estec

European Space Research
and Technology Centre
Keplerlaan 1
2201 AZ Noordwijk
The Netherlands
T +31 (0)71 565 6565
F +31 (0)71 565 6040
www.esa.int

DOCUMENT

STE-QUEST Payload Definition Document

Prepared by	**STE-QUEST Study Team**
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1 INTRODUCTION

1.1 Scope

This document describes the Payload of STE-QUEST, a mission in the Fundamental Physics domain conceived to test to high accuracy the different aspects of the Einstein Equivalence Principle. This document derives directly from the STE-QUEST Science Requirements Document and STE-QUEST Mission Requirements Document. It also integrates elements included in the STE-QUEST proposal (and associated reference documents), the STE-QUEST CDF Study and the STE-QUEST Instruments Mid-Term Review datapackages.
This document provides the baseline description of the payload, its instruments, supporting units and interfaces, as defined at the beginning of the STE-QUEST assessment study. It shall be consolidated as part of the study and shall be formally updated at the end of it. This is the first revision of the document, following the completion and closure of the Instruments mid-term Review held in May 2011.

1.2 STE-QUEST Mission Description

The Space-Time Explorer and Quantum Equivalence Space Test (STE-QUEST) mission aims to test different aspects of Einstein's Equivalence Principle (EEP). This theory has three cornerstones describing the properties of space-time and matter. The Local Lorentz Invariance (LLI) states that any non-gravitational experiment will yield the same result independent of the velocity of the locally free-falling frame it is performed in. For the Local Position Invariance (LPI), the outcome of such an experiment shall be independent of the position and time of its execution. Finally, the Weak Equivalence Principle (WEP) states the universality of free-fall of objects independent of their composition.

Tests of LLI and LPI can be done using clock comparisons. A dependence of fundamental constants determining the clock frequencies on the gravitational potential would violate the gravitational red-shift formula and hence the LPI. For LLI, two tests can be performed on STE-QUEST, one involving the test of the speed of light of an optical resonator, the other involving a test of the Zeeman splitting frequency under magnetic fields. The universality of free-fall will be measured in the quantum gravity domain by observing the evolution of a cloud of ultra-cold atoms.

Primary science goals are the measurement of the Earth gravitational red-shift to a fractional frequency uncertainty better than 2·10-7, the measurement of the Sun gravitational red-shift to a fractional frequency uncertainty better than 6·10-7, and test of the universality of the free propagation of matter waves to an uncertainty in the Eötvös parameter better than 1·10-15.

Secondary science goals include common view comparison of clocks on ground at the $1 \cdot 10^{-18}$ fractional frequency uncertainty level after a few days of integration time with the STE-QUEST microwave link and a few hours by using the optical link. Space-to-ground time transfer should be achieved with accuracy better than 50 ps and synchronization of clocks on ground to better than 50 ps. This can contribute to the realization of atomic time scales to fractional frequency inaccuracy lower than one part in 10^{16}. Monitoring of the stability of on board GPS, GALILEO, and GLONASS clocks could be accomplished. Cold atom physics under weightlessness conditions could be performed to study the evolution of coherent matter waves in a clean environment and over long free propagation times. There are also application to geodesy, ranging, and atmospheric delay investigations.

STE-QUEST will perform the clock comparisons using dedicated Science Links in addition to the standard TT&C links provided through ESOC. These links will establish a connection to a baseline of three ground terminals in the vicinity of three high-performance atomic clocks (e.g. Boulder, Torino, and Tokyo). The spacecraft will make use of standard GNSS and SLR techniques for precise orbit determination. An overview of the mission scenario is given in Figure 1.

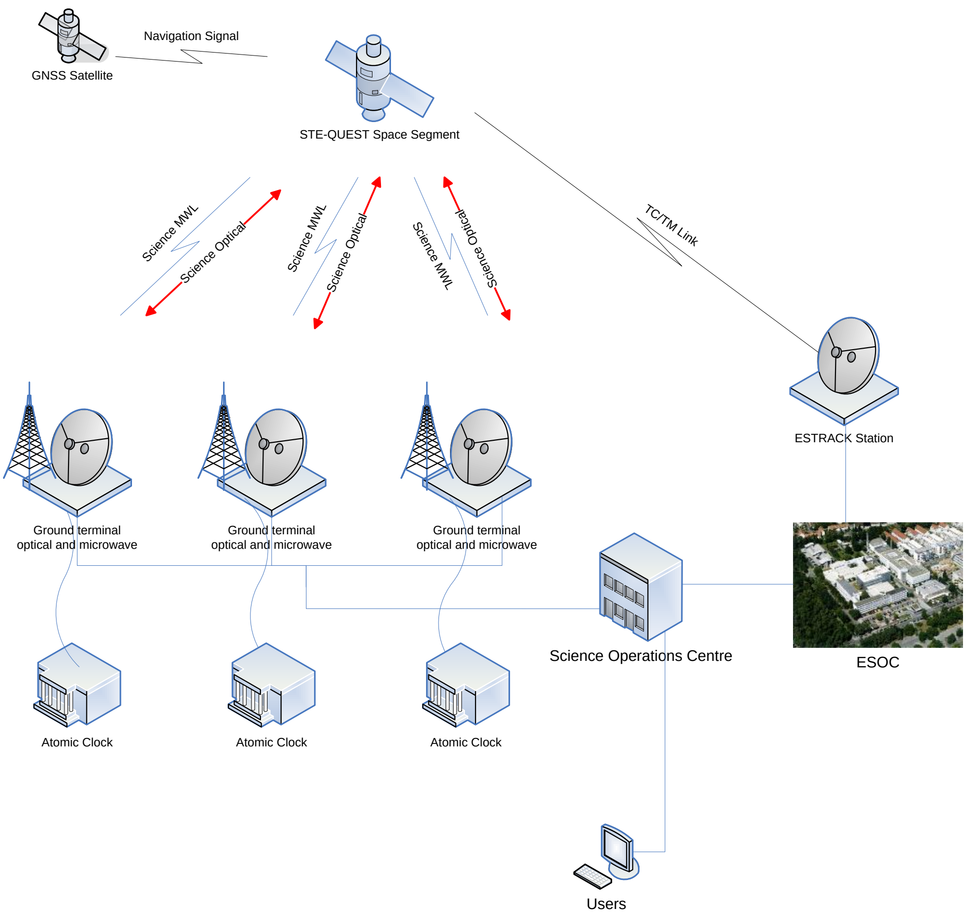


Figure 1: STE-QUEST mission scenario

For the purpose of the industrial assessment study, the baseline STE-QUEST Payload is divided into three parts (that may be re-defined in later stages):

1. Core Science Instruments
    a. Atomic Clock
        i. Pharao Next Generation
        ii. Microwave-Optical Local Oscillator
        iii. Microwave Synthesis and frequency Distribution (including USO)
        iv. Instrument Control Unit
    b. Atom Interferometer
2. Science Links
    a. Microwave Link
    b. Optical Link
3. Supporting Units
    a. Precise Orbit Determination Equipment (GNSS receiver, corner cube reflectors)

Due to the sensitivity of the core science instruments to external disturbances, these instruments have been placed in a volume compatible with accommodation within the central cylinder of a typical spacecraft structure during the CDF. An overview of the payload, as defined during the CDF study, is provided in Figure 2.

The **atomic clock** instrument consists of a microwave clock based on ensembles of cold Rubidium atoms, a short term frequency reference (MOLO), an instrument controller, as well as a microwave synthesis and frequency generation system (MSD). The microwave clock could be based on the Pharao Cesium cold atom clock which is to be flown on the ACES mission on-board the International Space Station. For this mission, the clock would be upgraded to Rubidium atoms to mainly reduce the collision shift effects, and shall include a 2-dimensionnal Magneto-Optical Trap in order to increase the number of atoms. For the short term stability, a microwave-optical local oscillator (MOLO) generates an ultra-pure and stable microwave reference frequency using a reference cavity-stabilized laser and optical frequency comb technology to down-convert the optical signal to the microwave domain. These two signals yield the total high clock performance with a fractional frequency inaccuracy of $1\cdot10^{-16}$.

The **atom interferometer** measures the evolution of two overlapping clouds of Rb^{85} and Rb^{87} atoms in an ultra-cold state. The atoms will be cooled in magneto-optical traps and subsequently in an atom chip/optical dipole trap setup before being released into a Mach-Zehnder atom interferometer. The atomic wave packets are coherently split, re-directed, and re-combined using Raman laser systems to create an interference pattern, representative of the differential acceleration of the two species.

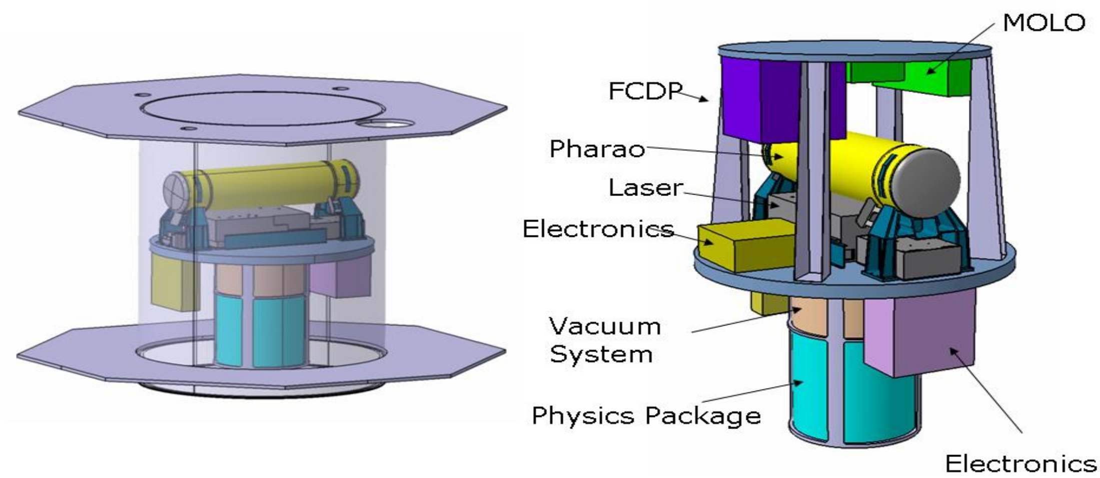


Figure 2: STE-QUEST model payload accommodation (as defined during the CDF study). Left the payload compartment with the clock subsystems in the top part and the atom interferomenter systems in the lower part. Right the accomodation of the compartment in the main spacecraft structure.

Supporting the clock measurements, two time and frequency transfer links are specifically reserved for science use. One is a microwave link in S and Ka band, the other an optical communication link in the infrared domain. Together they allow ultra-stable, fast and reliable clock comparisons.

Precise orbit determination to support the clock and interferometer measurements is currently foreseen with an on-board GNSS receiver locked to an external reference (the atomic clock via the FGCD) and corner cube reflectors for laser ranging.

