Case Studies

Low Cost Upper Atmosphere Sounder (LOCUS)

Summary	LOCUS is a novel and breakthrough limb sounding, multi-channel radiometer operating in the terahertz (THz) spectral range (0.8 – 5 THz). Its objective to enable global measurements with high spectral resolution of important mesosphere and lower thermosphere atmospheric species, particularly atomic oxygen and hydroxyl radical.
Lead Organisation	Surrey Satellite Technology Ltd./University of Leeds/University College London
Partner Organisations	STAR-Dundee, STFC-RAL, JCR Systems
Projects Funded	**Open Call 6**: Low Cost Upper Atmosphere Sounder (SSTL) – Project to assess the requirements and feasibility of providing a low cost space mission to observe terahertz frequency atomic and molecular transitions to monitor chemical species in the mesosphere and lower thermosphere. (SSTL) **Open Call 7**: LOCUS Critical Payload Development For Future In Orbit Demonstration Project – Project to advance the development of the terahertz radiometer and high speed signal processing technology in conjunction with miniature spaceborne cryogenic system. (University of Leeds) **Open Call 8**: Critical Technology Advancement of the LOCUS Mission – Project to design, construct and test in a representative thermal environment an "elegant breadboard" of the LOCUS payload optics and support infrastructure. (University College London)

TRL Achieved	4 (1THz system)	**Papers/Conference Presentations**	12
Patents	0	**Students (e.g. CASE/PhD)**	1 PhD

Spinout Opportunities	Significant advances achieved in waveguide integrated quantum cascade lasers show promise for commercial exploitation. Advances made to Schottky barrier diode, receiver system integration and digital sampling technology also offer very significant spinout potential, particularly in the field of spectral imaging.
Outcomes	Through CEOI-ST support, the LOCUS concept has evolved both component and system technology towards TRL 4. For instance, integration of quantum cascade laser (QCL) technology within waveguide cavities has been demonstrated to be very effective with substantial improvements gained in QCL source THz output power and free-space coupling. Mixer diode technology has also advanced with the development of new diode types and their integration into a novel 1THz receiver system incorporating a space compliant cryogenic cooler. Additionally, digital spectrometer systems have been substantially enhanced and tailored to meet requirements of space flight, e.g. lower mass and power consumption. Excellent project team collaborations have been developed and the LOCUS mission concept has been very substantially refined.

Future Steps and Target Opportunities	Next steps of the LOCUS payload development follow a well-defined road map with major identified target opportunities of IOD and payload inclusion on an Earth Explorer mission, e.g. EE9. To achieve the above, further technical refinements are needed to ensure payload compliance with scientific and space platform requirements. This necessitates a further evolution of the core mixer and QCL technologies to beyond TRL 4. A step towards this goal will be accomplished via the CEOI-ST 8th Call and within which the LOCUS elegant breadboard concept will be demonstrated. A further major step forward would be to realise a fully integrated multi-channel receiver system, incorporating future advances in mixer, QCL, spectrometer and cooler technologies. To support EE9 evolution, and to further enhance the LOCUS mission concept, greater science evaluation is also necessary and includes, for example, in-depth simulation of atmospheric features to improve retrieval modelling and to help refine aspects of the overall system payload. Additionally, the breadboard systems developed through the 7th Call can achieve very substantial enhancement, potentially achieving TRL 5/6, through ground based and airborne demonstration. For instance, deployment in the Chilean Atacama desert would allow demonstration of the 1.1THz 7th Call receiver in-the-field and in a harsh environment. An airborne demonstration involving the UK Met Office/NERC FAAM would further demonstrate the 1.1THz system and allow incorporation of the supra-THz receiver, e.g. 3.5 and/or 4.7THz. In all deployments, useful science data would be returned and the LOCUS mission concept raised to TRL 6.
CEOI-ST Leadership Team Contribution	• Created opportunity for funding through first CEOI mission study (OC6) to allow team to prepare for ESA IOD opportunity • Support to team during current R&D activities (OC7 and OC8) to help navigate through technical R&D issues • Provided platform for team to present their outputs and capability to ESA and other Agencies through conferences, KE workshops and technology showcase events • Assisted team with development of publicity materials and technical brochures to promote technology and capability

