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
Mission Requirements Document

Prepared by	**STE-QUEST Study Team**
Reference	**SRE-PA/2011.074/RQ/MG**
Issue	**2**
Revision	**3**
Date of Issue	**18/09/2012**
Status	**Conditionally approved**
Document Type	**RQ**
Distribution	

APPROVAL

Title STE-QUEST Mission Requirements Document	
Issue 2	**Revision** 3
Author	**Date** 18/09/2012
Approved by	**Date**

CHANGE LOG

Reason for change	Issue	Revision	Date
Updated version for the start of the CDF assessment phase	1	0	11/05/2011
Updated version for the start of the industrial assessment phase, New SciRD.	2	0	22/09/2011
New SciRD Revision (I1R2) and multiple corrections/clarifications on requirements	2	1	15/01/2012
New SciRD Revision (I1R2) and corrections on requirements	2	2	15/02/2012
New SciRD I1R3 and multiple clarifications/corrections, preparation of AO	2	3	14/09/2012

CHANGE RECORD

Issue 2	**Revision** 3		
Reason for change	**Date**	**Pages**	**Paragraph(s)**
Transfer of Updated SciRD into MRD and multiple clarifications on Requirements R-SPM-010 to -040 and 140-160: updated to new SciRD R-SPI-010: removed TBC w.r.t new SciRD R-SPI-020: Note associated with requirement deleted. R-SPI-030: Corrected according to pointing standards. R-SPI-040: Cleanliness defined to be at mu-metal interface. R-SPI-060: Added “within instrument volume” R-SPI-070: Added note for clarification. R-MISD-050: New axis definition. R-MISD-080: Deleted. R-SYS-030: Modified due to insufficient data in the referenced AD. R-OGS-140: Changed to R-OGS-145 (double numbering before) and a maximum of 2 G/S and	15/01/2012	throughout	throughout

added note. R-OGS-160: Added note for clarification.			
R-SPM-010: Misspelled exponent change from 10^-11 to 10^-10	15/02/2012	14	3.1
Updated SciRD (I1R2, 05/03/2012) Added a definition in section 1.4. R-MOBJ-010 and 020: changed to accommodate the new goal formulation and lower the sun red-shift requirement to 2E-6 from 6E-7. G-MOBJ-110: added “in the gravitational potential” for clarification. R-MIS-050: Clarifications on where to achieve this number. R-SPM-010: Change from 6.3 back to 6.2E-10 and added “reference value”. R-SPM-020: Change from 7.7 to 6.9E-11 and added “reference value”. R-SPM-030: time requirement for perigee relaxed to 1E5 sec from 4.5E5 and added requirement on apogee time. R-SPM-040: removed fragment “in a four(4”. R-SPM-060: 5h increased to 25000s. R-SPM-150: Modified to reflect total duration rather than perigee duration. G-SPM-170: added requirement (goal) G-SPM-180: added requirement (goal) R-SPL-010: change from ADEV to MDEV and applicable time interval now from 10 s instead 1 s. R-SPL-020: change from ADEV to MDEV and relaxation of short term requirement, change of time intervals from [1,1E4] to [10, 2E4] and [1E4,1E5] to [2E4, 1E5]. R-SPL-030: relaxation from 1E-18 to 3E-17 and addition of ground clock comparison down to 5E-19. R-OGS-180: refined definition of distance requirement.	09/03/2012	throughout	throughout
Preparation of AO Loss of trace for R-SPM-150 R-SPM-140: updated to include delta-t(clock, perigee) R-SPM-120, R-SPM-130: updated to clarify that these performances will need to be reached after post-processing only. Changed AD9 to be inline with updated Agency policies to ECSS-U-AS-10C. Added RD4: ESA pointing error handbook, changed SciRD to AD from RD, added orbital solution as AD, added environmental spec as AD Added Mission Description R-MIS-010 updated for no backup R-MIS-020 for launch date R-MIS-030: orbit provided R-MIS-040, 050, deleted R-MIS-070 updated to reflect EID-A (Phases)	18/09/2012	Throughout	throughout

R-MIS-081 added R-MIS-091 inserted R-MIS-100 to 160 : deleted R-MIS-170, 180 updated to reflect phases G-MIS-200 changed, R-MIS-201 added R-MIS-211 added R-MIS-240 to 260 on mission modes/spacecraft added R-SPM-010 to 060: note added R-SPM-050 deleted, superseded by SPL-060/070 R-SPI-010,020 deleted (superseded by EID-A) R-SPI-030 to 070: changed and added requirements for better definition. R-THRM 010,020 deleted R-AOCS 010 to 040 deleted R-PLD-021 added R-OGS-110,111,112 modified added to reflect SOAD, EID Inserted Annex 1			

Table of contents:

1 INTRODUCTION

1.1 Background

STE-QUEST is an M-class mission candidate for the M3 slot within the Cosmic Vision programme, for a planned launch between 2022 and 2024. STE-QUEST, with 3 other science missions, was recommended by the Space Science Advisory Committee (SSAC) to enter an assessment study (Phase 0), starting by an ESA internal study followed by parallel industrial study activities.

Within the M3 boundary conditions, the readiness for launch by end 2022/2024 is a severe requirement which in practice requires designing the space segment without major technology developments and with minimum developments risks. Therefore, only technologies with estimated Technology Readiness Levels (TRL) of at least 5 by the end of the Phase A (estimated at the end of 2014) may be used.

1.2 Scope of document

This document aims at providing a complete and comprehensive list of all high level mission requirements (including S/C and payload, launcher, ground segment and operations) necessary to achieve the science goals detailed in [[AD 1]]. It is hence an applicable document that shall be complied with for all mission design activities. The MRD will be further reviewed matching the results of future study phases (e.g. definition phase) to finally evolve in the System Requirements Document at the start of the implementation phase.

1.3 Requirements identification

1.3.1 Requirements and Goals

Requirements are mandatory and must be complied with. They shall be verified by the Contractor using a verification method approved by ESA.

Performance goals are desirable in order to maximise the science return while keeping the impact on the cost and complexity to a minimum. They are to be the subject of system trade-offs and analysis, and which are to be fulfilled under restricted conditions which are to be defined and quantified.

1.3.2 Requirement Identification

All requirements in this specification that require verification are marked with a unique reference, which is given as follows:

X-YYYY-nnn

where:

- *X* is the requirement type: “R” for a requirement or “G” for a goal
- *YYYY* is the requirement category consisting of 3 to 4 letters

- *nnn* is the requirement identifier (sequential number of 3 digits).

1.3.3 Explanatory Text

Supplementary text added to explain the source or reasoning behind a requirement is written after the requirement in *italics*.

1.4 Definitions

For the purpose of defining clear interfaces and responsibilities and in no means implying or anticipating any proposal or decision on such matters due at a later stage of the process (the AO) the following nomenclature for the **payload** shall apply, i.e. the term payload refers to the full set:

1) **Core Science Instruments** (or short: **instruments**) shall refer to
    a. **The Atomic Clock** and its subsystems
    b. **Atom Interferometer** and its subsystems
2) **Science Links (Time and Frequency Links)** shall refer to
    a. **The Microwave Link** (as used for Time and Frequency)
    *b. **The Optical Link** (as used for Time and Frequency)*
3) **Supporting Units**
    a. **POD equipment** (e.g. GNSS receiver and Corner Cube reflectors)

In addition to the definitions above, the following definitions shall apply:

τ	Time
U	Gravitational Potential
ΔU	Difference in gravitational potential between two specified points
c	speed of light
f	frequency

A 4-year time period, as used in many requirements refers to a time-span within R-MIS-180. The use of a 4 year period assures sufficient margin to achieve the objectives in 4.5 years.

