GSTP HIGH STABILITY LASER CONTROL MODULE

EXECUTIVE SUMMARY

	Name	**Signature / Date**
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1 Aims and Requirements

This project aimed to develop and test an integrated laser lock control module, with a clear route to space applications, that is capable of driving ultra-stable laser light sources for quantum technologies in a robust and automated manner. By designing the system from the outset with clear consideration of space component limitations and design processes the project aims to reduce the future development steps needed to reach to higher TRLs.

Most quantum technologies depend on stable and reliable laser light sources. For primary quantum technology applications such as atomic clocks, laser spectroscopy, gravity sensors and atom interferometry, there is a need for an ultra-stable laser, down to the 10^{-9} to 10^{-10} level.

The intrinsic stability of high-end scientific lasers do not provide this required level. To enable primary quantum applications an electronic feedback loop is required to lock the laser to an external reference such as an atomic/molecular spectroscopy line, a stabilised reference cavity or an external reference laser.

For terrestrial applications commercial off the shelf (COTS) equipment and components are used to achieve this. These systems are often comprised of individual units performing specific functions and typically require a high level of user input to manually find the correct locking point for the laser. For space applications there is a strong need to develop a robust set of electronics, suitable for the space environment, which is able to drive lasers whilst automatically finding and maintaining the required locking frequencies.

A tightly integrated solution will optimise the size, weight and power of the laser control system, whilst increases to the robustness, automation and usability of the system will open new exploitation opportunities in both space and ground-based environments.

Requirements
The Laser Control Module shall be capable of controlling suitable laser sources with a measured linewidth of < 1 MHz, with a goal of < 100 kHz.
The Laser Control Module shall be capable of automatically locking the master laser frequency to a defined Rubidium transition.
The Laser Control Module shall be capable of locking the slave laser to a defined offset up to 7 GHz from the master frequency, with a goal of up to 10 GHz from the master frequency.

2 Technical Overview

The High Stability Laser Control module consists of three core electronic sub-systems; a low-noise laser driver, automated spectroscopy lock controller and offset lock controller.

The low-noise laser driver is responsible for directly driving a laser diode with a controllable current whilst also operating a control loop to stabilise the laser package temperature utilising the integrated temperature sensor and thermo-electric cooler (TEC). Any changes to the laser drive current or package temperature affects the laser output frequency, making the output very susceptible to both short-term and long-term drifts.

The spectroscopy lock controller allows the laser frequency to be locked and maintained at a precise frequency corresponding to an atomic transition. The ability to independently find and lock to the appropriate atomic transitions in the spectroscopy signal is a key technological development to allow future deployment in space applications. Figure 1 shows the Rubidium absorption signal and the resultant modulation transfer spectroscopy (MTS) signal that is used as an error signal for locking the laser frequency.

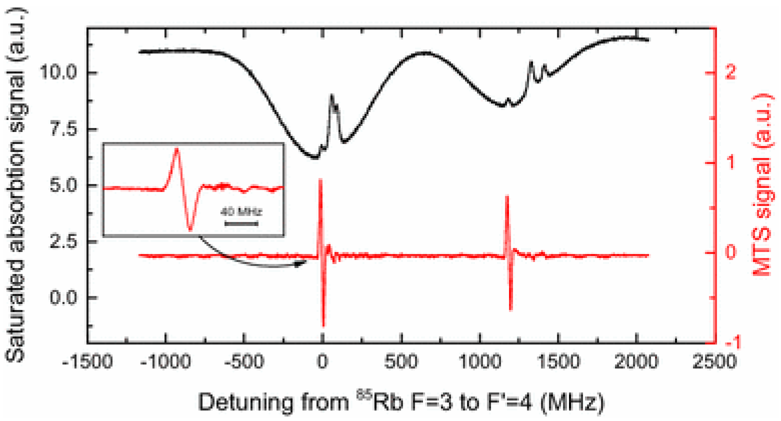

Figure 1: Example 85Rb saturated absorption and MTS signal.

"A Tunable Low-Drift Laser Stabilized To An Atomic Reference" Leopold, T., Schmöger, L., Feuchtenbeiner, S. et al. Appl. Phys. B (2016) 122: 236

Once the primary laser is locked to a known atomic transition, the output frequency of others laser sources in the system can be fixed at defined offsets from this, thus enabling them to precisely manipulate atoms during the experiment sequence.