Passive Microwave – Metop-SG

Summary	The Metop-SG programme is the major European programme with multiple passive microwave instruments: Microwave Sounder (MWS), Microwave Imager (MWI) and Ice Cloud Imager (ICI). The CEOI has funded the development of innovative and/or critical technologies required for these instruments to enable credible proposals for the implementation of one or more of the instruments to be lead from the UK.
Lead Organisation	Airbus DS Ltd., Queens University Belfast, TAS UK Ltd
Partner Organisations	JCR Systems, Queens University Belfast, STFC-RAL
Projects Funded	**Open Call 2**: Frequency Selective Surface (FSS) Filter Technology (Queens University Belfast) – Development of a prototype sub-millimetre wave FSS for Metop-SG, demonstrating capability in FSS design, fabrication and spectral measurement up to 700 GHz. **Open Call 4**: Passive Microwave and Sub-millimetre Wave Imager Technologies – Development of key Metop-SG instrument technologies not covered by ESA Phase A to position UK consortium for the Phase B programme. **Open Call 4**: The Use of Meta-materials in Sub-millimetre wave quasi-optical systems – Study to assess the potential of meta-materials to study suppression of unwanted fields and overall performance of the system. **Open Call 5**: Pre-development of Critical Technology for Metop-SG MWS Instrument – Development of 165/183 GHz waveguide diplexer to reduce complexity of quasi-optical network. **Open Call 5**: Innovative Ice Cloud Imager (TAS UK) – Study to investigate simplifications to the Metop-SG ICI or future instruments. **Open Call 6**: Finite Frequency Selective Surface Modelling (Queens University Belfast) – Development of a new numerical model for finite FSS to provide high accuracy numerical predictions of beam propagation and reflection.

TRL Achieved	3-4	**Papers/Conference Presentations**	21
Patents		**Students (e.g. CASE/PhD)**	3

Spinout Opportunities	Communications, security
Outcomes	The work across industry and academia has strengthened UK expertise and capabilities in passive microwave instrumentation. The development of FSS technology at frequencies up to 700 GHz is state-of-the-art within Europe. The investment in the Metop-SG passive microwave instrument technology has directly enabled the UK consortium to position itself to win the competition for the ESA Phase BCD Microwave Sounder contract to design and build for three instruments for MetOp Second Generation (total contract value 155M€)

Future Steps and Target Opportunities	*Next steps in development* • Increased integration of instrument front end components • Direct detection at higher frequencies (>100 GHz) • Increased spectral discrimination – analogue and digital filter design • Development of higher power/higher frequency LO sources • Wide bandwidth digital instrument back ends • Beamsteering LC antennas *Target opportunities:* • Coastal Altimeter Radiometer Antenna feed (ESA EXPRO PLUS) • LC based beam steering ground station antennas (ARTES 5.1) • Future meteorological radiometers (ESA/EUMETSAT) • THz and sub-mm limb sounders (ESA)
CEOI-ST Leadership Team Contribution	• Created multiple opportunities (CEOI Ph-1&2, OC 4, 5, 6 & 7) for development of key technologies and capability in preparation for Metop-SG MWS • Provided support to FSS Filter team (QUB) in early development phases, leading to considerable leveraged funding for on-going development of technology, including KE through technology showcase meetings, preparation of technical brochures and case studies • Provided platform for team to present their outputs and capability to ESA and other Agencies through conferences, KE workshops and technology showcase events • Assisted team with development of publicity materials and technical brochures to promote technology and capability

Passive Microwave – STEAM-R

Summary	STEAM-R is a passive, millimetre-wave limb-sounding radiometer being developed by Sweden as a nationally-funded contribution to a national/bilateral atmospheric sounding mission such as ALiSS. It has also been proposed previously as a national contribution to the Earth Explorer 7 candidate mission PREMIER. The concept for STEAM-R includes novel single-channel, sideband-separating receivers and a focal plane design that avoids the need for mechanical scanning of the main antenna. CEOI has funded a series of activities related to the development of passive millimetre wave sounder technology and to support UK development for a next generation millimetre wave limb sounding instrument.
Lead Organisation	STFC-RAL
Partner Organisations	Airbus DS Ltd., Queens University Belfast, STAR Dundee

Projects Funded	**Phase 1**: Passive Millimetre Wave Sounding – Development of radiometer technology to improve sensitivity, frequency performance and resource use for applications in the millimetre wave region. **Phase 2**: STEAM-R (Passive Microwave) – Continuation of development of radiometer technology relating to the focal plane and receiver design. **Open Call 2**: Support to STEAM-R Phase A Study – Support to enable further work on technology development activities and participation in the ESA PREMIER Phase A Study. **Open Call 4**: STEAM-R TRL Raising – Project focussed on the finalising the design and manufacture of the critical sub-harmonic single sideband image rejection mixer (SHIRM) to achieve TRL 5 to meet ESA requirements for the technology to be admitted to the mission. **Open Call 5**: High Level System Integration of UK Receiver Technology for STEAM-R & MWS – Demonstration of system level performance of critical receiver (mixer and spectrometer) technology for STEAM-R. The activity also had relevance for the Metop-SG Microwave Sounder.

