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EO INSTRUMENT DEVELOPMENTS IN THE UK CENTRE FOR EARTH OBSERVATION INSTRUMENTATION

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ABSTRACT

The UK Centre for Earth Observation Instrumentation (CEOI) is carrying out a series of earth observation instrument development projects using innovative technologies. It was created in 2007 as a result of joint support from the Natural Environment Research Council (NERC) and the Department for Innovation, Universities Skills (DIUS) and is operated by a partnership of academia and industry, led by Astrium with QinetiQ, University of Leicester and the Rutherford Appleton Laboratory. Its key aim is to build and strengthen UK capabilities in future space instrumentation for earth observation through the teaming of scientists and industrialists. In this paper the authors describe the novel technologies and instrumentation under development by the Centre partners in preparation for future earth observation missions. These include compact optical systems for air quality monitoring; the use of hollow waveguides in near infra-red LIDAR systems for remote sensing of the Earth's canopy and carbon dioxide; and passive microwave radiometry for remote sensing of atmosphere composition. In addition some 'seedcorn' activities are underway to investigate novel techniques for remote sensing of variables important in the understanding of climate change and Earth system science. The paper also describes the methods that the Centre has used to understand the main UK science priorities and to match these to UK technical and instrumentation capability.

INTRODUCTION

The Centre for Earth Observation Instrumentation (CEOI) brings together scientists and engineers from academia and industry to develop the UK capability in Earth Observation (EO) technologies and instrumentation and supports the preparation and submission of EO mission and instrument proposals to ESA.

The CEOI is set up as a partnership led by Astrium together with QinetiQ, University of Leicester and STFC/Rutherford Appleton Laboratory.

The CEOI has a science-driven, project-based vision with key drivers being scientific need, priority and user benefit, technological innovation, development of advanced instrumentation, reduction of mission risk and cost. The CEOI is distributed in nature, using the strengths of the partners to provide key staff and permitting cost effective access to senior and experienced personnel. This combined expertise, available across all the relevant areas of science and technology, ensures successful delivery of the CEOI's strategy.

During its first year the CEOI has delivered measurable results through well-targeted technology projects. The first instrument development programmes address the key atmospheric problems of climate interactions and air quality. These are near term science priorities well matched to existing UK academic and industrial capability.

The projects address clearly identified gaps in short- and mid-term instrumentation requirements that have opportunities in ESA EOEP, GMES Sentinel and post-EPS programmes, where UK developed technology will have the largest impact.

Three further seedcorn technology development projects were carried out in Phase 1 following selection of proposals through an Open Call to the UK EO community.

The CEOI has worked with leading scientists from the NERC Centres of Excellence, the NERC Centre for EO (NCEO) and the broader user community. They have been actively engaged by the CEOI in the development of the science drivers and critical instrument technologies. Scientists are part of each instrument project team to ensure that technology development is aligned with scientific need. This has the added benefit of developing the science team members' skills - as leaders and advocates - so that they may themselves lead future international mission proposals and programmes.

Challenge Workshops

During its first year the CEOI led a series of Challenge Workshops to bring together leading UK EO scientists and technologists in the major areas of Earth system science (land, ocean, atmosphere, cryosphere and solid earth). These workshops identified the scientific drivers of high importance to the UK science community, the future EO missions required to support these and the technologies relevant to each of these missions. A final 2-day Emerging Technologies Workshop was held to bring together the findings from the 4 science-based workshops and to identify the existing UK technical strengths, from both space and non-space sectors. These workshops successfully attracted and received input from a significant section of the UK EO scientific and technological community.

Knowledge Exchange

Knowledge exchange (KE) is the process of applying knowledge gained by experts in one area to skilled staff in the same and additional application areas. KE is a significant part of the CEOI activities, including through the instrument development programme, which has allowed young engineers and scientists from academia and industry to work alongside, and learn from more experienced colleagues from both sectors. A targeted KE programme has been commissioned from Qi3 Ltd, the CEOI KE partner. The programme has focused on 'technology mining' to identify potential applications of CEOI developed technologies in both space or non-space areas, with detailed investigations of the CEOI technologies matched against potential users. In addition a Space Instrumentation Special Interest Group has been set up to further opportunities for KE between the space and non-space sectors, in both directions. Finally, a KE workshop was held at University of Leicester in June 2008 to present the CEOI technologies to an audience of more than 60 attendees from the space and non-space industries, resulting in establishment of contacts between the CEOI teams and potential applications outside of the EO space sector.