1.5 Acronyms

AD	Applicable Document
AIT	Assembly, Integration and Test
AIV	Assembly, Integration and Verification
AOCS	Attitude and Orbit Control System
APE	Absolute Pointing Error
CDMS	Control and Data Management System
CDF	Concurrent Design Facility
CPU	Central Processing Unit
CReMA	Consolidated Report on Mission Analysis
e.c.	Economic Conditions

ECSS	European Cooperation for Space Standardisation
EGSE	Electrical Ground Support Equipment
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EOL	End of Life
EPS	Electric Power System
ESA	European Space Agency
ESTEC	European Space Research and Technology Centre
FAR	Flight Acceptance Review
FMECA	Failure Mode, Effects, and Criticality Analysis
GSE	Ground Support Equipment
G/T	Ground Terminal
H/W	Hardware
LEOP	Launch and Early Orbit Phase
MAG	Mission Analysis Guidelines
MGSE	Mechanical Ground Support Equipment
MOC	Mission Operations Centre
MOLO	Microwave-Optical Local Oscillator
MRD	Mission Requirements Document
MSD	Microwave Synthesis and frequency Distribution
OBDH	On-Board Data Handling
OTS	Off-The-Shelf
PA	Product Assurance
PDR	Preliminary Design Review
POD	Precise Orbit Determination
RD	Reference Document
RPE	Relative Pointing Error (pointing stability)
Rx	Receive
S/W	Software
SciRD	Science Requirements Document
SI	International System of Units
SOC	Science Operations Centre
SPF	Single Point Failure
SSAC	Space Science Advisory Committee
STE-QUEST	Space Time Explorer and Quantum Equivalence Principle Space Test
SVT	System Verification Test
TBC	To Be Confirmed
TBD	To Be Determined
TC	Telecommand
TM	Telemetry
TRL	Technology Readiness Level
TTC	Telemetry, Tracking and Command
Tx	Transmit
UTC	Universal Time Coordinated

1.6 Documentation

1.6.1 *Documentation architecture*

The mission requirements document is one of the documents that constitute the complete documentation set for the STE-QUEST study. This MRD is supported by:

- Science Requirements Document [AD 1]
- STE-QUEST Payload Definition Document [RD 04], reference only
- Experiment Interface Document Part A (binding requirements document for the instrument studies.

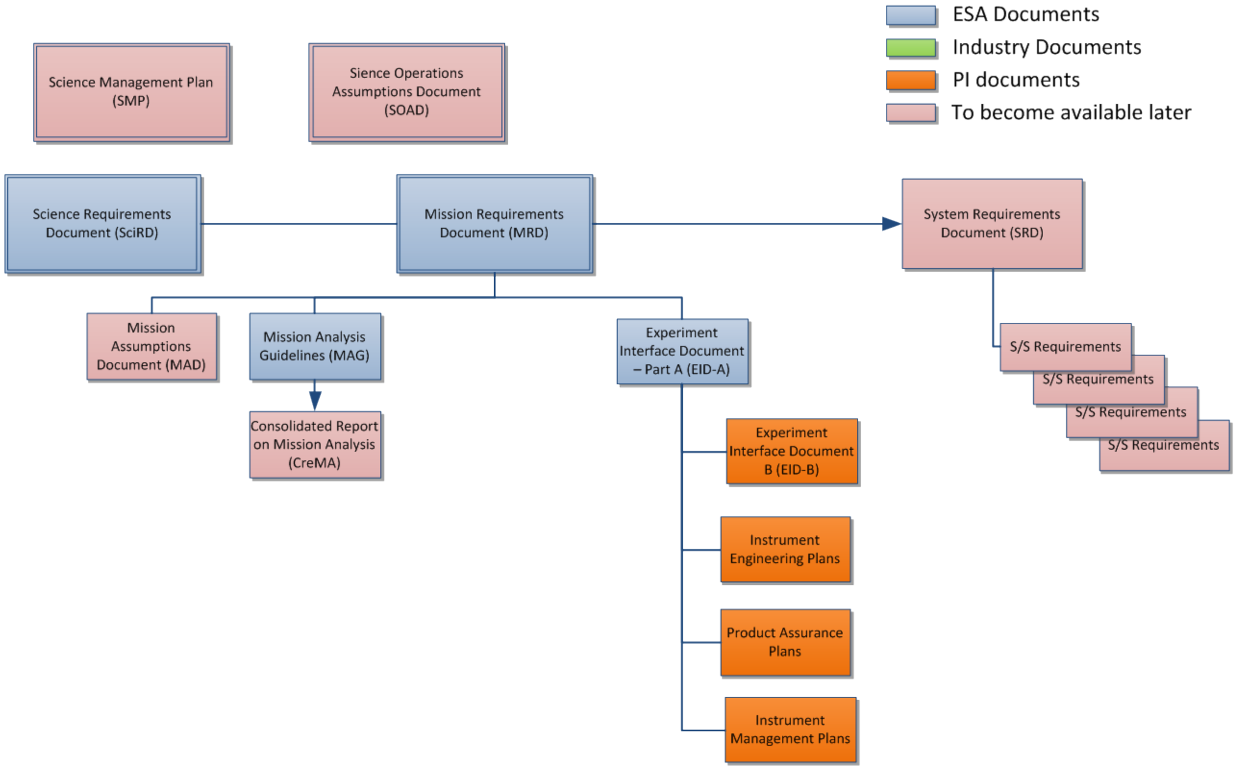


Figure 1: ESA Top Level Document Tree

1.6.2 *Documentation Issue Schedule*

This document follows the issuing schedule as described below.

Issue	Description
0	Draft
1	Issue before CDF
2	Issue before industrial study
3	Issue for PRR

This document is currently an open document. Refinements or updates are to be expected. These refinements/updates will be issued as a new revision during the validity of any issue.

Given the preliminary nature of a requirements document for assessment studies, a full re-issue including a new numbering will take place after the industrial studies.

1.6.3 Applicable documents

[AD 1] STE-QUEST Science Requirements Document FPM-SA-Dc-00001

[AD 2] Experiment Interface Document – Part A SRE-FA/2012.096/STEQ/EID

[AD 3] Margin Policy for SRE-PA Studies, SRE-PA/2011.097

[AD 4] ESA Tracking Stations Facilities Manual, DOPS-ESTR-OPS-MAN-1001-OPS-ONN

[AD 5] Soyuz CSG User Manual (Arianespace), Issue 2 Revision 0 or later

[AD 6] List of ESA Approved Standards ESSB-AS, I3.2, Dec 2010

[AD 7] ECSS System - Description, implementation and general requirements ECSS-S-ST-00C

[AD 8] ECSS Set of Space Engineering Standards, ECSS-E-Series

[AD 9] ECSS Set of Space Product Assurance Standards, ECSS-Q-Series

[AD 10] ECSS-U-AS-10 Space sustainability. Adoption Notice of ISO 24113: Space systems - Space debris mitigation requirements

[AD 11] Mission Analysis Guidelines, ESOC WP570

[AD 12] Full Orbital Solution (file), To be provided

[AD 13] STE-QUEST Environmental Specification, JS-10-12.

1.6.4 Reference documents

[RD 01] STE-QUEST CDF Report CDF 117(C)

[RD 02] STE-QUEST Mission Proposal, http://www.exphy.uni-duesseldorf.de/Publikationen/2010/STE-QUEST_final.pdf

[RD 03] ESA Pointing Handbook ESSB-HB-E-003, Jul 2011

[RD 04] STE-QUEST Payload Definition Document, SRE-PA/2011.075/TN/PW

[RD 05] S. Vitale et al., “Recommendation for an algorithm for Power Spectral Density estimation for LISA Phathfinder”, S2-UTN-TN-3040, Issue 1 – Rev. 0 (2006)

3 MISSION DESCRIPTION

3.1 Science Goals

Einstein's Theory of General Relativity is a cornerstone of our current description of the physical world. It is used to describe the flow of time in the presence of gravity; the motion of bodies, from satellites to galaxy clusters; the propagation of electromagnetic waves in the presence of massive bodies; and the dynamics of the Universe as a whole.

Although successful so far, the Theory of General Relativity, as well as numerous other alternative or more general theories of gravitation, are classical theories. As such, they are fundamentally incomplete, because they do not include quantum effects. A theory that solves this problem by accounting for both relativistic and quantum effects, would represent a crucial step towards the unification of all the fundamental forces of Nature.

Several approaches have been proposed and are currently under investigation: examples are string theory, quantum gravity, extra spatial dimensions. All of these tend to lead to tiny violations of basic principles. Therefore, a full understanding of gravity will require observations or experiments which can determine the relationship of gravity with the quantum world. This is currently a 'hot' topic and includes the study of dark energy.

Improvements in technology mean that several experiments can now be performed in space with significantly improved accuracy. Taking advantage of this, STE-QUEST is designed to test the different aspects of Einstein's Equivalence Principle using quantum sensors.

Einstein's Equivalence Principle (EPP) can be expressed as follows:

1. Weak Equivalence Principle (WEP): The trajectories of freely falling test bodies are independent of their structure and composition;
2. Local Lorentz Invariance (LLI): In local freely falling frames, the outcome of any non-gravitational test experiment is independent of the velocity of the frame;
3. Local Position Invariance (LPI): In local freely falling frames, the outcome of any non-gravitational test experiment is independent of where and when in the Universe it is performed.

