

Current Calibration Activities involving UAV Imagers and Marine Optics

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1. NERC Field Spectroscopy Facility (Edinburgh, UK)



Overview of the facility

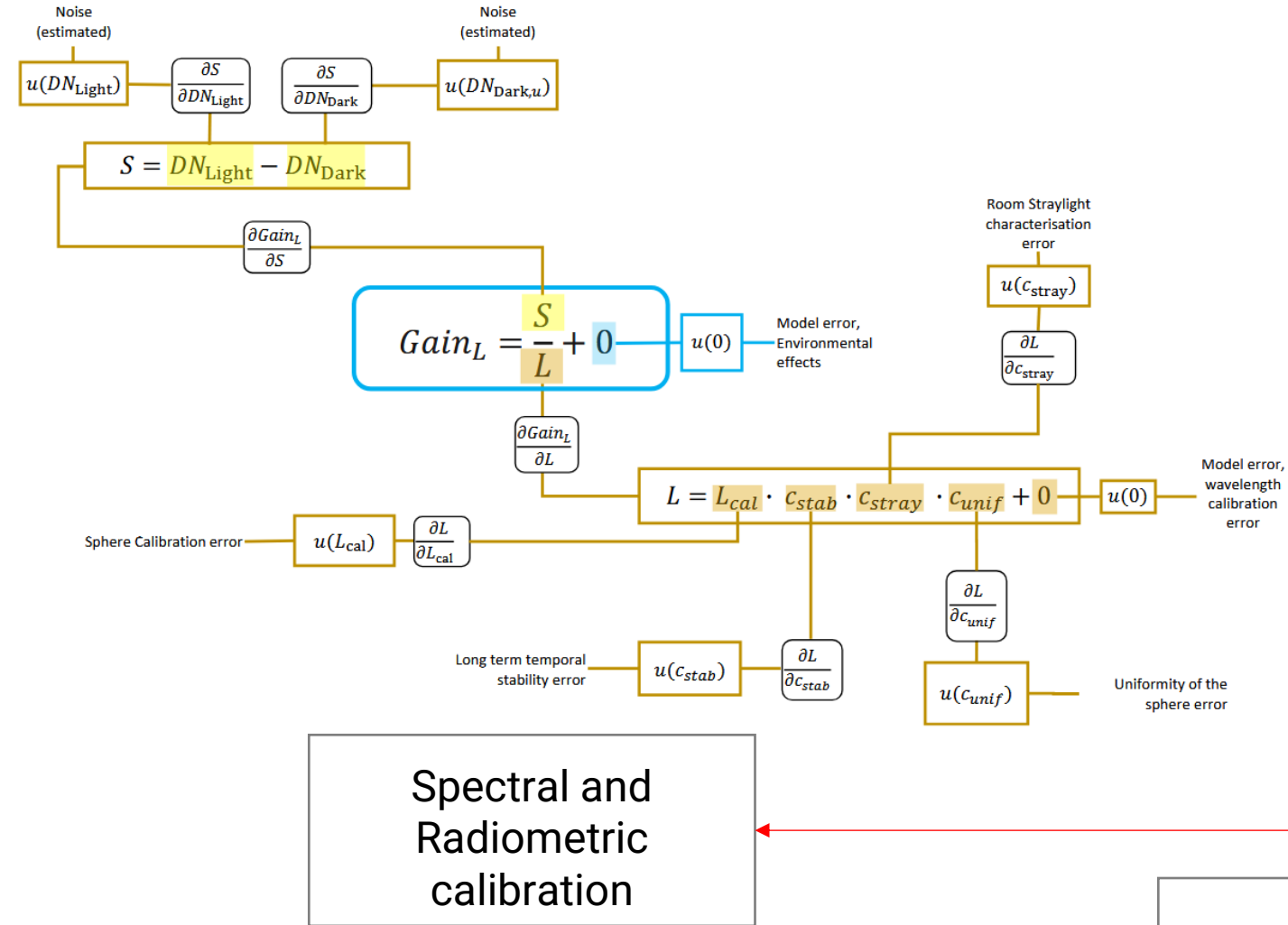
- The NERC Field Spectroscopy Facility (FSF), based at the University of Edinburgh, is a “lending library” of high quality field spectroscopic instrumentation, calibrated and maintained at our optical laboratory.
- Instruments are available either for loan for NERC supported research, or for hire for commissioned research projects.
- Access to FSF resources is available free of charge to the UK research community (international partnerships encouraged), subject to expert peer review by the FSF Steering Committee.
- Multiple equipment pools (pertinent to discussion):
 - **Bio-optical Underwater Suite** – hyperspectral radiometers for water column attenuation and remote sensing reflectance measurements
 - **UAV Sensor Suite** – point based spectroradiometers, multispectral cameras, and pushbroom imagers, mounted to UAVs
 - **Optical Calibration Laboratory** – radiance spheres, irradiance standards, monochromator and other calibration equipment.



The framework for calibration



“Raw signal”, “digital count”, “digital number”, *per pixel*



$$R_w = \frac{L_w}{E_d}$$

What do we want from calibration?

- **Spectral**

- Link the pixel number of the sensor's array (0, 1...n) to a wavelength value (which will be the centre wavelength, the wavelength at which maximum response is measured).
- For imagers, provide a .hdr file or equivalent that lists these wavelengths

- **Radiometric**

- Provide a gain value for each pixel that, when implemented into processing, converts the raw signal measured by the sensor into a radiometric quantity e.g. spectral radiance, spectral irradiance.
- Provide that as a .cal file
- Additionally, incorporate a means of calculating the background noise for subtraction / further understanding on how the sensor array performs in different illumination conditions (from the photon transfer curve, linearity).

- **Uncertainty**

- Throughout, a quantification of the uncertainty associated with both the spectral and radiometric coefficients provided.
 - Following the BIPM Guide to Expression in Uncertainty in Measurement steps
 - Law of Propagation of Uncertainties (8 stage process from determination of input quantity uncertainty, to combined standard uncertainty in final measured value)
 - Monte Carlo analysis method (multiple simulations while altering input quantities)

Point based radiometer – Calibration Case Study

1 – An overview of systems calibrated

Multiple Sensor Models Calibrated

- **SeaBird Scientific HyperOCR** - 140 band detector, 3.3 nm spectral resolution, spectral range 350 nm to 800 nm; upwelling radiance and downwelling irradiance models
- **TriOS RAMSES G1 and G2 Sensor** - 190 band detector, 3.3 nm spectral resolution, spectral range 320 nm to 950 nm; upwelling radiance and downwelling irradiance models
- **Hyperspectral Radiometer for Global & Diffuse Irradiance (HSP1)** – downwelling irradiance sensor, 3 nm resolution, range 350 nm to 1050 nm

FRM4SOC, Plymouth Marine Laboratory / Tartu Observatory

- Facility involvement with first phase of the Fiducial Reference Measurements for Satellite Ocean Colour (comparison of FEL standards and white reference panels)
- Growth from that – collaboration with Plymouth Marine Laboratory to calibrate TriOS RAMSES G1 and G2 sensors, following Tartu Observatory suggested calibration file format