TRL Achieved	5	**Papers/Conference Presentations**	10
Patents	0	**Students (e.g. CASE/PhD)**	2

Spinout Opportunities	EO instruments for millimetre wave limb sounding
Outcomes	The funded activities have enabled the development of new technologies that position the UK well for involvement in the STEAM-R instrument. Specific technology outcomes include: • Development of a novel image separation mixer technology (SHIRM) and qualification at TRL-5, enabling selection of the technology for flight. • The development of an optical design methodology to accurately predict antenna patterns for sub-millimetre radiometer instruments. • Development of novel, generic filter technology with state-of-the-art low loss performance
Future Steps and Target Opportunities	The ESA MARSCHALS airborne limb sounder instrument will be deployed in the STRATOCLIM aircraft campaign in the Asian monsoon region during 2016. The upgraded instrument will include both SHIRM receiver and WBS backend for the first airborne demonstration of both technologies.
CEOI-ST Leadership Team Contribution	• Created multiple opportunities (CEOI Ph-1&2, OC 2, 4, 5 & 7) for development of key technologies and capability for STEAM-R, either through ESA (Earth Explorer 7 candidate mission) or as bilateral mission with Sweden • Provided platform for team to present their outputs and capability to ESA and other Agencies through conferences, KE workshops and technology showcase events • Assisted team with development of publicity materials and technical brochures to promote technology and capability • Created opportunity through EOMAG working group to develop proposal for a potential bilateral mission with Canada and Sweden

GNSS Reflectometry

Summary	Signals from GPS/GNSS navigation satellites reflected from land, ice and ocean can be analysed with an instrument flying on a separate small satellite and important scientific data on the nature of the reflecting surface and the atmosphere, such as the sea-surface roughness or soil moisture content can be derived. Measurements of ocean roughness are important for operational ocean and weather forecasting. CEOI provided funding to define applications, specify technical requirements and develop a flexible multi-channel receiver of reflected GNSS signals.
Lead Organisation	Surrey Satellite Technology Ltd
Partner Organisations	National Oceanographic Centre, University of Surrey, University of Bath, Polar Imaging Ltd
Projects Funded	**Open Call 2**: Use of GPS Signals to Measure the Ocean Surface State – Project to define the applications, specify the technical requirements and develop an engineering model of the receiver instrument. **Open Call 3**: Space GNSS Receiver – Remote Sensing Instrument (SGR-ReSI) – Further development of the receiver instrument towards flight standard to fly on TechDemoSat-1 and parallel development of the science applications for the instrument. **Open Call 6**: Review of state of the art and outstanding issues for ocean roughness retrieval with GNSS Reflectometry (National Oceanographic Centre). **Phase 3 Extension**: Preliminary work to prepare for the launch of TechDemoSat-1 and validation of the SGR-ReSI instrument (National Oceanographic Centre).

TRL Achieved	9	**Papers/Conference Presentations**	11
Patents		**Students (e.g. CASE/PhD)**	4

Spinout Opportunities	The SGR-ReSI is also the basis of Surrey Satellite Technology Ltd's next generation space GNSS receiver product, the SGR-Axio. This has been selected and delivered for the NovaSAR satellite, and will be delivered for four external satellite missions.

Outcomes	Successful development of a low mass GNSS reflectometry instrument and demonstration in orbit of the measurement of ocean roughness and wind speed on TechDemoSat-1. The SGR-ReSI made the CYGNSS mission possible, and enabled Michigan to win the $150m NASA Earth Venture funding out of 18 other proposals. SSTL and Surrey Satellite Technology US subsequently won the contract to supply eight instruments for NASA's CYGNSS microsatellite constellation mission.
Future Steps and Target Opportunities	SSTL and partner NOC are releasing data from the SGR-ReSI on TechDemoSat-1 to consolidate the science case, stimulate applications and develop commercial applications for the measurements, with support from ESA. They are working with end users such as the Met Office and ECMWF to encourage incorporation of measurements into future weather systems. SSTL is investigating the potential for a constellation of satellites that may provide a remote sensing and weather service. ESA has expressed support for the concept of a combined Reflectometry and Radio Occultation sensor that could be accommodated on a microsatellite. ESA undertook a Concurrent Design Facility (CDF) exercise to develop the concept further.
CEOI-ST Leadership Team Contribution	• Created multiple opportunities (OC 2, 3, 6 & Ph3-Ext) for development of key technologies and capability, leading to deployment of SGR-ReSI on TechDemoSat-1 • Created opportunity through EOMAG working group to develop proposal for a potential bilateral mission • Provided platform for team to present their outputs and capability to ESA. Supported NOC and SSTL in their discussions with ESA (Pierluigi Silvestrin) and CEOI provided small amount of funding, leading to the current activities with TechDemoSat data analysis and ultimately with CYGNSS • Attended the SGR-ReSI science meeting in NOC where the TechDemoSat GNSS reflectometry results were presented, with ESA in attendance, CEOI advised release of TDS-1 data to science community to accelerate the development of the ground processing algorithms and flush out any instrument issues.

