Narrow bandpass multispectral imagers for atmospheric chemistry: NIMCAM

Near Infrared Multispectral Camera for Atmospheric Methane

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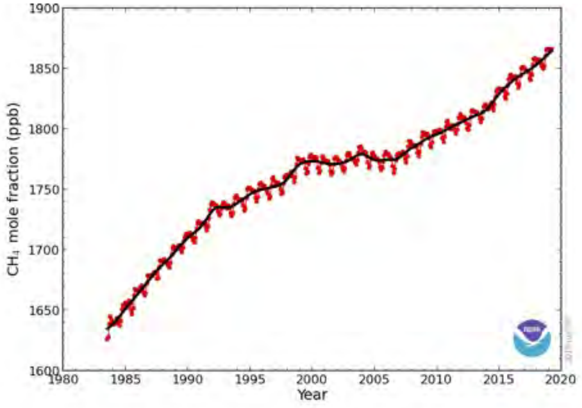
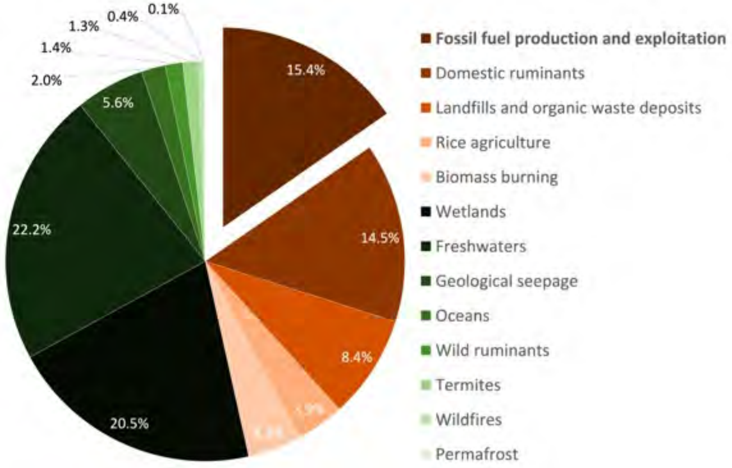
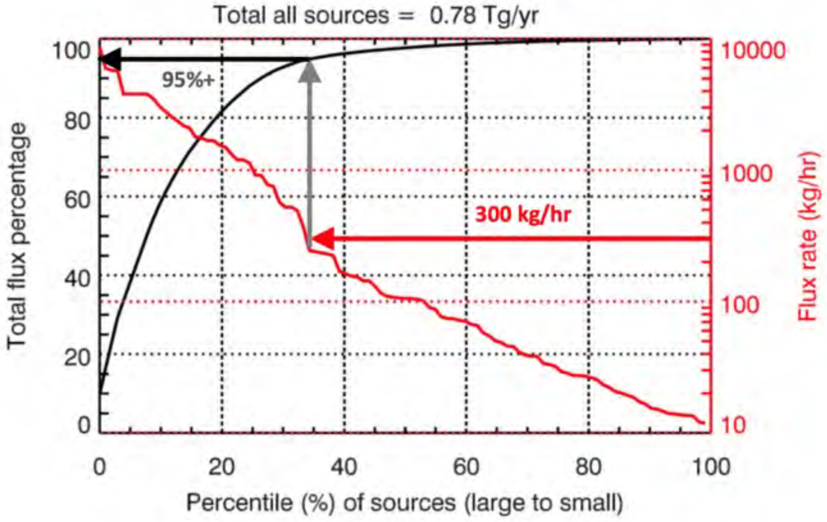
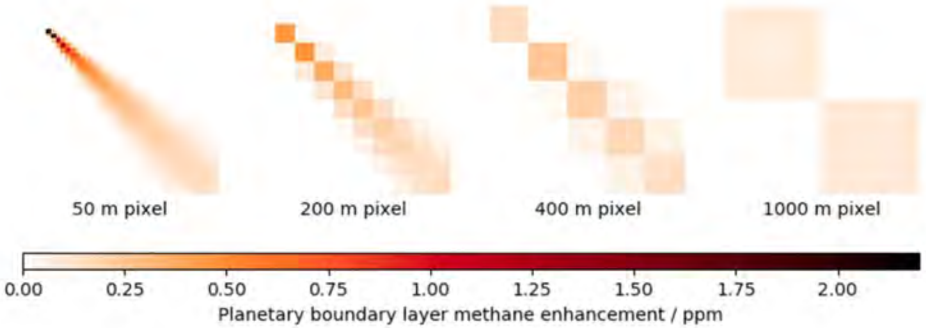
Background

Benefits of high spatial resolution methane imaging









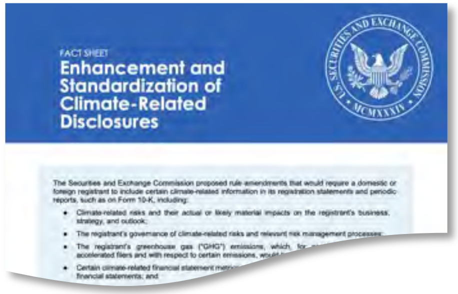
HM Treasury

Interim Report

Interim Report of the UK's Joint Government-Regulator TCFD Taskforce

Final Report

Recommendations of the Task Force on Climate-related Financial Disclosures



FACT SHEET

Enhancement and Standardization of Climate-Related Disclosures

The Securities and Exchange Commission proposed rule amendments that would require a domestic or foreign registrant to include certain climate-related information in its registration statements and periodic reports, such as on Form 10-K, including:

- Climate-related risks and their actual or likely material impacts on the registrant's business, strategy, and outlook;
- The registrant's governance of climate-related risks and relevant risk management processes;
- The registrant's greenhouse gas ("GHG") emissions, which, for accelerated filers and with respect to certain emissions,
- Certain climate-related financial statement financial statements; and

NIMCAM

Near Infrared Multispectral Camera for Atmospheric Methane

- Smallsat instrument optimised for fugitive emissions detection: 50 metre resolution, near-surface sensitivity.
- Provides **continuous swept-area monitoring** – detecting leaks others miss. Key USP compared to alternative technologies.
- Targeting eventual **constellation deployment** to reduce revisit time to around 1 week with a constellation of 10 satellites.
- Data rich – in-house AI algorithm for plume **detection**, **quantification**, and **attribution**.
- **Quality and traceability** with NPL involvement.