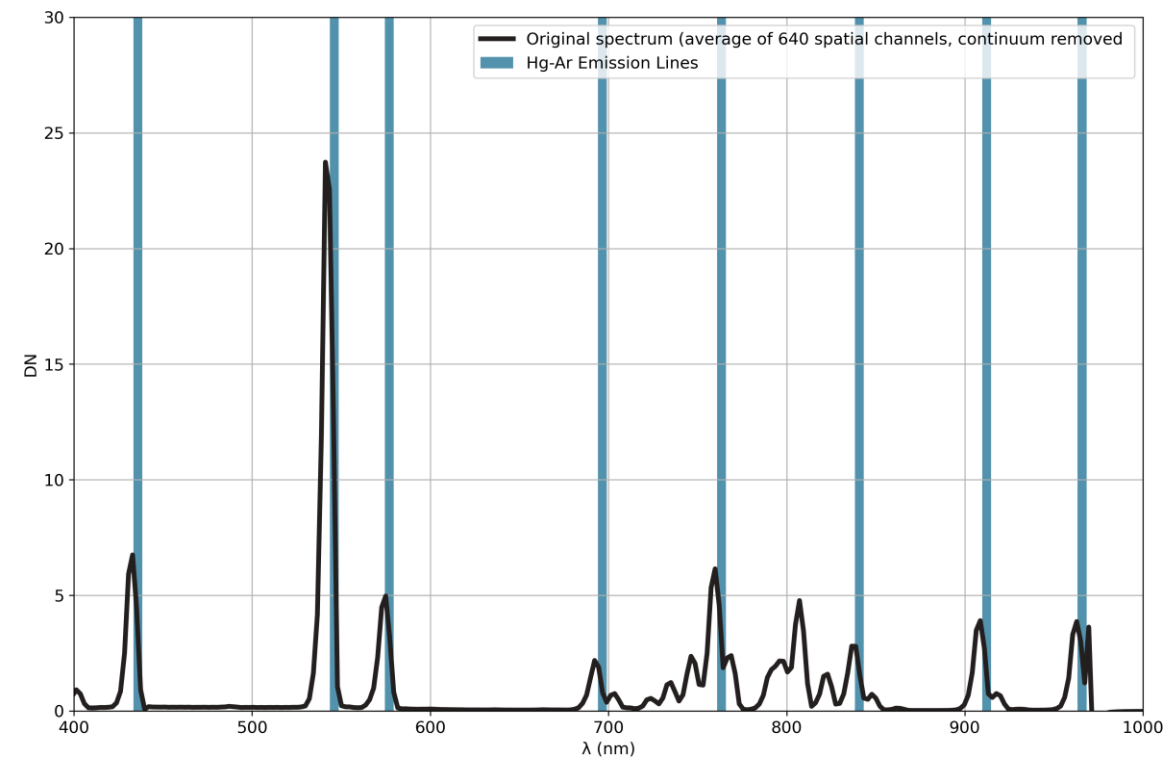


Point based radiometer – Calibration Case Study

2a – Spectral calibration, a walkthrough

- Pencil gas lamps with known atomic emission lines used as reference (Hg-Ar and Ar)
- Radiometer collects series of “dark signal” spectra, then series of “light spectra” signal of the Hg-Ar lamp; repeated for Ar
- Averaging spectra of dark and light frames to one averaged spectrum
- Subtraction of averaged dark spectrum from light spectrum
- Continuum removal process – determine continuum curve via fitting, then remove by dividing the average spectra by it's continuum curve
- Line fitting of the average spectra to gas lamps.
- Centre line of fit (sub-pixel) set as matching pixel number for emission line e.g. 435.84 nm emission line = 15.61 pixel of radiometer array

Emission Line	Centre Pixel #
435.84	15.61
546.08	64.34
576.96	78.46
696.54	131.10
763.51	160.56
840.82	195.34
912.32	226.58
965.81	250.76



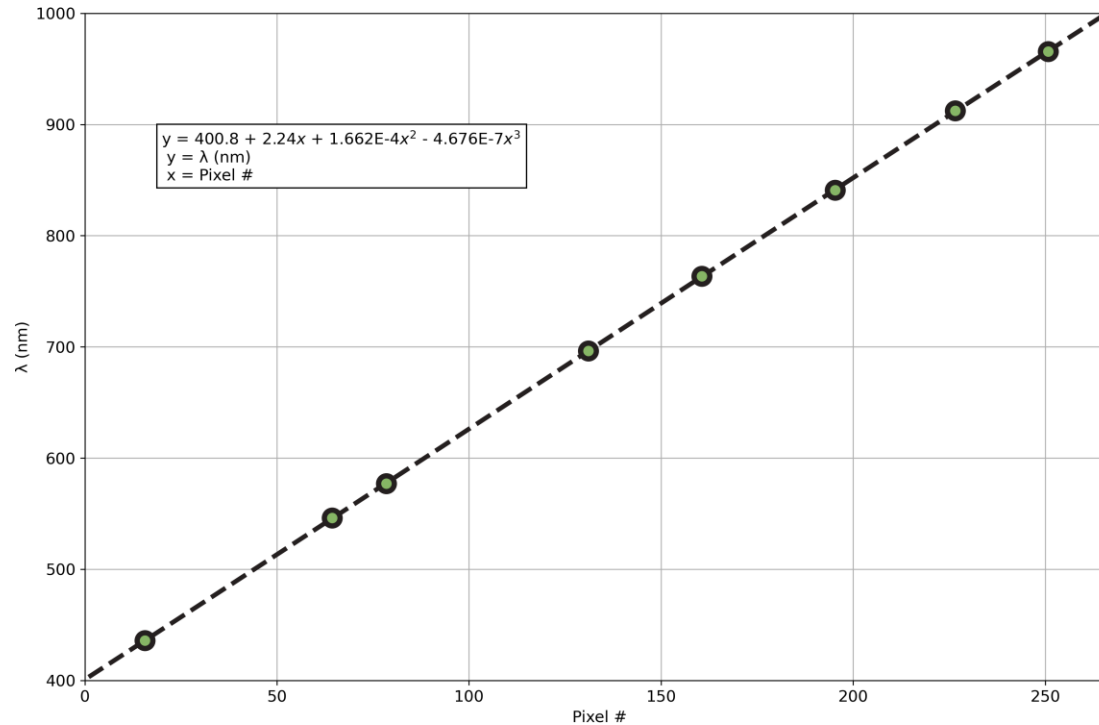
Point based radiometer – Calibration Case Study

2c - Spectral calibration, a walkthrough

- Pixel # from Gaussian fitting matched to emission lines – basis of polynomial third order equation:

$$y = 400.8 + 2.24x + 1.662 \cdot 10^{-4}x^2 - 4.676 \cdot 10^{-7}x^3 + \varepsilon$$