3.1.1 Primary Scientific Objectives of STE-QUEST

Scientific objective	Target accuracy
Gravitational Redshift Tests	
Earth gravitational redshift	Measurement of Earth's gravitational redshift effect to a fractional frequency uncertainty of 1x10$^{-7.}$.
Sun gravitational redshift	Measurement of the Sun's gravitational redshift effect to a fractional frequency uncertainty of 2x10^{-6}, with an ultimate goal of 6x10^{-7}.
Weak Equivalence Principle Tests	
Universality of propagation of matter waves	Test the universality of the free propagation of matter waves to an uncertainty in the Eötvös parameter better than 1.5x10^{-15}.
The mission will also have the capability to perform Lorentz Invariance and Standard Model Extension (SME) tests. The accuracy levels achievable in these tests are currently under evaluation.	

3.2 Mission Overview

Orbit

The tests to be conducted with STE-QUEST require a highly elliptic orbit with the following characteristics:

- Large variations in the gravitational potential
- Long contact times at perigee to compare the clocks at the ground stations with the STE-QUEST clock in space
- Long common-view durations to simultaneously compare two ground clocks separated by intercontinental distances with the STE-QUEST clock in space.
-

A highly elliptical Earth orbit with a 16h orbital period and a semi-major axis of about 32000 km is being studied for the mission.

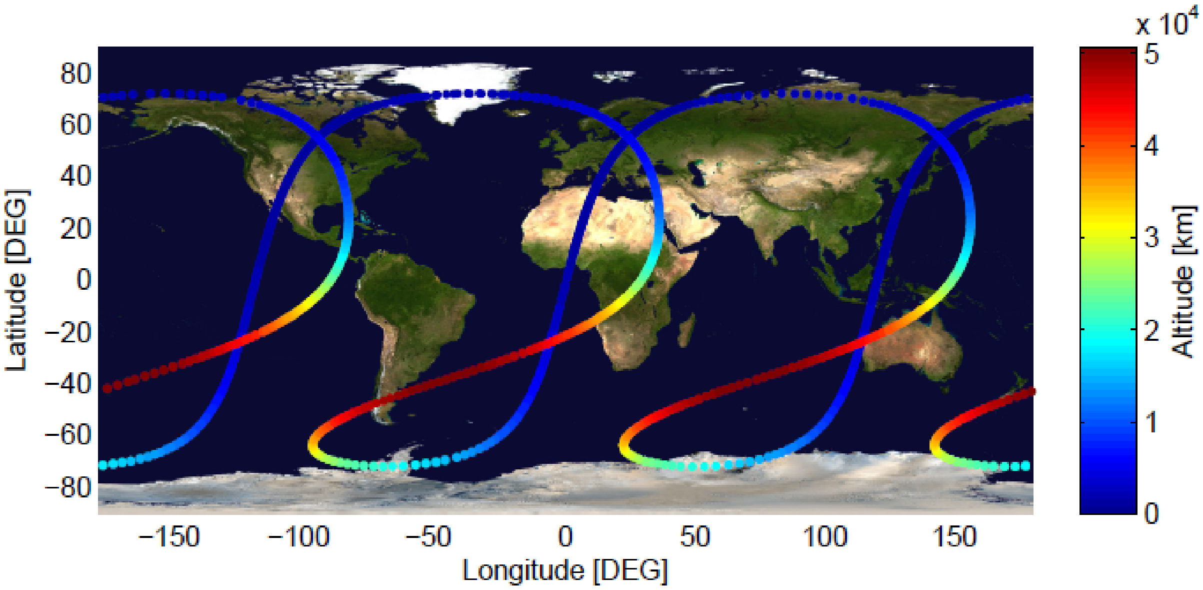


Figure 2: Ground Track of the STE-QUEST orbit. (Example)

The ground track can be optimised to maximise visibility at the STE-QUEST ground stations, which may be located in Boulder (USA), Turin (Italy), and Tokyo (Japan). These locations are particularly favourable because of their geographical distributions and vicinity to research laboratories operating highly stable and accurate atomic clocks.

Ground Segment

The STE-QUEST ground segment is composed of:

- the Mission Operations Centre, which is responsible for performing all spacecraft, payload, and ground segment related operations and receiving, processing, storing and distributing the complete payload telemetry.
- the Science Operations Centre, which is responsible for the definition of the STE-QUEST scientific operations (both payload and ground segment), for the analysis and processing of the science data, for the generation and archiving of mission data products.

- Supporting elements like Instrument Operation Centres and Data Processing Centres for instrument operations and data analysis, respectively.
- a Distributed Network of Science Ground Terminals for comparing high-performance atomic clocks on ground with the signals from the STE-QUEST clock in space;

Close monitoring of the spacecraft will be necessary during the on-orbit characterisation phase which is expected to last for the first 6 months of the mission.
The payload will be operated on the basis of scheduled sequences of commands which will be uploaded to the spacecraft and executed on board
The estimated data volume is compatible with small ESOC ground stations.

3.3 Measurement Concept

Measurement Strategy

The primary data product of the STE-QUEST mission will be:

- Space-to-ground comparisons between the STE-QUEST on-board clock and clocks on the ground;
- Atomic interferometry measurements of the differential acceleration between ultra-cold samples of different atom species.
-

Space-to-ground clock comparisons will be performed all along the orbit, and in particular, while the spacecraft is at apogee and perigee. In this way, Einstein's prediction of the gravitational frequency shift will be verified both by an absolute measurement between space and ground clocks and by examining the modulation of the redshift effect on the STE-QUEST clock between perigee and apogee.

STE-QUEST will also allow common-view comparison of terrestrial clocks, which can be used to measure the periodic effect of the gravitational frequency shift induced by the Sun.
The atom interferometer will primarily perform differential acceleration measurements while the spacecraft is around perigee (spacecraft altitude below 3000 kilometres), thus maximising the signal-to-noise ratio of a possible violation of the Weak Equivalence Principle.

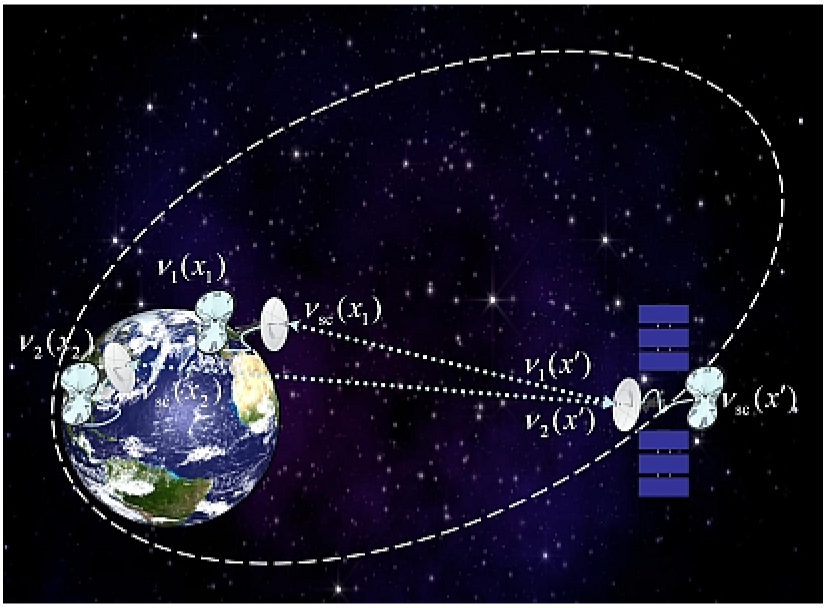
3.3.1 Gravitational Redshift Tests

A direct consequence of Einstein's Equivalence Principle is that time passes (or clocks tick) more slowly near a massive body. This effect can be detected when comparing the time intervals measured by identical clocks placed at different positions in a gravitational field, or when their tick rates (frequencies) are compared. Time and frequency can be transferred between remote locations using electromagnetic waves generated directly from the local clock and transmitted to a particular detection position (denoted by x').

The comparison of two clocks (i = 1, 2) with identical oscillation frequency and operating at different locations x_1 and x_2 yields a frequency ratio:

$$\frac{\nu_2(x')}{\nu_1(x')} = 1 + \frac{U(x_2) - U(x_1)}{c^2}$$

In this gravitational redshift formula, $\nu_i(x')$ is the frequency of clock i located at x_i, as observed (measured) at the particular location x' where the comparison between the two clocks takes place (see Figure below); U is the gravitational potential. According to Einstein's Theory of General Relativity, this frequency ratio is universal, and independent of the nature of the clocks.