1.3 Applicable Documents

[AD1]. FPM-SA-Dc-00001, STE-QUEST Science Requirements Document
[AD2]. SRE-PA/2011.074/RQ/MG, STE-QUEST Mission Requirements Document
[AD3]. JS-10-12, STE-QUEST Environmental Specification

1.4 Reference Documents

[RD01] STE-QUEST Proposal
[RD02] STE-QUEST CDF Study Report
[RD03] Atom Interferometer Technology Readiness Review
[RD04] STE-QUEST Atomic Clock Assessment Study MTR Datapackage
[RD05] STE-QUEST Atom Interferometer Assessment Study MTR Datapackage

1.5 Acronyms

AD	Applicable Document
AI	Atom Interferometer
AO	Announcement of Opportunity
AOM	Acoustic-Optical Modulator
BEC	Bose-Einstein Condensate
CAD	Computer Aided Design
CCD	Charge-Couple Device
CCR	Corner Cube Reflector
CDF	Concurrent Design Facility
CoM	Centre-of-Mass
CW	Continuous Wave
DFB	Distributed Feedback (laser diode)
DLR	Deutsches Zentrum für Luft- und Raumfahrt
EOM	Electro-Optical Modulator
EU	Electronics Unit
FGCD	Frequency Generation, Comparison and Distribution (unit)
FLFC	Femtosecond Laser Frequency Comb
FORT	Far-Off Resonance Trap
GEO	Geostationary Orbit
GNSS	Global Navigation Satellite System
GT	Ground Terminal
HEO	Highly Elliptical Orbit
HGA	High-Gain Antenna
ICU	Instrument Control Unit
LEO	Low-Earth Orbit
LGA	Low Gain Antenna
LCT	Laser Communication Terminal
MOLO	Microwave-Optical Local Oscillator
MWL	Microwave Link (unit)
ODT	Optical Dipole Trap
OPL	Optical Link (unit)
PD	Photo Detector/Diode
PDHU	Payload Data Handling Unit
PHARAO	Projet d'Horloge Atomique par Refroidissement d'Atomes en Orbite
PharaoNG	PHARAO New Generation (with Rubidium Atoms)
PL	Payload
PRN	Pseudo-Random Noise
QI,II,III	Quantus I, II, III (DLR experiment)
Rb	Rubidium
RD	Reference Document
Rx	Receive
S/C	Spacecraft
SEU	Single-Event Upset
SSPA	Solid State Power Amplifier

STE-QUEST	Space-Time Explorer and Quantum Equivalence Principle Space Test
SQRT	Square root
TBC	To be confirmed
TBD	To be determined
TID	Total Ionizing Dose
TM-TC	Telemetry – Telecommand
TWT	Travelling Wave Tube
ULE	Ultra-Low Expansion

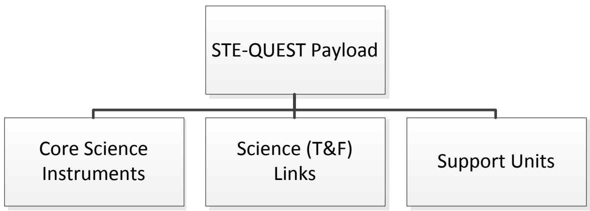
2 PAYLOAD OVERVIEW

The satellite payload consists mainly of two instruments: a cold atom-based clock and an atom interferometer.

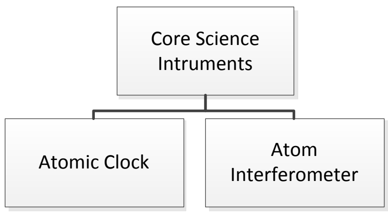
The clock is derived from cold atom microwave clock PHARAO, as employed on the ACES mission. The performance of the clock is improved compared to the current implementation for ACES by an optically derived ultra-pure microwave signal and by using the more favourable atomic species Rubidium. During the mission, the tick rate of the space clock will be compared with atomic clocks on the Earth, using frequency transfer links in the microwave domain, similar to the links on ACES, as well as in the optical domain.

The atom interferometer will compare the free propagation of coherent matter waves of two isotopes of rubidium (85Rb/87Rb) under the influence of the Earth's gravity. The two isotopes will be simultaneously prepared to an ultra-cold state, released into a Raman beam interferometer and subsequently state-detected.

For the purpose of the industrial assessment study, the baseline STE-QUEST Payload is divided into three parts:

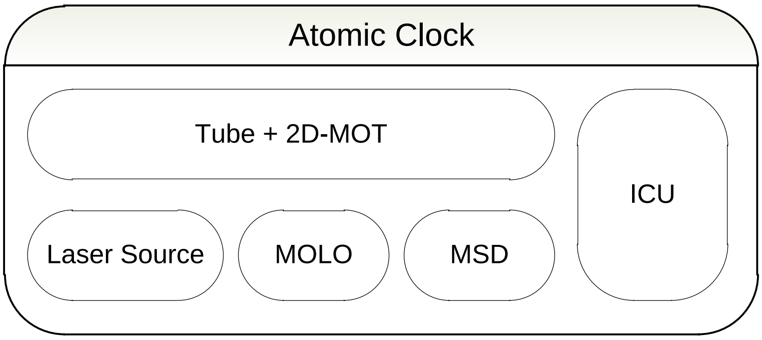


There are two Core Science Instruments:



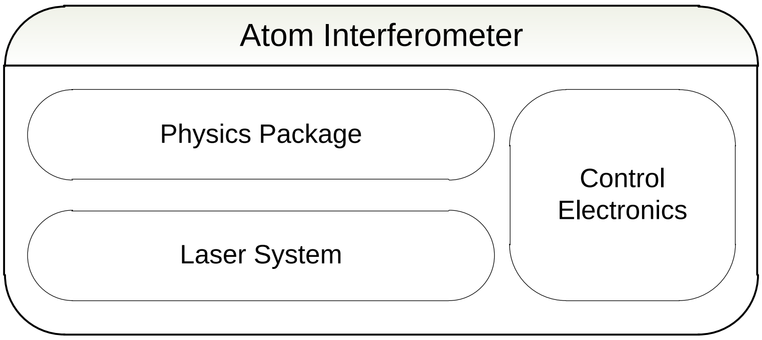
The Atomic Clock is composed of:

1. The Rubidium Tube (derived from Pharao/ACES) and a two-dimensional Magneto-Optical Trap (2D-MOT)
2. The Laser Source (derived from Pharao/ACES)
3. The Microwave-Optical Local Oscillator (MOLO)
4. The Microwave Synthesis and frequency Distribution (MSD) unit, including a USO
5. The Instrument Control Unit (ICU)



The Atom Interferometer is composed of:

1. The Physics Package (including a 2D-MOT)
2. The Laser Source
3. The Control Electronics (including a separate Ion Pump controller box)



While only the core science instruments are currently foreseen to be procured through member states, this document gives a short description of the science link design as well. The industrial contractor, however, is expected to design the science links and their performance in detail. This shall only be used as a guide to what has been done during the CDF so far.

The instruments are supposed to have a direct mechanical, thermal and electrical (power) interface with the STE-QUEST Spacecraft, as well as a data interface their own Instrument Control Unit.

There are two Science Links for Time and Frequency transfer, including both an on-board terminal (and associated antennas/telescopes) and a set of ground terminals:

1. The Microwave Link (MWL)
2. The Optical Link (OPL)

In addition to a direct mechanical, thermal and electrical (power and TM-TC) interface with the STE-QUEST Spacecraft, the on-board terminals have a bi-directional free-space interface (microwave and optical) with the ground terminals.

Finally, the Supporting Units include an on-board GNSS Receiver (and associated antenna) that is part of the spacecraft and needed for the time tagging of on-board TM. It also includes and a Corner Cube Reflector for Precise Orbit Determination (TBC).

The Figure 3 below describes a high level block diagram of the STE-QUEST Payload.

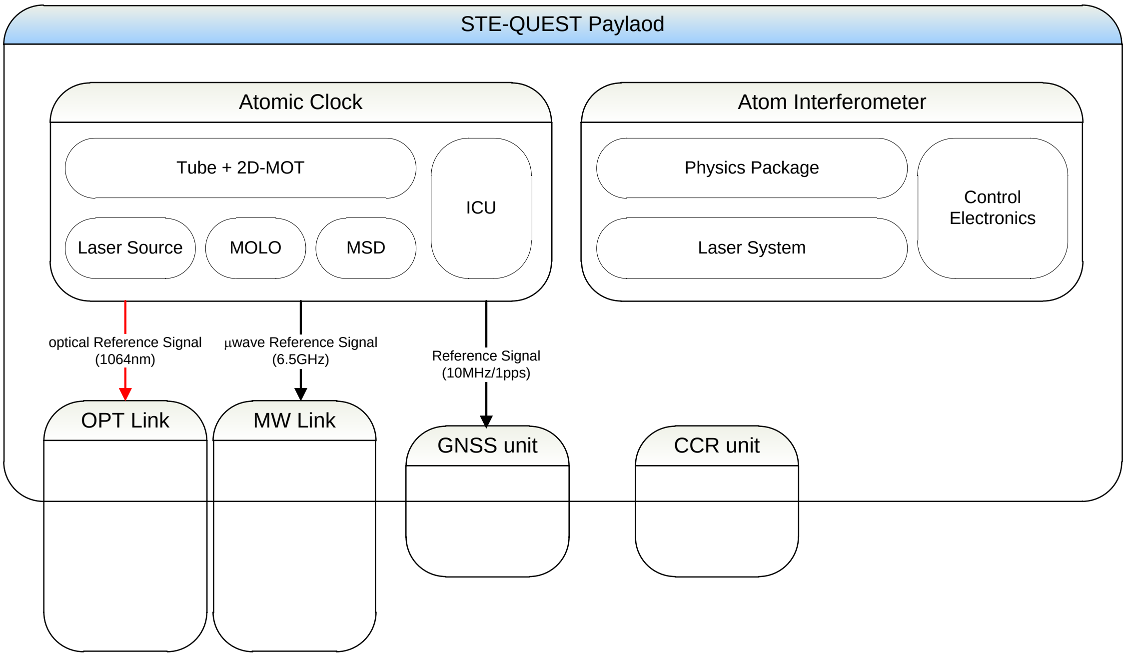


Figure 3: Block Diagram of the STE-QUEST Payload

3 STE-QUEST ATOMIC CLOCK

3.1 Instrument Concept

The STE-QUEST Atomic Clock generates an ultra-stable frequency signal based on a combination of:

- an ultra-pure reference signal in the microwave domain generated by an optical reference oscillator (MOLO)
- an ultra-stable reference signal generated by a cold Rubidium atoms clock (PHARAO-NG), derived from the existing cold Caesium atoms clock PHARAO
- as a backup, the MOLO signal can be replaced by the USO signal from the MSD.

The clock signal comparison, combination and distribution are expected to be controlled and managed by the microwave synthesis and frequency distribution unit (MSD) and the Instrument Control Unit (ICU).

3.2 Overview of Clock Subsystem

Figure 4 below presents the block diagram of the STE-QUEST Atomic Clock and the type of signals exchanged between the main elements

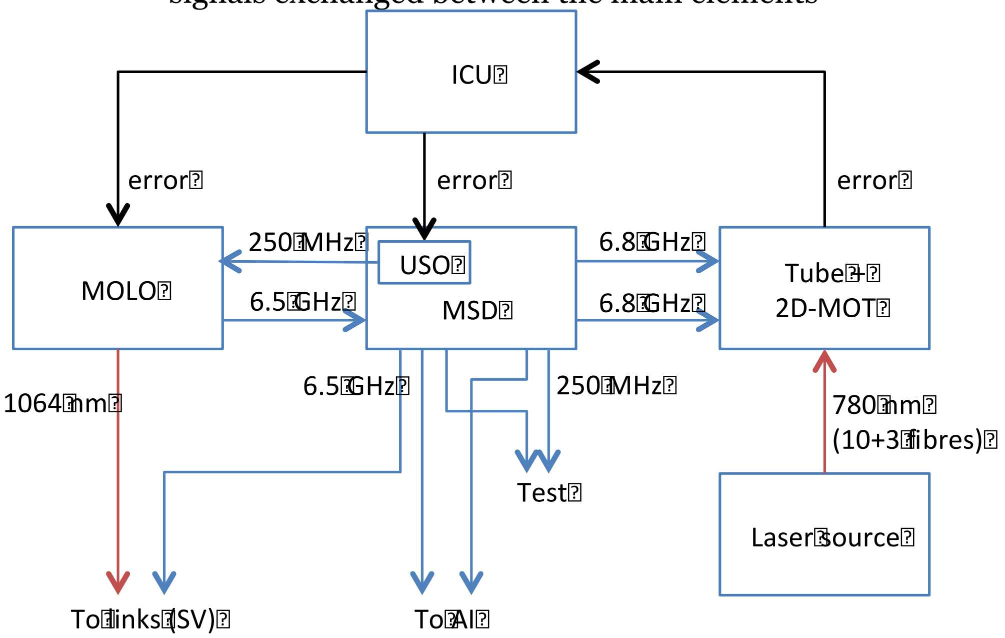


Figure 4: Clock Subsystem Block Diagram

The STE-QUEST Atomic Clock includes five subsystems:

1. The Rb Tube and 2D-MOT, also including a proximity electronics (BEBA) and ion-pump supply (CVT-HT)
2. The Laser Source
3. The Microwave-Optical Local Oscillator

4. The Microwave Synthesis and Frequency Distribution Unit (MSD), including a back-up Ultra-Stable Oscillator (USO)
5. The Instrument Control Unit (ICU)

The signals delivered by the STE-QUEST Atomic Clock to the Spacecraft are:

1. An ultra-stable Microwave Signal at 6.5GHz
2. An ultra-stable Optical Signal at 1064nm

Note that the STE-QUEST Atomic Clock generates only a frequency reference. The reference time and associated epoch is expected to be generated in the Science Links terminals.

