Report on the Activities of the

Centre for EO Instrumentation

in Phase 2

July 2008 – March 2011

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Technology Strategy Board
Driving Innovation

UK SPACE AGENCY

NATURAL ENVIRONMENT RESEARCH COUNCIL

Contents

Executive Summary

With a vision to develop and strengthen UK expertise and capabilities in EO instruments, the Centre for EO Instrumentation is helping to position the UK to win leading roles in future international space programmes. The CEOI was created in 2007 as a result of joint support from the Natural Environment Research Council (NERC), the Technology Strategy Board (TSB) and industry, with the aim to develop key capabilities through the teaming of scientists and industrialists. The CEOI is set-up as a partnership led by Astrium together with the University of Leicester, STFC/Rutherford Appleton Laboratory and QinetiQ. From April 2011 it will be funded through the UK Space Agency.

There is significant evidence that man's industrial and other activities are modifying our environment by changing the composition of the atmosphere through emissions of carbon dioxide and other greenhouse gases and by through changing land use. Satellite instruments are essential tools to improve our understanding of the processes driving the climate, to provide a health check and to monitor the changes to the environment in which we live. The Centre supports projects to design and build new instruments used in observing the Earth from space.

This Executive Summary provides an overview of the main achievements of the CEOI in the 4 years since its inception. The main activities have centred on the technology development programme, which includes projects carried out by the CEOI partners and those selected through a series of Open Calls, which are held around once per year, resulting in participation of many industrial and academic groups throughout the UK. In all the CEOI has funded the development of 18 technologies.

CEOI technology programme

The programme supports mainstream projects and smaller 'seedcorn' projects, both selected through Open Calls to the EO community. The technical drive has been to produce instruments for space, but in many cases the resulting technologies have non-space applications.

Business Development

In addition to and often as a direct result of the CEOI funded projects, teams have won funding from a variety sources, increasing the overall investment by more than a factor of two. SSTL has secured a 10 M€ project from ESA, following a CEOI funded technology project, to develop the short wave IR instrument for the Sentinel 5 Pre-cursor mission. Also many CEOI developed technologies have potential applications in areas other than space and the CEOI has supported project teams in identifying spin-out opportunities into non-space applications.

The CEOI knowledge exchange programme focusses on identifying potential non-space applications for the technologies under development by CEOI project teams. The CEOI Knowledge Exchange partner, Qi3, carries out technology mining and brokering activities to identify Intellectual Property position, technology maturity and potential for additional funding.

Horizon Scanning

The Centre has organised a series of Challenge Workshops to bring technologists and scientists together and carry out horizon scanning to identify future scientific and technology priorities for Earth observation instrumentation.

The Challenge Workshops are designed to draw through the science drivers in each of the key Earth system areas and assess the requirements for instrumentation and technology. The CEOI has developed a close relationship with the National Centre for Earth Observation (NCEO), whose scientists played a key role in the success of the science Challenge Workshops, resulting in a list of indicative high priority UK EO missions. In total the CEOI has held 14 Challenge Workshops and more than 200 scientists and technologists have attended.

Executive Summary

ESA Earth Explorer 8 proposals

The CEOI has supported UK teams in developing concepts for the recent ESA Earth Explorer 8 rounds, funding technology activities and providing a firm basis for the technology underpinning their mission proposals. It held a joint town meeting with BNSC to allow UK PIs to present their initial ideas and the CEOI conferences and workshops have provided opportunities for networking with potential UK partners.

Learning and Development

A long-term CEOI objective is to develop the highly skilled workforce and leadership necessary to maintain the UK at the forefront of the world-wide EO community. The CEOI training and development programme addresses the needs of the academic and industrial community at all stages, from early stage training through to leadership development. CEOI funded projects are encouraged to use the development activities as a training opportunity for younger staff. The CEOI also supports NERC funded studentships on novel EO instrumentation. In total ten CEOI supported studentships have been allocated.

Publications

The CEOI publicises its technologies and achievements to a wide audience through articles and presentations of its activities at conferences and seminars. Articles have been published in NERC and STFC Newsletters and in a variety of technical journals including the IET Journal, SPIE Newsletter and publications from the KTNs. The CEOI project teams have published more than 40 technical papers and 2 patents resulting from CEOI technology developments have been applied for.

Further Information

More information about the CEOI is available at www.ceoi.ac.uk, or contact the CEOI Director:

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Introduction

This Report for Phase 2 of the Centre for EO Instrumentation summarises the activities of the CEOI from July 2008 to March 2011, including progress towards the longer term strategic objectives of the CEOI, a summary of the technology projects, the horizon scanning, the knowledge exchange and the training activities.

What is the CEOI?

The CEOI was created in 2007 as a result of joint support from the Natural Environment Research Council (NERC), the Technology Strategy Board (TSB) and industry. It has the key objective to develop capabilities in future space instrumentation for Earth Observation through the teaming of scientists and industrialists. With a vision to develop and strengthen UK expertise and capabilities, the CEOI aims to position and support UK-led teams to win leading roles in future international programmes. The CEOI is led by Astrium in partnership with STFC/RAL, QinetiQ and University of Leicester. The leadership team is drawn from the Partners and consists of the CEOI Director, Mick Johnson (Astrium) working with Co-Directors Paul Monks (Leicester), Chris Mutlow (STFC/RAL) and Rob Scott (QinetiQ).

Further information about the CEOI can be obtained at www.ceoi.ac.uk.

Governance

The CEOI Management Board is responsible for overall governance of the CEOI. It is chaired by the CEOI Director, with the CEOI Leadership Team as executive members, with further membership consisting of Dr Bill Eason (NERC), Mr Michael Lawrence (TSB) and since 2010 Mrs Maria Adams (UK Space Agency), as representatives of the funding bodies. Professor Alan O'Neill (NCEO) and Mr Ben Olivier (Systems Engineering & Assessments Ltd) represent the user community. The Board has met at 4-6 month intervals to review the CEOI progress, to consider and approve future plans and to advise the Director on strategy.

The CEOI programme

The driving objective of the CEOI is to develop UK space instrument capability, leading to missions funded by national, bi-lateral or ESA programmes which implement the mission concepts and instrument technologies developed through the Centre's programme. Innovative ideas are developed within the instrument technology programme, with projects initiated by the Centre and others selected through a series of Open Calls. Combined academic/industrial teams are encouraged, with horizon scanning linked to the NERC science priorities. The addition of technology transfer by spin-in of non-space technologies and spin-out of the developed technologies to non-space applications is used to maximise overall economic benefit.

The Centre also provides horizon scanning, knowledge exchange and training/ development programmes. Full participation of the UK EO and technology communities from academia and industry is encouraged through all CEOI activities to ensure exploitation of existing UK capability. The CEOI Leadership Team ensures that the programme is delivered cost effectively and has high impact on UK EO capability and international standing.

CEOI Main Achievements

Major Successes in Technology Development

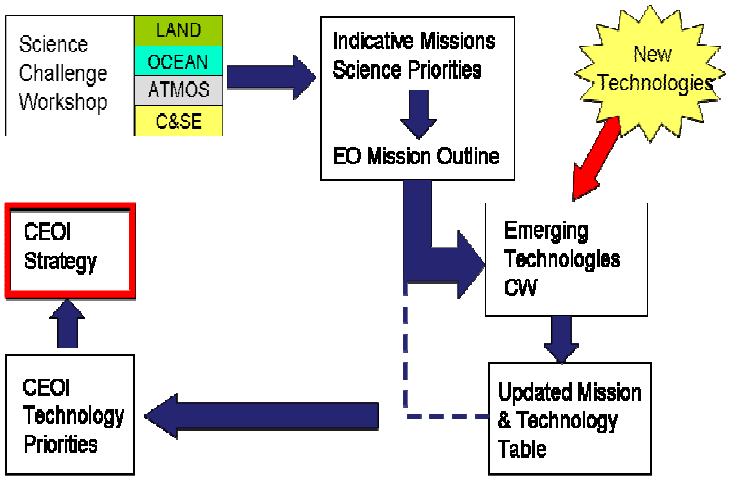
The main activity of the Centre is the development of technologies for the next generation of EO instruments. The Centre has funded 18 technology developments in Phase 2, each of which has taken significant steps. Highlighted below are some major successes of the programme, with full descriptions of all projects included later in this report.

- The **millimetre wave limb sounder** project (RAL lead) has undertaken the development of key millimetre wave technologies and analysed the critical design issues of the STEAM-R instrument on the ESA Premier mission. The team has built and tested a 320-360 GHz Sub-Harmonic Image Rejection Mixer (SHIRM) mixer. STEAM-R will measure atmospheric composition in the upper troposphere and lower stratosphere, an area important to scientific climate studies.
- The CompAQS benchtop demonstrator of a **compact UV/visible spectrometer** for monitoring air quality (University of Leicester lead) has led to the CityScan project to develop a ground-based monitoring system to provide real-time 3D maps of air quality in urban areas. Prototype instruments have been built to be deployed on buildings in London and Leicester
- A development project led by SSTL to exploit **bi-static reception of GNSS** 'reflections of opportunity' from the Earth's surface to determine sea state and surface properties has resulted in a flight opportunity for the instrument on TechDemoSat-1
- STFC-RAL in partnership with QinetiQ have studied the use of hollow waveguide technology to provide an optically integrated and **miniaturised laser heterodyne radiometer** (LHR), a high spatial and spectral resolution passive infra-red spectrometer to study atmospheric composition. If the development is concluded successfully, it will be a highly capable instrument with both space and terrestrial applications.
- Surrey Satellite Technologies Limited (SSTL) has produced **Grism designs** for future missions, leading to a contract for 10M€ for SSTL to develop the short-wave infrared (SWIR) spectrometer for the Global Monitoring and Environmental Security (GMES) Sentinel-5 Precursor mission. The SWIR instrument will provide accurate assessment of methane and carbon monoxide.
- SuperSar is a **dual-azimuth Synthetic Aperture Radar** concept which requires only a single satellite platform to detect deformation in 3D and should provide a major advance in the capability of Interferometric SAR (InSAR) instrumentation. The design study led by University of Leeds supported a proposal into the recent ESA Earth Explorer Announcement of Opportunity.
- Two CEOI seedcorn projects have investigated the use for EO of technologies originally developed for astronomy. **Integral field techniques** slice up the field of view of a telescope into multiple zones which can be taken independently to several dispersive systems. This can lead to spectrometers that are compact in design and use expensive detector 'real estate' most efficiently. The projects are led by the STFC Astronomy Technology Centre in Edinburgh and the University of Durham.
- Thawing permafrost regions threatens to release vast amounts of methane, a potent greenhouse gas, into the atmosphere. One method of estimating the methane flux is by the observation of **methane ice bubbles** trapped within lake ice. A CEOI seed-corn project led by Cranfield University considered the potential of spaceborne SAR, by using laboratory simulations of ice bubbles, and making representative radar backscatter measurements.

CEOI Main Achievements

Challenge Workshops

Challenge Workshops were held during Phase 2 to investigate:



- potential future missions, resulting in conclusions and priorities for the indicative missions identified in the Phase 1 Challenge Workshops, in the process shown in the diagram.
- potential future missions to observe surface-atmosphere interactions (snow-atmosphere, biosphere-atmosphere and ocean-atmosphere).
- operational EO missions and instruments, to identify potential opportunities matched to the capabilities of UK academia and industry.
- the technology for future space-based Lidar missions, including a review of the science drivers, the range of Lidar missions being considered, the driving technology requirements and the current UK technology capability
- advances in detector technologies that have the potential to open up new opportunities in Earth Observation, and meet future EO instrumentation needs
- science drivers and technology for future space-based radar missions. Radar technology developers gained improved understanding of user needs, whilst users become aware of new measurement possibilities.

The CEOI has held Conferences in 2009 and 2010 at the University of Warwick Conference Centre, with more than 60 attendees at each. The conferences addressed future EO missions and instrumentation, emerging instrumentation technologies and CEOI projects.

Training

The CEOI held a one-day training workshop on "Designing and Delivering an EO Instrument Concept" in March 2010 in London. The workshop built on the highly successful first CEOI training workshop and was particularly timely given the call for Earth Explorer 8 missions.

The CEOI has allocated ten fully funded NERC PhD studentships in EO instrumentation following calls for studentship proposals.

Technology Transfer

Technology exchange is an important part of the CEOI programme, looking at both spin-in of non-space technologies and spin-out of CEOI developed technologies into non-space applications. The Knowledge Exchange programme is carried out on behalf of CEOI by Qi3 and the activities include evaluations of the CEOI projects to identify potential for spin-out into other applications. A KE Conference was held in June 2010 to showcase the CEOI developed technologies to non-space industries.

The CEOI Technology Programme

The most important element of the CEOI programme is the development of new technologies for future world-class EO instruments. The majority of the funding is directed to these projects, with £1.9M of CEOI funding allocated in Phase 2 together with £0.7M of industrial co-investment. Projects were continued from Phase 1 where technologies were identified as high priority for near term flight opportunities. In addition new projects were identified through Open Calls to all the UK EO community. The Open Calls were released in July 2008 and September 2009, with a closing date 6-8 weeks later.

The bulk of the funds were allocated to Earth Observation (EO) instrument technology research and development projects, with the aim of positioning UK consortia for flight opportunities in future national and international space missions. Proposals of the highest scientific and technical quality which demonstrate that funding is urgently required to access an important mission opportunity were given precedence over proposals addressing longer-term opportunities. In addition, a number of 'seed-corn' technology projects were funded (not exceeding £50k cost to CEOI). These are projects which have strong enabling potential for future space EO activities.

Bidders were asked to propose new activities, or new development phases of existing activities in order to access international funding lines and missions. Proposals were encouraged from small teams combining academic and industrial organisations, although CEOI also funded a number of smaller 'seed-corn' projects from single organisations. We also considered collaborative proposals which form part of a larger activity funded by one or more other organisations, provided that the proposed work under CEOI falls fully within CEOI objectives.

The bids were assessed by a review board consisting of independent reviewers drawn from academia, stakeholder organisations, and industry. They selected the best mainstream and seedcorn projects, judged against the criteria set out in the Open Call documents.

Six mainstream projects have been funded under Phase 2 of the CEOI:

STEAM-R: Passive millimetre wave limb-sounding radiometer (STFC-RAL Space with Astrium) – Predicted science performance, designs and microwave technology for a planned joint Sweden/UK instrument, operating in the submm-wave (320-360 GHz), targeted at the ESA PREMIER EE7 mission.

CompAQS: UV/VIS spectrometer for gas analysis (University of Leicester with SSTL) - This compact and novel optical system uses ultraviolet-visible (UV/VIS) spectro-photometric techniques to measure air quality derived using differential optical absorption spectrometry.