Training

The CEOI has provided training for the next generation of EO instrument scientists and technologists through the technology projects and through a specific training workshop held at Kings College, London in May 2008. The workshop, 'Leading a Successful Space Mission', was attended by more than 30 participants and included presentations by leading industrialists and academics from the EO community.

Further information about the CEOI and its activities is available at www.ceoi.ac.uk.

TECHNOLOGIES UNDER DEVELOPMENT

[a]Passive Sounding of the Atmosphere

Passive remote sensing of the atmosphere from space at millimetre and sub-millimetre wavelengths is directed towards the investigation of processes linking atmospheric composition and climate and their assimilation into operational systems used to forecast weather and in the future, air quality. Further improvements of radiometer technologies in terms of sensitivity, frequency performance and resource use is crucial to the improvement of applications in the terahertz spectral region.

The work being undertaken in CEOI is designed to address this issue, so that the UK will be well positioned to exploit future millimetre and sub-millimetre radiometry in programmes already proposed for both EU/ESA GMES Sentinel and Eumetsat post-EPS satellite missions. Specifically developments have focused on new, critical technology for two distinct, but complementary instrument developments.

1. STEAM-R is a passive microwave limb sounder, proposed by Sweden as a nationally funded contribution to the PREMIER mission. STEAM-R is dedicated to the investigation of chemical, dynamical, and radiative processes in the upper troposphere and their links with the Earth climate. It is designed to measure emission from H_2O, O_3, CO and other trace gases (e.g., HNO_3 and N_2O) in the frequency range 300-360 GHz. STEAM-R will utilise an array of receivers, which will image different tangent heights simultaneously to providing unique information about the 2-D structure of the atmosphere.

2. Cirrus sounding instruments have been presented as possible Explorer missions (CIWSIR and GOMAS) and post-EPS will include a sounder and/or imager for which extension to sub-millimetre is under consideration. A similar instrument has been base-lined for the UK Facility for Airborne Atmospheric Measurements (FAAM). In general, these instruments consist of a number of radiometers (extending from millimetre wavelengths to near-terahertz frequencies) that can sound the atmosphere in order to discriminate cirrus components intermediate between those accessible in the IR and microwave. Although Schottky diode receiver technology is known to work at frequencies up to 1THz, the high frequency radiometer channels required by a future cirrus instrument, e.g. at frequencies around 462, 684 and 875GHz, have not yet been demonstrated with the required performance.

Key technologies chosen for development include a new sideband separating sub-millimetre, mixer, local oscillator (LO) source technology and a novel substrateless optical filter. In addition, a new optical methodology for designing microwave instruments was investigated [2] and scientific support has been provided to the STEAM-R Phase 0 Explorer study.

Excellent success has been achieved. CEOI Phase 1 highlights include the following:

- Radiative transfer and retrieval simulations have underpinned the STEAM-R instrument baseline design.
- STEAM-R is focused on the upper troposphere, in alignment with scientific objectives of PREMIER, NCEO Atmospheric Composition Theme and the wider UK community,
- Novel image separation mixer technology (SHIRM), based on UK Schottky diodes, has been demonstrated by Astrium and RAL [1]. The UK is well positioned to supply critical technology (mixers, optical filters) and other hardware for STEAM-R.

