EO Instrument Technology Developments April 2011 to March 2013

Version 1.2

CEOI Leadership Team
April 2013

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INTRODUCTION TO THE CEOI

This Report for Phase 3 of the Centre for EO Instrumentation (CEOI) summarises the EO instrument technologies developed within the CEOI programme between April 2011 and March 2013.

What is the CEOI?

The UK Centre for EO Instrumentation was set up in 2007 with 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 was created in 2007 as a result of joint support from the Natural Environment Research Council (NERC) and the Department for Innovation, Universities and Skills (DIUS) and industry, who combined to fund the CEOI, with the role of DIUS taken over by the Technology Strategy Board (TSB) in 2009. Most recently in April 2011 the newly formed UK Space Agency took over responsibility for the funding of CEOI.

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). The latter was replaced on the Leadership Team by Chris Brownsword (QinetiQ) in April 2012, with Rob Scott continuing to support CEOI in his new roles in ScottSpace Ltd and STFC-RAL.

Organisation

The CEOI Management Board oversees the progress and strategy of the Centre. The Board consists of representatives of the UK Space Agency, key stakeholders (NERC, Met Office and TSB), together with independent representatives from industry and academia and the CEOI Leadership Team.

The CEOI has built excellent links with all of the UK EO community, both industrial and academic, including the NCEO, NERC institutes and the Met Office. It has also been successful in bringing together the UK EO community through conferences and workshops. The partnership has proven to be efficient and effective, receiving a high level of support from the community.

CEOI Phase 3 Programme

During Phase 3 (Appril 2011 to March 2013) the majority of the funding continues to be directed into technology development. New projects, both mainstream and seedcorn have been selected, as in previous phases, through Open Calls which are accessible to all the UK community and which encourage academic/industrial partnerships. Independent panels are set up for each Open Call to assess the proposals submitted and select those for funding.

The Centre has continued with the successful horizon scanning activities of the previous phases, with an annual conference, challenge workshops and other meetings to engage with and bring together the academic and industrial EO communities. These workshops addressed future EO missions and technologies of high priority to the UK, including the water cycle, SAR missions and applications, and calibration techniques. We have also continued with the knowledge exchange programme to ensure maximum economic benefit is gained from the technology investments by identifying spin-out opportunities into other space and non-space applications, as well as potential for spin-in of technologies into EO.

We have put in place a training programme consisting of specific workshops and continue to support NERC funded PhD studentships in EO instrumentation.

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

THE CEOI TECHNOLOGY PROGRAMME

ADVANCES IN TECHNOLOGY DEVELOPMENT FOR EO

The main activity of the Centre is the development of technologies for the next generation of EO instruments. During Phase 3, the Centre has funded 3 mainstream technology developments, 17 seedcorn projects and 6 small mission/instrument studies.

The CEOI also commissioned a study of the TRUTHS concept, which is a mission to provide improved radiometric calibration of instruments, traceable to SI standards.

Highlighted below are some major successes of the programme, with full descriptions of all projects included later in this report.

Passive Microwave Projects

- The **Passive Microwave and Sub-millimetre Wave Imager Technologies** (PMSIT) mainstream project (Astrium) addressed TRL raising and de-risking of important microwave technologies for the MetOp Second Generation MWS, MWI and ICI instruments. These include the on-board calibration scheme, receiver technologies, quasi-optical components, and the mechanical scanning mechanism. The receiver work has focussed on the 183.31 GHz channel applicable to all passive microwave instruments on MetOp-SG.
- **Development of 166/183 GHz Diplexer for Metop-SG MWS Instrument** (Astrium): The study developed a low loss 166/183 GHz diplexer, with the first batch achieving an insertion loss of 0.6 dB (target 0.5dB). Analysis of the physical and RF measurements of the diplexers indicates that acceptable performance can be achieved by improving the surface roughness to 1 µm and substituting silver for the current gold plating.
- **Innovative Ice Cloud Imager** (SEA): Alternative technologies for sub mm radiometers were investigated. The key simplifications are to reduce the number of bands observed and to simplify the rotating part of the instrument. The study found no fundamental problems in conically scanning radiometers with only passive rotating elements.
- A team from Queens University Belfast developed an improved **finite modelling technique for Frequency Selective Surface filters**, applicable to future micro and millimetre wave instruments such as the Microwave Sounder (MWS) on MetOp-SG
- **STEAM-R TRL Raising** is a mainstream project (STFC RAL) progressing work on technologies for the STEAM-R instrument, which is a millimetre wave limb sounder planned for flight on the Earth Explorer 7 candidate mission PREMIER or on a Swedish national mission. A Single Sideband Image Rejection Mixer (SHIRM) receiver was constructed and tested at TRL-5. A series of atmospheric observations at Jungfraujoch in Austria demonstrated very good results, giving sideband separation of better than 24dB.
- **High Level Integration of Passive Microwave Technology** is a mainstream project due to complete in June 2013. The project is demonstrating the integration of a single sideband receiver with a high resolution spectrometer, which is able to perform real-time analysis of 2 GHz bandwidth signals at 1.5 MHz resolution. The work is in preparation for the planned upgrade of the MARSCHALS airborne limb-sounder.
- **Wideband Spectrometer** (WBS) (Star-Dundee) The study quantified the performance of a novel prototype digital FFT based spectrometer and explored its potential as a highly compact, power efficient, space-borne payload in support of climate studies. The WBS performed well when tested with a simple microwave test receiver and with the complex millimetre-wave airborne instrument, MARSCHALS. A flight implementation with a bandwidth of 2 GHz is practical with current flight qualifiable components.
- **Metamaterials in Sub-mm Quasi-Optical Systems** (Astrium) This project investigated the potential of meta-materials, i.e. micro-resonant structures, for matching of components to reduce unwanted reflections The metamaterial concepts identified as

suitable for mm-wave applications include GRIN lens for matching horn/lens combinations and reflection suppression on surfaces i.e. cloaking.

- **Advanced GRIN Lens Design for mm-wave Radiometer Systems** (Astrium): The programme has investigated design methodologies for a GRIN (Graded Index) lens including transformational optics. A GRIN lens at 50 GHz has been designed using constructed metamaterials, and manufactured using PCB multilayer technology. The lens has been tested in a quasi-optical system.
- The National Oceanographic Centre is reviewing the state of the art and outstanding issues for ocean roughness retrieval with **GNSS-reflectometry**, and will provide recommendations for the timely exploitation of GNSS-R data from the SGR-ReSI instrument on TechDemoSat-1, in anticipation of the NASA CYGNSS mission.

SAR and Radar Projects

- **Emulation and Performance Study of a SAR On-Board Processor** (Astrium). An emulator of a highly efficient on-board SAR processor algorithm has been developed and its operation verified against an existing SAR processor, using data from ESA's ERS-2 spacecraft. This emulator has successfully produced SAR images at Level 1 from raw echo data, including intermediate range compressed images.
- **Emulation and performance Study of an On-Board Level 1 Processor for Squinted SAR** (Astrium): The study successfully investigated whether modern processing hardware make it feasible to implement Level 1 processing in the space segment, utilising the relatively modern 'wavefront reconstruction' techniques for SAR image reconstruction. They also assessed the practical implications of implementing these in on-board processing hardware. A key mission opportunity for this technology is the Wavemill oceanographic SAR concept. Other relevant applications include 3D InSAR products for glaciology and volcanology, planetary SAR missions and there is a strong link to maritime surveillance and UAV applications.
- Astrium led a study of the **Wavemill concept**, which is conceived as an ESA Earth Explorer 9 candidate mission to provide wide swath measurements of ocean current. The study demonstrated a viable concept within the constraints of the VEGA launch vehicle, with 13 day repeat cycle, 100 km swath and on-board processing to significantly reduce the data downlink requirements.
- **High-frequency Doppler Radars for a Polar Precipitation Mission** (University of Leicester): The team have found that significant improvements in retrievals of snow water content and snowfall rate can be obtained by observing using frequency pairs (35/220 GHz) and triplets (35/90/140 GHz or 35/90/220 GHz). An end-to-end radar simulator was set up and tested on snow scenes at various frequencies. The requirements for radar transmitter power were assessed at frequencies of 140 and 220 GHz, and the technical routes to realise these powers, based on frequency multiplication were investigated.
- A study of **POLarization-diversitY Doppler Radars On Satellites** (POLYDOROS) was carried by a team led by STFC RAL. It showed that pulse compression is a plausible option for a conically scanning W-band polarization diversity radar system and will provide useful Doppler with accuracies better than 2 m/s at 1 km vertical resolution and 10km integration on roughly half of the cloudy regions as detected by CloudSat.
- **System and Applications Study for a Future Geosynchronous Radar Mission** (Cranfield University) Synthetic aperture radar (SAR) imaging from geosynchronous orbit (GEO) has not yet been demonstrated. The study investigated the principles and outlines the options for implementing GEO SAR, it then considers some applications, and finally identifies a number of opportunities for implementation.

THz Sounder and Thermal IR Imagers and Sounders

- **Towards a Fully Encapsulated Miniature LHR for EO** (STFC RAL). The project took further steps in miniaturisation of the LHR (Laser Heterodyne Radiometer), using hollow waveguide integrated optics techniques to build the core heterodyne mixing block. Highly accurate methods were developed to integrate the main active elements such as the quantum cascade laser, the detector and support components such as lenses and heat sinks.
- **A Fully Integrated Hollow Waveguide Laser Heterodyne Radiometer** (STFC RAL): Developing the capability to machine complex ceramic structures with a few microns dimensional tolerances and the expertise to integrate other Laser Heterodyne Radiometer components, including a quantum cascade laser, beam combiner, polariser and detector into the ceramic substrate, has resulted in the final design of a fully integrated LHR, miniaturized down to a foot print of 15x9 cm2. The instrument is being assembled and will be put under test in 2nd quarter 2013.
- **Thermal IR for monitoring atmospheric trace gases** (STFC RAL) Conclusions of the study indicate that a miniature LHR about the size of a shoe-box size would be capable of sounding with high spectral resolution (from 0.02 to 0.002 cm-1) in the mid infrared and with spatial resolution of a few 100 metres in lower Earth orbit and few kilometres in geostationary orbit. The best candidates among the molecules tested are carbon dioxide and ozone.
- **Application of a New Detector Processing Technique for Space-borne Fire Measurement and Monitoring (SSTL):** The project has explored new processing techniques and the performance of new broadband uncooled detectors to assess the feasibility of achieving adequate performance at much lower cost. Two Ulis PICO detectors have been procured and the test rig is under construction. The test programme is expected to vcomplete in the 2nd quarter of 2013.
- SSTL led a team to study a **Low Cost THz Sounder (LOCUS)** which will monitor the mesosphere and lower thermosphere (approx 50-150 km). They have completed an outline payload and mission design and identified critical areas for further study. The team also prepared a proposal for an In-Orbit Demonstrator study, which has been selected by ESA for the next stage.

Hyperspectral Imaging

- **Demonstrating the Quantitative Recovery of Structural and Biochemical Parameters from Forest Canopies Using a New Hyper-Spectral LiDAR** (HSL) (Heriot-Watt University). A novel multi-wavelength photon counting LiDAR system has been built, and tested on campus and in the field on a forest canopy. Retrieval algorithms for canopy biomass and biochemical parameters have been evaluated. The technique has the potential to give more accurate and informative data in comparison with currently deployed systems on small tree samples.
- **Concept Studies for a Methane Emission Imager** (University of Leicester): The study objective is to define a novel concept for measuring atmospheric concentrations of the important greenhouse gas methane (CH_4) based on the use of discrete shortwave infrared spectral bands. The team developed a basic instrument concept and investigated a number of design options, investigating the possibility of developing an instrument suitable for the SSTL TechDemoSat platform
- **The Ultra-Compact Air Quality Mapper** (UCAM) (University of Leicester): The team investigated the feasibility of developing an ultra compact remote sensing instrument capable of enabling discrete wavelength retrievals of atmospheric nitrogen dioxide (NO_2) from a space borne platform. They demonstrated that discrete wavelength retrievals of NO_2 are possible using an artificial neural network. The study suggests that fit errors of < 10% are achievable with an SNR of 500.
- An **airborne version of the CompAQS instrument** (University of Leicester) was flown over the east midlands area and mapped NO_2 at 20 x 20 m resolution. This has

demonstrated key concepts of source identification and exposure mapping and was also the first flight of CEOI developed instrument technology.

- **TRUTHS Study** (National Physical Laboratory). The study is investigating the requirements of a climate benchmark mission, based on measurements of solar radiation incident upon and/or reflected from the Earth. It is considering a range of options including: incremental improvements of existing or planned sensors; the payload requirements/options for a dedicated self-contained mission; upgrade of performance of other sensors by reference calibration against a “high accuracy satellite” or some combination of these approaches. The study is expected to complete in 2nd quarter 2013.

Optical and IR Imaging

Six small ‘Peppercorn’ projects, each lasting no more than 6 months, investigated novel concepts and techniques in future EO instruments and missions:

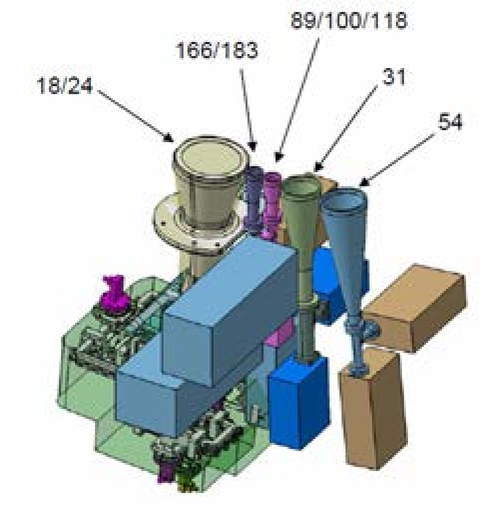
- **Prototype Earth obseRving System using Image Slicer Technology** (PERSIST) (STFC UK ATC). The project exploits image slicing techniques using a multi-faceted focussing mirror to provide a compact and lightweight optical design, which allows the imaging of spectra from 3 separate wavebands onto a single detector array. Tests of a prototype with respect to stray light and crosstalk show that the performance is good.
- **Assessment of a New Low Weight Mirror Fabrication Technique for Future EO Space Systems** (Gooch & Housego Ltd): The team have successfully demonstrated adhesive free bonding of lightweighted mirrors using a method suitable for efficient manufacture. Prototypes have been fabricated and exhibit excellent stability after temperature cycling.

The following pages contain descriptions of these projects, list their main achievements and document their outputs

PASSIVE MICRO/MMWAVE PROJECTS

PASSIVE MICROWAVE AND SUB-MILLIMETREWAVE TECHNOLOGIES

The next-generation of the ESA/Eumetsat MetOp platform (MetOp-SG) is approaching Phase B. Certain key technologies for the microwave imaging instruments (such as the MWI and ICI) are not covered by the existing ESA Phase A study programme. The current CEOI programme aims to close this gap by developing and derisking these technologies. As a consequence it will be possible to position a UK consortium led by Astrium UK to bid strongly into the MetOp-SG Phase B programme.

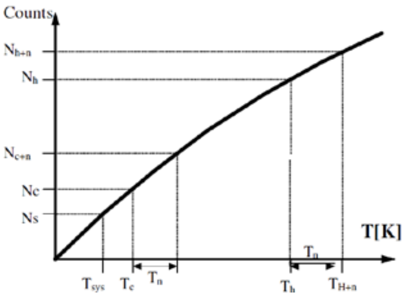


The technologies of interest are the microwave calibration scheme and subsystem, the active balancing for the mechanical scanning mechanism for the antenna, and the quasi optical system design and analysis, and receiver subsystem design and analysis.

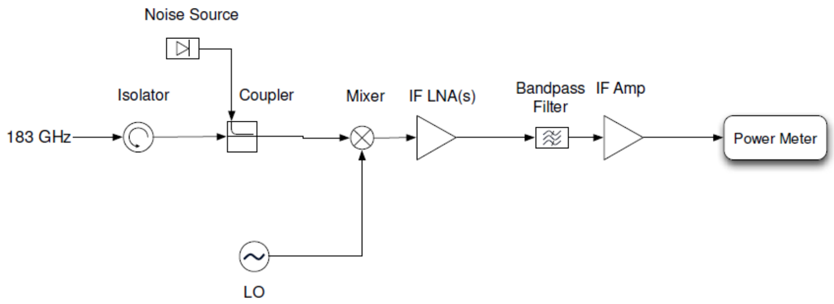
Lead investigator(s): Yvonne Munro, Astrium; Janet Charlton (JCR Systems); Brian Moyna (RAL Space); David Summers (System Engineering & Assessment Ltd)

Calibration

The previous generation of imaging microwave instruments has a long history of poor calibration. This CEOI project work is part of an international effort to improve matters. Simple 2-point calibration schemes have been used in the past and have proven to be deficient. Four-point calibration is a hybrid approach that uses cold space view, hot load and noise diode measurements to provide inputs to the radiometric transfer function (RTF). This allows transient effects and receiver non-linearities to be tracked in orbit.

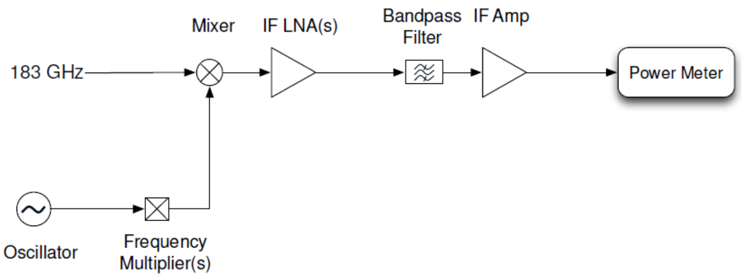


To realise the 4-point scheme at 183GHz, a directional coupler must be used. This arrangement allows a Cold, Cold + Noise source, Ambient, Ambient + Noise source to be used. The use of a coupler should not degrade system reliability. This technique has been adopted for the receiver breadboard. Due to difficulties in procuring a suitable COTS noise source at 183GHz, an alternative solution has been developed by RAL.



Receiver technology

The MWI features channels with centre frequencies from 18.7GHz to 183.31GHz while the ICI includes channels from 183.31GHz to 664GHz. In general, these channels are relatively broad band (channel bandwidths >1GHz), so that both heterodyne and direct detection techniques are applicable in principle.



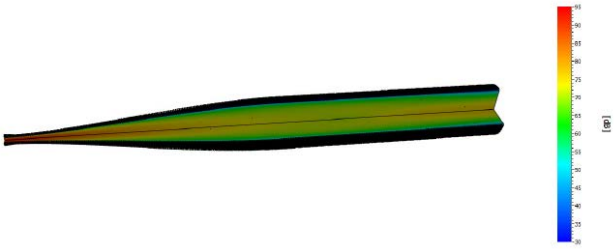
However currently available technology limits LNA performance to around 200GHz. Therefore the ICI channels are likely to be heterodyne (no LNA), while the MWI channels may be either heterodyne (with or without an LNA) or direct detection.

To address development of technologies with the broadest possible application to both MWI and ICI, a heterodyne receiver at 183.31GHz, without an LNA (above), is a logical platform with which to work. Although the present activity is targeted towards supporting Microwave Imager activities, the 183GHz channel is also common to the Microwave Sounder (MWS); selection of this frequency for the breadboard therefore keeps it relevant to all potential MetOp SG microwave instruments.

At the selected frequency of 183GHz, both fundamental and subharmonic mixer (SHM) architectures may be employed. However for MetOp-SG the subharmonic mixer route has a number of advantages, and a 183GHz subharmonic mixer recently developed by RAL (right) can be deployed.

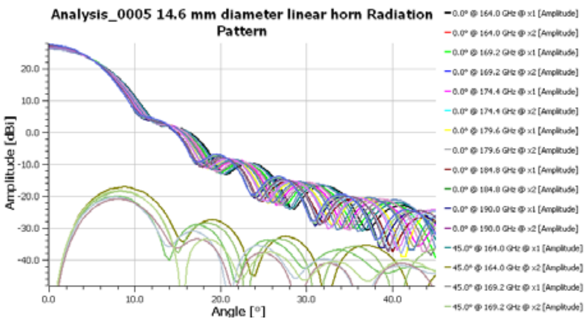
The local oscillator is at 91.66GHz, and is readily available from lab Gunn oscillator sources. For breadboard receiver stability, a thermally-stabilised IF chain has been assembled.

Quasi optics



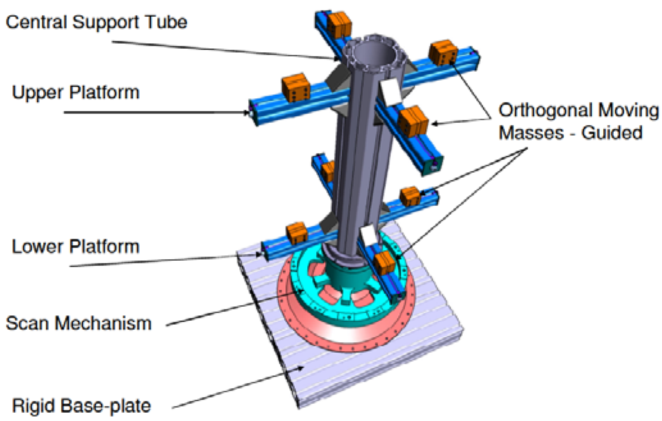
A choice must be made for the optimal design of the feedhorn at the 183GHz frequency in order to meet the requirements of different radiometer systems. This is driven by the reflector and Quasi-Optical system that the horn is to be fitted to. In general for a radiometer system (unlike a communications system) the system must achieve a gaussian like beam shape, with minimum sidelobes. This choice, although not at all optimum for aperture efficiency or antenna gain, does assist in reducing scattering and spillover in the QO system, and matches to some extent the gaussian mode optics techniques used in designing the radiometer.

Two basic choices of feed horn are available for producing HEII gaussian beams, a stepped conical horn (Potter Horn), optimal for relatively narrow band operation, and a corrugated horn design suited to wide band operation. A trade-off has been carried out on the many horn configurations and the analysis favours an ultra-gaussian corrugated design (above & right) which offers a good compromise to the often conflicting requirements.



Active balancing for the scan mechanism

Rotating antennas for microwave instruments can propagate disturbance torques to the main spacecraft. This element of the project has investigated the possibility of an active vibration cancellation system using movable masses which can be used to trim the antenna rotation whilst in orbit. For this project a mechanical demonstration rig has been modified from a system originally developed for the MIMR programme. It has the following elements: a representative scan mechanism with integrated Kistler washers for force measurement, a rigid baseplate, and an instrument rotor simulator with movable masses.



Before balancing can be performed, the test bench needs to be understood and a series of calibration activities carried out. A major task is to develop and test a number of algorithms for use in the active compensation system.

Verification is about developing understanding of the balancing process, in particular understanding the measuring process and what limits its accuracy and repeatability. Tests indicate that the rotational dynamics of this system are complicated, and mechanical noise complicates the analysis.

Publications

I. Maestrojuán Biurrun, "Caracterización de técnicas de medida de mezcladores a frecuencias milimétricas," submitted to: XXVII Simposium Nacional de la Unión Científica Internacional de Radio, URSI 2012

Grants and Contracts

Contracts	Title	Participants	Value	Status
NSTP Fasttrack	Development of a Quasi-Optics System for the Metop-SG MWS 183/229 GHz Channels	Astrium Ltd JCR Systems Ltd RAL Space SEA Ltd	£100,000 Grant	Awarded (pending contract agreement)
ESA	MetOp-SG MWS Phase A/B1	Astrium Ltd RAL Space	€280,000	Awarded

Training

The breadboard 183GHz receiver development and characterisation was carried out by Itziar Maestrojuán Biurrun, a PhD student from the Antenna Group, Electrical & Electronic Engineering Department, Universidad Pública de Navarra, Pamplona, Navarra, Spain, on secondment to RAL. Her work was supervised by Dr Simon Rea at RAL.

Spin-out and Exploitation

The principal objective of PMSIT and associated activities is to derisk technologies for the MetOp-SG passive microwave instruments and to promote UK lead of at least one instrument. An near term opportunity for exploitation may be provided in 2012 as ESA has indicated that it intends to fund a MWS quasi optic network breadboarding study. The study will be led by RAL Space with Astrium and JCR as subcontractors, thus reinforcing the teaming established in the PMSIT study.

DEVELOPMENT OF 166/183 DIPLEXER FOR METOP-SG MWS INSTRUMENT

Astrium, is undertaking development of a 165/183GHz waveguide diplexer, supported by STFC Rutherford Appleton Laboratory (RAL), and supplier Thomas Keating. The diplxer has the potential to greatly reduce the complexity of the Quasi-Optical Network (QON) for the MetOp-SG Microwave Sounder (MWS) instrument.