- ε via propagation of error of SSE in coefficients ± 0.09 nm

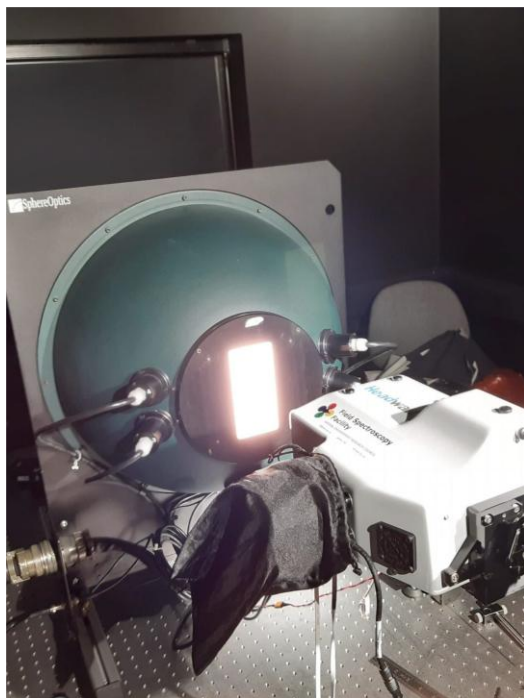


Point based radiometer – Calibration Case Study

3a - Radiometric calibration, a walkthrough

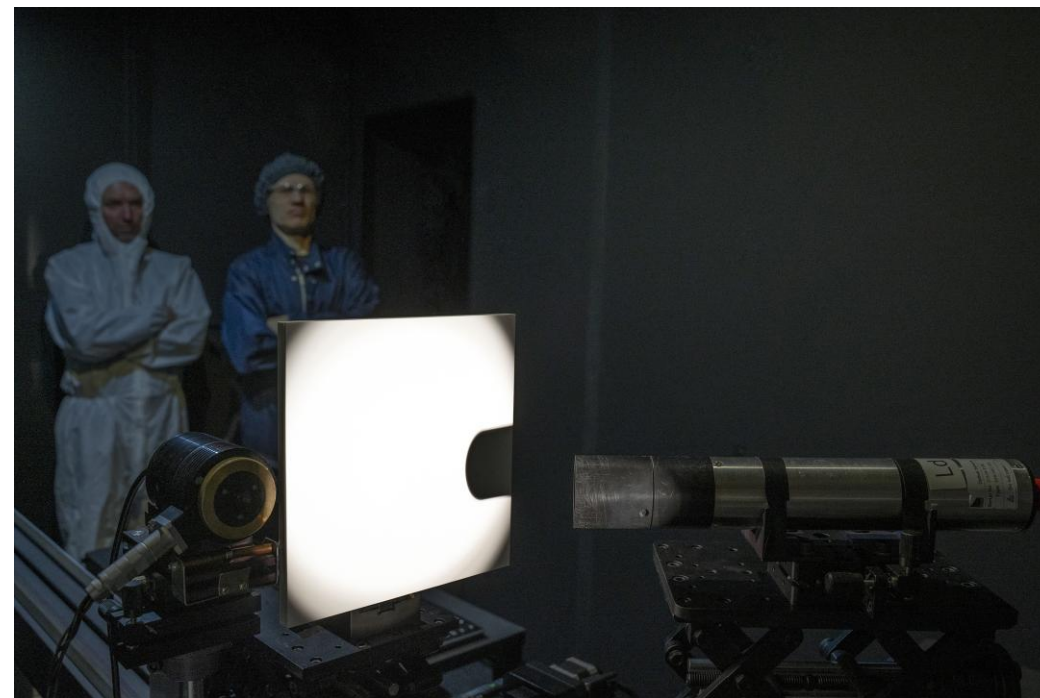
Radiance Sphere

- Setup optical table radiance source.
- Centre and align radiometer to sphere's output port.
- Check for retro-reflectance -safe distance test (use internal photometer or connected radiometer to check if signal increases as instrument moved towards sphere output port).
- Optimise integration time to maximize signal without saturation.
- Acquire "light signal" spectra
- Cover output port, cover optic, acquire "dark signal" spectra



Reference Plaque and irradiance standard

- Removes the complex issues of sphere uniformity present in radiance spheres (caution using with imagers, however); used for calibration of downwelling irradiance sensors.
- Position plaque at known distance from irradiance standard
- Position imager at 45° angle from plaque, viewing centre.
- Switch on irradiance standard, illuminating the plaque fully.
- Inverse square law = known irradiance at distance; known radiance from panel, factoring in panel reflectance



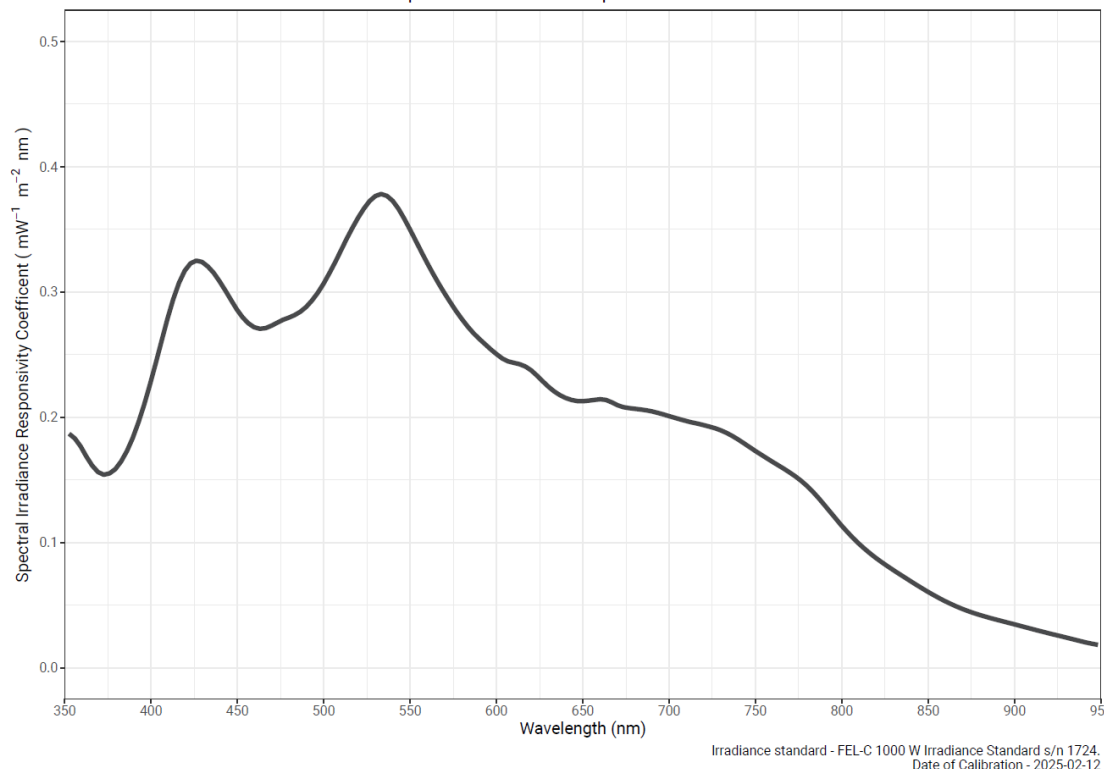
Point based radiometer – Calibration Case Study

