DOCUMENT

STE-QUEST
Preliminary Requirements Review (PRR)
Technical Report

Prepared by	**STE-QUEST PRR Panel**
Reference	**ESA-STEQ-RP-0001**
Issue	**1**
Revision	**1**
Date of Issue	**16/12/2013**
Status	**Approved/Applicable**
Document Type	**RE**

European Space Agency
Agence spatiale européenne

Distribution

APPROVAL

Title	
Issue 1	**Revision** 1
Author STE-QUEST PRR Panel	**Date** 16/12/2013
Approved by	**Date**
Alberto Gianolio	17/12/2013

CHANGE LOG

Reason for change	Issue	Revision	Date

CHANGE RECORD

Issue 1	**Revision** 1		
Reason for change	**Date**	**Pages**	**Paragraph(s)**

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1 INTRODUCTION

1.1 M3 mission in ESA Cosmic Vision plan

Following the Call for M3 mission proposals that was issued in July 2010, five mission candidates are today competing for M3 nominal launch slot in 2024:

- EChO, an Exoplanet Characterisation Observatory,
- LOFT, a Large Observatory For X-ray Timing,
- MarcoPolo-R, a Near-Earth Asteroid (NEA) sample return mission,
- PLATO, an Exoplanet mission devoted to PLAnetary Transit and Oscillations of stars,
- STE-QUEST, a Space-Time Explorer and Quantum Equivalence Principle Space Test.

M3 timeline is recalled in Table 1. With the exception of PLATO, for which an assessment study was completed in 2011, the other missions have recently completed their Assessment Phase (phase A). A Preliminary Requirements Review (PRR) of all candidate missions has been performed to review their status in support of the M3 selection. This document reports the results of the technical and programmatic review for the STE-QUEST mission candidate.

Event	**Date**
Selection of M3 mission candidates	*Feb 2011*
Industrial studies kick-off	*Feb 2012*
Industrial studies mid-term reviews with model payload	*Jul 2012*
Instrumentation AO	*Sept 2012*
Selection of instrument teams	*Feb 2013*
Industrial Phase A studies data package delivery for PRR	*Sept 2013*
ESA technical and programmatic reviews completed	Dec 2013
Public presentations, Science Advisory Structure assessment and SSAC recommendation for M3 selection	Jan 2014
M3 mission selection by the SPC	Feb 2014
Phase B1 completion for the selected mission	Nov 2015
M3 mission adoption by the SPC	Q1 2016
Industrial Phase B2/C/D kick-off	Sept-Oct 2016
M3 nominal launch	by 2024 (*)

Table 1- Timeline for M3 selection and implementation

(*) Compatibility of M3 implementation with a launch by 2022 was requested

1.2 M3 Reviews: Process and Objectives

The independent reviews followed a common procedure and have several objectives:

1) Assess the design maturity of the mission at the end of Phase A
2) Evaluate ESA Estimate at Completion (EaC)
3) Provide recommendations for the next phases

While objectives 1) and 2) serve the M3 selection process, the third objective is actually applicable only to the mission that would be selected.

For each mission candidate, the reviews were chaired by an experienced project manager and supported by a number of senior engineers and technical experts across the Agency, involving typically about 20 people per mission, with a natural dispersion depending on the mission needs and the review Chairman requests. The reviewers are independent of the study team, and the latter was supporting the review process on the request of the Chairman e.g. by providing the historical background and answering questions raised by the reviewers.