The 165 GHz channel must be separated from the 183 GHz channels in order to allow these to use separate mm-wave receivers since it is not possible for a single receiver to cover the full bandwidth. The separation of the channels can, in principle, be performed quasi-optically using a dichroic beam splitter but the resultant QON would be complex. An alternative approach is to use a common QON path for both sets of channels and then perform the separation within a waveguide diplexer. The diplexer will consist of a Y-junction with suitable cavity waveguide filters in the 2 output arms.

The main requirement will be to achieve low insertion loss (< 1 dB) between 164 – 167 GHz and between 175 – 191 GHz. Since the diameter of the waveguide will be ~1mm, manufacture of the diplexer will only be possible by electroforming. Three identical waveguide diplexers will be manufactured and tested to verify that both the required mechanical tolerances of <5µm and the insertion loss performance over the required 165 and 183 GHz MWS channels have been achieved.

The development will not only enable the UK to prepare for the Phase B MWS instrument opportunity by addressing a key instrument technical issue not covered by the ESA Phase A and parallel technology development studies but also has potential application to other instruments operating in the 100 GHz to 200 GHz frequency range.

Lead investigator: Yvone Munro (Astrium)

Science and operational case

The MetOp Second Generation (MetOp-SG) satellites, to be launched from 2020, will provide continuity of Low Earth Orbit (LEO) meteorological observations currently performed by the MetOp series of satellites. The MWS is one of the MetOp-SG instruments with the highest priority ranking. The MWS will provide continuity with the mission of the AMSU-A and MHS sounding instruments in the provision of wide-area weather measurement of temperature and humidity profiles over land and sea. Hence, it has a significantly wider frequency range compared with its predecessors:

	AMSU-A	**MHS**	**MWS**
No. of channels	15	5	24
Frequency Range	23 – 89 GHz	89 – 190 GHz	23 – 229 GHz

The high number of other instruments on the MetOp-SG satellite A, and consequent payload accommodation constraints, preclude either splitting the instrument into a pair of complementary instruments similar to AMSU-A and MHS or adopting a dual aperture instrument design similar to ATMS. Hence, instrument designs based on a single aperture have been selected by both competing ESA MetOp-SG Phase A/B1 study teams.

A single aperture system potentially demands a highly complex QON. The science requirements for the MWS instrument include high spatial resolution (< 40 km at all channels), high sensitivity and accuracy. These factors combine to make the design of the MWS QON highly challenging. This has been recognised by ESA, which has funded the predevelopment of the low-frequency, low-loss frequency selective surface (FSS), and has initiated a direct negotiation 18 month predevelopment of a representative QON with STFC RAL. The study is therefore complementary to the ESA QON pre-development as the availability of a 165/183 GHz diplexer has the potential of significantly reducing the complexity and hence the risk associated with the QON.

Study results

All 4 diplexers exhibited a higher insertion loss that expected from the original design model. The overall spectral shape of diplexers 1-3 is in very close agreement with the design model with the exception of insertion loss, whereas diplexer 4 showed a response, which deviated slightly from the designed response. It should be noted that measurement of structures at these frequencies is always difficult, which results in calibration and measurement errors which tend to manifest themselves as measurement ripple. It is therefore normal to take averages of the values to estimate the real insertion loss.

In the cases of diplexers 1 - 3 this results in an average insertion loss of 0.75 dB. Subsequent HFSS analysis suggests that the discrepancy between expected and measured insertion loss may be due to surface roughness of the diplexers' internal structure, which was not included in the original model, but has been quantified from the sectioned diplexer 4 and included in an updated HFSS model. Increased surface roughness effectively decreases the conductive properties of the waveguide surfaces, resulting in an increased insertion loss. It is believed that these factors account for the additional insertion loss seen in the manufactured diplexers compared to the original model.

Conclusions

The study has been partially successful in achieving its objective of the development of a low insertion loss 166/183 GHz diplexer, all be it that the target performance requirement of an insertion loss of 0.5 dB has not quite been met. However, analysis of the physical and RF measurements of the batch of 4 diplexers indicates that acceptable performance can be achieved by improving the surface roughness to 1 µm and substituting silver for the current gold plating. A second batch of 4 diplexers will be produced and tested and the performance compared with that of the current design. If this proves successful then it will be relatively easy to space qualify the technology given the flight heritage of this type of component.

Training and Knowledge Exchange

- The project has provided an opportunity for on-the-job training for a student, Mr Anup Mistry (Department of Physics, University of Bath), who assisted in the RF measurement of the 4 diplexers undertaken at STFC RAL.

Spin-out, exploitation and UK Capability enhancement

The MWS baseline instrument configuration does not include a 166/183 GHz diplexer and no ESA funding was available during the Phase A/B1 to investigate this as an option. However, the CEOI funding facilitated the timely investigation of the feasibility of the technology, with initial test results available in time to enable the diplexer to be identified as a possible option in the successful MWS Phase B2/C/D proposal.

The 166/183 GHz diplexer development has not only enabled the UK to prepare for the Phase B MWS instrument opportunity by addressing a key instrument technical issue not covered by the ESA Phase A and parallel technology development studies but also has potential application to other instruments operating in the 100 GHz to 200 GHz frequency range. The study has led to improved RF modelling of components, specifically leading to more accurate quantification of the effects of surface roughness and materials on insertion loss.

In addition, this CEOI study has provided an opportunity to bring together the key members of the UK MWS instrument team in advance of release of an ESA MetOp-SG Phase B ITT. Building on the existing strong instrument system capability of the team, the project has enhanced the system knowledge of all partners and provide each with insights that will further their international competitiveness and has helped contribute to the successful award of the Phase B MWS instrument contract.

ASTRIUM AN EADS COMPANY

STFC RAL Space

DESIGN OF AN INNOVATIVE ICE CLOUD IMAGER FOR GLOBAL MEASUREMENT OF CIRRUS CLOUD

Sub-mm wavelengths are interesting to the Scientific (Earth Radiation Budget) and Earth Observation communities for their sensitivity to the ice content in clouds. Operational space based radiometers in the sub-mm wavelength region are currently being developed, primarily for use as part of the Ice Cloud Imager (ICI), part of the MetOp-SG mission. The ICI instrument has been selected to fly on MetOp 2G but current designs for the ICI are for a large and complex instrument.

This study investigates the simplifications that can be made to ICI for future instruments. The aim is to make the instrument less expensive and less complex, but still meeting scientific and operational needs. We propose to compare the submm technology approach with the infrared approach in order to identify the lowest cost instrument which would provide useful data. This will lead to a high value-for-money solution and will enable the disruptive technology developed in the UK to be deployed in a timely manner.

Lead investigator: Dave Summers (SEA)

Science and Operational Case

Cirrus clouds both reflect a significant part of incoming solar radiation and absorb upwelling thermal radiation. Depending on the ice crystal size distribution and shape, the balance between the cooling albedo effect and the warming greenhouse effect may be of either sign. Radar is useful for the measurement of the large particles in water clouds, and infrared measurements are sensitive to the small particles, but, most of the size distribution requires submm measurements. So the Ice Cloud Imager proposed for MetOp 2G includes a number of such channels. High cirrus appears cold in continuum channels, and can be distinguished from water through simultaneous observation in water vapour rotation lines.

There is a scientific consensus that submm (100GHz-1THz) radiometers are required to make global measurements of cirrus clouds. Measurement of spectral lines (the shape of which gives altitude information), and the continuum gives information on the cirrus ice clouds.

Studied solution:

A requirements review was undertaken to establish what relaxation of the MetOp ICI requirements for sub-mm radiometers would be possible for them still to be of interest to the Scientific and Earth observation communities. It was concluded that reducing the number of channels to 184GHz, 325GHz and 664GHz give a good compromise between coverage and sensitivity while still providing useful (but reduced) information on cirrus ice clouds. Other requirements were either kept the same as ICI (e.g. the Off Zenith Angle), or relaxed slightly (horizontal resolution, oversampling, lifetime, NEDT).

A technology assessment and trade-off analysis considered various applicable technologies: Bolometers require cooling to sub Kelvin temperatures to meet the NEDT requirements. Heterodyne RF solutions require extensive hardware for detection. The quasi-optics required for scanning the scene drive the mechatonics complexity, primarily because the usual configuration has the detectors and associated electronics rotating with scan makes the mechatronics both heavy and complex. An option for passive scan was considered.

Cost drivers' were looked at for the various technology options. Both Bolometer and RF Heterodyne solutions had significant cost drivers:

- Sub K bolometer detectors require acryogenic solution, which RF solutions do not require.
- RF heterodyne detectors require significant hardware, for the LO generation (typically a low frequency synthesis, followed by frequency multiplication) significant mixers, channel filtering, amplification and power detection.

Hence although the cost drivers in these two technologies are very different it has been estimated that they would come out at approximately the same cost.

The one area where a very strong cost saving looked possible was for the mechatronics, where having an active detector rotating requires significant design overhead for the following systems:

- Both power and data need to be transferred to the rotating elements, requiring a complex system
- The detectors require front end electronics as well as much of the data processing electronics. This splits the electronics between the rotation and non rotating halves – which increases the amount of electronics needed.

Hence a design with only passive rotating elements, if technically feasible, is clearly favoured from a cost point of view

An detailed design was undertaken to describe a conceptual design. From the previous work, it was clear that the main area to look at in more detail was the passive scanning solution. For the detector technology, the RF heterodyne solution was selected; this was primarily because sub K cryogenic bolometers had already been studied in previous work.

The detail design investigated the polarisation artefacts introduced though a passive rotating element, these were found to be minimal at the wavelengths considered, and unlikely to be a strong driver. The design of the RF has been significantly elaborated, a key conclusion of which is that RF solutions cannot detect the sum of the two polarisations, instead both polarisations need to be independently measured, and only summed after detection of the powers.

Whilst methods have been investigated for defining the polarisation of radiation with respect to the scene, if the RF heterodyne needs to separately process the two polarisations – then the full polarimetric information can be reconstructed in ground processing, without the need to have an additional RF polarising element.

Conclusions

Alternative technologies for sub mm radiometers are available. However, other technologies do not at this stage present significant advantages over the traditional RF heterodyne solution baselined for use on ICI.

The key simplifications that can be made to drive down costs are:

- Reduced requirements, specifically: reduction in the number of bands observed.
- A solution requiring only passive rotating elements The detailed study has found no fundamental problems in conically scanning radiometers with only passive rotating elements; however a full study has not been performed – and so this technology is not as mature as the traditional radiometer design baselined for ICI.

Spin-out, exploitation and UK Capability enhancement

Study has reviewed technology and strengthened SEA system understanding of sub-mm instruments.

At least as important has been the relationships developed/reinforced: Consolidated links with RAL, Cardiff University, JCR systems, Met Office and established new links with non-UK scientists.

ICI on MetOp-SG now confirmed, so the opportunity to propose a lower cost ICI design for MetOp-SG opportunity has faded.

However the UK is now well placed for future sub-mm radiometers.

But, a single step from simulations direct to 3× operational instruments and a >20year commitment is not ideal. A simple quick demonstrator is still desirable (ICI flight 2023)

FINITE FREQUENCY SELECTIVE SURFACE MODELLING

The purpose of this project is to develop a new numerical model for finite Frequency Selective Surfaces (FSS) which will provide extremely accurate numerical predictions of beam propagation and reflection, when the filter is illuminated by a Gaussian beam and expand QUB's capability in FSS design.

The primary objective was to extend the modelling for a broadband low loss quasi-optical filter for the microwave sounder (MWS) instrument on the Post-EPS mission. The electromagnetic model was developed at 23.8 GHz and uses microwave Gaussian beam illumination, to replicate the electromagnetic environment in the instrument. Currently FSS electromagnetic modelling methods use an infinite array approach, which does not allow investigations into the effects of edge illumination, and the prediction of the radiation pattern. These effects become important in precision measurement systems such as the MWS instrument. The MWS FSS is 250 mm in diameter, and is the largest resonant FSS ever constructed in Europe. It has the largest beam illumination in the QO system; therefore, particularly for this FSS it is important to extend the FSS modelling capability to consider the effects of edge illumination.

Lead investigator: Raymond Dickie (Queens University of Belfast)

Summary report

This project develops a new numerical model for finite FSS design which provides accurate numerical predictions of beam propagation and reflection, when the filter is illuminated by a microwave beam. Finite FSS modelling requires significantly more computer resources than previous approaches but these are now becoming more accessible due to the availability of hardware accelerated high performance computing.

An example of the modelling carried out at QUB is shown in Figures 1-2, where a linear array approach was used to model the 250 mm FSS. The radiation pattern and Gaussian beam illuminated FSS are presented, and show the electric field and power flow along with the main beam which propagates at 45°. This model was further developed to calculate the bistatic scattering for a range of microwave beam sizes, providing information for various edge illumination conditions.

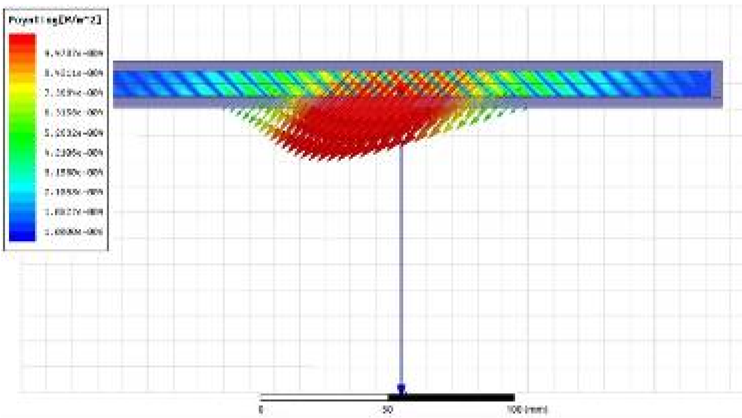


Figure 0-4: TE 45^0 incidence microwave beam illuminating of the 250 mm long linear array

To achieve the project objectives the following tasks were carried out:

- Setup of hardware and software required to solve the finite FSS problem
- Investigation of the numerical solvers HFSS and CST for finite FSS analysis
- Model convergence studies, comparing the spectral response of unit cell FSS, finite sized FSS, and measured results

- Finite FSS radiation pattern outputs at 23.8 GHz for different levels of edge illumination

Conclusion

In the course of this project, the team at QUB setup the hardware and software required to solve the finite FSS problem at 23.8 GHz. The modelling was a significant challenge due to the FSS's large overall length of 250 mm and small feature size of 0.03 mm. Two methods were investigated, linear array and complete array modelling. The linear array method was shown to provide valuable radiation pattern scattering information, and a study was carried out using different sized microwave beams.

These results are significant as future instrument designs will require the radiation patterns. Past experience has shown deviation of the beam within the instrument (AMSU B), and antenna far field pattern distortion with the introduction of the FSS in the receiver. Therefore the simulation tool will provide a cost effective solution for FSS design in QO instrumentation, compared to experimental solutions.

The work is aligned with the breadboarding phase of the MWS QO network phase which started in January 2013 by a UK consortium consisting of QUB, RAL Space and QMUL.

Publications and dissemination

- Planned publication in IET Electronics Letters Journal

Grants, contracts and intellectual property/patents

- The work is aligned with the breadboarding phase of the MWS QO network phase which started in January 2013 by a UK consortium consisting of QUB, RAL Space and QMUL, as described in RFQ 3-13642/12/NL/BJKO.

Training and Knowledge Exchange

- n/a

Spin-out, exploitation and UK Capability enhancement

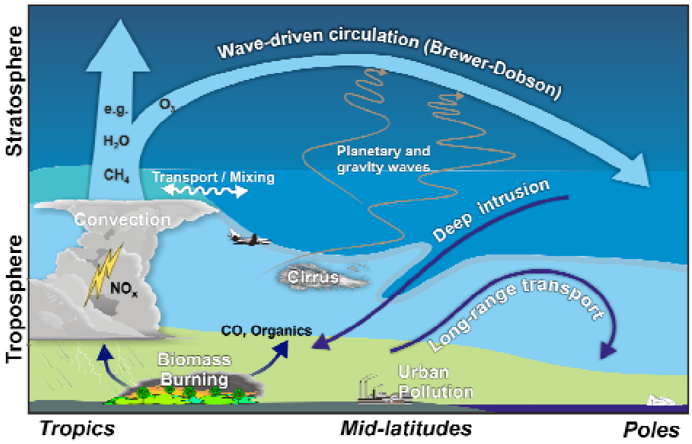
The work addresses a critical technology need for the MWS instrument which is under development (Phase B) and scheduled for launch in 2020 and consequently:

- Strengthens UK expertise and capabilities in EO instrumentation
- Helps to position us, together with our industrial partners EADS Astrium UK and RAL, to bid for future work

This work particularly important for the breadboarding phase of the MetOp-SG MWS instrument quasi-optical (QO) feed network that has recently started a by a UK consortium consisting of QUB, RAL Space and QMUL. This project will compare the predicted radiation patterns with measured results will take place during the breadboarding phase of the MWS QO network.

STEAM-R TRL RAISING

This project follows on from previous CEOI projects to develop critical mm wave technologies as a UK contribution to the Swedish STEAM-R mm-wave limb sounder instrument, which is expected to fly on PREMIER, a Phase A candidate (in competition with 2 other missions) in ESA's Earth Explorer 7 programme.

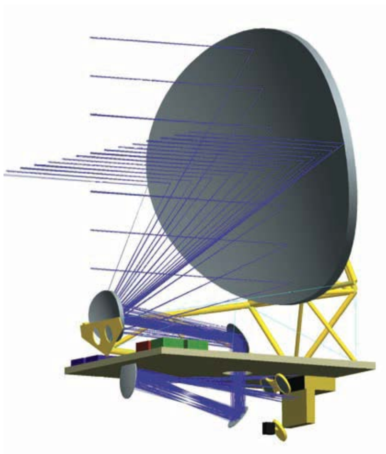


This project focusses on finalising the design and manufacture of the flight variant of the critical sub-harmonic single sideband image rejection mixer (SHIRM) and raising its TRL to 5 in order to meet ESA requirements for the technology to be admitted to the mission.

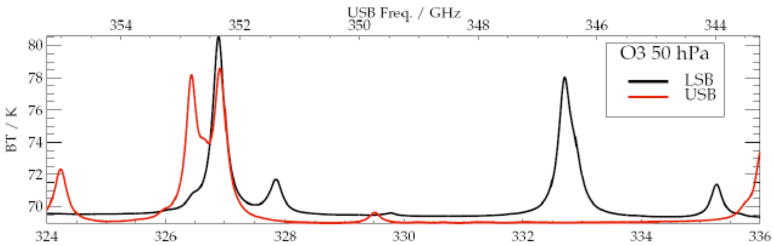
In addition to the design of the new device (led by Astrium) and manufacture by RAL, a suitable TRL5 qualification test campaign has been carried out at RAL, and field measurements have been made at the Jungfraujoch observatory in Switzerland.

Lead investigator(s): Brian Moyna (STFC RAL Space), Yvonne Munro (Astrium)

STEAM-R is a passive, millimetre-wave, limb-sounding radiometer for atmospheric chemistry measurement in the UTLS region. The instrument is proposed by Sweden as a nationally-funded contribution to the candidate ESA Earth Explorer core mission candidate, PREMIER. ESA has recognised the pivotal role of limb-emission sounding for exploring processes that control atmospheric composition in the height-region of particular importance to climate by selecting PREMIER for Phase A study. If PREMIER is selected as Earth Explorer 7, STEAM-R is due to be launched in ~2018.



The UK has been invited to contribute to the STEAM-R radiometer, which is being developed by Omnisys Instruments AB on behalf of the Swedish National Space Board. Final down selection of ESA's 7th Earth Explorer mission is likely to be early in 2013. In the event that PREMIER is not selected, it is likely that STEAM-R will then be developed by Sweden for an alternative platform. In short, the prospects for a near-term flight opportunity are excellent.



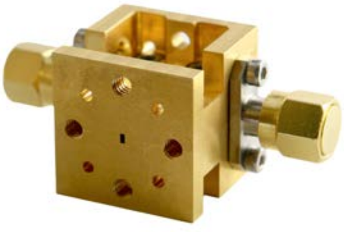
Previous CEOI work has focussed on mm wave quasi-optical design, feedhorns, filters, and early versions of the single sideband mixer. The single sideband mixers in particular are a critical element, as they are able to separate upper and lower sideband spectra (which would be overlapped and confused in a double sideband implementation), enabling observation to lower altitudes in the upper troposphere.

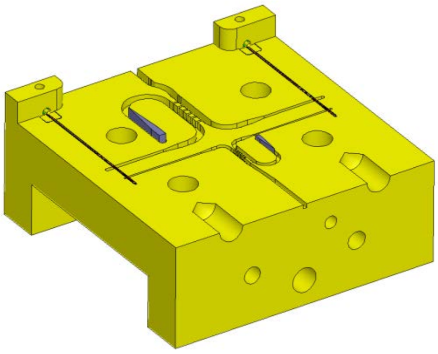
ESA has insisted that any technology admitted to the mission at Phase B must have reached TRL5. Therefore this project is aimed at production of a flight representative SHIRM which has been qualified to TRL5 level with a suitable laboratory test campaign. The goals were:

- Demonstration of a further iteration of the SHIRM, to undergo flight-representative environmental testing required to achieve TRL5.
- Modelling of the proposed measurement scenario to confirm expected performance of a SHIRM-based receiver viewing laboratory or atmospheric emission spectra.

- Development of additional equipment to support testing
- Ground based atmospheric measurements and analysis of the measured data.

ESA have not defined precisely the acceptance criteria for the SHIRM at TRL5. In order to establish that the equipment is at TRL5, RAL have therefore defined their own TRL5 criteria (based upon a previous subharmonic mixer flight qualification programme for EOS AQUA) in a Technical Note which has been sent to ESA for information. Due to the extended test campaigns and the engineering issues encountered, the project has been allowed to continue at zero cost to CEOI.





The new version 5 SHIRM has been assembled and tested. While sideband separation performance is excellent, demonstrated noise performance is currently disappointing. Tests continue, and it is expected that this issue can be corrected with noise levels consistent with previous generations of SHIRM. It has been possible to complete a series of atmospheric observations at the Jungfraujoch site which have demonstrated very good results with the previous SHIRM models (v1.0 and 3.0), giving sideband separation of better than 24dB.

Publications

S. P. Rea, M. Renker, B. P. Moyna, D. Gerber, M. Whale, A. Murk, "First-Light Observations with a 340 GHz Sideband Separating Schottky Diode Receiver," submitted to 37th Infrared, Millimeter and Terahertz Waves Conference, IRMMW-THz 2012, Sept. 2012, Wollongong, Australia

Grants and Contracts

Contracts	Title	Participants	Value	Status
5th CEOI Open Call	High Level System Integration of UK Receiver Technology for STEAM-R and MWS	RAL, Star-Dundee	Grant of £188,562	Awarded
NSTP Space for Growth	UK Contribution to STEAM-R	RAL	Grant of £250k	Awarded

Spin-out and Exploitation

This activity has had the objective of demonstrating a SHIRM design which can be considered for Phase B of PREMIER, and to deploy the SHIRM at a high altitude ground-based site to obtain first atmospheric measurements with a sideband separating Schottky based receiver. An early opportunity for exploitation is provided by the new NSTP project (listed above) which will see the deployment of a SHIRM-based receiver on board ESA's MARSCHALS airborne limb sounder to obtain SSB mm-wave atmospheric spectra alongside the GLORIA-AB limb-imaging IR instrument; this configuration emulates the intended PREMIER payload.

STFC RAL Space

ASTRIUM AN EADS COMPANY

SYSTEM INTEGRATION OF RECEIVER TECHNOLOGY FOR STEAM-R & MWS

This project is a collaboration between the Millimetre-Wave Technology Group, RAL Space and STARDundee Ltd. The aim of the project is to demonstrate system-level performance of critical receiver technology as part of the continued UK support to the STEAM-R instrument. STEAM-R, a millimetrewave limb-sounding radiometer, is a Swedish contribution to the PREMIER mission. The main aim of this project is to develop and characterise the performance of a total-power radiometer comprising a 340 GHz sideband-separating receiver with high-resolution back-end. The key component of the sideband-separating receiver is a sub-harmonically pumped image-rejection mixer (SHIRM). The SHIRM was previously developed by RAL Space and Astrium with funding from CEOI. The highresolution back-end is a digital FFT-based spectrometer which is being developed by STAR-Dundee Ltd as part of the project. A prototype of the wideband spectrometer (WBS) was previously developed by the company and was successfully characterised with funding from CEOI. In preparation for the planned upgrade of the MARSCHALS airborne limb-sounder, a preliminary design study will investigate the integration of a sideband-separating receiver with high resolution back-end into the instrument. The spectrometer development within the project is also relevant to the Microwave Sounder (MWS) within the scope of the Post-EUMETSAT Polar System (Post-EPS) mission. The MWS will be developed by European industry with a launch in the 2018-2020 timeframe.