3.2.1 Rb Tube and 2D-MOT

In the Rb Tube and 2D-MOT, Rubidium atoms of the same isotope are first sequentially captured, cooled, launched and prepared in a high-vacuum tube by a set of six orthogonal laser beams. In order to achieve a high number of cooled atoms, a 2D-MOT is used to prepare an initial sample of atoms that is then transferred into the secondary cooling/preparation sphere co-aligned with the interrogation tube. The placement of the 2D-MOT can be altered around the cooling sphere, the current baseline is shown in Figure 5. The full assembly of 2D-MOT and Main tube assembly shall be referred to as Rubidium tube (TRb).

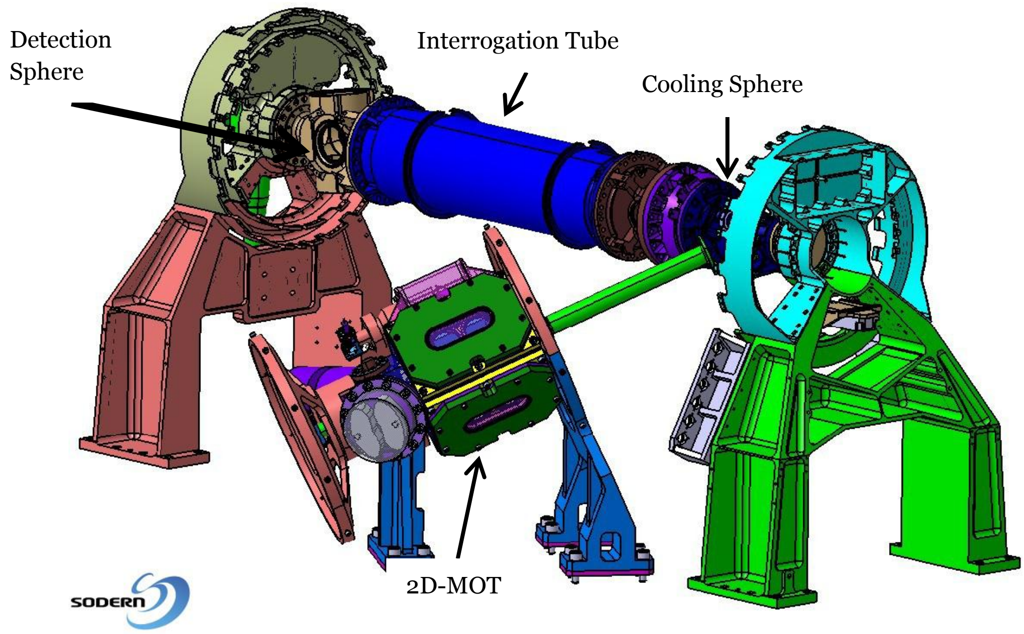


Figure 5: Current baseline design of Pharao NG (Rubidium Tube) shown without mu-metal shields.

The atoms then undergo two successive interactions (separated in space) with a microwave magnetic field inside the Ramsey Cavity that is oscillating at the Rb Hyperfine frequency and coherently generated from the ultra-pure MOLO signal. Atoms finally enter a detection region where the hyperfine transition probability is measured by light-induced fluorescence using two laser beams. This cycle is repeated while scanning the microwave field around the resonant frequency and the error signal is used to lock the Atomic Clock reference signal.

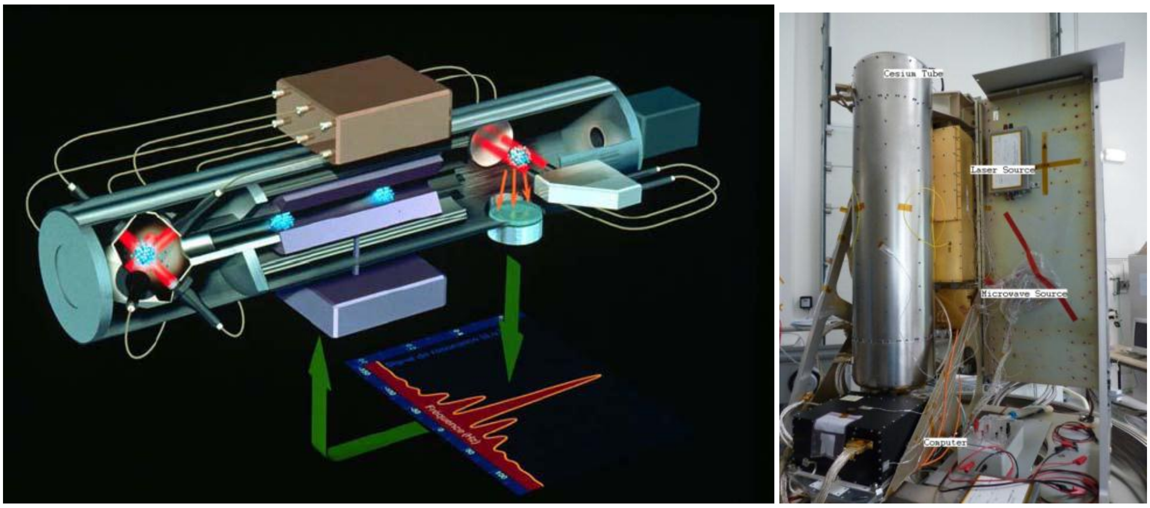


Figure 6: Pharao NG operational concept and Pharao (ACES) Engineering Model (right)

The Rb Tube and 2D-MOT subsystem also includes 2 electronics boxes directly responsible for the tube operation: the BEBA is a proximity electronics box in charge of generation and monitoring of magnetic field; the CVT-HT is a high-voltage supply for the ion-pump.

3.2.2 The Laser Source

The Laser source is responsible for the generation, distribution and control of the optical signals for the cooling, trapping, manipulation and interrogation of the Rb atoms. The transport of the light signals to the Rb Tube and 2D-MOT is performed through optical fibre. In terms of functionality, it is similar to the one of Pharao/ACES with two exceptions. First, it operates at 780nm (Rb D2 transition line) instead of 852nm. Second, it is extended to include the generation and processing of optical beams for the cooling and atom manipulation of the 2D-MOT (which is not present in Pharao/ACES).

The current baseline design of the Laser Source is based on the Pharao/ACES one, namely a set of Extended Cavity Laser Diodes locked on a Rb absorption cell and slave lasers for power amplification. The laser beams generation and processing is performed in free-space using optical components mounted on a double-sided optical bench. The final optical beams are accessible through a set of optical fibres. To benefit from Pharao/ACES heritage, the baseline design relies on the duplication of the current Laser Source box, one supplying the Rb Tube and the other supplying the 2D-MOT.

An alternative design based on the frequency doubling of telecom lasers at 1560nm is also being considered. This technology alternative shall have no impact on the Laser Source budgets.

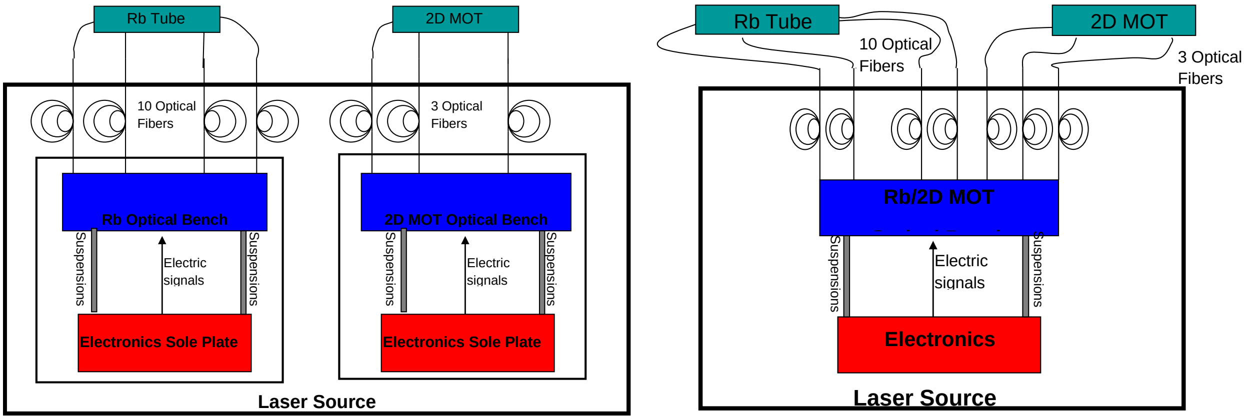


Figure 7: Preliminary Design of STE-QUEST Atomic Clock Laser Source: baseline design based on Pharao heritage (left) and alternative design based on telecom fibre lasers (right)

3.2.3 Microwave-Optical Local Oscillator

In MOLO, a CW reference laser is locked to an Ultra-Low Expansion (ULE) optical cavity whose finesse drives the spectral purity of the optical signal. This ultra-pure optical signal is locked to one of the tooth of a stabilised Femtosecond Laser Frequency Comb (FLFC). The derived stabilised optical pulse trains are then detected on a fast photodiode that generates the ultra-pure microwave reference signal feeding PHARAO-Rb and the Atom Interferometer (in external operation mode). A block diagram of MOLO is presented in Figure 8.

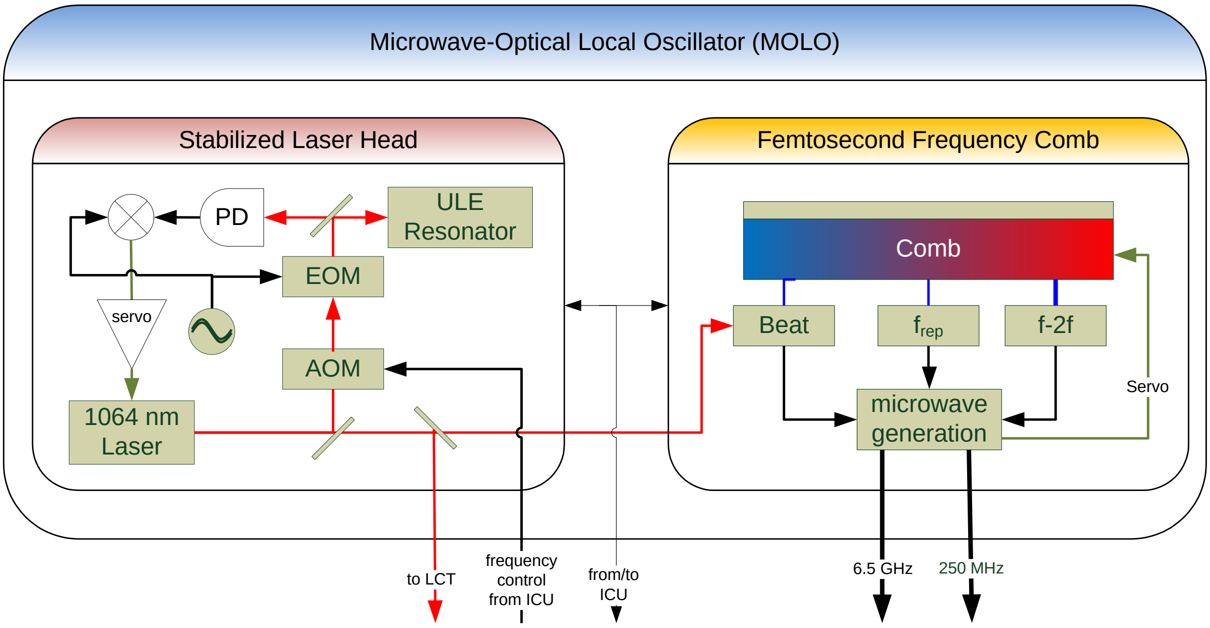


Figure 8: Block Diagram of MOLO

The MOLO includes two main subsystems:

1. The stabilised Laser Head (including a 1064nm Laser Head, an Optical Resonator and control electronics)
2. The Optical Frequency Divider (including the femtosecond frequency comb laser and the microwave generation)

The stabilised laser head is responsible for the generation of an ultra-pure and narrow line laser signal at 1064nm to be distributed to the optical link terminal. It includes the laser head itself, the optical resonator and the control electronics. The laser head at 1064nm is based on the Nd:YAG Tesat design used in the LCT and also considered for LISA Pathfinder. For the Optical Resonator, two designs are considered. One based on force-insensitive squeezed cube with a four-point tetrahedral support (NPL design) and one based on force-free cylindrical cavity with multi-point support (PTB design).

