Designing Avionics for Lasers & Optoelectronics

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Abstract

Unlike imagery-based Earth observation (EO) which has become very widely and cheaply available, gravity sensing EO has not yet emerged from its fundamental science roots. The challenge therefore is to develop gravity sensing instruments that can replicate the success of widespread imagery based EO. There are three main gravity sensing mechanisms under investigation: laser ranging (e.g., GRACE-FO [1]); atom interferometers, which measure gravitation perturbations to the wavefunctions of individual atoms; and 'relativistic geodesy' which uses atomic clocks to measure the gravitational curvature of spacetime. All three of these measurement systems use stabilised lasers as their main enabling technology. However traditional laboratory laser systems struggle to meet the robustness, reliability, or low size, weight, and power (SWaP) requirements for use in space.

A demonstrator was build that adapted telecommunications industry COTS components, and software radio FPGA/DSP techniques, to develop a new all-fibre space-qualified stabilised laser systems for geodesy that have equivalent performance to laboratory systems. This instrument was used to develop a 780 nm laser system that is stabilised to the Rubidium D2 line - the stabilised laser most commonly required by the quantum and atomic sensing field achieving sufficiently high laser performance for the laser system to be immediately useful for quantum applications (stability: 1-10 kHz, accuracy: 1 MHz); and in an ultra-compact package that has the potential to be used in space (1 litre, 0.5 kg, 10 W) [2].

This paper reports on the current student work that advances the instrument further towards a flight payload – and key avionics design considerations for future researchers. This takes lessons learnt from the ESA ESEO software radio payload in utilising ECSS design practices [3] to fabricate a robust and modular avionics back-end board that can operate with numerous front-end laser or opto-electronics configurations for different quantum applications.

The new board consists of a single PCB containing circuitry for TT&C reporting of power supply and voltage conditioning, the current and temperature electronics needed to control a diode laser on orbit, interfaces for photo detectors and opto-electronics, and a high-speed analogue-to-digital conversion network centred around a FPGA. As an example, digital signal processing performed frequency-modulated spectroscopy on a warm Rubidium vapour using an all-fibre optical arrangement.

Keywords
Laser, Optoelectronics, Avionics, FPGA

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1. Background

Gravity sensing mechanisms that range from optical atomic clocks and quantum gravimeter to laser ranging, all require multiple stabilised lasers with Hz-to-kHz resolution over GHz as their enabling technology. Optical atomic clocks are the key payload to evaluate the gravitational time dilation effect by interrogating laser-cooled atoms at an ultra-narrow optical transition with highly stabilised laser [4]. Atom interferometry uses the wave-like properties of atoms to detect the impact of the gravity perturbation on the laser-cooled atoms [5]. Laser ranging interferometry (LRI) have been used to measure the changes of distance between two spacecraft to detect the mass changes of the Earth which contributes the changes of the Earth's gravity field [6].

The laser requirements of existing laser systems for above quantum applications are summarised in Table 1. Although the applications are different, what can be clearly seen in this table is the similar avionics requirements of kHz of frequency stability, MHz tuning for laser cooling and 10^{-2} to 10^{-3} of power stability.

However, the average SWaP of these systems is above 150 kg, 300 L and 400 W means that it is difficult to fit them into small satellites that enable low-cost missions, which are in the reach of research projects with limited budgets. The conventional design approach of these systems is to use multiple tunable laser sources to provide the optical frequencies used in different stages of the experiment. The tunability is achieved by modulating each laser with numerous narrow bandwidth optical modulator. Moreover, the control loop for frequency stabilisation of the lasers is implemented with fixed frequency and complicated analogue circuits. For instance, electronic component can be degraded by the space radiation effect. With the low flexibility in such control loops, the control settings cannot be optimised according to the degradation of the components. Thus, it becomes a challenging task to convert these systems into space payloads.