TIDAS: Instrument on-board processing for thermal infra-red detectors (Astrium with Selex Galileo, STFC-RAL Space and University of Leicester) - The project has developed a demonstrator of a 2D thermal infrared detector array system and its associated signal processing unit for use in Fourier Transform Spectroscopy (FTS).

Hollow Waveguides: Technology for optical and laser systems (QinetiQ with University of Leicester and University of Sheffield) - Hollow optical waveguides offer a fundamentally new way of manufacturing compact, low mass, low cost optical systems which can maintain optical alignment in harsh vibration and thermal environments.

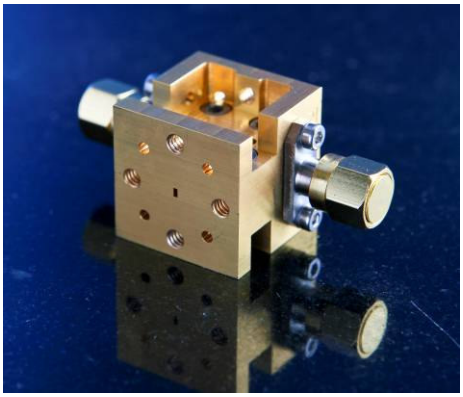
Laser Heterodyne Radiometer: High resolution radiometry in the infra-red (STFC-RAL Space with QinetiQ) - The Laser Heterodyne Radiometer uses a low-power, highly-stable quantum cascade laser to down-convert the spectral analysis into the radio-frequency domain, providing high spectral resolution, sensitivity and spatial resolution.

GNSS Reflectometry: SGR-ReSI development with flight opportunities (SSTL with NOC, Universities of Surrey and Bath, Polar Imaging Ltd) - This project is developing a flexible multi-channel receiver of reflected GNSS signals for surface sea-state measurements.

These are described in the following pages.

STEAM-R

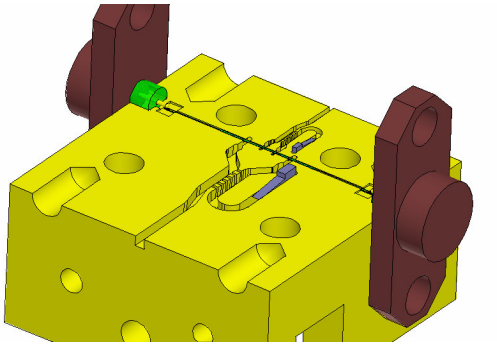
A consortium led by the Rutherford Appleton Laboratory is developing instrument technology for passive microwave radiometry in the frequency range 300 to 360 GHz. This technology represents the UK component of the STEAM-R passive limb-sounding instrument, which is the Swedish national contribution to the PREMIER mission, a leading candidate for ESA's Earth Explorer 7. The sounder views the Upper Troposphere, Lower Stratosphere (UTLS) region of the Earth's atmosphere to measure emission from water, ozone, carbon monoxide and trace molecules such as HNO_3 and N_2O.



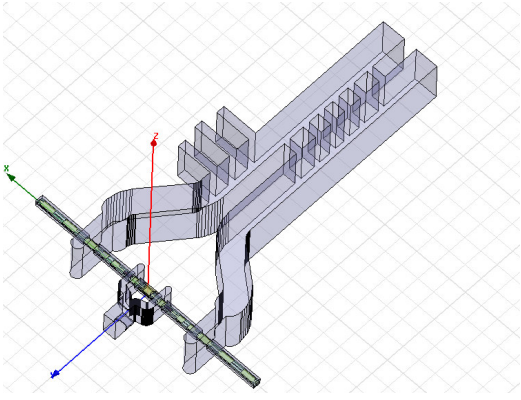
Lead investigators: David Matheson, Brian Moyna, RALSpace

The STEAM-R project builds on the work done in Phase 1 of CEOI, and is an activity continuing from the first open call of CEOI Phase 2. It has been scheduled to synchronise with the work of the Phase A study for the PREMIER mission and will continue beyond the end of CEOI Phase 2, in order to complete vital testing.

A major contribution to the instrument specification process has been to refine and prioritize critical instrument parameters. Most important with respect to the CEOI millimetre-wave study, side-band separation for the UTLS receivers is highest priority of L1b target requirements. Advances in the characterization of instrument parameters have been achieved in defining the geo-location, spectral and radiometric requirements. The rationale to incorporate side-band separating receivers is strong, and would be strengthened further through future simulations to quantify the scientific benefit based on performance characterization of the next version SHIRM design.



The sub-harmonic image-rejection mixer (SHIRM) is the key component enabling a compact, broadband single sideband receiver suitable for accommodation in the receiver array proposed on the STEAM-R instrument. The development of this device has been central to the work performed by the team throughout the various CEOI phases. Initial testing of two devices, differing in the phasing topology employed, revealed anomalous behaviour; namely that the level of sideband rejection was strongly dependent on the local oscillator frequency. This was a strong indication that the internal waveguide loads were not performing well - subsequently confirmed through independent measurement. New improved loads were designed and retro-fitted into the existing devices resulting in a significant performance improvement: a sideband rejection >20 dB over a broad IF bandwidth (2-14 GHz) has been achieved. Furthermore, a tolerance analysis has identified another area for potential performance improvement, leading to an improved design for diode grounding.



In line with ESA requirements for critical technology to achieve TRL-5 by end of the EE7 Phase A studies, a preliminary SHIRM design for TRL-5 qualification has been completed. The primary objective of this design was to ruggedize the device for deployment in space. The consortium is confident that a device can be designed to address a specific frequency plan providing a high level of sideband rejection.

Patents

Patent: European Patent Application No. 09781143.4: "Apparatus for an antenna system", Graham Maxwell-Cox (Astrium Ltd.)

Publications

Papers:

1. 'Progress on the Performance Improvement of Sub-Millimetre Wave Sub-Harmonically Pumped Image-Rejection Schottky Mixers', S. P. Rea, B. Alderman, M. Henry, D. N. Matheson, Y. Munro, 6th ESA Workshop on Millimetre-Wave Technology, Espoo, Finland May 2011.
2. 'Développement d'un Radiomètre Compact pour le Sondage Atmosphérique Multicanaux aux Longueurs d'Onde Sub-millimétriques', J. Treuttel, A. Maestrini, H.Wang, Y. Jin, C. Jung, Peter de Maagt et Christophe Goldstein, URSI France 'Les radio-télescopes du futur' CNAM 29-30 March 2011.
3. 'Compact Sub Millimetre Wavelength Heterodyne Radiometer for Arrays', Jeanne Treuttel, Alain Maestrini, Byron Alderman, Hui Wang, Hosh Sanghera, David Matheson, and Peter DeMaagt, URSI International, August 2011 (submitted)
4. 'A 320–360 GHz Sub-harmonically Pumped Image Rejection Mixer Using Planar Schottky Diodes', B. Thomas, S. P. Rea, B. Moyna, B. Alderman, D. Matheson, IEEE Microwave and Wireless Components Letters, Vol. 19, No. 2, Feb. 2009, pp. 101–103

Grants and contracts

Nearly €1.5M has been leveraged from CEOI investment to date.

Contracts	Title	Participants	Status
ESA C21806/08/NL/ST	Micro-machined receivers	RAL	Won
ESA O/1-6386/10/NL/MP	Cloud and Precipitation Airborne Radiometer	SEA, RAL, JCR, RPG.	Won
MetOp-2G	Phase A/B1 study (imagers)	Astrium, RAL	Won
ESA RFQ/3-12893/09/NL/JA	Quasi Optical Filter for EPS 2nd Generation Mission	RAL, QU Belfast	Won

Training

A CEOI NERC CASE student was awarded to the University of Leeds and RAL. The project is entitled 'Development of sub-mm heterodyne technology (frequency multipliers and fundamentally pumped mixers) for Earth Observation'. The project was supervised by Dr Paul Steenson at Leeds and Dr Byron Alderman at RAL and is close to completion.

With funding from CNRS and CNES a French student has been jointly supervised by LERMA (Paris) and RAL. The thesis, entitled "Realization of a linear multi-pixel heterodyne receiver at sub-millimeter wavelengths for atmospheric studies" was submitted in March 2011.

Spin-out and exploitation

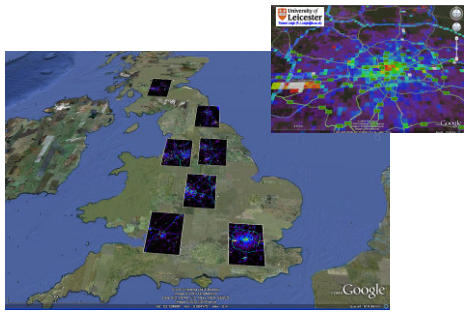
Expected through STEAM-R

CompAQS

CompAQS is a novel spectrometer design, which as the name suggests, uses concentric optics to produce a very compact imaging spectrometer instrument. The instrument addresses the UV/Visible region and measures atmospheric air quality by detecting polluting substances using the DOAS[1] technique. CompAQS was developed as a breadboard instrument for space applications in Phase 1 of CEOI, and continues as the CityScan project under external funding to produce a ground-based instrument which looks upwards to assess urban air pollution. It is thus an excellent example of spin-out from the space domain.

Lead investigator: Dr Roland Leigh, University of Leicester

Air quality is a trans-boundary, multi-pollutant/multi-effect environmental problem. Measurement of atmospheric compounds with climate change or air quality implications is a key driver for the ground and space-based Earth Observation communities. Real-time knowledge, sufficient to observe and predict the evolution of extreme atmospheric conditions, can be achieved through a combination of climate models, chemical transport models and measurements of the important chemical species involved.



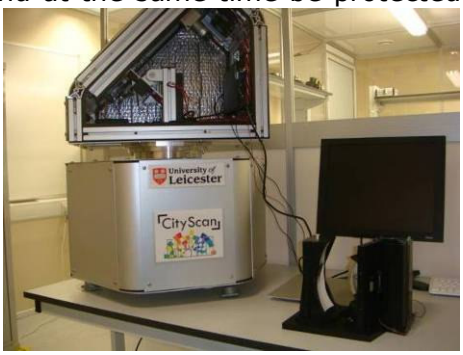
Techniques using UV/VIS spectroscopy such as DOAS provide measurements of ozone profiles, aerosol optical depth, certain volatile organic compounds, halogenated species, and key air quality parameters including tropospheric nitrogen dioxide. Compact instruments providing the necessary optical performance and spectral resolution are therefore a key enabling technology. The compact design offered by the CompAQS provides efficiency and performance benefits over traditional designs, improving the precision and spatial resolution available from space borne instruments with limited weight and size budgets, and is ideally suited to both ground and space based observations.

The instrument will enable an air quality data service at urban scale, with 1 x 1 km data product aimed at specific targets from e.g. ~1000 cities and ~100 volcanoes. A novel commercial model for data distribution has been developed with collaborators SEA and SSTL. The instrument is suitable for satellite constellations, such as DMCii, or as a passenger payload on ESA EO missions.

The CompAQS concept can also be used in a terrestrial context for urban air quality monitoring, by using it in a ground-based instrument looking upwards. This has been implemented as the CityScan project. The objective is to deploy several instruments around cities, which allows 3D, near real-time pictures of the air chemistry to be constructed. CompAQS is not currently funded by CEOI, but the consortium still reports on a periodic basis to the Centre, as the instrument design for CityScan continues to evolve, and these developments will benefit future space applications.

[1] Differential Optical Absorption Spectroscopy

The terrestrial version of CompAQS has been mounted in a special housing made by Magna Parva, which will enable the spectrometer to view the sky and at the same time be protected from the weather and contamination. The instrument has been adapted with diamond-turned entrance optics (Kaleido Technology – Denmark). The original meniscus lens and mirror (Jenoptik – US) have been transferred to the new spectrometer mounts. A new grating (Horiba Jobin Yvon – France) has been installed into a modified mounting. These modifications are compatible with the new 33 mm-long entrance slit, a significant improvement on the laser-etched version sourced in CEOI Phase 1. It will provide a 90 +/- 2 micron slit width.



The first instruments for deployment have been assembled, and 'first light' spectra have been obtained. They will be integrated into the CityScan housings in May 2011, allowing full imaging sky viewing DOAS to be demonstrated. The system is scheduled for demonstration during the Olympics in July 2012.

Further development will commence in mid 2011, to reduce focal plane complexity and expense, and improved algorithm development will reduce instrument data volumes.

Publications

- C. Whyte, R. J. Leigh, D. Lobb, T. Williams, J. J. Remedios, M. Cutter, and P. S. Monks, Assessment of the performance of a compact concentric spectrometer system for Atmospheric Differential Optical Absorption Spectroscopy, Atmos. Meas. Tech., 2, 1–12, 2009

Grants and contracts

- CityScan, University of Leicester, NERC Follow-on funding to develop ground based instruments to monitor the quality of air easily and continuously across physically large urban and industrial spaces
- Linking Innovation in NERC, Fellowship, University of Leicester, NERC, Commercialisation effort, of which about 25% will be dedicated to CityScan.
- EMDA grant, providing support for regional company involvement (sub-contracting money dedicated to engineering and focal plane of CityScan).
- A NERC "Air Quality in London" grant, called ClearFlo, which will be the first deployment of the system, and contribute to its development.
- Participation of spectrometer in ESA-IAP project iTRAQ (Integrated Traffic and Air Quality) scheduled for July 2010.

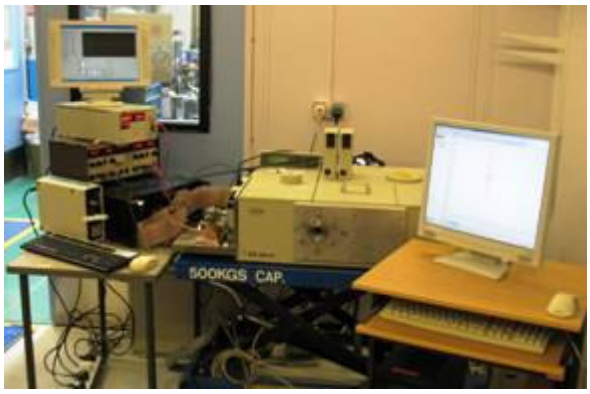
Training

CEOI Studentship started 1st Jan 2011, ensuring full exploitation of ground-based developments back into UK mission concepts.

Spin-out and exploitation

The CityScan project has been a very successful spin-out from the CEOI- funded CompAQS project, attracting both NERC and RDA funding to develop a very promising service to monitor urban and other terrestrial environments in 3D and in very near real time.

