol{C}^{BA} = \boldsymbol{K}\boldsymbol{C}^{AA}$$

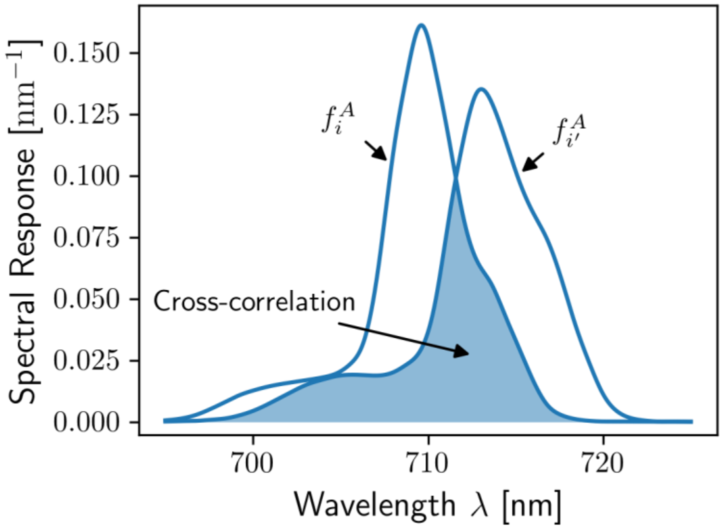
- C^{AA}: Cross-correlation matrix of sensor A pixels with sensor A pixels

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

- C^{BA}: Cross-correlation matrix of sensor B pixels with sensor A pixels

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





Determination of Transformation Matrix K

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

Using Tikhonov regularization to stabilize ill-posed problem

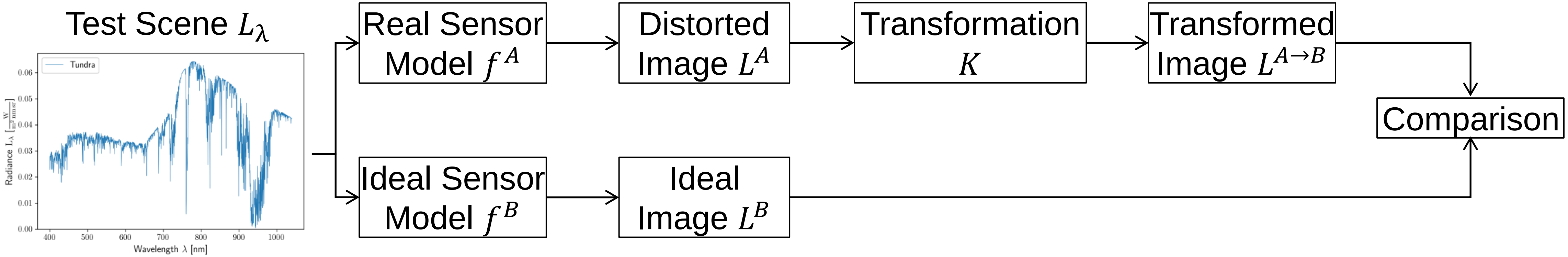
$$\hat{\boldsymbol{K}} = \arg\min_{\boldsymbol{K}} \left\{ \left\| \boldsymbol{K}\,\boldsymbol{C}^{AA} - \boldsymbol{C}^{BA} \right\|_2^2 + \gamma^2 \left\| \boldsymbol{K}\boldsymbol{\Gamma} \right\|_2^2 \right\}$$

Γ: Tikhonov matrix → discrete Laplacian → penalize high frequencies
γ: Regularization parameter (here $\gamma^2 = 10^{-11}$)

Simulation

- Ideal sensor with
  - Gaussian response functions
  - Constant sampling distance
  - Constant FWHM = 5 nm
- High resolution test scene
- Individual simulation of each pixel (ARF + SRF) using cubic splines

