The work package LIST – Lorentz Invariance Space Test

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The unification of the Standard Model with gravity remains one of the *biggest challenges in modern physics*. Numerous theories exist and many of them involve breaking Lorentz symmetry at small energy scales. Hence, *high-precision tests of Lorentz invariance are required to search for an experimental evidence* for those theories. In this work package, **we propose the LIST experiment to utilise quantum technology for realising a precision experiment to probe the constancy of the speed of light on the International Space Station (ISS)**. Due to operation in micro-gravity, *we expect to improve on the precision of state-of-the-art Earth-bound experiments by at least one order in magnitude*. **UKSA has already agreed to nominate such a mission as a national payload and thus could pave the way to achieving world-leading sensitivity for probing Lorentz Invariance.** Moreover, LIST on the ISS would *demonstrate the UK's capabilities in quantum technology and precision metrology*. In order to achieve this ambitious goal, the work package has the following objectives:

1. **Design, construct, and test a ground-based engineering model of the LIST experiment** with the required stability to potentially detect variations in the constancy of the speed of light.
2. **Design, construct, and qualify the LIST experiment as a flight model for operation on the ISS** with an improved design that takes full advantage from the engineering model and its performance under ground-based environmental testing.
3. **Provide a theoretical framework** for data analysis and interpretations capable of identifying variations in the speed of light in the measurement data obtained with the flight model during its mission on-board the ISS.

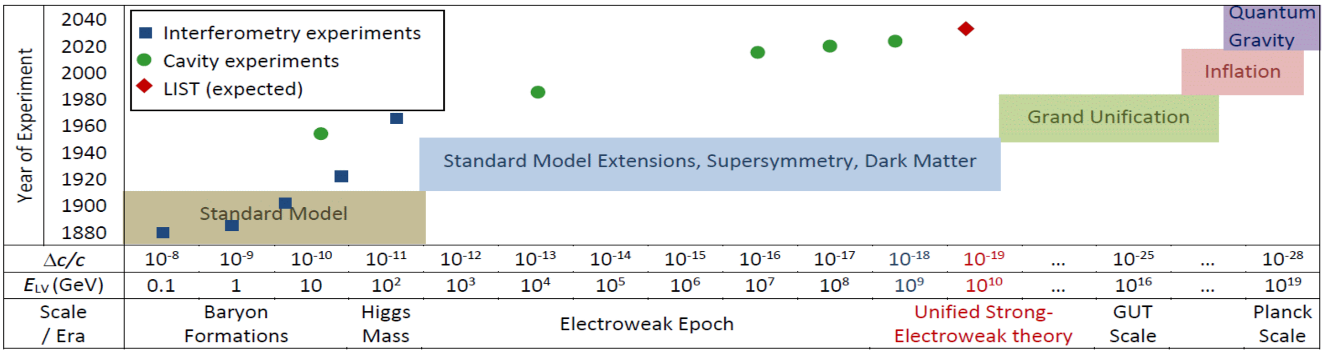

Figure 1: Quantisation of gravity suggests that space and time acquire a discrete character. As a result, a fuzzy dispersion effectively describes light with a speed variation $\Delta c/c \approx E_{ph}/E_{LV}$, where E_{ph} is the photon energy and E_{LV} is a model-dependent Lorentz violation energy. Without a complete quantum gravity, E_{LV} is an experimental parameter. For 1eV-photons, by evaluating E_{LV} with measured $\Delta c/c$, various theories with this energy scale have passed the Lorentz Invariance tests. The proposed experiment here aims to achieve up to $\Delta c/c \approx 10^{-19}$ and to test Standard Model extensions and supersymmetric theories up to $E_{LV} \approx 10^{10}$ GeV. This scale covers the entire electroweak epoch and the crucial separation stage of strong and electroweak forces. ***The anticipated results of this work package would therefore set a cornerstone in testing our fundamental understanding of the Universe**.*

Objectives 1 and 2: Realising an engineering model and a flight model of the LIST experiment for probing the constancy of the speed of light on-board the ISS