3b - Radiometric calibration results, and ancillary measurements

Radiometric Gains

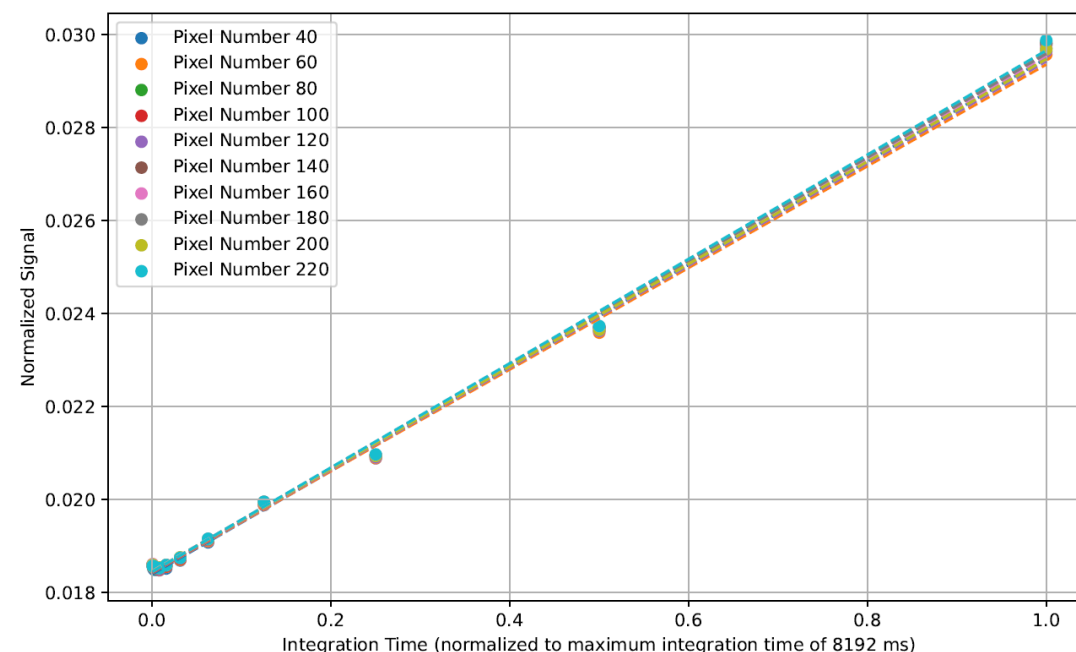
- Light signal spectra – Dark signal Spectra = “S”
- Gain = S / L . L = radiance of sphere, or the radiance of panel when illuminated by FEL standard
- L can be determined from NIST traceable calibration of FEL lamp
- Sources of uncertainty identified (e.g. sphere or panel uniformity, uncertainty associated with FEL lamp irradiance values)
- Underwater radiometry – immersion factor

TriOS RAMSES ACC-2 VIS SAM 8750 Spectral Irradiance Response



Other measurements

- Linearity – dark signal measurements taken at various integration times; signal $\propto$ integration time; first order linear relation determined
- Cosine correction – deviation of the sensor response from ideal cosine law (i.e. how does signal change as incident angle of light varies; should follow ideal cosine law, rarely does!)
- Polarization sensitivity – wire grid polarizer, rotated in increments; change in signal measured and correction implemented
- Stray (internal and external) – bandpass filter method for characterising internal stray light



UAV DFOV Spectrometer– Calibration Case Study

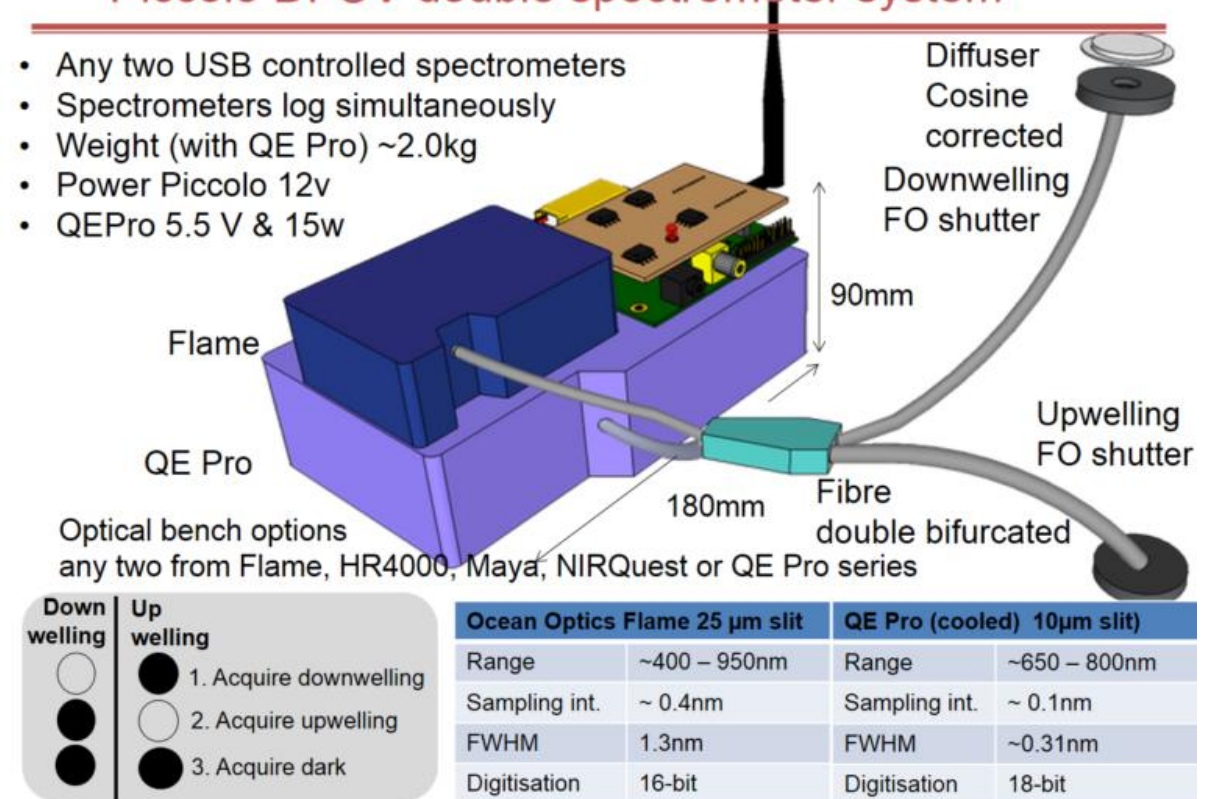
1 – Overview of UAV Piccolo Doppio System

PICCOLO DOPPIO

- Dual Field of View Spectrometer – simultaneous measurements of downwelling irradiance and upwelling radiance
- Control unit – Raspberry Pi Model 4B with Piccolo OS
- Standard Spectrometers – Ocean Insight QE Pro High Resolution Fluorescence Spectrometer (650 – 800 nm); Ocean Insight FLAME (400 – 950 nm); **modular, can be changed** (e.g replacing SIF with NIR spectrometer, replacing FLAME with UV-VIS)
- Foreoptics – bifurcated fibre optic bundle with electromechanical shutters; cosine corrected sensor for hemispherical downwelling planar irradiance measurements; upwelling radiance fibre, 25° field of view, nadir