2. LEGO Configuration

2.1.1. Overview

The Lasers for Earth Gravitational Observation (LEGO) project was a CEOI 12th Call Fast-Track project to develop compact rubidium stabilised lasers for gravity sensing Earth observation undertaken by Surrey Space Centre at the University if Surrey and Twin Paradox Labs.

Table 1. Laser system requirements for quantum applications

Application	Laser System	No. of Lasers	Frequency Stability	Frequency Tuning	Power Stability	Weight (kg)	Volume (L)	Power (W)
Atom Interferometry	STE-QUEST [4]	5	~100 kHz	Cooling: 200 MHz Raman: 1 GHz	10^{-2}	220.7	469.5	608.1
	Trimeche [7]	7	NS	Cooling: 100 MHz Raman: 1 GHz	10^{-3}	264	635.145	849
	Luo [8]	1	30 kHz in 1 s	Cooling: 120 MHz Raman: 6.8 GHz	NS	150	540	500
	MIGA [9]	4	~100 kHz in $2 \cdot 10^4$ s	Cooling: 1 GHz Raman: 7 GHz	$1.7 \cdot 10^{-3}$	150	500	300
	Theron [10]	1	Below 100 kHz	Cooling: 200 MHz Raman: 1.7 & 6.8 GHz	NS	NS	NS	NS
Microwave Cold Atomic Clock	PHARAO [11]	6	~400 kHz	80 MHz	± 1% over 20 days	91	147.6	114
	SCAC [12]	3	~40 kHz	17 GHz	± 5% for 5 mon	NS	2.61	NS
Optical Cold Atomic Clock	ISOC [13]	5	Cooling:1 kHz Clock: 1 Hz	Cooling: 400 MHz	NS	75	116	62
Coherent Links	Chiodo [14]	1	NS	±12 GHz	NS	NS	NS	NS

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All three of these measurement systems use stabilised lasers as their main enabling technology. However traditional laboratory laser systems struggle to meet the robustness, reliability, or low size, weight, and power (SWaP) requirements for use in space.

The project adapted modern telecommunications industry COTS components, and software radio FPGA / DSP techniques, to develop a new all-fibre space-qualified stabilised laser systems for geodesy that have equivalent performance to laboratory systems. These tools were used to develop a 780nm laser system that is stabilised to the Rubidium D2 line - the stabilised laser most commonly required by the quantum and atomic sensing field.

We set out to achieve two goals: 1) achieving sufficiently high laser performance for the laser system to be immediately useful for quantum applications (stability: 1-10 kHz, accuracy: 1 MHz); and 2) achieving this performance in an ultra-compact package that has the potential to be used in space (1 litre, 0.5 kg, 10 W). These goals were completed. The laser system, shown in the following figure, was fabricated.

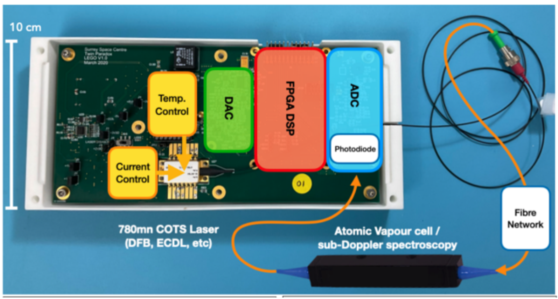

Figure 1. LEGO Digital & Fibre-coupled Payload

It consists of a single PCB containing a power supply and voltage conditioning circuitry, the current and temperature electronics needed to control a diode laser, photo detectors and opto-electronics, and a high-speed analogue-to-digital conversion network centred around a FPGA. Digital signal processing techniques were used to perform frequency-modulated spectroscopy on a warm Rubidium vapour using an all-fibre optical arrangement. The resulting Doppler-broadened, and sub-Doppler spectra are shown, along with the FM-demodulated error signal computed by the FPGA. FIIR filters were used to implement PID control to stabilise the laser to these signals achieving kHz stability.