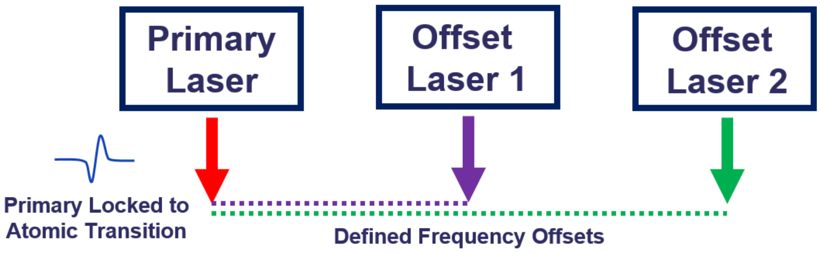

Figure 2: Defined frequency offset from a reference laser.

The work included within this activity has built upon expertise and prototype electronic modules developed as part of the MCLAREN consortium (Innovate UK/EPSRC - EP/R019304/1). The first phase of the project focused on the development of three core electronic sub-systems. These work packages made use of the MCLAREN prototype electronic modules, and additional bread boarding activities, to measure and characterise the effect key performance requirements have on the cold atom system performance.

Once these development work packages were complete, the technical effort switched to the design and manufacture of the integrated laser control module breadboard. This breadboard aimed incorporate all of the development steps and lessons learned identified in the previous work packages into a single module capable of fulfilling the technical requirements.

The core outcome from this project is the development of a breadboard for High Stability Laser Control Module that contains both Spectroscopy and Offset locking functionality into a single subsystem. The component selection process includes a clearly identified route to high-reliability space applications, whilst the breadboard component choices are broadly consistent with the choices for a short-duration technology demonstration mission.

Whilst no specific mission or payload form-factor has been selected, the breadboard design intended to demonstrate the overall volume that may be achievable.

The breadboard design is split into two halves that handle the Spectroscopy and Offset locking functionality independently. The Spectroscopy lock module provides a single reference laser, whilst the Offset lock module provides two independents laser outputs at a configurable offset from the reference.

