# RESPONSE FUNCTION-BASED CALIBRATION OF IMAGING SPECTROMETERS

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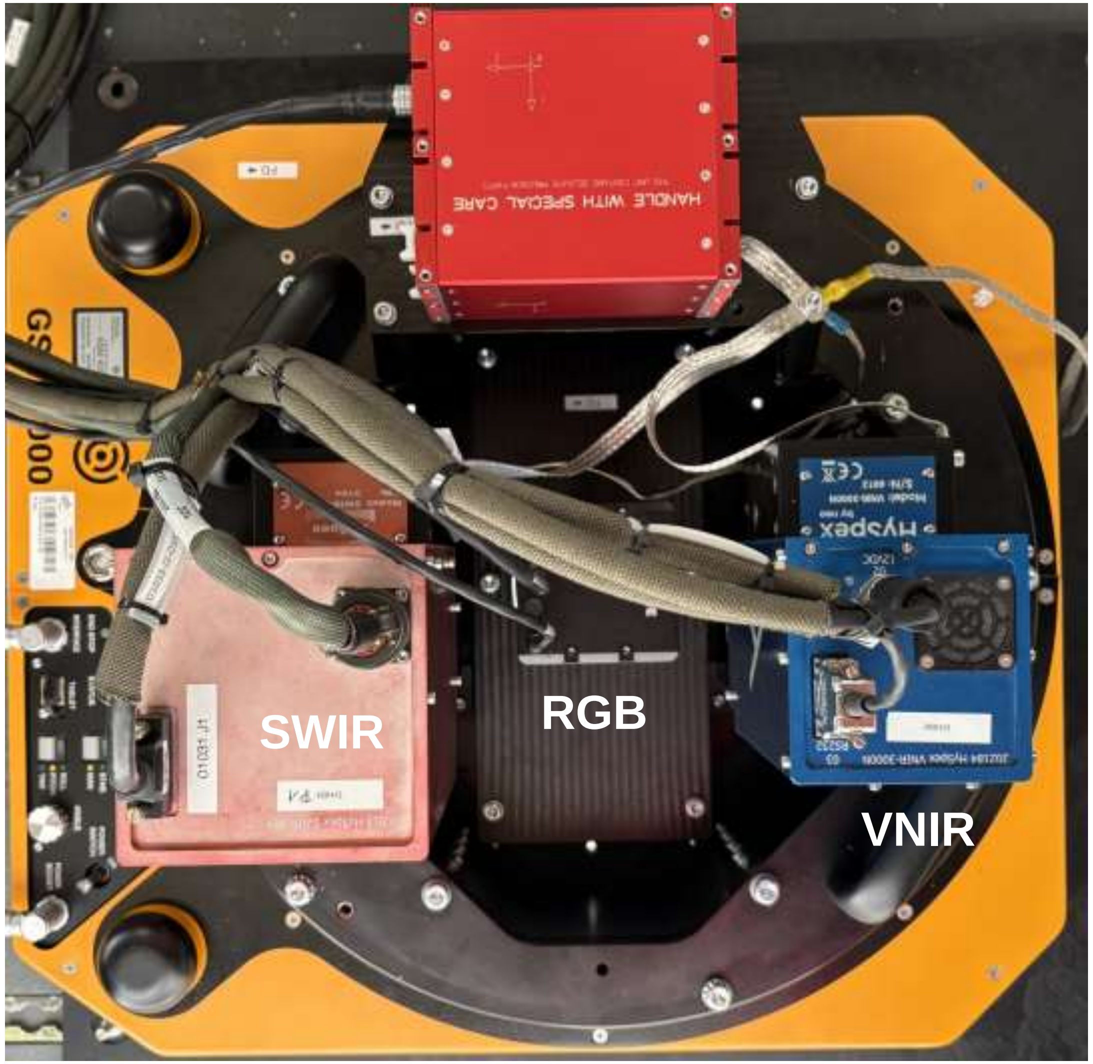
# HySpex Sensor System

## HySpex VNIR-3000N

- *N* → **Nyquist (sampled)**
- 700 bands, 3408 pixels
- Spectral Range: 400 – 994 nm
- FWHM: 3 – 7 nm