Instrument /mission	Launch date	Spatial resolution	Approx. XCH4 precision	Approx. plume detection limit	Data capture mode
TROPOMI	2017	7 x 7 km	20 ppb	10,000 kg/hr	Continuous
GHGSat-C1	2020	30 x 30 m	200 ppb	200 kg/hr	Tasked
MethaneSAT	2024	1 x 1 km	2 ppb	500 kg/hr	Tasked
CO2M	2026	2 x 2 km	10 ppb	?	Continuous
TANGO	2026	300 x 300 m	?	400 kg/hr	Tasked
NIMCAM	TBD	50 x 50 m	50 ppb	400 kg/hr	Continuous

Current and planned activities

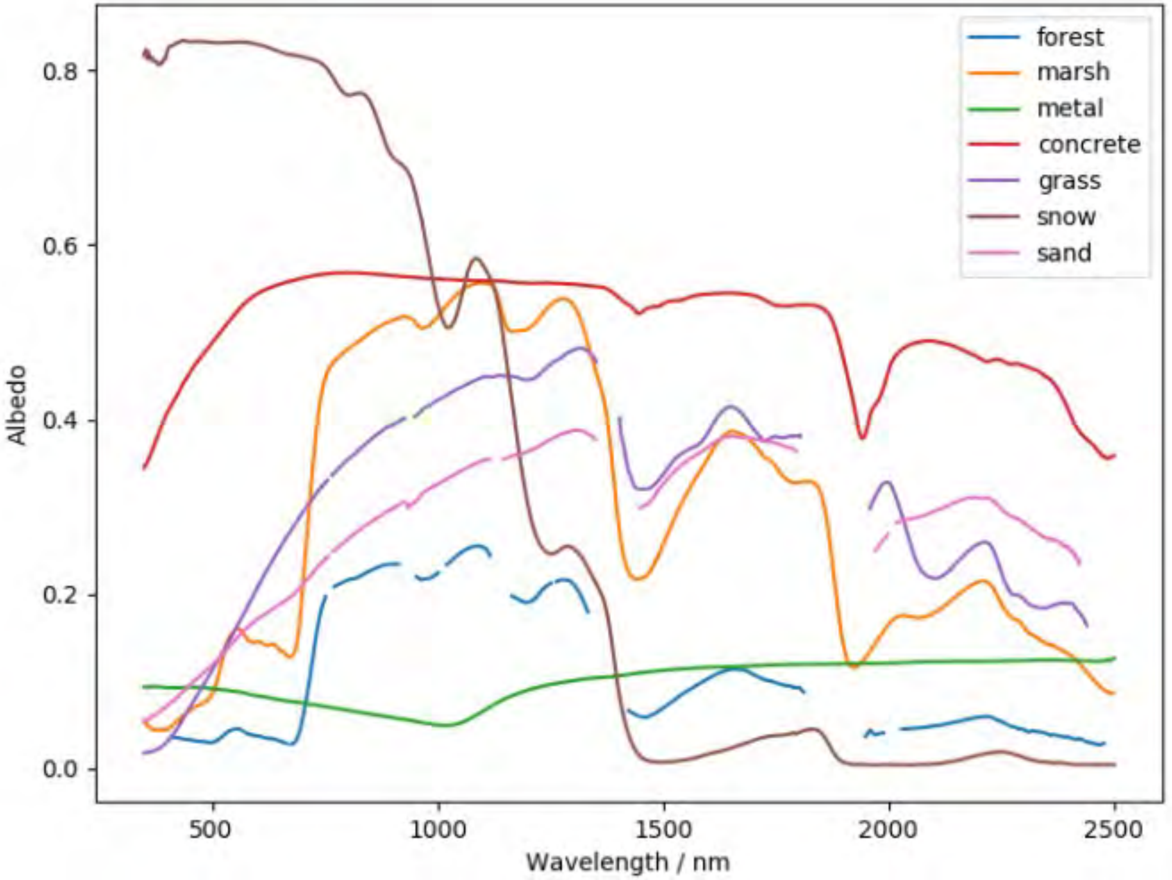
CEOI Flagship project

- WP1: demonstration
    - Field testing of the Field Demonstrator instrument
    - Design and construction of Flight Demonstrator instrument
- WP2: mission design
    - Some work led by Airbus
    - Platform, orbit, ground segment conceptual design
- WP3: satellite instrument design
    - Some work led by Airbus, some by UKATC
    - Optical, mechanical, thermal, electrical design
- WP4: data processing and product development
    - Some work led by NPL
    - Sensitivity analysis, on-board algorithm development
- WP5: narrow bandpass filter array development and evaluation
    - Design, manufacture, and testing of narrow bandpass filter arrays