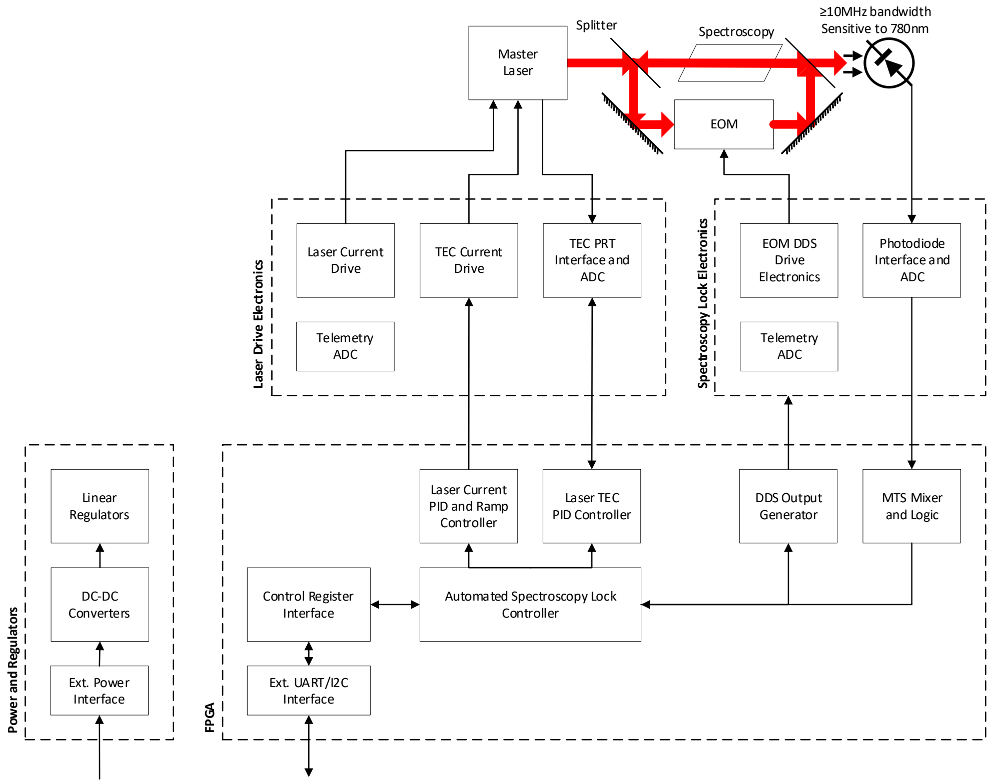

Figure 3: Spectroscopy Lock Subsystem Block Diagram

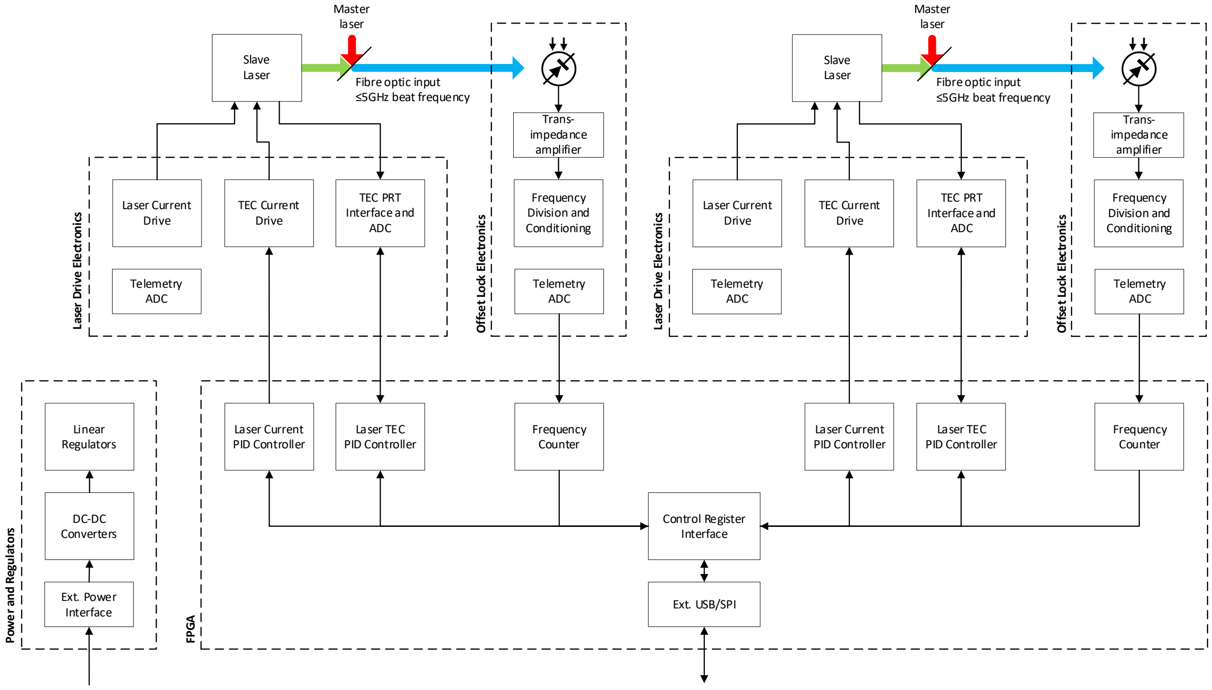

Figure 4: Offset Lock Subsystem Block Diagram

Whilst it is feasible to incorporate all breadboard functionality into a single FPGA, splitting in this manner provided a more efficient design solution and allows for additional Offset locks modules to be easily added to extend the number of available laser frequencies.

All of the required laser drive and temperature stabilisation circuity is incorporated within both PCBs. The laser diodes, in a 14-pin butterfly packages, are also mounted directly within the system. The breadboard has utilised low-insertion force sockets similar to those found on commercial drivers to allow the laser to added and removed without damage. Flight applications would likely incorporate direct solder connections and mechanical mounting. The thermal design and mounting of the laser diode is a key consideration; the control module breadboard has incorporated aluminium mounting plates with the stack to demonstrate a possible solution however this will likely require further iteration with wider system-level engineering in any future payloads.

