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Cold Atom Space Payload Atmospheric Drag Mission (CASPA-ADM)

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ABSTRACT

To gain better understanding of the upper atmospheric dynamics requires more accurate determination of the mass density distribution in the thermosphere. Improved measurements of drag, by means of satellite accelerometery, can be used to more precisely determine this distribution. In addition, atmospheric drag in Low Earth Orbit (LEO) is particularly of interest for climate modelling, weather forecasting and satellite orbit prediction. RAL Space, Teledyne-e2v and the University of Birmingham are developing a Cold Atom Space Payload Atmospheric Drag Mission (CASPA-ADM). The aim of the project, supported by the UK Centre for Earth Observation Instrumentation (CEOI), is to develop a technology demonstrator based on Cold Atom Interferometry (CAI) to take sensitive measurements of atmospheric drag. The underlying CAI technology has been previously flown on the Chinese Space Station, the International Space Station, and in sounding rockets. However, it has not yet been used as the fundamental sensor technology in a free flight space mission. The team is producing a space-suitable accelerometer that can be embedded in small satellites such as 16U CubeSats and are addressing the engineering challenges associated with space qualification and miniaturisation, while keeping the performance level of systems with larger Size, Weight and Power (SWaP)

INTRODUCTION

The Thermosphere is the layer of Earth's atmosphere that stretches from an altitude of 100 km to approximately 600 km and is commonly where most of the satellites orbit. Low Earth Orbit (LEO) is an altitude of great interest for new constellations like Starlink (SpaceX, 12000 satellites planned) or Kuiper (Amazon, 3236 satellites proposed), together with the International Space Station (ISS). It is a highly variable region, which is driven to a large extent by solar extreme ultraviolet emissions and the interaction of the solar wind with Earth's magnetosphere[5], resulting in atmospheric density variations and high-altitude winds. However, it is not widely understood. Satellites operating in LEO, providing communication services and Earth observation data, are greatly affected by the atmospheric drag in this region. With the advance of small satellites, the number of objects in the Thermosphere will drastically increase in the coming years, increasing the risk of collisions. To better predict the orbit trajectories, avoiding collisions, accurate accelerometers have been used on satellites in LEO. Studying the atmospheric drag those satellites experience due to solar and Earth radiation pressure, atmospheric density variations and high-altitude winds. Technology based on classical physics has the risk of short-term drifts, relying on the electrostatic principle and requiring calibration, typically via GPS[7], for example in the Swarm Satellite Constellation mission[8]. More accurate observations of this atmospheric density are needed to improve models of the thermosphere and better predict satellite orbits, contributing to mission planning, lifetime prediction and collision mitigation. The use of quantum technology overcomes the problem of drifts by interrogating atoms, that act at the same time as, perfectly repeatable, inertial test mases as well as absolute frequency references. Thus, allowing for an absolute measurement with high accuracy.

As a result of a previous study[1], it became apparent that the suitability of the previous development of a Cold Atoms Space Payload (CASPA)[9], together with the added functionality of accelerometery sensitivity provided by a Cold Atom Interferometer (CAI), would fulfil the scientific requirements for the proposed mission.

The accelerometer technology at the heart of this mission, which has seen rapid development in recent years, has already been used in space, on space stations[2,3] and during a suborbital flight of a sounding rocket[4]. However, these missions have used CAI technologies for the basic understanding of the technology itself. CAI has not yet been used as the main sensor technology in a space mission. CAI relies on the trapping and cooling of a vapour of atoms inside an Ultra-High Vacuum (UHV) so that the atoms exhibit a wave-like behaviour, required for interferometry. The first stage is a Magneto-Optical Trap (MOT) which is achieved using lasers tuned close to the frequency of the atoms' energy levels applied orthogonally in all 3 axes and a magnetic field. Atoms are slowed and trapped until they are almost stationary, at temperatures of ~200 μK[6]. After this, the magnetic fields are switched off and a short (∼10 ms) optical cooling phase, known as "optical molasses", is applied to cool the atoms down to ∼2 μK[6]. The cloud of cold atoms is left to freely evolve over a period of time to form a matter-wave Mach-Zehnder type interferometer[10] that is extremely sensitive to accelerations. The phase difference between the two interferometer arms, imprinted by three laser pulses, changes proportionally to the acceleration of the atoms with respect to the laser reference frame. The phase at the output of the interferometer is determined by the probability of detecting the atoms in their ground or excited state. The acceleration of the atoms relative to the laser is therefore measured by reading out the number of atoms in each internal state using laser-induced fluorescence imaging.