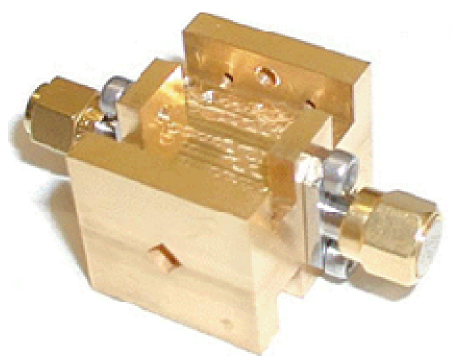

Fig 1 SHIRM 360 GHz image separator mixer using Schottky diode technology

- Astrium has developed an optical design methodology that accurately predicts antenna patterns for sub-millimetre radiometer instruments
- Novel, generic, filter technology has been developed by Queen's University Belfast and Astrium and demonstrates state-of-the art low loss performance [3].
- Two studies, precursors of a possible airborne cirrus instrument have been started.

The UK involvement in STEAM-R through continued work under CEOI in preparation for the PREMIER Explorer Phase 0 study will consolidate UK excellence in THz radiometry.

This work is led by Dr Dave Matheson of STFC-RAL with Astrium and Queens University Belfast

[b]CompAQS – The Compact Air Quality Spectrometer.

Measurement of atmospheric compounds with climate change or air quality implications is a key driver for the ground and space-based Earth Observation communities. Techniques using UV/VIS spectroscopy such as differential optical absorption spectroscopy (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 a key enabling technology.

Using designs from Surrey Satellite Technology Ltd (SSTL) [4], a breadboard demonstrator of a novel UV/VIS spectrometer has been developed. The Compact Air Quality Spectrometer (CompAQS) demonstrator has been constructed and tested at the University of Leicester's Space Research Centre, significantly improving the maturity of this technique. The spectrometer provides an exceptionally compact instrument for DOAS applications from LEO, GEO, HAP or ground-based platforms.

The spectrometer features a concentric arrangement of a spherical meniscus lens, a concave spherical mirror and a curved diffraction grating. This compact design provides efficiency and performance benefits over traditional concepts, improving the precision and spatial resolution available from space borne instruments with limited weight and size budgets.

The spectrometer offers high throughput with a spectral range from 300 to 450 nm at 0.5nm resolution, suitable for DOAS applications. The concentric design is capable of handling high relative apertures, owing to spherical aberration and coma being near zero at all surfaces. The design also provides correction for transverse chromatic aberration and distortion, in addition to correcting for the distortion called 'smile' – the curvature of the slit image formed at each wavelength. These properties render this design capable of superior spectral and spatial performance with size and weight budgets significantly lower than standard configurations.

Following successful specification, design, procurement, and build phases, the instrument was characterised at the University of Leicester, with the following key conclusions:

1. The required gratings for concentric spectrometers can be manufactured effectively.
2. The stray light characteristics of such gratings are exceptionally good, with the grating made for this project exhibiting stray light ranging from 0.14% at 300 nm to 0.06% at 450 nm.
3. With highly-polished optics (eg surface roughness of 0.1 nm), the stray light within the CompAQS instrument, based on measurements of grating stray light by the grating manufacturer, could be in the region of 0.16% at 300 nm, and 0.072% at 450 nm.
4. The target spectral resolution of 0.5nm has been achieved, with a spectral resolution of 0.3 nm also measured using a narrower entrance slit.
5. A Gaussian line shape has been measured along the entrance slit with an R2 value in the range 0.996 to 0.999
6. The spatial resolution has been measured as 0.1 mm on the entrance slit, giving over 500 resolved elements over the 52mm entrance slit.

7. The “smile” of the system has been measured as being less than half a pixel (13 μm) over the 13 mm of the focal plane sampled by the CCD detector.
8. An atmospheric spectrum has been measured using the CompAQS spectrometer which demonstrates the potential of this spectrometer for DOAS applications when coupled with appropriate entrance optics.

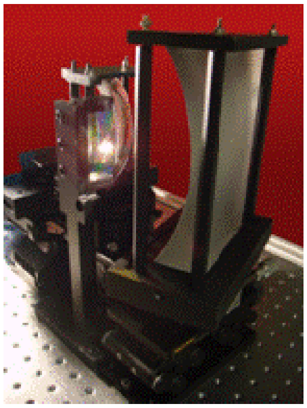

Fig 2 CompAQS optical breadboard

The CompAQS project has brought together a very successful academic and industrial team, strengthening the UK capability in UV/Visible spectroscopy. A complex and novel optical system has been designed, built and tested to budget and within timescales. This operational breadboard demonstrator significantly enhances the maturity of this approach for future space missions and for potential terrestrial applications.
This project has been very successful to date, with continuing activities under CEOI between the partners to further increase the maturity and demonstrated potential of the CompAQS concept.