## HySpex SWIR-384

- 288 bands, 384 pixels
- Spectral range: 952 – 2516 nm
- FWHM: 5.5 – 8.5 nm



# Calibration Home Base (CHB)

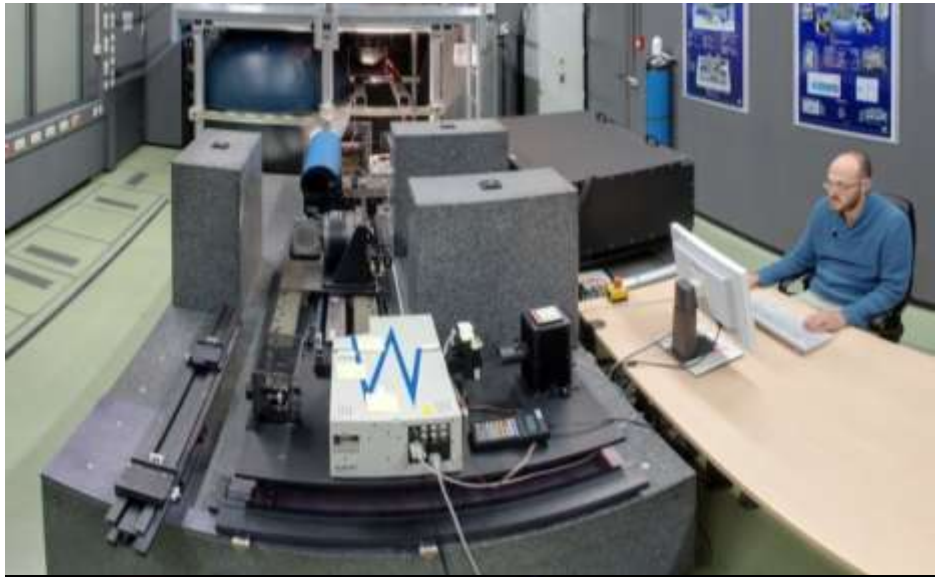
## Operational Setups

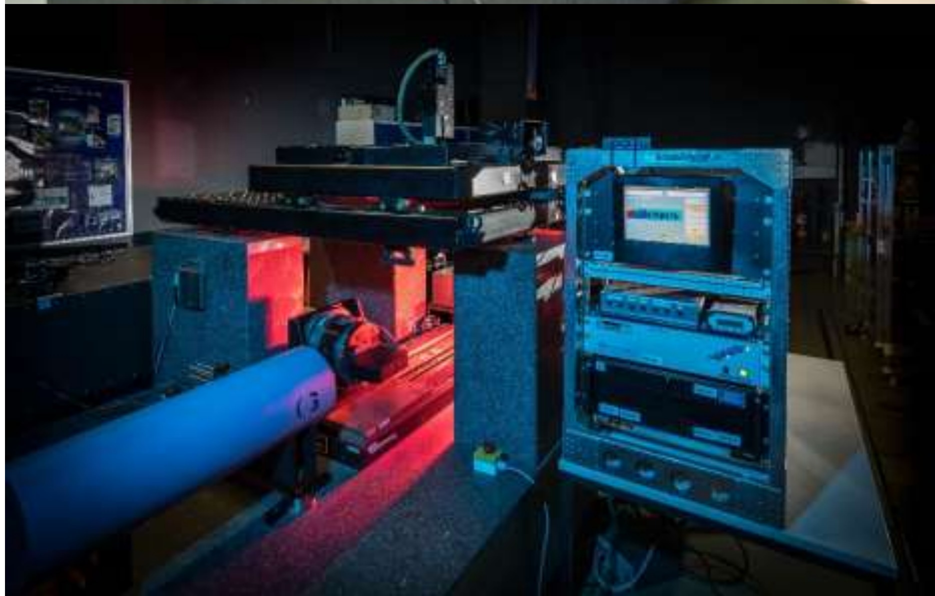
- Geometric Response Function
- Spectral Response Function
- Radiometric Response & Polarization