2.1.2. Telemetry & Monitoring

One of the main features of the full control system is adding digital control into the firmware for live monitoring and control. To communicate with the temperature controller and provide serial data telemetry, an external UART interface is added. By designing a new I2C controller, it allows us to control and receive telemetry from Power rails monitoring ICS and current controller.

The I2C controller provides different modes for a specific purpose such as basic scanning of all channels and reading specific channel at full speed. End users could select the mode by sending a single specific command in the serial telemetry. Using a cyclic redundancy check (CRC) error checking routine, a robust and efficient serial data packet format allows us to obtain reliable telemetry points from numerous slave devices. Sending ID byte allows us to identify different telemetry points.

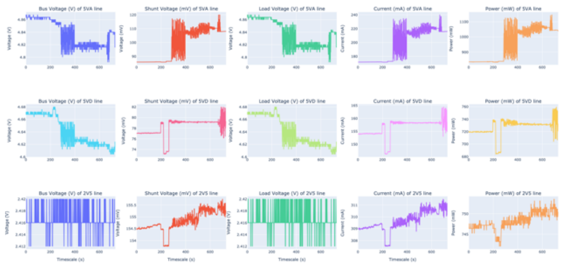

Figure 2. Offline data monitoring via UART

An offline data monitor shown in Fig. 2 is built for presenting streaming offline data from the firmware. Firmware with streaming data enables system health monitoring and control as a spacecraft payload. This real-time monitor is in development still. In the future, we would like to present real-time data with a custom-made GUI and SQL database.

3. Testing & Guidance

3.1.1. Frequency Stability

Frequency stability is one of the key parameters of laser used in gravity sensing applications.

The in-loop frequency stability of LEGO is measured by monitoring the changes in amplitude of the error signals, that represents the laser frequency noise, in the laser current control loop. The laser frequency noise can be analysed with Allan deviation which is a useful statistics method to examine the long-term stability of a signal [11]. Figure 3 uses the Allan deviation to depict the in-loop frequency noise of LEGO during different operations. A 10 kHz of flicker noise floor at 100 ms is achieved with the laser locked to random perturbation.

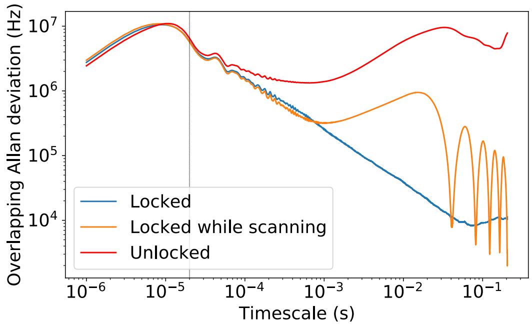

Figure 3. Allan Deviation of the Doppler-broadened stabilised laser's frequency noise during locked to random perturbation (blue), locked under a large 25 Hz perturbation (yellow) & unlocked (red).

3.1.2. *Phase Tolerance Measurement*

To maximise the gradient of the error signal, the photodiode signal is needed to be in phase with the sinusoidal modulation for locking. However, phase lag can be caused by the increased length of the optical path, reduced speed of the electronic components and FPGA calculations, etc. Therefore, if the phase lag exceeded the phase tolerances of the system, the gradient of the error signal will be reversed so the laser frequency won't be stabilised to the lock point. To assess the magnitude of phase lag that LEGO can cope with, a step change of magnitude of phase shift is introduced to the sinusoidal modulation shown in Figure 4 while the gradient of the error signal is measured

3.1.3. *Beat note Measurement*

When coupling two laser beams with different optical frequencies, a beat note, with a difference of two optical frequencies, can be observed in the frequency spectrum. The most common case is to evaluate the behaviours of the laser under test with a reference laser that has a known linewidth and frequency stability. Optical characteristics such as long-term frequency drift, linewidth, and power stability, can be obtained from the beat note.