TIDAS-SPU and TIDAS II



Recent missions for climate and atmosphere studies have made extensive use of thermal infra-red spectrometers such as IASI on MetOp and MIPAS on ENVISAT, with very significant impact. These Fourier transform instruments employ a single element thermal infra-red detector. A 2-D detector array can offer significant advantages, but will generate significantly more data and require more on-board processing. The CEOI TIDAS-SPU and the follow-on TIDAS II projects have demonstrated a 2-D thermal infra-red detector array system and an associated on-board processing capability. This system has been used to perform an initial series of characterisation and performance experiments with representative signal sources. The demonstration system uses Selex's LW Hawk 2-D TIR array detector technology which operates in the 8-9.4 micron band, together with custom software and firmware implemented on a COTS DSP hardware platform. The integrated system is coupled to the Bruker IFS66 spectrometer at NERC's Molecular Spectroscopy Facility at the Rutherford Appleton Laboratory.

Lead investigator: Professor John Remedios, University of Leicester

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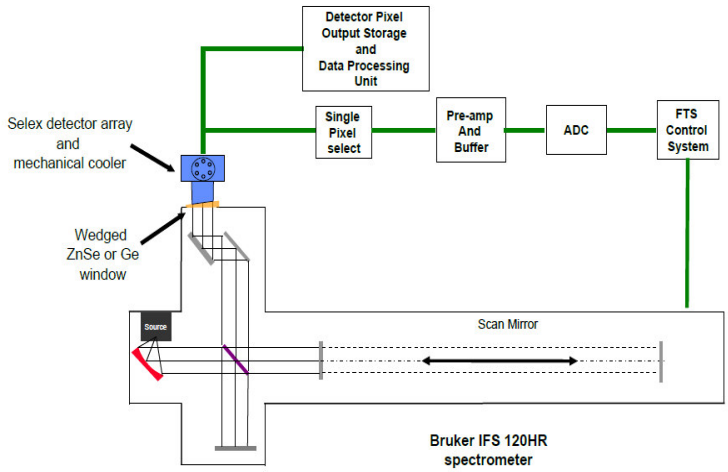
Accurate and well-sampled measurements of trace gases in the Earth's lower atmosphere, the troposphere, are required to understand the evolving radiative forcing of trace gases, the lifetime of greenhouse gases, and surface-atmosphere fluxes (natural and anthropogenic) of carbon, water and oxidising gases.

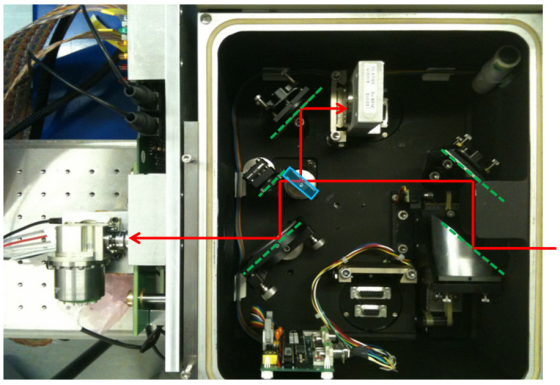
Infrared systems are excellent for measuring height resolved profiles of H_2O and O_3, as well as CH_4 and CFC related species which have anthropogenic sources. The sensitivity and high spectral resolution of thermal infrared Fourier Transform Spectrometers (FTS) allows a host of less abundant species, from CO to organic compounds to be observed. These science drivers will benefit significantly from use of a 2D detector array to improve resolution and coverage. The array offers a significant multiplexing advantage by combining 2D spatial information with simultaneous acquisition of spectral information. Each array pixel records an interferogram, which is a modulated optical path difference function and the Fourier transform of the input radiance signal.



The TIDAS-SPU project has brought together a team with expertise in climate/ atmosphere science, FTS techniques, thermal infra-red detector arrays, fast electronics and on-board processing. The project demonstrates how the latest infrared detector array technology may be coupled with an FTS in a generic design for infrared spaceborne FTS instruments requiring fast read-out and windowing capabilities.

The system has been optimised to test the performance appropriate to limb sounding missions such as PREMIER, although the findings are also relevant to nadir sounding missions. The findings from this project will help improve future infrared imaging FTS systems for space applications and for terrestrial remote sensing. The work has assessed nadir and limb instrument applications, surveyed extension of the Hawk detector wavelength band to 6-13

microns, assessed the effect of radiation in the space environment on the array detector read-out circuitry, and enhanced the demonstration system in key aspects of FTS processing from TRL 3 to TRL 4-5, and hence enabled a breadboard, ground-based demonstrator to be verified through measurements of atmospheric spectra.



The project has successfully developed and tested a fast electronics processing system which provides control of a 2D imaging array and manages the data generated from the array. The tests have shown that end-to-end functionality places a heavy demand on speed of data capture, processing and storage which remain key challenges if the full spatial resolution of the array is to be exploited. It also requires synchronisation of the laboratory FTS scanning mirror position (measured with the Bruker's internal reference laser), and the interferogram sampling electronics in the SPU.

The performance of the demonstration system is limited by two factors; firstly, the maximum frame readout rate of 400Hz sets a limit on the spectral resolution. It is expected that future developments in detector array read-out technology (such as, for example, in-pixel ADC) would enable this issue to be solved, whilst improvements in processor device technologies such as FPGAs and solid state mass memory will allow the on-board processing of the array data to keep pace. The second factor is the noise in the interferograms (and therefore the spectra) acquired by the system. The exact source of the noise observed is unknown, though the Hawk test data from Selex Galileo indicate it is not due to detector performance. This suggests that the noise is introduced at some point in the detector read-out/processing chain: further investigations would be needed to identify the exact cause.

The system has been used to perform a series of experimental tests with the Bruker IFS66 to measure the infrared transmittance spectrum of N_2O. The results of these tests have been analysed and provide insight into the system performance drivers. They demonstrate that the TIDAS-SPU demonstration system, as it stands, is able to detect gaseous species absorbing in the mid-infrared with some degree of spatial resolution, provided that the absorption features are broad enough to be resolved at a fairly coarse spectral resolution.

Publications

None to date

Grants and contracts

NERC has awarded two grants of MSF facility time to the project.

Training

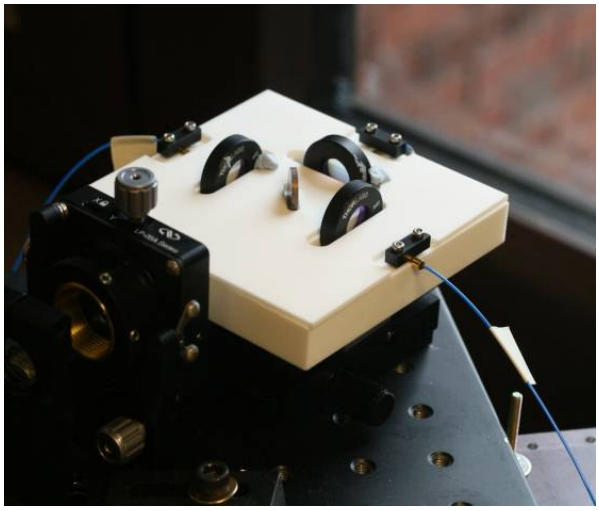
Cross disciplinary training in the methods and application of Fourier Transform Spectroscopy for Earth Observation satellites

Spin-out and exploitation

The TIDAS methodology is applicable to the following missions:

- PREMIER IR Limb Sounder 2016 (studied so far)
- MTG IR Sounder 2017/8
- EPS Second Generation IR Sounder 2018+
- Future high accuracy FTS for climate monitoring in the far infra- red e.g. CLARREO
- Spin-off to non-space instruments

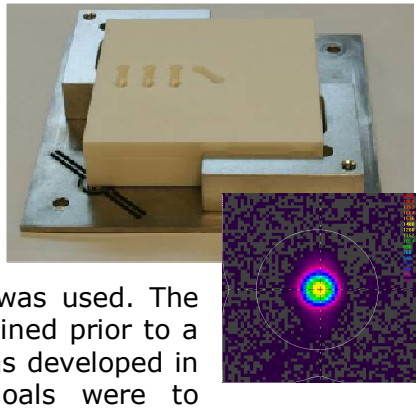
Hollow Waveguide Integration with Fibre



Current space LIDAR technology (e.g. ADM Aeolus) suffers performance problems with their high-powered lasers. LIDARs based on heterodyne detection are typically ten times more sensitive than direct detection systems, and thus need far lower power lasers. However the alignment of the transmitter and receiver optics must be near perfect for the system to work, and misalignment problems have plagued heterodyne LIDARs implemented with conventional free-space optics.

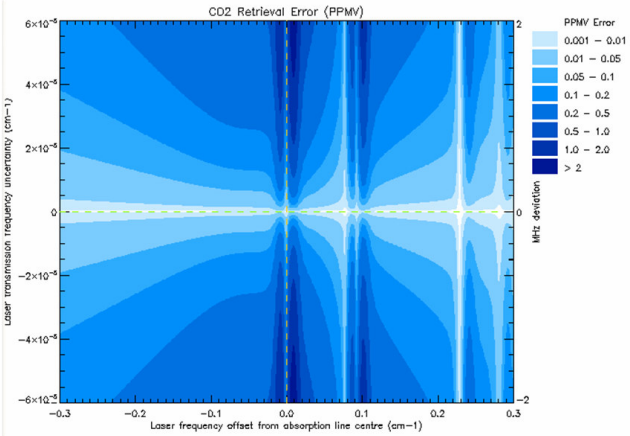
A hollow waveguide (HWG) is a way of implementing optical systems as channels cut into a solid stable substrate. It is directly analogous to familiar microwave waveguide systems, but scaled to optical wavelengths. Standard but miniature optical components such as mirrors and beam splitters are inserted into the optical paths in precision alignment slots. The implementation of heterodyne optical systems in a HWG in principle eliminates vibration-induced misalignment, making miniature heterodyne systems feasible. The work carried out by QinetiQ in CEOI Phase 2, set out to demonstrate the advantages of HWG for space optical systems, demonstrated space-worthiness of the technology, and developed techniques of integration of fibre optic couplings into a HWG.

Lead Investigator: Dr Brian Perrett, QinetiQ



In CEOI Phase 1, a HWG heterodyne Differential Absorption LIDAR (DIAL) instrument breadboard was demonstrated, and during CEOI Phase 2, the space qualification issues of HWG 'optical benches' were examined. Most recently, a CEOI seed-corn study examined the crucial step of coupling HWG systems to optical fibres for integration into complete systems.

For the qualification work a HWG test piece comprising a simple Michelson interferometer cut from a Macor ceramic substrate was used. The optical transmission and performance of this system were examined prior to a number of standard space environmental tests. The test plan was developed in collaboration with Leicester University. The performance goals were to withstand temperature extremes of -45 to +80ºC, far field instantaneous shock values of 2000 g and sustained vibration of 30 g RMS. The test piece was subjected to appropriate tests covering these thresholds and after each test the optical performance was measured. No significant deterioration was noted and therefore it was concluded that properly constructed HWG systems will perform well in space.

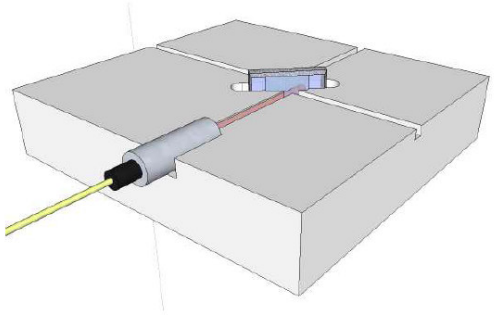


At the University of Leicester, the LIDAR instrument and atmospheric modelling work proceeded in parallel with the hardware testing. Their software model is now a flexible tool with which to investigate the retrieval accuracy of measurements by a specific or generic DIAL system. Here the focus of the work has been on retrievals of atmospheric CO_2 concentrations. The model accounts for atmospheric profiles of temperature and pressure and accurately models atmospheric scattering by

aerosols. The model also allows errors due to variation in the laser wavelength and line-width to be modelled, one of the primary sources of error in a Differential Absorption Lidar (DIAL) system. Terrain dependant effects are also modelled. The model predicts retrieval accuracy for the most important HWG and system design parameters which best fit the conditions for a heterodyne or direct detection system.

In most cases it will be necessary to couple a HWG system into other optics such as telescopic fore optics or beam scanning systems. One way to do this is using optical fibres. However the mechanical arrangement to deliver the beam accurately on axis and with an optimal beam waist is not yet mature. A CEOI seed-corn project addressed this issue.

A miniature HWG heterodyne mixer was mated with fibre feeds, and deployed in an existing terrestrial imaging LIDAR system. In order to keep costs low, COTS fibre couplings using GRIN lenses were used. This however caused difficulty as the optical axes of the COTS fibre tails were not aligned well with their geometric axes.



The HWG system was substituted for a fibre circulator in an existing 3D LIDAR instrument. The tests showed that combined fibre/HWG systems work extremely well in overcoming stability and alignment problems of free-space heterodyne systems. There is scope for further optimisation of the fibre coupling method to improve optical coupling efficiency. The technique promises a very compact and robust future generation of instruments, with general applicability, not restricted to space applications.

A further application of HWG technology of potential significant benefit is to RAL's Laser Heterodyne Radiometer Instrument is described in the following section. This combination of CEOI technologies represents a highly innovative development.

Publications

None to date

Grants and contracts

Pursued through RAL's LHR activities.

Training

- Provided increased exposure of HWG technology to other internal stakeholders
- Developed relationship with RAL precision manufacturing facility and were exposed to capabilities of RAL metrology facility.

Spin-out and exploitation

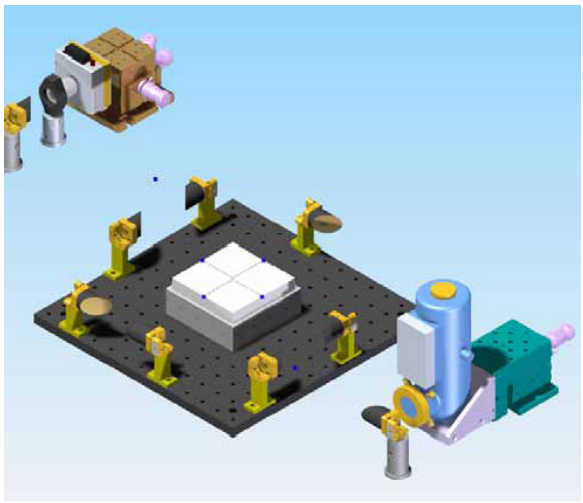
The HWG technology has been very successfully applied to RAL's Laser Heterodyne Radiometer instrument, which paves the way for a profound miniaturisation of RAL's instrument. This has led to consideration of LHR for terrestrial gas and vapour sensing applications. The CEOI LHR project is fully described separately below.