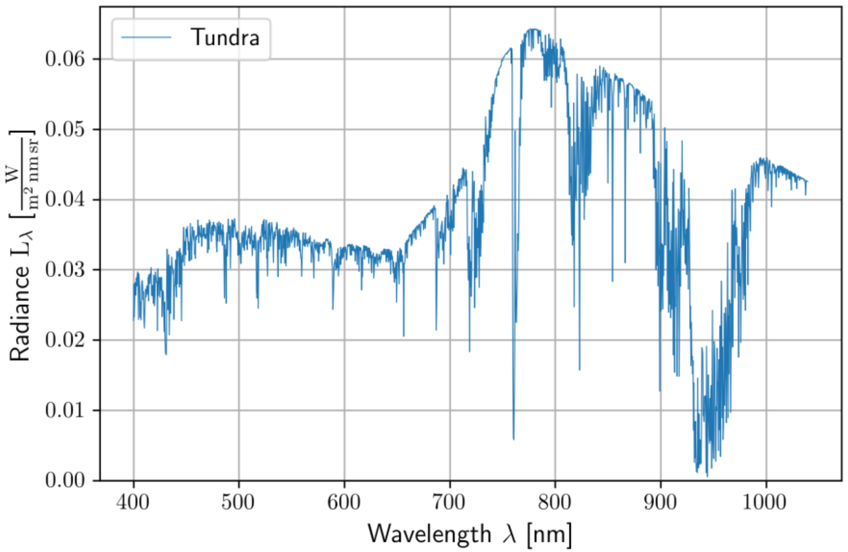
$$L_i = \int_0^{2\pi} \int_0^{\infty} f_i\ (\beta, \lambda) L_\lambda(\beta, \lambda)\, \mathrm{d}\lambda\, \mathrm{d}\beta$$