A two-way link compares the clock on-board the STE-QUEST spacecraft (ν_{sc}) with two clocks on the ground (ν_1 and ν_2). The link transfers the clock signals in both directions (space-to-ground and ground-to-space) allowing the received signal to be compared with the local clock at both ends.

STE-QUEST will search for a possible violation of the gravitational redshift formula. Phenomenologically, such a violation may be described by a dependence on the gravitational potential of one or more of the fundamental constants that determine the clock frequency: X = X(U l c^2), where X is a generic dimensionless fundamental constant or a dimensionless combination of fundamental constants. Such dependence would correspond to a violation of the Local Position Invariance principle (LPI).

The Earth's gravitational redshift was measured with an accuracy of 7×10^{-5} by the 1976 Gravity Probe-A experiment by comparing the frequency of a clock on the ground with the frequency of a clock on a rocket, as the height changed. The Atomic Clock Ensemble in Space (ACES) mission, planned to fly on the International Space Station (ISS) in the 2014-2015 timeframe, seeks to improve this test by a factor 10 to 30, with its *Projet d'Horloge Atomique par Refroidissement d'Atomes en Orbite* (PHARAO) cold atom clock.

STE-QUEST will make use of the improvements in cold atom clocks and an orbit optimized for such measurements, resulting in improvements in sensitivity by 1 to 2 orders of magnitude.

STE-QUEST will also perform a comparison of clocks on ground, by measuring the daily variation of the redshift effect in the Sun's gravitational field. This will provide a means to search for the neutron's scalar charge and to test the anomalous coupling of matter to the Standard Model quantum fields.

3.3.2 Weak Equivalence Principle Tests - Testing the Universality of Free Fall with Matter Waves

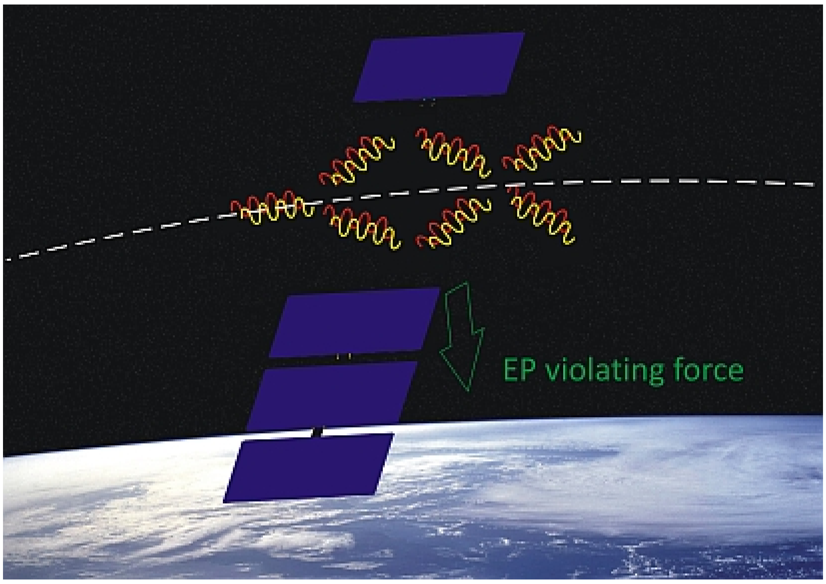
The Weak Equivalence Principle (WEP) postulates that the world line of a freely falling test body is independent of its structure and composition. This hypothesis is a cornerstone not only of Einstein's Theory of General Relativity, but also for almost all modern theories of gravitation.

Experimental tests of this principle are therefore based on the detection of tiny differential accelerations between test masses of different structure and composition.
The Eötvös parameter (η) is historically used to quantify a deviation from the WEP of two test bodies with different compositions (*A* and *B*), inertial mass m_i, and gravitational mass m_g:

$$\eta = 2 \cdot \frac{(m_g/m_i)_A - (m_g/m_i)_B}{(m_g/m_i)_A + (m_g/m_i)_B} .$$

An experiment measuring a value of η not equal to zero would disprove the universality of free fall and violate the Equivalence Principle.

In tracking the free propagation of matter waves, free-fall experiments extend into the domain of quantum objects. This approach is conceptually different from all other free-fall tests based on classical bodies. As per the principles of quantum mechanics, particles have to be described as wave packets; in the context of an atom interferometer (as adopted by STE-QUEST) this introduces the concept of coherence of the different partial matter waves. STE-QUEST will compare the free-fall of the two isotopes of rubidium (^{85}Rb and ^{87}Rb) while the spacecraft orbits around perigee (see Figure below), in order to conduct a quantum test of the Weak Equivalence Principle with an accuracy down to 1×10^{-15}.



Principle of the atom interferometry measurement to be performed with STE-QUEST. The spacecraft's atom interferometer compares the free fall of matter waves generated from ultra-cold rubidium isotope (^{85}Rb and ^{87}Rb) samples. *Credit: ESA*

3.4 Additional Science with STE-QUEST

In addition to the science goals outlined above, STE-QUEST has applications in areas of research other than fundamental physics:

- **Time and frequency metrology**: STE-QUEST will connect atomic clocks on Earth in a worldwide network, bringing important contributions to the generation of atomic time scales and to the synchronization of clocks on ground and in space.
- **Relativistic geodesy**: The comparison of clocks on Earth will give access, via the redshift formula, to differential geopotential measurements on the Earth's surface. A resolution at the level of 1 centimetre on the differential geoid height can be achieved by STE-QUEST.
- **Cold-atom and matter wave physics in conditions of weightlessness**: STE-QUEST will study the evolution of ultra-cold atomic samples in an environment free from perturbations, over long free-propagation times.
- **Optical and microwave ranging**: The optical and microwave links will allow the cross-comparison of different ranging techniques and the measurement of differential atmospheric propagation delays in the optical and microwave domains.

4 MISSION REQUIREMENTS

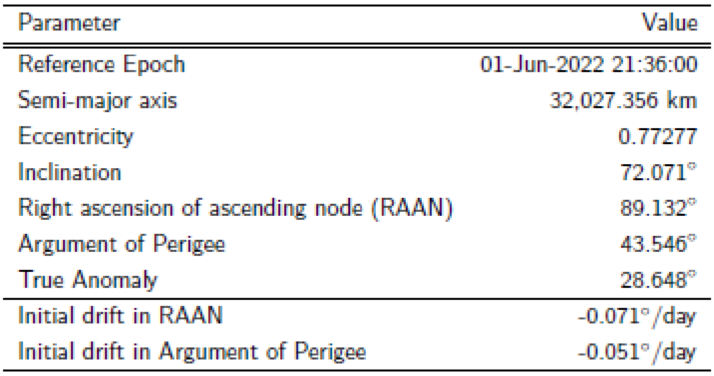
4.1 Launch vehicle, site and date

R-MIS-010 The spacecraft shall be compatible with a launch on Soyuz Fregat from Kourou. *Note: No backup launcher/launch site is foreseen within the M3 missions.*

R-MIS-020 The mission shall be compatible with a launch date in 2022 (study baseline), with a launch in 2024 as study backup . *Note: The M3 mission is intended as a backup candidate for the 2022 launch slot, depending on JUICE schedule. Although in the science programme the baseline launch slot for M3 is 2024, all current study planning should remain compatible with a 2022 launch. The final decision on the nominal launch date will be made following JUICE mission adoption.*

4.2 Injection, transfer and operational orbits

R-MIS-030 The spacecraft shall be launched into a highly elliptical orbit, defined by:



Parameter	Value
Reference Epoch	01-Jun-2022 21:36:00
Semi-major axis	32,027.356 km
Eccentricity	0.77277
Inclination	72.071°
Right ascension of ascending node (RAAN)	89.132°
Argument of Perigee	43.546°
True Anomaly	28.648°
Initial drift in RAAN	-0.071°/day
Initial drift in Argument of Perigee	-0.051°/day

Detailed description is available in the MAG [AD 11] and a full orbital solution is provided in [AD 12] *Note: The orbit provided is achieving the target accuracies in [AD 1] with the assumed payload performances, based on the algorithm in Annex 1 (TBW).*

G-MIS-035 The operational orbit shall be reached with direct insertion. *Note: insertion correction manoeuvres are allowed.*

~~R-MIS-040~~ *(Deleted)*

~~R-MIS-050~~ *Deleted*

R-MIS-060 The gravity-gradient at perigee shall not be larger than $2.5 \cdot 10^{-6}$ s^{-2} after LEOP.