This project brings together a consortium of UK organisations who lead the commercialization of quantum sensors and have a well-established heritage in delivery of space applications. This project directly addresses ESA's ambition for a near-term cold atom pathfinder mission that can establish quantum sensors in space for the first time.

MISSION CONCEPT AND OBJECTIVES

The applications of Cold Atom Interferometry (CAI) on Earth have been demonstrated in many projects. In order to de-risk a future space mission, this project aims to develop a breadboard of the CAI Accelerometer satellite payload that will measure acceleration and will develop technologies for future missions with better accuracy and lower noise. The satellite attitude must be kept such that the accelerometer constantly points along track and therefore must constantly rotate (pitch) at a rate of approximately 1 mrad/s. The rotation in the roll direction is, in principle, only limited by the optimum orientation of the solar arrays with respect to the sun.

The CAI Accelerometer breadboard resulting from this project has two objectives; to fulfil the requirements needed for an atmospheric drag measurement mission and to develop the relevant technologies required to progress to future CAI accelerometer missions. To fulfil the first objective, the mission should measure the acceleration within the expected range for the orbital altitude of 300-400km, with the smallest signal strength being $3x10^{-8}$ m/s^2 (highest altitude, lowest solar activity) and the greatest signal strength being $1.1x10^{-5}$ m/s^2 (lowest altitude, high solar activity). The signal will be measured every 10 seconds, which may include multiple CAI cycles in order to average down the noise and will give an absolute value of acceleration. The pitch of the satellite during its orbit causes a reduction in interferometer contrast that constrains the interferometer duration.

It has been determined that an optical molasses cooled system would be sufficient to achieve the required performance and would enable a low SWaP solution compatible with a CubeSat platform. The use of an atom chip is desirable to enable an increase in performance for future CAI missions and to allow the noise requirements to be reduced. An atom chip allows for further cooling, down to Bose-Einstein Condensation (BEC), with low SWaP, which would substantially increase the performance of the system; however, this would increase complexity and compromise the compatibility with a CubeSat platform with the current technology. There is, therefore, a trade-off to be made between the system meeting the requirements for acceleration measurements for an ADM mission while being designed to allow for future development without needing to completely change architecture.

The current concept aims for a modular design, where appropriate, to allow for the expansion of the system (such as the addition of a 2-dimensional MOT pre-cooling stage, and the utilisation of the atom chip for evaporative cooling to achieve BEC). The addition of these systems at a later date should not require a complete architecture re-design. The University of Birmingham will perform a functional test to achieve an acceleration measurement; however, further cooling of the atoms to BEC is beyond the scope of this phase of the project.

PAYLOAD

The accelerometer payload consists of 3 subsystems, the atom chip, the laser system and the physics package.

Atom Chip

The magnetic fields necessary for a CAI Accelerometer are often complex and require large SWaP devices. However, this project utilises an atom chip, which generates the majority of the necessary magnetic fields. An atom chip based design allows for a lower SWaP instrument with built-in capability to extend to Bose-Einstein Condensate (BEC) generation for future missions for increased performance. The atom chip, which is developed at RAL Space, is the second generation of atom chips designed and built in-house. It is composed of several current carrying structures able to generate the required magnetic field gradients needed to operate a MOT and have the capability of creating a Magnetic Trap (MT) for future development. The design of this device is such that inductance is minimised, improving the speed in which magnetic fields can be altered. In addition, as the field is generated very close to the location of the atoms, the absolute magnitude of the required fields is smaller than the one required if using standard coils, therefore the electrical power required is also minimised.