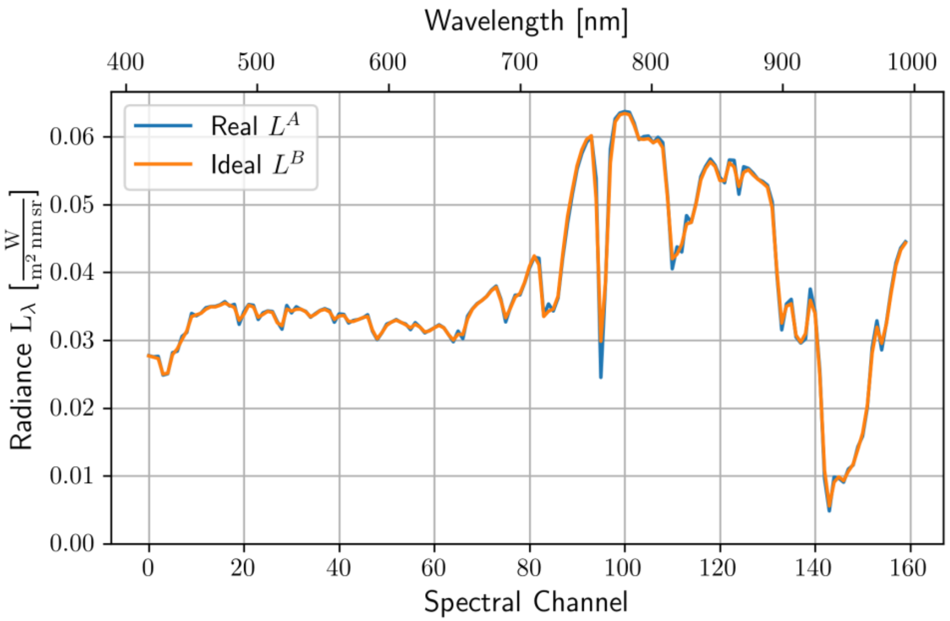


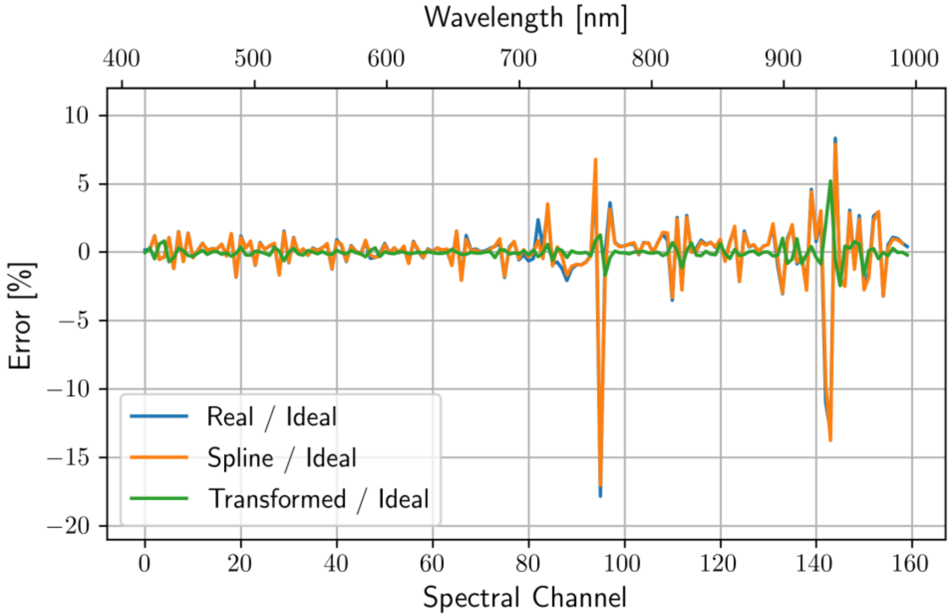
Simulation Results

- ~1.4 Channels / FWHM
- Better agreement, since also the SRF shape is transformed