4.3 Mission phases

R-MIS-070 The mission phases shall be defined as follows:

0	Pre-launch Phase (Launch Campaign)	
1	Launch and Early Operations Phase (LEOP)	
2	Commissioning Phase	
	2.1	Spacecraft Operational Commissioning Phase
	2.2	Spacecraft Science Commissioning Phase
3	Nominal Mission Phase	
4	Extended Mission Phase	
5	Decommissioning Phase	

4.3.1 Pre-Launch

R-MIS-080 Pre-launch s/c state shall support vacuum maintenance for instruments.

R-MIS-081 The spacecraft systems shall be compatible with a shelf lifetime of 2 years. *Note: In case of launch delays, the dry spacecraft will be stored in an appropriate clean-room.*

4.3.2 LEOP

R-MIS-090 During launch and until a safe attitude is acquired, all payload systems shall be switched off with the exception of vacuum systems and the spacecraft in a minimal power stage using s/c batteries.

R-MIS-091 LEOP shall last no longer than 3 days

~~R-MIS-100~~ *Deleted.*

~~R-MIS-110~~ *Deleted.*

~~R-MIS-120~~ *Deleted.*

~~R-MIS-130~~ *Deleted.*

4.3.3 Commissioning

~~R-MIS-140~~ *Deleted.*

~~R-MIS-150~~ *Deleted.*

~~R-MIS-160~~ *Deleted.*

R-MIS-170 Spacecraft Science commissioning phase (2.2) shall last no longer than 6 (TBC) months. *Note: during science commissioning phase, the spacecraft* *shall be fully operational following the operational commissioning running in parallel for the first month max.*

R-MIS-180 Spacecraft operational commissioning phase (2.1) shall last no longer than 1 month.

4.3.4 Nominal Operations

R-MIS-185 Nominal operations phase shall last at least 4.5 years. *Note: for the purpose of SR-OP-01, nominal performance levels shall already be reached in science commissioning phase*

R-MIS-190 During nominal operations phase, the s/c shall fulfil all science performance requirements in section 5. *Note,: does not apply during AOCS/mode transitioning operations.*

4.3.5 Extended Operations

G-MIS-200 Extended operations shall start at 5 years from launch.

R-MIS-201 Consumables shall be calculated for 6 years.

4.3.6 Decommissioning

R-MIS-210 Design and operations of the space segment shall comply with the rules and procedures put forth in [AD 10] with the exact measures towards compliance to be traded and subsequently agreed upon. *Note: Currently, only active, controlled de-orbit is believed to fulfil the requirements*

R-MIS-211 Consumables for de-orbiting shall be calculated for the worst case required delta-V within Phase 4 with margins according to R-MISD-070.

4.4 Mission lifetime

R-MIS-220 The mission shall be designed for a lifetime of 5 years.

G-MIS-230 The mission shall be designed for an extended lifetime of 6 years total lifetime.

4.5 Mission Modes

R-MIS-240 The spacecraft shall distinguish between nominal modes for science operations and manoeuvring/transitional modes. *Note: Definitions for nominal modes shall be defined by the contractor. E.g., two main nominal modes can be foreseen: perigee mode (below 3000km); apogee mode (remainder of orbit, except transitional modes).*

R-MIS-250 During nominal modes, no spacecraft re-orientations and/or orbit maintenance manoeuvres shall be performed.

R-MIS-260 Manoeuvring/transitional modes shall not last longer than 60 min (TBC) per orbit.

5 MEASUREMENT REQUIREMENTS

The Contractor is advised that he will be provided with an orbit fulfilling the requirements on the orbit by ESA/ESOC and will not be required to take any action on the orbit requirements, but is invited to check their impact on other parts of the system design.

R-SPM-010 The STE-QUEST orbit shall be compatible with a reference value in the difference of the gravitational potential between Earth surface and apogee of $\Delta\mathrm{U}_{\text{apogee-ground}}/\mathrm{c}^2 \sim 6.2 \cdot 10^{-10}$. *Note: reference value for the orbit – foreseen for deletion in next release*

R-SPM-020 The STE-QUEST orbit shall be compatible with a reference value in the difference of the gravitational potential between Earth surface and perigee of $\Delta\mathrm{U}_{\text{perigee-ground}}/\mathrm{c}^2 \sim 6.9 \cdot 10^{-11}$. *Note: reference value for the orbit – foreseen for deletion in next release*

R-SPM-030 The total measurement duration around apogee and perigee, at distances from the Earth corresponding to a gravitational red-shift $\Delta\mathrm{U} > 0.9 \cdot \Delta\mathrm{U}_{\text{apogee-ground}}$ and $\Delta\mathrm{U} < \Delta\mathrm{U}_{\text{perigee-ground}} + 0.1 \cdot \Delta\mathrm{U}_{\text{apogee-ground}}$ respectively, within 10% of the gravitational red-shift experienced between apogee and ground shall be longer than $\Delta\mathrm{t}_{\text{apogee}}^{\text{clock}} > 3 \cdot 10^6\mathrm{s}$ and $\Delta\mathrm{t}_{\text{perigee}}^{\text{clock}} > 1 \cdot 10^5\mathrm{s}$ in a four (4) year time period. *foreseen for deletion in next release*

R-SPM-040 The total measurement duration for the atom interferometer at a distance from the Earth corresponding to a gravity acceleration higher than 4.5 $\mathrm{m/s^2}$ (altitudes below 3000 km), shall be longer than $\Delta t_{\text{perigee}}^{\text{AI}} > 3.5 \cdot 10^6\mathrm{s}$, in a four (4) year time period. *foreseen for deletion in next release*

~~R-SPM-050~~ *Superseded by R-SPL-060 and G-SPL-070*

R-SPM-060 Any pair of two ground clocks shall be compared for at least 500 times (common view) with a duration of at least 25000s for each comparison over a four (4) year time period. *foreseen for deletion in next release*

R-SPM-070 Atom interferometer measurements for the WEP shall be taken at least continuously around perigee, at altitudes below 3000km.

R-SPM-080 It shall be possible to perform atom interferometer measurements in parallel with the clock measurements.

R-SPM-090 *Deleted.*

G-SPM-100 It shall be possible to operate the atom interferometer during all nominal modes (defined in R-MIS-240) along the full orbit in addition to performing the measurements at perigee passage.

G-SPM-110 It shall be possible to operate the atomic clock during all nominal modes (defined in R-MIS-240) along the full orbit.

R-SPM-120 The precise orbit determination of the spacecraft shall be better than: 2 m in position radial to the centre of gravity of the Earth, 2 m along and across

	track, and 0.2 mm/s in velocity after post-processing with no more than 15 days delay. *Note: Currently it is foreseen to fulfil this requirement using a GNSS receiver locked to the on-board frequency reference and laser ranging.*
R-SPM-130	The error in the determination of the gravitational potential at the space clock location shall lead to a fractional frequency uncertainty due to the red-shift effect of less than 3E-17, after post-processing. *foreseen for deletion in next release*
R-SPM-140	The position of ground clocks shall allow comparisons with the STE-QUEST clock for a minimum duration of $\Delta t_{\text{apogee}}^{\text{clock}}$ within the boundaries defined in R-SPM-030.. *foreseen for deletion in next release*
R-SPM-150	The position of ground clocks shall allow comparisons with the STE-QUEST clock for a minimum total duration of 2.5E7 seconds for each clock in a four (4) year time period.. *foreseen for deletion in next release*
R-SPM-160	The ground clocks distribution shall allow establishing at least two common-view contacts (preferably three) of pairs of ground clocks with the STE-QUEST spacecraft clock per orbit, the two contacts involving at least three different ground clocks.
G-SPM-170	It shall be possible to compare the same ground clock (out of the available ground clocks) with the on-board clock of the spacecraft in the vicinity of apogee and perigee of the same orbit in any order (i.e. first perigee then apogee or vice versa). *Note: Vicinity to be understood in the terms of R-SPM-030.*
G-SPM-180	The same ground clock (out of the available ground clocks) shall be compared with the STE-QUEST on-board clock for most of the time (70%) spent by the spacecraft between apogee and perigee (or vice versa). *Note: apogee and perigee boundaries as defined in R-SPM-030.*

5.1 Core Science Instruments requirements

~~R-SPI-010~~	*Deleted.*
~~R-SPI-020~~	*Deleted.*
R-SPI-025	The spacecraft shall be inertial pointing during perigee pass (below 3000 km).
R-SPI-030	In all three s/c axes, the angular velocity of the STE-QUEST spacecraft with respect to a non-rotating freely falling reference frame averaged over the atom interferometer sequence duration (<15 seconds) shall be within the interval $[-10^{-6}, +10^{-6}]$ rad/s during main atom interferometer operations (i.e. at least during periods below 3000 km altitude). *Note: It is preferable to fulfil the requirement during all atom interferometer*

measurement operations. The requirement assures a separation between the atomic clouds of less than 10 μm.

