Proceedings Paper:

Swinyard, B, Auriacombe, O, Bradshaw, T et al. (22 more authors) (2016) The LOw Cost Upper atmosphere Sounder: The "elegant breadboard" programme. In: Millimeter Waves and THz Technology Workshop (UCMMT), 2015 8th UK, Europe, China. 2015 8th UK, Europe, China Millimeter Waves and THz Technology Workshop (UCMMT), 14-15 Sep 2015, Cardiff, United Kingdom. IEEE . ISBN 9781467374347

https://doi.org/10.1109/UCMMT.2015.7460627

The LOw Cost Upper atmosphere Sounder: the ”Elegant Breadboard” programme.

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***Abstract*—The LOw Cost Upper atmosphere Sounder (LOCUS) mission has a core objective of probing the Earths mesosphere and low thermosphere (MLT) region using THz receivers combined with an infrared (IR) filter radiometer. This will give the first comprehensive data on the energy balance and chemical processes in the MLT from direct detection, including the important atomic oxygen which until now has never been mapped by remote sensing measurements. The payload and mission design concept has very recently, and very successfully, concluded an ESA sponsored phase A0 study, led by SSTL. It is essential to build upon this success and to maintain the mission momentum towards achieving a high readiness level (TRL) and eventual flight. A key step in this process is the demonstration and proof of operation of the THz payload in a representative environment (towards TRL 6). We therefore have begun working on a hi-fidelity breadboard of the LOCUS payload suitable for both extensive laboratory and environmental testing, and with a potential for deployment on a high-altitude platform, such as NASAs Global Hawk. The latter will prove the system technical operation in a closely representative environment, and will return valuable and useful scientific data. The breadboard will consist of the system primary antenna; optical bench; one or more THz receivers; back-end electronics, and a physical realisation of the spacecraft payload bay. An extensive test programme will be undertaken to raise the payload and receiver system towards level 6, and we will seek opportunities to test the system in an observational campaign.**

I. Scientific Background

The MLT region comprises of the mesosphere (55 - 90 km) and lower thermosphere (90 - 150 km). Together they form the gateway between the Earths atmosphere and the near-space environment. The MLT region is affected from above by the inflow of solar radiation and energetic particles from the space environment, roughly matched in energy by upward energy transfer from gravity waves propagating from the lower atmosphere [1]. It is also linked to both natural and anthropogenic surface processes by proxy of stratospheric chemistry [2]. 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. It therefore provides a highly geared indicator of global climate change. Increasing remote-sensing measurements from satellites observing the MLT have added to 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 will be target species for the proposed LOCUS mission. In particular LOCUS will target atomic oxygen, which is the major component of the atmosphere above 120 km, the hydroxyl radical (OH) which, together with carbon monoxide (CO), is a major atmospheric coolant and nitrous oxide (NO) which is a disequilibrium species formed by the impact of Solar particles. Although the abundance of these species can be inferred through infrared observations (in conjunction with complex modelling) up to 110 km, they can only be directly observed in the MLT via their THz emission lines which lie from $\sim$1 to 5 THz. This makes direct observation impossible except from a space platform with an advanced supra-THz receiver, a prohibitively complex instrument concept when built using existing technologies. The novel receiver technologies developed for the LOCUS mission will make these measurement possible on a comparatively low budget, thus providing a major breakthrough by allowing direct observation of these atomic and molecular lines on a global basis.

In order to observe the MLT efficiently we require a space mission capable of limb sounding the atmosphere as frequently as possible over an altitude range of at least 50-150 km. A previous CEOI seedcorn grant (2012) provided funding for

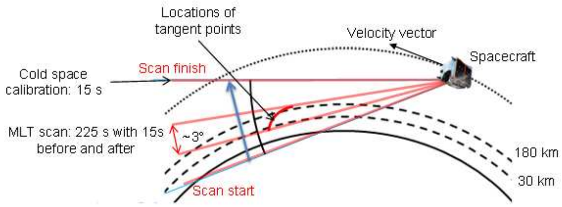

Fig. 1. LOCUS mission concept. Payload is pointed along the spacecraft velocity vector and the spacecraft scans vertically. Data is collected with a 3 second dwell time per vertical spatial resolution element, each scan taking 225 seconds. Additional scan modes are considered for campaign modes (i.e. NO from auroral forcing).