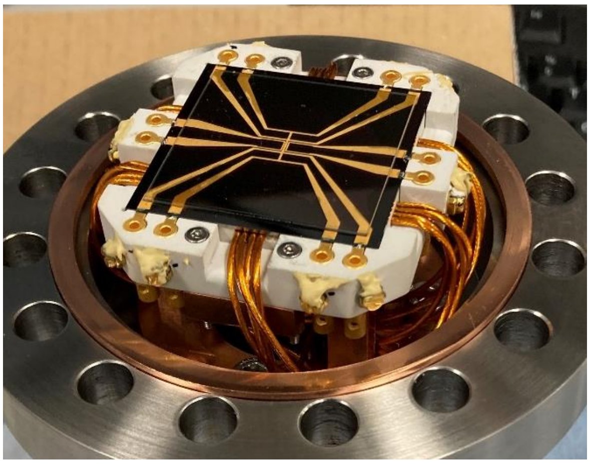

Figure 1: Photograph of the second generation of atom chip developed at RAL Space (STFC-UKRI).

The chip comprises two sets of structures, a macroscopic wire-based (a H structure) and a set of microscopic, on silicon “inscribed”, Z wires. The H-wires are arranged in two layers separated by a ceramic spacer that allows correct alignment of the wires and provides support to the silicon chip. The microscopic Z structures are gold filled trenches engraved in the silicon chip. In addition, there are two U- shaped RF antennas also engraved in the chip to allow the possible utilisation of an RF field for evaporative cooling purposes. On top of the chip, a highly reflective surface (at 780 nm) is located permitting the implementation of a mirror MOT using 4 (or 2 retro-reflected) laser beams, as shown in the diagram. The atom chip is mounted on a highly thermally conductive ceramic carrier. Bespoke electrical terminals have been designed for the microscopic Z structures. These microscopic Z structures are wire-bonded to the copper terminals that are bolted into position with screws.

The atom chip has been tested to the GEVS vibration levels, as well as thermally tested in vacuum up to a temperature of 200°C, successfully passing both tests. A similar atom chip is currently fitted to one of the quantum sensors experiments at RAL Space, where it has proven its functionality and advantages.

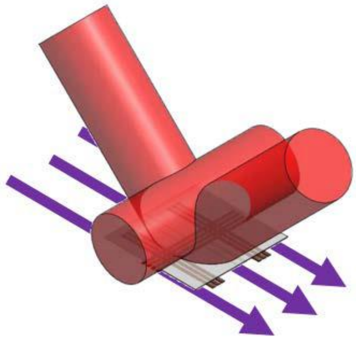

Figure 2: Schematic of a mirror MOT, depicting the required laser beams (in red) and the macroscopic H wires. Purple arrows denote the direction of the required external, homogeneous, magnetic field (bias field).

Laser System

The laser system will be based upon the frequency doubling of a telecom laser frequency, using a fibre Bragg grating approach to achieve the requisite frequencies for laser cooling and atom interferometry[11]. Of critical importance to this project is the development of a robust, space-compatible seed laser package for this system. The seed laser package integrates the laser diode package and associated drive electronics into a single module that can form part of a wider cold atom experiment and control system. The use of fully radiation-hardened space qualified components is beyond the scope of this project; however, the implementation architecture and choice of electronics components has been made with a clearly defined route to space applications. In most cases, this is likely to include components that are functionally equivalent to radiation-hardened alternatives or based around technologies or processes known to perform well in the space environment. As such, the resultant seed laser module is likely to be close in form and function to a version suitable for technology demonstration missions on a small satellite platform.

The seed laser module will use a dedicated experiment stack connector to share power supplies, communication buses and synchronisation signals between different modules in a wider experiment control system. An FPGA is used for the central logic to run the communication interfaces, control loops and circuit functionality. The frequency of a laser diode is influenced by the temperature of the diode and the current flowing through it, therefore, to stabilise the frequency both parameters need to be controlled. A high resolution ADC is used to digitise the laser diode temperature sensor reading, and a control loop modulates a TEC current to hold the diode temperature at a user-defined set-point. The steady state temperature stability to one standard deviation was measured to be 1.8 mK r.m.s.

The laser diode drive current is controlled using an analogue feedback circuit with a digitally controllable set-point; to minimise the current noise introduced by the modulation scheme it is envisaged a fixed hardware-configurable baseline current shall be defined with a smaller controllable modulation current range that is applied on top of this.

The integrated laser driver board shown in Figure 3 was first tested for functionality using a less sensitive laser diode. Then a RIO Planex laser diode was mounted in order to test the performance of the device. The seed laser module was installed in RAL Space Cold Atoms Laboratory in order to verify the linewidth.