The work is led by Dr Roland Leigh, University of Leicester with SSTL and Astrium

[c]GRISM technologies

A study has been performed by Surrey Satellite Technology Ltd (SSTL) in partnership with the University of Leicester (UL) Space Research Centre on the specification and design of imaging spectrometer instruments using immersed diffraction gratings – called “grisms”.
The essential advantage of grisms over conventional diffraction gratings, particularly in the context of space-based instrumentation, is that they provide higher spectral dispersion. Larger dispersion angles imply that grating sizes can be smaller, and the optics associated with the dispersing element can also be smaller. Grism designs can therefore offer imaging spectrometers of acceptable size, where conventional grating designs tend to be excessively large.

Grism imaging spectrometers will be applied particularly where there is a need for very fine spectral resolution over narrow spectral bands; the main area of interest for the study has been monitoring of atmosphere chemistry from space, by measuring the spectral absorption of selected gas species. High resolution is needed in the short-wave infrared (SWIR) band for measurements of concentrations of greenhouse gases CO_2 and CH_4, and the air quality pollutant CO. High-resolution measurements in the visible region are needed on the oxygen A-band for cloud and pressure measurements, to provide data to interpret measurements in other spectral ranges.
Representative spectrometer requirements have been investigated and defined by UL, using inputs from sources such as the CAPACITY study report which informs requirements for the ESA Sentinel 4 and 5 missions. Whilst the CEOI study has concentrated particularly on CO_2 absorption bands and the Oxygen A band, the requirements for measurements of other species are similar, so that the results of the study have broad relevance, particularly in the SWIR band.
Instrument requirements have been refined by radiometric analysis to calculate the optical apertures and system sizes needed to achieve target signal-to-noise ratios. A baseline low-earth orbit (LEO) mission scenario has been selected for detailed design of instruments. Observation from LEO will offer global coverage over a 2-day period at spatial resolution around 6 km; a constellation of small satellites may be used to provide more frequent observations. A grism spectrometer system designed for GEO would offer more-frequent coverage of part of Earth surface at coarser resolution.

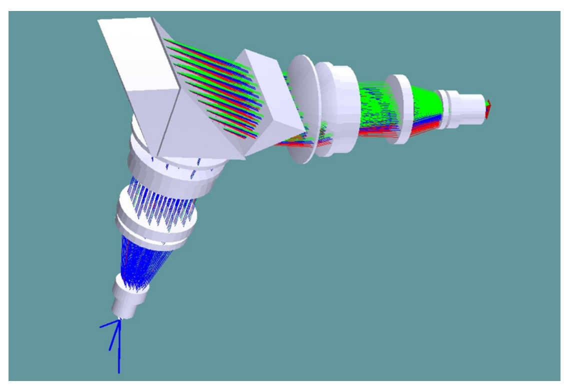

Fig 6 Concept for O2A band spectrometer showing compact optical design

Initial spectrometer designs have provided target specifications for the key grism components, used to initiate an investigation of grism technology, including both theoretical computation of grism efficiencies (as a function of grism materials, grating angles and profile shapes) and discussions with the most likely manufacturer. The investigation has clarified the feasible designs and potential performance capabilities of immersed gratings. The final task has been to revise spectrometer system designs and to confirm the performance that can be achieved.

In conclusion, grism designs can meet the requirements of high-resolution spectrometers for remote sensing of atmosphere chemistry in the visible and SWIR bands. The designs have very significant advantages in terms of compactness of optics and structures, making them ideally suited for deployment on Earth orbiting satellites. Similar designs can be considered for use on airborne platforms and at ground level.