The HWG technology is now a candidate for deployment in DIAL-based active gas monitoring applications, and also in 3D imaging LIDAR for short-range space applications, and up to medium range terrestrial applications. Long-range applications e.g. for LEO Earth remote sensing are feasible, but further developments in laser technology are needed.

Laser Heterodyne Radiometer

Under NERC and CEOI funding, STFC RAL have developed a breadboard Laser Heterodyne Radiometer (LHR), which is a high spatial and high spectral resolution infra-red spectrometer for air quality applications, operating in the region 5-50μm region. It is a novel and alternative technique to the Fourier transform spectrometer (FTS). In the LHR, upwelling radiation from the Earth's surface is captured by a small aperture telescope and mixed with radiation from a low power miniature solid-state quantum cascade laser (QCL), acting as a heterodyne local oscillator. The mixed signal is imaged onto a high speed photomixer. The spectrum can be recovered either by tuning the frequency of the QCL, or by using a high-speed spectrum analyser. The breadboard is working well but needed to be miniaturised for spaceflight.

Hollow waveguide (HWG) uses waveguide techniques, familiar from microwave technology, at optical wavelengths. The waveguides are grooves cut in a dielectric (in this case ceramic) substrate, which allows optical systems to be miniaturised in an analogue of an electronic printed circuit. In another series of CEOI projects QinetiQ has been developing HWG for space instrumentation applications. CEOI noted that the technology could benefit the LHR project as a mechanism to miniaturise the instrument. In a recent CEOI seed-corn activity QinetiQ and RAL have replaced the core of the instrument with a hollow waveguide optical circuit, and achieved excellent performance

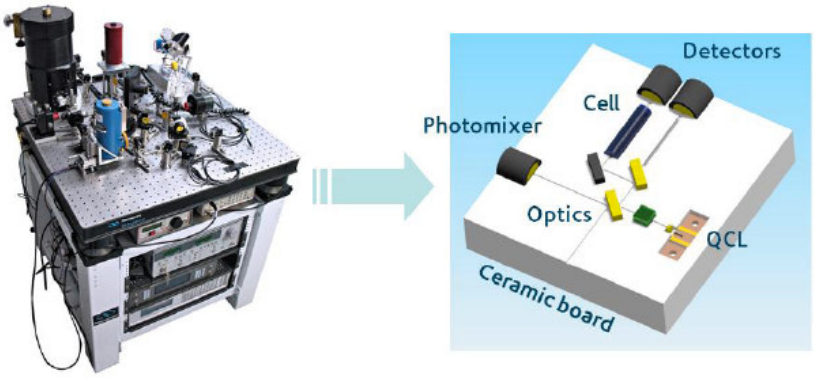


Lead Investigator: Dr Damien Wiedemann, STFC RAL

The overall objective of the Laser Heterodyne Radiometer development is to develop a new kind of remote sensing instrument of high sensitivity, with high spatial and spectral resolution, suited to atmospheric chemistry applications. A key step is to evolve the current bench-top instrument into a fully optically integrated design which is compact, rugged and cost effective, and therefore suited to space or airborne deployment. In addition, such a compact instrument is also suitable for terrestrial remote sensing of chemical species in the atmosphere. The LHR can retrieve concentration data in addition to identification of species.

The fundamental principle of the instrument is the heterodyne mixing of the radiation from the Earth's atmosphere, with radiation from a local oscillator derived from a miniature quantum cascade laser. The mixing produces a lower frequency RF signal on the photo mixer that can be analysed electronically. To this end, the CEOI funding allowed the core mixing section of the instrument to be replaced with a small hollow-waveguide optical circuit. This was found to work extremely well, and demonstrated three key advantages: (1) the new circuit required no time-consuming alignment, (2) it is proof against misalignment due to vibration or thermal disturbances and (3) the waveguide filters the incoming beam and significantly improves the transmission and mixing efficiency over the free-space version of the instrument.

Thus the principle is established that HWG is a viable method of producing a miniature LHR instrument, and the way is now open for the construction of a fully integrated LHR.



Laser Heterodyne Radiometer

A fully miniaturised instrument could fly on virtually any Earth or planetary orbiting spacecraft, including a cubesat. It is also ideal for deployment on aircraft or high altitude platforms such as airships. In terrestrial applications it can function as a very sensitive remote sensing 'nose' for gas and vapour detection in environmental monitoring, or in the security domain.

Publications

- Gerard Wysocki, Damien Weidmann, Kale Franz, Stephen So, Yin Wang, Coherent detection schemes for ultra-sensitive molecular spectroscopy in the mid-IR, Laser Applications to Chemical, Security and Environmental Analysis, Jan 31 to Feb 3 2010, San Diego, California
- Damien Weidmann, Using infrared laser heterodyne radiometry to search for methane on Mars, ESA Workshop on Methane on Mars, Nov 25-27, 2009, Frascati, Italy
- Damien Weidmann, New spectroscopic sensing applications with broadly tunable external cavity QCLs, Field Applications in Industry and Research, Sep 6-11, 2009, Grainau, Germany
- Damien Weidmann, Broadly tunable external cavity quantum cascade lasers and applications, Tunable Diode Laser Spectroscopy Conference, July 12-17, Zermatt, Switzerland
- Damien Weidmann, Applications of External Cavity QCLs: Broadband mid-IR Laser Heterodyne Radiometry Conference on Lasers and Electro-optics, May 31 – June 5 2009, Baltimore, USA
- Damien Weidmann, Brian J. Perrett, Neil A. Macleod, and R. Mike Jenkins, Hollow waveguide photomixing for quantum cascade laser heterodyne spectro-radiometry, Optics Express Journal, May 2011.

Grants and contracts

- Explosive detection platform - WP2.2 LWIR heterodyne system feasibility study. ITI Scotland Ltd
- Development of active heterodyne systems for stand-off chemical detection, Scottish Enterprise
- Widely tunable LHR for multi-species atmospheric tuning, NERC Technology Grant Award
- Systematic Comparison of LHR and FTS, STFC Innovation Ltd, Proof of concept award

Training

During the project a new member of the RAL spectroscopy group was trained in laser heterodyne detection methods and performed some of the performance evaluation measurements. A PhD student based at Oxford University Physics Dept. and Ph D student from Princeton University Elec. Eng. Dept. were trained in Quantum Cascade Laser optical systems and LHR developments.

Spin-out and exploitation

It is expected that the LHR can be adapted for High Altitude Platforms (dirigible) for localised remote sensing applications. Further, the concept, once fully miniaturised could form the basis of a stand-off detector for atmoshpheric contaminants in a variety of civil, commercial and security applications.

SGR-ReSI

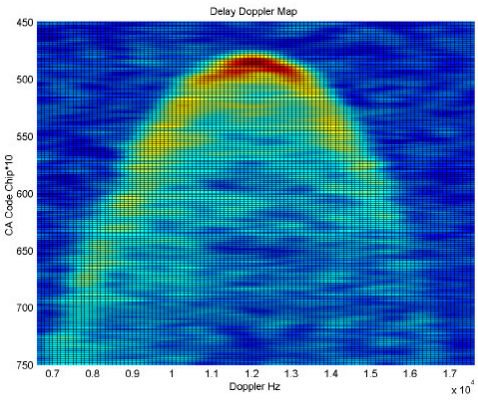
The SGR-ReSI instrument is a specialised space GNSS receiver which, in addition to providing timing, orbit and attitude information for the spacecraft, is able to perform remote sensing by a group of techniques known collectively as GNSS-R: The instrument exploits bi-static reception of GNSS 'reflections of opportunity' from the Earth's surface to determine sea state and surface properties. In addition reception of line of sight transmission of GNSS transmissions through the Earth's atmosphere to determine temperature, pressure, humidity and electron content profiles.

The instrument serves the dual purpose as the prototype of the next generation of SSTL's space GNSS receiver and, when equipped with suitable RF front-end amplifiers and antennas, as a low cost and novel GNSS-R remote sensing instrument.

This is the second development under CEOI funding, which was initially proposed to realise an engineering model of the instrument. Subsequently, SGR-ReSI has been selected to fly on TechDemoSat-1 and the instrument is being upgraded to flight standard for a technology demonstration mission.

Lead investigator: Reynolt de vos van Steenwijk, SSTL

In the SGR-ReSI project, SSTL and partners have pursued studies of the remote sensing potential of the instrument, and performed significant development and testing of hardware and on-board software. Good progress has been made, with a proto-flight-ready design available at completion. Some of the key achievements of this development have been:



- Use of the LEON3 processor and RTEMS operating system, realising a significant performance gain;
- Hardware design of the main electronics and the front-end daughter boards and the mechanical accommodation for the unit.
- Design of a dual-frequency LNA module with calibration load and temperature sensor LNA
- Antennae designs by the Surrey University Space Centre to meet the measurement needs.
- Implementation of software and VHDL for the System Controller, including a boot loader for stand-alone operation
- Implementation of an on board, real time Delay Doppler Map generator in the Virtex 4 co-processor, allowing on-board processing to greatly reduce downlink transmission requirements;
- Implementation of raw data playback capability and of reflection prediction algorithms;
- Completion of prototype testing, producing a range of representative measurements and performance indicators, over a range of temperatures.
- GPS L2C acquisition & tracking has been demonstrated, including enhanced testing conducted at ESTEC;

There is continuing effort to fully implement stable baseline software that will enable full testing of the hardware and all the operational targets of the SGR-ReSI in orbit.

The science investigations have continued in parallel. Only very small GNSS-R datasets are available to date from the receivers on the DMC spacecraft. The potential has therefore largely been assessed by modelling and simulation. A few months of data from the flight of SGR-ReSI on TDS-1 will allow these predictions to be verified and the full science potential to be assessed. However the current studies show that:

Ocean: GNSS-R can measure ocean winds (directional mean square slope - DMSS) to high precision with good spatial and temporal sampling, if sufficient instruments are flown simultaneously. This is potentially valuable for short-term (meteorological and operational) forecasting of wind and waves. Main conclusions:

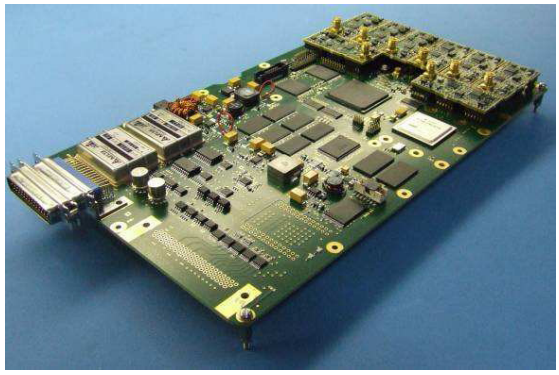
- The loss of NASA's QuikSCAT/SeaWinds instrument in 2009 created a gap that could be filled by GNSS-R, as ESA's ASCATT only partially compensates for the loss of QuikSCAT.
- In the longer term, SGR-ReSI can contribute to the GCOS observation programme, addressing wind/wave climate issues.
- The DMSS measurements provide valuable ancillary information for other instrument retrievals, such as SMOS Sea Surface Salinity and infra-red Sea Surface Temperature.

Atmosphere: The science case for using GNSS radio occultation to make measurements of humidity, temperature and pressure of the troposphere, and TEC from the Ionosphere has been well established. This study therefore focused on possible new applications of SGR-ReSI to atmospheric science, and the conclusions were:

- It is not clear that TEC can be derived from sea-reflected data. It may be possible from ice-reflections, but real data are needed.
- Open loop tracking may be beneficial in the ionospheric E-region (around 110 km), the tropopause (9-14km) and the lower troposphere (below 5 km).
- Monitoring other constellations such as Galileo would be beneficial in the future to provide a better ionosphere monitoring service.
- Real-time data offers the possible use in weather forecasting and has been shown to be very useful. Nevertheless data with greater latency can be used in global atmospheric and ionospheric modelling.

Cryosphere: The potential science applications of SGR-ReSI over ice covered terrain include:

- frequent observations of poorly sampled dynamic processes, particularly in regard to the marginal sea-ice zone;
- a long term observing infrastructure for detecting subtle changes over time, in relation to Arctic and Antarctic pack ice, snow accumulation and snow and ice facies on the ice sheets;
- penetration of ice and snow by L-band signals has the potential for altimetric observations leading to information on sea ice thickness and perhaps internal layers in ice sheets.



The development work undertaken was significantly influenced by the selection of SGR-ReSI as a payload on the UK technology demonstration mission TechDemoSat-1, when it became imperative that the hardware design was suitable for flight on this mission. Due to the very successful testing that had taken place on the prototype SGR-ReSI, the focus of the development was modified to iterate the design of the hardware and produce both an engineering model and a flight model for TDS-1 in parallel. This enabled SSTL to respond to the very demanding schedule required by TDS-1, but resulted in delays to the hardware manufacture due to the additional burden of review and checking required for manufacture of flight hardware. In consequence, the project schedule has been extended, and work continues with SSTL R&D funding to meet the TDS schedule. Testing to date shows that the build is in very good shape.

Publications

SSTL and SSC have produced many papers on the subject of the SGR-ReSI and GNSS reflectometry in general. The most recently published papers are as follows:

1. P.J. Jales, Surrey Space Centre, University of Surrey, UK; GNSS-Reflectometry: Techniques for Scatterometric Remote Sensing; ION GNSS 2010, Portland, Oregon, US;
2. M. Unwin, R. Steenwijk, SSTL, UK; C. Gommenginger, NOCS, UK; C. Mitchell, University of Bath, UK; S. Gao, Surrey Space Centre, UK; The SGR-ReSI - A New Generation of Space GNSS Receiver for Remote Sensing; ION GNSS 2010, Portland, Oregon, US;
3. Dr. Martin J. Unwin, SSTL, UK; The SGR-ReSI – A Small Satellite Instrument for Sensing the Earth using GNSS Signals; IAC 2010, Prague, Czech Republic
4. de Vos van Steenwijk, R; Unwin, M; Gommenginger, C; Mitchell, C; Gao, Steven; Jales, P; Introducing the SGR-ReSI: A Next Generation Spaceborne GNSS Receiver for Navigation and Remote-Sensing; Navitec 2010, Noordwijk, the Netherlands
5. M Maqsood, Bidhan Bhandari, S Gao, R de Vos van Steenwijk and M Unwin, "Dual-Band Circularly Polarized Antennas for GNSS Remote Sensing onboard Small Satellites", 7th IEEE, IET Symposium on communication Systems, Networks and DSP, July, 2010
6. M. Moazam, B. Bandari, S. Gao, R. de Vos van Steenwijk and M. Unwin, Development of dual band circularly polarized antennas and arrays for space-borne satellite remote sensing, 2010 European Space Agency Antenna Workshop for Space Applications, Oct. 2010, ESTEC, Netherlands
7. Clarizia, M. P., Di Bisceglie, M., Galdi, C., Gommenginger, C., and Srokosz, M.: A Numerical Study On The Influence Of Ocean Surface Waves On GPS-Reflected Signals. IGARSS 2010, Honolulu, 25-30 July 2010, 2010.
8. Clarizia, M. P., Di Bisceglie, M., Galdi, C., Gommenginger, C., and Srokosz, M.: What do reflected GPS signals tell us about ocean waves? A numerical study; GNSS-R 2010: Workshop on GNSS-Reflectometry, Barcelona, 21-22 October 2010.