Next Generation Radar Electronics

Summary	The objective of this Flagship project is to further develop existing Airbus DS radar products, to enable them to support a broader range of future missions. Potential targets include the ESA Earth Explorer 7 mission, Biomass, and SAOCOM-CS, a joint ESA-Argentina L-band SAR mission.
Lead Organisation	Airbus DS
Partner Organisations	

Projects Funded	**Open Call 8**: Project in progress for Next Generation Radar Electronics – Project to raise the TRL to level 5/6 for: • Receive Module modification for low frequency operation and enhanced science data interface flexibility • Qualification of the Virtex-5 FPGA • Development of an embedded computer option for the NIA product to broaden its applicability

TRL Achieved	6 at completion	**Papers/Conference Presentations**	2
Patents	IP developed	**Students (e.g. CASE/PhD)**	N/A

Spinout Opportunities	None so far (early stages)

Outcomes	Project still in progress, on track; current status: • Receive Module modification for low frequency operation and enhanced science data interface flexibility → design completed, build and test into Q1 2016 • Qualification of the Virtex-5 FPGA → planning activities done and agreed with ESA, tests to start Q4 2015 • Development of an embedded computer option for the NIA product to broaden its
Future Steps and Target Opportunities	Next steps are to successfully finish the project, which is well aligned with the need dates of the main target missions: • Biomass central electronics competition against French and German suppliers in Q2 2016 – the Rx module task positions us well having demonstrated in hardware the key design changes needed on top of our heritage Sentinel-1 architecture. • SAOCOM-CS from 2016/2017 onwards – development and breadboarding activities are ongoing ahead of any decision for full mission implementation (linked to the 2016 ESA ministerial?). A key point for ESA is the choice of a heritage-derived architecture (Sentinel-1 from Airbus, Exomars from TAS-I) or a new approach (NIA from Airbus, unknown from other suppliers). Successful qualification of the Virtex-5 FPGA in an ESA framework is an important stepping stone to offering a newer, lower-cost solution that supports the programmatic and budget needs of SAOCOM-CS. • Other ESA missions – A passive follower satellite to Sentinel-1 is seen as one attractive idea for a potential Earth Explorer 9 mission. Given the budget constraints around EOEP-5 and EE-9, an emphasis on low cost and flexibility with small platforms will be important. The CEOI activity lays some good groundwork for this type of approach. • Other missions including non-ESA – 2015 has seen the rise of constellation concepts across telecoms and earth observation, including several industry announcements on radar ideas. Airbus Defence and Space UK is engaged with some of the players with a view to being a potential supplier of radar payloads or electronics subsystems. The third task in the CEOI activity assists with preparedness in a wider marketplace.
CEOI-ST Leadership Team Contribution	• Created opportunity (OC8) for development of key technologies and capability • Assigning experienced SAR expert to oversee project on behalf of CEOI-ST and UKSA, providing continuing technical review of activities • Creating opportunity to present development to ESA and other Agencies through Challenge

On-Board SAR Processing/Wavemill

Summary	Wavemill, an Earth Explorer 9 candidate, is a novel dual-beam interferometric SAR concept which offers the prospect of generating wide swath, high resolution, high precision maps of ocean surface currents and winds. As a single spacecraft systems, it avoids the difficulties of synchronisation and baseline estimation associated with single pass interferometric SAR. On-board processing of data generated by the instrument to Level 1 SAR products is necessary due to on-board data storage and downlink constraints. Along-track SAR interferometry relies on high-precision phase calibration that calls for good knowledge of the interferometric baseline and of the platform attitude. CEOI-ST funding has been provided in a number of calls to develop the mission science, concept and on-board processing techniques.
Lead Organisation	Airbus DS Ltd
Partner Organisations	BAE Systems, National Oceanography Centre, Starlab Ltd
Projects Funded	**Open Call 3**: Wavemill – Study focussing on the science case for Wavemill in the context of actual and planned oceanographic systems, and on the on-board processing required to manage large raw image data volumes of the SAR instrument. **Open Call 4**: Emulation And Performance Study of a SAR On-Board Processor – Development of a software prototype of a Level 1 on-board processor. **Open Call 5**: Emulation And Performance Study of an On-Board Level 1 Processor For Squinted SAR – Further development of the on-board SAR processing algorithms to include highly squinted SAR using wavefront reconstruction algorithms. **Open Call 6**: Wavemill Mission Concept For ESA Earth Explorer 9 – Development of the Wavemill mission concept at instrument and system level to ensure a mature concept is available for submission to the Earth Explorer 9 mission call. **Open Call 7**: Wavemill ATI SAR Phase Calibration – Study to investigate the ATI phase calibration approaches for the Wavemill mission, including recommendations for the development of the antenna for the airborne demonstrator and the spaceborne system.