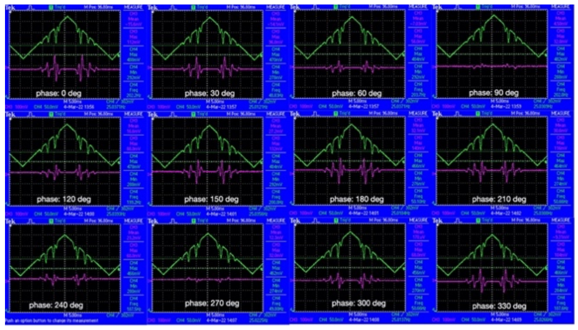

Figure 4. Changes in gradients of the error signals with a step change of 30º phase shift. Rb Spectroscopy (green) & coresponding error signal (purple).

3.1.4. *Guidance*

The top priority of conducting optical experiments is safety - LEGO has some safety features. Compared to the free space optics (FSO) approach, LEGO, which is a fibre-optic system, has a lower level of risks in health & safety. Moreover, the laser system can be remotely operated as USB controlled power relays are installed in power lines and operations of the laser can be commanded in the PC firmware. Thus, it enables frequency stabilised lasers related experiments within the reach of undergraduate students.

Apart from the advice for safety, when debugging optical setups, the first step is to make sure all connectors are well tightened and cleaned. The optical characteristics of optical components could be degraded with the presence of dust. Optical power meters are useful tools to validate the actual optical power with estimated values at the connections. Here are our selected Do's & Don'ts for optical measurement:

<u>Do's</u>

- Do turn off the laser when modifying the optical setup to avoid direct exposure of laser beams.
- Do wear laser safety eyewear during experiment.
- Whenever the fibre connectors are not plugged-in, protect the connectors with dust-caps.

<u>Don'ts</u>

- Don't point the laser beams vertically or toward anyone's head and eyes.
- Don't bend fibre cables under a radius of 3 cm.

4. Avionics Considerations

ECSS refers to the European Co-operation for Space Standardisation. This organisational body have created a series of standards that aim to make space technologies more coherent and user friendly for all engineers working to send a project into Space. These standards apply to electronic hardware, all mechanical parts, communication protocols, material choices and even administrative applications such as management and product assurance.

Within the scope of the LEGO project our aim is to raise all compliance where applicable and verify that the current design is qualified for spaceflight based on the ECSS requirements for electronic hardware and PCB layout.

The board has been designed using Altium Designer, and so all specific tolerances and values that can be applied to the layout have been incorporated into the project's design rules, allowing for a design rule check (DRC) to be run at each stage of the layout's design to ensure it is correct and compliant for all hardware revisions.

Standards that have been referenced for creating the Altium rules:

- ECSS-E-ST-20 – Electrical and electronic [15]
- ECSS-Q-ST-70-12C – Design rules for printed circuit boards [16]
- ECSS-Q-ST-70-60C – Qualification and procurement of printed circuit boards [17]
- ECSS-E-ST-50-11C - SpaceFibre - Very high-speed serial link [18]

The above documents were best for populating the Altium rules as they contain specific values related to PCB design.

The design is also aiming to utilise SpaceFibre design practices, and so layout and routing has taken considerations from ECSS-E-ST-50-11C. For example, this document specifies that differential pair signals should be routed with an impedance of 100 Ω +/- 10 Ω.

4.1.1. Updated Design Rule Checking

The standard Altium DRC can allow for editing of 63 conditions, ranging from electrical constraints, manufacturing constraints or even signal integrity checks. 38 rules were configured in the original LEGO project to meet the design's needs and qualify the board in its first revision. Of these 38, 8 rules were edited and 5 added to match ECSS requirements.

When the DRC is run on the current LEGO board with 'regular' electronic design rules in place, no errors are flagged.

Figure 5. Altium Designer Output Success

This did not change when the new Altium rules were run on the PCB, meaning the current revision of the board is already compliant with the ECSS additions. Any further work on the PCB layout will aim to keep this DRC clear.

Future work on the board will prioritise adding protection on the ADCs to ensure hardware will be protected both in the space environment and for general operation, and then larger changes such as moving subsystems to improve signal routing and performance will be completed.

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