The work is led by Dan Lobb, SSTL with University of Leicester

[d]Utilizing hollow waveguide hybrid integration technology for carbon cycle measurements

Measurement of atmospheric CO_2 levels from space could provide regional and seasonal information on global atmospheric carbon dioxide levels. This information would aid in the quantification of surface fluxes of CO_2 and their variation by providing consistent global measurements of atmospheric CO_2.

Forests are critically linked to the carbon cycle and provide 90% of the above-ground carbon storage capacity. Reliable estimates of their carbon storage capability obtained from measurements of forest canopy height can provide additional information on the sources and sinks of carbon dioxide in the biosphere.

A multifunction space borne differential absorption LIDAR (DIAL) system could provide an excellent approach to making the required measurements of both atmospheric CO_2 concentrations and forest biomass

A space-borne DIAL system can measure over the full diurnal cycle, together with coverage at high latitudes, where solar zenith angles are too large for reliable passive NIR measurements. Furthermore the small footprint of LIDAR systems offers the potential to use gaps in cloud cover to probe surface CO_2 in cloudy regions, such as the Amazon basin.

The University of Leicester has developed a model to assess the performance of a 2.05 µm differential absorption LIDAR (DIAL) system and to generate appropriate system performance specifications. The model incorporates the impact of laser pulse shape and duration, skewing, atmospheric absorption and scattering, sampling phenomena and detection noise. Both direct and heterodyne detection have been modelled and their performance compared. Results indicate that heterodyne detection has advantages where return signals involve small photon numbers.

A separate model has also been developed to investigate the possibility of acquiring forest canopy height measurements (and hence forest biomass) using range measurements from the same 2.05 µm DIAL system. To extract useful information on forest biomass, LIDAR returns from the canopy and ground must be separable to reliably estimate tree height. The canopy cover can be derived from the fractional energy returned from ground and canopy. This can then be related to biomass and leaf area index.

Unfortunately the requirements for DIAL and canopy LIDAR systems differ significantly. Ideally a canopy LIDAR would operate in the 0.85 µm to 1.1 µm wavelength range where vegetation reflectivity is high. Furthermore, an illuminating beam footprint around the size of a tree crown (20 m to 30 m) would be optimum in conjunction with a range resolution of < 50 cm. Conversely, 2.05 µm is preferred for CO_2 column concentration measurements and here the vegetation reflectivity is low. Furthermore, to achieve the narrow linewidths required for DIAL measurements the transform limited laser output pulse duration will be 20-100 ns which will blur range returns and making traditional feature extraction impossible.

To examine the feasibility of performing canopy height measurements with a laser source suited to measuring atmospheric CO_2 concentrations a computer model which simulates canopy height measurements with a long-pulse 2.05 µm DIAL system has been developed. It is concluded that frequency doubling some of the 2.05 µm source laser pulse to provide a second waveband at 1.03 µm would allow structural measurements over steep topography in many cases.

The atmospheric CO_2 and canopy modelling work combined with the literature review has been used to provide an instrument specification for a DIAL system based upon QinetiQ's hollow waveguide (HWG) technology [5]. This is a hybrid integration technology in which HWGs formed in the surface of a dielectric substrate are used to guide light through a circuit of optical components which are themselves mounted within precision alignment slots formed in the surface of the substrate.

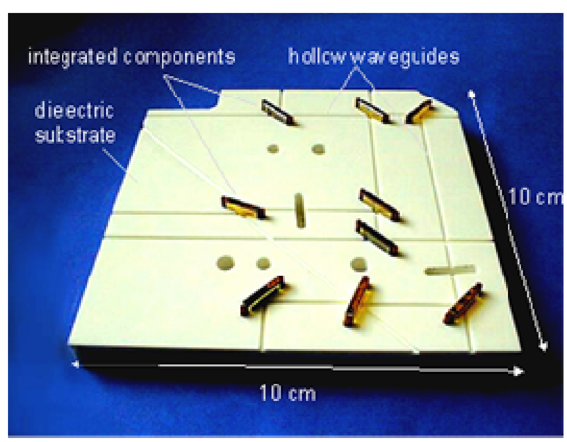

Fig 3 HWG breadboard showing mounting of integrated optical components

By physically constraining each component and guiding the light from one component to another, the resulting optical systems are more immune to misalignment making this technology highly suited to space applications.