Test Scene





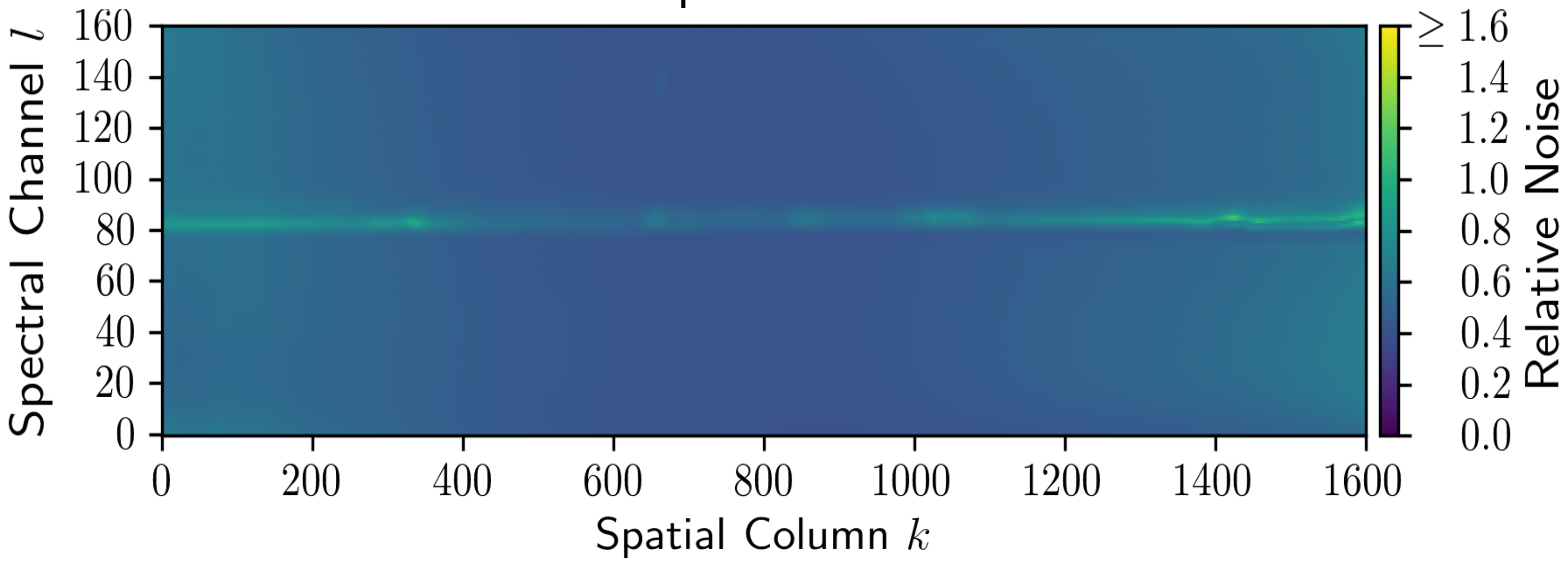


Uncertainties

- Linear operation -> geometric and spectral uncertainties propagate linearly
- Covariances can be propagated by