an inital concept study while a Phase 0 study sponsored by ESA as a candidate mission for an In Orbit Demonstrator (hereafter LOCUS-IOD) has also taken place. Hereafter we describe the main outcome points of these studies and indicate the way forward for turning the LOCUS mission concept into reality. The outline mission concept is illustrated in figure 1. The overriding consideration in the LOCUS-IOD is to keep the mission costs low and within 50MEuro. To this end an SSTL-150 platform is proposed to be used with an integrated payload mounted on one side with the satellite placed in a 600 km Sun-synchronous orbit and the viewing direction along the velocity vector. To achieve limb scanning the entire spacecraft is rotated to move the viewing direction across the limb as illustrated in figure 1. The primary science scan is achieved by scanning the spacecraft over 3° , covering an extended 30 to 180 km altitude range, with an additional viewing direction to cold space for calibration purposes.

Science goal evaluation carried out during the phase 0 study emphasized three driving requirements:

- Correlation between direct THz and IR measurements of O, O_3 and OH and O_2 and probing the energy balance in the MLT region.
- Investigations into the chemistry and formation mechanisms of Noctilucent Clouds (NLC) from humidity and temperature soundings.
- Observations of chemical processes and energetic particle precipitation in the MLT during and following auroral forcing events, e.g. a Coronal Mass Ejection (CME).

From these requirements a detailed analysis of the mission requirements was carried out and a preliminary payload and mission design has been constructed. The resulting innovative payload design consists of an all-aluminium antenna feeding a focal plane consisting of a mixture of four THz heterodyne receivers (Table I) and a four channel IR spectrometer (Table II). The combination of simultaneous observations of both the abundance of a species (through the THz channels) and the cooling rate from these and their associated species (through the IR channels) will be a unique and highly innovative data product. It is emphasised that while these data will support the science topics outlined above, they will also find utility in, for instance, improved medium range weather forecasting, predictive climate change modelling and modelling the impact of Solar weather on the Earths atmosphere

Band	Centre ν (THz)	Species Covered	Predicted Performance (NETD K)
1	4.7	O, O_3	46
2	3.5	OH, CO, HO_2	12
3	1.15	NO, O_3	4
4	0.8	O_2, O_3	3

TABLE I. THz RECEIVER BAND DESIGNATION

Centre λ (μm)	Bandwidth (μm)	Species Covered	Required Detectabililty ($Wm^{-2}sr^{-1}$)
15	5.2	CO_2	1x10^{-3}
9.3	1.74	O_3	3x10^{-4}
5.3	0.41	NO	1x10^{-5}
2.07	0.54	OH	1x10^{-5}

TABLE II. IR RECEIVER BAND DESIGNATION

II. LOCUS PAYLOAD

A sketch of the first mechanical concept of the optical assembly is illustrated in figure 3. The planned payload currently consists of a 45 cm used-diameter off-axis antenna mounted on an aluminium optical bench feeding a combination of THz and IR receivers. The receivers need to be cooled to <100 K which is achieved using a space qualified close cycle Stirling cooler (or coolers) mounted close to the receiver housing on a dedicated radiator. A second radiator is used to cool the payload environment to ∼250 K. The thermal stability of the payload and receivers was modelled during Phase 0 and, whilst the temperature of the receivers stays within reasonable bounds, this part of the design shows little in the way of margin and requires further attention. The necessary attributes of the THz frequency channels were evaluated in detail against the scientific requirements, and resulted in the identification of micro-windows as shown in Table 1. The requirements on the IR channels were derived from those used in the NASA SABER [3],[4] instrument which is currently in orbit: these are given in table 2.

Each THz receiver band is a self-contained system comprising a front-end Schottky barrier diode mixer; local oscillator (LO); cryogenic intermediate frequency (IF) low noise amplifier (LNA); and a subsequent room temperature chain of IF amplification and signal down-conversion. In the baseline design, each band also includes a fast Fourier transform (FFT) spectrometer which digitally samples the IF output and provides a power spectrum of the incident THz signal, typically with a 2GHz bandwidth and 1MHz spectral resolution. This Wide Band Spectrometer (WBS) (in Fig.2) is based on the use of fast ADCs coupled to a FPGA which performs the computation of the FFT. The power consumption of the individual WBS units was identified as a concern during the study and various reconfigurations of the receiver channels have been proposed to reduce the number of units required.