R-SPI-040 Magnetic cleanliness at the interface to the mu-metal shields of the instruments (AI, clock) shall meet the following limits:

Frequency (Hz)	B-Field (T)
DC to 0.001	0.1 mT
0.01	0.01 mT
0.1	0.001 mT
1	0.001 mT
10	0.001 mT
100	0.01 mT
1000	0.1 mT

R-SPI-050 The power spectral density of acceleration noise/disturbances at payload interface shall be lower than $10^{-3} \cdot f \text{ m/s}^2/\sqrt{\text{Hz}}$ for frequencies f expressed in Hz, between 1 mHz and 20 mHz and 10 kHz $2 \cdot 10^{-5} \text{ m/s}^2 \big/ \sqrt{\text{Hz}}$ in [20 mHz, 100 Hz], when measuring The PSD shall be calculated according to the algorithm in Annex 2.

R-SPI-051 The RMS value of quasi-sinusoidal accelerations at the atomic clock and MOLO volumes shall be smaller than $1 \cdot 10^{-4} \text{m/s}^2 \cdot (f \cdot T_c + 0.1 \cdot f^2 \cdot T_c^2)$ for frequencies f, expressed in Hz, between 0.5 Hz and 10 KHz, T_c being the clock cycle duration (T_c = 1 second, TBC).

R-SPI-052 The RMS value of quasi-sinusoidal accelerations at the atom interferometer volume during atom interferometer measurements (i.e. below 3000 km altitude) shall be smaller than

Frequency range	Acceleration RMS (m/s^2)
$f < 0.01$ Hz	$4 \cdot 10^{-7}$
0.01 Hz $< f <$ 10 Hz	$4 \cdot 10^{-5} \cdot f$
$f > 10$ Hz	$4 \cdot 10^{-4}$

R-SPI-060 DC non-gravitational accelerations on the spacecraft shall be less than 1E-6 m/s^2 , within the instrument volume, when measuring.

R-SPI-061 DC non gravitational accelerations on the spacecraft along the sensitive axis of the atom interferometer shall be less than $4 \cdot 10^{-7}$ m/s^2 , during atom interferometer operations.

R-SPI-070 At any time, the gravity gradient induced by the self-gravity of the spacecraft measured at the atom interferometer reference point (centre of mass of the atomic cloud during the measurements) shall be smaller than the gravity gradient induced by the Earth at perigee passage. *Note: Until detailed definition of the instrument, it is reasonable to assume the reference point on the central axis of the mu-metal cylinder around the AI volume at a height of around 1/3 the cylinder length.*

5.2 Science Link Performance Requirements (Time & Frequency)

R-SPL-010 For space to ground comparisons: the modified Allan deviation of the noise introduced by the STE-QUEST microwave link in the comparison of the on-board clock with clocks on the ground shall be smaller than $\sqrt{(5.0 \cdot 10^{-13}/\tau^{3/2})^2 + (1.6 \cdot 10^{-13}/\tau)^2 + (7.1 \cdot 10^{-15}/\tau^{1/2})^2}$ for integration times τ expressed in seconds, between 10 s and $7 \cdot 10^5$ s.

R-SPL-011 For ground-to-ground clock comparisons: The modified Allan deviation of the noise introduced by the STE-QUEST microwave link in the comparison of two clocks on the ground shall be smaller than $\sqrt{(5.0 \cdot 10^{-13}/\tau^{3/2})^2 + (1.6 \cdot 10^{-13}/\tau)^2 + (5.9 \cdot 10^{-17}/\tau^{1/2})^2 + (5.0 \cdot 10^{-19})^2}$ for integration times τ, expressed in seconds, between 10 s and $7 \cdot 10^5$ s.

G-SPL-020 For space-to-ground comparisons: The modified Allan deviation of the noise introduced by the STE-QUEST optical link in the comparison of the on-board clock with clocks on the ground shall be smaller than $\sqrt{(3.2 \cdot 10^{-14}/\tau^{3/2})^2 + (1.0 \cdot 10^{-14}/\tau)^2 + (7.1 \cdot 10^{-15}/\tau^{1/2})^2}$ for integration times τ, expressed in seconds, between 10 s and 10^5 s.

G-SPL-021 For ground-ground comparisons: The modified Allan variance of the noise introduced by the STE-QUEST optical link in the comparison of two clocks on the ground shall be smaller than $\sqrt{(3.2 \cdot 10^{-14}/\tau^{3/2})^2 + (1.0 \cdot 10^{-14}/\tau)^2 + (5.9 \cdot 10^{-17}/\tau^{1/2})^2 + (5.0 \cdot 10^{-19})^2}$ for integration times τ, expressed in seconds, between 10 s and 10^5 s.

R-SPL-030 The STE-QUEST time and frequency transfer links shall be able to compare the space clock and clocks on ground to a fractional frequency inaccuracy smaller than 3E-17 as well as to compare ground clocks to a fractional frequency inaccuracy smaller than 5E-19.

R-SPL-040 The STE-QUEST time and frequency transfer links shall be able to provide at least one phase comparison measurement per second between the space clock and the ground clock with 1Hz measurement bandwidth.

R-SPL-050 The space and ground terminals of the STE-QUEST time and frequency transfer links shall be able to carry out space-to-ground and ground-to-ground time transfer with the link-induced differential time error between any two observations separated by a dead-time T_d being less than TDEV(T_d), where TDEV represents the time deviation[1] resulting from R-SPL-10, R-SPL-11, for the microwave link. This requirement shall be maintained over a minimum measurement interval of 20 days.

G-SPL-051 The space and ground terminals of the STE-QUEST time and frequency transfer links shall be able to carry out space-to-ground and ground-to-ground time transfer with the link-induced differential time error between any two observations separated by a dead-time T_d being less than TDEV(T_d), where TDEV represents the time deviation resulting from G-SPL-20, and G-SPL-21 for the optical link. This requirement shall be maintained over a minimum measurement interval of 20 days.

R-SPL-060 The STE-QUEST microwave link shall be able to simultaneously compare the space clock with at least four clocks on ground. *Note: whenever the G/T associated with the clock has visibility.*

G-SPL-070 The STE-QUEST optical link shall be able to simultaneously compare the space clock with two clocks on ground.

R-SPL-080 The differential delays of the Science Links shall be calibrated to a time uncertainty smaller than 50 ps for all applications. *Note: This includes calibration of the differential delays between uplink (transmission from ground to reception in space) and downlink (transmission from space to reception on ground) and of the differential propagation delays in the atmosphere due to the non-reciprocal paths of uplink versus downlink.*

R-SPL-090 The differential delays of the STE-QUEST links (both optical and microwave) used for the synchronization of two clocks on ground shall be calibrated to a time uncertainty better than 50 ps. *Note: This includes the calibration of the differential delays (uplink-downlink) for each space-to-ground link.*

---

[1] The time deviation (TDEV) related to the modified Allan deviation (ModADEV) by the following relationship: TDEV(τ) = ModADEV(τ)$\cdot \tau/\sqrt{3}$, where τ is the integration time.

6 SPACECRAFT REQUIREMENTS

6.1 Design requirements

6.1.1 Metric standard

R-MISD-010 In general, the SI system of units shall be applicable.

R-MISD-020 The kg, m, s system shall be used for all documentation.

R-MISD-030 For radiation, the use of “rad” with or without standard SI-prefixes shall be permitted.

R-MISD-040 For angular measurements, the use of “degree”, “arcmin”, and “arcsec” shall be permitted as accepted by the SI.

6.1.2 Coordinate system

R-MISD-050 The coordinate system along the orbit shall be right-handed orthogonal with the origin as defined in R-MISD-060, the +z-axis towards nadir, and the +y-axis in the direction of the negative orbit normal, and the +x-axis completing the system.