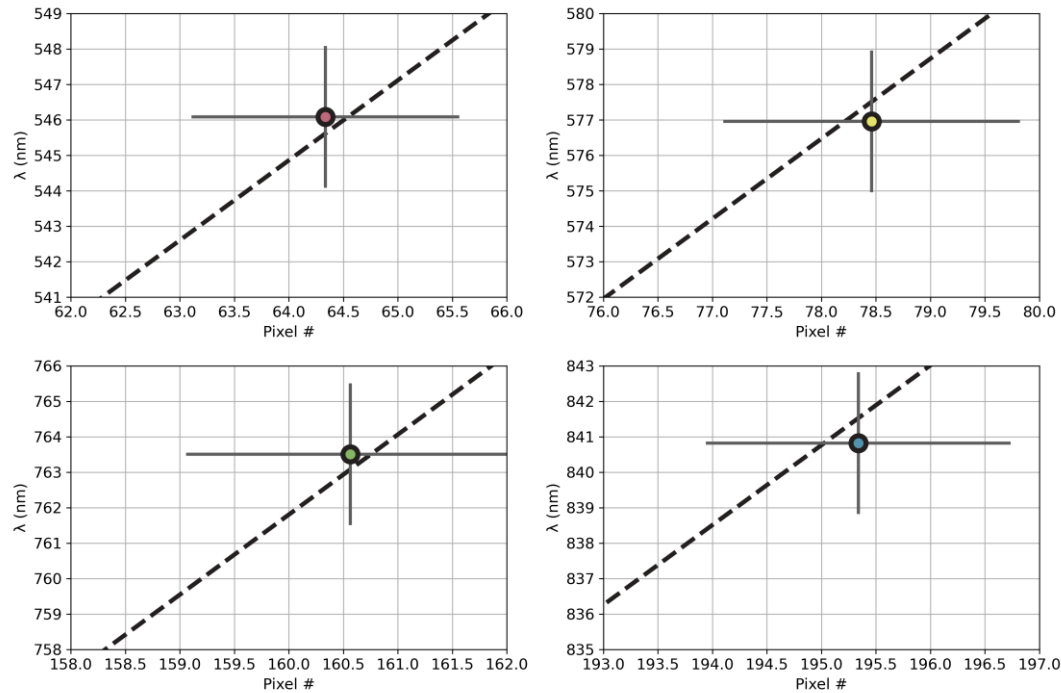
Piccolo DFOV double spectrometer system

- Any two USB controlled spectrometers
- Spectrometers log simultaneously
- Weight (with QE Pro) ~2.0kg
- Power Piccolo 12v
- QEPro 5.5 V & 15w



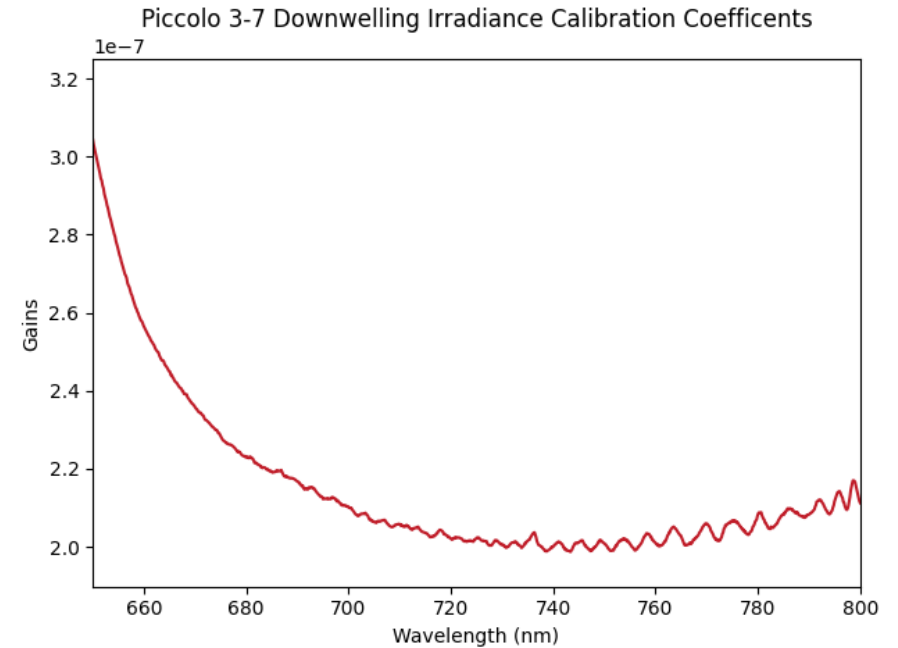
UAV DFOV Spectrometer– Calibration Case Study

2 – Spectral and Radiometric Calibration of Piccolo Doppio System



Spectral Calibration

- Atomic emission line lamps (Hg-Ar and Ne)
- Monochromator for measurements at 762 nm region
- Gaussian fit of measured peaks, sub-pixel
- 3rd order polynomial regression between sub-pixel peak measurement and known wavelength of peak



Radiometric Calibration

- **Irradiance** – Optronic Laboratories FEL 1000W QTH Irradiance standard. Measurements @ 0.50 m, validation measurements at 0.75 and 1.00 m
- **Radiance** – LabSphere HELIOS Dynamic Range radiance source, known radiance output.
- Radiometric gains determined by known irradiance/radiance divided by raw, dark corrected signal from spectrometer
- Linearity measurements

UAV DFOV Spectrometer– Calibration Case Study

3 – Integration of Piccolo Doppio onto UAV, challenges

Integration must ensure:

- Power is provided to sensor (10.5V to control unit, 5V to QE Pro spectrometer)
- GPS from drone IMU linked to SIF triggering system
- Correct orientation of fore optics
- Safe positioning of sensor unit
- Wireless control from ground station

Correct orientation of fore optics

- 3D printed pigtails and mounting posts.
- Loop design to ensure fibre optics safe and within bend radius.
- Pitch, yaw, roll – important factor to consider for incidence angle on irradiance sensor, viewing angle of radiance sensor. Work implementing correction for NERC Treescape project (SIF)

Wireless control from ground station

- Long range paired WiFi transmitters, one at ground station, the other mounted to drone and connected to control unit via I2C port
- IMU GPS and timestamp logs matched with **Piccolo triggering system**.