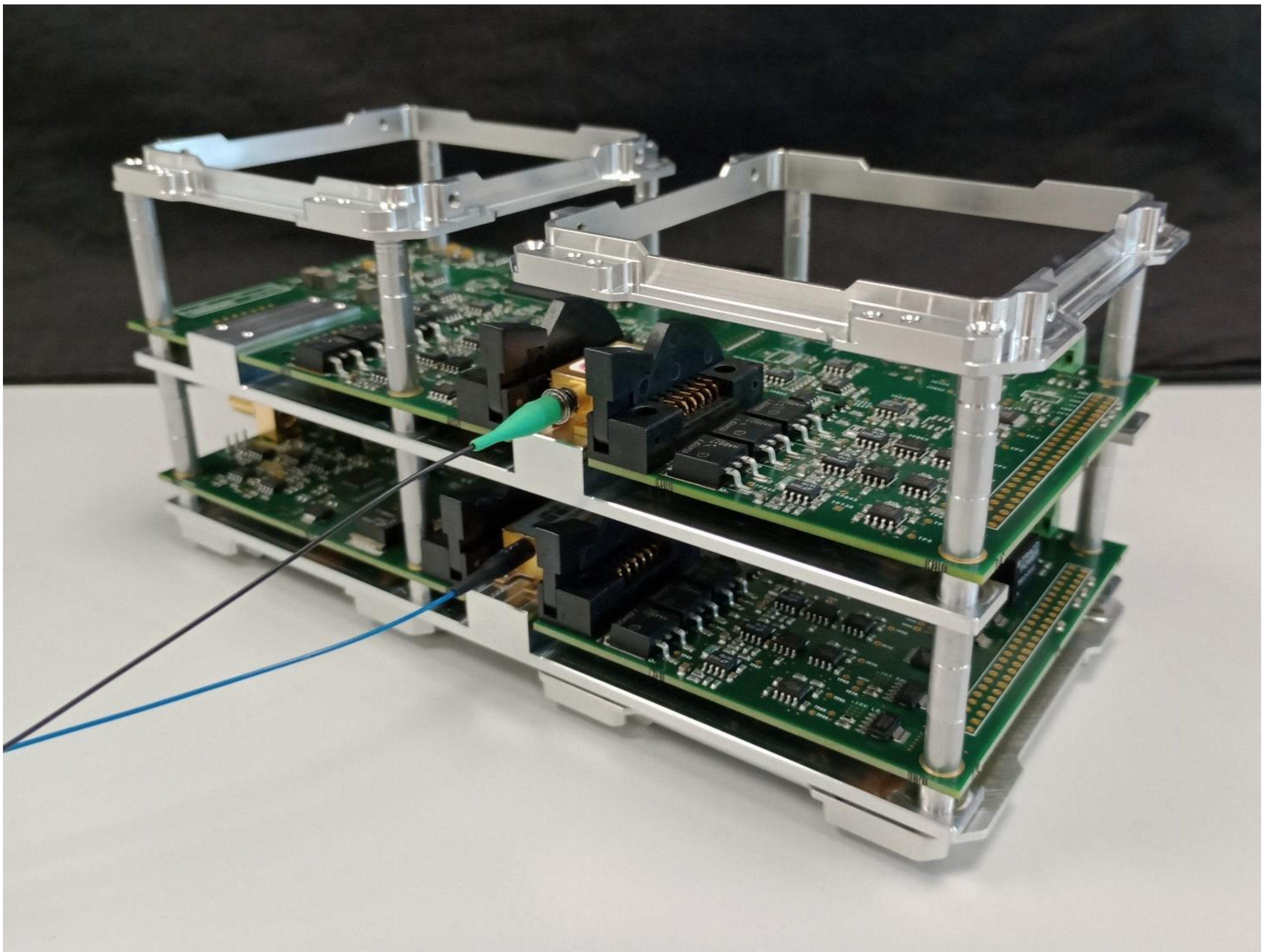

Figure 5: Complete High Stability Laser Control Module Breadboard

3 Characterisation Results

3.1 Laser Drive

Testing of the temperature control aspects of the circuit were first completed using a representative TEC, PRT & Heatsink combination to safely model laser package. An FPGA-based PID controller was written, using 16-bit integer and 16-bit fractional tuning parameters. To further improve noise performance the PRT was over-sampled with a rolling average window applied.

Once the prototype laser driver was installed within a laser-safe laboratory the temperature stability measured was re-run using the RIO PLANEX laser diode. This gave a temperature stability standard deviation of 0.029mK.