R-MISD-060 The spacecraft internal coordinate system shall be right-handed orthogonal with

- The origin in the geometrical centre of the separation plane between the launch adapter and the spacecraft
- $+Z_{SC}$ coincident with the launcher symmetry axis and skywards
- $+Y_{SC}$ parallel to a line joining the solar array joints/mounting points
- $+X_{SC}$ completing the system

6.1.3 Design margins

R-MISD-070 The margin policy described in [AD 2] shall be applied to the assessment study (Ph.0/A). *The margin philosophy and margin depletion scheme will be defined fully at a later stage.*

R-MISD-080 Deleted.

6.2 System Requirements

6.2.1 Spacecraft lifetime

R-SYS-010 The spacecraft shall be dimensioned for the mission duration.

G-SYS-020 The spacecraft shall be dimensioned for the extended mission duration.

6.2.2 Spacecraft mass

R-SYS-030 The spacecraft wet total mass including all applicable margins and launcher adapter shall not exceed the launcher performance for the chosen orbit. *Note: cf [AD 11] for the orbit and cf [AD 5] for information on Soyuz from CSG.*

6.2.3 Reliability and fault management

R-SYS-040 The spacecraft design shall eliminate or prevent single-point failures with a severity of catastrophic or critical as per [AD 9].

R-SYS-050 Non-compliance to R-SYS-040 above shall be subjected to formal approval by ESA and an issued waiver.

R-SYS-060 No failure of any single component at unit level shall lead to failure of or damage to another component or subsystem.

R-SYS-070 No failure of any instrument shall lead to failure of or damage to other instruments or subsystems.

R-SYS-080 Individual or multiple failures of instruments and/or instrument subsystems shall not lead to a transition into safe-mode on spacecraft level.

R-SYS-090 Degradation or delayed loss of the spacecraft caused by failures of either instruments or spacecraft subsystems on any level shall be prevented or protected against by design.

R-SYS-100 The spacecraft shall have a safe-mode which assures spacecraft and payload survival.

R-SYS-110 The spacecraft shall enter safe-mode in case of anomalies or failures from which it cannot recover autonomously.

6.3 Structures and Configuration

G-STR-010 The spacecraft shall be designed in a modular way in order to obtain simple interfaces to the payload, but with the core science instruments contained and protected within the structure of the spacecraft.

G-STR-020 No interface shall require the presence of more than one instrument, i.e. no routing of interfaces and no common use.

G-STR-030 The accommodation of the payload shall be designed such that any instrument can be tested individually and removed or added to the spacecraft for these tests.

R-STR-040 The spacecraft shall ensure an environment compatible with instrument specifications.

R-STR-060 The spacecraft shall provide structural interfaces to the instruments and launch vehicle.

R-STR-070 The spacecraft shall be compatible with the launch payload allocated volume of the launcher as specified in [AD 5].

R-STR-080 The spacecraft shall be compatible with the launcher environment as specified in [AD 5] at any stage before and during LEOP.

6.4 Mechanisms

R-MECH-010 The use of mechanisms shall be avoided as far as possible. Use of mechanisms shall be subject to ESA approval.

6.5 Thermal Control

~~R-THRM-010~~ *Deleted.*

~~G-THRM-020~~ *Deleted.*

R-THRM-030 Thermal Control shall control the interface to the instruments to a relative stability of +- 3 K (TBC) over 1 orbit. *Note: thermal interface to POD, MWL, OL, is assumed to be handled by the industrial contractor according to their design.*

R-THRM-040 The operating temperature of the payload shall be kept between 283 K and 303 K.

R-THRM-050 The non-operating temperature of the payload shall be kept between 233 K and 333 K.

6.6 AOCS

~~R-AOCS-010~~ *Deleted.*

~~R-AOCS-020~~ *Deleted.*

~~R-AOCS-030~~ *Deleted.*

~~R-AOCS-040~~ *Deleted.*

R-AOCS-050 The spacecraft shall be 3-axis controlled to assure proper orientation of science payload instruments w.r.t. the gravitational field.

R-AOCS-060 Pointing strategy along orbit shall comply with the requirements in section 5.

6.7 Propulsion

R-PROP-010 The propulsion subsystem shall be sized to correct injection errors according to [AD 5] and perform orbital maintenance/attitude control during the full mission duration.

R-PROP-020 The propulsion subsystem shall support end-of-life measures according to [AD 10].

R-PROP-030 The propulsion system shall be sized to support the compensation of non-gravitational accelerations exerted on the spacecraft by its environment to the levels specified in Section 5 during all nominal operation modes in Phases 2 and 3 and 4.

G-PROP-040 The propulsion system shall be sized to according to R-PROP-030, but taking as a baseline the optional orbit with perigee altitudes below 600 km (as defined in the MAG [AD 11]).

6.8 Power

G-PWR-010 The power for the spacecraft and all its subsystems and payload shall not rely on radio-isotopic generators or other radioactive materials and processes.

R-PWR-020 The Power subsystem shall provide sufficient power for the spacecraft systems and payload instruments during all modes and mission phases.

R-PWR-030 A detailed power usage scenario shall be derived per operational and mission phase which demonstrates the power consumption and necessary storage requirements.

6.9 Telemetry, Tracking & Command, Communications

R-TTC-010 The spacecraft TTC subsystem shall comply with the ESA telecom standards within [AD 8].

R-TTC-020 The spacecraft shall be able to simultaneously perform the following actions throughout all the mission phases and spacecraft modes following launch and regardless of spacecraft attitude:

- Receive and demodulate the uplink signal from the ground segment and transmit the telecommands to the data handling system.
- Receive a telemetry data stream from the data handling system and transmit these data to the ground segment
- Transpose the ranging signal.

R-TTC-030 The TTC subsystem shall interface with the ESA network of ground stations, as defined in the Estrack facilities manual (DOPS-ESTR-OPS-MAN-1001-OPS-ONN 1.1. [AD 4] *Note: As a baseline for the current baseline orbit, New Norcia and Malargüe may be assumed.*

R-TTC-040 The TTC-link shall support range and range-rate measurements.

R-TTC-050 The receive function of the TTC subsystem shall be hot-redundant, the transmission function shall be cold redundant.

R-TTC-070 The TTC subsystem shall enable spacecraft mode-changes through ground commands.

R-TTC-080 The uplink and downlink data rates shall be compatible with the data transmission requirements during all mission phases.

R-TTC-090 Link budget calculations for uplink shall be based on a maximum BER of 1E-5 at decoder input.

R-TTC-100 Link budget calculation for downlink shall be based on a maximum FER of 1E-7 at decoder output.

R-TTC-110 Link budgets shall have a nominal margin of 3dB

6.10 Command and Data Handling

~~R-CDH-010~~ *Deleted.*

R-CDH-020 Timelines shall be supported, i.e. the execution of several commands according to a timeline and according to specified conditions.

G-CDH-030 Handling of nested timelines shall be possible.

R-CDH-040 Housekeeping data from all spacecraft subsystems shall be acquired, processed, stored, and transmitted to ground independently.

R-CDH-050 For all mission phases, the OBDH shall provide sufficient memory to store all data (science and platform housekeeping) in between downlinks and with a margin of 4 orbits.

R-CDH-060 The OBDH system shall provide for payload science and housekeeping data processing and storage.

R-CDH-070 The spacecraft time reference shall be UTC.

R-CDH-080 The OBDH shall support file-based operations. TBC

R-CDH-090 On-board software updates shall be possible.

R-CDH-100 Mode changes through telecommand shall be possible.

6.11 On-Board Software

No special requirements identified

6.12 Payload Requirements

6.12.1 General

R-PLG-010 The payload shall perform according to specifications in the on-board environment of the spacecraft during all nominal modes (defined in R-MIS-240).

6.12.2 Science Links (Time and Frequency Transfer)

G-PLL-010 The antennas for the microwave links shall be placed on a dedicated s/c face or panel compatible with their task with no obstructions within the main beamwidth of their radiation pattern.

G-PLL-030 The optical link terminals shall be placed such that their beam can reach any point on the currently visible (i.e. reachable) face of the Earth from the current orbital position at any time during the orbit. Exception is during the execution of specific, time-limited, manoeuvres of the spacecraft.