Lead investigator(s): Simon Rea (STFC RAL Space), Steve Parkes (Star Dundee)

Science & Operational Case

Changes in composition of the upper troposphere and lower stratosphere (UT/LS) are driving climate change, yet understanding of the processes controlling this region are inadequate due to its complexity and fine scale structure which has not been resolved by current satellite missions.

Detailed spatial structure must be resolved in order to understand these processes and to represent them accurately in models, which is difficult to achieve from space. Advanced instrumentation will allow PREMIER to resolve this structure adequately for the first time, including processes of major importance in this height range, e.g. plumes from biomass burning and industrial pollution, and convective uplift in the Indian monsoon circulation. The primary aim of PREMIER is to explore processes controlling global atmospheric composition in the UT/LS, a region of particular sensitivity for surface climate, by resolving 3D structures of trace gases, thin cirrus and temperature in this region on finer scales than previously accessible from space.

Observations in the mm-wave region are much less sensitive than IR observations to cirrus clouds. The unique contribution of STEAM-R to the PREMIER observation capabilities is to extend the measurement range to lower altitudes in the UT/LS region. Sideband-separating receivers are a highpriority option for the STEAM-R receivers which view deep into the upper troposphere. Separating the sidebands eliminates the potential for spectral confusion and/or masking of emission lines which may occur in a conventional double-sideband receiver. This effect is compounded by the pressurebroadening of emission lines at lower altitudes. A high-resolution spectrometer back-end is a key requirement of STEAM-R to enable the instrument to fully resolve the emission of species in low abundance and with very narrow emission lines in the stratosphere.

Study Results

This section to be updated on receipt of the final report

The WBS II is a high performance spectrometer which is able to perform real-time analysis of 2 GHz bandwidth signals to 1.5 MHz resolution. The received signal is provided as an in-phase and quadrature pair. The two input signals are sampled at 3 Gsamples/s by a pair of 8-bit Analogue to Digital Converters (ADCs). A field programmable gate array (FPGA) device is used to implement a custom-designed, high-performance 2048-point complex-complex FFT. Each spectral sample is power detected to provide a power measurement. The power of each frequency bin is integrated to improve signal to noise ratio. The integration time is configurable. Connection to a host computer is via a USB 2.0 or SpaceWire. A graphical user interface written in LabVIEW, may be used for controlling the unit and for displaying the results. Final testing of the WBS II is currently underway.

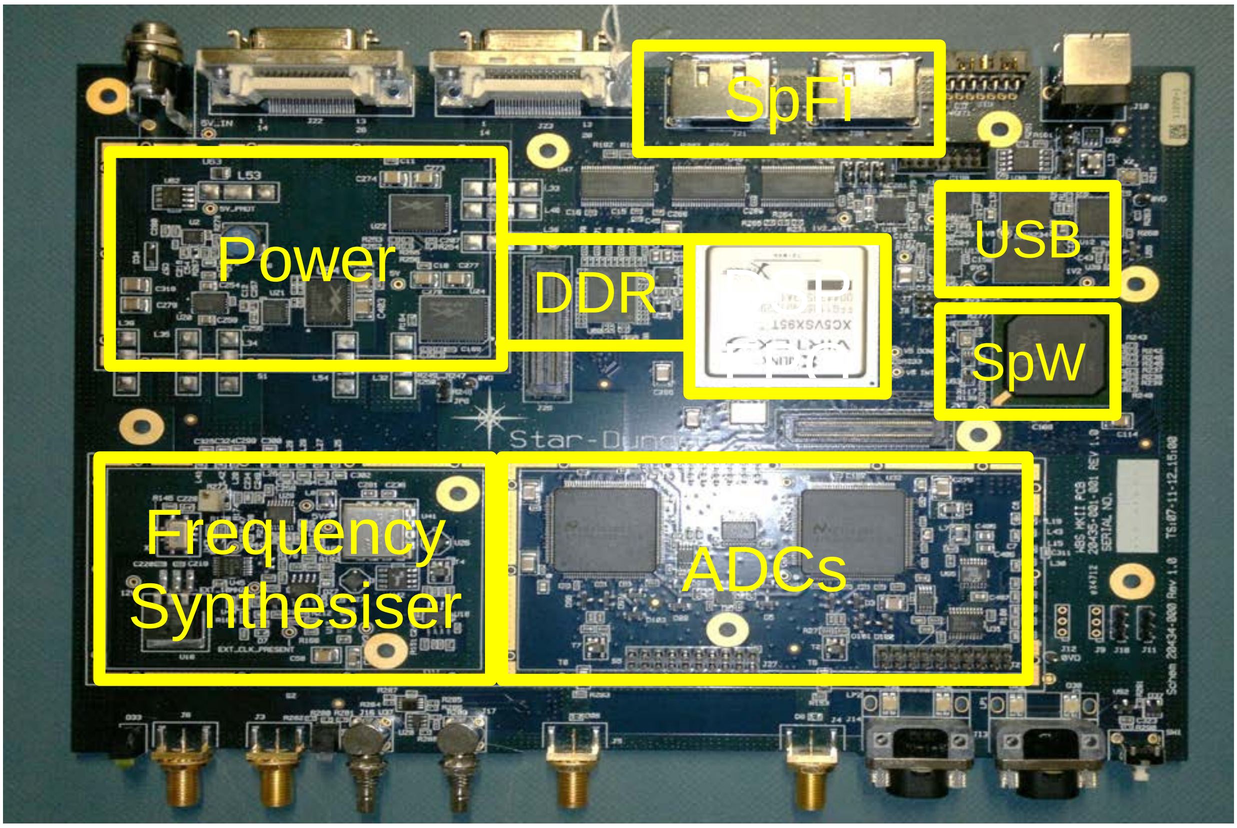


Figure. 1: Wideband Spectrometer II

The SHIRM-WBS demonstrator breadboard is in the final stages of assembly, Fig. 2. Component-level testing has been completed and receiver sub-system testing and calibration has begun in preparation for system-level characterisation. The demonstrator is a self-contained total-power radiometer which has been designed for future deployment at a ground-based high-altitude observatory. The demonstrator comprises a scanning sub-system for periodic viewing of the scene and internal hot and cold calibration targets. The sideband-separating receiver comprises a SHIRM which is pumped using a local oscillator source consisting of a microwave synthesizer followed by several stages of frequency multiplication and amplification. Two WBS II units are incorporated into the demonstrator providing an instantaneous bandwidth of 4 GHz and a spectral resolution of 1.5 MHz.

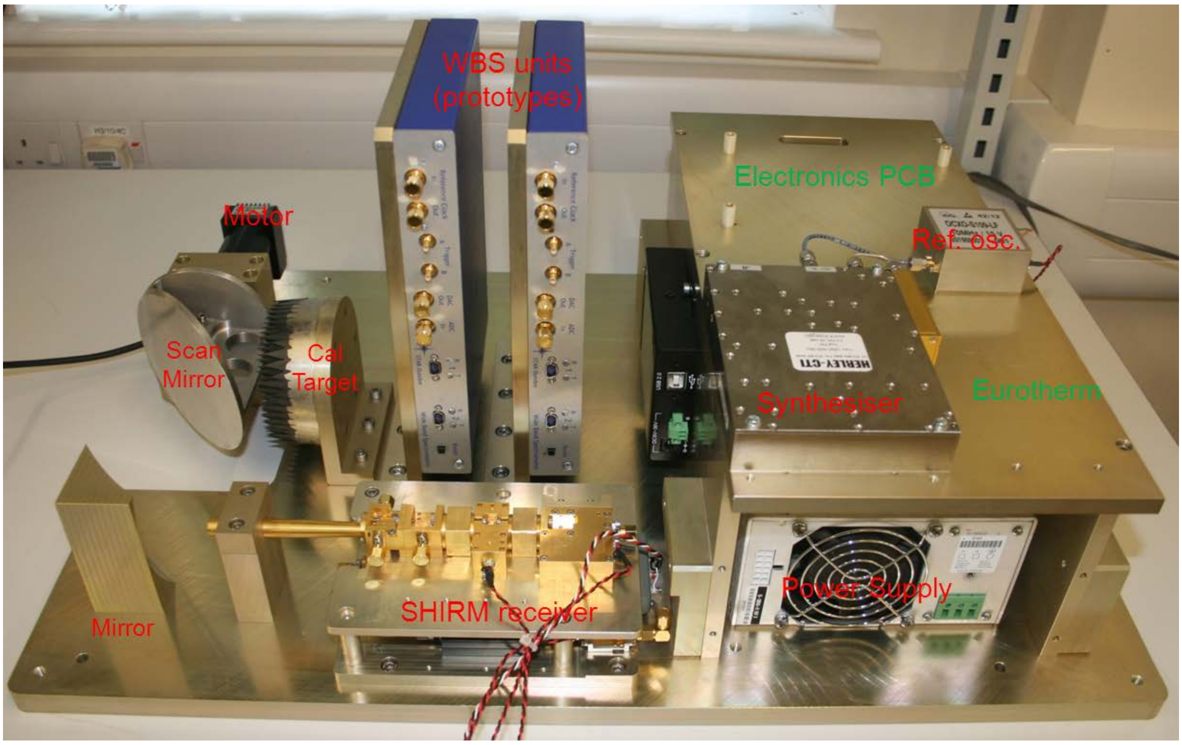


Figure. 2: SHIRM-WBS II Breadboard

A preliminary design study assessing the feasibility of integrating a sideband-separating receiver and high-resolution back-end based on the WBS II is progressing in collaboration with Omnisys Instruments AB. This is focussing on accommodation of the new hardware into the existing instrument and calculation of upgraded instrument budgets (mass, power consumption etc.).

Main Achievements

1. Design, manufacture and test of WBS II - Input bandwidth: 2 GHz, Spectral resolution: 1.5 MHz.

2. Development of SHIRM-WBS breadboard demonstrator for system-level characterisation.

Conclusions

The work undertaken on this project will enable the system-level characterisation of a sidebandseparating receiver with high-resolution back-end based on critical technology developed in the UK. As well as providing important system-level performance data the demonstration also acts as a risk mitigation exercise for the planned integration of such a receiver into MARSCHALS (funded by STFC/NSTP). The wideband spectrometer (WBS II) developed as part of the project provides a unit with extended input bandwidth and the functionality required to operate in a remote-sensing instrument. RAL Space is currently supporting an FP7 proposal (StratoCLIM) which aims to deploy the upgraded MARSCHALS instrument alongside GLORIA-AB, the airborne demonstrator of the IR limbsounder on PREMIER, in 2014/2015. The synergistic deployment of the upgraded MARSCHALS instrument and GLORIA-AB will be the most representative airborne demonstration of the proposed PREMIER payload.

Publications and dissemination

- “Progress on the Breadboard Development of a Sideband-Separating Receiver with High-Resolution Back-End”, S. Woodley, et. al.
- “High-Level System Integration of UK Receiver Technology for STEAM-R and MWS”, D. Gerber, et. al.
- Poster presentations at the Innovations in Remote Sensing Event, 23rd Jan. 2013:

- "UK Support to the PREMIER Mission – Critical Hardware Development", S. P. Rea, et. al.
- "Wideband High-Resolution Spectrometer", S. Parkes, et. al.

Training and Knowledge Exchange

- Sandwich Placement Student at RAL Space: Sean Woodley (University of Bath)
- Supporting development of SHIRM-WBS II breadboard

Spin-out, exploitation and UK Capability enhancement

STFC/UKSA funding for UK support to STEAM-R for FYs 12/13 and 13/14: £500,000

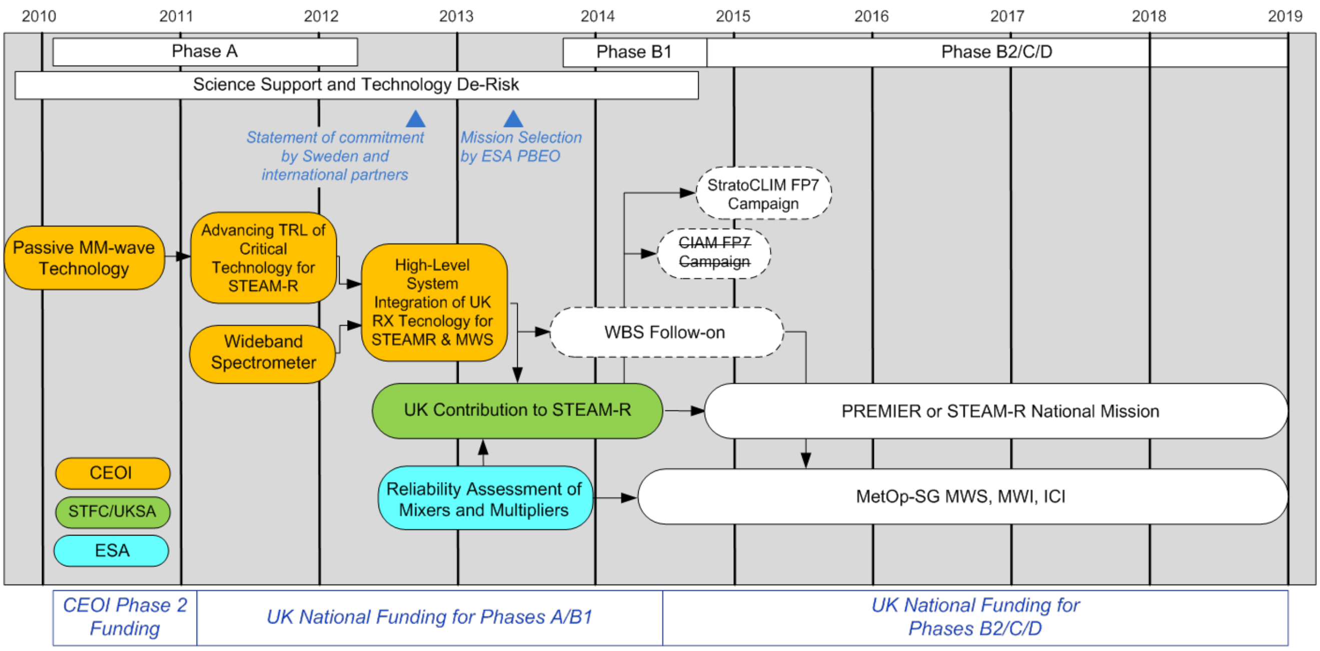
Activities:

- Upgrade of MARSCHALS airborne instrument to incorporate a sideband-separating receiver and high-resolution spectrometer
- Characterisation of the upgraded instrument
- Deployment of MARSCHALS on a scientific campaign and subsequent data analysis

This project continues the collaboration between RAL Space and STAR-Dundee Ltd in the development and characterisation of wideband high-resolution spectrometers for passive millimetre-wave instruments.

The spectrometer development within the project is also relevant to the Microwave Sounder (MWS) within the scope of the Post-EUMETSAT Polar System (Post-EPS) mission. The MWS will be developed by European industry with a launch in the 2018-2020 timeframe.

Roadmap



STFC RAL Space | STAR-Dundee

WIDEBAND SPECTROMETER

High-resolution spectrometers are essential instruments for Earth observation missions performing atmospheric chemistry measurements. When combined with a high sensitivity microwave/terahertz receiver front-end, a digital spectrometer allows characterisation of the spectral signature of molecular species present in the Earth's atmosphere (and planetary atmospheres) and the study of its perturbed chemistry. From a terrestrial perspective this is of considerable importance as it will, for example, enhance our knowledge and understanding of climate change and increase the accuracy of meteorological forecasting.

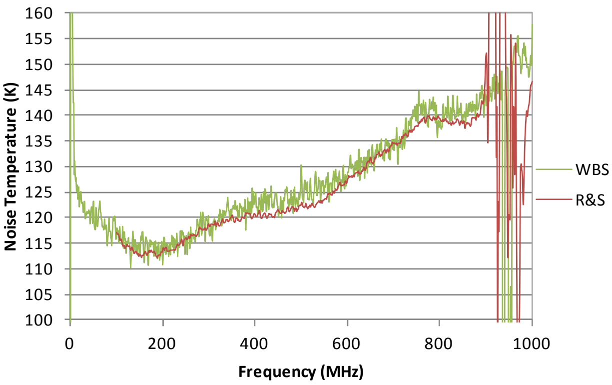
Digital Fast Fourier Transform (FFT) based spectrum analysers have the potential to provide greater observing capability and scientific return. Beyond 1024 high-resolution spectral channels, a digital FFT spectrometer is more efficient that competing filter-bank, auto-correlator or chirp-Z transform techniques. It promises better spectral quality, improved resolution and enables advanced multi-resolution spectrometers with selectable sub-bands at high resolution for 'zoom' analysis of spectral lines.

The aims of the Wideband Spectrometer (WBS) study are to quantify the performance of a novel prototype digital spectrometer and to explore and develop its future potential as a highly compact, power efficient, space-borne payload in support of climate studies. The Digital FFT based WBS uses novel signal processing techniques to improve bandwidth and reduce power consumption, while adding flexibility to support applications like Doppler wind sensing. It has significant advantages compared to alternative technologies when applied to next generation terahertz single and multi-pixel receiver systems.

Lead investigator: Steve Parkes, STAR-Dundee

The baseline FFT architecture for the WBS was developed in a recent ESA study of a heterodyne radiometer for the observation of gas giant planetary atmospheres. The prototype WBS unit incorporated key FFT processing technology from Astrium in the DSP FPGA and was demonstrated as a standalone spectrometer within an ESA funded Wideband Spectrometer study. The hardware for the protype WBS unit had already been developed by STAR-Dundee Ltd using internal R&D funding.

The WBS prototype unit requires versatile software to set up, control, display and store the spectral data produced. This software was developed by STAR-Dundee and integrated with the WBS prototype unit during the CEOI WBS activity.



Characterisation of the WBS was performed through tests conducted with a simple microwave test receiver and a complex millimetre-wave airborne instrument, MARSCHALS. Furthermore, where possible, a performance comparison was made between the WBS and commercially available test equipment (e.g. a spectrum analyser or power meter). The test receiver had a very low noise temperature and was thermally stable, hence well suited for investigating spurious signal content and a better test-bed for the new software functionality. The MARSCHALS instrument by comparison has a much higher noise temperature and was more difficult to thermally stabilise, however it represents a fully-functional airborne instrument and a candidate platform for future WBS integration.

Integration of the WBS with MARSCHALS was successful and system noise temperature measurements were in good agreement with measurements performed with a commercially available spectrum analyser. The manual approach to the measurement procedures with MARSCHALS and the difficulty thermally stabilising the instrument led to issues with gain drift over the measurement period. However, the current study has identified several options for a higher level of WBS integration to enable automatic triggering.

In parallel with the testing of the WBS prototype unit, potential improvements to the FFT technology were explored with the aim of extending the bandwidth of the WBS unit. Hybrid techniques, combining analogue filtering and digital FFT were examined aiming to support the full bandwidth of the MARCHALS instrument. The path to a flight system was also investigated for space qualified digital ASIC technology and analogue to digital converters.

The WBS CEOI seed-corn study has fully achieved the study goals:

- Test software was developed to support tests to be run on the prototype WBS unit allowing its capabilities to be explored and its performance characterised.
- Detailed testing and characterisation of the prototype WBS unit has been performed with the WBS connected to a simple microwave test receiver and subsequently to a complex millimetre-wave airborne instrument, MARSCHALS. The test results were analysed, with the WBS performing well. Recommendations were made for various improvements: increased bandwidth, reduction of dead-time between acquisitions, reduction of spurious breakthrough at $f_s/4$, and addition of an external trigger facility.
- Techniques were studied for increasing the WBS bandwidth by a factor of two. The use of I & Q sampling was recommended. This would enable double the bandwidth to be achieved using the same chip technology as used in the prototype WBS.
- The flight technology was considered, concluding that a flight implementation with a bandwidth of 2 GHz is practical with current flight qualifiable components.
- The roadmap for future exploitation was defined, considering candidate missions that require a WBS and the technical milestones along the route to a flight system.

The FFT based WBS has been shown to be a very attractive and viable technology for future Earth observation missions performing atmospheric chemistry measurements. The position of the UK has been substantially enhanced by this seed-corn study, with international interest in the application of this type of technology expected to expand considerably as the number of Earth observation missions increase to match future requirements for operational meteorology and climate monitoring.

Grants and contracts

RAL and STAR-Dundee Ltd have won a further CEOI contract to develop a second generation high-resolution wideband spectrometer (WBS) and to undertake critical system-level design and breadboarding activities in preparation for full integration of a sideband-separating (SHIRM) receiver with high-resolution spectrometer back-end into the MARSCHALS millimetre-wave airborne instrument.

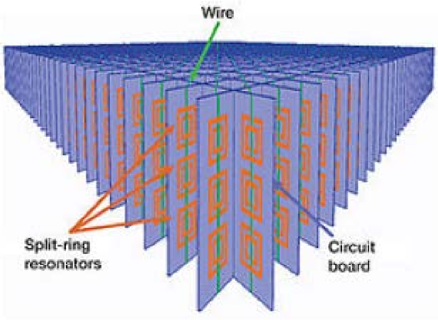
Spin-out and exploitation

The WBS will be exploited within MARSCHALS in support of the STEAM-R, PREMIER and post-EPS missions. The WBS can potentially be exploited on other passive microwave systems such as RALs Laser Heterodyne Radiometer, which are to be investigated in future studies.

Publications

STAR-Dundee   STFC RAL Space   ASTRIUM AN EADS COMPANY

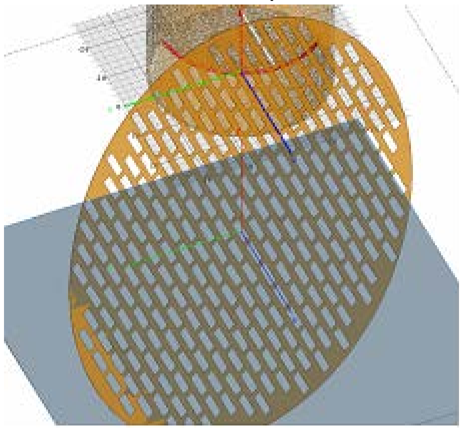
METAMATERIALS IN SUB-MM QUASI-OPTICAL SYSTEMS



A common problem in quasi-optical systems is the formation of unwanted standing waves owing to the dielectric interfaces in lenses and various other optical components. There are methods to reduce the effect using absorbers etc, which are at best inconvenient, and at worse seriously degrade system performance. This project aims to exploit the potential of meta-materials, i.e. micro-resonant structures, for matching of components to reduce these unwanted reflections, in an analogy with multi-coating at visible wavelengths.

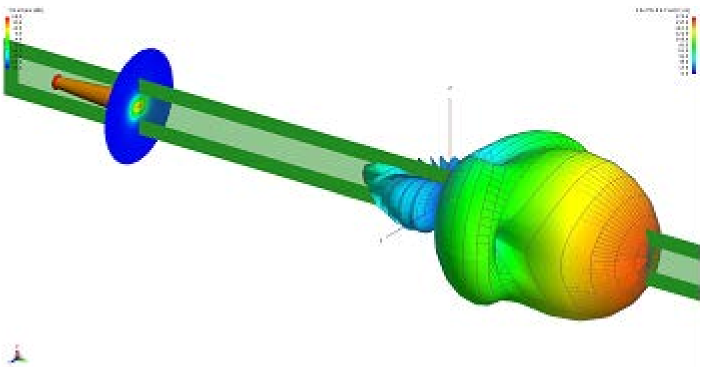
Lead investigator: Graham Maxwell-Cox, Astrium Limited

Metamaterials, i.e. materials with either both negative permittivity and permeability or with either permittivity or permeability negative, one can in principle reduce or redirect un-wanted reflections in any arbitrary quasi-optical system. Metamaterials are constructs, not appearing in nature, formed artificially by using collections or layers of tuned elements, individually much smaller than a wavelength, but offering, at a macroscopic level, useful negative permeability / permittivity values over a certain bandwidth. The ultimate goal is to exploit the benefits in microwave radiometer instruments on missions such as MetOp Second Generation.