TRL Achieved	2	**Papers/Conference Presentations**	11
Patents	1	**Students (e.g. CASE/PhD)**	

	The FPGA-based SAR level 1 processing could be used
Spinout Opportunities	(a) in a ground segment SAR archival and processing facility, to improve response time for users (b) in an airborne SAR platform to transmit SAR imagery in real time for users.
Outcomes	The sequence of studies has enabled the Wavemill mission and instrument concept to be matured. Development of the on-board SAR processing techniques has been progressed, demonstrating the ability to generate Level 1 side looking and highly squinted SAR imagery using on-board digital signal processing techniques.
Future Steps and Target Opportunities	The next step for a spaceborne system would be to build an integrated breadboard in flight representative technology which combines the FPGA, memory and control functions. Some additional work is needed on the processing algorithms to generate the accurate radar echo time of flight data (needed for image focussing) from information on the platform's position and attitude. This problem is strongly related to the issues involved in the proposed Doppler centroid technique for ocean current mapping. The Wavemill airborne Proof-of-Concept study led to an Airbus DS airborne prototype being built and flown over Liverpool Bay in October 2011. This represents the only experimental data available to demonstrate the feasibility of the system and of its joint current and wind measurement principle. Further airborne campaigns are needed to develop the system and validate the geophysical measurements in a wider range of ocean current and wind conditions. There are opportunities both for the development of an improved UK airborne system and for taking the UK to take a leading role in performing airborne campaigns with the ESA OSCAR airborne system. The ESA and CEOI-ST studies have led to a mature mission concept based on dual-beam ATI SAR which could be proposed to the ESA Earth Explorer 9 call expected in late 2015 if the EE9 funding envelope remains consistent with a Core class Earth Explorer mission.
Patents	European Patent Application EP11275041.9 SAR Data Processing
CEOI-ST Leadership Team Contribution	• Created multiple opportunities (OC 3, 4, 5, 6 & 7) for development of key technologies and capability, leading to development of WaveMill proposal and necessary supporting technologies • Assigning experienced SAR expert to oversee project on behalf of CEOI-ST and UKSA, providing continuing technical review of activities • Provided platform for team to present their outputs and capability to ESA.

Compact Air Quality Spectrometer (CompAQS)

Summary	CompAQS is a novel spectrometer design, which uses concentric optics to produce a very compact imaging spectrometer instrument. The concept enables a compact, low mass design suitable for a new generation of smaller space missions. The instrument addresses the UV/Visible region and measures atmospheric air quality by detecting polluting substances using the Differential Optical Absorption Spectroscopy (DOAS) technique.
Lead Organisation	University of Leicester
Partner Organisations	Surrey Satellite Technology Ltd.
Projects Funded	**Phase 1**: CompAQS – Development of CompAQS instrument from concept to a working breadboard at TRL 3/4. **Phase 2**: CompAQS – Demonstrate full imaging DOAS capability using the breadboard instrument developed in Phase 1, developing concepts for suitable imaging optics, detectors, structure and retrieval algorithms. **Open Call 6**: Flying The CompAQS Air Quality Instrument As An Airborne Demonstrator To Map NO2 Over Leicester At High Resolution **Open Call 7**: CompAQS Hyperspectral Imaging – Study into application of a hyperspectral imaging suite for 3D retrievals. **Open Call 8**: CompAQS TRL Raising – Project to advance the design and TRL of high risk items including structural/thermal design, focal plane design and alignment issues. Testing of the integrated system verify qualification.

TRL Achieved	5	**Papers/Conference Presentations**	20+
Patents/IP	2	**Students (e.g. CASE/PhD)**	2

Spinout Opportunities	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. The Air Quality Mapper is now a commercial service offered by Bluesky International Ltd (http://www.bluesky-world.com/#!air-quality-mapper/c1q3c)
Outcomes	A strong collaborative ethos has been established between the University of Leicester and Surrey Satellite Technology Ltd, strengthening the UK capability in UV/Visible spectroscopy. The successful development of a compact DOAS instrument, a candidate payload on TDS1. Three CityScan instruments have been developed and tested in Leicester. They were successfully deployed in London to monitor air quality in 2012 as part of the ClearFlo project. An airborne demonstration of an instrument has also been completed, with the production of a unique high-impact dataset.

Flight opportunities continue to be sought for the CompAQS spectrometer with India being a particular focus of current activity.

Developments under the 8th open call will develop a new airborne demonstrator with a more capable, higher TRL system. This will be demonstrated in late 2016, with the expectation of ultra-high fidelity measurements of pollutant concentrations at 20x20m resolution.

The airborne CompAQS demonstrator is currently in the final stages of certification for use on a commercial aerial survey aircraft. Following this certification in November 2015, the instrument will be permanently installed on this aircraft and will capture data over the UK through a range of piggyback opportunities. This will further enhance the demonstrated capability of the CompAQS spectrometer, and illustrate the scientific and societal benefits of increased spatial resolution. The commercial offering, via partner company Bluesky International Ltd, will continue to be promoted through a range of activities.

