Recent progress in the Elegant Breadboard supra-THz activities for LOCUS and a view to an astronomy application.

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***Abstract*—We report on ongoing technology activities on the Elegant Breadboard for the LOCUS telescope and its 1.15THz receiver. LOCUS is a Low-Earth orbit small satellite (150kg category) with the objective of linking observations of climate, the upper atmosphere and space weather by performing simultaneous high spectral resolution measurements of molecular signatures of molecules which drive the thermal exchange in the highest layers of our atmosphere. These measurements are performed both in the THz frequency region and in a photometric narrow-band near and mid-IR channels allowing to decouple molecular abundances from temperature and pressure profiles.**

The elegant breadboard under development will reproduce representative optics and explore the thermal implications of a compact optical-bench with a small cryo-cooler and radiator stage for a small LEO satellite. An extensive test programme will be undertaken to raise the payload and receiver system and we will seek opportunities to test the system in an observational campaign. Technology developments will benefit future technology activities related to both a future Earth-Orbit mission and potential astronomy missions.

***Index Terms*—THz receivers, Earth Observing, Optical Breadboard, QCL**

I. INTRODUCTION

The Mesosphere Lower Thermosphere (MLT) is a region of the Earth's atmosphere which lies at the interface between Earth's atmosphere and the space weather phenomena ($\sim 55-90km$ the Mesosphere and $\sim 90-150km$ the LT). From above the MLT is influenced from the flow of solar radiation and energetic particles which is also modulated by solar activity, while from the lower end it is balanced by energy transfer from the lower region of the Earth's atmosphere [1]. The detailed physics of the chemistry processes taking place in the MLT are poorly understood, however, because this is the least well-observed region of the atmosphere.

Global radiative balances have been computed based on thermal IR measurements but with little detail of its exact chemical composition a complete picture cannot be formed. Observations which have been performed in these bands and that show decreasing temperature values is a predictive indication of climate change and potential anthropogenic effects as the mesosphere cools in response to increased greenhouse gas concentrations. In order to unequivocally interpret thermal fluctuations, a direct measurement of chemical species which can be observed via molecular transitions in the THz regions are needed.

Previous missions (SABER-TIMED) have in the past indirectly measured the main constituent (atomic oxygen) of the upper MLT dominates from IR measurements [2],[3] of ozone chemi-luminescence which in itself relies on theoretical reaction rates. The LOCUS mission goal is to directly measure atomic oxygen by heterodyne detection, as well as simultaneously measuring the thematically linked trace gases CO, CO2, NO, O3 and OH, several of which present novel measurements in their own right. LOCUS does this by combining THz and narrow band IR channels, therefore providing a more complete picture of mesospheric transport and thermal structures.

The overall mission objectives of the LOCUS satellite as proposed for the EE9 ESA call, can be summarized as:

1.Energy Balance, 2.Noctilucent Clouds (NLC), 3. Energetic Particle Precipitation, 4.Improved MLT models (foir climate and weather prediction).

II. The LOCUS mission concept

The LOCUS mission concept moved from a Phase 0 ESA-sponsored study as a candidate mission for the IOD (In-Orbit Demonstration) of supra-THz technology. This fitted the requirements of a small payload for a 150kg category satellite. The latest EO proposal submitted (2016) allowed the LOCUS concept to undergo a review of the science and strawman concept design.

The conceptual design of the LOCUS mission (payload and platform) stems from the scientific requirements.

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. This target altitude is inaccessible for direct measurements globally and in a repeated fashion due to residual atmospheric drag being prohibitive for orbital in-situ sampling. The MLT is also above the reach of long duration (Stratospheric) balloons. As a consequence remote-sensing in the form of Limb-Sounding is required to yield the desired vertical resolution to infer the distribution of the main target species.

Hence on this limb-sounding LEO platform a payload is required to electromagnetically directly detect the atoms and molecules which are the primary targets of this mission (O, OH, O2, NO) and possibly CO. In order to do this, the relevant emission lines need to be detected with sufficient spectral resolution to infer additional pressure and temperature information. The platform considered for the previous IOD study and optimal for its heritage and overall payload mass allocation is the SSTL-150 bus, which has flown on a number of missions since 2005.