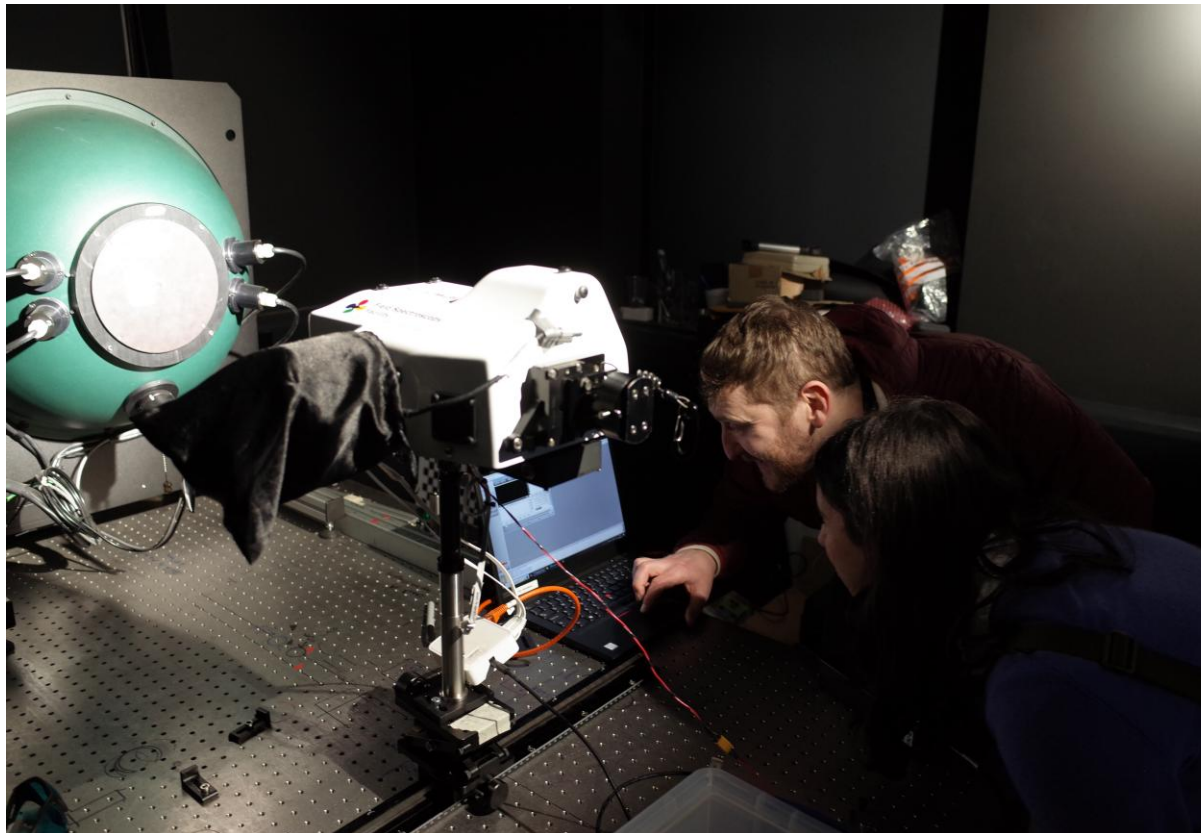


UAV Pushbroom Imager – Calibration Case Study

1 – Overview of Activities Conducted

IEEE P4001 Standard

- Characterization and Calibration of Hyperspectral Imaging Devices
- Project began in 2021, concluded 2025.
- Agreement on characterisation metrics
- Adoption of specific guidelines for both spectral, spatial and radiometric testing
- Unit used – Headwall Photonics Co-aligned VNIR-SWIR Imager (400 nm – 2500 nm; 640 spatial channels; 267 spectral bands between 400 nm to 1000 nm, 270 spectral bands between 1000 nm to 2500 nm)



UAV Pushbroom Imager – Calibration Case Study

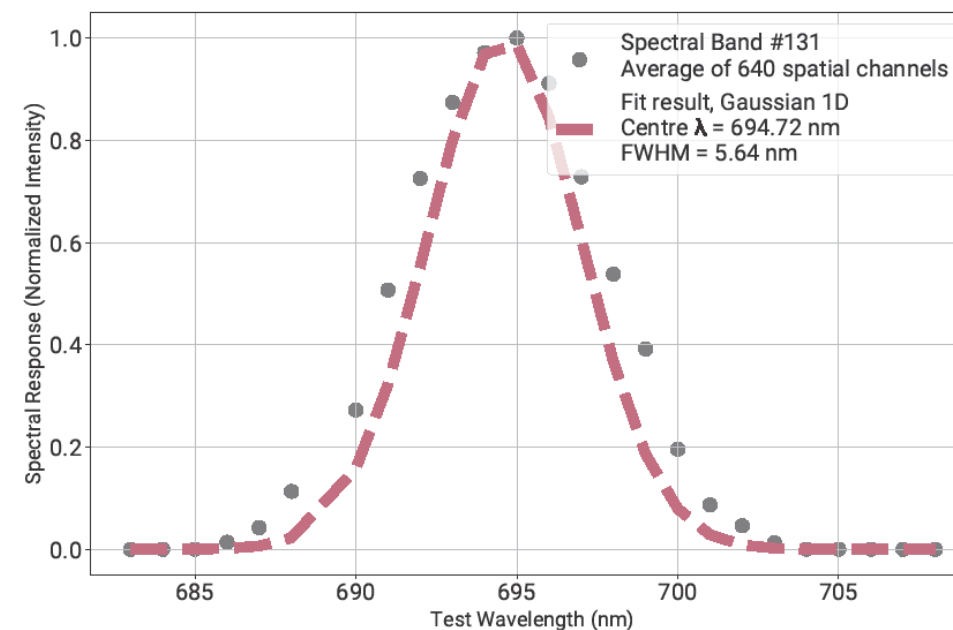
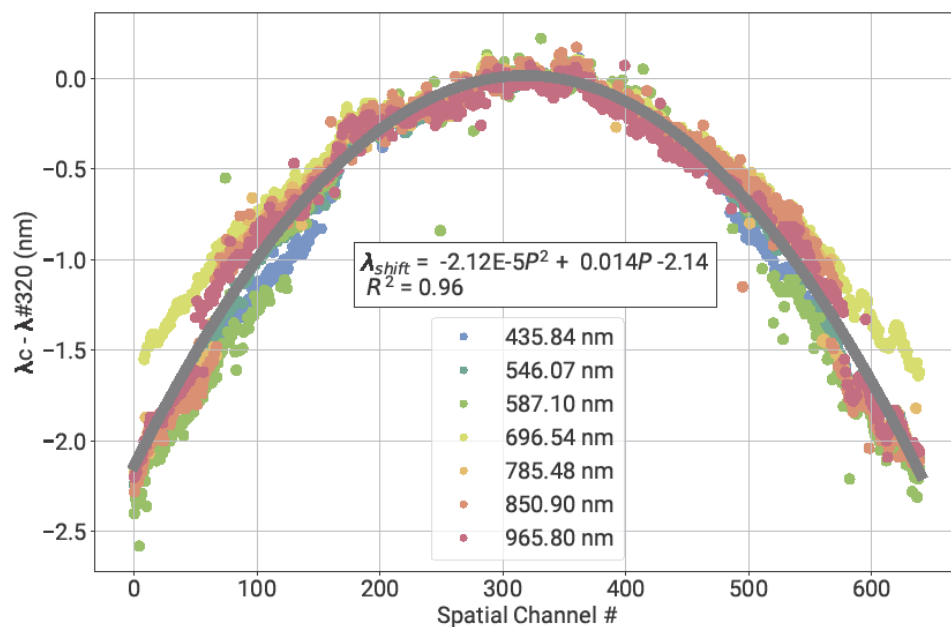
2 – Spectral Characterisation and Calibration

Spectral Calibration

- **Objective** – map spectral band to a discrete wavelength value; determine spectral interval
- **Method** – Monochromator scan across the spectral range of imager; assume Gaussian spectral response; 3rd polynomial fit of λ central to spectral band number.
- **Outcome** – Polynomial fit mapping spectral band N to wavelength λ

Spectral Characterisation

- **Objective** – For each spectral band N , determine the distribution of responsivity in the spectral dimension; determine the centre wavelength shift within spectral band between spatial channels (spectral coregistration error, “smile”).
- **Method** – Monochromator scan across the spectral range of the VNIR imager; for each spectral band, fit Gaussian curve; wavelength deviation between spatial channels at selected spatial bands, taken central spatial channel at #320 as point of comparison.
- **Outcome** – SRF determined for each band of imager; centre wavelength deviation across spatial channels characterised for seven spectral bands.