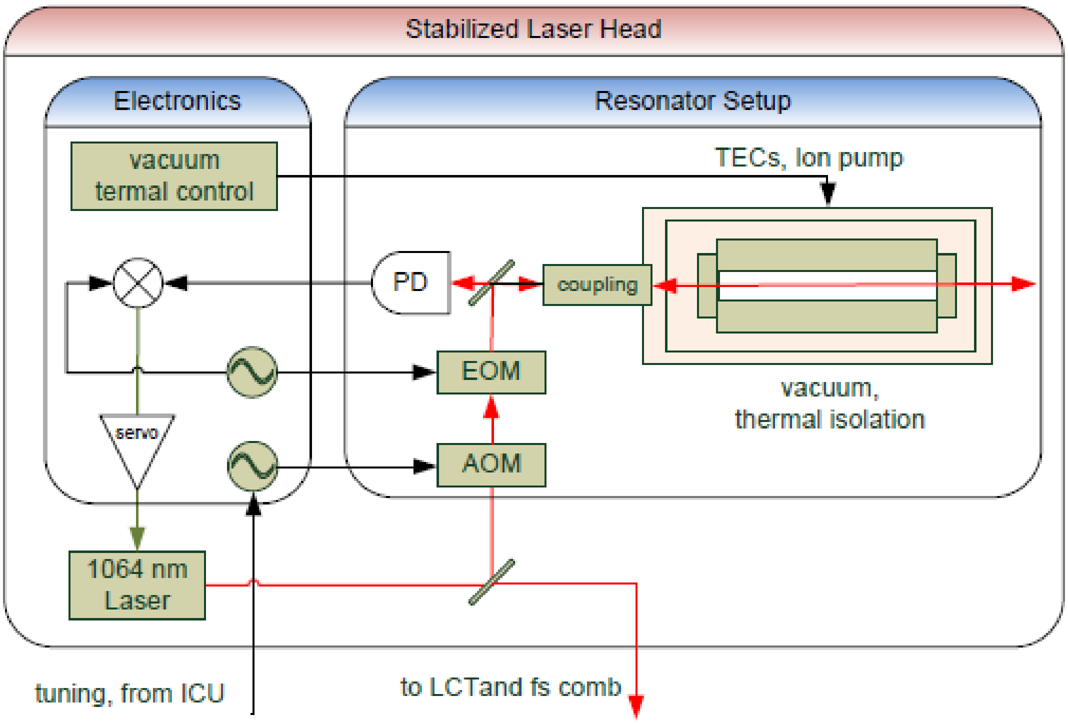


Figure 9: Block Diagram of MOLO Stabilised Laser Head

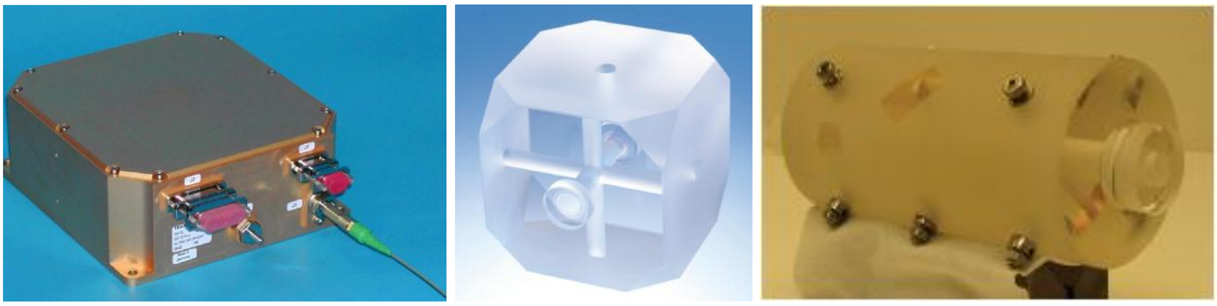


Figure 10: Elements of MOLO Stabilised Laser Head: Tesat Laser Head at 1064nm (left), NPL squeezed-cube optical cavity (centre), PTB multi-point supported cylindrical cavity (right)

The Optical Frequency Divider is responsible for down-converting coherently the ultra-pure optical signal generated by the stabilised laser head to microwave frequency (6.5GHz). It includes a femtosecond frequency comb and a microwave generation unit. The baseline design considered for the femtosecond frequency comb is the 100MHz repetition rate erbium-doped fibre comb selected for the DLR TEXUS mission (Menlo Systems design). In order to mitigate the risk related to radiation hardness of fibre lasers, an alternative solution based on single crystalline material lasers is also being considered.

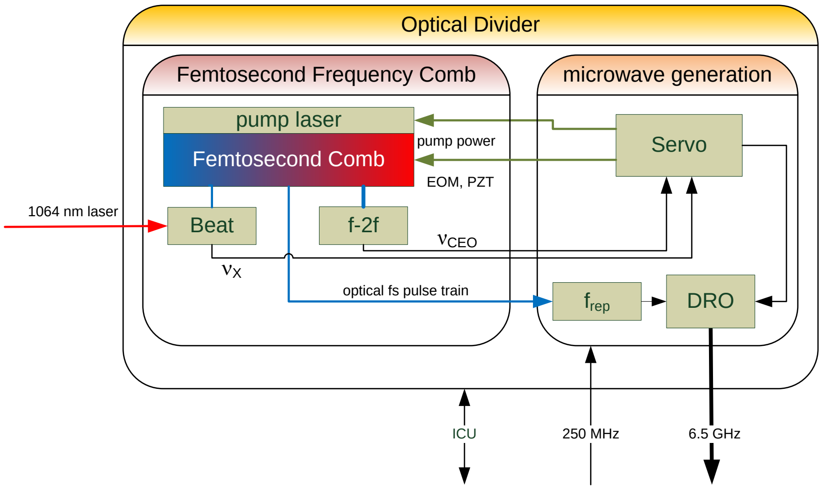


Figure 11: Block Diagram of MOLO Optical Frequency Divider

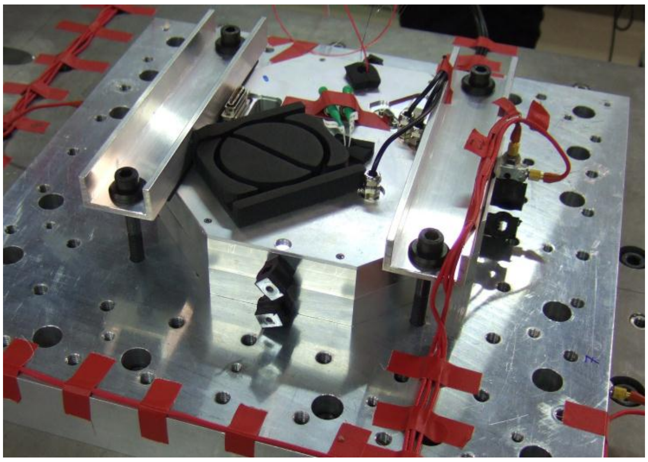


Figure 12: Menlo Systems femtosecond frequency comb for TEXUS experiment

3.2.4 Microwave Synthesis and frequency Distribution

The principle functions of the Microwave Synthesis and frequency Distribution (MSD) are to take the 6.5 GHz signal from MOLO and to distribute it to the space vehicle (i.e. the links) and to the atom interferometer, and to synthesise two 6.834682610 GHz signals for the rubidium tube. MSD also contains a USO which it can use as a backup for MOLO, and it provides a signal from the USO to MOLO for startup. (In normal operation the USO will be switched off.)

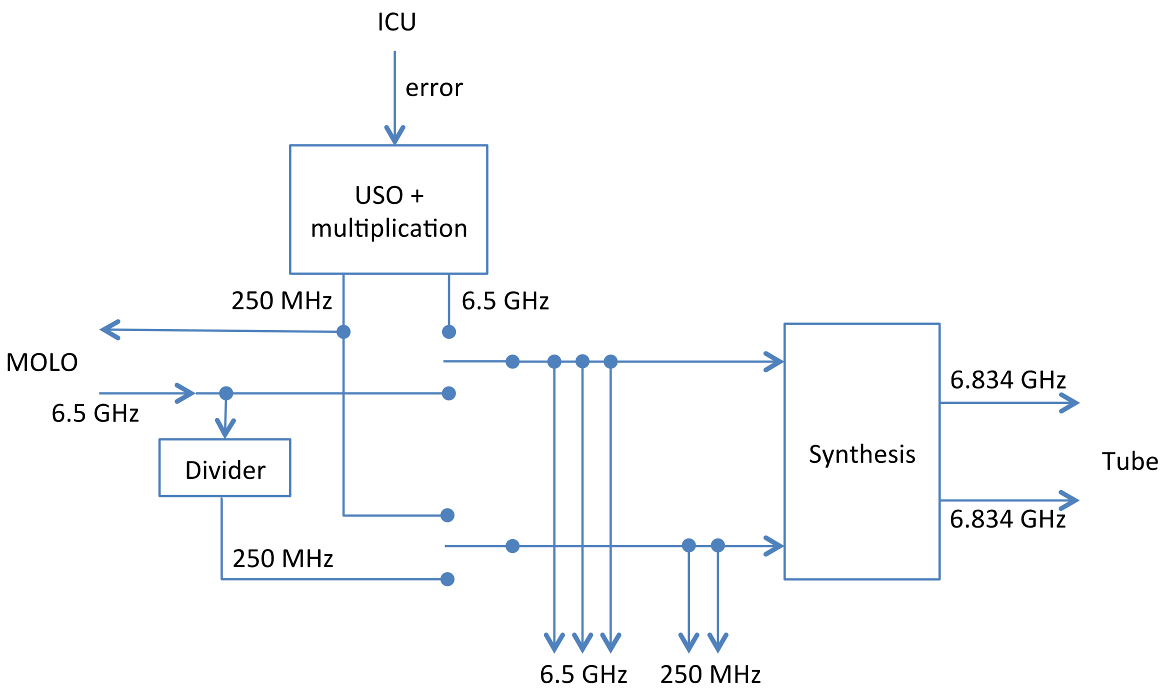


Figure 13: Block Diagram of MSD

3.2.5 *Instrument Control Unit*

The Instrument Control Unit, ICU, for the STE-QUEST atomic clock performs control and monitoring of the different clock subsystem. It is also the interface to the satellite platform for Telecommand and Telemetries. A review of the existing HW and SW for the control of Pharao and comparison with existing generic ICU architectures has concluded that the latter solution is the preferred one for the STE-QUEST ICU. It is expected that the design of the ICU will be elaborated in the course of the instrument assessment study.

3.3 Orbit, Operations, and Pointing

The orbit, operation and pointing of the STE-QUEST atomic clock, as required to meet the scientific objectives, are specified in the STE-QUEST Science Requirements Document and STE-QUEST Mission Requirements Document.

In terms of orbit, the uncertainty on the orbit determination of the Pharao NG Vacuum Tube (centre of the Ramsey cavity) shall not affect the intrinsic noise of the Atomic Clock. Further, the residual red-shift effect due to the error in the determination of the Gravitational Potential at the Pharao NG location is specified to be below 3.10-17.

In terms of operations, the Atomic Clock shall be able to operate in both internal (MOLO is used as reference signal) and external (external Ultra-Stable Oscillator is used) modes. Further, the Atomic Clock shall be able to operate on different Zeeman transitions.

In terms of orientation, the axis of the Pharao NG vacuum tube shall be preferably oriented perpendicularly to the orbital plane.

Additional orbit, pointing and operation requirements are expected to be defined as part of the STE-QUEST assessment and the STE-QUEST instruments studies.

3.4 Interfaces and Physical Resources

Interfaces and Physical Resources requirements as consolidated after instrument MTR are summarized in the tables below. For power consumption and dissipation, “typical” assumes steady-state operation in the middle of the temperature range and “maximum” corresponds to the warm-up period of the instrument. Further, safe mode power (e.g. vacuum pump + survival heaters, TBC) is considered to be 5W.