For practical reasons, the reviews were conducted in parallel for the five missions and the reviewers were distributed in two panels:

- A technical and programmatic panel (also called Review Panel), assessing all technical aspects for the mission implementation, including: mission requirements and flow down to engineering level; spacecraft definition and technology readiness; science payload definition and technology readiness; launch aspects and launcher compatibility; ground segment and operations; spacecraft development plan (model philosophy, schedule for the spacecraft and payload elements) and the associated development risks.
- A cost panel, in charge of assessing ESA costs (EaC), taking into account the technical and programmatic findings

The input documentation is constituted of:

- ESA requirement documents (e.g. Science Requirements Document, Mission Requirements Document, Experiment Interface Documents, etc)
- The data packages provided by the two industrial contractors
- The data package provided by the instrument consortia

The Review Panel was specifically tasked with the following activities:

a- Confirmation of the Mission and System requirements:
  - Adequacy and completeness of ESA Mission Requirements (MRD)
  - Adequacy, completeness and traceability of spacecraft, payload, ground segment and launcher requirements
  - Adequacy and completeness of interfaces definition

b- Confirmation of the mission technical feasibility:
  - Mission design justification and compliance with applicable requirements
  - Concept of operations, observing strategy and modes (where applicable), calibration aspects, driving requirements on mission, spacecraft and payload design

- Validity and maturity of the spacecraft and payload design concept
- Margin philosophy
- Adequacy, completeness and credibility of system, spacecraft and payload budgets and margins
- Availability of appropriate models and analyses in support to design definition
- Identification of critical technologies for the spacecraft and payload, identification of current technological maturity and availability of credible roadmap to achieve TRL 5 before adoption, critical review of ongoing technology development activities

c- Confirmation of the mission programmatic feasibility:
  - Critical review of the spacecraft and payload development plans
  - Adequacy and completeness of the proposed development and verification approach
  - Model philosophy
  - Realism and completeness of spacecraft and payload development schedule (incl. margins)
  - Compatibility of payload need and delivery dates
  - Critical path analysis
  - Risk assessment and related mitigation plan
  - Credibility and compatibility of technology maturation roadmap schedule with system schedule

The reviews were implemented through a series of meetings held throughout October and November. Towards the end of the review process, the major findings were presented to a common management board in the science directorate, who further challenged some findings and, in some cases, requested additional clarifications. A substantial effort was devoted to the harmonisation and cross-verification of the cost estimates.

This report provides a summary of the Review Panel findings. It is made public for the sake of transparency and for providing feedback to all teams who actively contributed to the mission assessment phase, namely: the study science team and the science community supporting the mission, the science instrument consortia, the industrial study teams, and ESA study team.

2 STE-QUEST MISSION OVERVIEW

2.1 Mission Description

STE-QUEST is designed to test the different aspects of Einstein's Equivalence Principle using quantum sensors.

Scientific objective	**Target accuracy**
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 $2x10^{-15}$.
Gravitational Redshift Tests	
Sun gravitational redshift	Measurement of the Sun's gravitational redshift effect to a fractional frequency uncertainty of $2x10^{-6}$, with an ultimate goal of $5x10^{-7}$.
Moon gravitational redshift	Measurement of the Moon gravitational red-shift effect to a fractional frequency uncertainty of $4\cdot10^{-4}$, with an ultimate goal of $9\cdot10^{-5}$.
Earth gravitational redshift - optional	Measurement of Earth's gravitational redshift effect to a fractional frequency uncertainty of $2x10^{-7}$. Optional
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.	

STE-QUEST will 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 and the Moon.

The atom interferometer will primarily perform differential acceleration measurements while the spacecraft is around perigee (spacecraft altitude below 3000 kilometres), thus maximizing the signal-to-noise ratio of a possible violation of the Weak Equivalence Principle.

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

- **Ground-to-ground comparisons** of high performance atomic clocks with worldwide distribution;
- **Atomic interferometry measurements** of the differential acceleration between ultra-cold samples of different atom species.

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.

STE-QUEST will be launched by Soyuz Fregat into a highly elliptical orbit with a semi-major axis of ~32000 km, an orbital period of 16 hours, and an inclination of 62.6 degrees. The orbit is in a 3:2 resonance, providing three constant apogee locations of the orbit with respect to the Earth surface. The mission duration is planned for 5 years, mainly driven by the common-view clock comparisons.