6.12.3 *Precise Orbit Determination equipment*

R-PLD-010	The precise orbit determination equipment shall ensure the performance specified in section 5.
R-PLD-021	A GNSS receiver capable of receiving signals from least two independent GNSS constellations shall be used.
R-PLD-020	The GNSS receiver shall have an interface to receive an external clock reference providing signals in one single frequency. *Note: this might include a pulse-per-second signal.*
G-PLD-030	The spacecraft shall be equipped with corner cube reflectors compatible for use with the International Laser Ranging Service stations. *Note: in case GNSS performance is not high enough to ensure POD.*
R-PLD-040	The POD equipment shall be compatible with the standard spacecraft reliability requirements in Section 6.2.3.

7 INTERFACES

7.1 Launcher interfaces

R-IFL-010 The spacecraft shall be compatible with launcher requirements.

7.2 Payload interfaces

R-IFP-010 The spacecraft shall provide all necessary interfaces to the payload.

7.3 Ground facilities

R-IFG-010 *The spacecraft shall be compatible with standard practices for ground operations. No special requirements have been identified.*

8 SPACECRAFT ENVIRONMENT

8.1 Mechanical Environment

R-SEM-010 The spacecraft shall be compatible with the environment specified in [AD 5].

R-SEM-020 The spacecraft shall be compatible with standard ground handling environments (TBC)

8.2 Thermal Environment

R-SET-010 The spacecraft shall be compatible with the thermal-vacuum environment expected during all mission phases described in [AD 13]

8.3 Cleanliness and Contamination

R-SEC-010 Standard cleanliness and contamination requirements for missions to Earth orbit shall apply.

8.4 Radiation Environment

R-SER-010 The spacecraft shall be compatible with the predicted energetic particle environment for all mission phases, described in [AD 13]

8.5 Meteoroids

R-SEMI-010 The spacecraft shall be compatible with the micrometeoroid environment predicted for all mission phases, as described in[AD 13]

8.6 Electromagnetic Compatibility

R-SEMC-010 The spacecraft shall be compatible with the standard EMC requirements.

9 ASSEMBLY, INTEGRATION AND VERIFICATION

R-AIV-010 The AIV programme shall include a clear path of timely (at least 24 months before launch TBC) payload delivery and a clear AIT process of all instruments to be implemented on the S/C.

10 OPERATIONS AND GROUND SEGMENT

10.1 Operations

R-OGS-010 There shall be a dedicated single mission operations centre run by ESA and a dedicated science operation centre for centralized science data processing and storage.

R-OGS-020 The mission shall support file-based operations (TBC).

10.2 Ground Segment

R-OGS-030 The ground segment shall be split into the ground segment for mission and spacecraft control as well as telemetry reception (mission operations) and the science ground terminals for the clock comparison links (science operations)

R-OGS-040 The mission operations segment shall forward science telemetry as well as applicable housekeeping data (such as range, range-rate, status data) to the science operations centre.

10.2.1 Mission Operations Centre (MOC)

R-OGS-050 Mission Operations Centre shall be responsible for spacecraft operations after launch, including mission planning, spacecraft monitoring and control, and orbit and attitude determination and control.

R-OGS-060 MOC shall be responsible for STE-QUEST science operations, including instrument control, collection of science data and transmission to the SOC, and intervention in case of anomalies.

R-OGS-070 MOC shall provide all science telemetry to SOC following reception via internet.

R-OGS-080 MOC shall provide quick-look orbitography data to the SOC to an accuracy of 10 m TBC as soon as the data becomes available.

10.2.2 Science Operations Centre (SOC)

R-OGS-090 SOC shall be responsible for instrument characterization and calibration.

R-OGS-100 SOC shall be responsible for operating the ground terminals for the clock comparison links.

R-OGS-110 SOC shall be responsible for analysing the science data received from the spacecraft via the MOC as well as data reduction and coordination of the production of the final scientific products.

R-OGS-111 The SOC shall be supported by DPCs (Data Processing Centres) for generation of higher level science data products.

R-OGS-112 The SOC shall be supported by Instrument Operation Centres (IOCs) for the operation and monitoring of instruments, as well as data processing.

R-OGS-120 SOC shall prepare the science operations plan and provide operational requests to the MOC

R-OGS-130 SOC shall be responsible for the science data archive.

R-OGS-140 The complete set of STE-QUEST raw data and higher data products shall be archived at the SOC

10.2.3 Ground Stations

R-OGS-145 The mission shall rely on a maximum of two MOC ground stations for TT&C during nominal operations. *Note: Propositions for a suitable ground station, that is part of the available stations in the ESTRACK network, are encouraged. Two G/S might be required to cover gaps in single station coverage, however, one G/S is preferred. As a baseline for the current baseline orbit, New Norcia and Malargüe can be assumed as ground stations.*

10.2.4 Ground Terminals

R-OGS-150 The clock measurements shall be done with ground terminals linked to high precision clocks meeting the science requirements.

R-OGS-160 There shall be at least 3 ground terminal locations. *Note: as an example, ground terminals shall be located sufficiently near (as required by the link performance) to the high-performance ground clocks in Boulder (US), Turin (IT), and Tokyo (JP).*

~~R-OGS-161~~ *Duplication of requirement - deleted*

G-OGS-170 At least one microwave and one optical ground terminal shall be transportable. *(Note: For calibration purposes at least one optical and microwave terminal shall be available)*

R-OGS-180 The ground terminals shall be located such that the projection of the difference vector (G/T's – centre of Earth) on the equatorial plane between any pairs of different ground terminals has a length of at least 4500 km. *Note: If there are more than 3 ground terminals, only three of them have to fulfil this requirement.*

R-OGS-190 The ground terminals design shall be equipped with high-precision position and velocity determination equipment down to at least 1 m (TBC) in all directions.

10.3 Spacecraft Autonomy

R-OAUT-010 Operation of the spacecraft shall be possible during all mission phases using either direct communication with ground or on-board intelligence using on-board storage followed by periodic communication.

R-OAUT-020 It shall be possible to upload timelines with commands for on-board time-tagged deferred execution for at least 10 days.

R-OAUT-030	The spacecraft shall perform autonomously a nominal operation scenario when ground intervention is not possible.
R-OAUT-040	The spacecraft shall respond to on-board failures by switching, independently from ground control, to a redundant functional path for operations critical to mission survival.

11 PRODUCT ASSURANCE

No special requirements have been identified. Standard practices (ECSS) shall be adhered to. PA requirements will be developed at a later stage.

12 PROGRAMMATIC

12.1 Technology Readiness and Availability

R-PROG-010 All spacecraft components and payload items shall be predicted to reach TRL 5 or higher by the end of 2014.

12.2 Schedule

R-PROG-020 The schedule for Phases A/B/C/D shall be compatible with a 2022 launch date.

12.3 Cost

R-PROG-030 The overall mission cost to ESA shall be less than 470 M€ Cost at Completion, e.c. 2011, excluding the parts of the payload that are nationally provided.

ANNEX 1 RECOMMENDED ALGORITHM FOR PSD ESTIMATION

This annex describes the recipe adopted for the estimation of power spectral densities. Timescales relevant for STE-QUEST are defined by the cycle time of the instruments, which are on the order of 10 s. As such, acceleration PSD specifications need to be fulfilled within each 10 s interval of instrument operation. It is advised to raise a flag at instrument level when PSD acceleration specs are not met, thus identifying those measurements requiring further analysis or to be rejected. Such events shall not exceed 1% (TBC) of the total number of measurements.

The algorithm described below is based on [RD 05]:

1. Data are acquired at least at 2 kHz sampling rate after appropriate anti-aliasing filtering. It is assume that the reader is aware of the need of low-pass filtering data before sampling to prevent aliasing effects. For a discussion of the role of aliasing in spectral estimation, we refer to any standard textbook in numerical data processing.
2. Data are acquired continuously for 50 s giving a total of at least $1 \cdot 10^5$ data points.
3. Data are divided into segments 2 s long, two contiguous segments overlapping by 1 s. Thus, for instance, in the case of 2 kHz sampling each segment would contain 4000 data points.
4. Each segment is de-trended by fitting the linear function c1·n+co and by subtracting the resulting best fit function to the data of that segment. De-trending applies to data prior multiplication by the window function w(n).
5. A Blackman-Harris window function is used (see [RD 05]).
6. In addition a PSD estimate on the entire 50 s data time series without dividing it into segments is produced. The window function is again the Blackman-Harris one, with Nd now being the entire length of the data series. Linear de-trending should also be applied to the entire data series.
7. The above algorithm is not supposed to deal with anomalies like spikes and sudden jumps that are visible above the noise in the data time series at the time of their occurrence. Therefore, data shall be inspected against the occurrence of these features and data streams containing them should be reported for further processing.