A 2.05 µm DIAL HWG breadboard has been designed, manufactured and assessed (Fig 3). Where the performance of the system has related to the optical alignment achieved within the hollow waveguide DIAL circuit itself, the measured performance of the demonstrator system has, in all cases, been excellent. Homodyne detection efficiency was ~90% of the theoretical maximum, the Doppler line-of-sight velocity from a rotating speckle target was successfully measured in a laboratory environment and the attenuation within the hollow waveguide circuits was close to theoretical level of 0.0005 cm^{-1}. The optical assessment of the HWG DIAL demonstrator has highlighted the significant potential of the technology to enable the manufacture of compact, rugged, low mass, high performance optical systems for space instrumentation applications.

Work led by A Davies, QinetiQ with University of Leicester and CTCD.

[e]Hyperspectral Imaging LIDAR (LADAR)

The main scientific driver for the development of an Imaging LIDAR system is to improve knowledge of the Earth's carbon cycle through better measurement of biomass from space. In particular, measurement of canopy height and canopy cover/fraction above sloping ground (strongly related to biomass) was chosen as the main scientific application. This driver resulted in a requirement for a 1m ranging accuracy from an orbit around 350-400km with a 30m LIDAR footprint and the ability to identify individual tree crowns so that measurements or extrapolation could be performed across a wide area.

The approach used to design a putative space-borne or airborne LIDAR consisted of a combined simulation system based on a pre-existing LabView application developed at LTL, interfaced to a scene simulation system based on Monte Carlo ray-tracing developed at UCL [6].

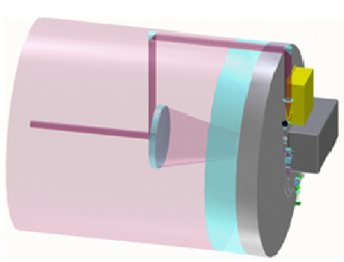

Fig 5 Conceptual design of LIDAR imaging system mounted on 1m class Cassegrain telescope

An initial assessment was made of the potential of new Geiger mode Avalanche Photo-Diode (APD) detector imaging array technology. However, employing the full LIDAR simulator, it was found that, with a low mass (<150kg), low power laser at the required orbital altitude, insufficient photons would be returned, so that the Geiger mode APD array could not be used. A revised concept was produced, consisting of a profiling LIDAR coupled in the same optical path as a stereoscopic imager. The stereoscopic imager would allow the canopy top height to be determined, with the profiler providing 2D height slices running down the middle of the image. The two together enable an extrapolation of tree height and tree cover across the scene. The stereoscopic imager allows a more detailed Digital Elevation Model to be built over vast areas of forest cover. To meet the requirement to measure tree height over sloping terrain (with typical slopes of 30º) with a 30m footprint LIDAR, a 2-wavelength system (either 425/850nm or 532/1064nm) was selected. The two wavelengths were chosen so that the lower wavelength was sensitive to soil and the upper wavelength to vegetation. Simulation studies were performed which showed that a fairly reliable and robust retrieval should be feasible dependent on tree spacing and crown closure/density.

Hyperspectral sampling using tunable filters was envisaged for measuring both reflectance and fluorescence from a multispectral laser's interaction with a vegetation canopy. Two technologies were tested at UCL-MSSL: Liquid Crystal (LCTF) and Acoustic-Optical (AOTF). These technologies were demonstrated as being "fit for purpose" for sampling with spectral bands as narrow as a few nm in milliseconds. However, only AOTF is suitable for spaceborne applications, as LCTFs are extremely temperature sensitive and insufficiently robust.

Simulations were also performed of sensitivity to tree crown density (fractional vegetation cover), from which it appears that LIDAR can estimate biomass over a much larger range than P-band SAR but this is still to be quantified. In fact the LIDAR was shown to be sensitive to canopy-top height up to fractional covers of 65% and could obtain reasonable results for certain Sitka Spruce densities up to 98%.