For our primary species (atomic oxygen) two emission lines can be used (4.7 and a weaker 2.1 THz).OH also has very few spectral emission lines, the strongest ones at 2.5 and 3.5 THz respectively. The third target species that has its strongest transitions in the THz range is HO2. Other target species (i.e. H2O, O3, O2, NO, CO) have a more ubiquitous choice of transition lines from sub-millimetre up to THz wavelengths. High spectral resolution at these frequencies can only be achieved by heterodyne detection, which uses a local oscillator to down-convert the high frequency atmospheric signal to a low-frequency signal which can be digitized and electronically processed.

The scientific target therefore calls for a heterodyne radiometer at THz frequencies using high-resolution spectrometers complemented in the case of LOCUS with a set of infrared detectors to measure the thermal emission of key species in addition to abundance measurements from the THz instrument.

In the past heteorodyne receivers in the THz range are generally large and power hungry and require a larger and more expensive spacecraft design.

LOCUS aims to address the above limitations by making use of a number of recent technological advances to achieve a compact and low-cost payload design which can perform such measurements.

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

Centre λ (μm)	Bandwidth (μm)	Species Covered	Required Detectabililty ($Wcm^{-2}sr^{-1}$)
4.35	0.153	OH	$1.3x10^{-9}$
5.41	0.309	NO	$2.5x10^{-9}$
9.39	0.672	O_3	$3x1.10^{-8}$
15.14	3.594	CO_2	$2.8x10^{-8}$
15.2	0.632	CO_2	$1.7x10^{-8}$

TABLE I

THz receivers and IR channel updated designation. The spectral resolution for all THz receivers is set at 3 MHz from the science requirements

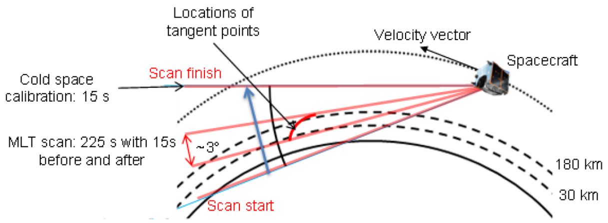

Fig. 1. LOCUS scanning strategy. LOCUS will operate as a limb scanning radiometer. This will be achieved with a fixed antenna, the spacecrafts AOCS will drive the scan of the boresight of the instrument up through the 30-180 km altitude region. During the scan the payload will make 75 observations with 3s integration times which result in a vertical spatial resolution of 2 km. The scan will finish with an observation of cold space for calibration purposes after which the spacecraft will reorient itself to begin another scan.

LOCUS would be launched as an auxiliary payload to a Sun Synchronous Orbit (SSO). A major mission level trade is the selection of the mission orbit taking into account the likely launch opportunities available for an auxiliary payload, compared to the requirements arising from the science interest in the MLT. Although, a non-SSO orbit would be ideal for the science measurements as it allows observations over a range of local times and latitudes, the cost implications (both in terms of spacecraft design and launch costs) mean that a typical mid-morning SSO has been selected as a baseline option. This allows the minimum of changes from heritage SSTL spacecraft as platform, as well as maximising launch opportunities.

The majority of the ground infrastructure will be existing SSTL ground stations (Guildford and Bordon) and Mission Control Centre (Guildford) with the Payload Operations Centre located at the Rutherford Appleton Laboratory (RAL) in Harwell (part of the Science Technology Facilities Council (STFC) site at that location).

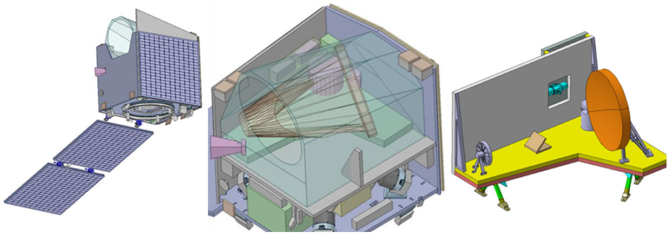

Fig. 2. Structural design of the LOCUS satellite as intended in the IOD study and proposed for the EE9 mission concept .

III. INSTRUMENT CONCEPT

Having identified a potential ideal platform for LOCUS, the challenge was to design a telescope (which for the first time combines THz and mid-IR receivers in the same focal plane) and which would fit within space and mass requirements of a small satellite (SSTL-150 initially considered a requirement set in the IOD mission definition).

The material to be used for the telescope mirrors is polished Aluminum. The quality of a polished Al sample of the mirrors has been tested in IR spectrometers as part of the elegant breadboard program and yielded a 96% efficiency at the lowest wavelength end ($2.5\mu m$) and higher everywhere else.