Mass – Power – Dimensions:

		Mass (kg)			Power(W)						Dimensions (mm)				
					typical			max							
		mass	margin	total mass	power	margin	total power	power	margin	total power	shape	L	W	H	total(l)
Rb Tube + 2D-MOT	Tube	45	20	54.0	4	20	4.8	4.6	20	5.5	box	1100	340	460	172.0
	2D-MOT	18	20	21.6	5	20	6	5.6	20	6.7	box	550	240	340	44.9
	BEBA	1.2	20	1.4	7	20	8.4	9	20	10.8	box	134	118	96	1.5
	CVT-HT	0.7	20	0.8	1	20	1.2	1.1	20	1.3	box	100	50	50	0.3
	total:	**64.9**		**77.9**	**17**		**20.4**	**20.3**		**24.4**					**218.7**
Laser Source	Tube Laser Source	22	20	26.4	47	20	56.4	53	20	63.6	box	532	335	198	35.3
	2D-MOT Laser Source	22	20	26.4	47	20	56.4	53	20	63.6	box	532	335	198	35.3
	total:	**44**		**52.8**	**94**		**112.8**	**106**		**127.2**					**70.6**
MOLO	Stabilised Laser Head	10	20	12.0	18.5	20	22.2	22	20	26.4	box	400	300	250	30.0
	Comb+mwave generat.	23	20	27.6	105	20	126	105	20	126.0	box	300	300	380	34.2
	total:	**33**		**39.6**	**123.5**		**148.2**	**127**		**152.4**					**64.2**
MSD	MSD	**8**	20	**9.6**	**26**	**20**	**31.2**	31	**20**	**37.2**	box	300	270	103	**8.3**
ICU	ICU	**6.1**	20	**7.3**	**75**	**20**	**90**	75	**20**	**90.0**	box	230	277	107	**6.8**
	Harness	9	20	10.8								-	-	-	-
	Insulation	4	20	4.8								-	-	-	-
	total:	**13**		**15.6**											
	grand total:	**169**		**202.8**	**335.5**		**402.6**	**359.3**		**431.2**					**368.6**
+20% system margin:				**243.4**			**483.1**			**517.4**					**N.A.**

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Thermal:

	Thermal					
Operational Temperature Range	Required Temperature Stability (operational)	Thermal gradient	Non-operational Temperature Range	Required Temperature Stability (non-ops)	Thermal dissipation	Required connections and expected heat load
283-303K	+- 3K per orbit	TBD	233-333K	+-10K per orbit	TBD	1) Power for heaters 2) H/K data port

Telemetry:

Telemetry		
Typical Sience data rate generated during operation	7.3	kbits/s
Maximum Sience data rate generated during operation	9.7	
Science data rate for TM to Earth (after compression/pre-processed data)	TBD	
Housekeeping TM data rate	TBD	
Telecommands Rx data rate	TBD	
Required on-board storage	TBD	Mbit

The Interfaces and Physical Resources requirements of the STE-QUEST atomic clock shall be consolidated and updated as part of the STE-QUEST assessment and the STE-QUEST instruments studies.

3.5 Environment

The space environment requirements of the STE-QUEST atomic clock are specified in AD03.

The environment of the STE-QUEST atomic clock, as required to meet the scientific objectives, are specified in the STE-QUEST Science Requirements Document. They mainly relate to the magnetic field variation with time and to non-gravitational accelerations.

The other environment requirements applicable to the STE-QUEST atomic clock shall be defined and updated as part of the STE-QUEST assessment and the STE-QUEST instruments studies, in particular in terms of:

- Tolerance to ionizing radiation (TID, SEU, SEE) as specified in AD03

- Mechanical environment from S/C to instrument: Max disturbing accelerations/vibration environment, max thermal distortions at instrument interface to S/C, shocks.
- Mechanical environment produced by the instrument (due to cooling, e.g.): Vibrations, thermal distortions of instrument, instrument resonance frequencies.
- Location with respect to CoM.
- Magnetic cleanliness requirements (AC and DC components)

3.6 Calibration

The calibration of the STE-QUEST atomic clock, as required to meet the scientific objectives are specified in the STE-QUEST Science Requirements Document. They relate to the minimum duration of the in-orbit calibration.

The requirements for the STE-QUEST atomic clock calibration both on ground and on board and its associated procedures shall be defined as part of the STE-QUEST assessment and the STE-QUEST instruments studies.

3.7 Cleanliness and Pre-launch Activities

Vacuum inside the Rb Tube and 2D-MOT has to be maintained at specified levels during all pre-launch and launch activities through the supply of power to the Ion Pump.
The further definition of the Cleanliness and pre-launch activities for the STE-QUEST atomic clock shall be defined as part of the STE-QUEST assessment and the STE-QUEST instruments studies.

3.8 Redundancy Concept

The baseline redundancy concept for the STE-QUEST atomic clock relies on a single clock with partial redundancy at sub-system level (e.g. laser system of PHARAO-Rb). This concept shall be consolidated and updated as part of the STE-QUEST assessment and the STE-QUEST instruments studies.

3.9 Heritage and Critical Issues

PHARAO-Rb is a direct evolution of PHARAO, a cold-atom clock based on Caesium atoms, currently in Proto-flight phase to be flown on the ACES Mission on-board the International Space Station. The main difference of the PHARAO-Rb is the use of Rb atoms requiring lasers at different wavelength (already commercially available) and the use of a 2-dimensional Magneto-Optical Trap to increase the number of cold atoms. Furthermor the control electronics will have to be updated.

The MOLO concept and performances have been demonstrated in a laboratory environment on ground in various places (including its operation with a fountain clock).

Beyond these experiments, there is no identified on-going development for an integrated and continuously operated on-board unit.

CW reference lasers are conventional commercial instruments. A reference laser at 1064nm has been successfully qualified for the Laser Communication Terminals currently flying on two LEO satellites (TerraSAR-X and NFIRE) and to be flown on Alphasat (GEO), Sentinels 1A-2A (LEO) and EDRS (GEO). Other reference/seed lasers are being developed for Lidar systems.

A few optical cavity technologies have been developed and qualified for space (e.g. Aladin laser head or LCT), however their finesse is not at the performance required for MOLO. A preliminary study is on-going under ESA contract (TRP-C#22461) for the development of stable optical reference cavities for use in an optical clock. However the finesse required for such cavities is likely to be significantly higher than the one required for MOLO which will have detrimental impact on accommodation (mass and power of vibration, temperature isolation…).

The Femtosecond Laser Frequency Comb is a commercial instrument supplied by at least one company in Europe (Menlo Systems GmbH, D) and sold at a few units per year. Preliminary studies for the possible space qualification of this unit have been conducted under ESA contract (C#20071) and have identified the radiation hardness of the optical fibre as a critical item. In addition, one commercial unit has been updated and successfully subject to acceleration tests in a drop tower and further evaluation/pre-qualification activities are planned under DLR programme.

MSD functionalities are similar to the ones of and the microwave source under development for the ACES mission, except for the handling and distribution of the optical signal for which no specific activity has been identified. In addition, the most probable highly frequency values combined with a factor 3 improvement in frequency stability as compared to ACES is expected to require design update and validation.

The Heritage and Critical Issues related to the STE-QUEST Atomic Clock shall be consolidated and updated as part of the STE-QUEST assessment study.

4 STE-QUEST ATOM INTERFEROMETER

4.1 Instrument Concept

The STE-QUEST Atom Interferometer senses differential accelerations experienced by ultra-cold atoms with very high sensitivity.

The atom interferometry will test the Weak Equivalence Principle (WEP) and is based on a differential measurement performed by two atom interferometers simultaneously probing the acceleration experienced by two clouds of two different atomic species.

The WEP violation can be expressed by using the Eötvös parameter. The use of two different isotopes of the same element, e.g. ^{85}Rb and ^{87}Rb, significantly simplifies the instruments at the same time ensuring a better control on common-mode noise sources (e.g. microvibrations or noise generated in the atom-optical beam splitting process) and on measurement systematic (e.g. gravity gradients, spurious rotations etc.).

STE-QUEST will make pair wise comparisons between the two isotopes of rubidium while it orbits around the Earth. Testing the universality of free fall at a level of one part in 10^{15} implies a measurement of the differential acceleration between the two atomic species at the same level of precision.

In the Atom Interferometer, Rubidium atoms of two different isotopes (^{85}Rb and ^{87}Rb) are sequentially captured, cooled, trapped and prepared in a high-vacuum vessel by a set of orthogonal laser beams and magnetic fields. The atoms undergo a second stage of cooling in a magnetic trap on an atom chip. After loading into a dipole trap and further evaporation cooling, the BEC state is reached. The atoms then undergo three successive interaction pulses (separated in time) with two detuned laser beams (the "Raman Lasers") whose detuning is coherently generated from either the ultra-pure MOLO signal (external operation) or from an internal ultra-stable local oscillator (internal operation). After these pulses, the position of the atom clouds is detected by light-induced fluorescence using laser beams and a photodiode. A CCD camera allows to obtain spatially resolved images for commissioning and diagnostic purposes. This cycle is repeated every 20 seconds and in contrary to PHARAO-Rb, there is no need for coherent repetition between the cycles. A top-level block diagram of the Atom Interferometer is presented in Figure 8 and an overview of the experimental cycling (excluding the 10 sec free evolution and detection) is shown in Figure 9(as provided by the instrument team).

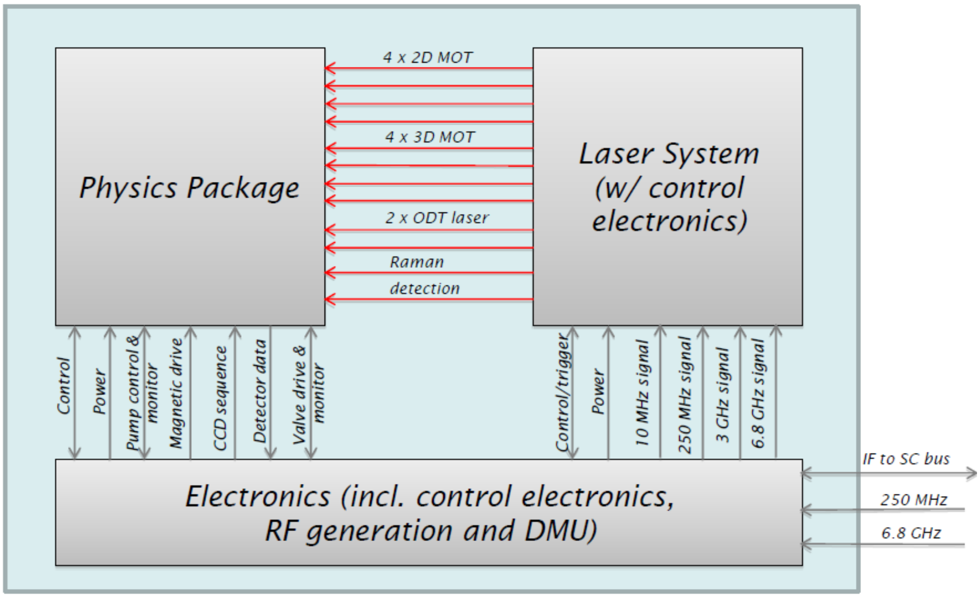

Figure 14: Atom Interferometer Top-Level Block Diagram

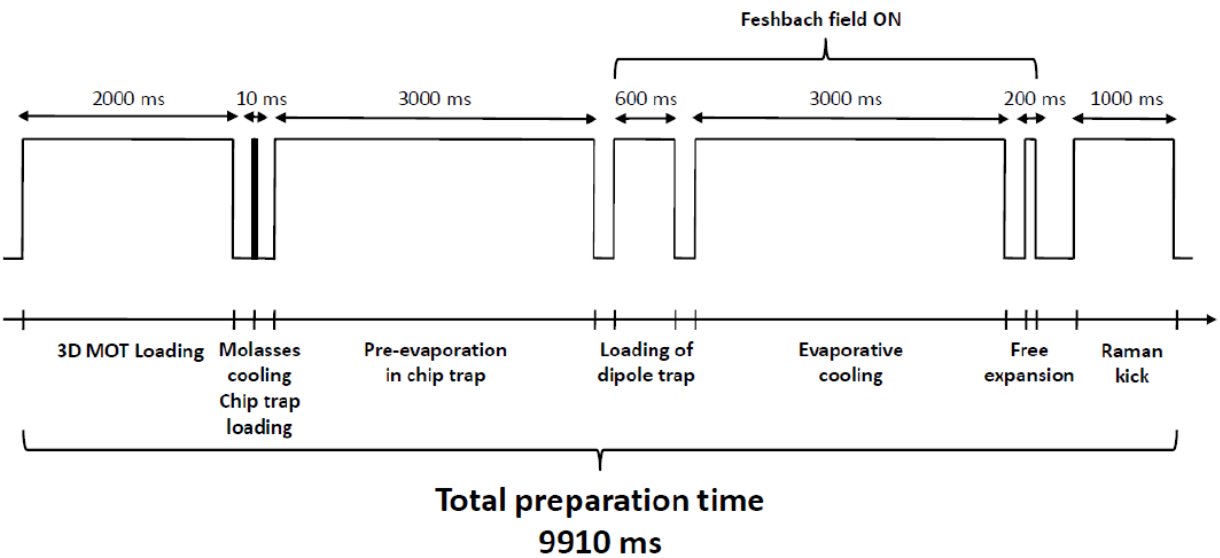

Figure 15: Time sequence for trapping and cooling the atom clouds. The 10 seconds expansion time and the detection sequence is not shown.

