CEOI Funded Projects on Miniaturisation of Remote Sensing

A Brief Overview

1. Introduction

Over the past few years, CEOI (Centre for Earth Observation Instrumentation), a UK Space Agency programme, has funded a range of projects looking at miniaturisation of components, subsystems, and remote sensing instruments. The key drivers behind these projects are the growing portfolio of small / cubesat instrument platforms and the need for affordable access to space. This article provides a brief overview of some of the most advanced projects, summarising the technology, applications, and potential deployments in space and non-space scenarios.

2. Remote Sensing Instrument Miniaturisation

Key drivers for remote sensing instrument miniaturisation in space applications are size, mass, and power consumption. The main reasons are cost of deployment (launch), lifetime of the mission (power availability) and the highly constrained power budget. The CEOI funded projects addressing these challenges can be split into three groups.

A. Miniaturisation – Remote Sensing Instrument Examples

__Laser Heterodyne Radiometers__

Source: STFC RAL

The Laser Heterodyne Radiometer (LHR) is an innovative, passive spectro-radiometer using similar principles to radio receivers. It uses a low-power solid-state laser as a highly stable local oscillator, together with optical mixing using high-speed photodiodes to observe the unique spectral signatures of atmospheric constituents and pollutants in the mid infrared. The LHR has the performance advantages of high sensitivity, high spectral resolution, and high spatial resolution combined with relatively low complexity. The technology has potential for extreme miniaturisation, enabling it to compete with or exceed the performance of the costly, heavy and bulky Fourier Transform Spectrometers normally used in these wavelength domains.

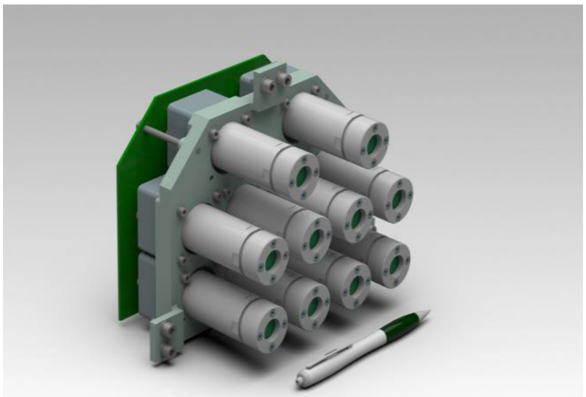
Applications include environmental, security & defence, and industrial monitoring.

The technology is being developed for deployment on several science missions, and for laser sensing products addressing medical, industrial and environmental markets. The

LHR technology development has also led to the concept of mid-infrared hyperspectral heterodyne lidar, currently being exploited by the security / defence sector.

High-resolution Anthropogenic Pollution Imager (HAPI)

HAPI applies a novel approach to sensing of atmospheric nitrogen dioxide (NO_2) using 20-30 times fewer spectral channels than traditional hyperspectral imaging based on Differential Optical Absorption Spectroscopy (DOAS). A new retrieval approach called Discrete-Wavelength DOAS (DW-DOAS) underpins a miniaturised spectral imager. Due to their small size, they could be accomodated at reasonable cost on a satellite constellation, which would enable multiple daily revisits of cities globally to provide new insights into the diurnal cycle of NO_2, as well as high-resolution identification of combustion point sources for both regulatory and defence related monitoring of emissions. An unprecedented sub 1 km spatial resolution captured 3 or more times per day is achievable with a HAPI constellation, compared to the current best resolution of 3.5 x 5.5 km from TROPOMI on the Sentinel 5 Pre-cursor satellite, with a daily overpass.