Future Steps and Target Opportunities

The ground-based CityScan technique will be progressed through a NERC-funded CASE PhD studentship held by Jordan White. This studentship is focused on optimising measurements from airborne and ground-based CompAQS measurements, enabling tomographic retrievals over urban environments. An element of this capability will be demonstrated under the ESA-IAP project, uTRAQ in early 2016, proving Leicester with novel air quality monitoring and management capabilities.

The airborne and ground-based systems are now proposed for use as part of the Sentinel 5-Precursor calibration/validation team efforts in 2016 and beyond. This activity will promote awareness of the capabilities of CompAQS, and will demonstrate performance in this high-profile forum.

The spin-out potential of these technologies has been substantially advanced in 2015, under the new umbrella of Air Quality Innovations(http://www2.le.ac.uk/colleges/scieng/research/airquality). There is a high likelihood of a spin-out company being formed from the University of Leicester in 2016 to develop these technologies among a wider suite of air quality offerings.

CEOI-ST Leadership Team Contribution

- Created multiple opportunities (CEOI Ph-1&2, OC 6, 7, 8) for development of key technologies and capability
- Guidance to the CompAQS team to access other funding sources (NERC, regional development funds etc)
- Created opportunity through EOMAG working group to develop proposal for a potential bilateral mission
- Provided platform for team to present their outputs and capability to ESA and other Agencies through conferences, KE workshops and technology showcase events
- Assisted team with development of publicity materials and technical brochures to promote technology and capability

Traceable Radiometry Underpinning Terrestrial- and Helio- Studies (TRUTHS)

Summary	The establishment of an observational climate benchmark data set of sufficient accuracy to enable the unequivocal detection of climate change with the ability to constrain and test climate forecast models on a decadal time scale is one of the key challenges laid down by the international climate science community. The UK led TRUTHS (Traceable Radiometry Underpinning Terrestrial- and Helio- Studies) and its US sister, CLARREO (Climate Absolute Reflectance and Refractivity Observatory) are mission concepts proposed to address this issue. TRUTHS' primary goal is to provide benchmark measurements of both incoming (solar) and outgoing (reflected solar) radiation with sufficient spectral resolution and accuracy to detect the subtle changes in as short a timescale as possible (~12 yrs), limited by natural variability of the climate system. Of equal value Is the missions ability to upgrade the performance of other sensors to near climate quality through in-flight reference calibration it can be seen as a 'plug in'
Lead Organisation	National Physical Laboratory
Partner Organisations	Surrey Satellite Technology Ltd, Airbus DS, STFC RAL & Imperial College London
Projects Funded	**Open Call 4**: Study to develop the mission and observation requirements. **Open Call 7**: Design study to trade-off complexity/risk/cost against science drivers to ensure core, climate benchmark objective is met, whilst maximising the opportunity for secondary objectives. **Open Call 8**: (In progress) Increasing TRL of the Cryogenic Solar Absolute Radiometer (CSAR) and the in-flight calibration system to level 5/6 – Design and build of a novel calibration system using

TRL Achieved	5/6 at end of EO-8 project	**Papers/Conference Presentations**	9 papers ~ 20 conf presentations
Patents	NA	**Students (e.g. CASE/PhD)**	1 part of project

Spinout Opportunities	CEOI 8 Will lead to a cryocooler with higher performance allowing opportunities for future sales. The carbon nano-tube black evaluated in CEOI8 will lead to potential sales as part of blackbodies

Outcomes

- A fully analysed and prioritised science to Mission technical requirements document and an optimisation based on technical readiness
- A design for a hyperspectral imager of high but achievable performance with analysis of radiometric and stray light performance
- An updated mission design achievable in space with a reduction in complexity from 5 to 2 instruments and seven to three movements.
- A costed, implementable mission (all elements) in readiness for an opportunity.
- A broad-based UK science and industry team promoting the mission as a desired opportunity together with support from international bodies and government departments
- Evidence to prove the viability and performance of both the on-board calibration system and also the ability of TRUTHS to upgrade other sensors .e.g Sentinel 2 from 3 to 0.5%.
- A UK led mission with sufficient credibility and uniqueness to facilitate the

Future Steps and Target Opportunities

*Ne*xt steps:

- Strengthened and broadened science case to include worked examples of secondary benefits in the near term of the mission lifetime
- Full Phase A/B to refine detailed design considerations for payload and spacecraft operations particularly thermal analysis
- Breadboarding of hyperspectral imager
- Full engineering model of On-board calibration system
- Establish international partners of joice to jointly exploit mission implementation
- Potentially work with Chinese to help implement their early demonstration of TRUTHS in their copy mission

Target Opportunities

- Long term as an operational deployment funded by EU Copernicus/Eumetsat

Range of potential steps and opportunities to reach the above goal

- Interim and as a step to above – As an EarthWatch mission
- As a UK Led and initiated Bi/multi-lateral mission with 'National funding'
- As a fully national mission
- As an EE9 candidate
- As a contribution to either NASA or China in their proposals