4.2 Instrument Description

4.2.1 Physics Package

The Physics Package of the Atom Interferometer includes the source of ^{85}Rb and ^{87}Rb atoms, the coils and laser interfaces allowing for the cooling and trapping of the atoms on the atom chip and the dipole trap, the photodiode and CCD sensor, all included in a high vacuum enclosure surrounded by magnetic shields. Figure 10 presents a design (used for sounding rocket experiments) of the inside of the cylindrical package as provided by the instrument team.

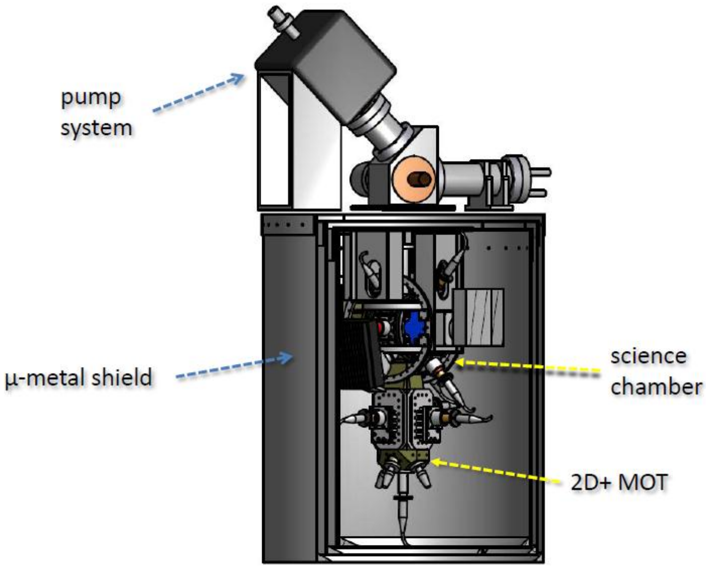

Figure 16: Sounding rocket design of the Physics Package

The STE-QUEST AI will be of a similar design, but with a different arrangement of the ports of the science chamber as shown in Figure 11. The sensitive axis of the AI will be coaligned with the sensitive axis of the cylinder hosting the instrument. The top part contains the UHV pump system and is separated from the lower part by a plate. This plate also provides the mechanical mounting interface to the spacecraft, either by a ring mount or by structural elements penetrating through the pump system section.

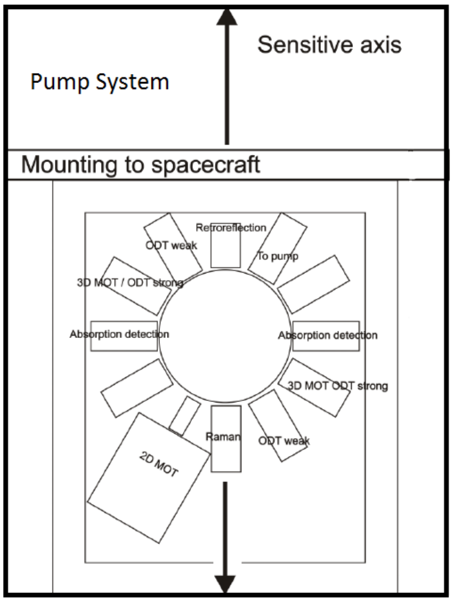

Figure 17: Conceptional design of the STE-QUEST AI.

4.2.2 Laser System

As for Pharao NG, the Laser Package of the Atom Interferometer includes a set of lasers for the cooling and detection of ^{85}Rb and ^{87}Rb atoms. In addition, it includes the medium power Raman lasers for the manipulation of the matter waves. A block diagram of the Laser Package for the Atom Interferometer is given in Figure 12 below.

The AI laser package consists of three sub-systems, the near resonant lasers, the dipole trap laser and the distribution and switching system (LDSS). The near resonant lasers can be either based on diode laser technology or on frequency doubled telecom lasers. Also the LDSS subunits can be a mixture between free space and fibre based components. No detailed baseline for the technology has been selected yet, but the listed budgets for mass, power and volume cover both options (diode or telecom lasers). The AI laser package is connected to the physics package by optical fibres.

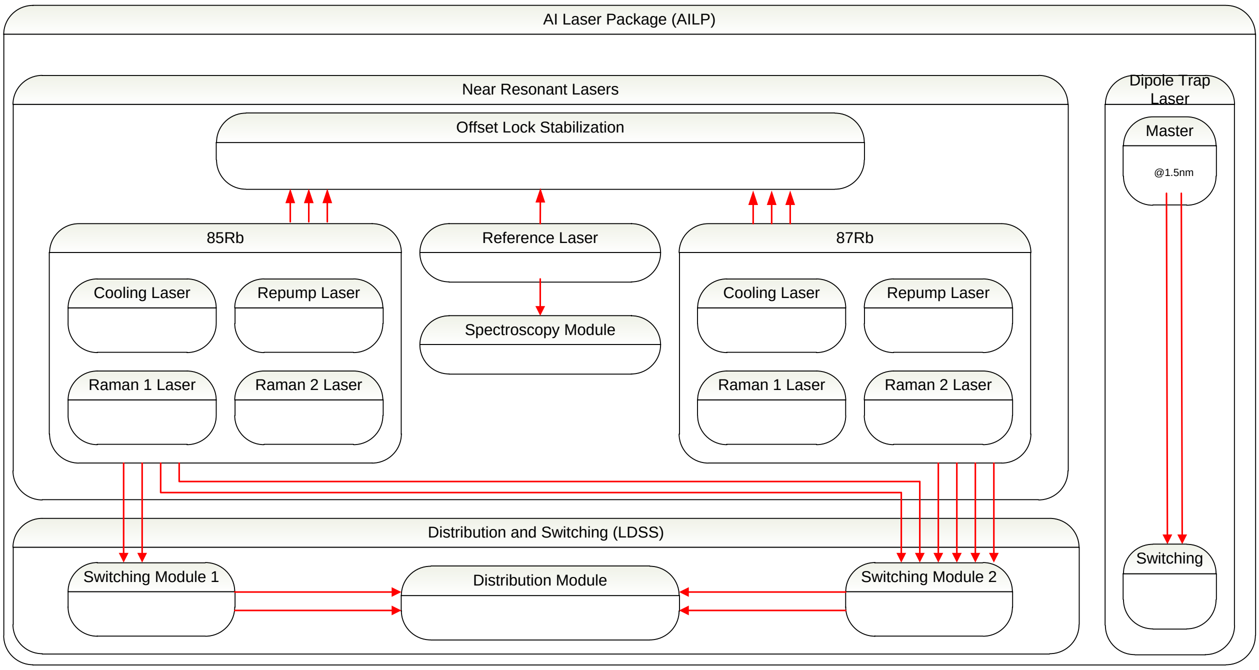

Figure 18: Example Block Diagram of AI Laser Package (redundant lasers are no shown)

4.2.3 Electronics

The AI electronics and control unit provides electrical power, rf signals, currents for the magnetic coils, signal and data processing. The electronics are distributed within two separate boxes. A small box contains the power and control unit for the ion pump, which needs continuous operation (also before and during launch) and provides high voltages in order to maintain the ultra-high vacuum. All other electronics are located in a second, larger box. A schematic overview of the electronics is shown in Figure 13.

The description and operation of the Atom Interferometer shall be consolidated and updated as part of the STE-QUEST Assessment and Instrument studies.

4.3 Orbit, Operations, and Pointing

The orbit, operation and pointing of the STE-QUEST atom interferometer, as required to meet the scientific objectives, are specified in the STE-QUEST Science Requirements Document and STE-QUEST Mission Requirements Document.

In terms of operation, the AI shall be able to operate in both internal mode (fed by an internal ultra-stable oscillator) and in external mode (fed by the ultra-stable signal of the Atomic Clock).

In terms of orientation, the sensitive axis of the atom interferometer shall point nadir to better than 3 deg at perigee. Rotation rates need to be limited to below 2 arcsec/sec.

Additional orbit, pointing and operation requirements are expected to be defined as part of the STE-QUEST assessment and the STE-QUEST instruments studies, in particular:

4.4 Interfaces and Physical Resources

Interfaces and Physical Resources requirements as extracted from the AI design at the time of the Mid Term Review of the instrument study are summarized in the table below.

Dimensions:

	Volume [mm] all instrument envelope box
Physics Package	Cylinder: 800 mm height, 600 mm diameter
Laser System	400x400x600
Electronics	450x400x300
Ion Pump Controller	100x100x100

The sensitive axis of the atom interferometer coincides with the cylinder axis. The location of the atom interferometer measurements is the centre of the cylinder. The mounting interface is the flat top surface of the cylinder or a ring interface as shown in Figure XX.

Mass:

	Current Best Estimate	Margin	Mass w/ margin
Physics Package	106.0	20%	127.2
Laser System	72.8	20%	87.3
Electronics	20.8	20%	26.0
Ion Pump Controler	1.0	20%	1.2
TOTAL	200.6		241.7
TOTAL with 20% System Margin		20%	290.1

Power:

	Typical	Typ w/ 20% margin	Peak	Peak w/ 20% margin
Physics Package	86.5	103.8	217.6	261.1
Laser System	303.5	364.2	307.5	369.0
Electronics	269.0	322.8	441.8	530.1
Ion Pump Controler	1.5	1.8	1.5	1.8
TOTAL	660.5	792.6	968.4	1162.0
TOTAL with 20% System Margin	792.7	951.2	1162.1	1394.5

The power consumption will be cycling with the measurement cycle as described in the instrument concept. The final cycle has yet to be decided. As a first estimate, one cycle of AI operations lasts 20 seconds, with roughly 10 seconds of peak power on the electronics and lasers. During the safe mode (instrument switched off), the Ion Pump Controller has to be operated (1.8 W).

Telemetry:

Telemetry		
Typical Sience data rate generated during operation	108	kbits/s
Maximum Sience data rate generated during operation	110	kbits/s
Science data rate for TM to Earth (after compression/pre-processed data)	TBD	
Housekeeping TM data rate	TBD	
Telecommands Rx data rate	TBD	
Required on-board storage	TBD	Mbit

Thermal:
The requirements given below are internal to the AI instrument. Interface temperature stability is expected to be the same as for the clock experiment, as defined in the previous chapter.

External Interface					
Operational Temperature Range	Required Temperature Stability (operational)	Non-operational Temperature Range	Required Temperature Stability (non-ops)	Thermal dissipation	Required connections and expected heat load
283-303K	+- 3K per orbit	233-333K	+-10K per orbit	TBD	1) Power for heaters 2) H/K data port

Internal						
	Operational Temperature Range	Required Temperature Stability (operational)	Non-operational Temperature Range	Required Temperature Stability (non-ops)	Thermal dissipation	Required connections and expected heat load
Laser modules	15 – 45°C	< 1 K/min	0 – 70°C	< 1 K/min	TBD	1) Power for temperature stabilization

Laser AOM	-10 – 40°C	< 1 K/min	-10 – 40°C	1 K/min	TBD	1) Power for temperature stabilization
Laser freq. stabilization	TBD	< 2 K/min	TBD	< 2 K/min	TBD	1) Power for temperature stabilization
Splitting module	TBD	< 4 K/min	TBD	< 4 K/min	TBD	1) Power for temperature stabilization
Current drivers	TBD	< 2 K/min	TBD	< 2 K/min	TBD	1) Power for temperature stabilization
Current driver for atom chip	TBD	< 4 K/min	TBD	< 4 K/min	TBD	1) Power for temperature stabilization

The Interfaces and Physical Resources requirements of the STE-QUEST atom interferometer shall be consolidated and updated as part of the STE-QUEST assessment and the STE-QUEST instruments studies.