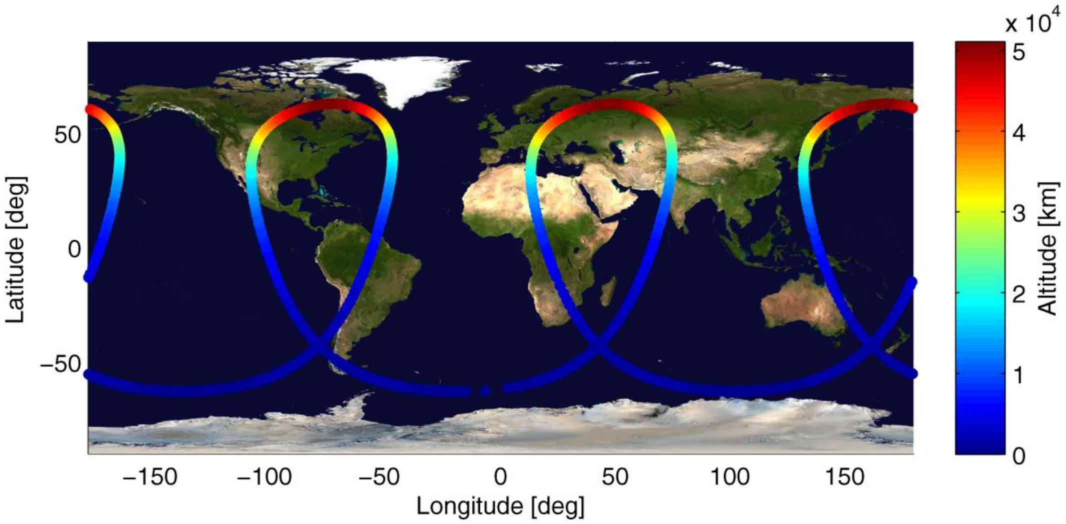


Figure 1: Ground Track of the STE-QUEST orbit. (Example)

2.2 Payload Complement

The original payload complement for STE-QUEST comprised an Atom Interferometer to perform the weak equivalence tests, as well as an Atomic Clock together with microwave time and frequency links, in order to measure the redshift effects. As an option, an optical link was proposed but currently not retained in the baseline.

The documentation provided for STE-QUEST included both the Atom Interferometer (ATI) and the Atomic Clock (ATC) instruments. The PRR panel has been informed just before the start of the review that the onboard Atomic Clock would not be part of the baseline P/L complement due to national funding issues. The microwave link for time and frequency transfer, though, remains part of the payload and enables measurements of the Sun- and Earth Redshift.

As the modification of the payload complement took place after the industrial studies had finished, the PRR could only consider at very high level the impact of the removal of the onboard clock on e.g. mass and power budgets. A more detailed assessment was beyond the scope and the resources of this review.

3 APPLICABLE AND REFERENCE DOCUMENTS

[AD01] PRR Procedure, SRE-F/2013.042/, Issue 2, Revision 0, dated 05/09/2013.
[AD02] M3 Missions Reference Schedule, SRE-F/2013.039/, Issue 1, Revision 0, dated 23/04/2013.

4 ACRONYMS

ACES	Atomic Clock Ensemble in Space
AD	Applicable Document
AIV/T	Assembly, Integration, Verification/Test
AOCS	Attitude and Orbital Control System
ATB	Avionics Test Bench
CDMU	Command and Data Management Unit
COG	Centre of Gravity
CTE	Coefficient of Thermal Expansion
DC	Direct Current
DOF	Degree Of Freedom
E(Q)M	Engineering (Qualification) Model
EID-A	Experiment Interface Document - Part A
ESA	European Space Agency
FDIR	Fault Detection, Isolation, and Recovery
FM	Flight Model
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
ITT	Invitation To Tender
KO	Kick Off
MRD	Mission Requirements Document
MWL	MicroWave Link
P/L	Payload
PFM	Proto-Flight Model
PRR	Preliminary Requirements Review
RD	Reference Document
SA	Solar Array