Grants and contracts

The current primary spaceflight opportunity for SGR-ReSI is TDS-1. Members of the SGR-ReSI team are involved in the WaveSentry study, a Technology Strategy Board 'Harnessing Data' study. This is a UK industry consortium including NOC & SSTL, led by Marine South East Ltd who are compiling diverse data sources for marine forecasting. NOC & SSTL's contribution involves provision and processing of UK-DMC data to demonstrate application to wave forecasting, and will lay ground work for TDS-1 data preparation & dissemination. There are ongoing discussions with ESA. An EE8 SGR-ReSI bid, although unsuccessful, has attracted interest. There is interest from NOAA via SSTL-US regarding SGR-ReSI for a NASA mission to investigate applications of GNSS-R

Training

SGR-ReSI has provided PhD training for four students from University of Surrey Space Centre, University of Southampton National Oceanography Centre and University of Bath.

Spin-out and exploitation

- The SGR-ReSI is also the basis of SSTL's next generation space GNSS receiver product.
- It is anticipated that the private sector will be interested in considering GNSS-R data in their services to deliver wave information to sea-going users, such as offshore wind farm services, long-haul shipping companies or passenger ferries, for which near real time measurements of wind and wave conditions with GNSS-R data could be a significant innovation.

Seedcorn Studies

The following pages contain information about smaller, seedcorn studies carried out under CEOI funding:

Optical Integral Field Unit (Astronomy Technology Centre) - A study of an instrument using a precision image slicing mirror to reformat the focal plane of a long-slit spectrometer, forming a highly efficient optical system for use in climate monitoring

Use of Microslice Arrarys for Hyperspectral Imaging (University of Durham) – Design and construction of a small breadboard instrument using 'integral field spectroscopy', based on an array of micro-lenses to provide many hundreds of spectra in an image plane

Frequency Selective Surface (FSS) Filter Technology (Queens University Belfast) Manufacture of very low loss quasi-optical filters at microwave and submillimetre wave frequencies, exploiting computational electro magnetics, precision micromachining and mm-wave metrology

SuperSAR (University of Leeds) – Study of a novel synthetic aperture radar instrument (SAR) mission to measure Earth surface deformation in 3-dimensions, to monitor ice sheet and glacial flow, the geology associated with carbon capture and storage, earthquakes and volcanoes

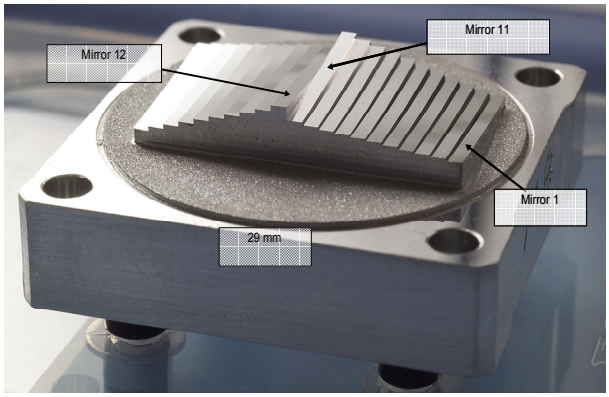
Detecting Methane Bubbles (Cranfield University) - A study to investigate the potential for using a satellite SAR to estimate methane release from thawing permafrost regions. The experimental work used laboratory simulations of methane bubbles in ice, and made representative measurements of the radar backscatter.

Wavemill (Astrium) – Development of the science case and on-board processing requirements and architecture to handle the large amount of data for an ocean topography synthetic aperture radar instrument

MISRlite – Multi-angular IR Stereo Radiometer (MSSL/UCL) – Development of a Thermal Infra-Red (TIR) instrument laboratory demonstrator to determine wind fields from day/night cloud observations. The project explored the optical and sensor design issues associated with an uncooled thermal IR (TIR) system and a linear pushbroom detector technology of low mass, power and size

Air Quality Monitoring from High Altitude Platforms (Astrium) - Use of high altitude platforms in the form of powered airships flying at 20km altitude for monitoring urban pollution. The study considered its potential for the continuous monitoring air pollution and considered technology readiness, operational scenarios and full-life mission costs

Optical Integral Field Unit

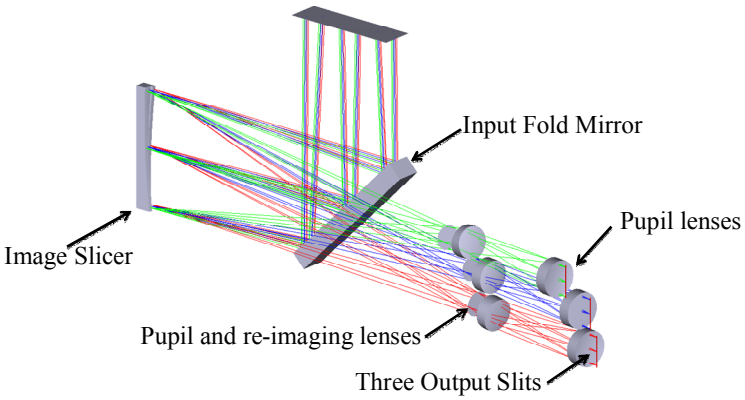


The Integral Field Unit is the first of two CEOI Seedcorn projects to adapt astronomical image slicing techniques to Earth remote sensing. The idea is to slice up the image plane of a telescope into multiple zones, which can be taken independently to several dispersive systems. This can lead to spectrometers that are compact in design, and use expensive detector 'real estate' most efficiently. In this project, ATC Edinburgh have adapted the concept from the Mid-IR Instrument MIRI on the James Webb Space Telescope to an infra-red spectroscopy application aimed at atmospheric greenhouse gas remote sensing. The slicing element is a diamond-turned multi-faceted mirror, the core of the Integral Field Unit (IFU).

Lead investigator: Andy Vick, STFC ATC Edinburgh

The aim of this design-only Seedcorn study was to demonstrate how IFUs can be applied in an EO instrument design to:

- Improve greenhouse gas measurement capability (bandwidth, throughput, resolution) compared to the Nasa Orbiting Carbon Observatory OCO.
- Reduce instrument weight/cost
- Increase instrument redundancy
- Springboard IFU designs into future EO missions
- Publicise UK capability in image slicer design and manufacture.



The diamond-turned multifaceted mirrors are in practice limited to the infrared region by surface finish issues, but this is ideal for many important atmospheric chemistry applications. ATC have studied the science need for greenhouse gas monitoring, re-examined the heritage of the OCO spectrometer, and have performed a design study for an IFU based instrument.

The output of the study is a spectrometer design with estimated mass of ~ 60kg as opposed to the OCO spectrometer which is ~150kg. The IFU instrument features two spectrometer arms versus three for the OCO instrument. However the IFU instrument features longer optical arms to achieve the desired dispersion on the detectors. Performance is estimated to be comparable or better than the OCO design, but there are a number of trade-offs and issues to be considered in future such as:

- Transmittance comparison: there are complications in comparison between the linearly polarised case (OCO) and polarisation scrambling.
- Costing complexity: Estimation of a complexity metric w.r.t. OCO is required
- Effect of detector performance: The availability of MCT detectors makes comparison difficult at the design level.

Optical Integral Field Unit

Publications

- Refereed publication is planned in JARS (Journal of Applied Remote Sensing)

Grants and contracts

Although early days, ATC will:

- Bid for additional funds from CEOI to develop breadboard model of IFU spectrometer
- Bid to NERC/STFC to develop and fly related (non-IFU) spectrometer on BAe146 and NASA Globalhawk UAV

Training

- ATC staff have received on-the-job training in EO technologies on this project.
- CEOI PhD student James Barlow (U. Edinburgh/ATC)

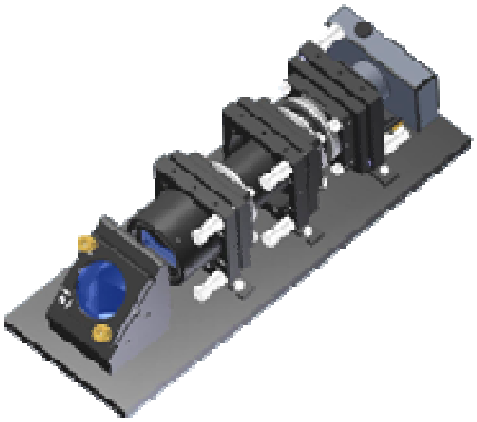
Spin-out and exploitation

A spin-across of technology from astronomy to EO. There has been knowledge exchange among the following:

- Edinburgh GeoSciences / UK ATC partnership
- Univ. Leicester
- NCEO
- COST UAV groups

MicroSlice

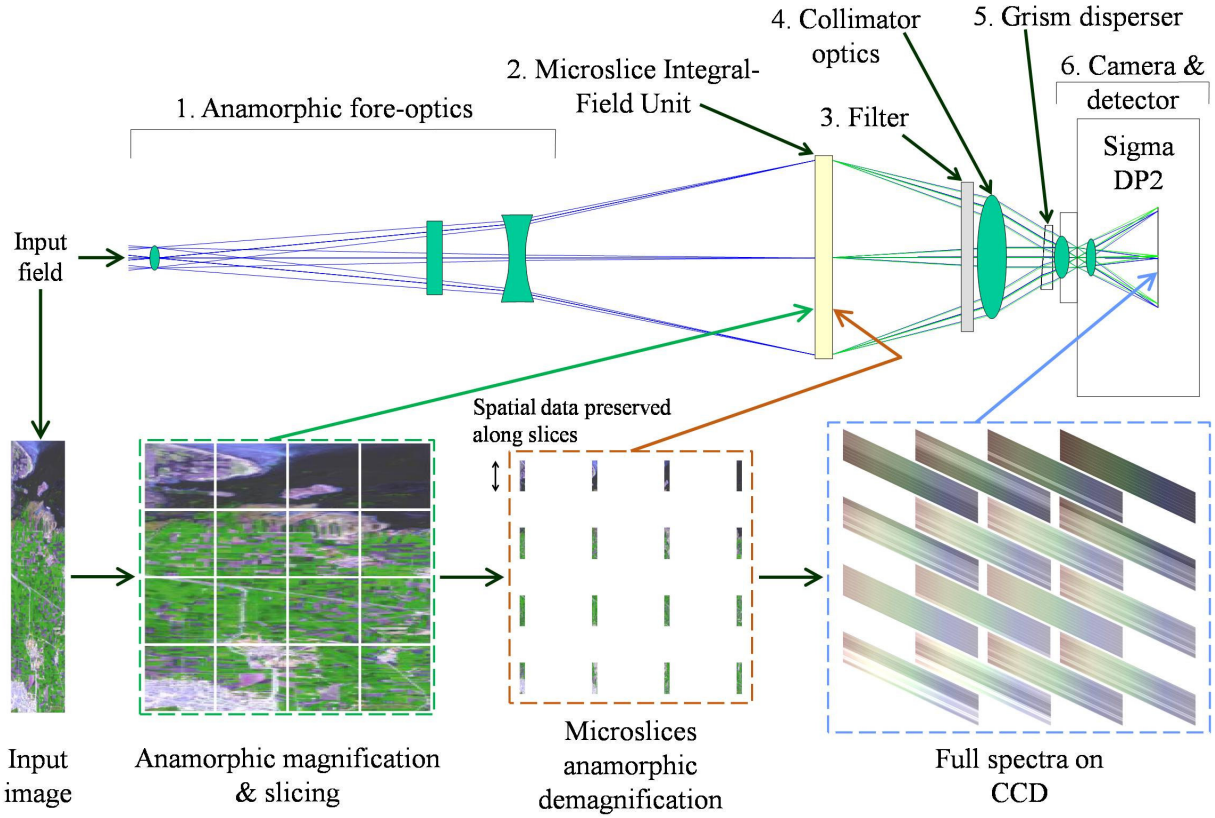
The Microslice project is a seedcorn activity which exploits image slicing techniques developed in astronomy. Unlike the IFU project from ATC, it uses a lenticular lens array as the slicing element. The purpose is to develop a compact visible and NIR hyperspectral imager for environmental monitoring from space. Following a design exercise it has been possible to build a practical demonstrator instrument using predominantly COTS components, which can be used in the laboratory and in the field.



Lead Investigator: Prof Ray Sharples, University of Durham

The science driver for the current project is to monitor spectral signatures from the environment such inland water biology, sediment and vegetation health from space. Durham also has interested science users who can exploit such a capability in terrestrial applications.

The fore optics of the instrument design is a telescope, which presents an image field to an anamorphic lens, which stretches the image in one dimensino. The microslicer (an integral field unit with lenticular lens array) chops up the stretched image into an array of slit images. A 'grism' is used to disperse each of these slit images onto a detector CCD array.



Costs have been kept low by using a COTS camera instead of a bespoke detector array, and COTS optical components have been used wherever possible. The Centre for Advanced Instrumentation at University of Durham have built custom mounts and have integrated all components to make a rugged instrument, which is indicative of the form a space instrument might take, and is also robust and stable enough to take out of the lab for some field trials.

MicroSlice

Publications

Journal paper planned (Optics Express and International Journal of remote sensing.

- UK Optical Designers Meeting, Culham, 16 Sep 2010 (Poster)
- Applications of Astronomy Conf, Edinburgh, 13-15 Oct 2010 (Oral)
- IoP Spectral Imaging Conf, Telford, 3 Nov 2010 (Oral)
- STFC Environment Futures Workshop, RAL, 11-12 Nov 2010 (Poster)
- Hyperspectral Imaging Conference, Strathclyde, 17-18 May 2011 [Oral]

Grants and contracts

- University capital projects fund
- University Seedcorn fund

Training

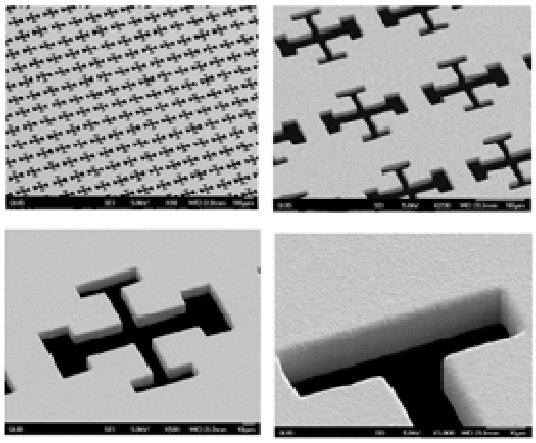
- NERC-funded CEOI studentship.