4.5 Environment

The space environment requirements of the STE-QUEST AI are specified in AD03.

The environment of the STE-QUEST atom interferometer, as required to meet the scientific objectives, are specified in the STE-QUEST Science Requirements Document. They mainly relate to the maximum rotation, spurious and non gravitational accelerations that can be experienced by the Atom Interferometer.

Radiation environment shall be assessed, but it is expected that the instrument boxes inside the spacecraft will require a TID of less than 100 krad after 4 mm of equivalent Aluminium shielding of the spacecraft (see AD03).

Magnetic Cleanliness and environment requirements are stated in the Mission Requirements Document [AD02].

4.6 Calibration

The calibration of the STE-QUEST atom interferometer, as required to meet the scientific objectives are specified in the STE-QUEST Science Requirements Document. They relate to the minimum duration of the in-orbit calibration.

First tests and calibration are to be done on ground, with further calibration and tests executed during the science commissioning phase for items not possible to test on ground (e.g. atom cloud evolution).

The requirements for the STE-QUEST atom interferometer calibration both on ground and on board and its associated procedures shall be defined as part of the STE-QUEST assessment and the STE-QUEST instruments studies.

4.7 Cleanliness and Pre-launch Activities

The ion pump within the physics package needs to be continuously operated such that the specified vacuum is maintained during testing, pre-launch, and launch.

4.8 Redundancy Concept

The baseline redundancy concept for the STE-QUEST atom interferometer relies on a single instrument with partial redundancy at sub-system level (e.g. laser system).

- Physics package: No redundancy
- Laser: yes, internal redundant
- Electronics: Hot redundant onboard computer

4.9 Heritage and Critical Issues

A number of Atom Interferometers experiments are operating in several Laboratories worldwide but remain at the level of experiments, without any objective for integration and autonomous operation.

At least three experiments (all represented in the STE-QUEST Science Study Team) have focussed on preliminary technology development and performance assessment in microgravity in a drop tower, on sounding rockets and in a zero-g aircraft respectively. However, the measurement concept proposed for STE-QUEST has not been demonstrated yet. Further, the design of the teams is quite different.

As a result, the mass-volume-power budget estimates are based on an early preliminary design based on the three heritage experiments and extrapolated to the STE-QUEST baseline design.

In terms of technology, substantial commonalities with PHARAO and PHARAO-Rb exist. The technologies for high-vacuum vessels and atom capture, cooling and manipulation are expected to be similar, thanks to the use of the same atom specie. Similarly, the technologies required for the fluorescence signal detection, laser stabilisation, microwave frequency generation and control are supposed to be similar. The main difference is the need for stable and relatively high power lasers. Such devices are however commercially available, although not space qualified.

The Heritage and Critical Issues related to the STE-QUEST Atom Interferometer shall be consolidated and updated as part of the STE-QUEST assessment study.

5 SCIENCE TIME AND FREQUENCY LINKS

This section is provided for reference only as the time and frequency links are part of the industrial study. The information provided is based on the CDF study.

5.1 The Microwave Link

5.1.1 Description

The Microwave Link includes one Microwave Link Space Terminal together with its associated antenna(s). From the ultra-stable Atomic Clock signal, it generates and PRN-modulates three (TBC) carriers that are transmitted to the earth. Simultaneously, it receives up to 4 channels and cross-correlates these PRN-modulated signals generated from Microwave Ground Terminals located on the earth with a replica generated from the on-board reference signal. The MWL is expected to operate in S and Ka-bands. The overall concept of the Microwave link is depicted in the Figure below, extracted from the STE-QUEST proposal. A possible block diagram (based on ACES heritage) is depicted in the subsequent figure.

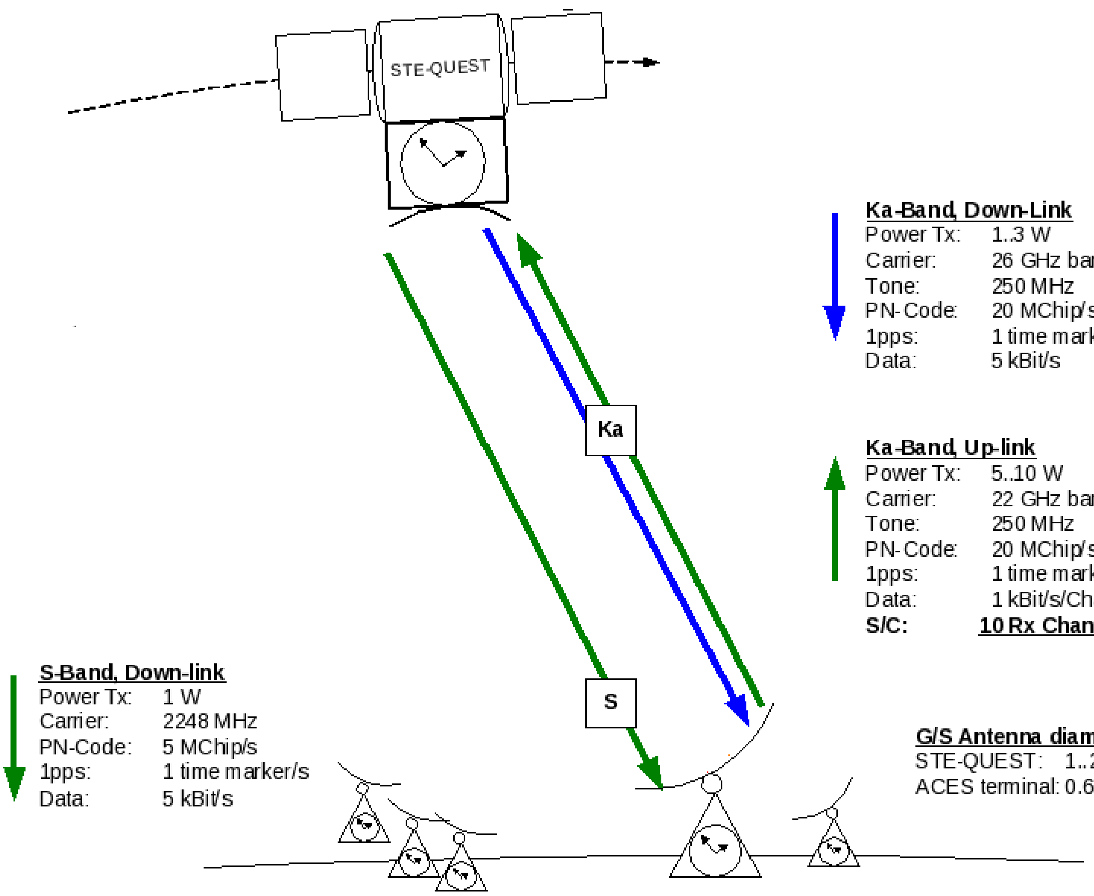

Figure 19: Microwave Link Overview

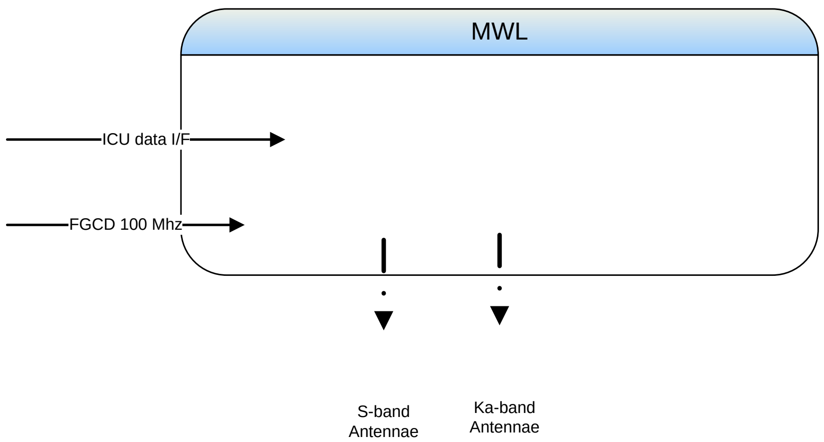

Figure 20: Example Layout for the Microwave Link

The description and operation of the MWL unit shall be consolidated and updated as part of the STE-QUEST Assessment and Instrument studies.

5.1.2 Operations, and Pointing

The operation and pointing requirements of the STE-QUEST MWL unit shall be defined as part of the STE-QUEST assessment study.

5.1.3 Interfaces and Physical Resources

The MWL has been accommodated on a dedicated panel during the CDF study to avoid obstructions in the radiation pattern and ease integration and test. An overview of the current layout is given in the figure below. Note the multiple horn antennae to obtain optimized radiation patterns for perigee and apogee passes.

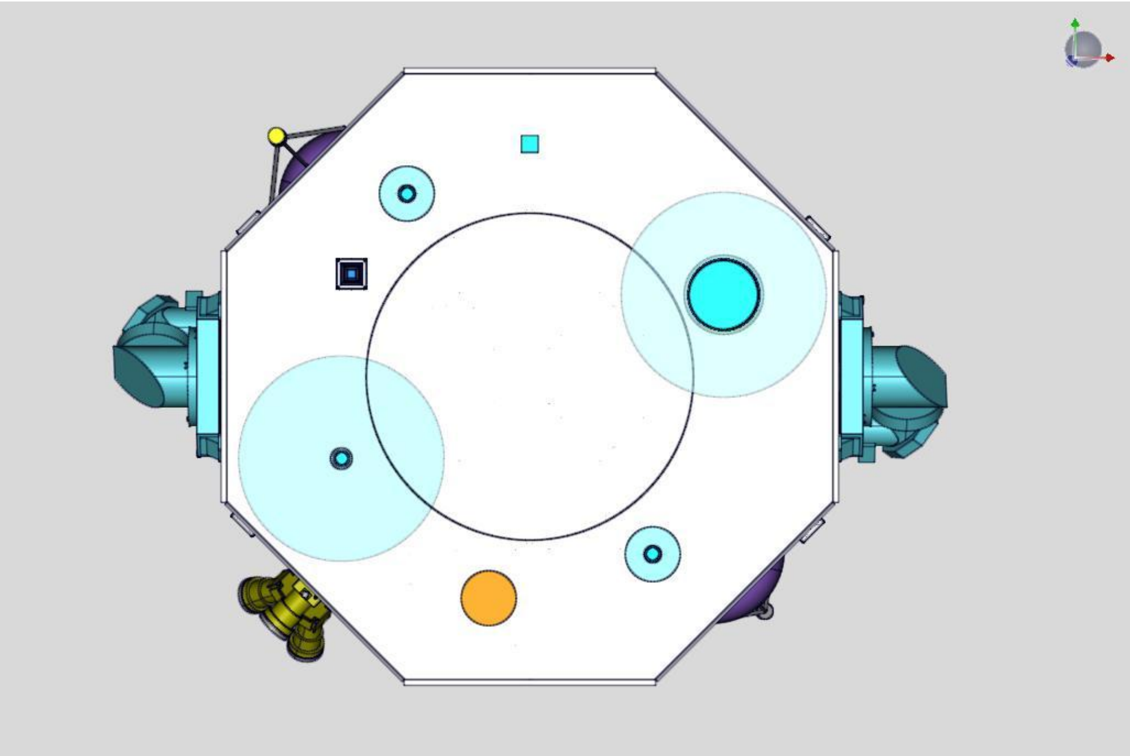

Figure 21: Antennae placement from the CDF study (light green shades denote minimum obstruction-free zones) .

Interfaces and Physical Resources requirements as extracted from the STE-QUEST CDF Study and are summarized in the table below.