Multispectral imaging with narrow bandpass filters

Isolate absorption features

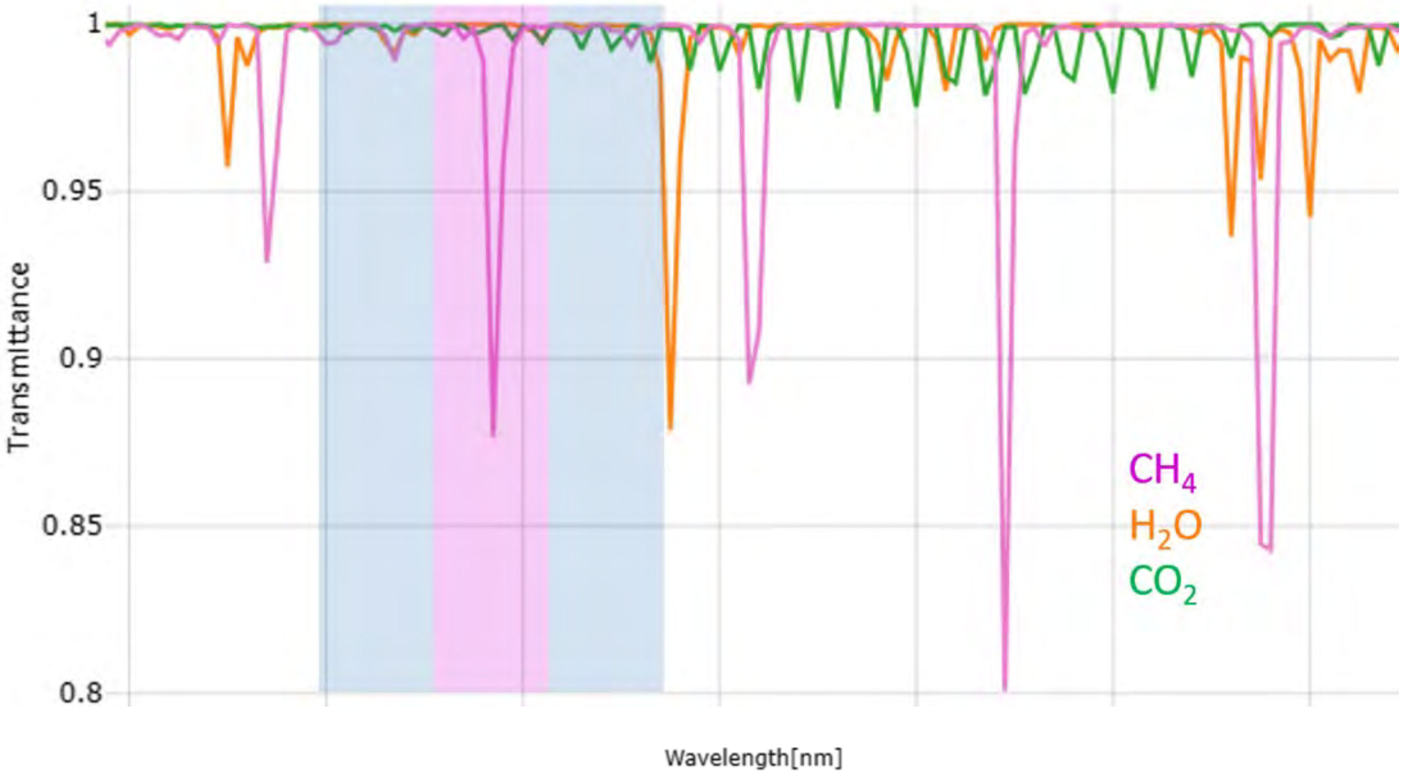
- Important challenge in trace gas detection (e.g. methane) at high spatial resolution is background removal.
- Attempts at using multispectral imaging with broad channel widths (e.g. Sentinel-2) to retrieve methane struggle with complex scenes.
- Other species with overlapping absorption features will also not be distinguishable – e.g. sensitivity to water vapour as well as methane.
- Reducing the channel bandpass helps isolate target gas absorption features.



NIMCAM spectral design

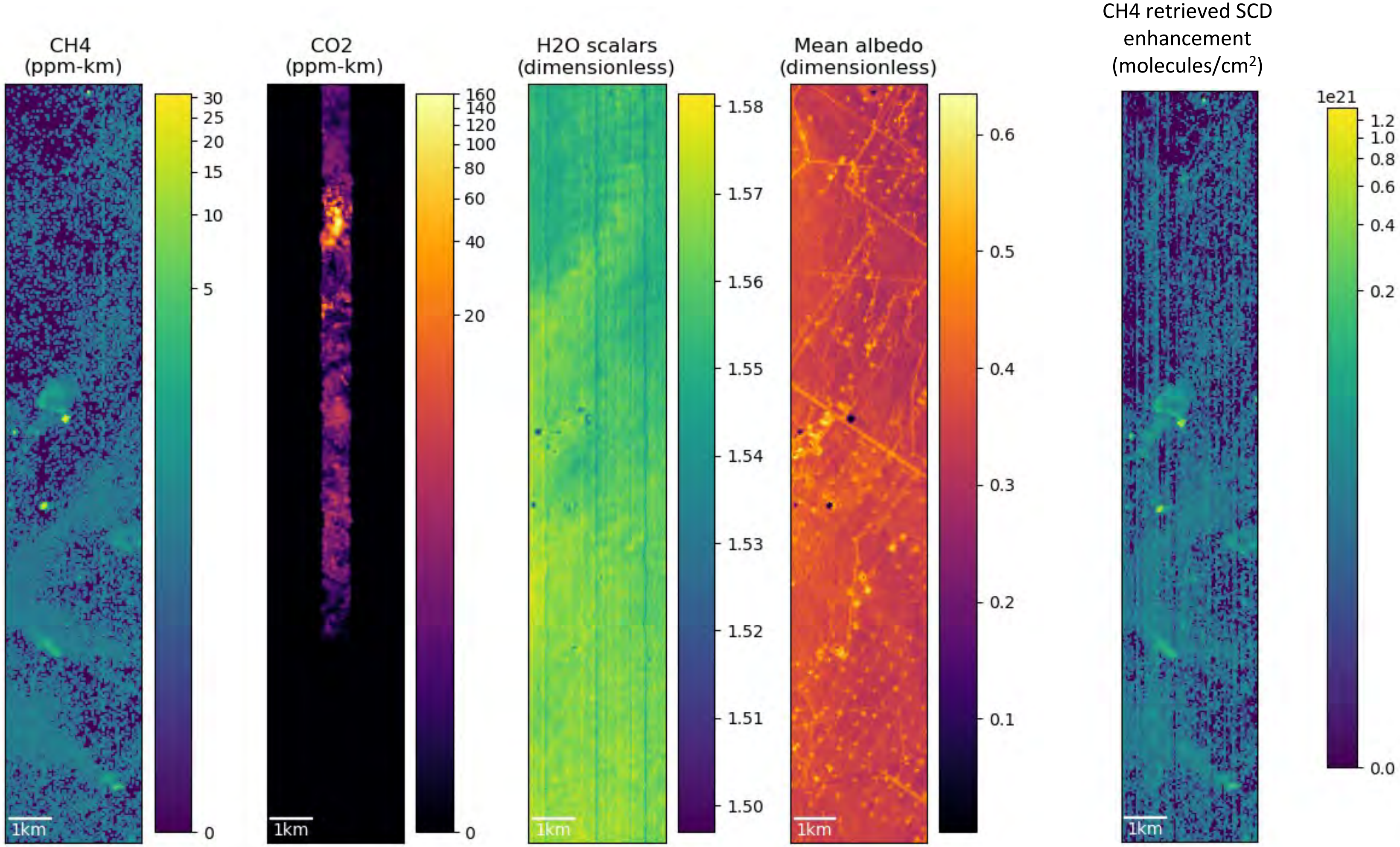
Compensating for spectrally varying surface reflectance and other confounding factors