What began with the Michelson–Morley interferometry experiment in the late 19th century is nowadays performed with ultra-stable resonators and with much higher precision. **The proposed LIST experiment is essentially composed of a continuous wave laser frequency-stabilized to an ultra-stable optical cavity**. Various optical and optoelectronic components allow us to split the beam from a single laser, frequency shift one beam component, and independently frequency-stabilise the two components to the orthogonal cavity resonances by means of the Pound-Drever-Hall technique. The beat frequency between these two resonance frequencies can be monitored with respect to the ISS orbit, with an observation of a modulation of the beat at the 92-minute ISS orbit periodicity indicating anisotropy of the speed of light. **Notably, microgravity is commonly expected to significantly enhance the high sensitivity critical for the planned measurements**. We expect to achieve a fractional frequency precision for $\Delta c/c$ between one part in $\approx 10^{18}$ and $\approx 10^{19}$, and thus realize an improvement by a factor of ten towards the precision of state-of-the-art ground experiments.

Objective 3: A theoretical framework to harness the experimental precision

Since the original Michelson–Morley interferometry experiment, the speed of light has been an unchanging speed limit of nature as Maxwell's electromagnetic theory that first predicted it. The resulting Lorentz Invariance not only underpins

Special Relativity, but together with the Equivalence Principle, it leads to General Relativity as a well-tested foundation of modern physics and cosmology. The proven non-locality of quantum mechanics, however, means not all physical processes are limited by the speed of light. Furthermore, attempts beyond the Standard Model to unify General Relativity with quantum theory, as a most challenging scientific endeavour of the time, often involve violations of Lorentz Invariance of varied degrees and in different scenarios (see Figure 1). For example, canonical quantisation requires space-time decomposition which may violate Lorentz Invariance. **Theoretical work is therefore important to guide experiments in the ISS environment orbiting the Earth, with tailored theoretical estimates of sensitivity to different parameters in extensions of the Standard Model**. Furthermore, recent theoretical progress on quantum-photon effects and quantum-gravitational interactions will be incorporated in the experiment with the aim to enhance the measurements with the development of new quantum sensors for fundamental physics.

The team for the LIST work package

The LIST work package builds on the expertise of UK-based researchers to develop and build a high-precision experiment on the ISS for probing fundamental physics in microgravity. The project is led by the **University of Birmingham (UoB)** which partners with the **National Physical Laboratory (NPL)**, the **University of Aberdeen (UoA)**, and the private company **Teledyne e2v (Te2v)**. Hence, the proposed work package brings together excellent complementary expertise in precision measurements with quantum sensors (UoB, UoA, and NPL) and a company with decades of experience in developing and qualifying hardware for space operation. All project partners are committed to work in close collaboration to make the work package a success within the given tight timeframe. Notably, **the work package team can build on the support from UKSA, which has agreed to nominate the LIST experiment as national payload for launch to the ISS**.

Partners' backgrounds and available infrastructure

The Cold Atoms Group at the University of Birmingham brings expertise and a track-record in miniaturisation towards transportability of high-precision optical clock setups. Ongoing and previous project involvements comprise, amongst others, research developments performed in a previous EU-FP7 project ("SOC2"), the ITN FACT, and the ongoing H2020 RISE project "Q-sense" as well as the recently started EC Quantum Flagship project 'iqClock'. Moreover, this **partner provides access to testing facilities for space flight qualification**.

The National Physical Laboratory has already demonstrated ultra-stable lasers with Hz-level linewidths and optical atomic clocks with uncertainties in the $5x10^{-17}$ – 10^{-17} fractional frequency range. Notably, the **NPL cubic cavity is seen by ESA as leading technology for a number of future ESA missions**. All these capabilities have led to a **space heritage across a wide range of wavelength and optical frequency standards applications within ESA and EU contracts**, totalling some 18 contracts over the last 15 years, of which NPL has primed 9.