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

Relative noise compared to source sensor A



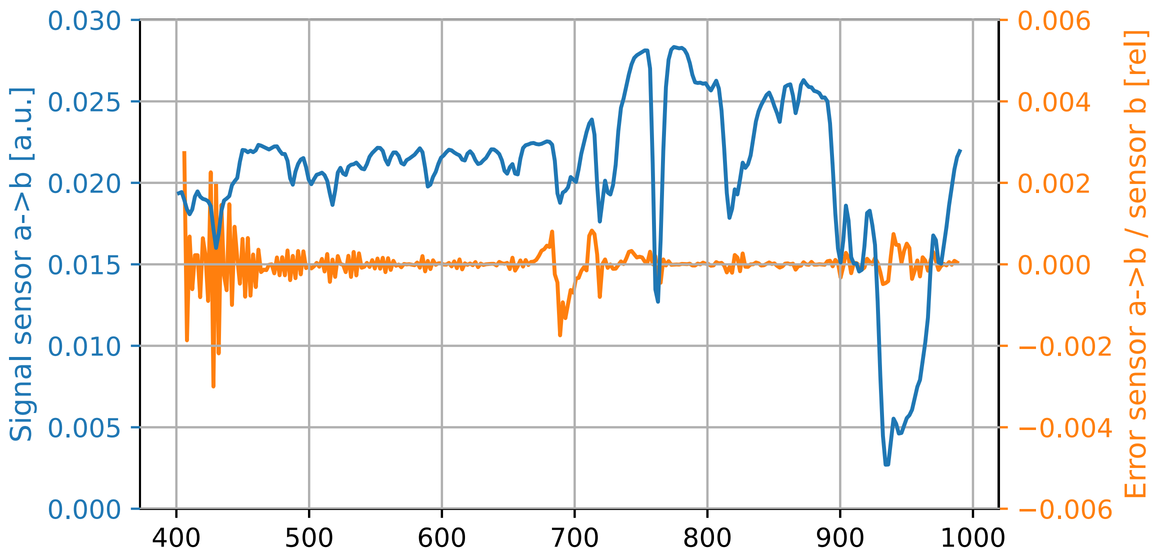
New HySpex VNIR-3400N Instrument

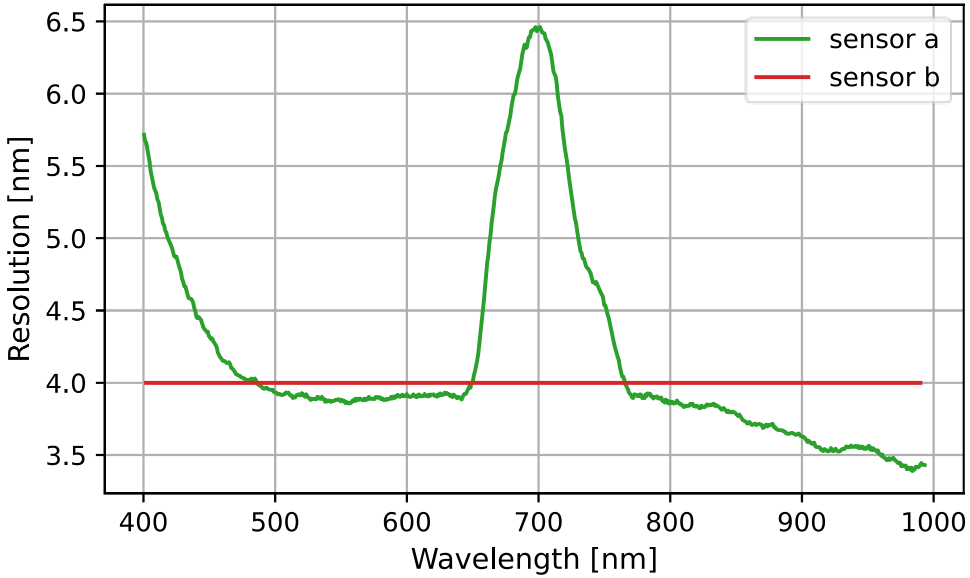
- Compared to VNIR-1600
  - Similar optics
  - Detector with ~10 x pixels

- 700 spectral channels
- 3408 spatial pixels
- Spectral oversampling 3 – 7
- Spectral sharpening (super-resolution) at certain channels

- After transformation 1338 x 296 pixels

- Ongoing work





Conclusion and Outlook

- Correction of smile, keystone and pixel individual response function shapes in one processing step
- It is possible to get “perfect” data from not so perfect instruments
- Building instruments with more pixels can reduce requirements and therefore costs, while increasing performance

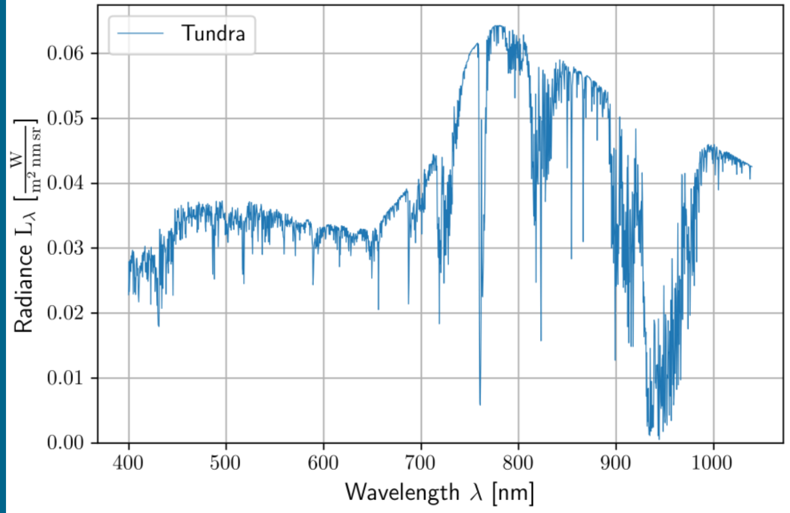
- Transformation algorithm can also be used to convert images between instruments:
  E.g., EnMAP to Sentinel-2, field-spectrometers, etc.
- Works also with snapshot instruments

Ongoing/future research

- Combining stray light correction matrix with transformation matrix
- Optimizing regularization method
- Uncertainty of under sampled data
- Adding along-track transformation