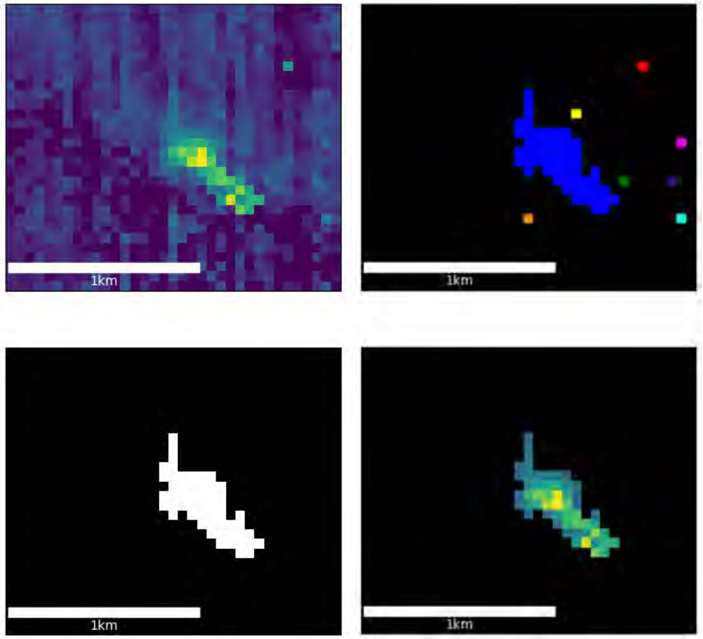
- NIMCAM uses one 1 nm wide central channel aligned with a methane absorption feature.
- Two side channels bracket this and are interpolated to give an estimate of the background signal in the central channel.
- Retrieval algorithm based on Beer-Lambert law.
- Additional forth channel may be used to detect water vapour, but modelling results show good robustness to influence of water for three channel design.