*Co-funded by ESA for APEX calibration*

## Research & Development

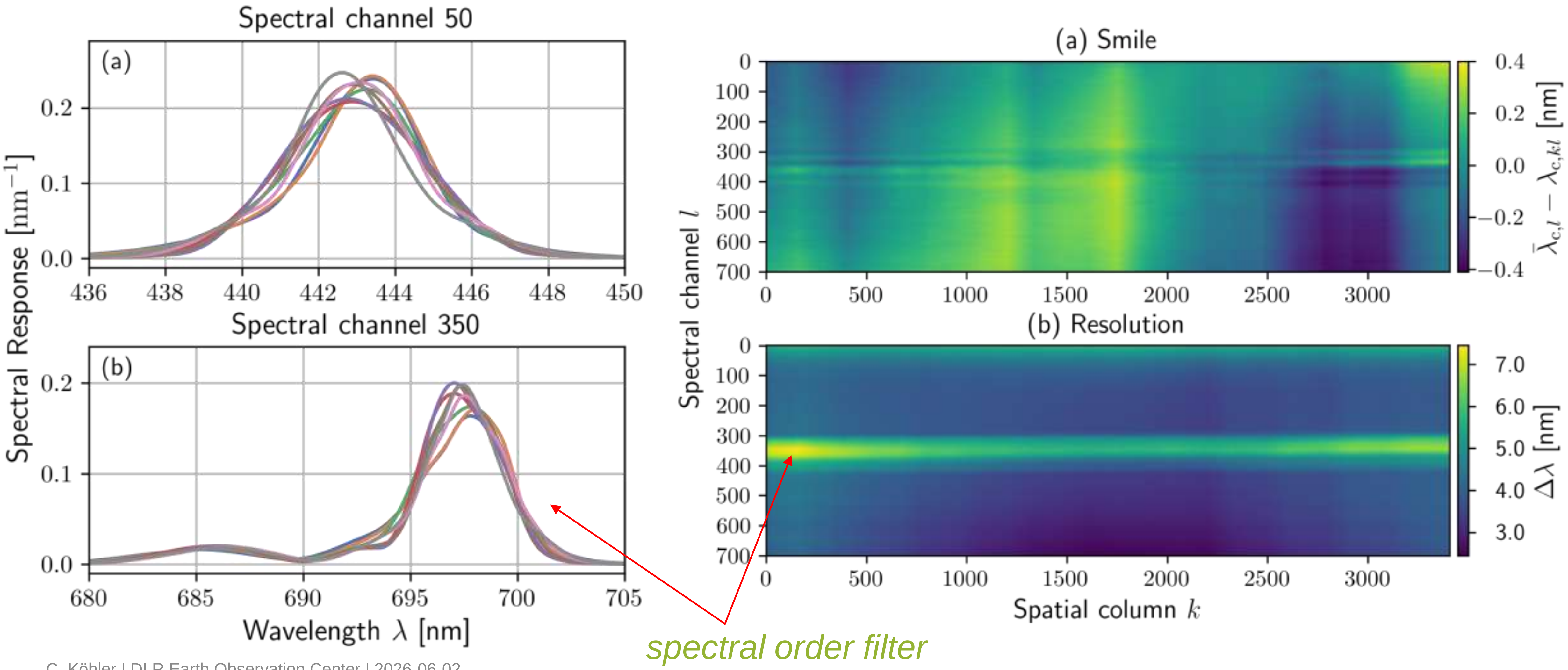
- Non-linearity correction
- Straylight correction
- Temperature dependence





# Exemplary Results for VNIR-3000N

*Similar information is available since 2013 for the original HySpex System*



# Nice …

State-of-the-art sensor system with extensive key calibration data

# … but

**A lot of these measurements may never find their way into derived products!**

# Question

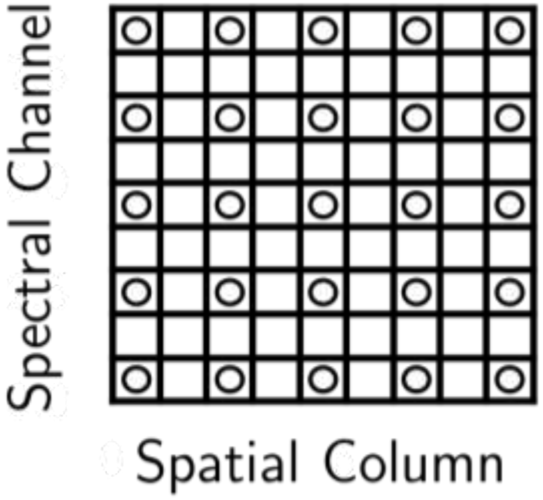
Is it possible to create a L1C product, which …