The final outline design for an imaging LIDAR system consisted of a 1m telescope, with a LIDAR weighing < 15kg, a 1m mirror system around 100kg with all the electronics components attached to the back of the mirror system. In the same optical path, the stereoscopic imager provides detailed information the tree crowns, their spacing and density.

An online demonstrator with further details for the project is at http://ImagingLidar.net.

The work is led by Prof Jan-Peter Muller, UCL-MSSL with Lidar Technologies Ltd

[f]Canopy LIDAR

This project demonstrated the feasibility of a multispectral canopy LIDAR (patent pending) for detailed structure and physiology measurements in forest ecosystems through the design and construction of a bread-board instrument.

The basic principle is to combine in one instrument the proven strengths of passive multispectral sensing to measure plant physiology (through the NDVI and PRI indices) with the ability of LIDAR systems to measure vertical structure information. Such an instrument is potentially superior to the use of single wavelength LIDAR systems combined with passive multispectral data since it generates "hot spot" reflectance data independent of solar illumination and is able to penetrate to otherwise shaded regions of the canopy understory. In addition to offering information on the vertical distribution of physiological processes, it also has value in separating canopy from ground returns, and in the calibration of passive multi- and hyper-spectral instruments. Such measurements will allow better mapping of forest structure and processes directly related to photosynthesis, significantly improve our ability to measure and map the terrestrial biosphere and our understanding of the carbon cycle, land cover use and biodiversity.

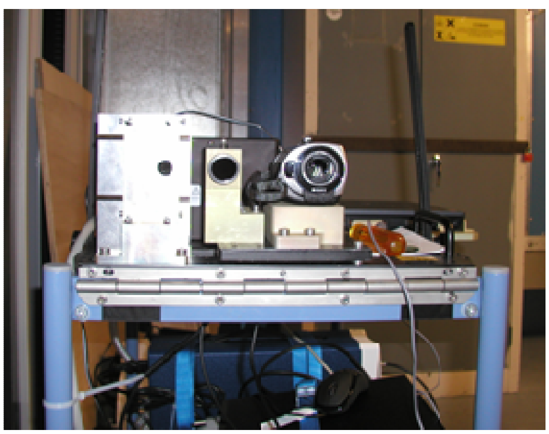

Fig 7 Canopy LIDAR breadboard, which shows range resolution of <0.5m is achievable

The breadboard instrument was built by Selex-Galileo. It was constructed with a tuneable laser that offered a degree of flexibility to investigate different wavelengths. In this project, four wavelengths were selected – 531, 550, 660 and 780 nm. These were selected to allow measurement of two indices commonly used in passive sensing, namely, the Normalised Difference Vegetation Index (NDVI) (660 and 780nm) and the Photochemical Reflectance Index (PRI) (531 and 550 nm). Since health and safety constraints hindered the use of the instrument from a forest tower, laboratory-based measurement were conducted for two trees and pseudo-vertical profiles were obtained for the two indices. Although not fully optimised, the instrument did allow realistic values of the indices to be measured. A follow-on PhD studentship is planned to expand on these measurements.

In parallel to the laboratory measurements a model-based analysis was also conducted [7]. The concept for a multi-spectral canopy LIDAR (MSCL) instrument was tested by simulating return waveforms using models providing tree structure (TREEGROW) and leaf reflectance (PROSPECT). The modelling was used to assess the structural and physiological information content that such a device could provide, especially if the normally structure-dominated return waveform would pick up small changes in reflectance at the leaf level. Multi-spectral waveforms were simulated for models of single Scots pine trees of different ages and at different stages of the growing season. It was shown that the LIDAR waveforms would not only capture the tree height information, but would also pick up the seasonal and vertical variation of NDVI computed from two of the four MSCL wavelengths inside the tree canopy. It could be demonstrated that a new multi-wavelength LIDAR predictor variable could significantly improve the retrieval accuracy of photosynthetically active biomass as opposed to using a single wavelength LIDAR alone. It remains unclear, however, if these findings would persist for forest stands; thus such experiments simulating more complex scenarios will be the next task in this modelling framework.