Although the basic properties and design of metamaterials have been studied in the laboratory, no one has looked at their use in space radiometry. Examples might be the addition of high impedance surfaces around the aperture of a corrugated horn to suppress induced current, also the addition of zero phase reflecting surfaces around plate and grid holders. Surfaces may be made to change the polarisation of reflected signals so not to interfere in the beam. Apart from field suppression there is the real prospect of constructing lenses from these metamaterials (super lenses) that can be operated so as not to present any surface reflections, but still act as a lens.

In this project the various real and conceptual forms of metamaterial components have been surveyed and examined for potential application in mm and sub-mm wave radiometers. Metamaterial components were included in a computer design model of the radiometer to study suppression of unwanted fields and overall performance of the system.



An Astrium quasi-optical model of the radiometer has been implemented in FEKO. This has been used to test concepts and cross-validate QMC's CEM software toolset. As corrugated horns in optical software packages like ZEMAX are represented by Gaussian beams and not by actual physical geometry, it is a challenging task to replicate proper EM field distributions on pure CEM software. An acceptable solution is to use a simple Potter horn which produces patterns very similar to a Gaussian beam distribution in a very narrow band frequency range. Several models have been built, including simple horn, mirror and lens combinations (above).

The following metamaterial concepts have been identified as suitable for mmwave applications:

- GRIN lens for matching horn / lens combinations
- Reflection suppression on surfaces - Cloaking

The project has demonstrated the use of non-sequential ray tracing in modelling complex microwave radiometers to identify beam distortions and standing waves. It has also demonstrated the use of Finite Element techniques to model the standing waves in a horn, lens and dichroic mirror combinations.

Publications and meetings

- EADS Metamaterial workshop, Suresnes, Paris 13th Dec 2011
- IET Microwave metamaterials and Applications Workshop, London Metropolitan University, 22nd Feb 2012

Grants and contracts

- On the basis of this MSQS study, a proposal has been submitted to CEOI to look at the methodology of the design of an advanced metamaterial GRIN lens for matching to feed horns (March 2012, Astrium).
- Application of the non-sequential and FE techniques to modelling the 183 GHz QO chain in MetOp-SG breadboard for Technology Space Board
(April 2012 Astrium, RAL)
- Opportunity to apply the outputs of the MSQS study to the ESA Breadboard Study for the QO network for MetOp-SG (June 2012 RAL, Astrium).

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ADVANCED GRIN LENS DESIGN FOR MM-WAVE RADIOMETER SYSTEMS

The reduction of standing waves within a quasi-optical beam waveguide system has been identified as an important performance enhancing measure [1]. Reflections from the surfaces of lenses, in particular, can produce pattern ripple and degrade the return loss of feed horns. Gradient-index (GRIN) lenses can potentially lead to improvements in this respect, since their focussing operation does not depend on refraction at the surface/air interface, but rather on modifying the ray trajectory within the body of the lens. That GRIN lenses are typically cylindrical with a fixed cross-sectional refractive-index profile, also means that surface matching layers are flat and therefore easily modified or removed. Furthermore, the focal length can be changed simply by making the lens longer or shorter, e.g. at millimetre wavelengths, the lens construction consists of a stack of identical wafers, so this design flexibility really amounts to an 'adjust on test' facility.

In addition to the use of matching layers, the reflection levels from the surfaces of a 'stacked layer' millimetre GRIN lens may be reduced by engineering the transmission medium so that the average refractive index is closer to unity, while maintaining the same gradient profile. This approach is examined in this study, and leads to a design based, in part, on metamaterial concepts.

The application of Transformation Optics/Electromagnetics to the practical design of a GRIN lens has also been investigated. This powerful new technique forms an important theoretical tool in the implementation of metamaterials within new types of antennas and guided-wave systems currently under development.

Lead investigator: Graham Maxwell-Cox (Astrium)

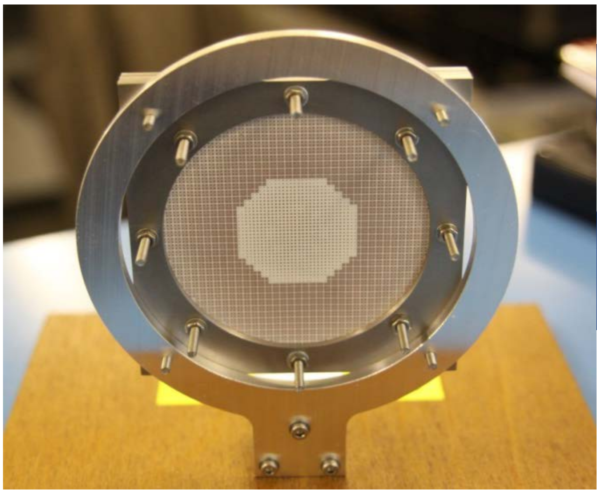
Study Results

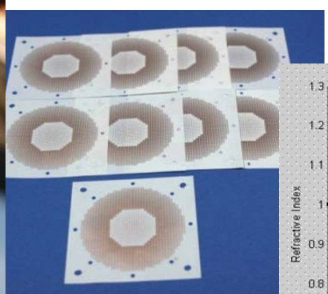
A metamaterial mm-wave GRIN lens has been designed to have a reduced surface mismatch in the centre region, and a prototype hardware model produced. The measurement program is ongoing; however the initial results look very promising.

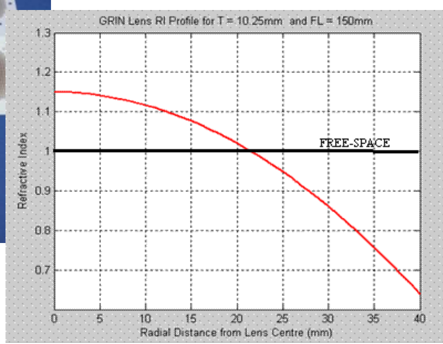
A theoretical study of the application of Transformation Optics to lens design has also been carried out and a viable analytical solution obtained based on the use of conformal mapping. This needs to be checked out using commercial ZEMAX ray-tracing software. Some ZEMAX analysis of the QO Test System has been performed.

Specific activities undertaken:

- Investigated Design methodologies for GRIN lens including Transformational Optics
- Designed a GRIN lens at 50 GHz using constructed metamaterials
- Manufactured a metamaterial lens using PCB multilayer technology







REQUIRED REFRACTIVE

Figure 0-7. Breadboard GRIN Lens

- Tested the lens at STFC- RAL using QO bench
  - performed in the context the of the TSB BB MWS Radiometer work (Astrium / RAL 2012)
- Zemax analysis of the QO Test System (further zemax modelling to be performed)

Conclusions

An experimental GRIN lens has been designed and manufactured to have a refractive index profile that extends from 0.64 to 1.15 and thereby test out a practical application of metamaterial technology in order to achieve a low surface reflection coefficient in the centre region of the lens (a Gaussian amplitude taper across the aperture was assumed to be the normal operating mode for beam waveguide).

In construction, the use of a stack of thin, air-spaced substrates was used in preference to a solid dielectric bonded assembly, as the reduction of transmission loss was regarded as being and important feature of the performance.

The prototype MTM lens performance has yet to be fully characterised, but from the measurements so far carried out at RAL, appears to have:

- The correct focal length and beam-waist diameter
- A reasonably low insertion loss of around 0.7dB dB
- Approximately 10% bandwidth

Etching misalignment error was found to be is up to ~25µm on double-sided lens substrate layers, accompanied by a worst-case dimensional error of around ~4%. The effect on lens performance does not seem to be dramatic, but remains to be fully assessed. Performance of the lens with single-sided lens substrate layers (which avoids the misalignment problem) remains to be measured.

A GRIN lens design has been derived analytically using a combination of Transformation Optics and conformal mapping. This is awaiting ZEMAX modelling.

Further lens measurements are planned when the facility becomes available:

- Repeat of insertion loss
- Surface reflection level
- Aperture field probing

TRAINING AND KNOWLEDGE EXCHANGE

- 6 months Support to Queens University London from previous CEOI Metamaterial study (Astrium QMUL) to March 2013

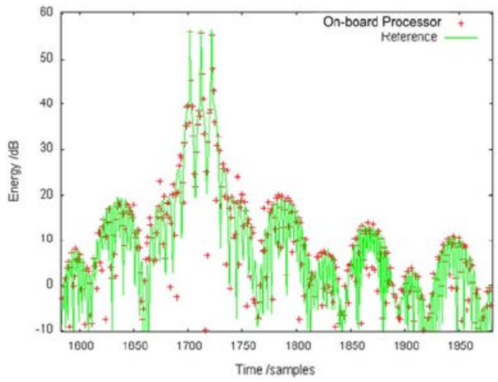
SPIN-OUT, EXPLOITATION AND UK CAPABILITY ENHANCEMENT

- UK QO design capability in lenses for mm-wave radiometer (Applicable to MetOp MWS Radiometer)
- Benefits to UK Space
  - Design and test capability in **advanced lens design** for mm-and sub-mm-wave applications
  - Development of **practical metamaterial systems**
  - Development of **Non-sequential Ray Tracing** techniques for QO design and analysis

SAR AND RADAR

EMULATION AND PERFORMANCE STUDY OF A SAR ON-BOARD PROCESSOR

Increasingly large data streams will be generated by new generation space instrumentation. This is particularly urgent for the emerging multi-view Synthetic Aperture Radar mission concepts such as WaveMill and SuperSAR, currently in their early study phases. These missions will generate potentially far more data than can be easily transmitted to ground. Current practice is to generate Level 1 products in the Ground Segment. However, due to improvements in on-board orbit determination, improvements to space-qualified processors, and the characterisation of the antenna patterns, it is now possible to consider Level 1 product generation on board the spacecraft.

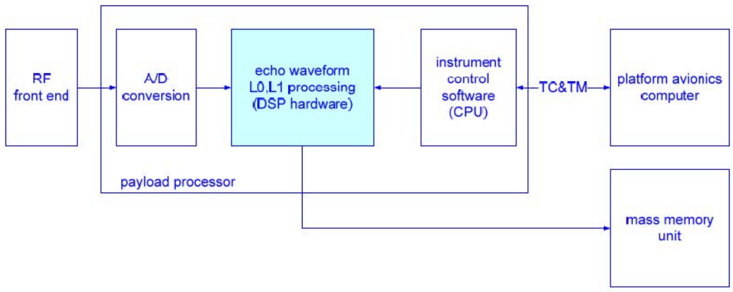


This project builds on prior CEOI studies to build a software prototype of a Level 1 on-board processor. The protpotype was tested using data from ESA's ERS-2 spacecraft.

Lead investigator: Alex Wishart, Astrium

Level 1 products may be detected SAR images (intensity) or complex images preserving phase for interferometric products. A necessary step to on-board generation is to implement the signal processing intensive parts of the imaging algorithm, i.e. range and azimuth compression, in space processing hardware such as an FPGA or ASIC, ideally with the flexibility to trade spatial resolution for radiometric quality.

A promising algorithm has been identified by Astrium (using 'spin-across' from multi-rate DSP techniques previously developed for telecommunications payload processors) which combines hardware efficiency with flexibility to vary the spatial resolution in a natural way. The aim of the study was to emulate this algorithm (in software) and to assess its performance by comparison with images generated using standard software techniques. In SAR, a radar chirp is transmitted periodically in a direction roughly perpendicular to the platform's directional of travel and a receiver samples and stores each of the resulting echoes from the terrain that lies in the prevailing field of view of the receive antenna. This process continues as the platform's field of view moves over a swath of the ground. Formation of an image from these echo data is accomplished via a two-dimensional correlation process.



For the purpose of on-board processing, the correlation processing in range and azimuth are the most computationally intensive steps, and it is these which are addressed in this study.

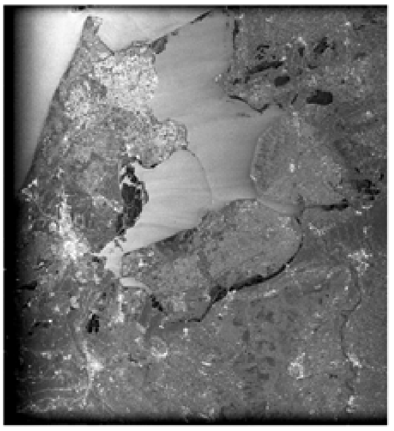
Raw data from the ERS-2 SAR was selected as test data. Compared to other SAR raw data such as Envisat ASAR, the real (I) and imaginary (Q) parts from ERS-2 SAR can be extracted easily from the source packets, as can the replica pulse. Four well characterised scenes were selected, from Flevoland, Neusterlitz, Kiruna and Greenland. The BAE ERS processor was upgraded to act as a representative control processor for the Astrium software emulator.

The new algorithm offers the required improvements in the efficiency of the most computationally intensive parts of SAR processing, i.e. range compression and azimuth compression, which is vital given the limited processing resources available in flight. The algorithm is naturally well suited to implementing a variable resolution processor. This is expected to be of utility in missions such as Wavemill where the desired resolution varies as the field-of-view of the instrument changes.

An emulator has been developed using Astrium's in-house processor emulation tool, PrEm2, and subsequently verified. This emulator has successfully produced SAR images from raw echo data, including intermediate range compressed images. A qualitative inspection of these images combined with a quantitative examination validates the use of this algorithm in SAR processing. This is a very good result for a study of seedcorn scope.

Implementing a full hardware processor suitable for flight is outside the scope of this seedcorn study and would require floating point operations as fixed precision arithmetic; azimuth chirps calculated from spacecraft motion and information in the scene; second order processing such as range migration correction; interpolation schemes and 'corner turning' procedures for hardware implementation. Trade-off studies between image quality and processing complexity are still required.

A hardware implementation estimate has been made, assuming an 80 MHz clock and 18 bit arithmetic with an input data rate of 20 MHz appropriate for the ERS-2 system. A single pass process (i.e. range or azimuth compression) requires less than half the computational resources of a single contemporary space-grade FPGA (Xilinx XQR4VSX55 or XQR5VFX130). The associated corner-turning memory requirements for this application are well within the capability of current space hardware.



Some SAR systems, such as Wavemill, employ a non-broadside antenna. The techniques developed here for orthogonal processing are likely to require modification for non-orthogonal processing geometries, a suitable topic for future work. For the processor, the next steps would be to develop a bit-true emulation of the DSP algorithms in PrEm2, to extend the method to squinted SAR, to develop the RTL and implement a real-time demonstration using, for example, the DRPM demonstrator system, developed by Astrium and IDA (Technische Universität Braunschweig) under ESA contract.

Publications

Although progress has been very encouraging, it is premature to address refereed papers. In due course submissions will be made to IGARSS or similar. The study was presented at the NCEO/CEOI Annual Conferences and the CEOI Emerging Technology Workshop.

Grants and contracts

This CEOI work will be used as heritage for bids into ESA on WaveMill-related matters, and in proposal preparation to future Explorer calls. A CEOI Seedcorn study award has been made to extend the technique to squinted SAR systems

Training

A junior engineer has been trained in techniques of SAR processing, in a project which exploits the same technology base as telecoms. There has been considerable knowledge exchange between BAE Systems and Astrium at both the project coordination and the technical level. A startup activity such as this is the ideal introduction to the somewhat arcane world of SAR processing.

Spin-out and exploitation

The work has significant potential for new systems applications including met-ocean data and sea ice products for ship navigation, offshore engineering (gas and oil platforms), and disaster monitoring. None yet, but exploitation in missions is anticipated in due course.

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EMULATION AND PERFORMANCE STUDY OF AN ON-BOARD LEVEL 1 PROCESSOR FOR SQUINTED SAR

The primary rationale for on-board generation of Level 1 products is real time dissemination of SAR images directly to users. Potential applications of such a service include met-ocean data for ship navigation, offshore engineering (oil and gas platforms), weather forecasting, sea ice products for navigation and disaster monitoring (earthquakes, floods, forest fires, oil spills). The data volume of the averaged Level 1 product may be considerably less than that of the raw echo data, which offers a solution to the data compression problem faced by interferometric bistatic SAR systems such as the Wavemill Oceanographic SAR. However, Wavemill is also an example of a squinted SAR system, i.e. one where the antenna boresight is directed at an angle to the range axis. It is difficult to accommodate high degrees of squint within the conventional range-Doppler formulation for SAR image reconstruction.

This CEOI Seedcorn Study Emulation and Performance Study of an On-Board Level 1 Processor for Squinted SAR has been performed by Astrium and BAE Systems Advanced Technology Centre (ATC). The study is motivated by the fact that technology advances in on-board processing hardware make it feasible to implement Level 1 processing in the Space Segment. These Level 1 products may be detected SAR images (intensity) or complex images preserving phase for interferometric products. (Current practice is to generate Level 1 products in the Ground Segment.)

The study activities have focussed on the SAR image reconstruction technique known as 'wavefront reconstruction' [Soumekh 1999]. Wavefront reconstruction algorithms include spatial frequency interpolation (also referred to as omega-k), range stacking and time domain back projection. The range stacking algorithm has been implemented in MATLAB and used to generate SAR images with selected ERS-2 echo datasets. The resulting images have been analysed by comparison with images produced using the standard ESA software. The performance of the algorithm in the presence of modest amounts of squint has been studied using range cell migration as a metric (echo datasets acquired by a squinted SAR were not available to this Study). The computational time required to process the outputs is also assessed, and the output images are also inspected for artefacts.

Lead investigator: Alex Wishart (Astrium),

Study Results

The Figure shows the same image strip of Greenland generated using data acquired by ERS-2. The range direction is horizontal, with near range at the left. The effect of uncorrected range cell migration (centre image) can be seen in the 'headland' feature at the left hand side. Note that the Astrium image has been generated to a spatial resolution along the range axis 4 times coarser than the other two images.

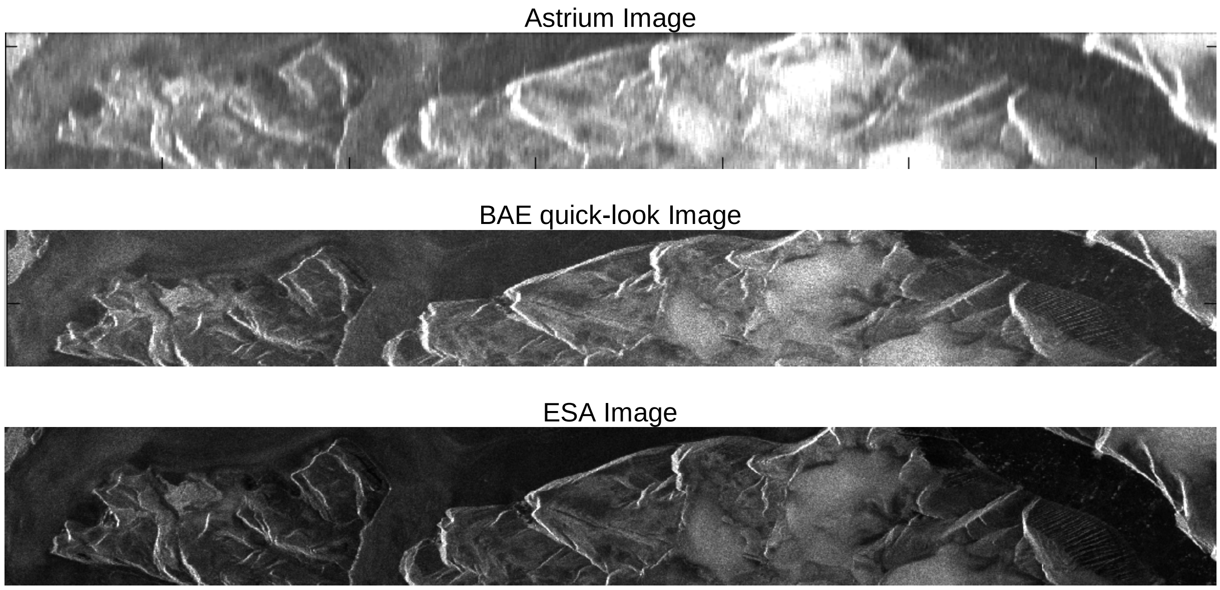

Figure 0-1: Comparison of Astrium, BAE quick-look and ESA processed images of Greenland scene

Conclusions

The study has improved the team's understanding of the relatively modern 'wavefront reconstruction' techniques for SAR image reconstruction. The practical implications of implementing these in on-board processing hardware have been assessed. This is a field which offers considerable potential for exploitation by UK industry, given existing strengths in payload data processing for science, earth observation and telecommunications. A key mission opportunity for this technology is the Wavemill oceanographic SAR concept, a core mission candidate for ESA's Earth Explorer 9 programme. Other relevant mission concepts include 3D InSAR products for glaciology and vulcanology. The same technology could have application to planetary SAR missions and there is a strong link to maritime surveillance and UAV applications.

Training and Knowledge Exchange

The opportunity to work on this study has provided Kehinde Latunde-Dada (Astrium) with a good introduction to SAR processing.

Spin-out, exploitation and UK Capability enhancement

The study has further strengthened the UK teaming of BAE SYSTEMS and Astrium, who have complimentary expertise in SAR image processing and satellite on-board processing. It is interesting to note that the signal processing techniques and technologies developed by Astrium for telecommunications payloads are equally applicable to the tasks involved in generation of SAR level 1 imagery.

Chris Buck at ESTEC has been kept informed of the progress of the study, due its potential relevance to the Wavemill oceanographic SAR mission with which he is closely associated.

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WAVEMILL MISSION CONCEPT FOR ESA EARTH EXPLORER 9

Ocean currents have a significant impact on the transfer of energy and moisture between the ocean and atmosphere. There is a strong scientific need to resolve mesoscale features such as eddies, fronts and filaments to help improve operational ocean models and the understanding of oceanic mixing. For the near-shore region maps of ocean surface currents are of key importance for scientists and policy makers dealing with a variety of fields including meteorology, ocean commerce, disaster management and mitigation.

Ocean circulation monitoring on a global scale is already possible with radar altimeters (e.g. from the Jason-1/2 satellites). However, the correct modelling of ocean flows and circulation requires significantly improved spatial and temporal resolution to avoid effects such as aliasing due to the periodicity of tidal signals. Furthermore, measurements derived from conventional altimeters provide poor coverage due to their small swaths (typically a few km) and will give ambiguous signal returns close to land.

The Wavemill concept is a novel wide-swath hybrid interferometric SAR instrument which addresses the mesoscale sampling issues. It offers the ability of generating wide swath, high resolution, high precision maps of ocean topography and surface currents in the open-ocean and coastal zone using a single spacecraft. It will utilise both along (ATI) and across track (XTI) interferometry to measure ocean current velocity and surface height in the sub-15km region, within multiple 100km wide instantaneous swaths. This capability gives Wavemill the unique ability to separate surface currents from the underlying geostrophic currents, a relationship of key interest to not only the scientific community, but also the commercial, governmental, and civilian sectors. These objectives are directly aligned with key NERC marine science objectives and the scientific challenges to understand and quantify variability in ocean dynamics and circulation as set out in ESA's Living Planet Programme.

The Wavemill mission is a rapidly maturing concept with strong UK academic and industrial involvement including the possibility of a UK science lead. It is a candidate for ESA's Earth Explorer 9 core mission series with a nominal launch expected around 2020. The purpose of this CEOI funded study will be to develop the concept further both at an instrument and system level to ensure a mature concept is available to be submitted into the ESA Earth Explorer call next year improving the prospect of mission selection.

Lead investigator: Benjamin Dobke (Astrium)

Summary report

The spaceborne Wavemill concept will fly just one instrument – Javelin – which combines along track (AIT) and cross track (XTI) interferometry simultaneously in a combination known as hybrid interferometry. It thus provides surface currents, swell and sea state along two parallel ~100km wide swaths, each with an inner edge ~50km perpendicular to the spacecraft ground track. To achieve this, Javelin consists of two in-line nadir-pointing antenna structures that squint their RF signal transit four beams: fore beam left and right and aft beam left and right.