The heat dissipation from the 100-K stage of the THz receivers is dominated by the Quantum Cascade Laser (QCL) Local Oscillators (LO) which are at the heart of the novel 4.7THz and 3.5 THz receiver development (Band1 and Band2). The cooler baselined for this stage is the RAL mini cooler which has undergone development under an ESA TRP contract. These lift ∼1 W at 100 K, weigh ∼ 600 g and consume 15 W making them extremely suitable for deployment on a

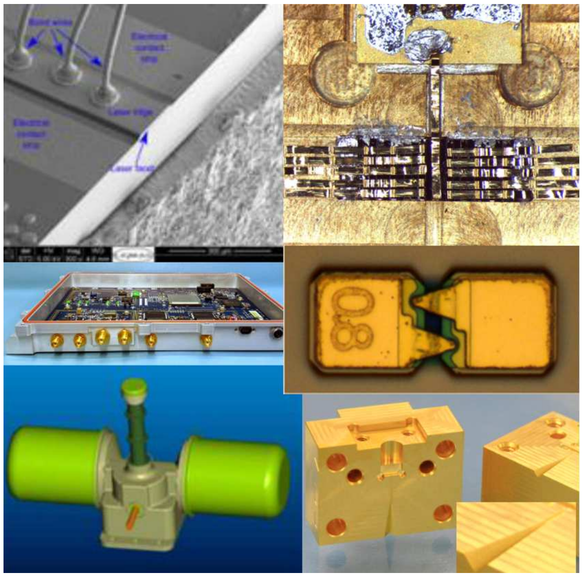

Fig. 2. A mosaic of the fundamental technologies developed concurrently in this and other activities in aid of the LOCUS mission. Quantum Cascade Lasers (QCLs) as Local Oscillators, Small mechanical cryocoolers, Wide-band digital spectrometers, Schottky diode mixers and integrated THz waveguide structures.

small spacecraft platform. An engineering model of one of these coolers (fig.2) will be made available to the LOCUS elegant breadboard for testing during the thermal verification campaign.

The overall conclusions of the IOD Phase 0 study were presented to ESA in July 2014 at ESTEC and a number of areas were identified that require further investigation or development. These include:

1) Demonstration of an operational QCL driven supra-THz receiver with low thermal dissipation.
2) End-to-end performance demonstration of the LOCUS prototype payload.
3) Verification of thermal stability requirements and performance of the payload.
4) Reduction in power of the WBS and/or reconfiguration of the THz receiver signal conditioning.

Item 1 is being directly addressed by our consortium through a combination of CEOI-ST and NERC funding (awarded during 2014). These programmes are designed to develop and advance fundamental technologies(showcased in Fig.2) associated with the LOCUS THz receiver detectors and signal processing. Specifically, we are integrating quantum cascade lasers (QCLs) with high frequency Schottky diodes to form novel supra-THz detectors, and are exploring related attributes of power consumption and frequency stability. We are also developing a 1.15THz receiver in order to demonstrate one of the LOCUS core science channel (Band 3). These technical developments closely follow our technical advancement roadmap and will be concluded next year.

Items 2, 3 and 4 are the subject of the present activity in which we are in the process of designing, and subsequently building and testing an elegant breadboard of the LOCUS payload. This will be used to prove the antenna optical performance, that LOCUS will operate within a representative thermal environment and to demonstrate the end-to-end performance of the instrument using the pre-existing THz receiver. At the conclusion of our proposed programme of work, we will have very significantly raised the TRL level of the LOCUS payload (from its current status of 3 to 5 as defined by ESA) and will be able to meet requirements of a future call for missions from ESA, the UKSA or other bi-lateral agencies. Furthermore, the integrated elegant breadboard instrument will also be capable of making scientific observations of the production and cooling rates of NO from auroral events and we will be seeking opportunities to demonstrate the instrument via either a high-altitude aircraft or from a high-altitude ground based site. The funding for a field campaign is outside of the scope of the present activity but, in parallel to the activities described here, we will seek flight opportunities and funding from other bodies such as the ESA, EU and NERC.

III. The "Elegant Breadboard" programme

The objective of this breadboard programme is to demonstrate a fully operational instrument and to address the majority of the outstanding technical and interface issues. The 1.15 THz breadboard receiver currently being developed in parallel will be made available for integration with the breadboard. We do not anticipate the 4.7 THz channel being available during the course of the proposed programme, although the breadboard will be designed to accept it. We further assume that the spacecraft Command and Data Handling System (CDMS) will be simulated by a standard computer system and the spacecraft power system replaced by laboratory power supplies.