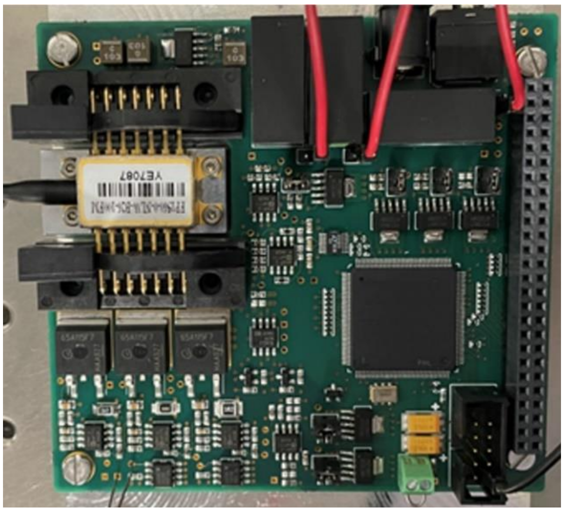

Figure 3: Prototype seed laser package with a 14-pin butterfly mounted laser diode.

Figure 4 shows a typical linewidth measurement. The measurement is taken by fitting the power spectrum of the beat note of the CASPA ADM seed laser against a reference laser (EYLSA EY780/MSA/NL) with a Lorentzian fit to the function in equation (1)

$$P = 10\ \log \frac{\frac{1}{2}\gamma}{(f - f_0)^2 + \left(\frac{1}{2}\gamma\right)^2} + P_0 \qquad (1)$$

Where the Power (P), in dBm, is given as a function of the frequency (f), f_0 is the frequency offset between the two lasers, P_0 is the peak power, and γ is the full width at half maximum of the power spectral distribution. The measured linewidth value was calculated by taking multiple measurements, extracting the value of the linewidth of that measurement (γ_i) and taking the mode of the distribution. This is required as the laser was free running and thus subject to drift, skewing the result. The spectral line shape of that beat note is the convolution of the line shape corresponding to the two lasers. Assuming that their individual lines are Lorentzian, the resulting line would be a Lorentzian with a width that would be the sum of the widths, therefore the width of the measurement gives us an upper bound to the unknown linewidth. As a result, it was obtained that the linewidth of the seed laser is $\gamma < 75$ kHz at 1 ms time scale. This is fully compliant with the frequency short term stability required ($\gamma_{req} < 100$ kHz) to fulfil acceleration measurement sensitivity requirements of the overall instrument.

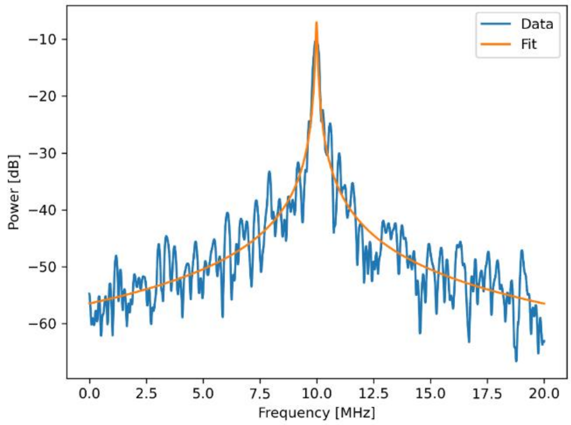

Figure 4: Power spectrum of the beat note between a laser of know linewidth and CASPA ADM's seed laser

Physics Package

The physics package comprises the UHV chamber, magnetic field coils, a magnetic shield, and the laser delivery optics. The vacuum chamber is currently under construction, with vibration and thermal analyses already complete. The atom chip will be fixed inside the UHV chamber. The seed laser will feed the demonstrator package optics, which will then feed into the laser delivery optics that are attached to the UHV chamber's viewports. In addition to the magnetic fields generated by the atom chip, a set of coils is necessary to generate a bias magnetic field that completes the quadrupole field generation. On top of that, two extra sets of coils are placed in the other two directions to compensate for stray fields. The magnetic coils are designed to serve three functions: to provide a constant bias field which in conjunction with the atom chip will provide the bias field gradient for Magneto Optical Trapping, to provide a bias field needed for interferometry and to provide a 3-axis compensation field to ensure required conditions for trapping and measurement. A magnetic shield has been designed to isolate the interferometry region from any external magnetic fields.