Dimensions:

STE-QUEST		DIMENSIONS [m]			
Unit Name	Quantity	Shape	Dim1 Length	Dim2 Width	Dim3 Height
MWL EU	1.00	box			
MWL S-Band LGA	1.00	cone		0.1	0.2
MWL S-Band HGA	1.00	cone		0.3	0.2
MWL Ka-Band LGA	1.00	cone		0.1	0.2
MWL Ka-Band HGA	1.00	cone		0.2	0.1
MWL S-Band SSPA	1.00	box	0.2	0.1	0.1
MWL Ka-Band TWT	1.00	box	0.2	0.1	0.1
MWL Ka-Band EPC	1.00	box	0.2	0.1	0.1

Mass:

STE-QUEST		MASS [kg]		
Unit Name	Quantity	Mass per quantity excl.	Margin	Total Mass incl. margin
MWL EU	1.00	15.00	20	18.0
MWL S-Band LGA	1.00	2.00	20	2.4
MWL S-Band HGA	1.00	2.00	20	2.4
MWL Ka-Band LGA	1.00	2.00	20	2.4
MWL Ka-Band HGA	1.00	2.00	20	2.4
MWL S-Band SSPA	1.00	0.80	20	1.0
MWL Ka-Band TWT	1.00	1.50	5	1.6
MWL Ka-Band EPC	1.00	0.90	5	0.9
				0.0

Power:

STE-QUEST		
Unit Name	Quantity	Ppeak
MWL EU	1.00	40.0
MWL S-Band LGA	1.00	0.0
MWL S-Band HGA	1.00	0.0
MWL Ka-Band LGA	1.00	0.0
MWL Ka-Band HGA	1.00	0.0
MWL S-Band SSPA	1.00	25.0
MWL Ka-Band TWT	1.00	30.0
MWL Ka-Band EPC	1.00	

The Interfaces and Physical Resources requirements of the STE-QUEST MWL unit shall be consolidated and updated as part of the STE-QUEST assessment studies.

5.1.4 Environment

The environment requirements applicable to the STE-QUEST MWL unit shall be defined and updated as part of the STE-QUEST assessment and the STE-QUEST instruments studies, in particular in terms of:

- Tolerance to ionizing radiation (TID, SEU, SEE)
- Mechanical environment from S/C to instrument: Max disturbing accelerations/vibration environment, max thermal distortions at instrument interface to S/C, shocks.
- Mechanical environment produced by the instrument (due to cooling, e.g.): Vibrations, thermal distortions of instrument, instrument resonance frequencies.
- Need of Drag-free-Control
- Location with respect to CoM.
- Magnetic cleanliness requirements (AC and DC components)

5.1.5 Calibration

The calibration required by the MWL unit in order to meet the STE-QUEST scientific requirements is defined in the STE-QUEST Science Requirements Document. The differential delays of the link shall be calibrated to better than 50ps.

5.1.6 Redundancy Concept

The baseline redundancy concept for the STE-QUEST MWL unit relies on 1 single unit with partial internal redundancy at sub-system level (TBC). This shall be consolidated and updated as part of the STE-QUEST assessment studies.

5.1.7 Heritage and Critical Issues

Overall, MWL functionalities are similar to the ones of the PRARE terminal (on-board ERS-2) or the MWL under development for the ACES mission. However the required performance will likely call for the implementation of a third channel in Ka-band. Further, the difference in orbit (HEO vs. circular LEO for ACES) affects significantly the link budget (including in S and Ka-band) due to higher propagation losses and much wider dynamic range. In addition, pointing requirements and antenna phase centre stability should also be demonstrated.

The Heritage and Critical Issues related to the STE-QUEST MWL unit shall be consolidated and updated as part of the STE-QUEST assessment study.

5.2 The Optical Link

5.2.1 Description

The Optical Link includes a space terminal and two optical telescopes with 2π steradian orientation allowing for simultaneous point-to-point bi-directional link with at least two ground stations equipped with an Optical Link Ground Terminal. The reference optical signal from the on-board Atomic Clock is used to generate the optical carrier while the microwave reference signal is used to PRN-modulate the optical carrier that is transmitted to a ground station. Simultaneously, the optical terminal receives and cross-correlates PRN-modulated optical carriers generated from Optical Ground Terminals located on the earth with a replica generated from the on-board reference signal. A possible block diagram of the optical link terminal is depicted in the figure below.

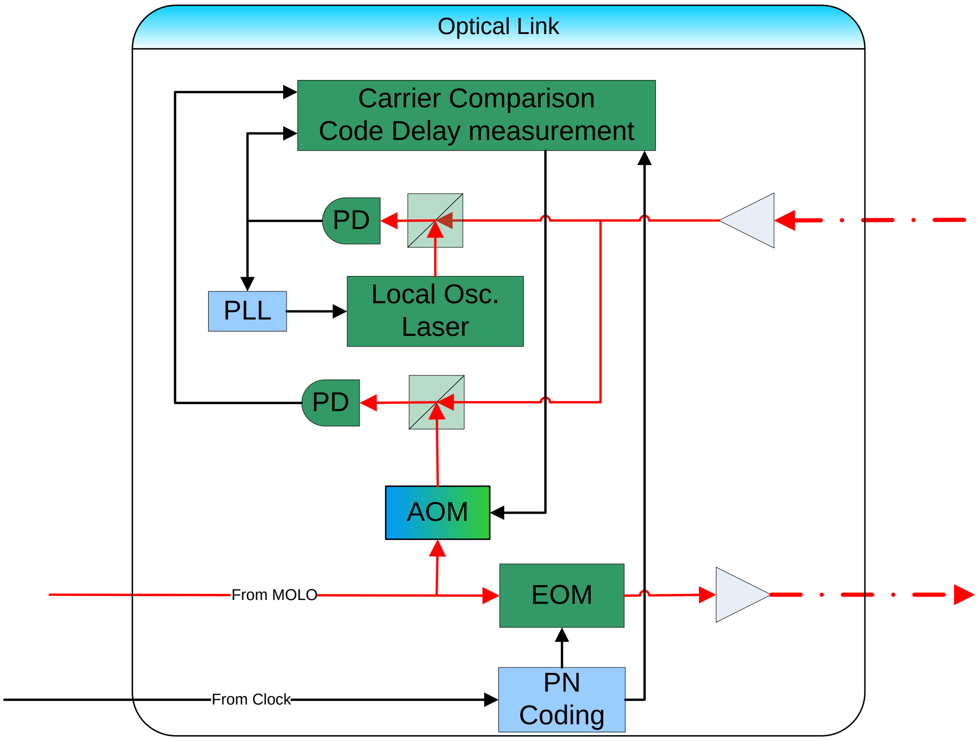

Figure 22: Example Layout for the optical link (space segment)

The description and operation of the OPL unit shall be consolidated and updated as part of the STE-QUEST Assessment and Instrument studies.

5.2.2 Interfaces and Physical Resources

Based on the Tesat Laser Communication Terminal (LCT), the CDF team has accommodated a sample OPL. In the figure below, the current placement is shown. Two terminals are placed to ensure two independent, simultaneous links.

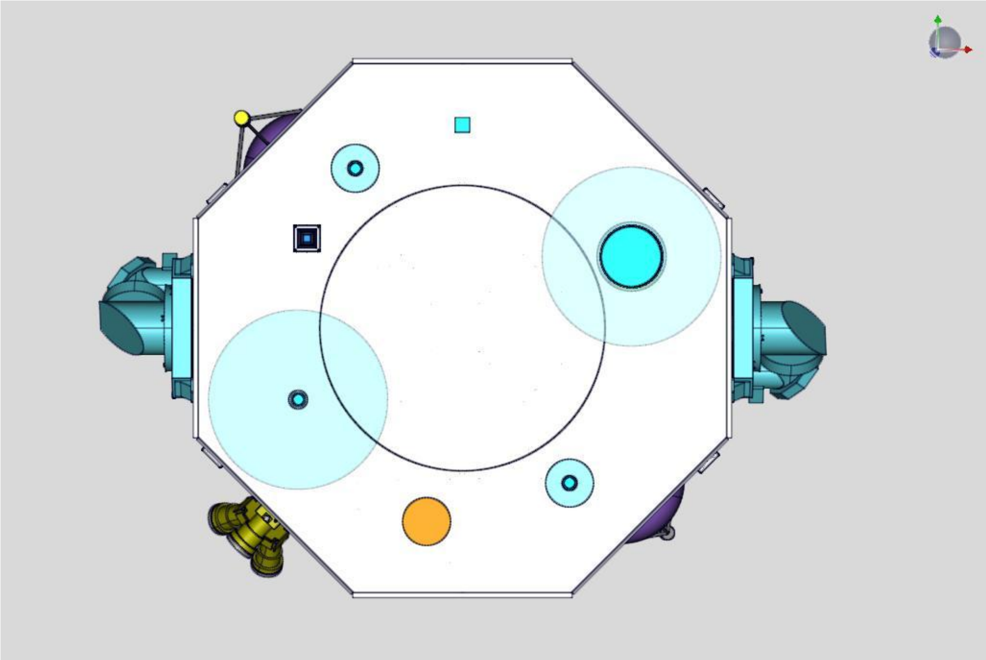

Figure 23: Placement of the two LCT heads on the CDF model of STE-QUEST. Placement on two different, opposite panels ensures the common view capabilities.

Interfaces and Physical Resources requirements as extracted from the STE-QUEST CDF Study and are summarized in the table below.

Dimensions:

STE-QUEST		DIMENSIONS [mm]			
Unit Name	Quantity	Shape	Dim1 Length	Dim2 Width or D	Dim3 Height
LCT	1				
LCT (except code/carrier meas. Unit)	2	box	600.0	600.0	700.0
Code/Carrier Measurement Unit	2				

Mass:

STE-QUEST		MASS [kg]		
Unit Name	Quantity	Mass per quantity excl. margin	Margin	Total Mass incl. margin
LCT	1			
LCT (except code/carrier meas. Unit)	2	50.0	10	110.0
Code/Carrier Measurement Unit	2			0.0

Power:

STE-QUEST		
Unit Name	Quantity	Ppeak
LCT	1	
LCT (except code/carrier meas. Unit)	2	360.0
Code/Carrier Measurement Unit	2	

The Interfaces and Physical Resources requirements of the STE-QUEST OPL unit shall be consolidated and updated as part of the STE-QUEST assessment and the STE-QUEST instruments studies.

5.2.3 *Environment*

The environment requirements applicable to the STE-QUEST OPL unit shall be defined and updated as part of the STE-QUEST assessment and the STE-QUEST instruments studies, in particular in terms of:

- Tolerance to ionizing radiation (TID, SEU, SEE)
- Mechanical environment from S/C to instrument: Max disturbing accelerations/vibration environment, max thermal distortions at instrument interface to S/C, shocks.
- Mechanical environment produced by the instrument (due to cooling, e.g.): Vibrations, thermal distortions of instrument, instrument resonance frequencies.
- Need of Drag-free-Control
- Location with respect to CoM.
- Magnetic cleanliness requirements (AC and DC components)

5.2.4 *Calibration*

The calibration required by the OPL unit in order to meet the STE-QUEST scientific requirements is defined in the STE-QUEST Science Requirements Document. The differential delays of the link shall be calibrated to better than 50ps.

Additional calibration and associated procedure for the OPL unit shall be defined as part of the STE-QUEST assessment study.

5.2.5 *Redundancy Concept*

The baseline redundancy concept for the STE-QUEST OPL unit relies on 1 single unit with partial internal redundancy at sub-system level (TBC). This shall be consolidated and updated as part of the STE-QUEST assessment and the STE-QUEST instruments studies.

5.2.6 *Heritage and Critical Issues*

On-board optical terminals for bi-directional telecommunication links are currently being used on-board two LEO spacecrafts (TerraSAR-X and NFIRE), demonstrating full telecommunication performance in wide dynamic ranges. The same will be used on-board Alphasat (GEO), Sentinels 1A-2A (LEO) and EDRS (GEO) with the goal to demonstrate LEO-GEO links. The technology required for the OPL implementation is not expected to be significantly different; however the actual time and frequency transfer performance have not been demonstrated yet.

Major disturbances affecting the link performance are expected due to the atmosphere. Due to the high relative speed during perigee passage, Doppler as well as quickly changing atmospheric disturbances will degrade performance. Typical compensation via e.g. a lambda configuration might prove difficult. These effects have to be taken into account and corrected for by proper design and compensation methods.

The Heritage and Critical Issues related to the STE-QUEST OPL unit shall be consolidated and updated as part of the STE-QUEST assessment study.