Spin-out and exploitation

- Applications for airborne and terrestrial instrumentation for environmental monitoring
- Applications in industrial process control under investigation
- Collaborations under investigation with SSTL, Leicester University

Frequency Selective Surfaces

Space-borne sub millimetre wave radiometers operate by detecting thermal emission from the Earth's surface and atmosphere. The wavelength of the thermal emission retrieved provides information on the observed geophysical phenomena important to numerical weather forecasting and climate monitoring. Detection of emissions at millimetre and sub-millimetre wavelengths enables the discrimination of cirrus cloud components intermediate between those accessible in the IR and microwave ranges. However current limitations in technology prevent full exploitation of this part of the electromagnetic spectrum.



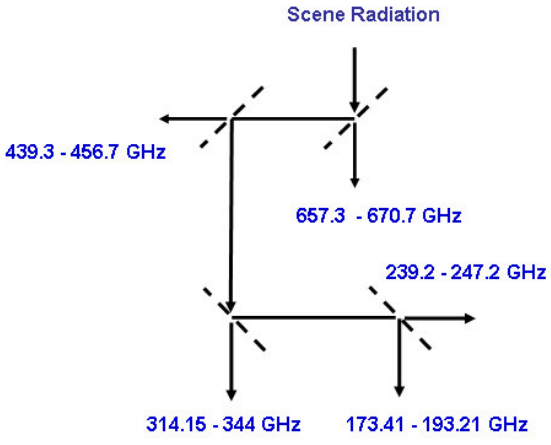
In sub millimetre wave instrumentation, frequency selective surfaces (FSS) are used both as beam splitters and to separate frequencies in the optical path. The usually consist of thin metallised grids of carefully fabricated apertures which act as tuned radiators. This seedcorn project was driven by the needs of ESA's planned EPS 2nd Generation mission, which will carry a radiometer operating at frequencies up to 700 GHz. The importance of this technology has been identified by ESA as critical to improving scientific instrument sensitivity for future scientific missions.

The current project builds upon a project from Phase 1 of CEOI technology, which developed FSS technology up to 456.7 GHz.

Lead investigator: Robert Cahill, Queens University Belfast

This seedcorn project aimed to develop a prototype sub mm wave Frequency Selective Surface (FSS) which is required for the EPS 2nd Generation mission (launch date ~2018). The required maximum operating frequency of 664 GHz is more than 50% higher than other resonant FSS structures previously constructed for EO missions. The objective of this project is to demonstrate the UK's capability in FSS design, fabrication, and spectral measurement techniques up to 700 GHz.

The selection of the preferred FSS element shape was obtained from a detailed design study using CST electromagnetic simulation software. Precision micromachining processes have been developed to construct freestanding FSS structures and new techniques have been employed to measure the transmission and reflection spectral responses. The experimental transmission and reflection coefficients are shown to be in close agreement with the computed results in the range 173 – 671 GHz, and the measured filter loss is significantly lower than the specification in all the discrete frequency bands.



This is the first time in Europe that a dual polarised resonant FSS has been designed and micro-machined in this frequency band. The UK's sub millimetre wave spectral measurement capability has been significantly enhanced by (i) the procurement and use of new corrugated feed horns which extend the frequency range to 700 GHz and (ii) the manufacture and installation of additional ellipsoidal mirrors which have been employed in the QO test system to enable reflection measurements to be made for the first time.

Frequency Selective Surfaces

Publications

- Cahill, R et al, Recent Advances in Submillimeter Wave FSS Technology for Passive Remote Sensing Instruments, EuCAP 2010
- Dickie R, et al, 664 GHz Dual Polarisation Frequency Selective Surface, IET Electronics Letters, date tba
- R. Dickie, R. Cahill, H. Gamble, V. Fusco, M. Henry, M. Oldfield, P. Huggard, N. Grant, Y. Munro, and P. de Maagt, Submillimeter Wave Frequency Selective Surface With Polarisation Independent Spectral Responses, Proc. IEEE Antennas and Propagation, vol. 57, pp. 1985-1994, 2009
- R. Dickie, R. Cahill, H.S. Gamble, V. F. Fusco, S. P. Rea, N. Grant, and B. Moyna, "Single sideband FSS with high image rejection," IEE Electron. Lett., vol. 42, pp.1137-1138, 2006.
- R. Dickie, R. Cahill, H. Gamble, V. Fusco, A. Schuchinsky, and N. Grant, "Spatial Demultiplexing in the Sub- mm Wave Band Using Multilayer Free-Standing Frequency Selective Surfaces", Proc. IEEE Antennas and Propagation, vol. 53, pp. 1903-1911, 2005.
- R. Dickie, R. Cahill, H.S. Gamble, V.F. Fusco, B. Moyna, P. G. Huggard, N. Grant and C. Philpot, " Micromachined 300 GHz high Q resonant slot frequency selective surface filter," IEE Proc. Microwaves Antennas and Propagation, vol.151, pp. 31-36, Feb. 2004.

Grants and contracts

- FSS Technology, QUB, Invest-NI, RDA project
- FSS Filters, MWS FSS development QUB/RAL for ESA, In relation to MWS and MWI instruments on EPS 2nd Generation
- FSS Filters, Liquid Crystal technology development, QUB/Astrium/Exeter/Spain, outcome awaited ESA, liquid crystal technology which includes tunable FSS for future spaceborne radiometers

Training

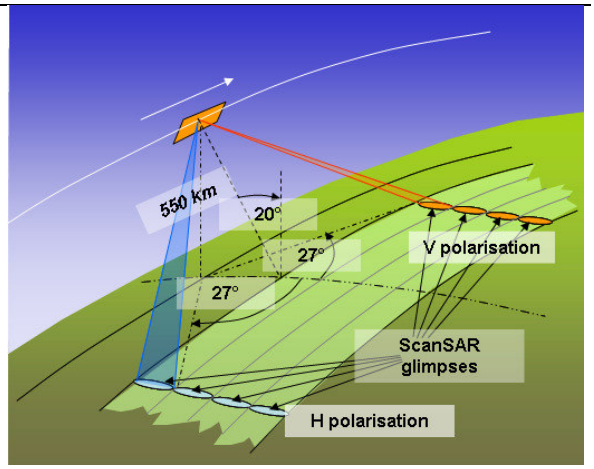
CEOI NERC CASE student at Queens University Belfast. The project is entitled 'Electronically Scanned Rotman Lens Antenna with Liquid Crystal Phase Shifters', supervised by Dr Robert Cahill and Dr N Mitchell at QUB and Dr Graham Maxwell-Cox at Astrium.

Spin-out and exploitation

The work addresses the technology needs for the EPS 2nd Generation Microwave Imager instrument which is under development (Phase A) and scheduled for launch in 2018. This therefore strengthens UK expertise and capabilities in EO instrumentation and will help to position QUB together with industrial partners Astrium Ltd and RAL, to win leading roles in future European space programmes.

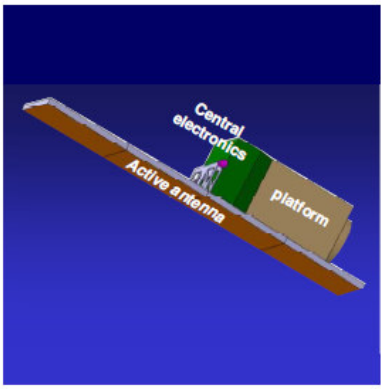
SuperSAR

SuperSAR was a design study led by the University of Leeds in support of a proposal into the recent ESA Earth Explorer Announcement of Opportunity. SuperSar is a dual-azimuth Synthetic Aperture Radar mission which requires only a single satellite platform to detect surface deformation in 3D, and should provide a major advance in the capability of Interferometric SAR (InSAR) instrumentation. The work was completed in spring 2010, in time to feed into the ESA call for proposals. Although unsuccessful, largely on the grounds of cost, the technical aspects were acknowledged to be of high standard and ESA remain very interested in the concept for future missions.



Lead investigator: Prof. Andrew Shepherd, University of Leeds

Earth surface deformation is the primary signature of a wide range of geophysical processes. The SuperSAR mission uses a space-based, L-band radar instrument to provide 4 distinct viewing geometries, enabling SuperSAR to make measurements of Earth surface motion in three dimensions. It uses a novel dual-azimuth interferometric SAR technique to detect simultaneously Earth surface motion in two directions - perpendicular and parallel to the instrument flight path. The study aimed to simulate the interferometric performance of the instrument when mounted on a satellite platform, and to quantify the improved capacity of the satellite to detect Earth surface deformation in three dimensions. The primary scientific objective is to measure Earth surface deformation to a sufficient precision to improve predictions of hazardous events, to assess the stability of geological formations for the processing of geo-resources, and to assess the stability of Earth's ice sheets.



The investigators have designed an instrument, a spacecraft platform, a mission scenario, and a data retrieval scheme, all of which formed the basis for the proposal into ESA. The proposed mission is capable of measuring tectonic strain rates with an uncertainty of 1.2 mm/yr (or better) over 100 km in three dimensions. The mission's ability to meet its objective was tested by computing the area of the planet where tectonic strain will be above SuperSAR's detection limit. The study concludes that SuperSAR has a dramatically superior capability over current and planned missions. Factoring in coherence, 93% of the areas straining above 1.2 mm/yr over 100 km will be measureable. This compares with just 31% for Sentinel-1 and 13% for Envisat.

Publications

Proposal to ESA Earth Explorer 8 Call. Not selected, but highly regarded technically.

UNIVERSITY OF LEEDS

ASTRIUM
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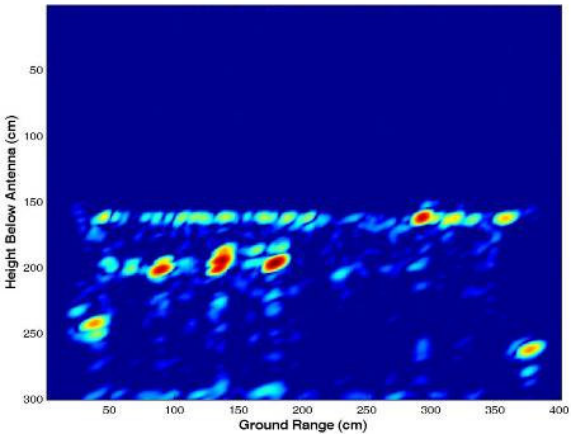
Detecting Methane Bubbles

Release of methane from thawing permafrost regions threatens to put vast amounts of this potent greenhouse gas into the atmosphere. One method of estimating the methane flux is by the observation of methane ice bubbles trapped within lake ice. Very recently, the potential of the use of SAR for estimating methane ebullition was reported, based on satellite measurements related to field observations. This CEOI seed-corn project pursued a programme of work to further investigate that link, using laboratory simulations of ice bubbles, and representative radar backscatter measurements.

Lead Investigator: Dr Keith Morrison, Cranfield University

It is possible to construct a good representation of gas bubbles in ice in the laboratory using a large trough filled with dry sand, and introducing expanded polystyrene shapes and spheres to represent the gas voids. A suitable radar scatterometer above the trough offers the opportunity to quantitatively analyse their radar signature in a carefully controlled, repeatable environment. In particular, the work aims to show the feasibility to use SAR backscatter for the detection and characterisation of methane ice bubbles. If satellite SAR can quantitatively characterise bubble spectra, it will allow us to provide regional and pan-arctic estimates of current and future methane fluxes.

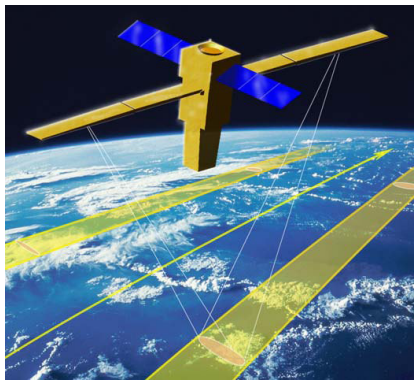
Realizations of various representative ice and bubble types were constructed using artificial materials with similar radar characteristics (sand and polystyrene). The new tomographic profiling (TP) technique was used to provide vertical profiles of the scattering through the sand volume. A bespoke microwave measurement facility was specially built for the project at Cranfield. This provided a 2D 3.7m x 0.5m horizontal linear scanner some 3.2m above the floor, imaging along the length of a 4m (l) x 1m (w) x 0.9 (h) sand trough.



A wealth of data was systematically collected against target type characteristics, radar frequency (4-19GHz), polarisation, and imaging geometry. It represents a huge data set, of which only a small part has so far been examined in any detail. Even so, the data has already provided new and informative insights into the scattering behaviour of ice and ice bubbles. In terms of recommendation of observation parameters for the best characterisation of bubble presence some results are clear, whilst others are still tentative.

Cranfield UNIVERSITY

WaveMill



Wavemill is a novel interferometric SAR concept which offers the prospect of generating wide swath, high resolution, high precision maps of ocean topography and surface currents. Wavemill is a single spacecraft system which avoids the difficulties of synchronisation and baseline estimation associated with single pass interferometric SAR based on spacecraft constellations (the so-called 'cartwheel' or 'helix'). Wavemill is a candidate core mission for ESA's Earth Explorer 9 series with a nominal launch in 2020. The Wavemill system provides oceanographic imagery over the open ocean and over coastal regions.

This CEOI seedcorn study has focussed on the science case for Wavemill in the context of actual and planned oceanographic mapping systems, and on the on-board processing which is required to manage the large volume of raw image data generated by the SAR instrument.

Lead investigator: Dr Alex Wishart, Astrium

The Wavemill study considered the main science drivers for oceanography, the international mission context, and on-board processing issues required to implement a successful oceanography mission with Wavemill. The algorithmic investigation was based upon multi-rate Digital Signal Processing (DSP) techniques developed by Astrium Ltd for telecommunications payloads. The study has concluded:

Science: Wavemill can satisfy the need for ocean topography and ocean current measurements with a single satellite system. Combined with reprogrammability, the onboard processing can be optimised to maximise the duty cycle, make best use of the downlink capabilities and address the user needs. It is suggested that the Wavemill processing should focus on cross-track interferomeric retrieval in the open ocean to retrieve sea surface height over relatively coarse spatial scales (10km), and should switch to high-resolution Along Track Interferometry (ATI) mode only over coastal and shallow water regions, where information on ageostrophic currents is required.