The Quantum Gravity Group at the University of Aberdeen contributes its **theoretical expertise in General Relativity, gravitation, quantum gravity, and their interactions with real-world quantum optical and atomic systems**. Supported by funding from EPSRC, STFC, SFC, and DSTL, the Aberdeen group has built up pioneering research with leading publications on subjects, e.g., loop quantum gravity, classical and quantum gravitational effects on light and matter in (open) laboratory environments**. Its unique experience in actively interacting with both theorists and experimentalists makes the Aberdeen group well suited to provide the required theoretical support in this project**.

Teledyne e2v delivers innovative technology solutions designed to meet complex requirements into a range of applications. **Teledyne e2v's space-qualified technology has been operated across the solar system without failure**.

Work package governance

As project lead, the University of Birmingham holds the overall responsibility for the proposed programme, although the project partners share the responsibilities for the success of the project when managing their respective share towards each work package task. In order to monitor progress against deliverables and milestones, UoB will ensure regular review meetings with all partners. **The partners jointly ensure overall quality and product assurance of the flight model as well as the establishment of configuration management for the entire length of the project**. NPL, UoA, and Te2v will contribute to this management task with their local project management and monitoring arrangements, to ensure that progress remains on track against the tight schedule. The project partners will also provide a data management plan. Further, task leaders will maintain contact with UKSA and ESA from work package start to **ensure that the LIST experiment complies with all necessary system and safety requirements and passes all reviews of the space agencies**.

Project plan to realise a flight model launch in three years

The major milestones of this work package will be the **realisation and testing (for space-qualification) of an engineering model (EM) towards the end of the first project year and the built of the flight model (FM) by the end of project year two**. These major achievements will allow **the flight qualification testing of the flight model (FM) in project year three**.

UKSA has agreed to nominate LIST as a national payload to ESA and thus we envisage **a launch of LIST in late 2022 or early 2023** (project year three and four, respectively). This way, we will be able to make use of **at least 22 months for data acquisition** (depending on the life time of the ISS) which will allow us to reach a precision of **at least one order of magnitude better** than current state-of-the-art Earth-bound experiments.