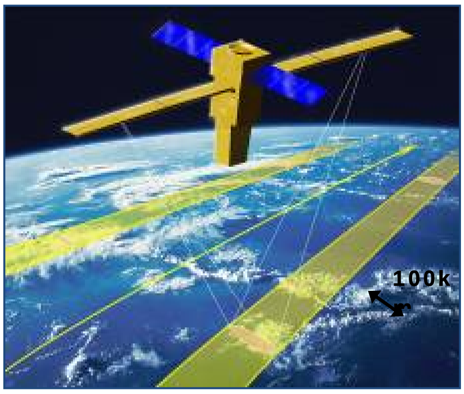


Figure 0-2: The Wavemill concept showing its two 100km wide swaths

Many of the Wavemill design drivers originate from the requirement that it fit within the VEGA launcher fairing. This directly influences the orbital altitude, mass, size, thermal, and power constraints, with many of these factors influencing one another in a complex trade-space. The primary task of this CEOI study was to better understand that trade-space, both in terms of the mission-systems and instrument design, and ideally to arrive at a feasible baseline mission concept. The key results of the investigation are as follows:

Mission Systems Results

- A complete review of the driving science requirements has been performed in conjuncture with the National Oceanographic Centre. The mission is now being modelled as an 'Ocean Current' focused mission, with Sea Surface Heights (SSH) and winds playing a secondary role.
- A full trade-off was performed between mass, power, altitude, radiator area, and size in order to better understand exactly what is capable in the context of the VEGA launcher limits. A mission operating in a 400km 13-day repeat SSO , with a total power of 2.24kW, and total wet mass of 1517kg (with adapter) was found to be feasibly within the VEGA constraints.
- While a maximum of ~29m^2 of solar array was found to be feasible within the VEGA fairing, the limiting factor became how much radiator area the platform could support. This radiator area was 9-13m2 (8m2 of which operates at ideal efficiency), which limited the resultant power so that it required only ~10m2 of solar array.
- Data handling was found to require on-board processing given the very high data output of the instrument. No feasible way to downlink 100% of the raw data was found, even at proposed future data rates.
- An on-board processing scheme was found with an entirely manageable 20-30 Kbits/s output rate. A provision to the science community of 1% raw data for the purposes of calibration is also feasible within the limits of downlink rate and time.
- A viable initial platform design was completed in CATIA (a Computer Aided Design (CAD) package), showing that packaging of the spacecraft was feasible within the constraints of VEGA.

Instrument Results

- A review of the RF-link budget showed that an improvement in the High Power Amplifier (HPA) efficiency from 30% to 40% has helped reduce the instrument power consumption.
- Calculations of reducing the orbit from the original nominal 546km to 400km showed that the associated combined gain/loss due to geometry, while present, were not critical given the advantages of going to a lower altitude.
- A design of a folding antenna, with associated introduced losses, was created and used in the CATIA packaging model
- A Carbon-Fibre Reinforced Plastic (CFRP) antenna structure was assessed for mass gain purposes. The gain was found to be ~20kg, but introduces both costly manufacturing processes and thermo-elastic issues.

Conclusions

The technical work performed in this CEOI study has allowed Wavemill to mature from a concept that was considerably over the allowed VEGA launcher power, mass and size limits, to a working baseline solution. There now exists a Wavemill solution that has the following overall configuration: Operation in a 13-day repeat 400km SSO, with a total power of 2.24kW, a total wet mass of 1517kg, a 65% orbital duty cycle, and generating pre-processed inteferograms at a rate of ~20 - 30 Kbits/s. These figures are based on a 5-year nominal mission. There are naturally still many challenges ahead in this concept's design, but the goals of the study were very much met and have resulted in a good baseline from which to mature the design further.

In addition to maturing the overall design concept, both mission science requirements and strategic partnerships have been strengthened with the NOC, a possible PI institute in the future. This will be important as the ESA Earth Explorer 9 (EE9) ITT for Wavemill is expected in 2013, and every advance in knowledge, both at a system and instrument level, will allow for a competitive bid to come out of the UK.

Training and Knowledge Exchange

Significant knowledge exchange has occurred between the team members from Astrium and the National Oceanographic Centre (NOC). This has occurred at the science review meeting in December 2012. It allowed both parties to directly inform the other of the key issues at hand on the interplay between the science return and mission/instrument engineering. The concept now moves forward with a better understanding of the science requirements, and the science community moves forward with a better understanding of the mission/instrument restrictions.

Spin-out, exploitation and UK Capability enhancement

The overall goal for all Wavemill studies is to strategically position the UK to be involved in the development of the Wavemill instrument through Astrium. The Earth Explorer 9 (EE9) ITT for Wavemill is expected in 2013 and every advance in knowledge, both at a system and instrument level, will allow for a competitive bid to come out of the UK.

Through this study, Astrium has enhanced its position as a possible instrument prime, as well as possibly contributing to the platform components and design. It goes into the latter half of 2013 with a better chance of producing a very competitive EE9 study bid.

In addition, the NOC's Christine Gommenginger has been identified as a possible UK candidate as the science PI for Wavemill.

HIGH-FREQUENCY DOPPLER RADARS FOR A POLAR PRECIPITATION MISSION

Despite the well-recognized role played by clouds and precipitation in affecting our climate, gaps in the remote sensing observational capabilities of their vertically resolved microphysics significantly hamper progress in understanding the physical processes within them, whose parameterizations underpin numerical weather and climate models. Accurate measurement of solid precipitation remains particularly challenging and accurate large-scale estimations of the snowfall are not yet available. While the CloudSat mission has paved the way towards the use of millimetre wave radars (94 GHz) for monitoring snow and for providing vertically-resolved precipitating cloud microphysical measurements, it has become clear that multi-frequency radar observations are irreplaceable assets to overcome the snow microphysical deadlock, i.e. the dependence of the snow rate on the snow microphysical characteristics: particle habit, fall velocity and size distribution.

Although the possibility of using multi-frequency radar techniques for precipitation retrievals has been studied previously, the focus has been on lower frequency radars (C, Ku, Ka and W bands) owing to limitations in radar transmitter technologies at higher frequencies. Impressive progress has been made in recent years in mm-wave radar technology -- specifically in high-efficiency antenna assembly, low-loss quasi-optical transmission lines, high-power amplifiers and low-noise-figure receivers. However, to date a 94 GHz pulsed system remains the highest frequency radar in operation. Higher frequency radars (operating at 140 and 220 GHz) would be advantageous for observations of snowfall in particular, since the improved sensitivity achievable through higher frequencies would enable improved detection and quantification of the lighter intensity snowfall events which comprise the majority of the total global snow precipitation.

This study aims to address two issues relevant to high frequency radar observations of snow. The first of these is to improve quantification of the information content available from dual-frequency reflectivity ration measurements, and to identify the optimal frequency pair for discriminating between snow habits and for minimising uncertainties in snow-rate estimates. 140 and 220 GHz are considered in addition to the 35-94 GHz frequency pair studied previously for the ESA Earth Explorer 8 Polar Precipitation Mission radar. Secondly, the critical technology development requirements for an Earth Explorer 9-like space mission are assessed, given how technically challenging it currently is to deploy space-borne radars at such high frequencies. More specifically, a subsystem to component level study of the high power mm-wave frequency multipliers needed to drive the radar transmitter output is carried out. The study provides design guidelines intended to accelerate eventual hardware development and contribute towards a technology development roadmap, including schedule and ROM cost estimates.

Lead investigator: Alessandro Battaglia (University of Leicester), Peter Huggard (STFC RAL)

Summary report

Single scattering property databases covering a variety of different snow particle habits have been used to calculate radar reflectivity and attenuation over a wide range of exponential particle size distributions. Both reflectivity and attenuation are strongly dependent on snow particle habit, particle size distribution and frequency. At 220 GHz and for typical size distributions, attenuation varies by over 20 dB km-1 (gm-3)-1 depending on the snow particle habit assumed. A similarly broad degree of variability is found in dual wavelength reflectivity ratios (dependent on the frequency pair chosen), with pairs including higher frequency reflectivities showing greater sensitivity to snow habit. By considering triple frequency combinations (for example, 35/90/220 GHz) there is potential for using this sensitivity to further discriminate between different habits and size distributions, by plotting dual wavelength reflectivity ratios against one another. The suitability of high frequency radars for snow remote sensing are investigated further using an end-to-end radar simulator coupled with output from a high resolution (better than 100 m at low altitudes) cloud resolving model, which provides realistic hydrometeor fields for snowy scenes. Measured reflectivities for a number of profiles are simulated at Ka band, W band, 140 GHz and 220 GHz, for each of the four types of snow aggregate in the Tyynela database. The simulations include the effects of attenuation, which are very significant in the presence of snow at the two higher frequencies. The attenuation is particularly evident in dual wavelength reflectivity

ratio profiles, owing to the strong dependence of attenuation on frequency, and represents a measurable signal (between 10 and 30 dBZ depending on snow habit for the 35/220 GHz pair) that could be used in snow water content and snowfall retrievals.

The operation of a radar system at these higher frequencies is technically challenging. A pulsed mm-wave radar system relies on Extended Interaction Klystron (EIK) tubes to provide the high power levels necessary. Recent improvements in EIK technology allow their use as linear amplifiers up to 220 GHz, allowing the application of pulse compression, coherent integration and Doppler processing techniques in the sub-mm wavelength range. The critical hardware element still in need of further development is the specialised frequency multiplier required to drive the EIK amplifier. This study has assessed the available drive power for the multiplier, along with its output power and frequency bandwidth requirements. For 140 GHz and 220 GHz multipliers, the target output power is 32 mW and 40 mW respectively, with bandwidths of 600 MHz and 300 MHz in each case.

STFC-RAL have recently demonstrated frequency multiplier technology with output frequencies up to 332 GHz, with efficiencies around 20%, tuning bandwidths of several GHz, and output powers in the 10 to 20 mW range. To achieve the highest frequencies, certain substrate materials with high thermal conductivity and low dielectric constant are required, e.g. aluminium nitride (AlN) or diamond. These materials can help overcome the major technical challenge for generating a higher output power multiplier, which is the achievement of adequate input power handling and thermal dissipation. An alternative approach also considered is to use a power combining scheme consisting of two or more GaAs MMIC multiplier circuits within a single waveguide block.

Multiplier design guidelines extending down to the sub-component level are presented here for both 140 GHz and 220 GHz sources. The 140 GHz source is based around a single chip frequency doubler on an AlN or CVD diamond substrate, and is expected to achieve conversion efficiency around 30%. Two possible designs for a 220 GHz source are considered, with the final stage of the source comprising either a frequency doubler or a frequency tripler. The doubler would require an input power (around 135 mW) greater than is commercially available; the MMT group at STFC-RAL are currently developing hardware to address this frequency range and power. The tripler, whilst achieving a lower efficiency (about 15-20~\% compared with 30~\% for the doubler), has the advantage of the higher drive power available at an input frequency of 73 GHz. The proposed design uses a power combining technique and high thermal conductivity substrates to achieve the target output power. However, the lower efficiency of triplers means that two devices operating in parallel would be required.

Publications and dissemination

- Findings from this study will contribute towards a paper currently in preparation for submission to the Journal of Geophysical Research – Atmospheres: ‘Radars operated at frequencies above 94 GHz: a way forward in cloud profiling’ by A. Battaglia, C. Westbrook, U. Loehnert, S. Kneifel.
- Alessandro Battaglia will present findings from this study at the Fourth International Workshop on Space-based Snowfall Measurement (4th IWSSM), 6th – 8th May 2013, Mammoth Lakes, California.

Training and Knowledge Exchange

- This was confined to the CEOI project partners: RAL staff learned about the demanding meteorological requirements and benefits of the dual frequency radar approach, and Leicester personnel had an overview of the challenges in providing high power hardware.

Spin-out, exploitation and UK Capability enhancement

This study helps to give the RAL and Leicester groups a key positioning in the UK, European and international high frequency space-borne radar community, particularly with regards to high frequency multiplier technology.

This project was the first collaboration between RAL Space and University of Leicester in the development of critical technology for pulsed millimetre-wave radars at frequencies above

140 GHz. The project has also fostered collaboration between the University of Leicester and the group at the Finnish Meteorological Institute (who provided single scattering property calculations for snow particle aggregates), as well as groups at the University of Reading and the University of Cologne.

The following capability enhancements arise from the completion of this CEOI project:

- Plans for hardware development. The partnership has identified the two optimum frequencies for operation of the pulsed radar and a critical component development roadmap to TRL 4 has been formulated and presented. Completion would place the UK in a position to offer ITAR restriction-free components, needed to drive the high power output stages of the radar, for development towards space flight qualification.

University of Leicester

STFC RAL Space

POLARIZATION DIVERSITY DOPPLER RADAR ON SATELLITE (POLYDOROS)

Wide swath scanning W-band Doppler radar systems have the potential of characterizing the three dimensional structure not only of clouds and precipitation microphysics but also of horizontal winds. Their unprecedented view of clouds and precipitation systems can provide unique observations for data assimilation and for modelling studies, with a great potential in the improvement of numerical weather prediction and in the forecasting of extreme weather events like hurricanes, typhoons and severe weather.

A W-band conically scanning radar concept with Doppler estimates based on the polarization diversity pulse-pair technique has been established in previous ESA studies. We propose to study the benefit of adding pulse compression to the radar design both to reduce the cross-talk between the H and V returns and to increase the overall signal-to-noise ratio, with expected improvements both in detection and in Doppler estimates accuracy.

A trade-off study will be performed by coupling sophisticated end-to-end radar Doppler simulators with pulse compression signal processing. Configuration parameters (e.g. chirp length, chirp bandwidth, pulse-pair distance) will be changed over a wide range of values in order to determine the configuration that optimizes coverage and/or accuracy for Doppler velocity estimates and that reduces the impact of the blind layer, of aliasing and of range side-lobes contamination.

This study will enable a critical refinement for a W-band conically scanning Doppler radar concept to be proposed for the upcoming Earth Explorer 9 call.

Lead investigator: Peter Huggard (STFC RAL), Alessandro Battaglia (University of Leicester)

Summary report

This study assessed the potential of a conically scanning radar for along line of sight wind retrievals. Specifically the benefits of adding pulse compression to the radar design both to reduce the cross-talk between the returns in the vertically (V) and horizontally (H) polarized channels and to increase the overall signal-to-noise ratio, with an obvious gain in Doppler accuracies.

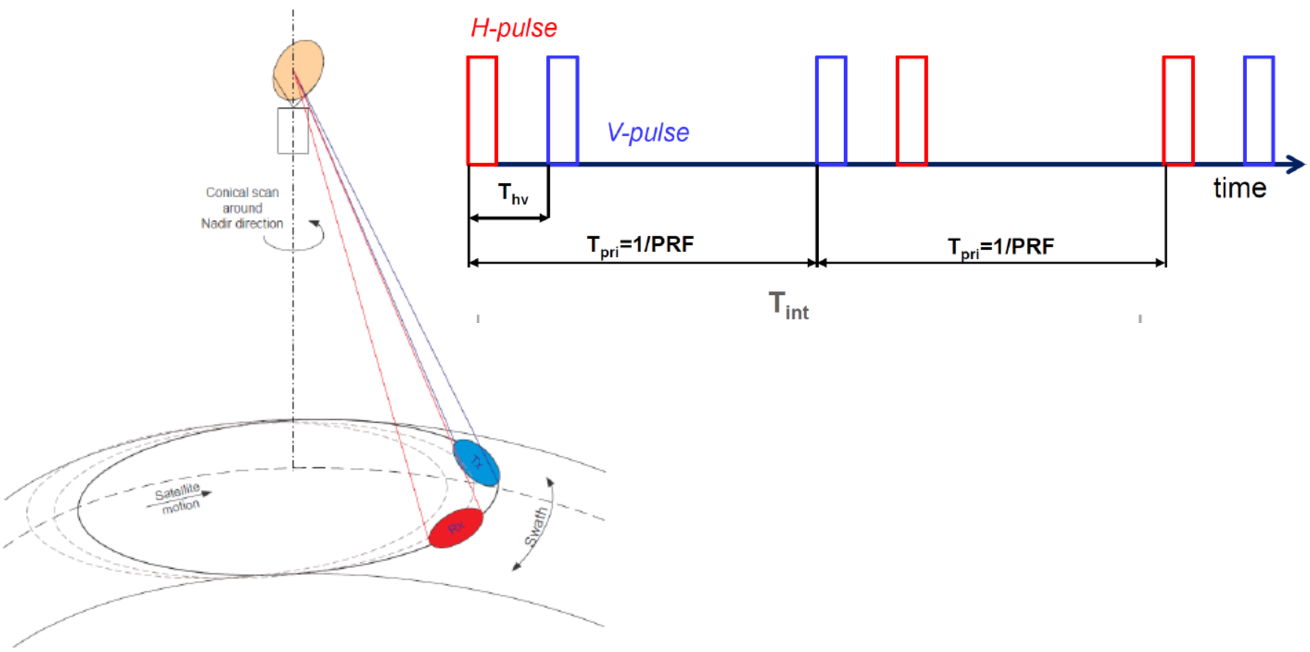


Figure 0-3. Mission concept with conically scanning radar with two separate Rx/Tx horns

Conclusions

From this study we can draw the following conclusions.

1. Pulse compression is a plausible option for a conically scanning W-band polarization diversity radar system. The key advantage of such systems is the low reflectivity of ocean surfaces at slant incidence angles, which poses less stringent constraints onto range side-lobe suppression. A system with a bandwidth of 0.25 MHz, with a chirp length of 40 μs and with Thv in the range between 10 and 20 μs provides a good balance between vertical resolution, Doppler accuracy and coverage. With a realistic radar configuration (specifics in Table 1) we expect that such a system will provide useful Doppler (accuracies better than 2 m/s) at 1 km vertical resolution on roughly half of the cloudy regions as detected by CloudSat.

2. The introduction of pulse compression significantly extends the complexity of the system, not only in terms of average power output, but also because of the necessity of having two transmitters. In fact the constrain of having a thin blind layer (lower than 2 km) forces one to adopt a pulse-pair interval below 20 − 25 μs; simultaneously the need of achieving MDTs in the region of −15 to −10 dBZ or better imposes the use of small bandwidths (< 0.25 MHz). To be effective, chirp lengths longer than Thv in the pulse compression scheme are needed, which excludes the possibility of having a single transmitter.

3. Simulated spectra from realistic scenarios are characterized by significant Doppler fading but with significative differences between different sectors of the scan. In uniform beam filling conditions at side view Doppler spectral widths range from 4.0 to 5.6 m/s for the 0.1◦ and the 0.14◦ beam-width antennas, respectively. In the forward/backward section of the scan the Doppler fading is reduced to 2.9 and 4.1 m/s for the two beam-widths, respectively. However, in regions of NUBF spectral widths can go up to 6-7 m/s in both cases. At 94 GHz these values correspond to a de-correlation time of 60−50 μs. The chirp length must be shorter than this value.

4. Polarization diversity has the great advantage of completely eliminating aliasing errors when adopting Thv < 20 μs (which corresponds to Nyquist velocities of ±40 m/s). Three other error sources remain in the estimate of the winds along the line of sight: noise errors, NUBF errors and MS errors. Noise errors are typically reduced to less than 1 m/s when considering regions with SNRs larger than 5 dB and when 10-km integration along footprint are performed (even with a very fast moving antenna). Longer Thvs tend to reduce this error. MS effects are relevant in convective cores: in such regions they can produce errors of the order of 1-2 m/s even when averaging at 10 km distance (convective scale).

5. NUBF seems to be the main driver of errors with increasingly importance when moving to-wards the forward/backward section of the scan. This is because in that case the NUBF is capturing the vertical variability of clouds: since clouds are horizontally stratified averaging along footprint track is not mitigating the problem. Biases are expected in correspondence of regions with vertical reflectivity inhomogeneity. On the other hand averaging along track at side view drastically reduces the NUBF error. Systems with increased sensitivity are more affected by this issue. There are no strategies in place to correct for such an error. This seems to be the real bottleneck in the error budget analysis.

6. There is an obvious benefit (in terms of NUBF reduction, MS reduction, Doppler fading and clutter reduction) when introducing larger antenna size. This is expected because footprints are linearly proportional to the beamwidth. Of course increasing the antenna size has the draw-back of considerably reducing the coverage because of the reduced footprint size and scanning rotational speed.

7. Pulse compression with sidelobe suppression approaching 40 dB for a 0.25 MHz chirp band- width can be achieved, with 50 dB suppression possible at a 1 MHz chirp bandwidth. The simulations suggest that this is adequate for this application and in any case, sidelobe suppres- sion significantly better than 40 dB is more difficult in practice as it can be limited by the phase and amplitude flatness of the transmitter/receiver chain and its stability over the lifetime of the instrument. This would require that the phase and amplitude response of

the system is characterised and the pulse compression waveform adaptively distorted to compensate.

8. The 2 chirp mode offers some improvement in Doppler accuracy by reducing crosstalk between H and V -polarized channels; the benefit may increase in the presence of larger depolarizing effects, for example with multiple scattering and over higher reflectivity surfaces.

9. The introduction of an interlaced mode, that measures the cross and the co-polar reflectivities, allows the identification of area contaminated by ghost signals, MS and of significant range- side lobes effects. This is extremely useful to pin down the regions where the Doppler signal will be extremely noise and inaccurate.

Publications and dissemination

- A paper fully describing the polarization diversity receiver simulator has been submitted, Battaglia et al. [2013b] (an electronic copy can be requested directly from Dr. Battaglia, ab474@le.ac.uk).
- A publication more focused at the conically scanning radar results contained in this report is also in preparation, Battaglia et al. [2013a].
- The outcome of this research will be presented at the 2013 European Space Agency Living Planet Symposium (an abstract entitled 'Potential of a conically scanning Doppler polarimetric 94 GHz radar for observing winds in extreme weather event cloud systems' has been submitted) and at the America Meteorology Radar Conference (an abstract is in preparation).
- Dr. Battaglia will also give a seminar on Polarization diversity Doppler radars at JPL, Pasadena at the end of April.

Spin-out, exploitation and UK Capability enhancement

This study gives to the RAL and Leicester groups a key positioning in the UK, European and international high frequency space-borne Doppler radar community. The highly sophisticated tools developed in this study are a unique asset. While industrial studies have been already carried out for the feasibility of a conically scanning system both by THALES-Alenia and by ASTRIUM, notional studies were not up to pace. We are confident to have filled that gap and to be able now to play an important role to further refining the W-band conically scanning Doppler radar concept to be proposed for the up-coming Earth Explore calls. We believe that the paper submitted to the Journal of Atmo spheric and Oceanic Technology will represent a cornerstone for feasibility studies of space Doppler systems with polarization diversity while the paper now in preparation will establish the key factors affecting velocity accuracies in Doppler estimates for scanning radar systems. Both will provide a huge leverage for securing funding in future feasibility studies.

The tools developed in this project are applicable to all Doppler (scanning) radars. Therefore they can be applied to a variety of space mission studies involving Doppler radars. This makes UK a crucial partner for all future international space missions involving Doppler radars.

Besides the strong collaboration forged between RAL and University of Leicester to carry out this project, this project has fostered other collaborations mainly with the group at LATMOS, Paris and with the radar group at JPL, led by Dr. S. Tanelli. Dr. Battaglia has been invited to both institutes to showcase the outcome of this project.

System And Applications Study For A Future Geosynchronous Radar Mission

All radar satellites so far have been in low Earth orbit (LEO). Images from these satellites are used for applications ranging from mapping forestry to measuring the movement of glaciers and even Earth's tectonic plates. Using LEO however means that we can't observe changes happening faster than about a week. Also, the atmosphere distorts images slightly and this complicates their use for very precise measurements.

An alternative to LEO is geosynchronous orbit (GEO). GEO is already used by weather satellites to take visible images using the Sun's illumination. Weather satellites produce frequent images over wide areas, but GEO has not been used so far for radar. Calculations and some initial experiments show that radar imaging from GEO is possible. This project's aims are to resolve some of the remaining technical problems, especially the processing needed to form good images, and to evaluate potential applications for GEO radar.

GEO radar could play a valuable role in monitoring natural hazards, weather and climate. One particular application would be to survey large areas for ground motion, e.g. landslide risk, subsidence and earthquakes. Another role may be measuring soil moisture: the frequent images mean that daily changes can be observed directly which will help early detection of drought or flood risks. GEO radar should also be much more responsive in cases of natural disasters: images will be available within hours whatever the weather, day and night.

A by-product of imaging from GEO will be maps of the Earth's atmosphere showing either humidity distribution or the state of the ionosphere. These data are valuable in themselves and will help with weather forecasting and climate studies. They may even help us to forecast space weather from the changes we will be able to detect in the ionosphere.Having measurements of the atmosphere as we image from GEO means that the atmosphere's effects can be removed, so GEO radar images could be used directly for precise measurements of changes at Earth's surface.

Although not yet demonstrated, the potential benefits of GEO radar justify this research which may lead to valuable new services from space.