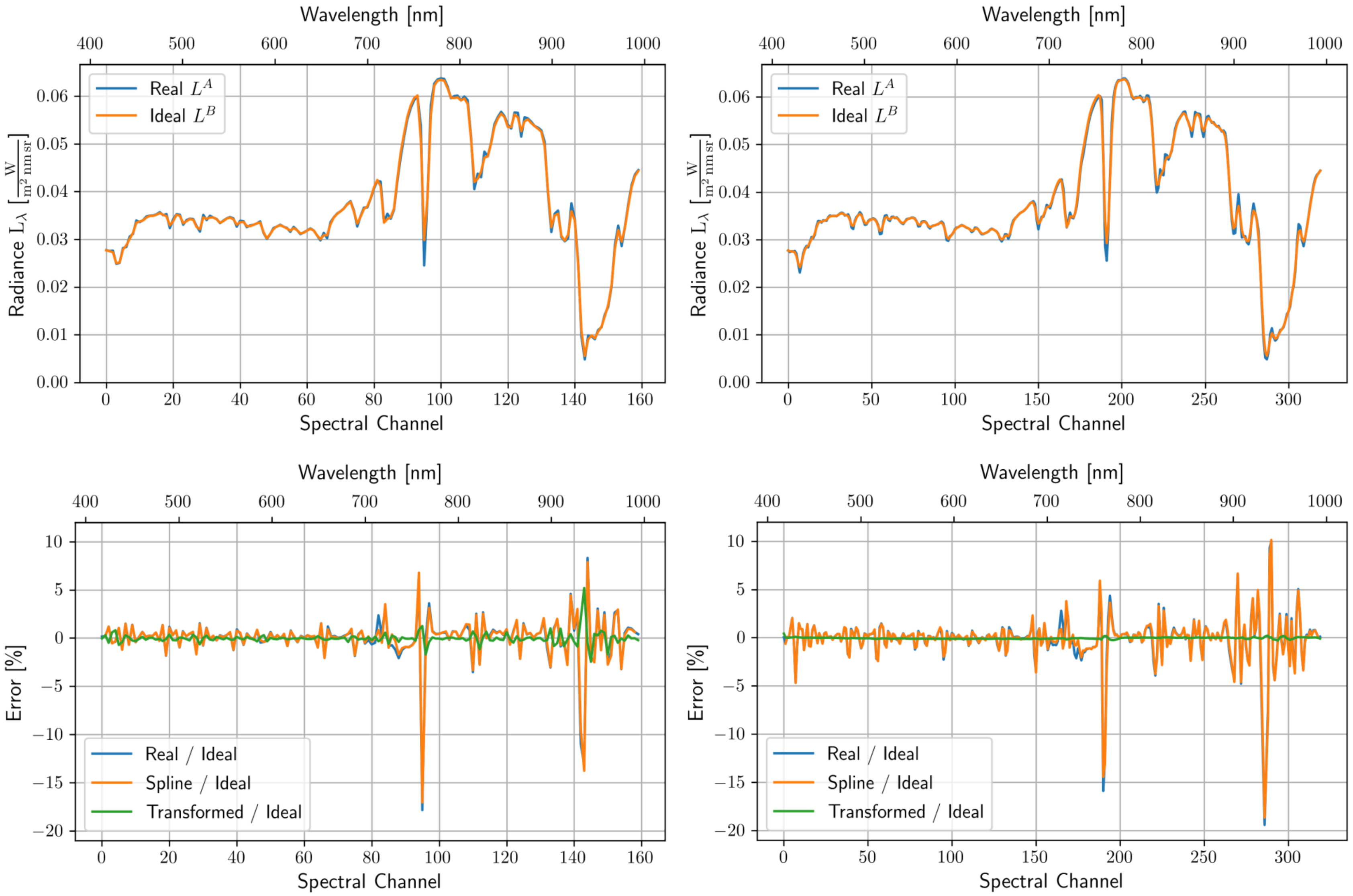
Simulation Results

Test Scene



~1.4 Channels / FWHM

~2.8 Channels / FWHM (Nyquist)



- Smaller errors than state of the art spline interpolation
- Almost perfect transformation of Nyquist-sampled data

HySpex VNIR-1600 Level-1 Calibration Chain

L1 processor:

- Modules can be individually activated
- Propagates uncertainties
- Usable with other instruments