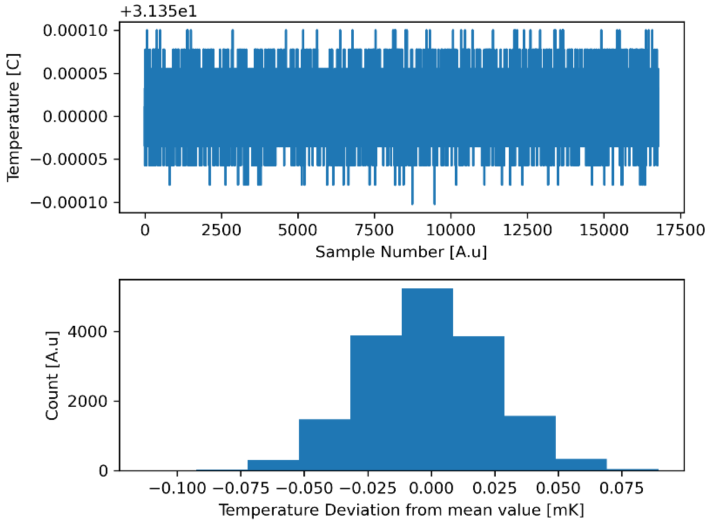

Figure 6 - TEC Temperature Stability

To measure the linewidth, the output of the laser was combined with a second frequency-locked reference laser of known linewidth such that the shape of the resultant beat note forms a Lorentz distribution where the full width at half maximum is the sum of the linewidths of the two lasers.

The development work used a high-performance RIO Planex Grade 4 laser diode with a spectral linewidth of <2kHz to enable characterisation of the drive electronics.

Using this measurement method the resultant laser linewidth (1ms) was found to be **73.54kHz**, however this figure also contains the noise contribution of the master laser, meaning the true linewidth is likely to be a further improvement.

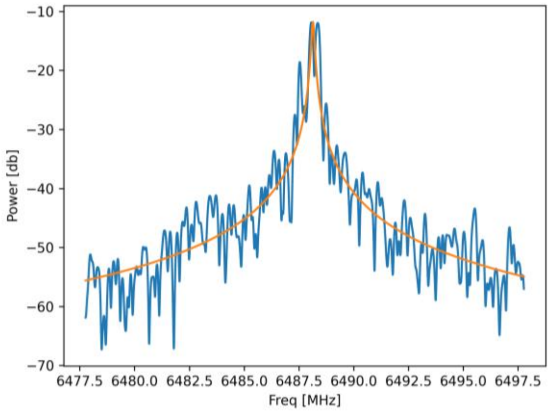

Figure 7 - Lorentzian Linewidth Fit

This work was conceived, in-part, due to the wide applications of laser driving technologies across different instruments. Outputs of this laser drive design activity have been used to form part of the HIROS instrument design baseline on the ESA SCOUT CubeMAP mission. Further testing of the design by the CubeMAP project team has demonstrated good correlation of the circuitry with a high-performance ground-based laser driver previously in use.

3.2 Spectroscopy Lock

Work with the RIO PLANEX laser diode has identified a relatively high degree of resilience to mode-hops, with consistently repeatable measurements, which have allowed the full 10 GHz absorption spectrum to be obtained within each frequency sweep.

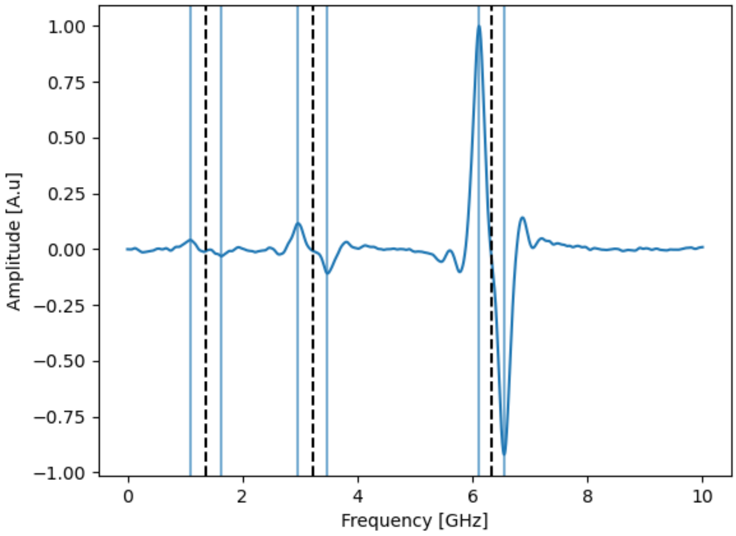

Figure 8 - Rubidium Absorption Sweep

This consistency has enabled a locking algorithm with relatively low computation complexity, more suited to space applications, to be achieved. By identifying the peaks and troughs in the MTS signal, and then characterising their relative amplitudes and frequency relationships, the required atomic transition can be identified. This offers increased tolerance to variation of the MTS signal as the relative relationship between transitions remains fixed, however it also offers less flexibility as finding the specified atomic transition relies on defining its relationship in the algorithm to the adjoining peaks/troughs.