Observation simulation modelling

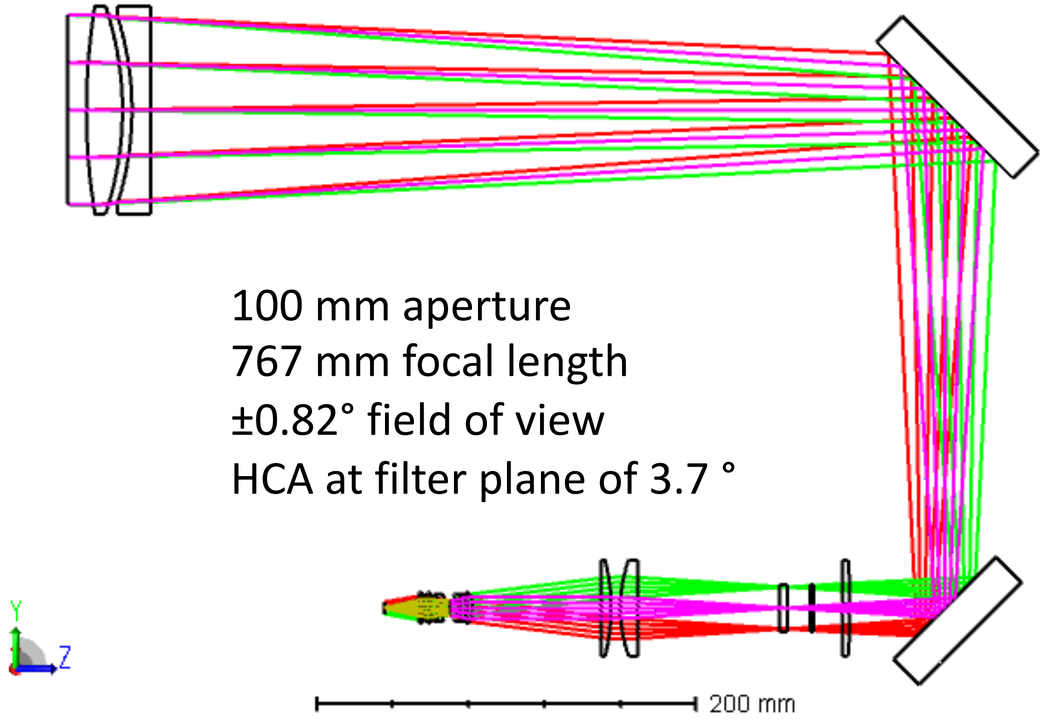
Using down-sampled AVIRIS-NG data



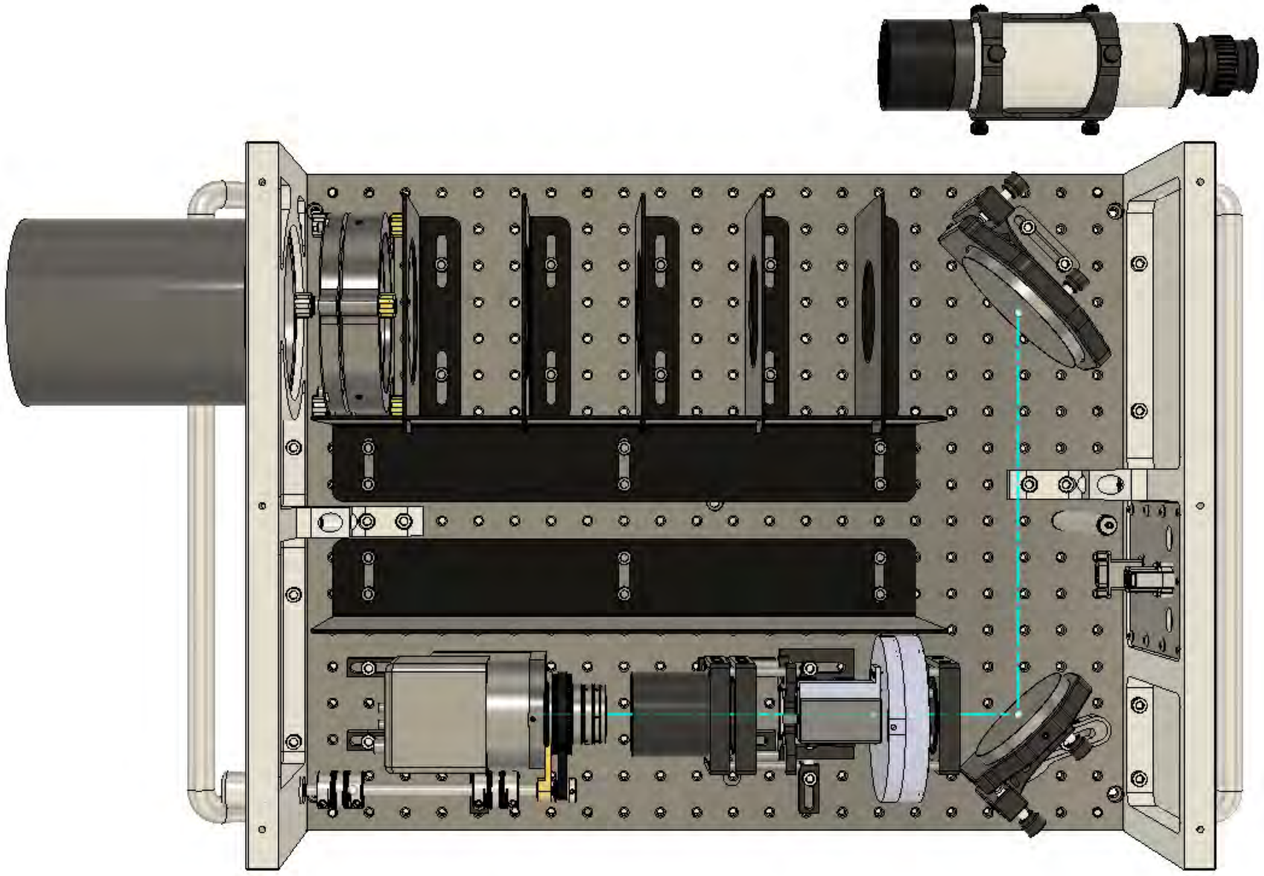


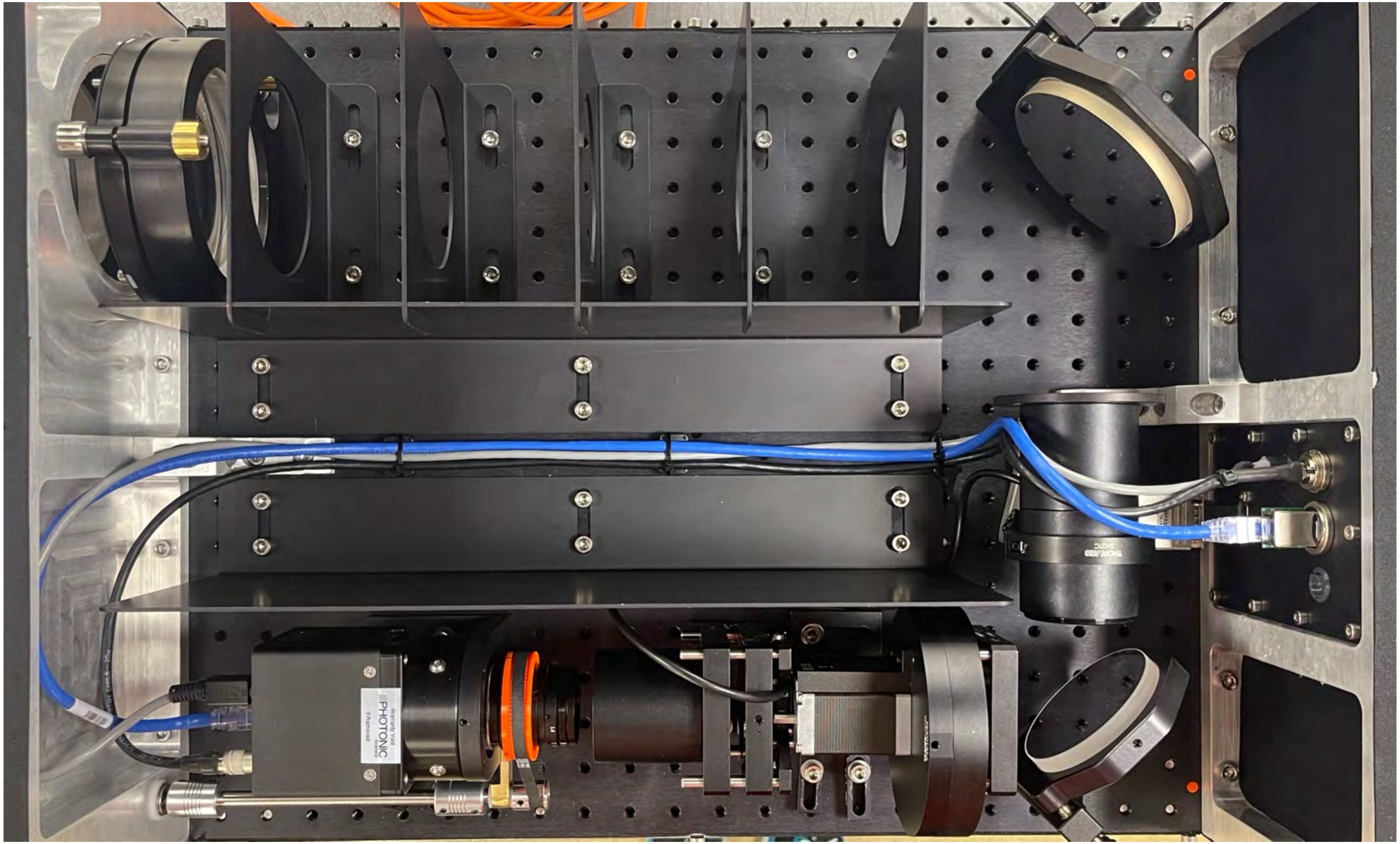
NIMCAM Field Demonstrator

Optical layout / CAD



100 mm aperture
767 mm focal length
±0.82° field of view
HCA at filter plane of 3.7 °