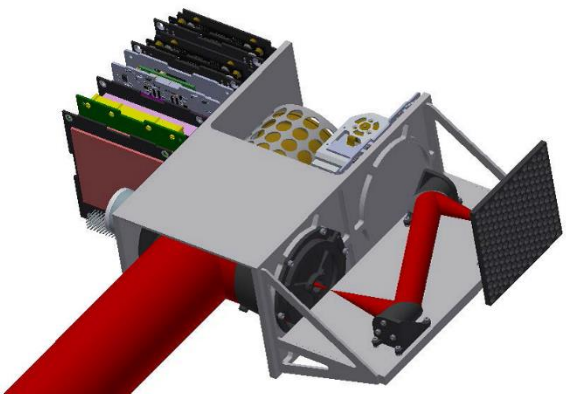


HAPI Breadboard with 10 optical channels
Source: University of Leicester

The HAPI approach could also be adapted to platforms such as HAPS or near-surface UAVs, due to highly simplified optics compared to traditional trace gas imagers. HAPS could enable long-term high resolution imaging of nitrogen dioxide in individual cities, and UAVs could enable detection and quantification of fine-scale point and area sources. Detection of NO_2 and other gases in other settings is also possible. HAPI has undergone considerable theoretical development plus preliminary laboratory and airborne testing.

Compact Infrared Imager and Radiometer

The Compact Infrared Imager and Radiometer (CIIR) is a new approach to infrared sensing of the Earth from space that can provide calibrated data over hours / years. Deployed as a limb sounder, the scientific objective is to understand effects of aerosols, clouds and stratospheric water vapour on the Earth's radiation budget, key to understanding our climate.



Source: University of Oxford

There is also significant market interest in filling the thermal IR observational gap and there is a wide range of potential commercial applications for this data (with the appropriate resolutions). These include agriculture and forestry, disaster management, environment, ecology & hydrology, geology, insurance, oil & gas, and aviation.

The CIIR concept builds on the design heritage of the Compact Modular Sounder (CMS) instrument demonstrated on TechDemoSat-1 and adapts it to work on smaller CubeSats. CIIR includes three components to ensure data return that reliably complements and enhances existing Earth observation data sets. First, it includes a traceable radiometric calibration target to guarantee accuracy of <0.2K. Second, it incorporates an intermediate focus between the input telescope and detector array; this allows a large (>10) number of discrete spectral channels to be used. Finally, the instrument uses an uncooled microbolometer array to combine medium resolution imaging with atmospheric sounding. The instrument design has now been selected for two space science missions, NASA's Lunar Trailblazer and ESA' Comet Interceptor.

B. Miniaturisation - Enabling Technologies

Phase Change Cells for Next Generation InfraRed Calibration Sources (NGenIRS)

To achieve the most precise measurements from infrared instruments, an on-board blackbody calibration system is required. Instruments requiring such calibration include satellite, airborne and field sensors for atmospheric and surface measurements; commercially available infrared cameras; future military and security surveillance systems; and future infrared remote sensing.

While the basic performance of infrared calibration black bodies has changed very little in the last twenty-five years, space requirements for radiometric accuracy, stability and traceability have become far more demanding. There is also downward pressure on the mass, power and volume of these calibration bodies to enable deployment on smaller, cheaper satellite missions.

Measuring the temperature of the radiating surface in the blackbody very accurately is critical to achieving the required calibration performance, but conventional thermometers and read-out systems are subject to calibration drift. In laboratories, high precision calibration is achieved using the phase change of pure materials (e.g. triple point, freezing point, melting point), all highly reproducible. Key points are the triple point of mercury and water, and melting point of gallium.

Figure 1: Left: phase-change cell. Right: phase-change cell immersed in aluminium block, also showing thermometer.

By embedding phase-change cells in a black body structure next to the temperature sensors, the material will absorb or release heat during the phase change, maintaining a constant temperature. The thermometer will show a 'plateau' at this known phase change temperature enabling the thermometer to be calibrated in-situ.

The phase-change cell is a robust, miniature (<1gm and <1cm^3) fixed point gallium cell, with a target calibration uncertainty of a nearby thermometer of 10mK.

Terahertz Multichannel Radiometer Using Stabilised 3.5-THz Quantum-Cascade Laser Local Oscillators and Schottky Diode Technology

The small frequency variations of quantum-cascade lasers (QCL) used as precision local oscillators in multi-channel terahertz radiometers (0.8 –5 THz) currently limits their spectral resolution. The frequency stability of THz QCLs is sensitive to fluctuations in the device supply current, heatsink temperature, and external cavity vibrations, and is typically limited to ~1 MHz. Improving this stability gives much better specificity to the measurements (i.e. ability to distinguish between different gas species), and better frequency-noise performance.