SEE	Single Event Effect
SET	Single Event Transient
SPC	Science Programme Committee
SSAC	Space Science Advisory Committee
STE-QUEST	SpaceTime Explorer and Quantum Equivalence principle Space Test
STM	Structural-Thermal Model
SW	Software
TAS (-I)/(-F)	Thales Alenia Space (-Italy)/(-France)
TFC	Time and Frequency Comparison
TRL	Technology Readiness Level

5 TECHNICAL REVIEW OUTCOME

5.1 Confirmation of the Mission and System requirements:

The mission requirements established for the STE-QUEST phase A study are complete and adequate for the study phase. The MRD already identifies the requirements that are only applicable to the optional payload elements (atomic clock and optical link), reflecting which requirements will be removed. The mission requirements document contains a set of system requirements that need to be migrated to the System Requirements Document, once it will be available.

Full traceability all mission requirements to the science requirements is provided.

The interface between instruments and platform is well defined in the EID-A; it requires some refinement in the areas of AIV/T and FDIR. The next version of the EID-A will need to take into account the results of the assessment phase.

The mission, payload, and ground segment requirements are fully traced to science objectives and judged complete.

5.2 Confirmation of the mission technical feasibility:

5.2.1 Spacecraft

5.2.1.1 General

The spacecraft platform design concept is considered technically feasible, no technical "show-stoppers" have been identified by the review panel.

However, the panel wishes to highlight two areas of concern that require attention in the next phase:

- change of payload baseline due to the removal of the onboard atomic clock, which is

expected to have considerable impact on the satellite design concept but also to provide additional margin. The general mission feasibility is not considered to be affected, but the spacecraft design is likely to be modified.
- the shortened phase A (both in terms of available time and budget for the external studies), resulting from the re-organization of the M-class schedule, leading to the fact that some design trade-offs have been postponed to the next phase.

As a result, it is strongly recommended to foresee an extended phase B1, in order to allow the STE-QUEST teams to establish a mature satellite technical baseline before starting the later project phases.

5.2.1.2 Overall satellite design concept

Both industrial consortia proposed a modular spacecraft approach, with separate payload module and service module. This enables to decouple the design, development and AIV of both modules to the maximum extent, which is considered positive by the review team. The TAS baseline uses a service module based on a modified version of the TAS Spacebus platform while the Astrium satellite design is more specific and is optimised for the STE-QUEST mission.

5.2.1.3 Mechanical design

Both study teams presented a mechanical design for the satellite, supported by a preliminary mechanical analysis to identify compliance with the baseline launcher. As indicated above, both industrial teams propose a modular design with separate service modules and payload modules, however the structural concepts of the 2 proposed spacecraft are quite different. Both designs result in limited accessibility to the instruments after payload module integration and especially after mating with the service module (this is a bigger issue with the Astrium design). Compatibility with the AIV needs at late stages of the project has to be verified.

Both study teams use a combination of different materials in the spacecraft structure, mainly for mass saving and for efficient heat distribution. However, due to the different CTE coefficients, this causes stresses at the interfaces in case of temperature excursions. Although the expected level of stress at these interfaces could be considered acceptable, this has to be demonstrated and in particular it has to be investigated that this does not result in complications in the heat-pipe connections through these interfaces. Integration of the heat pipes in the structure (including in load bearing panels) and the loads on the heat pipes need to be verified as well.

It is expected that the changed baseline for the payload (removal of the onboard atomic clock) will have a considerable impact on the satellite structural design and could allow simplifications, even though this implies the need to repeat all mechanical and thermal analyses.

5.2.1.4 Thermal design

The thermal design of the spacecraft, and particularly of the payload module, is one of the more challenging aspects of the STE-QUEST satellite. The high average dissipation of the payload units at the center of the spacecraft (especially the Atom Interferometer, which needs to be mounted close to the satellite COG) in combination with a relatively narrow operational thermal range requires extensive use of heat-pipes to transport the dissipated heat to the external radiators. This leads to considerable complications in the design as well as in the AIV of the payload module and of the satellite.