UAV Pushbroom Imager – Calibration Case Study

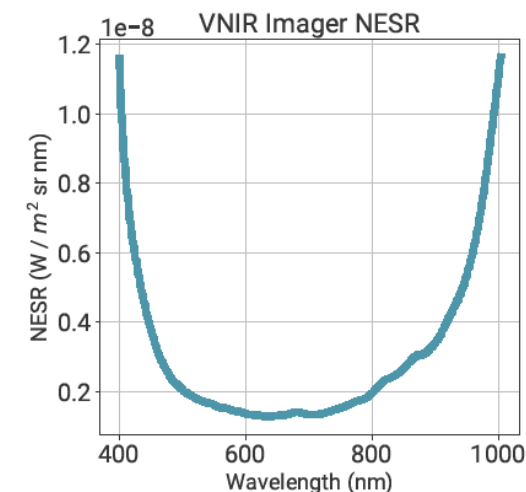
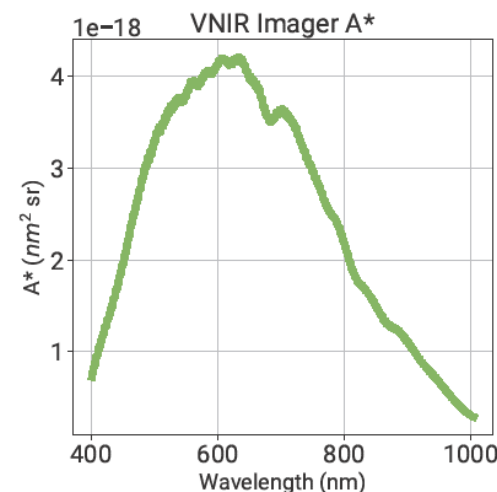
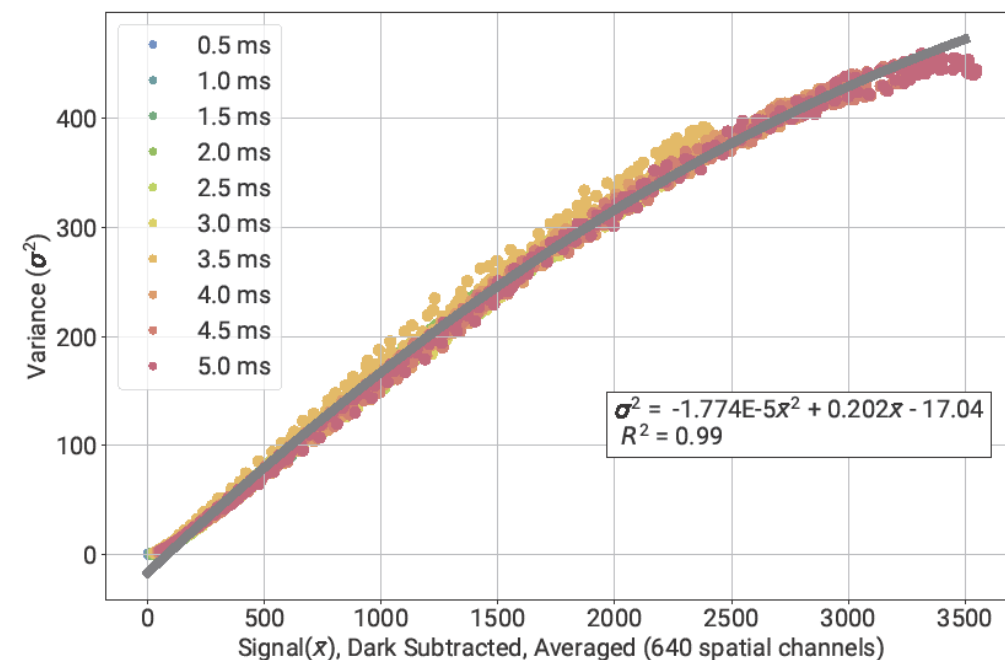
3a – Radiometric Calibration and Characterisation

Photon Transfer Curve

- **Objective** – Determine the scaling coefficient (G) and non-linear behaviour coefficient (γ) between image data and photoelectric count; determine read noise.
- **Method** – Using broadband QTH source with spectral power distribution across range of VNIR imager, take measurements of illuminated radiance sphere at different integration times; determine 2nd order polynomial fit between signal ($\bar{x}$) recorded by VNIR imager and variance (σ^2) in $\bar{x}$
- **Outcome** – PTC model determined

Determination of A^* and Noise Equivalent Spectral Radiance

- **Objective** – Determine A^* as metric for light collection; from A^* , use G and read noise to determine the noise equivalent spectral radiance (NESR).
- **Method** – Use measurements taken in 2.1; determine the photon spectral radiance output of sphere, $L\phi$; determine A^* from $L\phi$ and G ; determine NESR from A^* and the read noise.
- **Outcome** – A^* and NESR range determined.