A first mechanical concept of the optical assembly is illustrated in figure 2. 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 THz receivers need to be cooled to temperatures below 100 K achieved using a space qualified close cycle Stirling cooler (or coolers) mounted close to the receiver housing on a dedicated radiator.

Scientific definition of the THz lines of interest identified the micro-windows as shown in Table 1 together with requirements on the IR channels were derived from those used in the NASA SABER [3],[4] instrument currently in orbit. For each band of interest a single THz receiver front end comprising a Schottky barrier diode mixer, local-oscillator, low noise amplifier (LNA) and a subsequent stage of room temperature of IF amplification. The output is then down-converted and fourier-transformed by a digital FFT spectrometer which samples the IF output and provides a power spectrum of the incident THz signal. The desired resolution of the spectrum is 1MHz for a 2GHz bandwidth, but the band can be increased at the expence of spectral resolution. This Wide Band Spectrometer (WBS) (in Fig.3) is based on the use of fast ADCs coupled to an FPGA which performs the FFT.

The heat dissipation from the 100-K stage of the THz receivers is mostly due to the Quantum Cascade Laser (QCL)[**?**] acting as Local Oscillators (LO) for the novel 4.7THz and 3.5 THz receiver development (Band1 and Band2). The cooler baselined for this stage is the RAL mini-cooler [REF] which has undergone successive developments as a tactical cooler for small satellites. These closed-cycle Stirling coolers lift $\sim 1W$ at $100K$, weigh $\sim 600g$ and consume 15 W making them extremely suitable for deployment on a low-cost small platform.

IV. ELEGANT BREADBOARD PROGRESS

The 8th call of the UKSA CEOI program has supported the development of a breadboard on which to test the full optical chain for a single receiver. 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 receiver chosen for this development is the more mature 1.15 THz currently being developed in parallel with the 4.7 THz one under a different prgroam.

The major components of the ongoing breadboard are the all-alluminium telescope, the single-block integrated QCL and mixer, and the low-power digital WBS spectrometer.

A. An all-Alluminium antenna

The approach of using a single antenna system to span the entire wavelength range for both THz and IR channels is highly innovative. The requirement for the antenna to fit in the reduced volume envelope of the SSTL-150 constrained the overall primary-secondary distance. With this in mind the optimal design chosen to also allow a relatively decent size focal plane size which could be used for the set of THz and IR receivers lead to a Cassegrain design with a Primary sized to $\sim 480mm$.

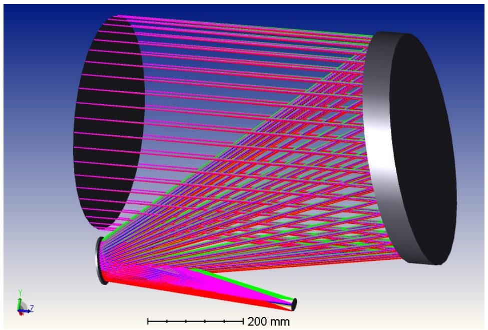

Fig. 3. Telescope rendering for the Cassegrain design.

Mirror	Size (ellipse axis) (mm)	R_C	Distance to next surface	k (conical constant)
M1	492.54x480.16	1557.227	650.0	-1.000
M2	101.14x100.4	368.567	425.0	-3.497

Telescope working $F\#$	5.768
Focal Plane Scale	1.32'/mm
Focal Plane Size[1]	25 mm (33')

[1] Diameter of the region with enclosed energy $[r < 0.5mm] > 98\%$.

TABLE II
BASIC CHARACTERISTIC OF THE MIRRORS AND OVERALL TELESCOPE DESIGN.

At the focal plane of this telescope, the 1.15THz receiver will be positioned within a small existing cryostat. In addition, a commercial IR detector operating at $5.3\mu m$ (for the NO channel) will be purchased and integrated with the antenna.

B. The optical bench

The mechanical optical bench that houses the elegant breadboard is designed to locate both the telescope mirrors and mounts as well as the cryostat housing the THz receiver, the cooler and the radiator panels. In figure 4 one can see the layout of the breadboard with the separate radiator panel designed to dump the power generated by the cooler.