CEOI-ST Leadership Team Contribution

- Set up initial study following recommendation from joint CEOI/NCEO Challenge Workshop to investigate the feasibility of the TRUTHS concept and expose it to the UK EO community
- Created multiple opportunities (OC 4, 7, 8) for development of key technologies and capability
- Created opportunity through EOMAG working group to develop proposal for a potential bilateral mission
- Provided platform for team to present their outputs and capability to ESA and other

Agencies through conferences, KE workshops and technology showcase events

Grism Technologies

Summary	The CEOI provided funding to study the specification and design of imaging spectrometers 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 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, using the spectral absorption structures of
Lead Organisation	Surrey Satellite Technology Ltd.
Partner Organisations	University of Leicester
Projects Funded	**Open Call 1**: GRISM Technologies - A study on the specification and design of imaging spectrometer instruments using immersed diffraction gratings – called “grisms”. **Phase 2**: GRISM Spectrometer Design - A study to continue the evaluation of alternative technologies for imaging spectrometers using GRISM technologies for applications in monitoring atmospheric chemistry from low Earth orbits, providing high spectral resolution in narrow spectral bands.

TRL Achieved	2 (CEOI study) 7 (TROPOMI SWIR)	**Papers/Conference Presentations**	4
Patents	-	**Students (e.g. CASE/PhD)**	-

Spinout Opportunities	None identified
Outcomes	The general conclusions from the CEOI study were that grism designs can meet the requirements of high-resolution spectrometers for remote sensing of atmosphere chemistry in 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 small satellites. Similar designs can be considered for use on airborne platforms and at ground level. As a direct result of the study work funded by CEOI, Surrey Satellites Technology Ltd was successfully able to propose the SWIR instrument for the Sentinel-5 Precursor mission. The Tropomi-SWIR instrument used a GRISM in total internal reflection (developed by SRON with SSTL’s optical design) successfully proving grism technology. This was a monolithic silicon grating. A further study was performed for ESA on immersed gratings at NIR, and papers were published on SPIE and ICSO. The grating was manufactured from fused silica, using optical contacting, and the main aim other than increasing dispersion was to have reduced stray light, especially important for measurement of the oxygen column in the A-band

Future Steps and Target Opportunities	TBD
CEOI-ST Leadership Team Contribution	• Created multiple opportunities (CEOI Ph-2, OC1) for development of key technology • Provided platform for team to present their outputs and capability to ESA and other Agencies through conferences, KE workshops and technology showcase events • Support to SSTL in getting Grism expertise accepted by Dutch Space, leading to the SSTL contract for the TROPOMI SWIR spectrometer (10M€ contract)

Laser Heterodyne Radiometer

The Laser Heterodyne Radiometer is a relatively new spectro-radiometer concept, which is a passive sounder despite the use of a low-power solid-state laser as a local oscillator. The instrument observes the unique spectral signatures of atmospheric constituents and pollutants in the mid infrared. It has the combined advantages of high sensitivity, high spectral resolution, and high spatial resolution. It features relatively low complexity, and is highly suitable for extreme miniaturisation, making it able to compete with, and in some cases, exceed the performance of the costly, heavy and bulky Fourier Transform Spectrometers normally used in these applications and wavelength domains.

Summary

Following initial NERC funding, which established the scientific principles, modest levels of CEOI funding have been used to address miniaturisation using the hollow waveguide IP, which was acquired by RAL Space from QinetiQ's work in miniature LIDAR for space. Work continues towards a space deployment and current work confirms the suitability of the LHR for sensing of CO2 levels.

The work has also resulted in a number of terrestrial and defence spin-off applications, including the spinout of a small company. These activities have realised significant leveraged funding as a direct result of the modest CEOI investment.

Lead Organisation	RAL Space
Partner Organisations	HollowGuide Limited, QinetiQ

Projects Funded	• **Phase 1:** TRL Raising – initial performance and technology improvement • **Open Call 1:** Hollow Waveguide LHR – first proof of concept with core instrument implemented in hollow waveguide • **Open Call 3:** Hollow Waveguide LHR – Further developments with hollow waveguide, including fibre integration • **Open Call 4**: Active Component Integration Towards A Fully Encapsulated Miniature LHR For EO • **Open Call 5:** Fully Integrated LHR – further integration of detectors to complete the instrument • **Open Call 6:** LHR Performance Analysis – analysis of performance and mission aspects • **Open Call 7:** LHR for CO2 – experiments with CO2-specific LHR in solar occultation mode.