Lead investigator: Stephen Hobbs (Cranfield University)

Radar system design

Geosynchronous orbit is special because satellites in GEO have a continuous view of part of the Earth's surface. This project has studied the feasibility and potential applications for a radar in GEO. The difficulty is that GEO is much further from Earth than most imaging satellites, and so the signals available are much weaker. The satellites and their radar payloads can be designed to compensate for this, by having large antennas and by collecting signal for long periods of time (from 10's of seconds up to a few hours). The images formed can see detail as small as 20 m (despite the range of around 40 000 km; this is resolution good enough to make out the print of this article from 1 km away).

An important challenge when viewing the Earth from orbit is the atmosphere. During the longer imaging times of several minutes or more, the atmosphere changes enough that it can prevent the radar forming clear images. We have shown that with careful system design using a sequence of images, the radar can measure the changing atmosphere and then produce both the surface image and also a set of images of the changing atmosphere. The atmospheric data may be as valuable as the surface images. Depending on the wavelength used, the part of the atmosphere seen is the ionosphere (for long wavelengths, due to effects of the free electrons) or the troposphere (for short wavelengths, due to the atmospheric humidity).
We have developed models of these processes to simulate the atmospheric effects and to develop automatic image focussing algorithms.

Applications

The particular strength of radar imaging from GEO is the temporal sampling – far better than is possible for a satellite in low Earth orbit. Another advantage is the way GEO imaging complements other satellites because of the different vantage point. There are applications for the atmospheric data and for images of the land surface.

Being able to image either the ionosphere or the troposphere every few minutes at a resolution of 1 km provides a new quality of data. Ionospheric applications are primarily in science, which may lead to improved navigation (GPS, etc.) and protection from "space weather" in the future. The tropospheric data are immediately valuable, and could help improve local short-term weather forecasting. Both sorts of data could also help immediately to improve the quality of other satellite data by providing high quality corrections for the atmospheric artefacts.

Surface applications are focussed on the land surface, because a stable surface target is needed. Possible applications are ground subsidence monitoring, e.g. urban subsidence, landslides, and other geo-hazards. It is also possible to measure volcano distortions as pressures inside develop, and glacier motion. Another class of applications relates to agriculture and hydrology. GEO SAR should be able to measure changes in soil moisture much more accurately than other satellites, because it can take frequent images during a day. It should also be able to identify critical crop stages, such as readiness for harvest, again due to the frequent imaging which is possible.

A third group of applications arise from GEO SAR's complementarity with other satellite systems. GEO SAR brings a new view direction which prevents some targets from being hidden, or it may mean that 3D rather than just 2D motion can be measured. This complementarity may increase the number of targets which satellites can usefully survey by up to 40%.

Future opportunities

The study has identified several GEO SAR mission designs which are feasible. The main distinction is between those which require atmospheric correction, and those which do not. Those which do not need atmospheric correction may need high transmitter powers and large antennas (areas ~103 m2 in some cases), although some designs are possible with more conventional solutions (mean RF power ~1 kW, antenna diameter 10-15 m). If atmospheric correction is needed then the atmospheric data are an additional data product, and the engineering required is less demanding: antenna diameter of 5-10 m and mean RF power of 1 kW or less.

Opportunities for future GEO SAR missions exist in Europe, through ESA's Earth Explorer programme, and through other international partnerships. Both the US and China have studied GEO SAR in the last decade: opportunities for collaboration with either of these (perhaps China in particular) are likely in the next few years through both ESA and the EU.

For initial technology demonstration, simpler missions are possible and could be implemented as a national UK or bilateral programme – e.g. a hosted payload technology demonstration using a SSTL comsat.

The study has identified the technical challenges and some of the potential applications for GEO SAR. A clearer view is now possible of feasible ways forward. The potential benefits are significant: GEO SAR may powerfully complement existing low Earth orbit satellites and provide an important part of a future EO system of systems. Summary report

Training and Knowledge Exchange

- An opportunity arose to involve postgraduate space engineering students in the GEO SAR research at Cranfield. Cranfield runs the MSc in Astronautics and Space Engineering and for the October 2012 intake, a GEO SAR group project was offered. Since October, a team of 13 students (from the UK, other EU countries, and China) has been working to develop a mission design for GEO SAR. Each student contributes around 600 hr to the project, so the total student effort is ~13 x 600 hr, or approximately 5 yr of effort. Students have been working with the mission concept during this period, and more generally have learned about the design of an Earth observation SAR mission. A public presentation of the project is planned for 14 May 2013.

- We have involved a research student (Boris Snapir) in the project, specifically to develop the data assimilation algorithm. This is the theme of his research, and so both he and the project have benefitted from the opportunity to apply the methodology to a novel application.

- Within the project team, discussions have helped to develop a wider understanding of the GEO SAR concept (as well as EO more generally). These discussions have been valuable for developing a deeper understanding of the concept and its applications, and also for spreading awareness of its potential.

- It is likely that Cranfield will host a visiting researcher in from China to work on aspects of GEO SAR.

Spin-out, exploitation and UK Capability enhancement

The project has significantly strengthened the UK's ability to contribute to development of geosynchronous SAR missions. The vertical integration represented by the team means that the benefits are spread to a range of UK sectors including academia, satellite manufacturers, and EO data users, each of which is represented by members of the project team.

Advances have been made in four areas which contribute to this improved positioning:

- Significant technical understanding of the system design has been developed, so that we are able to contribute actively to mission design on a par with international collaborators.
- The GEO SAR simulator appears to be as capable as any others available worldwide.
- The data assimilation methodology for phase screen compensation is an area of significant c`urrent research in Earth observation and allows GEO SAR to benefit from recent advances to optimise its measurement performance.
- Potential GEO SAR applications are understood across a range of domains, unmatched by any previous studies.

The CEOI project has been the basis of discussions with Chinese researchers active in GEO SAR studies. This has led to an invitation for Dr Hobbs to participate in the 2013 IET International Radar conference taking place in Xi'an in April. Dr Hobbs will chair a session and present the CEOI study, and is a member of the International Advisory Committee. In their next programmes, both ESA and the EU will emphasise opportunities for international collaboration (with China as a prime partner) and so developing good links with Chinese teams opens opportunities for joint projects within programmes such as Horizon 2020.

A further example of the UK's positioning is that Cranfield University (with colleagues in US) is now working with ITU to refine their guidelines for the use of the GEO region, so that they represent the needs of other users than just communication satellites.

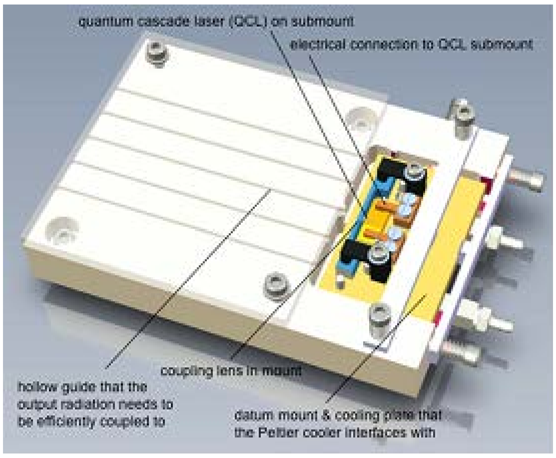
THZ AND THERMAL IR IMAGING

ACTIVE COMPONENT INTEGRATION TOWARDS A FULLY ENCAPSULATED MINIATURE LHR FOR EO

In prior CEOI projects, the Laser Heterodyne Radiometer technique for atmospheric chemistry sensing in the thermal IR was succesfully demonstrated, and first steps to instrument miniaturisation were taken using hollow waveguide integrated optics techniques to build the core heterodyne mixing block. In the current project, the main active elements such as the quantum cascade laser and the detector are to be integrated along with support components such as lenses and heat sinks. The result should prepare the ground to finalise a full miniature instrument that could in principle be flown on platforms in space as small as a cubesat, and for airborne and terrestrial applications in gas/vapour sensing.

Lead investigator: Damien Weidmann, RALSpace

A previous CEOI seedcorn project showed that the use of hollow waveguide integrated optics for the primary heterodyne mixing block not only resulted in a high degree of miniaturisation, but also gave excellent optical performance. To achieve miniaturization and full encapsulation of the instrument into ceramic, technologies to incorporate the active components such as the detector and quantum cascade laser local oscillator needs be developed. The difficulty is in the need to maintain optical alignment whilst launching the beam optimally into the hollow guide. In addition the quantum cascade laser must be heat managed in such a way that alignment is not disturbed.



A mount and heat sink for the quantum cascade laser, and a lens system to focus the very divergent laser beam into the guide have both been designed. Highly accurate mounting schemes have been developed. A challenge has been the metrology on the laser assembly in order to precisely locate the radiating facet (a few microns across) and align the laser optical axis with that of the hollow guide inscribed in the ceramic block. Several non contact metrology approaches have been tried. The use of optical microscopy in combination with locating pillars accurate to a micron has eventually been retained. Following complete metrologic assessment of all components, the design of an integrated QCL into hollow waveguide has been produced and is currently being manufactured.

Publications

- D. Weidmann, B.J. Perrett, N.A. Macleod, R.M. Jenkins, “Hollow waveguide photomixing for quantum cascade laser heterodyne spectro-radiometry”, Optics Express 19, 10, 9074-9085 (2011)
- Presentations at: NCEO/CEOI annual conference (Warwick), UK Space Conference (Warwick), 7th Appleton Space Conference (Harwell Oxford Campus), SET for Britain Competition (Westmister), EGU conference (Vienna)

Grants and contracts

- £250k has been awarded in anticipation of higher TRL by the defence and security community to investigate laser sensing technologies involving hollow waveguide integration.
- A £100k bid has been successful in collaboration with M Squared Lasers. The project is part the fast track UKSA/TSB NSTP programme, and will deliver on miniature electronics for laser heterodyne systems. This is complementary to the optical miniaturization pursued within the CEOI project, with the overall objective to have an instrument suitable for a CUBESAT deployment.
- £60k has also been granted to develop miniaturization of laser systems from the STFC Centre for Instrumentation in advanced optics. This development is synergistic to the CEOI effort.

Training

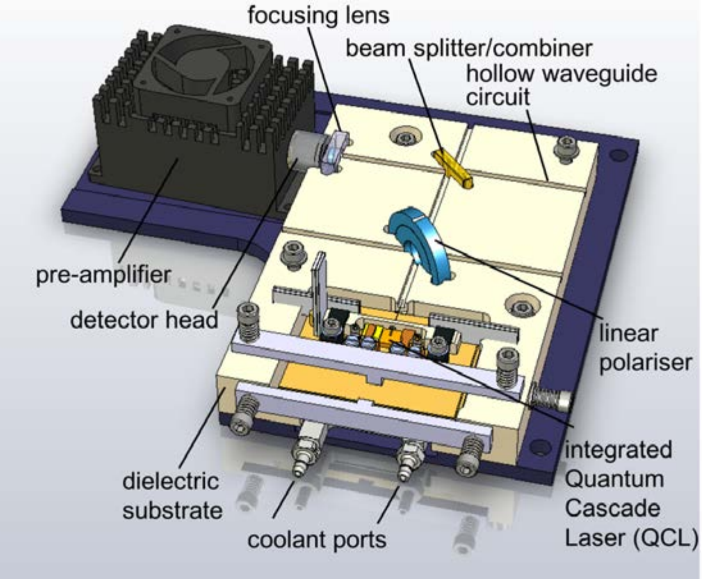
- During the project, Dr Rebecca Rose, a new member of the RAL Laser Spectroscopy Team, was trained in laser heterodyne detection methods and performed some of the non-contact metrology measurements. She will also continue to work on the project for the optical implementation and assessment of the hollow waveguide system.

Spin-out and exploitation

- A statement of interest to UKSA for a planetary instrument comprising a MIR heterodyne interferometer has been made. Hollow waveguide integration would certainly benefit such a mission.
- Various proposals for developing laser systems for Volcanology have been made. The prospect of hollow waveguide integration has been very attractive to the Earth sciences community.
- One of our existing hollow waveguide channels is currently being used at the RAL central laser facility and tested for pump and probe experiments for fundamental chemistry. Hollow waveguide could bring the benefit of a highly confined sample/light interaction in this type of experiments.
- Additionally an agreement has been reached with QinetiQ over the IP issues surrounding the patented hollow waveguide technology. Upon the completion of the proposed research project, if needed, a patent license would be sought from QinetiQ in order to make use of the IP.

A FULLY INTEGRATED, MINIATURISED AND RUGGEDIZED HOLLOW WAVEGUIDE LASER HETERODYNE RADIOMETER

This project addresses the design, manufacture and demonstration of a fully integrated, miniaturised Quantum Cascade Laser Heterodyne Radiometer for Earth observation. It represents the combination of highly successful work on laser heterodyne radiometry with novel hollow waveguide optical integration techniques. The work will culminate in demonstrating the integration, ruggedisation and miniaturisation of a laboratory bench based system which originally had a footprint of 75 x 75 cm and will be reduced to something that can be held in the palm of the hand, e.g. ~10 x 10 cm. Commensurate reductions in mass and optical robustness will also be achieved. These will be coupled with significant improvements in heterodyne mixing efficiency leading to a fundamental advance in laser heterodyne radiometer instruments for Earth observation applications and beyond.



The scope of the project encompasses the design, realization, demonstration, and assessment of a fully integrated system comprising both active (quantum cascade laser, optical detector) and passive (polarizer and beam splitter/combiner) components. The components will be integrated into alignment features in a common ceramic substrate which also incorporates a hollow waveguide mixing circuit. In this manner the aim will be to design, build and assess the very first fully integrated, miniaturised and ruggedized, laser heterodyne radiometer. The proposed work represents a critical step towards the development of an in-orbit demonstrator instrument.

The fully integrated instrument will be tested in the laboratory using blackbody sources and absorption spectroscopy to establish noise equivalent spectral radiance figures and compare them with ideal ones.

Lead investigator: Damien Weidmann (STFC RAL)

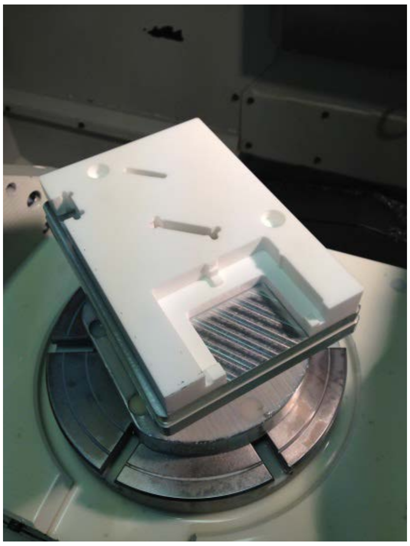
This section to be updated on receipt of the final report

Study Results

Through iterative steps integration of active components was achieved.

Iterative design with tests and metrology has allowed the miniature LHR final design to be produced:

Full assembly and testing scheduled in the next quarter.



Manufacturing in progress

Conclusions

Study completion awaited

Publications and dissemination

- "Getting QCL-based Remote Sensors to the Harsh Real World of Space". NSF Mid Infrared Technologies for Health and Environment Engineering center, Workshop, Baltimore, USA, 2012
- "Atmospheric vertical profiles of O_3, N_2O, CH4, CCl_2F_2, and H_2O retrieved from external-cavity quantum-cascade laser heterodyne radiometer measurements" , Tsai et al. Applied Optics, 51, 36, 8779-8792, 2012

GRANTS, CONTRACTS AND INTELLECTUAL PROPERTY/PATENTS

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SPIN-OUT, EXPLOITATION AND UK CAPABILITY ENHANCEMENT

Current leverage:

  - STFC centre for instrumentation, advanced optics funding
  - STFC CLASP project for security and defence applications
  - Collaboration with central Laser Facility for using hollow waveguide for ultrafast spectroscopy

- Development of unique expertise and know how in hollow waveguide integration of laser sensing instruments
  - High accuracy machining of ceramic (~μm)
  - Associated metrology
  - Laser spectroscopy sensing instruments
  - Simulations

STFC RAL Space HollowGuide Ltd

ASSESSMENT OF THE THERMAL IR LASER HETERODYNE RADIOMETER FOR MONITORING ATMOSPHERIC TRACE GASES.

Improved understanding, modelling, and predicting of climate & pollution underpins the importance of monitoring trace gases from space.

Major advances for both process understanding and monitoring applications require increased resolution on contemporary and planned future satellite missions (vertical, spatial and temporal) in order to bridge the gap in scales from satellite to surface networks.

LHR is identified to offer a solution through compact new technology, whose development is being pioneered in UK (CEOI, STFC, NERC). Developing to higher TRL would position UK to capitalize on its early worldwide lead in this technology and position for deployment on novel airborne platforms (UAVs, HAPs or Cubesats) in preparation for future flight opportunities.

This project is to perform a critical assessment of relevant applications and observing requirements to identify the priorities to drive design specifications of an LHR for initial field deployment. This will entail: a review of requirements for proposed future missions to sound atmospheric composition from space, identification of primary driver species and wavelength ranges which best exploit LHR capabilities, radiative transfer calculations to quantify benefit of LHR spectral resolution vs established techniques and establish sensitivities, and an initial assessment of spatial and temporal resolution achievable for different viewing geometries.

The study will reach conclusions and make recommendations concerning prioritisation of target species and application and next steps on instrument development and airborne deployment to demonstrate capabilities.

Lead investigator: Damien Weidmann (STFC RAL)

Science and Operational Case

The scientific challenges of understanding and quantifying the changes in the climate system, of better understanding and forecasting atmospheric composition and air quality, and of understanding and monitoring troposphere-stratosphere exchanges turns into specific instrumental requirements as far as Earth observation platforms are concerned. These requirements can be summarized as: a) observation at finer geographical scales, b) better resolution of altitudinal information, c) improved radiometric sensitivity, and d) the possibility to address the previous points from small, light, inexpensive platforms. The overall objective of the CEOI study was precisely to address the capabilities of LHR instruments against these requirements.

Study Results

For this study, a mathematical model of the LHR has been built and coupled to a high spectral resolution atmospheric forward model and an optimum estimation retrieval scheme. The LHR model coupled to the high resolution forward model generates simulated raw spectra as would be produced by an ideal instrument, including the noise. Subsequently, the retrieval scheme applied to these allows determining the atmospheric information that can be obtained from spectral data.

Carbon monoxide, nitric oxide, ozone, methane, nitrous oxide, sulphur dioxide, carbon dioxide (CO, NO, O_3, CH_4, N_2O, SO_2, CO_2) are the seven atmospheric molecules considered. Solar occultation, nadir, and limb viewing modes were included in the study. For each scenario and each molecule was determined a) the optimum spectral narrow window of 0.5 cm-1 in the thermal infrared, b) the vertical resolution, sensitivity, and error of the atmospheric retrieval, c) the impact of the total acquisition time on the information retrieved.

Conclusions

Conclusions of the study indicate that a miniature LHR (shoe-box size as a target) would be capable of sounding with high spectral resolution (from 0.02 to 0.002 cm-1) in the mid infrared and with high spatial resolution (few 100’s meters in lower Earth orbit and few kilometres in geostationary orbit). The best candidates among the molecules tested are definitively carbon dioxide and ozone. For these two molecules, lower tropospheric information could be obtained with good precision, while retaining the small package and the high spatial resolution advantages. The study on the integration time has established that relevant data can be obtained in few seconds with current ideal LHR. However, performances would be significantly enhanced through the development of spectral multiplexing capability, which will be in the scope of future technological developments.

Publications and dissemination

- "Getting QCL-based Remote Sensors to the Harsh Real World of Space". NSF Mid Infrared Technologies for Health and Environment Engineering center, Workshop, Baltimore, USA, 2012

- "Atmospheric vertical profiles of O_3, N_2O, CH_4, CCl_2F_2, and H_2O retrieved from external-cavity quantum-cascade laser heterodyne radiometer measurements" , Tsai et al. Applied Optics, 51, 36, 8779-8792, 2012

Training and Knowledge Exchange

- A joint PhD studentship between MSSL and RAL has been proposed to the UKSA in the field of isotopologue observation using LHR.

Spin-out, exploitation and UK Capability enhancement

This study provides information to shape a potential future mission, such as Earth Explorer 9. It also provides relevant material to a full proposal for an in orbit demonstrator.

The outcomes of the study also indicates two highly desirable technological developments to be included in a LHR technology roadmap: 1) the development of heterodyne photomixers with high efficiency in the 13-14 µm range, 2) the development of photo-mixer with high speed (~15GHz) to enable spectral multiplexing. Indeed, all the results presented do not include spectral multiplexing. Adding this capability to the LHR would significantly enhance performance in terms of integration time.

One pager LHR flyer distributed to scientists of the NOAA for potential prospects on Global Hawk UAVs

A proposal to the STFC Challenge Led Applied Systems Programme has been made to develop a miniature LHR for tropospheric ozone observation from high altitude platforms. The proposal has been rejected by the panel on the grounds that HAPs are not allowed to fly in populated areas.

An outline proposal for a miniature LHR in orbit demonstration mission has been submitted to ESA.

An outline proposal to the UKSA Collaborative Research in Exploration Systems and Technology has been submitted in collaboration to MSSL to develop the concept of miniature LHR for planetary exploration.

The project has delivered further inputs demonstrating the large potential of LHR for Earth Observation. As such it comfirms the UK leading position in the field of laser heterodyne systems. The insights on performances in observing tropospheric CO_2 are a major highlight, as tropospheric CO_2 observation from space is not only relevant to science but could offer business opportunities to the UK space sector driven by regulation enforcement.

STFC RAL Space

APPLICATION OF A NEW BOLOMETER PROCESSING TECHNIQUE TO FIRE MEASUREMENT & MONITORING FROM SPACE

Fires are important indicators for understanding the carbon cycle and for monitoring and forecasting atmospheric composition. Global biomass burning is the second largest source of trace gases and the largest source of fine carbon particles in the troposphere, and a key parameter for models is the emission rates of smoke from fires.

The detection and measurement of fires from space has been demonstrated using a variety of instruments including the NOAA AVHRR, MODIS and Bird HSRS infrared (IR) payloads. These measurements are achieved using spectral bands in the visible, middle-IR (3-5 μm) and long-wave IR (8-14 μm) to distinguish the signature of fires from those of clouds and sun glint.

To date the technology solution has dictated the use of expensive cooled detectors. The proposed programme will explore new processing techniques and the performance of new broadband uncooled detectors to assess the feasibility of achieving adequate performance at much lower cost.

The completion of the study is awaited for the final results.

Lead investigator: Mark Chang (SSTL)

This section to be updated on receipt of final report

Science and Operational Case

Fires are large contributor to annual carbon emissions to atmosphere.

Due to global appearance, satellite observations are the only method for wide scale quantification.

Study Results

Mission & Systems Requirements

- Specific end User requirements capture by KCL
- Mission & Instrument requirements proposal by SSTL
- Requirements iteration (2 instances) to generate requirements baseline
- Key results
- Reduction of 29 proposed requirement objects to 22 baseline requirements
- 3 driving requirements identified (see conclusions)

Detector Test Programme

- Ulis PICO640E detectors obtained
- Testbed developed
- Tests underway:
    - Detector Spectral Response
    - Detector NEDT (incomplete)
- Key results
    - Spectral response confirmation from 3 – 16 μm.
    - Assessment of normalised spectral response on 2 detectors selected from same production batch

Conclusions

- Absolute Radiometric Accuracy per channel
    - 0.5 K is defined
- Saturation Temperatures
    - MIR (3 to 5 µm) 800 K
    - LWIR (8 to 12 µm) 600 K
- Stray Light
    - Percentage of fire scene pixels leaking into neighbour <1.25% of fire scene pixels' level.

Publications and dissemination

- Fire detection and fire growth monitoring from satellite monitors", M. Cutter et al, proc. 63rd IAC, 2012.

GRANTS, CONTRACTS AND INTELLECTUAL PROPERTY/PATENTS

-

TRAINING AND KNOWLEDGE EXCHANGE

- KCL/SSTL and end user community knowledge exchange during specifications capture and baseline activity
- SSTL training of junior engineers on test equipment

SPIN-OUT, EXPLOITATION AND UK CAPABILITY ENHANCEMENT

- SSTL & KCL in position to undertake detailed characterisation of new detector product
- SSTL has made step towards a product design
    - Product design framework in place
    - Iterations required to refine design options
- Collaborations forged/furthered
    - Partnership between KCL & SSTL
    - Partnership between SSTL & detector supplier (Ulis)

SURREY SATELLITE TECHNOLOGY LTD

KING'S College LONDON University of London

LOW COST UPPER ATMOSPHERE SOUNDER (LOCUS)

This project aims to assess the requirements and feasibility of providing a low cost space mission to observe terahertz frequency (THz) atomic and molecular transitions to trace and monitor important chemical species in the Mesosphere (55 - 90 km) and lower thermosphere (90 - 120 km), a region known as the MLT.