International Context: For ocean surface current mapping, the main contender is an ATI SAR mission, but no mission is planned. For ocean surface topography, the two main missions are AltiKa and SWOT. AltiKa will demonstrate that Ka-band can deliver improved range retrieval with a smaller instrument than Ku-band systems, without detrimental sensitivity to rain. SWOT also operates at Ka-band, allowing a shorter interferometric baseline that relaxes some of the constraints on platform stability that plagued WSOA. Wavemill therefore would address important science for ocean surface topography and ocean current vector measurements with complementary approach to AltiKa and SWOT. A window of opportunity exists in the next 5-10 years when Wavemill could rapidly progress to a full space mission.

On-board processing: The Wavemill concept relies on the generation of Level 1 SAR products on board. The user community would prefer the raw data sent for ground-based processing to mitigate possible loss of science value in the on-board data processing. Wavemill therefore requires a trade-off between potential loss of information on-board, and the constraints of the on-board memory and downlink bandwidth. With averaging of the interferograms, the downlink data rate is comfortably within the capability of the system. Therefore margin exists to do less averaging on board and so preserve more of the basic information down-linked to the ground. The on-board generation of SAR images is computationally intensive. A relatively simple and flexible algorithm for range compression based on sub-band decomposition has been identified. The processing rates and memory requirements are achievable with current Xilinx FPGA and SDRAM technology. Physically, the processor would be similar to Astrium's GDPU in mass, volume and power consumption.

WaveMill

Publications

1. Gommenginger , C., Wishart, A., Srokosz, M., and Richards, B.: A Roadmap for the Wavemill 2D Ocean Current Mapping System: On-board Signal Processing & Hardware Architecture Definition. Towards High-Resolution of Ocean Dynamics and Terrestrial Surface Waters from Space, 21-22 October 2010, Lisbon International Fair, Lisbon, Portugal, 2010.

Grants and contracts

- ESA plans to issue ITTs in late 2011/early 2012 for a Wavemill Phase 0 study and technology studies, for the on-board processor and for the antenna. This CEOI Seedcorn activity has provided NOC and Astrium Ltd with positioning to make successful proposals when these ITTs are issued.
- Starlab is an important potential partner in any future ESA work on Wavemill, and through this study they recognise that Astrium Ltd has competence in the on-board processor implementation.
- In the immediate term, the links between National Oceanography Centre and Astrium Ltd have been very useful in preparing the winning proposal to ESA for the Wavemill Airborne Demonstrator, starts in May 2011.

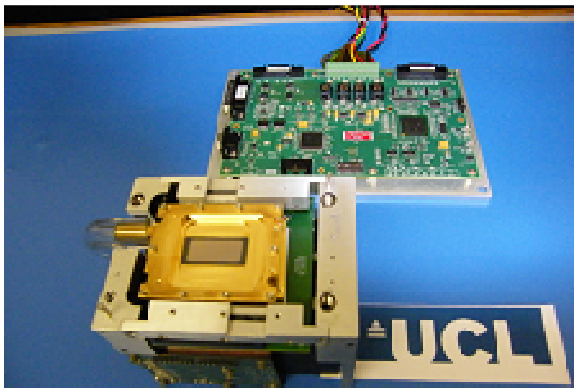
Training

- The Study has achieved the objective of making the UK science community, i.e. the National Oceanography Centre, aware of the satellite on-board processing competence within UK industry, and of the key technologies which would feature in a Wavemill processor.
- From the Astrium perspective, the study has been a valuable exercise in understanding the science application, the driving requirements, and how these are mapped onto a processor implementation.
- Two Astrium graduate engineers have been engaged on Wavemill system analysis.

Spin-out and exploitation

1. European Patent Application EP11275041.9 SAR Data Processing

MISR Lite



MISRlite is a seedcorn project to develop a laboratory demonstrator for a Thermal Infra-Red (TIR) Instrument to determine wind fields from day/night cloud observations. MISRlite is based on the approach pioneered by the MISR (Multi-Angle Imaging Spectro-Radiometer) instrument on the NASA Terra satellite, which has successfully operated in orbit since 2000. For MISRlite the use of a single set of optics and no in-flight calibration is proposed. The project explored the optical and sensor design issues associated with an uncooled thermal IR (TIR) system and a linear pushbroom detector technology of low mass, power and size.

MISRLite seeks to close an "observational gap" by providing dense cloud-top surface observations of winds and accurate heights both day and night, especially in data poor areas such as between 55-75º of latitude where there are insufficient wind observations, especially for the accurate prediction of (sub-)polar storm tracks and cyclogenesis

Lead investigator: Prof. Jan-Peter Muller, MSSL, University College London

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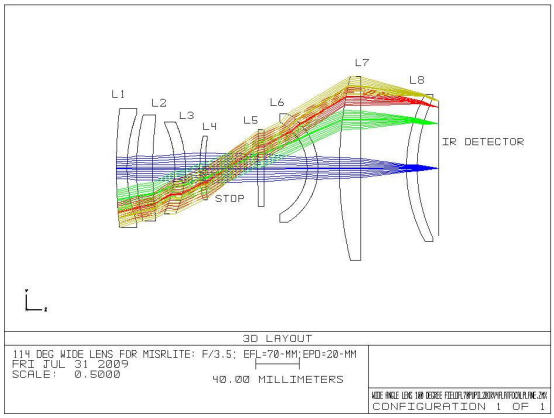
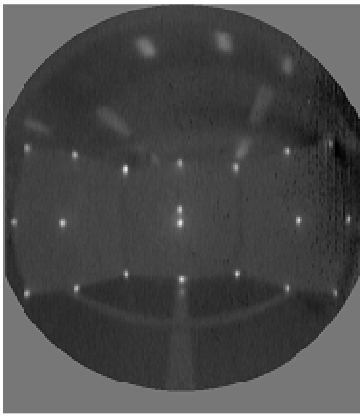


Existing TIR pushbroom sensors have insufficient NEdT (signal to noise ratio) for immediate spaceborne application without on-chip sensor signal averaging and subsequent reduction in spatial resolution. To explore superior alternatives, an experimental set-up was established to investigate use of both 2D arrays (ferro-electric) and a linear microbolometer array. Optical design was performed under sub-contract by the Astronomy Technology Centre in Edinburgh. who established a design and order specification which was one third of the mass of an equivalent system designed at JPL for a possible TIR version of WindCam.

Such MISRlite sensors carried on a constellation of some 3 micro-satellites will provide daily coverage and with 9 micro-satellites could provide synoptic 3-hourly coverage from a platform such as Iridium Next.

The MISRlite concept requires an instantaneous 1D FOV (swath) of ~1500km perpendicular to the spacecraft motion, and ground pixel size of ~300m. Thus, the detector requires 5000 pixels. INO (Quebec) are considering development of a 2500 pixel array, so two of these could provide the required FOV and resolution (although dealing with a data gap in the central line on a curved focal plane will be challenging). In the basic MISRlite configuration, 5 of these pushbroom units are required in a single focal plane behind the lens system:



- 2 looking forwards (~+57° and +30°)
- 1 looking down
- 2 looking aft (~-57° and -30°)

A more comprehensive version would have two additional pushbrooms looking approximately downwards with narrower spectral bandwidths (at 10.8µm and 12.2µm) to identify atmospheric features such as smoke and ash.

The requirement for low mass is addressed by using uncooled detectors, thereby saving the mass, power, complexity and expense of cooling systems. The microbolometer arrays being considered require temperature stabilisation rather than cooling, and this can be achieved using relatively low power thermoelectric coolers (TEC).

Owing to the high cost of building bespoke TIR instrumentation, a COTS approach appropriate to a seedcorn project was adopted for the demonstrator. A COTS TIR lens/camera was adopted for the main imaging optics. A microbolometer array system was rented from INO. A bespoke calibration target array was constructed at MSSL.

These lab based experiments have allowed the requirements for the WINDS instrument to be refined and have supported performance calculations for the EE8 WINDS proposal. It has been possible to image the sky and develop preliminary software to further verify the MISRLite concept.

Publications

1. Jan-Peter Muller, David Walton, Daniel Fisher, Mullard Space Science Laboratory, UCL, UK, "AMVS from ATSR2-AATSR and the proposed uncooled thermal IR pushbroom MISRLITE constellation", Tenth International Winds Workshop, 22-26 February 2010, Tokyo, Japan

Grants and contracts

The work in this small study has contributed to a bid submitted to the ESA Earth Explorer 8 call as part of a WINDS platform. Unfortunately, this bid was not successful due to extremely heavy competition.

Training

Through working on MISRlite and collaborating with partners on optics, detectors etc., the MSSL team has learnt a significant amount in areas such as TIR optics and TIR imaging detectors. Information has also been fed back to collaborators, for example 2D images to INO obtained using their 1D detector and electronics with MSSL's scan mirror.

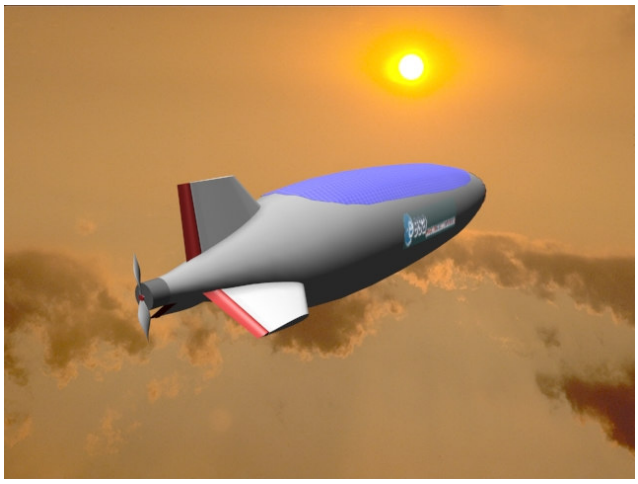
Spin-out and exploitation

Negotiations and investigations are under way to secure a flight on platforms such as Iridium, and joint US-European missions. Further development and launch opportunities are being sought to realise this unique concept over the next 5-7 years.

MISRlite is a suitable instrument candidate for the putative UK Sovereign mission with the UK Met Office as an anchor tenant. The UK Met Office is very enthusiastic about the concept after a recent presentation in Exeter.

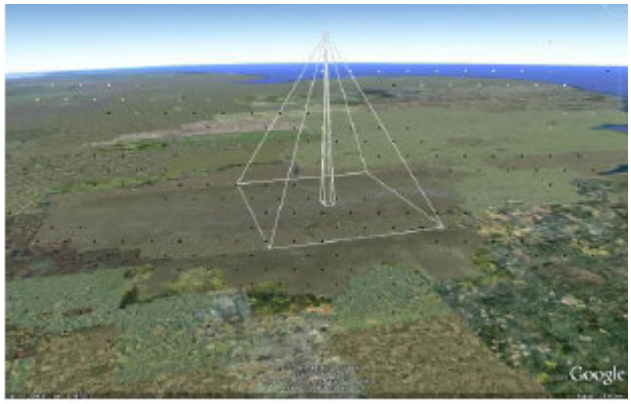
High Altitude Platforms

This seedcorn study examines the role of High Altitude Platforms as a component of the Earth observing system. The team have chosen a strawman payload addressing atmospheric chemistry and air quality using a mix of active and passive instrumentation. A large powered airship concept under development by Lindstrand has been chosen as a platform that can operate continuously at ~70,000 ft, and carry a large payload of up to 500kg. The study considers instrumental issues, systems issues, mission aspects, and looks at the regulatory aspects of operating such a platform above controlled airspace. The study outputs include a full assessment and a technology roadmap.



Lead investigator: Tony Sephton/Nic Leveque, Astrium Ltd

By flying at an altitude of ~20 km where wind speeds are lower, HAPs can maintain a roughly stationary position with respect to the ground, and hence provide an observing platform for key locations (e.g. cities) and the atmosphere (e.g. pollution). The aim is to provide near-continuous observations, with low operating costs, and long mission life, giving the prospect of dedicated platforms covering environmental "hotspots". As well as rapid deployment, HAPs can also provide benefits of close range (hence excellent spatial resolution), high data capacity, and flexible configuration. The ability to recover payloads from HAPs also offers a potential test-bed for the development of EO space-borne instrumentation. The current Lindstrand concept will exploit solar cells for power generation, and a regenerative fuel cell system to store energy for position and altitude maintenance at night.



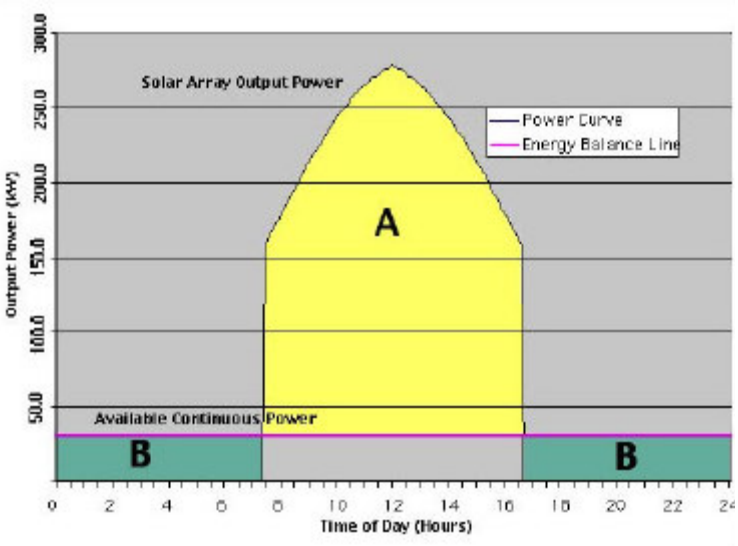
Poor air quality has been shown to adversely affect human health, and is the subject of international directives. Source quantification and trend assessment are significant challenges facing the UK air quality community. Many current data are derived from models and data interpolation, rather than absolute measurements. Monitoring from HAPs would provide a valuable new tool complementing existing satellite and ground-based measurements.

In order to operate in UK air space, the airship will need an EASA certificate of air worthiness. The time required for such certification could be up to 2 years. Air space restrictions while operating at the cruising altitude are virtually none. The transit altitude will probably require some form of air traffic permission, but providing this takes place in an agreed location there is no reason why this should be withheld.

The proposed payload complement is a UV/Visible/NIR/SWIR spectrometer and a Lidar. The UV/Visible bands (300-600nm) can be used to provide measurements of nitrogen dioxide, ozone, sulphur dioxide, some halogenated species, certain VOC's, water vapour and some aerosol information. The O2A (755-775 nm) band provides significantly more information on aerosol properties. Short-wave infra-red (1.6-2.4 μm) provides information on carbon dioxide and methane, while the thermal infra-red (3 μm upwards) contains strong bands for ozone,

sulphur dioxide and water vapour. Visible imagers provide valuable information on polluters and allow accurate geolocation of measurements.