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Demonstration – plans for 2024

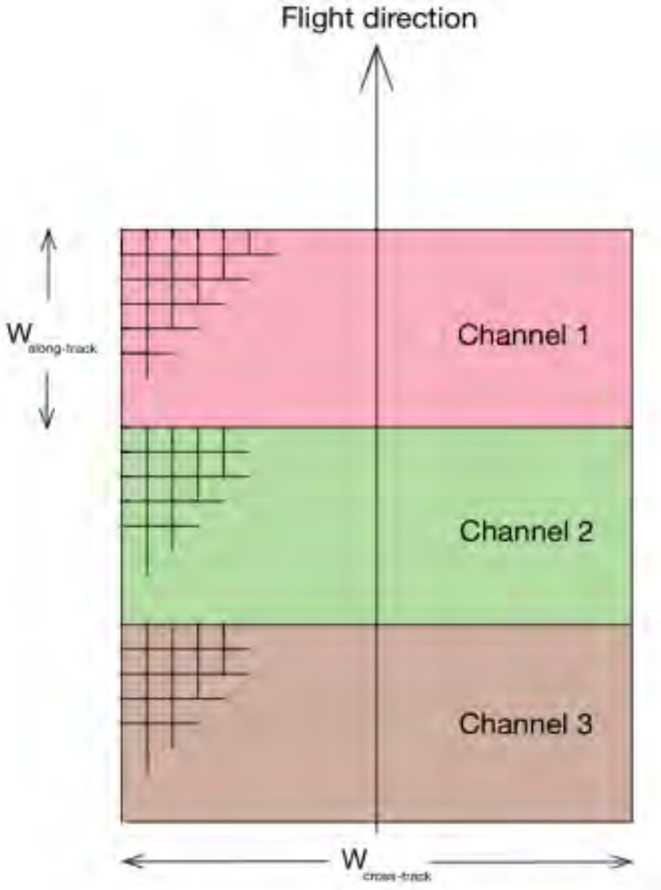
Controlled release trials – field and flight

- Field testing of field demonstrator instrument – ground based.
  - Using NPL controlled release facility in London, following initial small-scale trials in Edinburgh. Calibrated gas cells and controlled release rates.
  - Planning to attend controlled release trials in France as part of an international activity organised by Stanford University evaluating various new and existing methane detection technologies.
- Flight Demonstrator development.
  - Modification of the field demonstrator to create the flight demonstrator.
  - Move to filter array (no filter wheel) – engineering to adapt field demonstrator design.
  - Interfacing to aircraft.
  - Detailed design and build of Flight Demonstrator instrument
  - Flight trial planning

Flight / satellite data capture schemes

Improving system SNR through averaging

- NIMCAM satellite instrument spectral channels arranged in “butcher-block” fashion across intermediate image plane, perpendicular to the satellite ground track.
- Synchronise imaging frequency with ground track velocity to re-image same ground location multiple times through the same spectral channel as the satellite passes over.
- Reduction in random noise (e.g. readout, shot, thermal) by square root of the number of co-additions.
- Three channels, 640 pixel detector along-track – approximately 200 co-additions per channel – factor 14 theoretical improvement in SNR.
- Major challenge is pixel alignment – either requires relatively stringent pointing requirements (of the order 0.5°/minute maximum yaw rate, 0.1° ground track alignment), or an in-software image motion compensation approach.



On-orbit image alignment

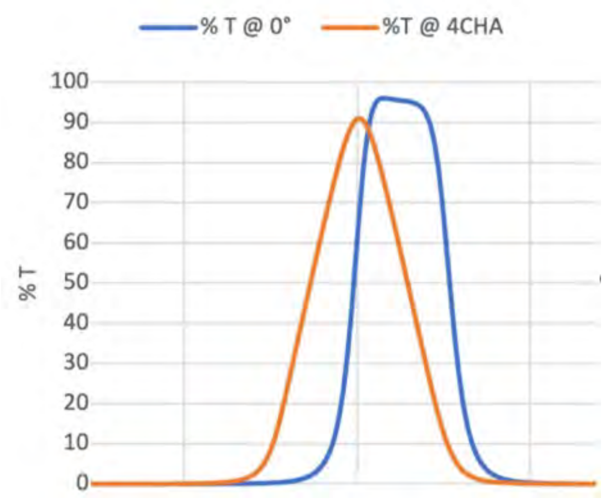
Onboard algorithm development

- NIMCAM will require on-board co-addition of high-frame-rate video to reduce data downlink from 100s GB to a few 100 mB.
- Co-addition needs to be robust to expected pointing jitter / drift / misalignment, and ideally minimise requirements on satellite ADCS.
- Software-based image stacking to register and align images:
  - Potential ML application, relatively easy to generate training data sets given representative vibration spectra / platform pointing stability specifications.
  - Data fusion with on-board accelerometers.
  - Accommodating other factors e.g. optical distortion across field of view, gross yaw offsets.
  - Needs to be computationally lightweight to minimise power requirements.
- Not a new problem, but challenge here is to do it on-board the satellite with an efficient and explainable algorithm.