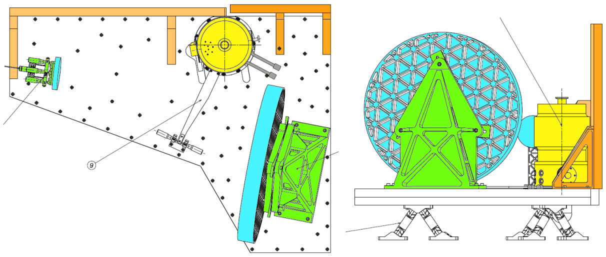

Fig. 4. Layout of the breadboard. Highlighting the mirrors (blue) their supports (green), the cryostat (yellow) and the radiator panels (orange).

The all-aluminium breadboard provides the location for all optical elements and the detector cryostat, with additional fine-tuning possibilities for the secondary mirror and cryostat positioning. The thermal simulations and testing are key element of the elegant breadboard to validate the 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.

C. The split-block integrated receiver.

The receiver block developed for this testbed (1.15 THz channel) combines the machined horn (diagonal currently) and waveguide leading to the Quantum Cascade Laser local oscillator. There are currently different designs of the split block being explored in the light of different LO technology and mixers as well as improved horn design.

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

A digital WBS based on high speed ADCs and an FPGA processor has been built and demonstrated in the context of various terrestrial instruments. The limited electrical power available on the SSTL-150 reduces the allowance to a single WBS unit, decreasing the overall bandwidth that can be covered. A new radiation tolerant FPGA family from Microsemi can potentially reduce the power consumption by a factor of two.

V. ASTRONOMY APPLICATIONS AND CONCLUSIONS

In order to improve our understanding of climate change and its causal relationship to society and future industrial developments, the study of the variations in the MLT thermal structure as well as the distributions of critical constituents is critical as indicators of anthropogenic climate variation [4] but also mediators of those of solar origin.

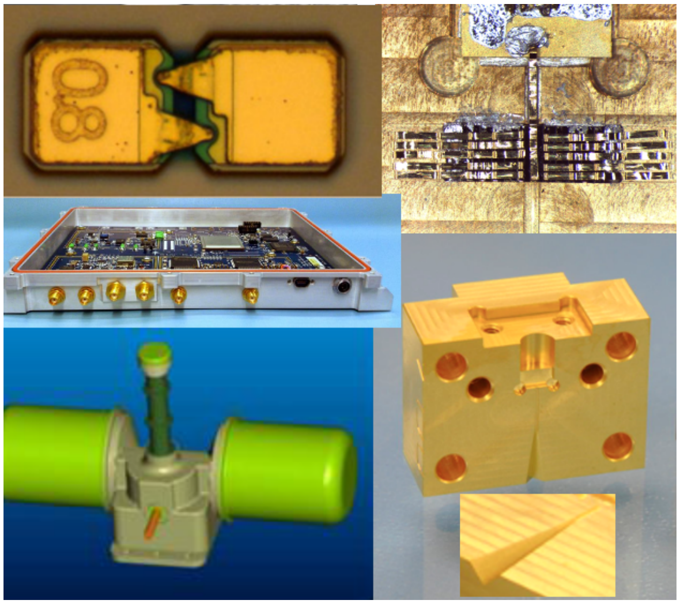

Fig. 5. (TopLeft) RAL THz Schottky barrier diodes, (Middle Left) The Star-Dundee WBS board; (TopRight) The QCL inserted directly in the split block;(BottomLeft) The RAL mini-cooler which provides a cooling power of $\sim 1W$ at 100K;(BottomRight) Open split-block with enlarged view of the diagonal horn machined directly on the block

Remote sounding through advanced instrumentation is a key objective, and the strategic development of related detection technology builds upon UK scientific and technical strengths. Our project takes advantage of the a number of recent technology advances in attempt to combine these in an In-Orbit-Demonstrator concept mission which can deliver much needed state-of-the-art atmospheric data whilst accelerating technology readiness levels of hardware which can readily be employed further in Earth Observing but also astronomy and astrophysics based mission concepts. THz spectroscopy is in fact essential for sounding of the key chemical species in the dense atmospheres of the Giant Planets and potentially the atmospheres of Mars and Venus. A number of these same atomic and molecular line features have also been abundantly observed in star formation complexes in our galaxy and the need for more extensive coverage of our galactic plane as well as in nearby galaxies is already been demanded by the community and considered for an upcoming medium class ESA mission (FIRSPEX).

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