The design iterations over the course of the project were primarily focussed on improving the signal to noise performance of the spectroscopy transitions, and in-turn increasing the number of identifiable transitions. The improved signal to ratio of the final breadboard is demonstrated in Figure 9, where the additional circuit elements to allow four Rubidium transitions to be observed in the signal.

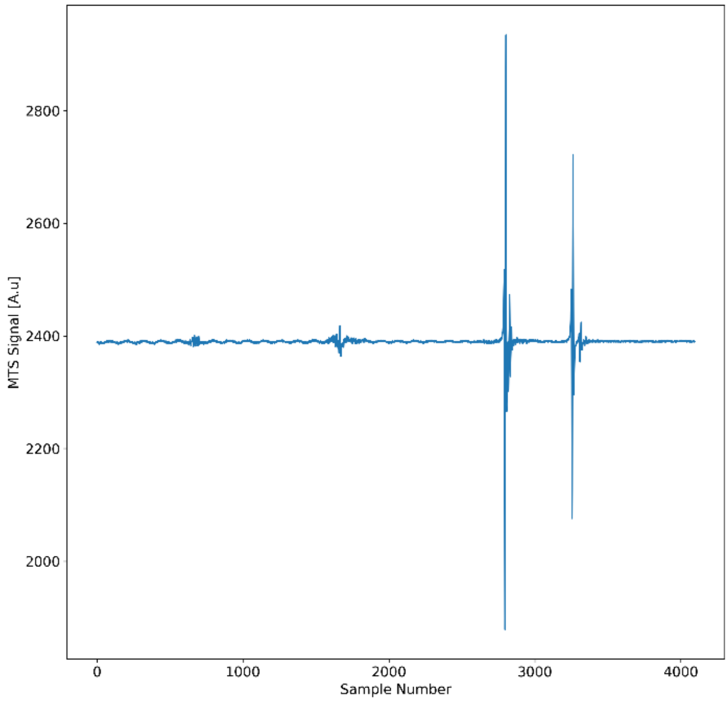

Figure 9: Spectroscopy sweep highlighting observable Rubidium transitions.

A PID controller was successfully integrated into the firmware to enable the breadboard to independently track multiple transitions. As a fully self-contained system, with a high control loop rate, this significantly increased the robustness of the lock. The system was able to retain the lock for extended periods (12+ hours) and overcome fluctuations in the laboratory environment that may otherwise have caused commercial systems to lose the transition. The frequency deviation of the spectroscopy lock out-performed the wavemeter measurement capability (~280kHz), however a first estimation the true performance of the system is that it likely lies in the 75 kHz to 150 kHz range.

3.3 Offset Lock

The final breadboard was used to characterise the performance of the offset lock over the desired frequency range up to 7GHz, with a goal of 10 GHz. The system demonstrated good performance in the key measurement range up to 8GHz, with frequency deviations of the locked output in the order of 200kHz. The final design iteration was not able to correct a design issue which intermittently affects the system's ability to lock below 2GHz, although the additional information obtained has informed a likely solution.