Narrow bandpass filter challenges

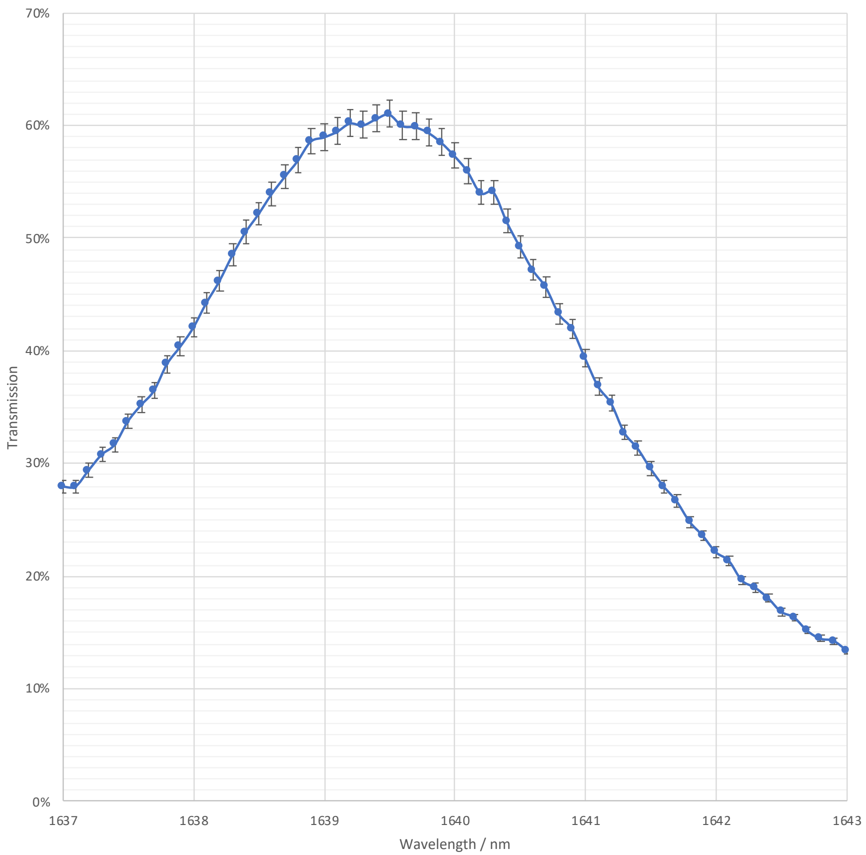
Trade-offs, potential issues

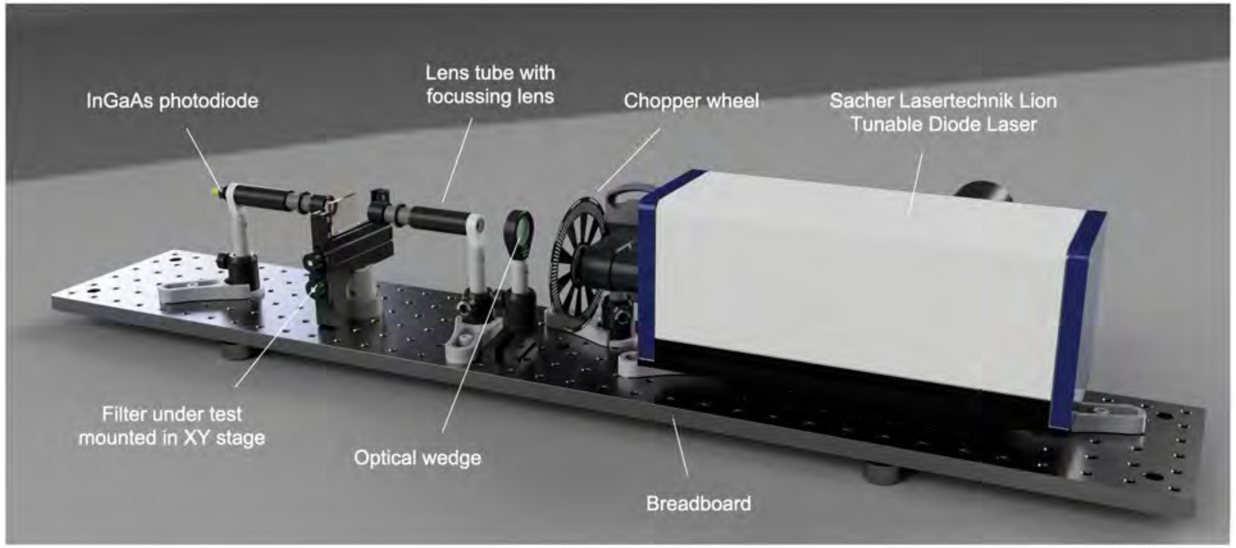
- Very narrow bandpass widths bring benefits in terms of spectral specificity, rejection of confounding factors, and high throughput compared to spectrometers.
- However there are some challenges to consider:
  - Optical design considerations – incidence angle and beam divergence both impact spectral performance, shifting transmission curve to shorter wavelengths and broadening the passband region. Bigger spectral shift for lower effective refractive indices. Minimise light cone half angle, need for field corrector.
  - Thermal considerations – expected shift in channel position with temperature of 0.01 – 0.02 nm/°C for NIMCAM design, however could be improved to 0.007 nm/°C with a different substrate.
  - Filter measurement challenges - need to replicate beam divergence to get instrument-relevant spectral characterisation, need high spectral resolution to resolve bandpass shape. Expensive instrumentation required to validate manufacturer data. Uniformity important.
  - Coherence length significantly increased after spectral filtering (~1 mm), may need careful optical alignment or use of anti-reflection coatings to avoid fringing.