To achieve the first space-compatible (compact, integrated, robust and low-power) subsystem for stabilising the frequency of a compact 3.5-THz laser source, a harmonic mixer based on Schottky diode technology was developed, and coupled to a ~500-GHz local oscillator. A precisely tuneable 3.5-THz quantum-cascade laser was also developed, and the resultant local oscillator /mixer system was integrated with a stabilisation / control loop to lock the QCL emission frequency to < 1 ppm precision.

Next generation THz technologies (components, sources, systems) will have many applications in diverse disciplines including environment, astronomy, spectroscopy, healthcare, defence, agriculture, automotive, security and communications.

C. Miniaturisation - Instrument Concepts

ESA Future Passive Missions Study

Retrieval of three geophysical parameters - ocean colour, sea skin temperature (SST), and aerosol optical depth (AOD) are essential to exploring mesoscale oceanic processes. However, the simultaneous retrieval of all three parameters leads to a better contextual and accurate measure of marine health as data from each parameter can improve our understanding and retrieval of the other parameters. For example, sea skin temperature requires accurate water emissivity estimates. In coastal waters emissivity can change due to increased loading of particles and dissolved substances, so in such regions, ocean colour may help improve emissivity estimates.

Surrey Satellite Technology (SSTL) has recently completed a study for the European Space Agency on a miniaturised triple instrument to retrieve the three parameters simultaneously. The resulting proposed design is three instruments in one, miniaturised to fit within SSTL-42 microsatellite which has overall dimensions of <450 x 450 x 700 mm. The three instruments are:

Oracle-C: an internally calibrated eight-band multi-spectral pushbroom imager with a GSD of 100m operating in the VNIR spectrum from 412nm to 865nm with bands varying from 10nm to 40nm.

Oracle-T: an internally calibrated tri-band multi-spectral pushbroom imager with a GSD of 300m operating in the LWIR spectrum from 9.2um to 12um with each band of 1.0um bandwidth (FHWM).

Oracle-A: an internally calibrated imager with a GSD of 900nm able to detect polarised light in the VISIR spectrum from 410nm to 1650nm in three polarisation orientations, and at seven viewing angles, operating using the same principles as POLDER.

The conceptual designs for this miniaturised triple-instrument have been presented to ESA, and SSTL are waiting for a decision on further funding.

3. Challenges and Trade-offs still to be addressed

However, a wide range of challenges and trade-offs remain. The trade-offs between spatial resolution and size / mass / power / cost are still a challenge. Selecting the best data quality for the application can have a significant effect on the instrument design (high or low resolution / sensitivity of detectors).

Other trade-offs may include physical limitations such as spatial resolution (diffraction limited), signal to noise limitations, or temporal data acquisition rates. Careful design and optimisation may be able to overcome most of the issues, but they will need to exploit the degrees of design freedom provided by the specific application needs.

4. Limits to Miniaturisation

There are some fundamental constraints that physics imposes on the performance limits achievable from the very smallest platforms. High-resolution imaging requires large aperture optics which may be difficult to accommodate on small platforms for example, even with deployable technologies. Similarly, microwave measurements may require very large antennas, especially at lower frequencies.

There are also limits to the power that can be generated from small solar panels, and active instrumentation such as radars and lidars in low Earth orbit require a lot of power. Similarly imaging instruments generate a lot of data requiring high data transfer rates and/or on-board data processing / storage, again which will be power hungry.

All this can lead to alternative instrument approaches, rather than attempting to simply miniaturise conventional large-scale instrumentation.

5. Conclusions

Significant advances are being made in the miniaturisation of remote sensing, opening up a wide range of innovative new applications. However, key challenges and trade-offs around resolution, data quality, size, weight, cost, calibration, and data validation need to be considered carefully to ensure that the technology delivers solutions appropriate to the application / market needs.

Further information about this technology and others funded by the CEOI can be found at ceoi.ac.uk. You can also contact the CEOI Director, Professor Mick Johnson: Tel: +44 (0)1438 774421 or email: mick.johnson@airbus.com