Observations show that the mesosphere is cooling an order of magnitude faster than the troposphere is warming in response to increased greenhouse gas concentrations and stratospheric ozone depletion. It therefore provides a highly geared indicator of global climate change.

Given its importance, it is surprising that the chemistry of the MLT has not been well studied to date by space based platforms. Part of the reason is that the best probes of the important chemical species (atomic O, OH, H_2O, NO etc) lie in the THz for the MLT and the technology for observing them has been seen as expensive to deploy in comparison to other wavebands.

Recent technical advances in heterodyne receivers, especially in the area of Quantum Cascade Lasers (QCLs) as local oscillators, planar Schottky mixers and digital signal processing, mean that payload resource demands (mass power and volume) are being significantly reduced and are evolving towards compliance with smaller spaceborne missions. This opens the possibility of using SSTL type low cost space platforms to deploy a multiple band THz system using UK developed technology for the receivers.

Lead investigator: Bruce Swinyard (University College London)

Project goals are to:

- Provide a scientific context through physical and chemical modelling of the MLT.
- Use the model outputs to provide a list of likely species and transitions that could be measured in the THz frequency band.
- Set the requirements for a compact THz receiver system to be employed on a limb sounding space platform.
- Set the mission requirements for a low cost space platform.
- Identify the critical technical items and developments required for the build and deployment of such a system.

Study Results

Atmospheric Modelling

The mesosphere (55 - 90 km) and lower thermosphere (90 - 150 km), known as the MLT region, forms the “gateway” between the Earth’s atmosphere and the near-space environment. The MLT is strongly affected both by natural and anthropogenic inputs from the surface, and by solar and space-weather impacts from the space environment above.

A key feature of this part of the atmosphere is the meeting of huge energy fluxes: solar radiation and energetic particles from above, roughly matched by upward energy transfer from gravity waves propagating from the lower atmosphere [Brasseur and Solomon, 2005]. Interestingly, observations show that the mesosphere is cooling, in response to increased greenhouse gas concentrations and stratospheric ozone depletion, an order of magnitude faster than the troposphere is warming [Beig et al., 2003]. It therefore provides a highly geared indicator of global climate change.

Advances in remote-sensing measurements from satellites observing the MLT have increased our knowledge, particularly within the last decade. Nevertheless, global measurements of a number of key atmospheric species have not been made directly by previous satellite missions – these species, particularly atomic oxygen and the hydroxyl radical (OH), will be target species for the proposed LOCUS mission. One of the main objectives of the present work was to determine whether a THz spectrometer could detect a number of important species (O, O_3, OH, NO, CO, H_2O and HO_2) between about 50 and 400 km. Since there are limited (or no) observations of several of these species, we employed two numerical models to predict typical concentration profiles: the semi-empirical model MSIS-E-90 (http://omniweb.gsfc.nasa.gov/vitmo/msis_vitmo.html), and the new global chemistry climate model WACCM-X [Liu et al., 2010]. The results of the model, in the form of abundance profiles, were used for the retrieval and prediction of the line strengths to feed into the design of the THz radiometer system. Comparison of the results between MSIS, WACCAM-X and the sparse data shows some discrepancies. This clearly indicates that we need more data from MLT specific measurements, with larger global coverage and higher temporal cadence to constrain the models and provide a greater understanding of the complex physics and chemistry driving the energy balance in the MLT.

Radiative Transfer study and micro-window selection

Radiative transfer simulations have led us to define a spectral band definition for LOCUS comprising of 4 frequency micro windows (see table 1), which allow the detection of all of the primary and secondary species required by the science case (including pointing information from O2 which will reduce systematic errors in the trace gas retrievals). The main focus was on the selection of strong transitions to optimise the retrieval results. There is the potential to reduce the cost of the mission by reducing the number of bands, but at the price of either losing out on some of the species, or having to choose weaker transitions.

More precise information on the detectability of each species will be gained from retrieval diagnostics. However, this would require a full retrieval study, the effort for which exceeds the current feasibility study and so will be conducted as part of a follow on study. Of foremost interest would be to determine to which altitudes atomic oxygen can be detected. The mesospheric contributions to the spectral line of O have lesser Doppler line width than the hotter thermospheric emissions and could therefore potentially be masked by the latter. There is however the prospect that mesospheric O could be seen in absorption against the 'hot' thermospheric background, which would be novel concept. LOCUS, with a spatial scan range from the stratosphere to the thermosphere and a high spectral resolution, will provide unprecedented measurements of important trace gases in this altitude range.

The proposed configuration of the LOCUS instrument, consisting of four spectral bands in the THz region, is shopwn in the table below. This is based on identifying the strongest lines of interest and avoiding ranges where technical difficulties in implementation may exist.

	Band Centre	**Primary Target Species**	**Secondary Target Species**
Band 1	4.7 THz	O	O_3
Band 2	3.5 THz	OH	CO
Band 3	1.1 THz	NO, CO	H_2O, O_3
Band 4	0.8 THz	O_2	O_3, H_2O

Payload Requirements and Design Study

We have developed a preliminary conceptual design for the LOCUS instrument based on using a heterodyne radiometer system. Our baseline conceptual design uses cooled (~100K) Schottky diode mixers and local oscillators (LO) with the LOs provided via Quantum Cascade Lasers (QCLs) for bands 1 and 2 and more conventional harmonic frequency up-converter technology for the bands 3 and 4. QCLs are an emerging and potentially disruptive technology with the promise of radically reducing the size and mass of heterodyne radiometers. In addition to the critical mixer and LO technology we have also identified all core technologies considered to be in need of development, at both a component and system level. In summary, a future in-depth evaluation of the LOCUS mission should consider the following core attributes so as to ensure a suitable technical readiness level can be achieved for the instrument payload:

- Primary antenna system design fore-optics/mixer interface, in particular steerabilty of the antenna and access to calibration targets, optimisation of the interface configuration and determination of the sidelobe levels.
- Supra-THz Schottky mixer diodes require an enhancement in noise performance in the 3THz to 5THz range and minimisation of the required LO power.

- QCL LOs, in particular efficient operation at ~100K ambient temperatures, reduction in heat dissipation to better than 2W per QCL and efficient optical coupling to the mixer diode.
- Digital back-end spectrometer would benefit from reduction in the power consumption to ~1W/GHz bandwidth and reduction of the mass.
- Cryogenic system is under continuous development for other missions, we will look to maximise the heat lift capacity and operational efficiency in conjunction with the design of the cold area to minimise parasitic sources of heat.

Mission Requirements Study

A 700 km dawn-dusk sun-synchronous orbit (DD-SSO) has been baselined for the LOCUS mission. This provides the advantage of continuous power and a constant space-facing face for the payload radiator. Heritage from the Sapphire variant of the SSTL-150 is proposed for the spacecraft bus. This version of the bus, launched in February of 2013 into a DD-SSO for an operational space surveillance mission, provides a larger payload deck and solar panel, and can provide an acceptable thermal environment for the payload. Modifications to the bus need to be analysed – such as larger deployable solar panel and increased size of payload deck – and may require a requalification campaign. The relative and absolute pointing stability requirements can be achieved with the SSTL-150 AOCS baselined for the Kazakhstan-MRES mission. However, further analysis is needed to verify that this solution is sufficient to meet the needs for a possible 2 minute scan time.

The study is not exhaustive and considerable additional work is required in order to produce a detailed instrument payload and mission design. The current work has shown, however, that the scientific case for LOCUS is strong, that the required measurements can be made using low cost technology and that the mission concept is feasible. We have also shown that, whilst some technology requires development, most of the mission and payload components have a significant degree of relevant technical maturity thus minimising the potential cost.

Conclusions

Outline payload and mission design completed; Identified critical areas for further study:

- Deployable solar panels - 84W heritage vs 96W needed
- Payload envelope/mass - re-qualification of SSTL-150 spacecraft
- Deployable sunshield may be required
- Accommodation of electronics dissipation - thermal control
- Second radiator for intermediate T intercept
- 2 min scan time - further analysis of AOCS needed
- QCL power output and integration into mixer

Publications and dissemination

Abstracts submitted to:

- ESA Living Planet Symposium 9 - 13 September, 2013, Edinburgh, United Kingdom
- SPIE Remote Sensing 23 - 26 September 2013, Dresden, Germany

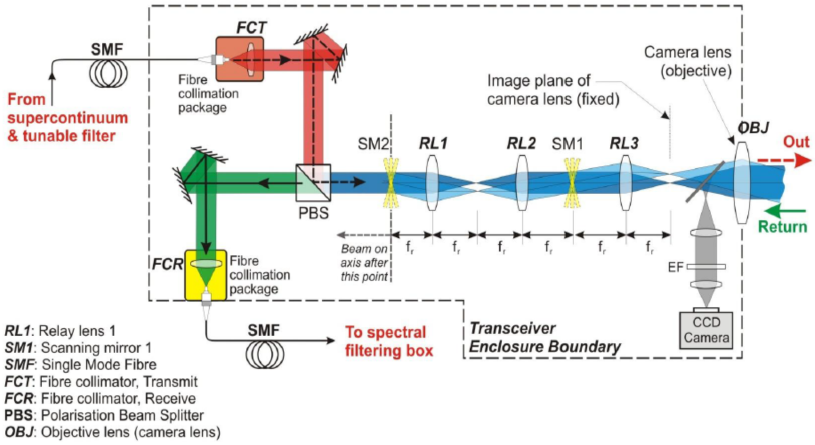
Spin-out, exploitation and UK Capability enhancement

- Outline proposal submitted in response to ESA ITT for an In Orbit Demonstrator AO/1-7359/12/NL/AF
- Accepted for next stage and full proposal to be submitted by 25th April 2013

HYPERSPECTRAL IMAGING

QUANTITATIVE RECOVERY OF STRUCTURAL AND BIOCHEMICAL PARAMETERS FROM FOREST CANOPIES USING HYPER-SPECTRAL LIDAR (HSL)

This project addresses proof of concept of the effectiveness of an airborne or space-borne hyper-spectral lidar system for the recovery of both biochemical and structural parameters from the forest canopy. The project created a hyper-spectral lidar (HSL) instrument by minor modifications to an existing innovative, photon-counting lidar system (see schematic, right). It also conducted ground and above canopy field trials on forest sites with this instrument, with independent measurement of 'ground truth' by field ecologists using off-the-shelf, portable instruments. It has demonstrated recovery of scientific parameters by inversion of the hyper-spectral lidar data using powerful Markov chain Monte Carlo algorithms, and to compare that analysis with the ground data.



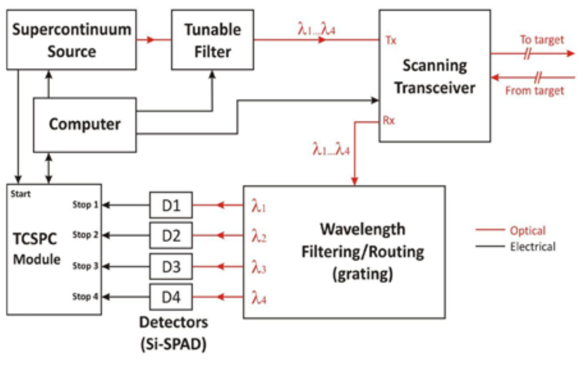
In addition the project has examined the feasibility of deployment of HSL on space and airborne platforms. There is considerable interest from space agencies (NASA, ESA) as well as the scientific community concerning multiple frequency airborne and space-borne lidar.

Lead investigator: Andrew Wallace, Heriot-Watt University

The ultimate science goal of this work is to detect seasonal changes in photosynthesis, light use efficiency and stress within forest canopies using LiDAR sensors as part of a larger sensor suite on air or space borne platforms. ESA regard this goal as very important, but note that the current LiDAR technology is immature.

Key parameters of interest include tree or canopy height, leaf area index, fractional cover, foliage height profile, biomass and tree volume, terrain and terrain slope. However, a multi-spectral canopy LiDAR (MSCL) or indeed a H(hyper)SCL can also provide information on the vertical distribution of physiological processes which carries information on actual carbon sequestration as well as existing stocks, and can discriminate ground from canopy returns.

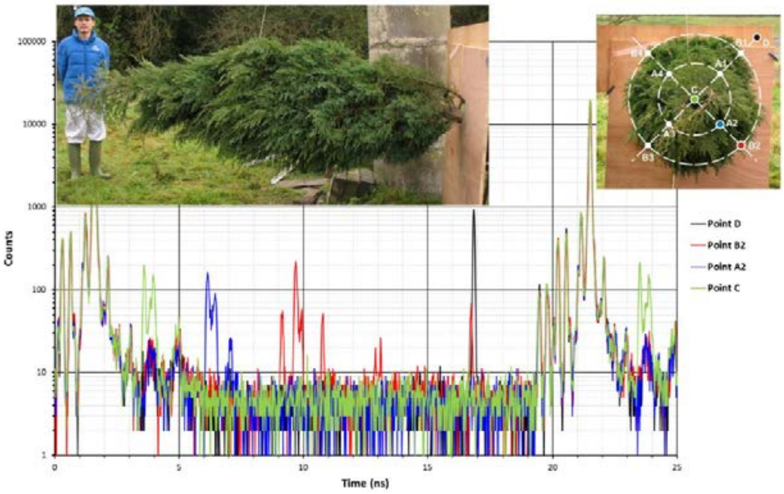
The LiDAR instrument design features a coupled supercontinuum source and a scanning transceiver that allows acquisition of simultaneous 3D images, profiles or single footprint data from tree samples or extended woodland. In the design (right), the return signal is split into discrete channels to focus simultaneously onto separate detectors (D1-D4) at the wavelengths of interest. More wavelengths can be accessed in a time-multiplexed configuration. The scattered return photons collected by the transceiver are coupled into a fibre connected to the wavelength routing optical system, which spatially de-multiplexes it into four separate fibres, one for each wavelength channel. Each of these four fibres is connected to a silicon Single-Photon Avalanche Diode (SPAD) detector.



A programme of modelling and theoretical studies of inversion techniques has been undertaken including the Reversible Jump Markov Chain Monet Carlo (RJMCMC) technique. Field tests are planned both in a test range set up across the HWU campus, and ultimately in a forestry field site. Preliminary data analysis using the RJMCMC technique has commenced, but fuller analysis awaits the full field trials.

One challenging aspect of the HSL design is the minimisation of the detected background solar photons without sacrificing SNR on the LiDAR returns. This is potentially a limiting factor that will determine the viability of the photon counting approach in space.

The laser source, SPADs and other novel components are not yet space qualified, and have therefore been the focus of the technology assessments. Whilst alternative laser technology can be considered, development of rad-hard SPADs is progressing, and suitable devices may be available by the time a new mission is accepted for study.



Photon counting systems generally have fast pulse retition rates (typically 2-100MHz) but collect single photons, so that data collection is from a wide footprint that displaces only slightly (3.6mm or less) between pulses. Hence pseudo-random sampling of a small area of a forest canopy could be supplemented by two dimensional scanning for either airborne or spaceborne deployment, but results in increased complexity.

Conclusions of performance over canopy await the results of the further trials to be completed in June 2012.

Publications

- IH Woodhouse C et al, A multispectral canopy LiDAR demonstrator project, IEEE Geosciences and Remote Sensing Letters, 8(5), 839-843, 2011
- AM Wallace et al, Recovery of forest canopy parameters by inversion of multispectral LiDAR data, Remote Sensing 4(2), 509-531, 2012.
- D Martinez-Ramirez et al, Developing Hyperspectral LiDAR for Structural and Biochemical Analysis of Forest Data, Proceedings of 32nd EARSel Smposium, May, 2012.

Grants and contracts

Following the conclusion of the CEOI programme, we are planning to seek funding for airborne trials of a suitable instrument as a prelude to space deployment.

Training

There are three PhD students associated with the project, Ximing Ren (HWU) who is studying photonics and has been assisting with sensor design and evaluation, Daniel Martinez-Ramirez (HWU) who has been working on parameter inversion, and Simone Morak (UoE) who is jointly responsible for the field measurement and evaluation.

Spin-out and exploitation

University of Edinburgh has spun out CArbomap Ltd. offering a route to commercialisation of the service (deployment, software, data product development). Results from the field trials will accelerate the development for airborne applications, although not for space borne as yet, by demonstrating the value of the measurements over a live forest canopy.

Concept Studies For A Methane Emission Imager

Methane (CH_4) is a greenhouse gas that has a global warming potential of 20 times higher than for CO_2, and a radiative forcing comparable with CO_2 over a 20 year period, due to its relatively short atmospheric lifetime. Current understanding of atmospheric CH_4 has been largely informed by sparse ground-based in-situ networks. Any successful mitigation strategy for CH_4 requires an emission verification mechanism (e.g., cap and trade). More broadly, insufficient knowledge of the magnitude and spatial and temporal distributions of CH_4 sources has far-reaching implications for the reliability of future climate projects.

The utility of space-based observations to better quantitatively understand regional CH_4 emissions has already been successfully demonstrated using SCIAMACHY and more recently by GOSAT. Space-based CH_4 observations are generally considered to be relatively mature, reflected in their inclusion in ESA's operational GMES space segment.

Global space-based CH_4 observations that extend SCIAMACHY and GOSAT datasets beyond 2020 will allow us to continue global monitoring of atmospheric CH_4 concentrations. However, it is unclear if there will be more than a single satellite in orbit at a time that will provide infrequent (due to clouds) and coarse observations (7x7 km2 resolution for Sentinel 5 precursor), which will limit the spatial and temporal scale of surface flux estimates to extended area sources.

The goal of this project is to define a novel concept for measuring atmospheric CH_4 based on the use of discrete shortwave infrared spectral bands. Such a system could offer significant advantages over existing systems in terms of instrument size and its ability to provide spatial resolution and coverage and consequently facilitate more advanced monitoring concepts (e.g., piggy-backing on telecommunication satellites). The concept utilizes the CH_4 proxy retrieval method that has been developed for the SCIAMACHY instrument (Frankenberg et al., 2010) and more recently for GOSAT (Parker et al., 2011). This method is based on the retrieval of the methane column from an absorption band in the shortwave-infrared around 1.65 μm together with a spectrally-close absorption band of CO_2 which serves as a proxy for atmospheric light path variations due to scattering from aerosols and clouds. The main advantage of this method is that accurate CH_4 retrievals are obtained without the need for specific aerosol or (thin) cloud information and it does not require high spectral resolution. The retrieval method is also very well suited for the retrieval of localized hot spots of CH_4 (e.g., land fills) or CO_2 (e.g., powerplants, www.carma.org) that are ubiquitous across the globe (Bovensmann et al, 2010).

Lead investigator: Hartmut Boesch (University of Leicester)

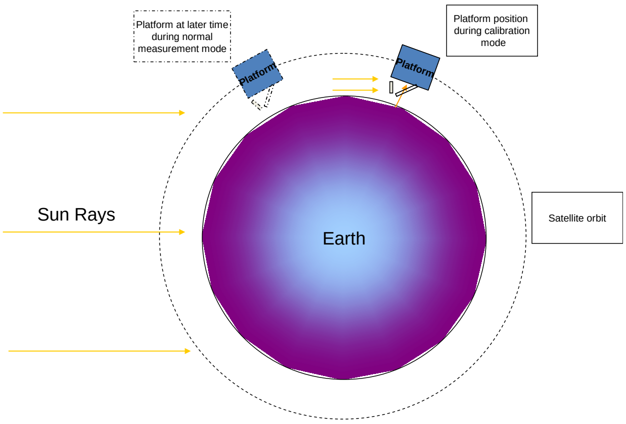
Summary report

From an investigation of CH_4 sources over the UK and CO_2 point sources, we have concluded that the proposed Methane Emission Imager will require a single sounding measurement precision of 1% or better and a ground pixel of 1km^2 or smaller with swath width of at least 50-100 km to capture plumes downwind of the various sources.

We have carried out a series of atmospheric simulations to establish the specification for a methane observing system based on five discrete shortwave infrared spectral bands in the shortwave-infrared spectral region to infer information on the CH_4, CO_2 and H_2O column and two bands for surface albedo. The main conclusions are that a signal-to-noise ratio exceeding 1000 is needed to achieve precision better than 1%. Especially for the CH_4 band a narrow spectral filter is needed (4 nm or smaller) while the requirement on width for the other bands can be relaxed. Radiometric calibration uncertainties on order of 0.1% between albedo and gas bands will already introduce biases of 1%. Spectral variations in surface albedo pose a significant problem and will require overlapping bands for albedo and gas information.

Instrument investigations indicate that adequate signal to noise ratios can be achieved using linear-array Indium Gallium Arsenide detectors which, crucially, are available at relatively low cost and do not require cryogenic cooling. Interference filters for suitable bands are difficult but feasible. The most significant problems for detailed development will be in control of errors due to detector response drifts, detector non-linearity, and effects of spatially- and spectrally non-uniform scene radiances.

The likely approach will include an in-flight sun-calibration system, shown schematically in Figure 2, that will allow correction for long-term response drifts, in combination with regular dark-level measurements. In a simplest configuration, a separate detector may be used for each of the required absorption and albedo-reference bands. However, errors due to differential drifts and non-linearity may be limited by use of common detectors for absorption and albedo-reference bands, by moving filters. Development of a small and low-cost instrument - <10kg and <10W - for methane detection is challenging but possibly feasible.



Gain calibration concept – platform location

Conclusions

We have defined a measurement concept for CH_4 detection based on a number of discrete bands in the shortwave infrared and analyzed the measurement performance with simulations (Obj. 1). Furthermore, a basic instrument concept has been developed and a number design options have been investigated (Obj. 2). Finally, the possibility of developing an instrument suitable for the SSTL TechDemoSat platform has been discussed (Obj. 3).

In this exploratory study several technical issues have been encountered and investigated:

- High SNR requirement (feasible)
- Band pass filter:
  - Need for narrow bandwidth (expensive but feasible)
  - Shift of filter transmission with angle (limit cone angle and use filters in front of optics)
- Errors due to detector and optics drift errors
- Need for calibration system (feasible but increased weight)
- Use same detector/optics for gas and albedo bands (possible with oscillating filters, but needs a solution for spatial co-registration)
- Surface albedo variations (use overlapping wide and narrow band filters or gas cells; will require higher signal-to-noise)

Spin-out, exploitation and UK Capability enhancement

There is significant interest by UK space industry on GHG monitoring and related downstream services and project represents a first step towards new measurement approaches relevant for commercial applications from very small satellites

Project has strengthened collaboration between key groups in UK with interest in GHG remote sensing from satellites (SSTL, University of Leicester and University of Edinburgh)

Project has fostered direct interaction between team members, resulting in significant knowledge exchange between SSTL and University groups in key areas SWIR spectroscopy, optical design etc.

THE ULTRA-COMPACT AIR QUALITY MAPPER (UCAM) TO MEASURE NITROGEN DIOXIDE IN THE URBAN ENVIRONMENT

Air quality continues to be a global challenge, with increasing urbanization and improved understanding of the impact of poor air quality on human health. The urban environment is where human NO2 exposure is at its highest, yet knowledge of its concentrations at ground level are derived from very loosely constrained atmospheric models.

Conventional satellite data (OMI & GOME-2) are very sparse and unable to provide much support, with only 2 or 3 overpasses over a particular city per day at fixed times, often obscured by cloud, with >14km spatial resolution and relatively poor accuracy at ground level.

To improve understanding of ground level NO2 the atmospheric models require better constraint. Amongst the options to achieve this improved constraint is the development of an instrument capable of retrieving atmospheric NO2 using the least amount of information possible with the intention of minimising its size and mass.

An ultra compact, relatively cheap and therefore mass producible purpose built instrument could be piggy backed on satellites and installed on aircraft to observe the urban environment with improved temporal and spatial resolution.

The Ultra-Compact air quality mapper (UCAM) is a novel instrument concept to measure nitrogen dioxide in the urban environment, thus providing vital information on emission sources and downwind exposure.

In this project the University of Leicester with Surrey Satellite Technology Ltd. will produce an instrument concept and outline design, suitable for a launch opportunity with very constrained volume, mass and cost budgets. from a space borne platform

Lead investigator: James Lawrence (University of Leicester)

This section to be updated on receipt of final report

Science and Operational Case

Atmospheric NO2 is one of many atmospheric pollutants prevalent in the urban atmosphere at ground level owing to its production via any combustion process, particularly internal combustion engines, power plants and central heating.

A day-to-day correlation has been found to exist between atmospheric NO2 exposure and human mortality.

Increased sensitivity to already existing respiratory conditions in humans has been associated with NO2 exposure through epidemiological studies.