- … enables users to profit from **all** our calibration measurements (e.g. full SRF instead of just center wavelength & FWHM)

- …  simplifies working with L1 data for non-experts by reducing complexity

# Idea

*ideal sensor B*

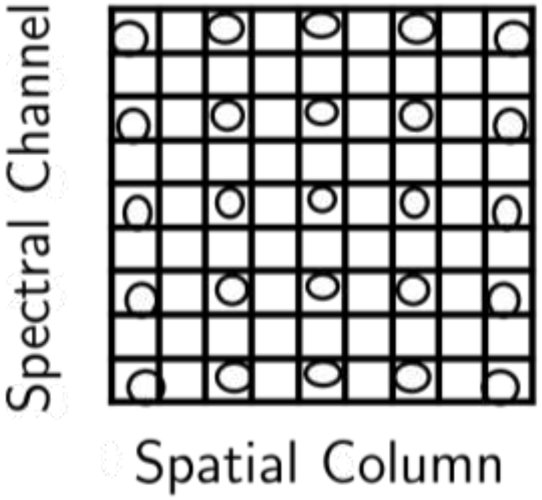



*sensor B signal vector*
*(nrows · ncols elements)*

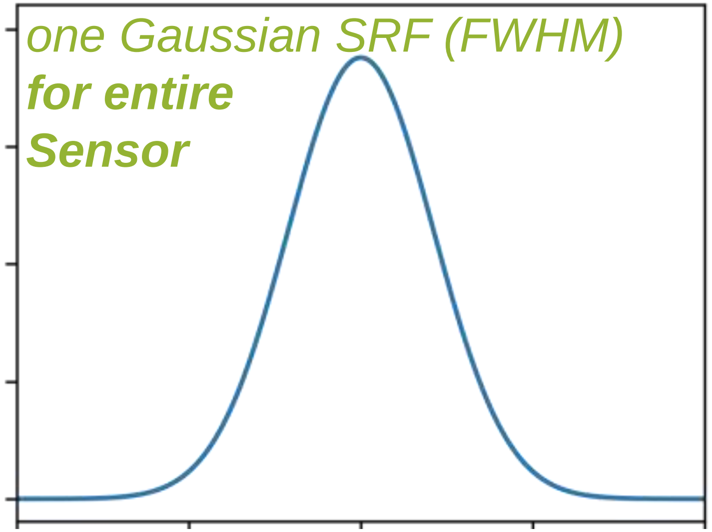
$$s_B = K \cdot s_A$$

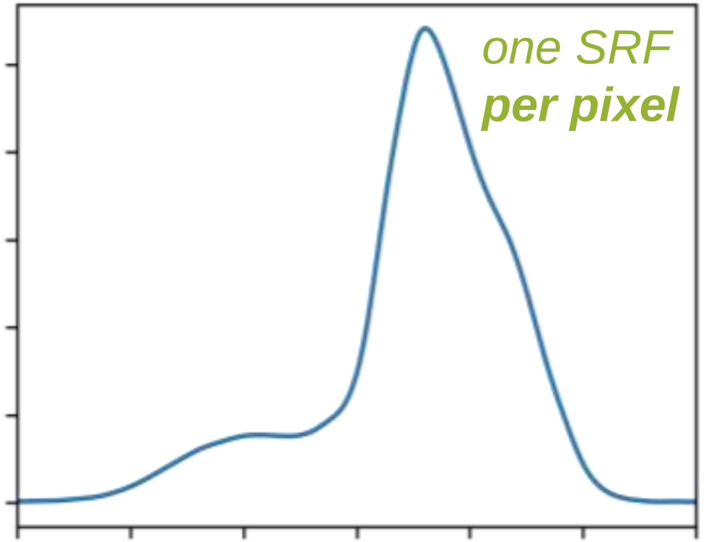
*sensor A signal vector*
*(nrows · ncols elements)*