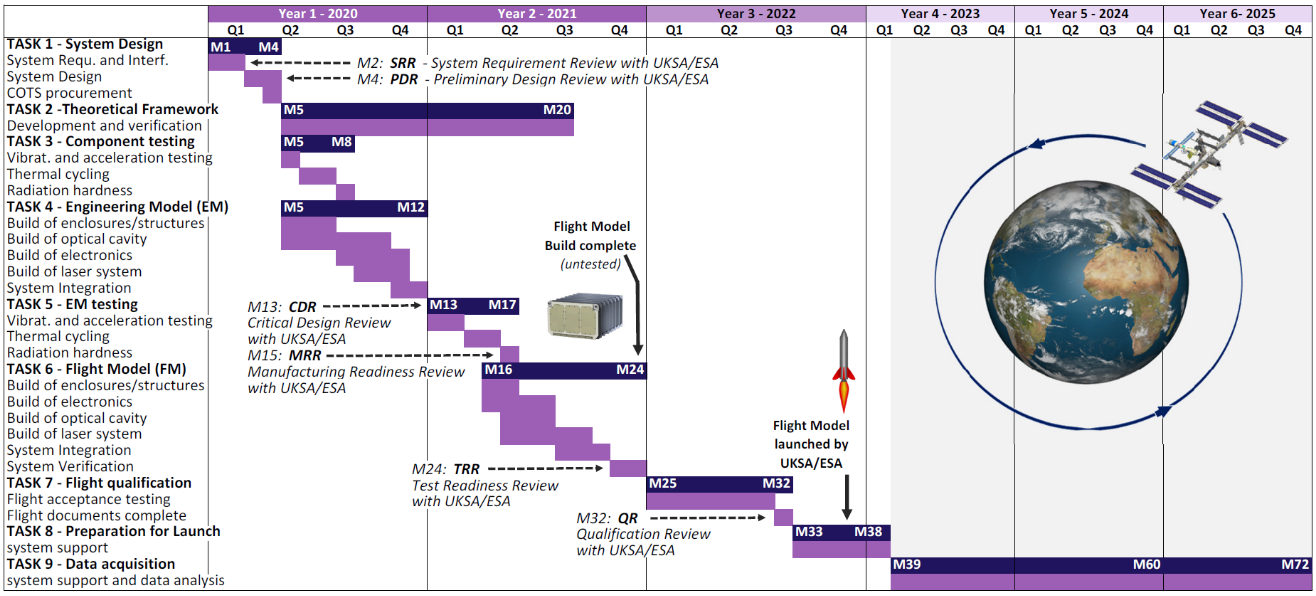

Figure 2: Gantt chart for first five years of the proposed work package for realising LIST on the ISS. The chart shows the nine main tasks and for each of those a set of sub-tasks. The work package spans 24+12+36 months, beginning in January 2020 at latest. We anticipate the completion of the engineering model by M12 and the completion of the flight model by M24. After this initial 2-year project phase, in the next 1-year phase, the flight model will undergo testing and qualification for launch. The launch of the flight model as a UKSA national payload is foreseen for late 2022 or early 2023 (between M33 and M38) to allow at least 18 month of operation of the LIST experiment on-board the ISS. An additional year of operation on board the ISS (i.e., project year six) will help to further drive the precision of LIST. The necessary reviews with space agencies are indicated in the chart.

As shown in the Gantt chart in Figure 2, the work package comprises nine tasks. In order to accelerate the system build to benefit from a maximum operation time on-board the ISS, some of these main tasks run in parallel. In **Task 1** (M1-M4), we will develop the LIST system design including documentation of system requirements, all internal and external interfaces of the LIST experiment, communication interfaces with the ISS infrastructure, and an outline for data management and its transfer to ground. As soon as the system design is finalised, we will begin a procurement of components for the EM and, if appropriate, the FM, to avoid any long lead time delays. Within **Task 2** (M5-M20), we will create a test data set based on the capabilities of the designed experiment and develop the theoretical framework for data analysis. In **Task 3** (M5-M8), critical and custom components will be subjected to test procedures as a pre-requisite to space qualification. **Task 4** (M5-M12), is dedicated to the construction of the EM and will begin while Task 3 is being completed. In subsequent **Task 5** (M13-M17), this engineering model will be subjected to extensive tests for space qualification. Insights and experience from the EM manufacture, assembly, integration and test (MAIT) will inform **Task 6** (M16-24), where we will construct the FM. The FM will undergo the necessary flight qualification process within **Task 7** (M25-M32). The launch of the FM by UKSA is anticipated for late 2022 or early 2023; and within **Task 8**¸we will provide system support to aid the launch preparations. Once launched and operating on-board the ISS, we plan at least 18 month of operation for data collection (**Task 9**, M39-M60); ideally – depending on the lifetime of the ISS – this task can be extended for a further year towards M72.

Table 1: Summary of deliverables (with month of delivery) and milestones.

Task	Month	Deliverables	Milestones
System Design	M4	Design documents	Preliminary Design Review (PDR) passed
Theoretical Framework	M20	Analysis framework	Theoretical framework established
Component Testing	M8	Component qualifications	
Engineering Model	M12	Engineering Model	Critical Design Review (CDR) passed
Engineering Model Testing	M15	Test documentation	Manufacturing Readiness Review (MRR) passed
Flight Model Construction	M24	Flight Model (FM)	Test Readiness Review (TRR) passed
Flight Qualification	M32	Flight readiness report	Qualification Review (QR) passed
Launch by UKSA/ESA	till M38	Launch report	FM operating on-board the ISS
Data acquisition	M72	Final report	Lorentz Invariance probed with a precision of one part in 10^{18} or better

The tasks are embedded in the space agencies' reviews which will help ensuring that flight readiness and ESA safety requirements are met by the LIST experiment. In conclusion, our project plan **uses strategic procurement and parallel tasking as far as possible, to meet the challenging timeline for the construction of the FM**. Table 1 summarizes the nine work package tasks and their respective deliverables as well as associated milestones.