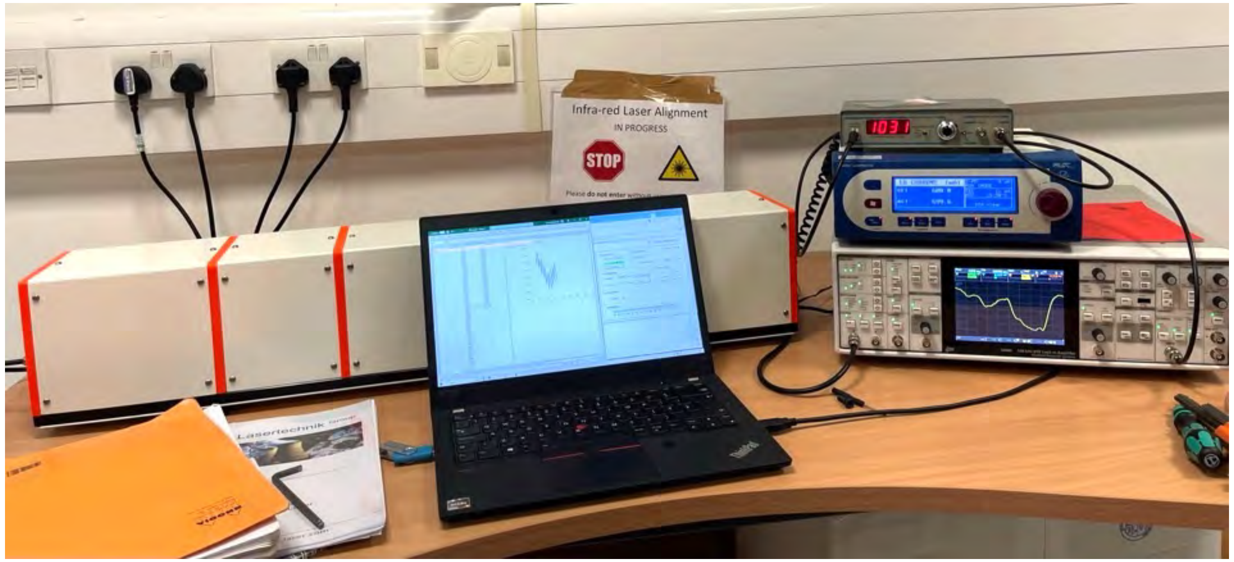


Tunable diode laser

Characterising narrow bandpass filters

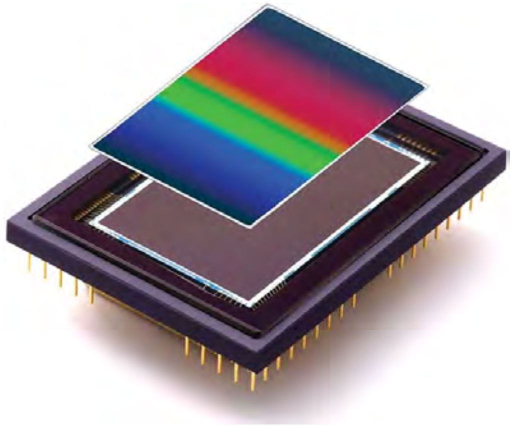




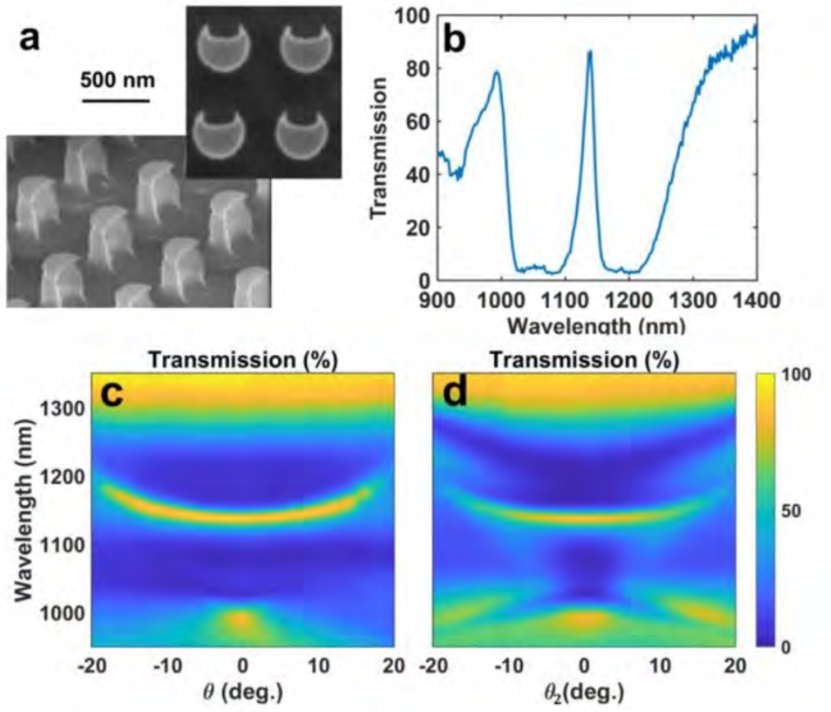


Opportunities for innovation

Spectral components



- Continuously / linear variable bandpass filters
  - Bandpass filter with smoothly varying centre wavelength value depending on linear position along filter.
  - Simultaneous capture of spectral and spatial information: requires relative motion to separate.
  - High throughput, but no co-addition possible.
  - Similar challenges of system pointing and alignment.
  - Hard to achieve the high spectral resolutions beneficial for gas sensing.
- Meta materials
  - Potential to meet or exceed performance of narrow band filters, e.g. Si nano-resonators, Zheng et al. 2020 – see figure right.
  - Still a developing field with a very different set of design and fabrication challenges.

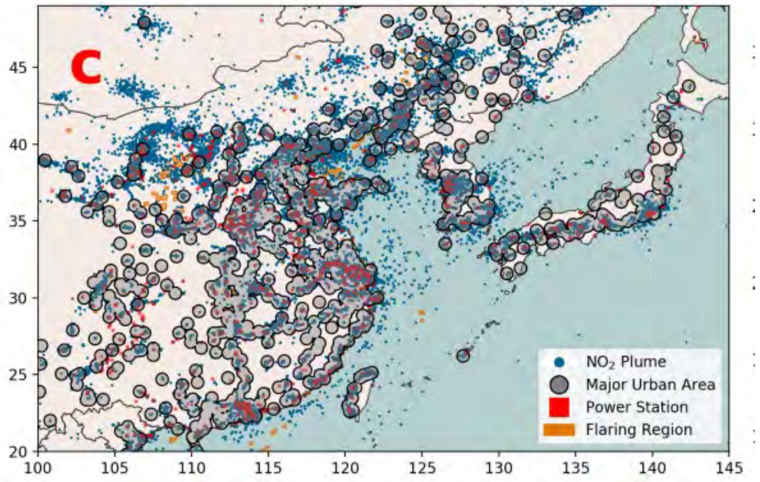


SNEEZI

Sensing NO_2 Emissions to Evaluate net-Zero Initiatives

- Proposed cubesat / smallsat instrument optimised for detection of NO_2 emissions at high spatial resolution (~200 metres).
- NO_2 used as a proxy for CO_2, as well as being important for air pollution and human health.
- Building on concepts from an earlier instrument, HAPI, developed at University of Leicester.
- Multispectral imager with multiple detectors.
- Collaboration with University of Leicester and UK Astronomy Technology Centre.
- Existing University of Edinburgh data expertise with NO_2 plume detection from Sentinel observations using machine learning.

- Part of the CEOI Earth Observation Marine and Climate Mission Development Programme.
- Develop instrument concept and design, build, and test laboratory breadboard.



Finch et al, 2022

Questions?