*real sensor A*



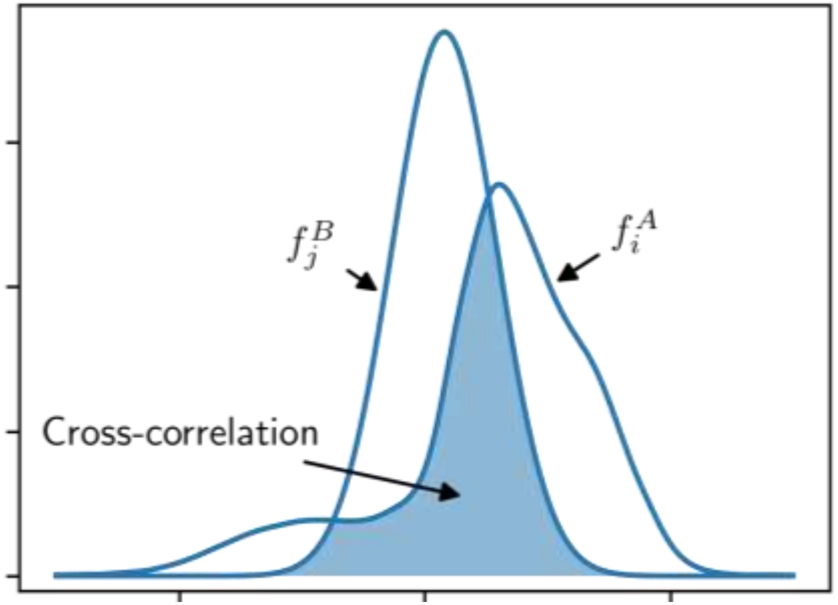

*Transformation Kernel*
*(len $\mathbf{s}_B$ x len $\mathbf{s}_A$)*



# The Convolution Kernel

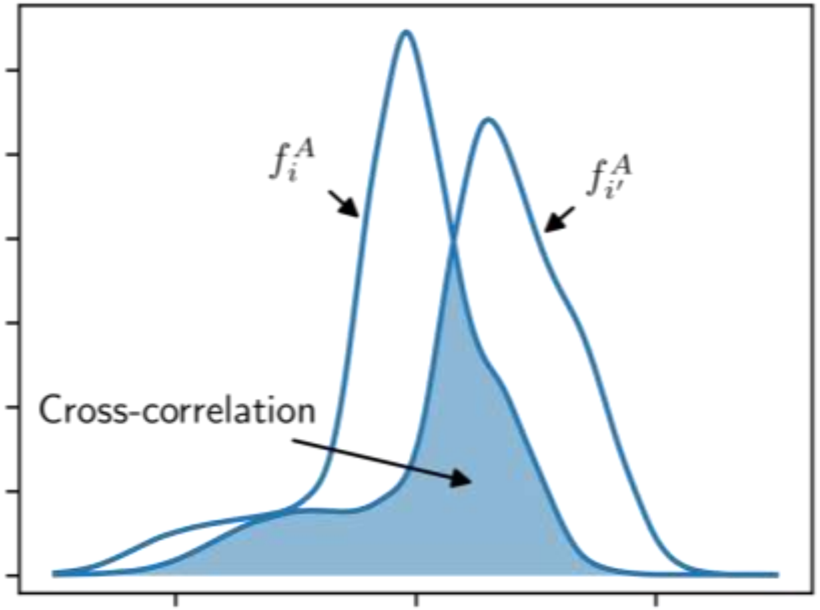
$$C_{ij}^{BA} := \left\langle f_i^B, f_j^A \right\rangle$$




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

*Kernel can be computed from Cross-correlation matrices*

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




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

*Tikhonov solution*

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

# Applications

| Sensor A | Sensor B | Application |
|---|---|---|
| HySpex | “**B**etter” HySpex | *homogeneous L1C product*<br>*smart binning*<br>*stray-light correction* |
| HySpex | EnMAP | *EnMAP validation* |
| CHIME | Sentinel-2 | *cross-validation* |
| ~~CHIME~~ | ~~Sentinel-5p~~ | *wishful thinking!* |

# HySpex VNIR-3000N Processing Settings

| Parameter | Original | Transformed | |
|---|---|---|---|
| **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 | |