The physics package fits in an envelope of 205 mm (width) x 200 mm (length) x 270 mm (height), so a total envelope of 11.07 U (1 U=100 mm x 100 mm x 100 mm), as shown on Figure 5. The ion pump, necessary to maintain the level of vacuum required, sticks out of the sensor magnetic shield in order to provide a cleaner magnetic environment for the atom interrogation region. The envelope of the magnetic shield itself is 205 mm x 200 mm x 230 mm = 9.43 U.

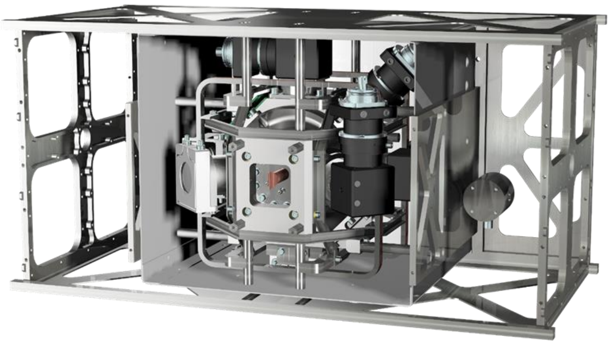

Figure 5: CAD rendering of the physics package inside a 16U CubeSat frame.

The weight of the physics package is 14 kg, including the shielding and the CubeSat structure. The physics package takes up 9.4U making the budget 14.1 kg, assuming a 1.5 kg per U budget. It should also be noted that the physics package contains most of the mass of the satellite, as the control system and laser system include PCBs that are inherently lighter for the space that they occupy. Hence, the satellite is within its initial overall weight budget of 24 kg.

The laser cooling beams, together with the magnetic field generated by the chip and the bias coils, generate a central force that traps the atoms at the centre of the MOT. To generate the trapping forces in all three directions of space, two retro-reflected beams are required. Cooling beam 1 is parallel to the atom chip and centred on the point where the atoms are intended to be trapped. Cooling beam 2 hits the atom chip at 45 degrees and its central ray is located in the plane passing through the centre of the MOT and orthogonal to Cooling beam 1. Cooling beam 2 delivery and retro-reflection design is shown on Figure 6. The Raman beam used for the interferometry is located in the same plane as Cooling beam 1.

Full vibration testing to the GEVS levels is planned to be carried out on the whole physics package. The structure will be assembled into a vibration jig for testing, which will be mounted in a similar way to how the CubeSat will be mounted in the deployer for flight.

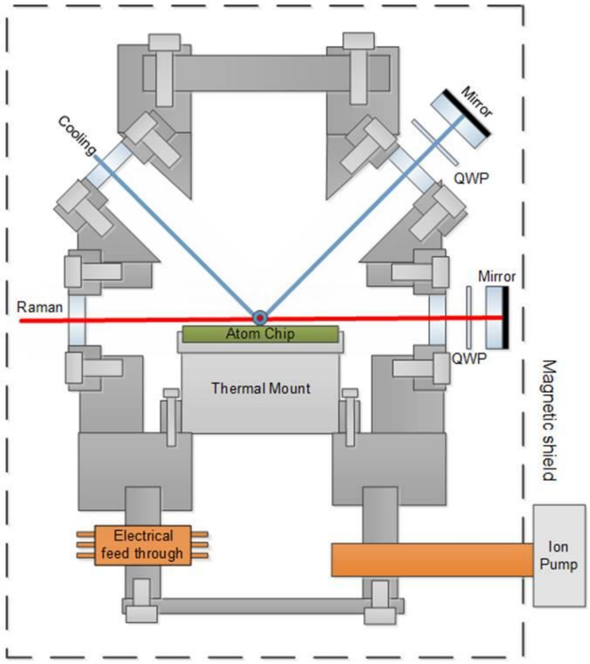

Figure 6: Schematic of the physics package. Optical ports on the vacuum chamber allow access to Raman and cooling retro-reflected beams. An atom chip (RAL Space), together with a pair of external coils, generates the magnetic field required to trap the ^{87}Rb atoms. A magnetic shield (dashed line) encloses the physics package.

ACKNOWLEDGMENTS

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