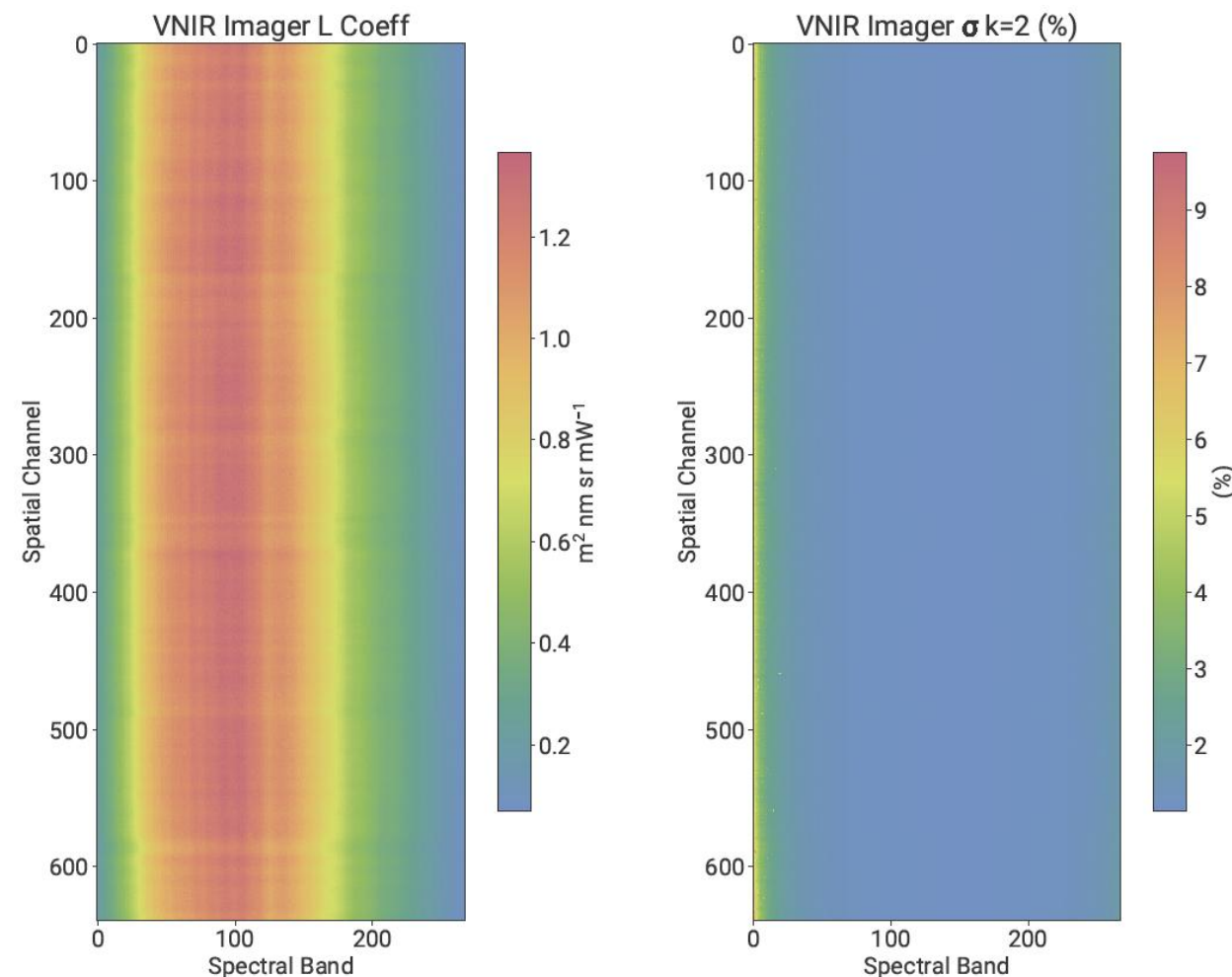


UAV Pushbroom Imager – Calibration Case Study

3b – Radiometric Calibration and Characterisation

Radiometric Calibration

- **Objective** – Map signal for each spatial-spectral pixel to radiance, L
- **Method** – Use measurements taken in 2.1; generate array of coefficients that map $\bar{x}$ for each spatial-spectral pixel to NIST traceable radiance output of QTH illuminated sphere.
- **Outcome** – Radiometric calibration coefficients with associated uncertainty determined.

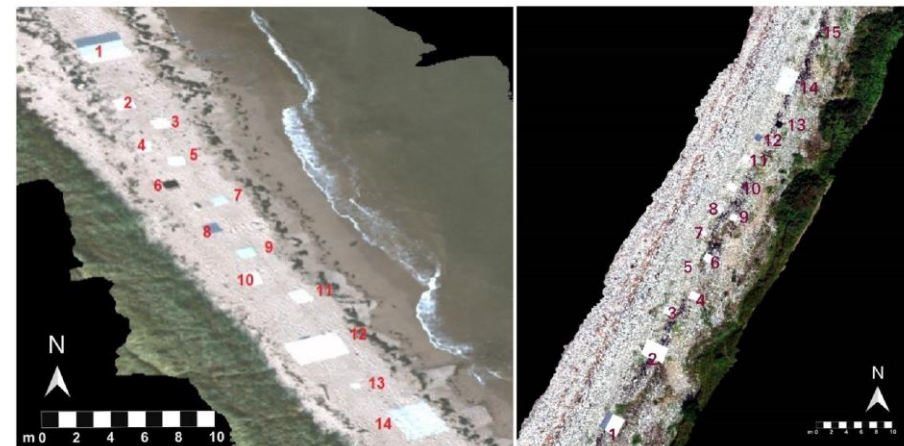


UAV Pushbroom Imager – Calibration Case Study

4 – Use cases in marine environment, challenges

ESA HyperDrone

- **Objective** – standardised indicator for in-situ radiometric detection of marine and coastal plastic debris
- **Method** – various plastics arranged as homogenous targets across two coastal sites in Scotland; ground based field spectroradiometer measurements coupled with UAV hyperspectral imagery survey
- **Outcome** – various indices for plastic detection developed based on random forest and support vector machine classifiers (Pérez-García et al., 2024, “Efficient plastic detection in coastal areas with selected spectral bands”)
- **Challenges and solutions**
 - No UAV irradiance data available (design of sensor, but also issues surrounding tilt of UAV on irradiance measurements)
 - Solution to use an empirical line method, by including in frame a 20% / 40% / 60% reflectance tarp
 - How to know if tarp calibration values correct?
Ground spectroradiometer took in situ measurements of tarp, and compared to a primary Spectralon panel (i.e. in situ calibration)
 - How to know if illumination conditions changed during flight? Continuous radiance measurements of primary panel using field spectrometer during flight
 - UAV height restrictions, flight times



Other Pertinent Calibration Activities

Panel calibrations, bi-directional reflectance factor characterisation

Panel Calibration and BDRF Characterisation

- **Objective** – Characterise the reflectance of plaques and tarps (used for measurements of reflectance, or conversion of radiance values to reflectance) at multiple angles of measurement incidence.
- **Method** – Use a goniophotometer, that will measure the radiance emitted from the test panel, illuminated at a set angle, at various azimuth and zenith angles. Compare to the facility's primary reference panel.
- **Outcome** – A calibration certificate providing the reflectance coefficients of the panel, given for each zenith and azimuth angle measured, and with associated uncertainty





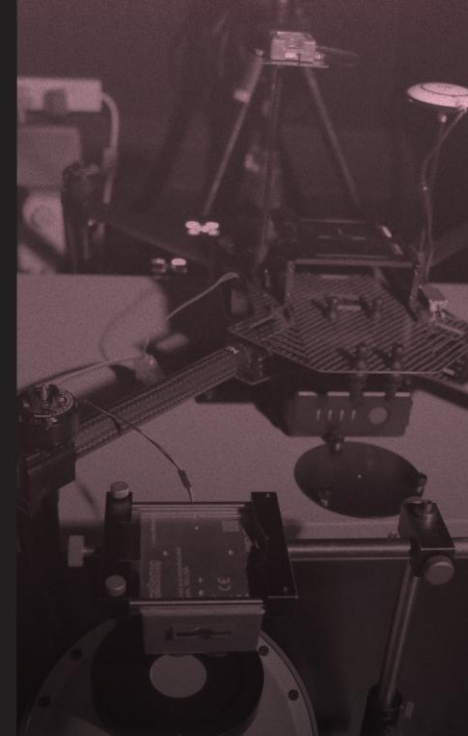
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PRECISION

High resolution instrument packages to monitor the health of our air and seas. Portable equipment suites for rapid deployment to point sources of emissions.

Portable, handheld, hyperspectral spectrometers for rapid and easy acquisition of target spectral properties.

UAV sensor and platform packages providing imagery from above for large scale, high spatial and spectral resolution surveying.

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Spectral Atmospheric Suite

- GHG Monitoring
- Urban pollution
- Volcanic gas detection

Field Spectrometers

- Material identification
- Vegetation health
- Satellite validation

Hyperspectral UAV Imagery

- Landscape
- Digital Elevation
- Materials detection

Bio-Optical Underwater Suite

- Coral reef health
- Ocean colour

Solar Induced Fluorescence

- Crop yield estimates
- Forest photosynthesis

Multispectral UAV Imagery

- Vegetation health
- Species tracking

Optical Metrology Laboratory

- Optics prototyping
- Absorption spectroscopy
- Data processing hub

NIST Traceable Calibrations

- Sensor calibration
- Uncertainty budgets