# HySpex SWIR-384 Processing Settings

| Parameter | Original | Transformed | |
|---|---|---|---|
| **Spatial columns** | 384 | 384 | |
| **Spectral channels** | 288 | 288 | |
| **Smile [nm]** | <0.7 | 0 | |
| **Keystone [mrad]** | <0.12 | 0 | |
| **Angular resolution [mrad]** | 0.5 – 1.1 | 0.8 | *super resolution* |
| **Spectral resolution [nm]** | 5.5 – 8.5 | 6.5 | *super resolution* |
| **SRF and ARF shape** | Spline model (complicated) | Gaussian | |

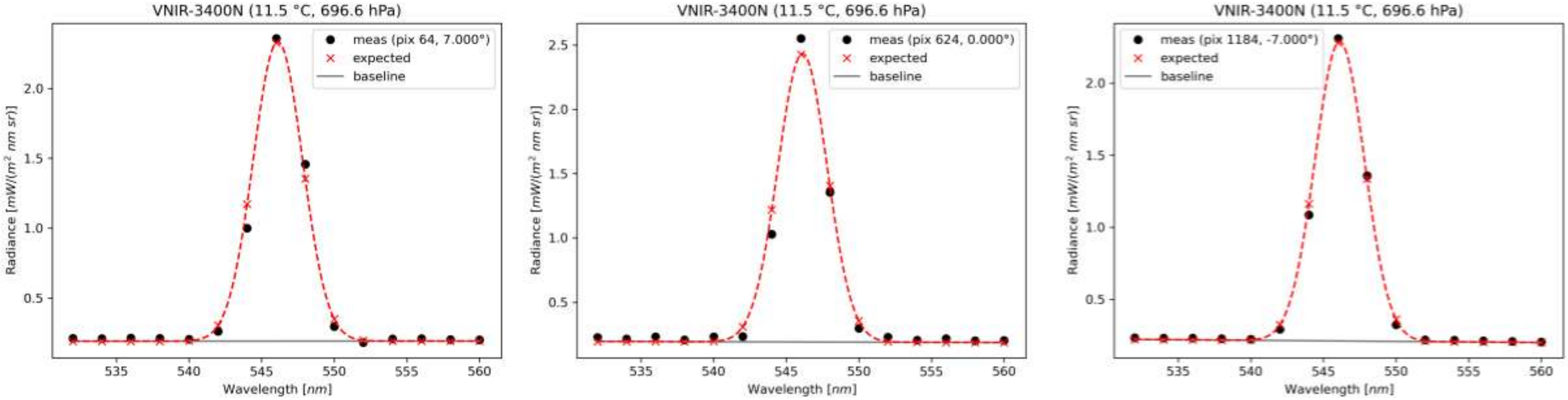
# In-Flight Validation of Transformed L1 Product

- Measurements with Hg pencil lamp and reflectance panel
- Altitude: 3300 m (FL100)
- Expect scalar product of Hg emission peak (δ) and Gaussian SRF
- Fit Intensity + linear baseline to compensate for ambient light
- Isolated narrow lines → high frequency stress test