Three major performance and interface issues will be tested and verified by the proposed elegant breadboard:

A. An all-Alluminium antenna

The employment of an all-aluminium antenna operating over the 2-375 m wavelength range. It is more usual to employ separate instruments to cover the different wavelength ranges used in LOCUS. Our approach of using a single antenna system to encompass both THz and IR channels is highly innovative. Designing and building the antenna will demonstrate that a single highly compact instrument can cover an ultra-broad spectral wavelength range. Moreover, it will prove advanced UK manufacturing techniques and the low cost mission approach. A commercial IR detector operating at 5.3 μm (the NO channel) will be purchased and integrated with the antenna and the pre-existing 1.15 THz receiver. A test facility will be built to allow comprehensive testing in the IR and THz ranges to both prove the performance of the antenna as a component, and demonstrate the novel nature of the LOCUS payload as a system.

B. A low power digital wide band spectrometer (WBS)

A digital WBS based on high speed ADCs and a FPGA processor has been built and demonstrated in the context of various terrestrial instruments. While the current WBS has excellent performance characteristics, the limited electrical power available on the SSTL spacecraft means that the use of only one WBS unit is practical, thus reducing the overall bandwidth that can be covered. A new radiation tolerant

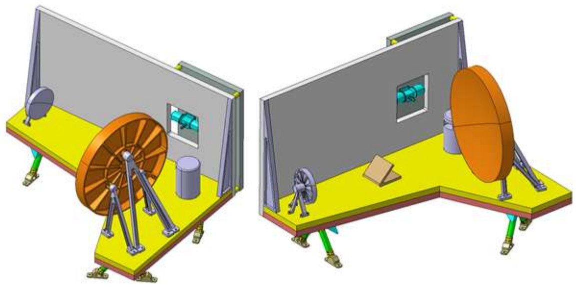

Fig. 3. Two views of the structural layout of the proposed LOCUS elegant breadboard. Note the cooler mounted on a separate radiator, the thermally isolating supports for the optical bench and the three point mount for the primary mirror.

FPGA family from Microsemi can potentially reduce the power consumption by a factor of two. Current CEOI-ST funding is being used to build a complete WBS subsystem using a Xilinx FPGA. The funding obtained for this activity will be used to reduce the power consumption by a factor of two using a Microsemi FPGA.

C. Thermal stability of the LOCUS payload

Standardised spacecraft such as provided by SSTL provide a cost efficient method of accessing space and are the platform of choice for the deployment of the LOCUS payload. However, there are significant limitations on the payload interfaces such as the power available and, in the case of LOCUS, the thermal stability of the sensor element due to the minimal amount of thermal shielding. LOCUS will be the first actively cooled payload to be deployed on an SSTL style spacecraft and it is therefore imperative that the thermal performance of the system be fully investigated and verified before committing to the flight programme. The breadboard that we will build will be as close to thermally representative as possible and will undergo a full evaluation of the thermal stability using an engineering model mini-cooler provided by RAL Technology Department.

IV. CONCLUSION

Study of the Earths atmosphere is essential to improve understanding of climate change and its causal relationship to society, future generations, and the economy. Variations in MLT thermal structure and distributions of critical constituents act not only as indicators of anthropogenic climate variation but also mediators of those of solar origin. Remote sounding through advanced instrumentation is a key objective, and the strategic development of related detection technology builds upon UK scientific and technical strengths, advances UK scientific leadership and technical prowess, and ensures that the UK remains at the leading edge. Our project takes advantage of the considerable UK strengths and expertise in antenna design, novel engineering, THz, IR, digital electronics, and cryo-cooler technology. It also provides wider potential benefit and space use through device and system technical evolution and exploitation of relevance to a broad range of scientific disciplines. For instance, THz spectroscopy is essential for sounding of the key chemical species in the dense atmospheres of the Giant Planets and potentially the atmospheres of Mars and Venus.

There is also strong industrial interest in applying THz sensors to weather monitoring and forecasting, communications, security surveillance, biological sensing, medical and plasma diagnostics, and laboratory based spectroscopy for industrial process control, materials examination and local pollution monitoring. Each of these topics has excellent growth potential through both space and ground-based industrial exploitation, and all represent opportunities for delivering a financial return to the UK.

ACKNOWLEDGMENTS

The work presented here is funded by the UK Space Agency through the Centre for Earth Observation Instrumentation and Space Technology (CEOI-ST). For more information on the CEOI-ST activities visit *www.ceoi.ac.uk* .

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