Organisation of the partners' joint efforts to establish a precision experiment on the ISS

In general terms, the work required to accomplish the tasks in this work package is shared according to each partner's expertise. System design will be carried out in a joint effort with partners working closely together, via teleconferencing and physical meetings, as required. For component testing in Task 2, and construction of the EM (Task 4) and FM (Task 7), we will apply a modular approach: **NPL** will be responsible for providing and testing of their ultra-stable cavity including locking electronics. **UoB** will be responsible for the laser system, computer control, external communication systems (with ISS infrastructure), and system packaging. UoB will be responsible for the system integration taking place in Birmingham. The partner **UoA** will develop the theoretical framework for the analysis of the experimental data. UoB and UoA will jointly prepare and analyse the measurement data. Testing on component and system level will be carried out in collaboration with the **Teledyne e2v**. In addition, the project partners will make use of the in-house thermal and radiation testing facilities of the Space Research Group at the University of Birmingham. UKSA has agreed to nominate LIST as a national payload to ESA who will launch the FM.

Estimated work package costings

The cost of the LIST work package are estimated to be k£4,985 over the period of six years (i.e., 2+1+3). In detail, as shown in Table 2 below, **k£3,341 will be required in the first two project years to develop and built the engineering and flight models of the LIST experience**. Flight qualification of LIST would cost another k£926 in the additional project year three. In the final phase of the project, which is dedicated to data acquisition and analysis, the operation of the project will cost k£718 over the course of the project years four, five, and six.

Table 2: Overview of the estimated costings for the LIST experiment according to project phases. The initial 2-year phase for the engineering and flight model built will require approximately k£3,300.

[k£]	Y1	Y2	Y3	Y4	Y5	Y6	SUM
Develop and Build Phase	1,403	1,939					**3,341**
Qualification and Launch Phase			926				**926**
Experiment and Data Analysis Phase				296	216	206	**718**
TOTAL							**4,985**

Context and competitiveness of the LIST work package

The proposed work package LIST for a precision experiment probing the constancy of the speed of light on the ISS falls within the remit of Fundamental Science and is in line with the grand challenges outlined by EPSRC strategies. This proposed work package has direct synergies with the UK National Quantum Technology Hub for Sensors and Timing.

Further, the proposed work package satisfies goals outlined in the UKSA strategy "Space environments and human spaceflight" as it has a fundamental intellectual merit (e.g., by addressing fundamental questions such as the constancy of the speed of light) as well as terrestrial benefits by driving quantum technology (i.e., improving TRL for an ultra-stable cavity-locked laser, a crucial sub-system of an optical atomic clock).

Moreover, significant outcomes from the proposed experiment include: Precisely quantified selection and guidance of quantum gravity and Theory of Everything, such as string theory and super-symmetry sought by particle physicists in UK, CERN, and worldwide to explain cosmological mysteries like Dark Matter.

Although the influence of gravity on light in the classical environment is well understood, the proposed experiment may lead to breakthroughs in understanding quantum corrections to the speed of light that can trigger a new wave of revolution in science and technology. The proposed experiment can for the first time put a bound on the influence of gravity on light in quantised (e.g., super-position or entangled) states. This feature will enable, for example, Penrose's influential theory of gravitational decoherence and its implication on light propagation and speed to be precisely tested with potential far-reaching implications on our fundamental understanding and new applications.

In an international context, there are other space missions outside Europe, where quantum technology has become a focus of significant activity. These missions include the Cold Atom Laboratory in Space to the ISS by NASA; a Chinese dedicated satellite for quantum communication, and more recently a Chinese demonstration for a space clock based on Cs atoms. Hence, the proposed LIST work package for a UK quantum technology-based precision experiment presents a unique opportunity for the UK to demonstrate leadership for quantum technology implementation in space.