Statistical enquiries have determined that the total cost to the UK economy of human exposure to NO2 can be up to £20 billion per year.

Study Results

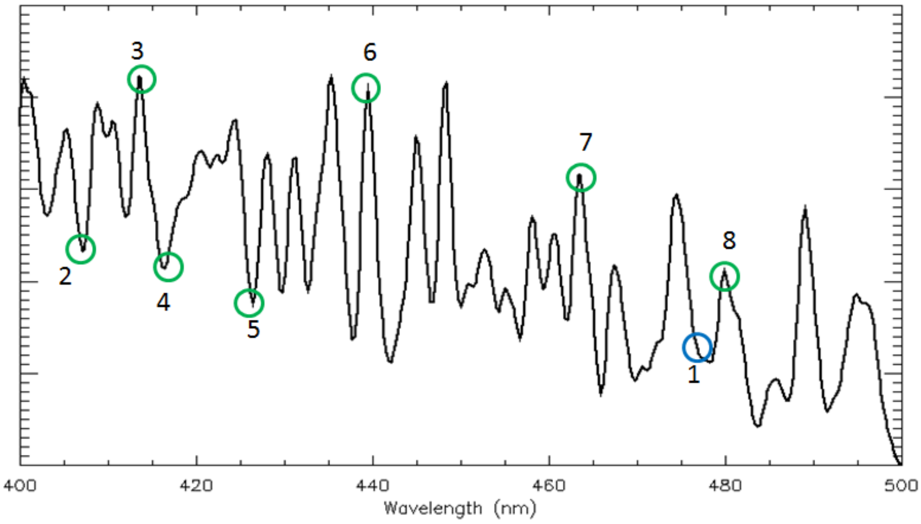


Fig. Wavelength selection

Conclusions

Using a BP-MLP-ANN it has been demonstrated that discrete wavelength retrievals of NO2 are possible using an ANN

Early tests suggest fit errors of < 10% are achievable with an SNR of 500

As a general rule more wavelengths = less noise sensitivity

The network fit error was found to be independent of the complexity of the data set owing to the automatic network configuration optimisation algorithm employed for UCAM

Publications and dissemination

- Work was presented at the Royal Society of Chemistry at the Air Quality Monitoring Conference, December 2012.
- Work to be presented at EGU in Vienna, April 2013

GRANTS, CONTRACTS AND INTELLECTUAL PROPERTY/PATENTS

- n/a

TRAINING AND KNOWLEDGE EXCHANGE

- n/a

SPIN-OUT, EXPLOITATION AND UK CAPABILITY ENHANCEMENT

- Collaboration with SSTL, an already established working partnership further developed.
- UK capability and infrastructure created for discrete wavelength retrievals of atmospheric NO2
- Dialogue with Ocean Optics established for the development of a breadboard demonstrator of a terrestrial UCAM instrument – funding yet to be confirmed.

University of Leicester

COMPAQS AIR QUALITY INSTRUMENT - AN AIRBORNE DEMONSTRATOR TO MAP NO2 OVER LEICESTER AT HIGH RESOLUTION

The CompAQS project, developed initially under CEOI funding and now supported by funding from NERC through the CityScan project, has demonstrated a key UK competence in remote sensing of Air Quality using visible spectroscopy. A CompAQS payload concept was developed for the TechDemoSat(1) flight opportunity, with a number of future possibilities for flight including EE-X, TechDemoSat-n, or a Bi-Lateral mission. Air Quality concerns remain high in scientific, economic and policy agendas with recent studies suggesting a European cost of poor air quality at €165bn p.a. There is increasing awareness of health and quality-of-life impacts of exposure to poor air quality, with health costs in the UK alone estimated at £15bn p.a. Furthermore, with increasingly high-resolution greenhouse gas missions such as CarbonSat being proposed, the use of NO2 as a short-lived tracer of combustion-related emissions could be a new use for a small-profile NO2 mapper, such as CompAQS.

This project takes the current CompAQS spectrometer, which has been tested as part of the CityScan ground-based network, and provides two flight demonstration opportunities. These flights will map NO2 over Leicester at 20 x 20 m resolution, and demonstrate key CompAQS concepts of source identification and exposure mapping.

Lead investigator: Roland Leigh (University of Leicester)

This section to be updated on receipt of final report

Science and Operational Case

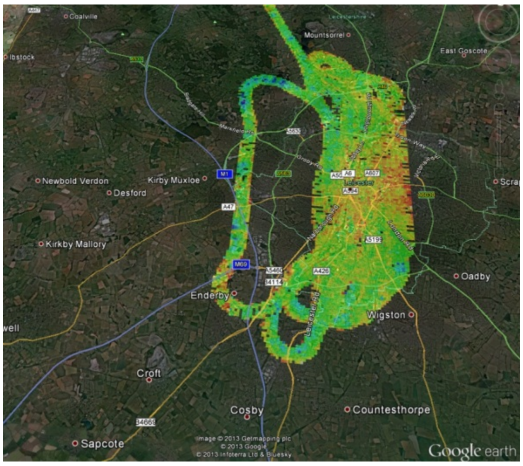
TBC

Study Results

- The First UK demonstration of an airborne pushbroom DOAS spectrometer.
- The First CEOI airborne demonstrator
- CompAQS TRL advanced through airborne demonstration.

Conclusions

TBC



CompAQS NO_2 concentration map over Leicester (preliminary data)

SPIN-OUT, EXPLOITATION AND UK CAPABILITY ENHANCEMENT

- Direct use of data in ESA-IAP project – Air Quality modelling and associated services for local authorities (including Leicester).
- Potential for spin-out of airborne demonstrator.
- Knowledge gained of airborne instrumentation deployment. Relationship established with plane operator, RVL.

TRUTHS – A Mission to Provide Observational Climate Data to Enable the Unequivocal Detection of Climate Change

The study objective is to evolve and refine the TRUTHS mission concept culminating in the production of a draft mission requirements document. The project brings together a consortium of UK partners from academia and industry with expertise in the fundamental science drivers, the design, construction and operation of EO satellite sensors and platforms. The study is building on the 2010 ESA EE8 proposal that, although not selected for phase-A/B, was highly recommended by ESAC and has attracted strong support from the international community: CEOS, WMO, GEO & other space agencies including NASA, reflecting the strong scientific justification and momentum also emerging from the proposed US CLARREO mission.

Lead investigator: Paul Green (NPL)

Science and Operational Case

Climate change is one of the key societal issues of our generation; the decisions made to address this issue over the next decades will directly impact the quality of life for many generations to come. Sound policymaking requires high confidence in future climate predictions, with these predictions primarily based on the output of complex climate model simulations. High confidence in the model predictions can only be achieved with verification against a high accuracy, rigorously anchored observational dataset, tailored to allow direct comparison with the model output. The climate change signal is entangled with the much larger natural variability signal of the climate system, subsequently; the signals that need to be determined are small, but critical. Our current observational capability is insufficient to confidently observe this small signal in the necessary decadal timescales, largely because the current sensors were not designed to perform this role so do not offer the high accuracy and orbital sampling necessary. A new observational benchmark dataset is therefore crucial for assessing the accuracy of climate change projections made by models, but importantly also to verify that the model is attributing the source of the observed change to the appropriate physical process. The need for a climate benchmark dataset is one of the key challenges laid down by the international climate science community, and one the TRUTHS mission has been conceived to directly address; primarily through its own observations but also secondarily through improving the performance of other space assets through reference calibration from orbit.

TRUTHS is baselined to measure SI traceable (in orbit) spectrally-resolved Earth-reflected solar radiance, incoming solar spectral irradiance and total solar irradiance to an accuracy approximately 10 times higher than is available from current sensors - the optimum level needed to establish a robust climate benchmark. The model output that will be directly verified is the global top-of-atmosphere (TOA) Earth-reflected radiance. When combined with the solar spectral irradiance measurement the dataset product will quantify the climate system energetic drivers, particularly those effecting feedback mechanisms such as cloud and albedo.

Study Results

The study initially refined the science case for the mission. The Imperial College team and NPL are members of the science definition team for the US CLARREO mission; a complementary mission to TRUTHS currently in extended pre-phase A at NASA. This partnership and an existing UK/US MOU enabled use of many of the studies undertaken for CLARREO as a foundation, adapting the results to define conclusions that applied directly to TRUTHS. This work developed some of the more advanced trade-off analysis, for example, the spectrally-resolved measurement extent into the UV against the instantaneous spectral accuracy requirement.

The enhanced technical specification resultant from these initial studies fed forward to an assessment of current and future planned sensors capabilities, to determine whether the required benchmarking dataset could be attained from a reduced risk strategy of adapting current sensors methodologies. Of the 399 distinct sensors (812 in total on the WMO OSCAR database) planned for launch between 2012 and 2027, only 7 could be considered as having some potential for climate benchmarking. However, for all these candidate sensors the ability to establish and maintain the required 0.3% (k=2) accuracy from pre-flight through mission life even with on-board references was the limiting factor. A review of calibration methods, including pre-flight, in-flight and using vicarious ground-targets concluded that the high, SI traceable, accuracy requirement could not be achieved by improvement of current calibration methodologies; so a step-change in methodology, as proposed in TRUTHS of taking the SI traceable radiometric standard, the cryogenic solar absolute radiometer (CSAR) on-board the satellite, allowing rigorous and repeatable calibration throughout the mission lifetime is essential to achieve a shortwave climate benchmark dataset of sufficient accuracy.

One point raised in the ESA EE8 proposal feedback was the perceived complexity and number of instruments contained in the TRUTHS satellite needed to mimic the traceability chain operated in the laboratory. Rigorous traceability, so vital for the TRUTHS concept, will inevitably lead to some increase in complexity over heritage sensor designs. It can be argued that, in part, the achieved accuracy of some heritage sensors is restricted by the necessitated simplicity of the calibration methodology and limited number of mechanisms, where similar levels of complexity have been used e.g. MODIS, higher accuracy has been achieved but still limited to the few % levels. To attain a 10x improvement in accuracy requires a revolution, not evolution in these methods and to some extent an inevitable increase in complexity over the simplest systems. However, with ingenious design the increase in number of mechanisms can be minimised, and through close collaboration between team members from SSTL & NPL, making use of the refined technical specifications and advancements in technology, a simplified methodology has now been baselined decreasing significantly the number of separate mechanisms from seven to three; and removal of one major instrument reducing overall mission risk as well as one of the key cost drivers, without any loss in science output performance. Together with an optimised instrument design, de-scoped 'TRUTHS-lite' options have been developed to address a reduced range of mission products (e.g. the solar spectral irradiance product removed and sourced from an external sensor) or reducing the spectral range of the measurements, simplifying the technology requirements appropriate for a technology demonstration mission pre-cursor. The study has confirmed the need for a hyperspectral imager with a specification that would facilitate the use of a CHRIS-2 or EnMap sensor with a relaxed ground spatial dimension but with higher spectral resolution. The data from such a sensor would of course not only deliver the primary mission objectives- climate benchmark, but also offer secondary hyperspectral products to underpin a wide range of other EO applications.

Conclusions

This project has achieved a significant step forward towards the development of TRUTHS, building on an already well supported project called for by the international climate science community, by assembling a world-class collaborative team of UK expertise to hone the many facets of the mission concepts. The questions highlighted in previous mission assessments have been addressed resulting in a significant evolution in all aspects of the mission requirements, culminating in the production of a draft mission requirements document (MRD) and an outline mission concept. The later with sufficiently reduced risk and potential that it would warrant (in line with ESAC recommendations) a more rigorous, 'Phase 0/A study' as early as possible to ensure maximum readiness for any early implementation options: nationally or partnering.

Publications and dissemination

- 'Monitoring the Climate system from space: progress, pitfalls and possibilities' - Grantham Institute briefing paper
  http://www3.imperial.ac.uk/climatechange/publications/
- Nature Climate
  http://www.nature.com/nclimate/journal/v2/n8/full/nclimate1642.html

  To be published in 'The Engineer' April 2013
- Referenced in:

  http://www.wmo.int/pages/prog/sat/documents/ARCH_strategy-climate-architecture-space.pdf

SPIN-OUT, EXPLOITATION AND UK CAPABILITY ENHANCEMENT

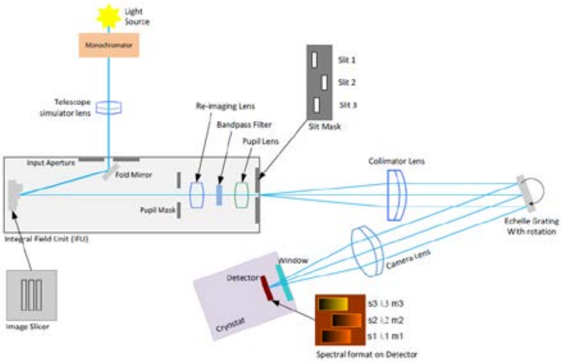
The TRUTHS project brought together a number of UK expert teams in Earth Observation, pooling resources and allowing a study impossible to be completed by any of its constituent parts. The project allows the UKSA to demonstrate internationally its interest to support mission concepts that have some international support and credibility and provide the means to improve the potential for future implementation by de-risking and strengthening the technical case. A small study such as this has allowed a small mixed team to refocus ideas and has led to the prospect of a simpler lower cost implementation of a highly novel unique mission. The study makes the case for further more detailed studies to enhance the readiness and potential range of exploitation options that are emerging including potential partnerships with other countries or agencies such as ESA and provides a strong candidacy for a UK led mission as part of the UK space Innovations and Growth strategy particularly Recommendation 6.

The project team worked closely with members of the NASA CLARREO science definition team in the UK and in the US, enhancing visibility for the TRUTHS mission to the point where even in the US climate benchmarking missions are described as CLARREO/TRUTH-like missions. Increased international exposure and mission requirements and name contained within international strategy documents of CEOS, WMO etc. (climate architecture doc above). Interest from potential international partners: NASA, China, India. ESA technical staff starting to recognise potential and looking for ways to support the mission.

OPTICAL AND IR IMAGING

PROTOTYPE EARTH OBSERVING SYSTEM USING IMAGE SLICER TECHNOLOGY (PERSIST)

Using techniques developed for the MIRI instrument for the James Webb Space Telescope, the UK ATC have designed and built prototype core elements of a novel hyperspectral imager, aimed at measurement of atmospheric CO_2 concentration from Earth orbit. The technique allows a more compact and lightweight design than conventional optical systems, and exploits image slicing techniques using a multi-faceted focussing mirror. The design allows the imaging of spectra from 3 separate wavebands onto a single detector array. The prototype has been assessed for stray light and crosstalk.

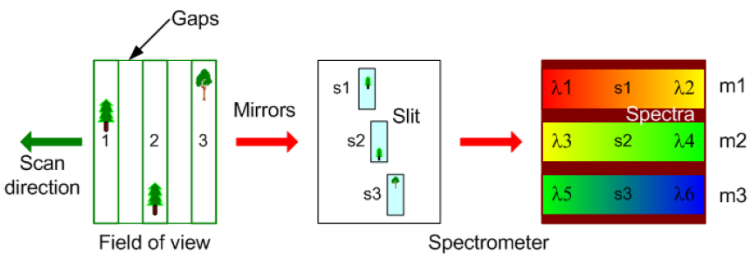


This project builds on design work done in a previous CEOI seedcorn project.

Lead investigator: David Lee, STFC UK ATC

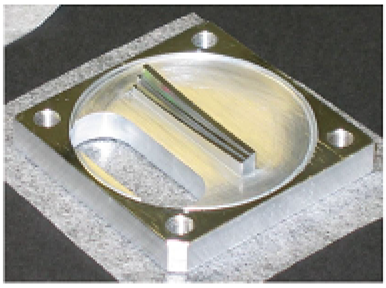
During the development of the MIRI instrument for the JWST, it was realised that the faceted mirror image slicing technique used to generate multiple optical paths may have applications in other applications such as Earth remote sensing. In particular, SWIR imaging spectrometers such as the Orbiting Carbon Observatory instrument (lost in the February 2009 launch failure) for atmospheric CO_2 sensing might be realisable in a more compact and lightweight form if image slicing could be successfully deployed. During a previous CEOI seedcorn project, such a spectrometer was designed. In the current project the design was refined and a prototype image slicer has been built which can be used in a laboratory demonstration of an imaging spectrometer.

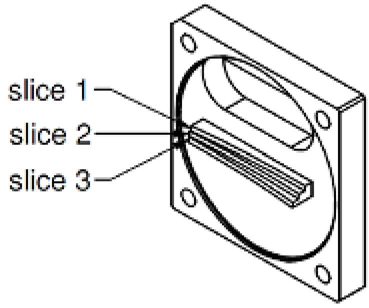
The design is a push-broom spectrometer with along-track scanning. A series of slits sample the field of view. The spectrometer uses multiple diffraction orders to simultaneously observe 3 wavelength ranges of interest. A full instrument would feature 2 redundant arms, i.e. providing 2 spectrometers and focal planes viewing the same field of view. This allows the possibility to observe 2 polarisations, and provide superior performance to OCO.



The prototype system will feature a custom-made image slicer assembly, with existing UK ATC light source, telescope, echelle grating, external lenses and a SWIR detector in a cryostat.

The custom Integral Field Unit (IFU) features a few simplifications over what would be needed for a flight standard spectrometer. However the unit is realistic enough to provide a guide as to the likely performance of a flight instrument. A diamond-turned image slicer mirror with three off-axis facets is the key device. Input light is imaged on to this slicer device by a flat fold mirror and the slicer splits up the light resulting in 3 beams. A large plano-convex collimator lens is used to focus the beams, removing the need for expensive off-axis lenses. Similarly the re-imaging and pupil lenses use simple plano-convex lenses with a common radius. The filters are 6mm thick, 12.5 mm diameter COTS products.





The lab setup allows the custom IFU to be thoroughly evaluated, in particular with respect to stray light and crosstalk. The tests show the performance in this respect is good. The IFU is a small lightweight unit that can be demonstrated at conferences with suitable visible band filters in place. The lab tests also demonstrated the ability of the multiple order spectrometer to simultaneously observe 3 wavebands.

Publications

- A poster presentation was given at the IWGGMS-7 conference in Edinburgh, May 2011.
- A poster was presented at the joint NCEO/CEOI conference, Warwick, September 2011.
- Abstract submitted to the SPIE Remote Sensing conference, to be held in Edinburgh, September 2012.
- Abstract submitted to the International Conference on Space Optics, to be held in Corsica, October 2012.

Grants and contracts

Although early days, ATC will:

- UK ATC will apply to the forthcoming ESA ITI call for funds to enable further development of the multiple order spectrometer concept.
- UK ATC has applied for NSTP FTPP funding for development of miniaturised spectrometers, using "Astro-Photonics" technology. These mini-spectrometers will enable more compact and efficient Earth observation instruments to be constructed.

Training

- A CEOI funded PhD student has been actively involved in PERSIST testing and data analysis. This involvement will be of great benefit to his future work on hyper-spectral imagers at the University of Edinburgh.
- The PERSIST project has been useful in providing awareness of the capabilities of technology developed for astronomical instrumentation for use in Earth observation and vice-versa. Some of the novel Earth observation instrument designs may well be useful for future astronomical instruments.

Spin-out and exploitation

- The capabilities of the PERSIST technology will be advertised as a general purpose multiple wavelength Earth observation tool adaptable to a range of scientific needs.
- The multiple order spectrometer concept will be further developed for a future instrument for an unmanned aerial vehicle.

Low Weight Mirror Fabrication Techniques

Lightweight mirrors are an essential component in many satellite systems. With the increasing aperture size it is essential that solutions are found to reduce the mass of the final unit while maintaining the optical performance. The current methods of profiling and open cavity milling are subject to significant risk during manufacture, with the thin webs having significant potential to flaw during grinding and later handling. Such a flaw renders the blank unusable and manufacture has to start again. This adds both cost and potential time delays to the manufacture of the mirrors. There is significant benefit in both the risk reduction and cost reduction of the manufacture process investigated in this project, as well as allowing higher weight reductions in the same size optic. However the process is at its early stages of development and many hurdles must be crossed before any such substrate can be declared flight-worthy. This seedcorn project funded by the CEOI was the first step in the process.

Lead investigator: Dr. Peter E. MacKay

Science and Operational Case

The interest in lightweight mirrors for space applications goes back many years and members of the SSTL Optical payload Group (OPG) have undertaken extensive reviews for the European Space Agency (ESA) for both cooled and uncooled telescopes initially driven for the requirements of the space science missions. A wide range of materials have been investigated including: Zerodur, Ultra Low Expansion (ULE) glass, Fused silica, Fused quartz, Borosilicate glass, Aluminium, Beryllium, Graphite Fibre Reinforced Epoxy, Graphite Fibre Reinforced Glass, Silicon, Carbide (SiC), CeSiC (carbon fibre based SiC).

The increased utility of small satellites, particularly, for Earth observation, demands a rethink of the choice of mirror materials and fabrication techniques, particularly with respect to overall cost and schedule, whilst still achieving accurate surface form and low surface roughness. SSTL for instance are developing 3 off imagers providing 1m ground sampling and the mass of the telescope, particularly the primary mirror, is not insignificant even though lightweighting of the mirror material is applied using profiled mirror cross-sections and open cavity milling techniques. The requirements of lightweight mirrors are not only confined to imaging systems, since the future lidar systems, that are of particular interest in the UK EO science community will require large mirrors to achieve adequate signal to noise. For the small satellite Earth observation missions the mass, price and delivery schedules are of paramount importance to ensure that the overall mission costs including launch are minimised and that the increasing demand for short schedules with low risk can be accommodated. Alternative fabrication techniques are clearly required to reduce the areal density further but in a way that results in low manufacturing risk and without a significant impact on schedule.

Study Results

The aim of the project was to investigate alternate methods of reducing the weight of mirrors for space applications while retaining the required stability of surface form. Two alternate means of joining Zerodur® components without epoxy were investigated and the optimum chosen for use in the second half of the project. Epoxy is to be avoided because of potential outgassing issues. Test pieces were fabricated in both Zerodur and ULE and then bonded using both thermal diffusion and adhesive free bonding techniques. The samples were subjected a four point bending test. The most successful bonding technique achieved bond strengths greater than 54MPa, significantly higher than the design strength of 15MPa typically used by SSTL.

D80mm mirror after bonding

Two different designs of fabricated lightweighted 150mm diameter planar mirrors were manufactured in the second half of the program. In the first lower risk method the mirror core was drilled many times to remove unwanted material. Two planar sheets were then bonded to the core, one to act as the mirror surface and a second purely for mechanical stability. Breathing holes were included within the design to prevent any sealed air pockets being formed. This mirror was subjected to a standard thermal cycling test without degradation in performance.

The second method building up the support webbing from individual components will also be investigated, offering the potential for lower mirror blank fabrication costs, but at significantly higher risk. This mirror is nearing completion at the time this report is written, and is being considered for a patent application.

Conclusions

Project was successful. Adhesive free bonding of lightweighted mirrors has been proven using a method suitable for efficient manufacture. Further development is required to confirm space flight worthiness, but existing heritage of similar technique supports a high level of confidence. Gooch and Housego are considering how to develop and exploit the technology in a wide range of market areas as well as space technology.

Publications and dissemination

- Contributed to ESA Technology Harmonisation 1st Semester, Mirrors and Stable Structures, February 2013
- Talk, “Bonding with Industry” at University of Glasgow’s Industry Day 28th Feb 2013
- Poster, “From University to Industry: Fabricating Lightweight Spacecraft Components” SET for BRITAIN 2013, Houses of Parliament, 18th March 2013
- Paper, “Characterisation of a low temperature and adhesive free bonding technique for optical materials”, SPIE Optics and Optoelectronics, Prague 17April 2013
- Paper, “Fabricating monolithic structures from separate piece parts", EOSMOC, Munich, 13-15 May 2013.

GRANTS, CONTRACTS AND INTELLECTUAL PROPERTY/PATENTS

- Gooch and Housego is in the processing of drafting a Patent with regard to the design features developed during Workpackage 3.

SPIN-OUT, EXPLOITATION AND UK CAPABILITY ENHANCEMENT

- This project enhances the transfer of the skill of adhesive free bonding from the Institute of Gravitational Research to a UK industry. This leverages the research funded by STFC and finds a commercial route to market in the UK.
- The acquisition of the skill allows Gooch and Housego to compete with the few companies around the world that have developed similar technologies. We have applied it to a new product line of lightweighted mirrors and structures, which has potential markets not only for space but also for any industry that desires to reduce the mass of large zero-expansion ceramic substrates for precisions engineering applications.