The work is led by Dr Iain H Woodhouse, University of Edinburgh with Selex Galileo Ltd

[g]Laser Heterodyne Radiometer

The laser heterodyne radiometer (LHR) is a passive instrument developed at the Rutherford Appleton Laboratory (RAL), based on quantum cascade laser (QCL) technology [8]. The original bench-top prototype, operating in the mid-infrared and targeting atmospheric ozone, was designed and constructed with funding from the NERC New Observing Techniques Programme. The project identified several technical developments required to improve the instrument performance, which formed the basis of the LHR objectives for the CEOI development programme.

Technical achievements of the CEOI project are:

1. Thermal and electromagnetic insulation: Following problems with interference from electromagnetic radiation in the 0 to 3 GHz range (from Wi-Fi, mobile communications, etc) and thermal instabilities the LHR has been fully enclosed in a protective shell. This provided thermal shielding and acted as a Faraday cage to suppress electromagnetic radiation. This has resulted in a 36% reduction in instrument noise.

2. Opto-mechanical stability: Long term stability is limited by the mechanical quality of the optical mounting systems, particularly those supporting

the laser collimation elements and the photo-mixer. Both components require sub-micron positioning and stability. Improvements have resulted in an order of magnitude improvement in long-term stability.

3. Optical isolation and suppression of optical feedback: Perhaps the greatest limitation on the performance of the prototype LHR was due to the incidence of back reflected radiation from the photo-mixer detector element on the laser. A very efficient optical isolation system has been designed and integrated with the LHR to reduce the amount of back reflected radiation by several orders of magnitude, leading to a reduction in the associated laser intensity and phase noise.

4. Back-end radio-frequency (RF) filtering and instrument line shape: Improvements have been made to the RF filtering system to reduce the amount of laser noise injected into the system and to enhance the instrument line shape. By carefully tailoring the filters a reduction in noise of 26% has been achieved.

5. Local oscillator high frequency noise study: QCLs from different manufacturers and operating under different physical conditions (e.g. operating temperature) can emit significantly different amounts of high frequency noise. It appears that the level of laser excess noise is related to the laser manufacturing process. A source of very "quiet" room-temperature lasers has been identified which has the potential to further improve the performance of LHR.

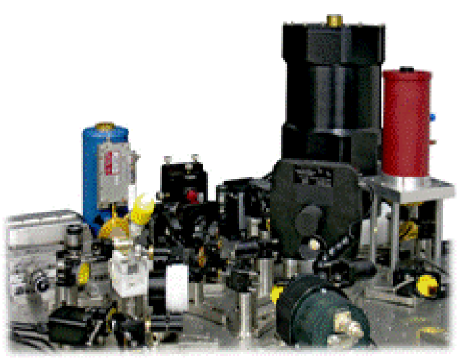

Fig 4 The laser heterodyne radiometer prototype hardware

In addition RAL have developed software to model the performance of the improved LHR for a variety of deployment scenarios. These included measurements from the ground, aircraft at various altitudes and satellite platforms. Simulated retrievals for atmospheric ozone were used to estimate instrument performance in terms of vertical resolution and sensitivity.

Outputs from the retrieval simulations have been fed into a mission assessment study conducted by Astrium. The most appropriate observational platforms and geometries for the instrument have been identified, considering the capabilities of alternative technologies, future mission opportunities and scientific requirements. For observations of atmospheric ozone concentration from a satellite platform in LEO, the simulations show that the LHR can provide high vertical resolution in limb and nadir viewing modes, due to the instrument's inherent spatial and spectral resolution respectively. The LHR can also be used to monitor other important atmospheric constituents including CO_2, CH_4 and NO_x.

The LHR is an emerging technology with significant potential for Earth observation instrumentation. The project has achieved its objectives under CEOI, with significant improvements made to the instrument and options for further development identified.

Work led by Dr Damien Weidmann, STFC-RAL with Astrium

FUTURE PERSPECTIVES

During its first 15 months the CEOI has successfully established a number of new technology developments and initiated opportunities for the application of these technologies into future ESA missions and elsewhere, in space and non-space sectors. Firm foundations for continuing productive activities in the development of an active and successful UK EO instrument community are in place.

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