*See also Poster by Gabriel Scheib*

# In-Flight Validation VNIR-3000N

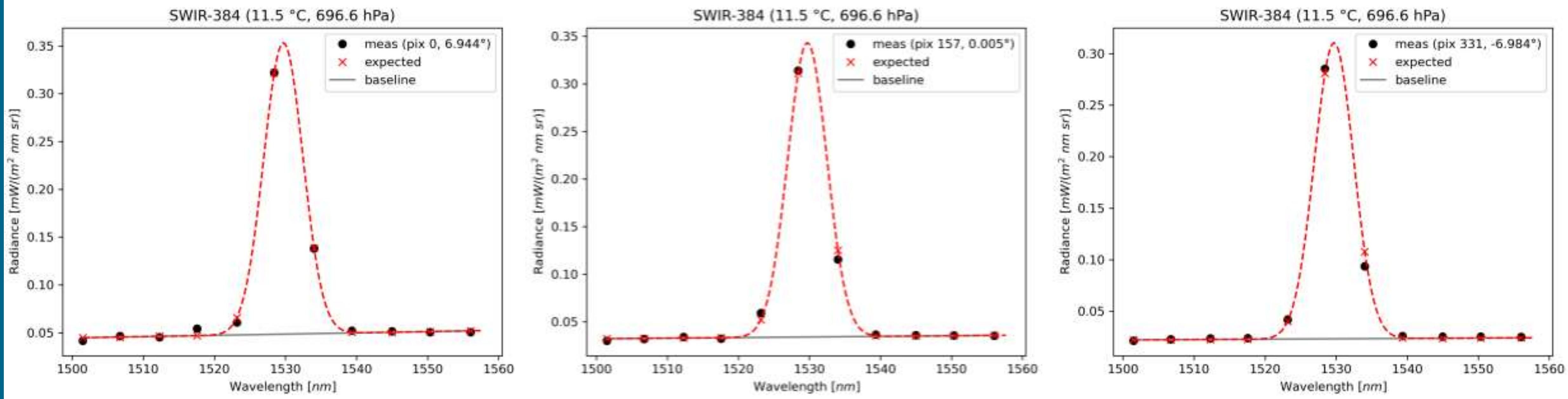
left edge | center | right edge | … of field of view




*Overall good agreement between transformed data and simulation*
*Potentially minor shift and SRF narrowing compared to lab*

# In-Flight Validation SWIR-384

left edge | center | right edge … of field of view




*Very good agreement between transformed data and simulation*

# 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*

# 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)

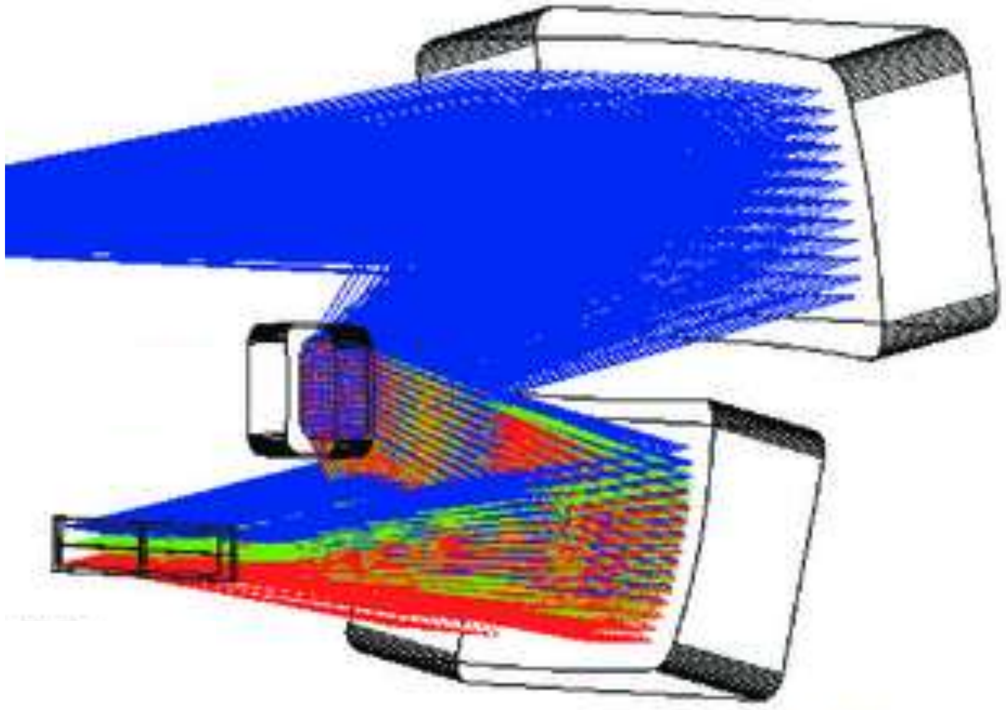


IMAGE: Buschkamp et al. 2021, doi:10.1117/12.2599428

# 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

Title: **Response Function Based Calibration of Imaging Spectrometers**

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Author: C. H. Köhler,  A. Baumgartner & G. Scheib

Institute: Remote Sensing Technology Institute, Oberpfaffenhofen



Venue: 14th EARSeL Workshop on Imaging Spectroscopy

2 – 4 June 2026, Helsinki, Finnland