TRL Start/End	Space: 1-2; now 4-5 Terrestrial: higher now 6-7	**Papers/Conference Presentations (no.)**	6 Refereed journal papers 22 Conference papers
Patents	Under consideration	**Students (e.g. CASE/PhD)**	1 CASE with Oxford (LHR on Mars) 5 Postdoctorals trained in LHR

Spinout Opportunities	• SME created for exploitation of LHR IP (Mirico Ltd) • Defence technology • Terrestrial gas sensing and analysis • Future – medical (breath analysis)

Outcomes	**National:** • IP from QinetiQ LIDAR work with Hollow Waveguide acquired by RAL space, and deployed in passive and active LHR variants. • SME spun out to exploit IP arising from LHR work • Active LIDAR for defence sensing of chemical species, leverages both LHR and early CEOI hollow waveguide LIDAR projects. • Promise of highly miniaturised instrument for airborne and space deployments • Highly suitable for atmospheric analysis in planetary exploration, and astronomy • Medical applications, Environmental applications • Collaboration with SELEX for solid-state high-speed photo-detector **International:** • Collaboration potential with UNSW (Australia) for cubesat mission for demonstration • Defence application with Lockheed Martin • Bidding into H2020 with Large European consortium

Future Steps and Target Opportunities	**Future steps include** *1)* Demonstrate and evaluate emission mode sounding in the laboratory to enable nadir sounding missions (NSTP pathfinder bid) *2)* Produce an airborne demonstrator and deploy for demonstration *3)* R&D towards imaging system (NSTP pathfinder bid) *4)* Miniature LHR space in orbit demonstration mission on micro-satellite **Target opportunity** The most promising short term opportunity is a bilateral mission with Australia as part of their cubesat and space technology development program, providing UKSA would join and support. (NSTP fast track bid). Otherwise more general opportunity in scope include: - NASA Earth venture with Lockheed Martin - Hosted payload on GEO telecom sat - Hosted payload on alternate platform - Small sat in orbit demonstration (ESA IOD or UK IOD) Larger mission are not yet within reach since in orbit demonstration needed for space heritage.
CEOI-ST Leadership Team Contribution	• Created multiple opportunities (CEOI Ph-1, OC 1, 3, 4, 5, 6, & 7) for continuing development of the LHR, its key technologies and capability • Brought together the QinetiQ Hollow Waveguide and RAL LHR technologies and teams to take forward a major step in miniaturisation of the LHR instrument • Created opportunity through EOMAG working group to develop proposal for a potential bilateral mission • Provided platform for team to present their outputs and capability to ESA and other Agencies through conferences, KE workshops and technology showcase events • Assisted team with development of publicity materials and technical brochures to promote technology and capability

Thermal Infra-Red Detector Array System (TIDAS)

Summary	Spectrometry is one of the most important assets of passive remote sensing systems since it is the ability to observe spectra of top of the atmosphere radiance that provides the most detailed information on atmosphere composition. Infra-red nadir and limb sounders can provide fundamental observations of the anthropogenic and natural greenhouse gases, as well as many related species. These systems are excellent for measuring height-resolved profiles of water vapour, ozone, methane and CFC-related species. The TIDAS project addressed the deployment of detector array technology to meet the challenge of building thermal infra-red Fourier transform spectrometers (FTS) for future EO missions
Lead Organisation	Airbus DS Ltd.
Partner Organisations	Selex Galileo, University of Leicester, STFC-RAL

Projects Funded	**Open Call 2**: TIDAS – Development of a two-dimensional thermal infra-red detector array system and on-board signal processing unit, targeted at IR sounding instruments for future meteorological and climate missions. **Open Call 3**: TIDAS Follow-on – Project to continue the development of the thermal IR detector system to provide a laboratory demonstrator for Fourier Transform Spectrometer measurements of the atmosphere. **Open Call 7**: Radiation Testing of CMOS ROICs – Project to perform heavy ion testing of large format ROIC technology for MCT infrared detectors.

TRL Achieved	4/5	**Papers/Conference Presentations**	1
Patents		**Students (e.g. CASE/PhD)**	

Spinout Opportunities	Potential terrestrial instrument applications.
Outcomes	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. The TIDAS methodology has potential applicability to the PREMIER IR Limb Sounder and future high accuracy FTS for climate monitoring in the far infra-red.
Future Steps and Target Opportunities	TIDAS uses a detector array to improve spatial resolution, to complement the high spectral resolution offered by the FTS optics. A high capacity back end signal processing and storage system is needed if the sensor's potential is to be fully exploited. This is a common theme across many types of sensor (infrared, microwave, optical) and TIDAS demonstrated that this can be achieved using current space qualified technologies (A/D converters, FPGA/ASIC, volatile and non-volatile mass memories). The next step would be to build a flight representative breadboard specified for a particular instrument and mission application.
Patents	None
CEOI-ST Leadership Team Contribution	• Created multiple opportunities (OC 2, 3 & 7) for development of IR detectors and technologies • Provided platform for team to present their outputs and capability to ESA and other Agencies through conferences, KE workshops and technology showcase events • Assisted team with development of publicity materials and technical brochures to promote technology and capability