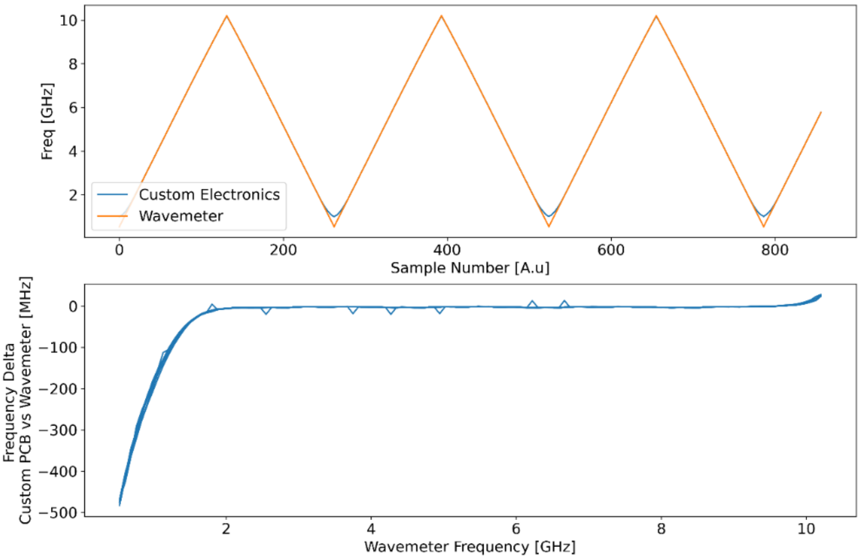

Figure 10 – Baseline Offset Lock Frequency Range Performance

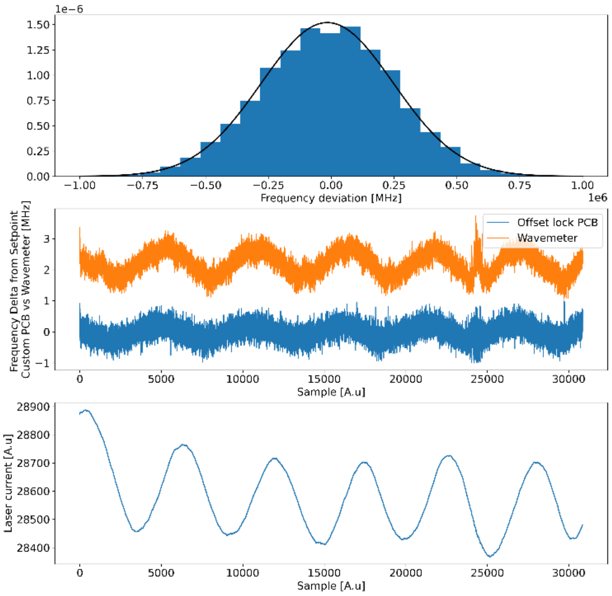

Figure 11: Baseline performance at 7 GHz setpoint requirement. 13 hour duration showing laboratory temperature variation. P=5e-07, I=5e-07, D=0,sample_time_PID=0.1, set point=-7000000000.0, sample period FPGA=1000000, div=64

4 Future Development Steps

The key performance parameters of the High Stability Control Module breadboard have been characterised in the laboratory environment. Whilst the electronics, in isolation, could be pushed further up the technology readiness levels it is likely developing complementary systems alongside it may offer improved overall performance and more holistic approach towards demonstrating the technology.

Characterisation work of the spectroscopy lock highlighted there was a high sensitivity to changes in the spectroscopy vapour cell and corresponding optical alignment for the test setup being used it the laboratory. In many cases, this was the limiting factor for the electronic system’s ability to find and maintain a lock on specific atomic transitions. For space applications, there is a clear requirement to develop a compact spectroscopy bench that is sufficiently robust to changes in the thermal/vibration environment. This work would also give a clear envelope on the expected variation of alignment, and corresponding optical power, for a given application and therefore allow the electronic system to be matched accordingly.

Integration of the high stability laser control module into a representative instrument or measurement sensor, whilst still in the laboratory environment, would enable the impact of different electronic performance parameters to be fully investigated. This would enable effort to be focussed on improving aspects that are impacting the true measurement performance and form the basis of a requirement set for future TRL-raising of a representative instrument.

The wider instrument control software system forms a key part of the automated transition identification aspects of the spectroscopy locking. Some aspects of the algorithm are better suited to higher-level processor driven architectures, as opposed to the timing-critical FPGA driven architecture that is used to maintain the lock. Development of a wider instrument concept would, in-turn, enable further development of the control software system to ensure this functionality is implemented at the appropriate level.

5 Conclusion

The High Stability Laser Control Module breadboard has been fully assembled and characterised in the laboratory environment (TRL 4) and has been shown to meet or exceed all of the key technical objectives. The technical developments completed as part of this project have already demonstrated wide applicability to other missions, including the HIROS instrument on CubeMAP (ESA SCOUT), and the technology is now well placed to continue development alongside wider instrument concepts.