The results show that 340 kWh's is sufficient energy storage in non-gusty conditions at low latitudes (e.g. London). The percentage of time spent at the target in 6 months was calculated as 92%. At higher latitudes, on-station time is reduced as the HAP must expend more power to maintain position. Hence, overall mission performance is critically dependent on winds, particularly in the winter.



A combined increase in three of the most important HAP parameters (i.e. energy storage to 2700 kWh, motor power to 400 kW, and solar panel area to 8000 m2), leads to a drastic improvement in mission success. The deviations from the way-points are directly associated with brief but strong gusting wind conditions which in many cases lie above the 95% capability of the individual parameters. The way-point coverage of the new HAP configuration is 90%.

The biggest technology challenges are on the platform design such as the fuel cell and electrolyser system and management of the thermo-balance between day and night. Other critical issues are the overall design and operating principles and concepts (such as ground handling, ascent / descent and in-flight operations), development of lightweight structures, selection of materials (particularly for the hull), the propulsion system (e.g. optimized propeller efficiency), and the integration of photo-voltaic cells into the hull material.

On the payload side critical technologies include a UV-sensitive detector and the manufacture and testing of 'grisms' and IR detector arrays for the UVNS spectrometer, and the laser reliability and the scan mechanism for the Lidar. However, these developments are not subject to the severe constraints of space instrumentation, but nevertheless provide a good intermediate step to space qualified variants.

Publications
None to date

Grants and contracts
None identified

Training
The HAP mission performance modelling has been supported by James Lawrence (CEOI PhD student).

Spin-out and exploitation
In addition to numerous Earth observation applications, there are numerous potential applications of HAPs in telecoms and navigation applications.

ASTRIUM AN EADS COMPANY University of Leicester Lindstrand TECHNOLOGIES

Knowledge Exchange

All the main CEOI technology projects are built on knowledge exchange through their academic-industrial partnerships, resulting in many practical benefits in cross-sector fertilisation and in training.

Qi3 Ltd are the CEOI KE partner and carry out specific KE activities targeted at maximising the benefit of the CEOI programme by identifying the full range of applications for the technologies under development. The activities include enabling the exchange of expertise and knowledge between the science base, industry and the EO user communities and aims to contribute to the economic competitiveness of the UK, effectiveness of public services, policy and quality of life.

Technology mining

Qi3 worked with the CEOI project teams to identify relevant existing technologies from outside the EO space community (spin-in) and/or technologies from the CEOI projects which can be applied in other areas (spin-out). This process is recognised as a long-term activity and spin-in/out benefits from the initial CEOI projects are still arising. The outputs from the activity are Technology Mining Evaluations and these have been provided for CompAQS, Microwave Millimetre & Sub-millimetre Radiometry, MISRlite, miniaturisation of the LHR and TIDAS.

Publicity and dissemination

More than 50 articles publicising the CEOI have been issued, targeted at audiences in space technologies and in related fields, including through the Sensors and Instrumentation KTN. Publicity has been through the KITE newsletter, the STFC Innovations Newsletter, NERC News, the Aerospace and Defence KTN and other publications.

A Technology Showcase was held in central London to advertise CEOI funded technologies for the purposes of possible technology exchange and collaborative development. It attracted 70 attendees from academia, industry (space and non-space) and public bodies.

Brokering Prospects

This activity is targeting opportunities in other application areas, identified as potential users of CEOI developed technologies. Qi3 make initial contact with candidate organisations on behalf of the CEOI, with a view to putting the parties in direct contact when justified by the potential. Three case studies have been produced which describe instrumentation and technologies developed by CEOI and their potential for application to alternative markets.

Qi3 has provided assistance to four CEOI project teams to prepare bids into sources of additional funding. They have also raised awareness and provided some initial guidance to a number of teams intending to bid into the CEOI Open Call.

Study of Commercial EO Requirements

A report was produced by Qi3 to identify the commercialisation requirements for Earth observation (EO) and the implications for future instrumentation capability. It highlights a number of opportunities to spin-out EO instrumentation capabilities to non space applications and markets. Particularly promising areas identified were the environmental, energy, and transport & safety sectors as first priority. This is due to the market sectors experiencing a higher level of maturity for EO instrumentation.

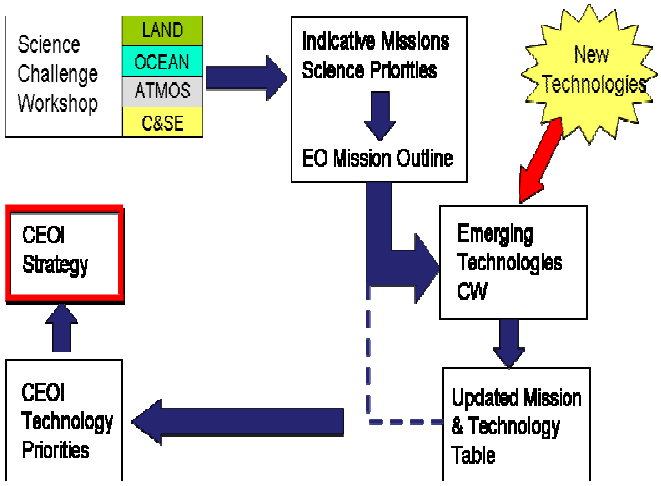
The report recommends that the CEOI better positions itself in the supply chain for the advancement of EO instrumentation in future phases by:

- Continuing to influence and educate the key players in the upstream portion of the supply chain on the technical and commercial benefits of the technology.
- Aligning activities in supporting instrumentation advancement to opportunities in EO value added services.
- Continuing to engage with the end user sector and feed back market requirements that can be translated into instrumentation programmes.

Horizon Scanning

The aim of the CEOI horizon scanning program is to assess science and policy needs, together with the potentially disruptive technologies that can be pulled through into EO. This includes adapting and adopting technologies being developed elsewhere and from applications other than EO. Out of this process of scoping the science, policy and technology drivers there is a requirement to identify and prioritise UK interests in current and future EO missions through a range of implementation (flight) options. This is described in the next section.

During Phase 1 of the CEOI a series of Challenge Workshops was held to investigate potential future missions arising from the main areas of Earth observation science: atmosphere, oceans, land, cryosphere and solid Earth. The 'Future Missions' Challenge Workshop held at the start of Phase 2 carried through this work by reviewing and rationalising the resulting 'Indicative Missions' and their instrument requirements. This was followed up with a 'Round Table Meeting with NCEO to bring together overall conclusions and priorities.



Challenge Workshops held during Phase 2 investigated a range of science and technology questions for EO. All these workshops brought together a wide range of expertise from academia and industry, provided insights into the future needs of EO instrumentation and of the technologies and expertise available in the UK to meet these challenges. In total across Phase 1 and 2 the CEOI Challenge Workshops have attracted more than 400 attendees from nearly 100 different organisations.

Workshop Title (Phase 2)	Number Attending	Venue
Future Missions	25	University of Leicester
Surface/Atmosphere interactions	40	Centre for Ecology and Hydrology (CEH), Wallingford
Instrumentation for Future Operational EO Missions	29	Leamington Spa, Warwickshire
Enabling technologies for future Lidar missions	50	The Cosener's House, Abingdon
Detector technologies	26	Stratford Upon Avon, Warwickshire
Future space-based radar missions	35	Gorse Hill, Woking, Surrey

CEOI Annual Conferences were held at the University of Warwick Conference Centre on 29/30 April 2009 and on 22/23 April 2010. The Conferences covered the UK science priorities for EO, the requirements derived from these and the technologies for future EO missions and instruments. More than 60 experts from academia and industry attended each conference.

Indicative Missions

A key element of the challenge workshops is the synthesis and integration of the science and technology outputs through development of indicative mission concepts, providing a vehicle to develop UK science and technology led mission concepts and to identify pathways for realisation.

The set of indicative missions were reviewed at the Future Missions challenge workshop held at the University of Leicester in October 2008. A follow up 'Round Table' meeting was held with NCEO on 16th February 2009 to discuss and prioritise the Indicative Missions. This section summarises the findings from the workshop and the Round Table meeting. It identifies the priority indicative missions for each of the science areas and summaries the main attributes for each of these missions.

The objective of the Future Missions Challenge Workshop was to draw some conclusions and priorities from a series of indicative missions and to answer the questions:

- Can we identify priority mission(s) for the UK to promote?
- What are priority science areas for future development and action?

These answers are drawn from an evidential base and outline mission assessments identified at the challenge workshop series. The output from the workshop started the development of a strategy for future UK missions.

The set of indicative missions was used as the basis for a joint round-table meeting with NCEO. The meeting was not constrained by known funding opportunities. In some cases there is a good matching of missions to potential funding sources e.g. GSTP represents a real funding opportunity for UK. In considering each of the indicative missions, three possible next steps were identified:

- Make a bid - interested parties (scientists and industrialists) could lobby the UK Government for funding, to help create a mission opportunity. Ideally the outcome would be to help create a funding line against which the potential mission could be bid.
- Carry out a study - identifies the need for further work to be carried out on the mission concept, the science case and/or the enabling technology to bring it to the required TRL
- Shelve the mission concept - indicates that it may be considered again, but not at this stage.

An additional outcome of the meeting was to identify key technology areas to develop UK capabilities. This must be based on a good understanding of existing UK technology capabilities and it was recognised that a considerable effort will be required to ensure good alignment is achieved between the priority missions and UK capability.

The recommendations from the meeting feed into the future CEOI programme, by underpinning and defining the CEOI technology/instrument strategy. It is used to define the priority for future Open Calls.

The meeting endorsed the CEOI recommendation that all three Earth Explorer 7 mission candidates are to be treated with equal priority.

NASA, as a potential partner, is following the Decadal Survey programme, which defines its immediate programme and which may be difficult to influence at this stage. It is understood that NASA is seeking an MOU with NERC in EO. In a discussion on the ITAR issue, at the mission level the RAL experience is that ITAR can become less of an issue when working with a US partner.

Indicative Missions

The Round Table meeting was the first time that UK EO community had come together to assess and agree priorities and is a vehicle to set the priorities for a significant period. Whilst it was not envisaged that this will be an annual or more frequent process, equally it was not likely to be a one-off event. It was felt that there should be a method of refreshing the strategy at approx 2-4 year intervals.

Science Area	Mission	Instrument /CEOI Technology	Flight Opportunity	Status
Methane Measurement	GMES Sentinel 5 pre-cursor	GRISM based high resln SWIR spectrometer	ESA Sentinel 5 pre-cursor	Flight development in progress
UT/LS Composition	PREMIER	STEAM-R TIDAS (eg for AMIPAS TIR-FTR)	ESA Earth Explorer 7	In Phase A
Sea State	Integrated Altimetry mission	SGR-ReSI	TechDemoSat-1	High Flight Readiness
Temperature and water vapour profiles	EPS 2nd-Generation	Microwave sounder and imager	MetOp – 2G	In Phase A
Air Quality	Tbd	CompAQS	Bi-lateral or TechDemoSat-n	Under development as CityScan (ground based)
Canopy Measurement	SpecL	Multi-spectral Lidar	ESA Earth Explorer 8+	Proposal not selected for EE8 - under further development
Clouds and Wind	MISR-lite	Multi Angular IR Stereo Radiometer	Iridium Next-generation & Earth Explorer 8+ NASA Earth Venture	Under consideration for NASA EV and Iridium Next
Topography/Strain	SuperSAR	Interferometric SAR	ESA Earth Explorer 8+	Proposal not selected for EE8 - under further development
GHG over the tropics	Tropical Carbon Mission	CMS (Carbon Monoxide and Methane Spectrometer)	NASA Earth Venture 2 bi-lateral	Bi-lateral funding required
Establishing climate benchmarks	Clarreo	SW spectrometer, IR interferometer, GNSS RO receiver	NASA Decadal Survey	Mission on hold
Atmospheric composition	Tbd	Laser Heterodyne Radiometer	tbd	Development and miniaturisation of instrument in progress
Atmospheric Composition	Tbd	Hollow Waveguide based Lidar	A-SCOPE et al (EE8+)	Technology well developed ~TRL5
Oceanography	Tbd	Wavemill	tbd	Early CEOI and ESA studies
Atmosphere, land	Tbd	Microslice and integral field spectrometers	tbd	Using technology developed for space science applications

Summary of Indicative Missions

Training

The long term objectives of the CEOI training and development programme are (1) to develop a highly skilled workforce capable of meeting the needs of academia and industry in EO instrumentation and (2) to provide a leadership pool able to deliver world-class EO missions and instrumentation.

The training programme addresses the needs of the academic and industrial community at all stages of their development, from early stage training, for those in industry and academia immediately following their first degree, through to skills and leadership development for those with more experience.

Training Workshop

The 2nd CEOI Training Workshop on 'Designing and delivering an instrument concept' was held in London in March 2010 with 45 attendees. The workshop looked at the fundamentals of EO instrumentation techniques and included two workshop sessions which allowed participants to develop a better understanding of the inter-relationship between the science requirements, the instrument design and the mission parameters. Excellent feedback was received from participants who found it a very worthwhile workshop.

PhD studentships

CEOI sponsored NERC PhD studentships are selected by an independent panel. Calls for proposals for additional NERC CEOI PhD Studentships were issued during Phase 2. Monitoring of these studentships is via an annual student report and student presentations/posters at suitable CEOI events. The CEOI has now approved and is supporting ten NERC PhD Studentships.

Title	Institution	Status
Potential for LiDAR to measure CO_2 sources and sinks from space.	Univ. of Leicester	Started Oct 2007, writing up
Development of sub-mm heterodyne technology	Univ. of Leeds	Started Oct 2007, writing up
Electronically Scanned Rotman Lens Antenna with Liquid Crystal Phase Shifters.	QUB (CASE with Astrium)	Started Oct 2009
Development of a Fabry-Perot Etalon Spectrometers for High-resolution NIR/SWIR observation	Univ. of Leicester	Started Oct 2010
LiDAR Measurement of Forest	UCL (CASE tbd)	Started Oct 2010
Study of a Far Infra Red Spectrometer for Climate Studies	Imperial College (CASE: Astrium)	Started Oct 2009
Multi-spectral imaging for EO	Univ of Edinburgh	Started Oct 2010
Optimisation and design of an air quality monitoring instrument	Univ. of Leicester	Started Jan 2011
Advanced Technologies Hyperspectral Imaging	Univ. of Durham	Started Oct 2010
Remote Sensing using GNSS Reflectometry	Univ. of Surrey	Starting Oct 2011