The proposed design is supported by a relatively extensive thermal analysis, especially in the case of the Astrium study team.

In the case of the TAS study team, thermal analysis remained at a higher level and the assumptions and input conditions used were not very clear.

Despite the fact that both study teams arrive at the conclusion that the thermal design is feasible, some concerns about the feasibility of the proposed heat pipe design remain. As such, it is recommended that in the next phase the thermal design, especially of the payload module and of the instruments themselves is revisited and consolidated in detail.

The changed baseline for the instrument (removal of the onboard atomic clock), is expected to positively impact the feasibility of the thermal design due to the significant reduction of the power demand by the STE-QUEST payload (and consequently the lower amount of power to dissipate), although the Atom Interferometer remains the main driver.

5.2.1.5 Electrical design

The main drivers for the electrical design are the power generation needs in combination with the relatively long eclipses, as well as the magnetic cleanliness requirement.

Power generation is ensured by deployable panels with one (in the case of Astrium) or two (in the case of TAS) degrees of freedom to ensure sufficient power along the orbit. Optimizations during the next phase are necessary to avoid micro-vibrations due to the rotations of the solar array (continuous versus discrete rotation, axis of rotation etc…).

The design proposed by the TAS team is marginal in terms of power generation and storage. Furthermore, assumptions and details of the analyses performed by TAS to justify the design are not always clear, making it more difficult to judge the suitability of the design itself (SA and battery sizing) and its available margins. Therefore, it is recommended to scrutinize and consolidate the electrical design at the beginning of the next phase.

Both instruments require a clean magnetic environment. Thanks to the use of magnetic shields at the level of the instrument, the magnetic cleanliness required of the satellite is more relaxed and ranges from 100 micro-Tesla (DC) to 1 micro-Tesla depending on the frequency range. This will require the establishment of a magnetic cleanliness plan, avoidance of specific materials, special precautions in accommodation of specific units and routing of harness, possibly combined with additional shielding. A corresponding magnetic verification plan will also have to be established.

5.2.1.6 Data handling and communications

The STE-QUEST requirements with respect to data handling and communication are not considered challenging, mainly due to the relatively low data rates, long visibility periods with the ground stations and relaxed time stamping accuracy requirements (especially in case of the new instrument baseline, without the onboard atomic clock). Both study teams propose to use the mass memory within the onboard computer for storage of the payload data. This is acceptable, but the data interface between the computer and the payload needs to be consolidated. The Agency requirements specify the use of Spacewire, but the currently identified payload data rates are so low that one industry proposes to use of the 1553 bus. It is therefore recommended that the payload data rate (including potential future evolutions) is carefully evaluated and subsequently the most suitable interface is selected.

Both study teams selected the X-band transponder for the transmission of the data to the ground segment.

The Astrium team presents an architecture based on a combination of a low gain and medium gain antenna in order to cope with the big variations in distance between ground station and satellite.

The TAS team presents an architecture only based on a low gain antenna, resulting in marginal performance under certain conditions. For instance, the Astrium design is compatible with smaller (15m) ground antennae whilst the TAS design requires the (currently baselined) 35 m antennae.

The onboard SW is not considered a particularly critical development due to the standard set of requirements imposed by the STE-QUEST mission.

5.2.1.7 AOCS

One of the biggest challenges to the AOCS subsystem is to maintain a sufficiently stable environment in terms of micro-vibrations, while maintaining the attitude along the orbit according to the mission requirements. Both study teams studied reaction wheels as well as propulsion-based actuators. Based on micro-vibration test results from existing wheels it was concluded that the micro-vibration environment could be kept sufficiently clean if the RPM’s of the wheels are kept in specific ranges.

TAS has selected the use of reaction wheels mounted on vibration isolators as actuators for the attitude control, resulting in a simplified design and a potential for re-use of an off-the-shelf service module design. However the feasibility of performing the required attitude control in the limited rotational range of the reaction wheels has not been fully demonstrated. In consideration of the more marginal compliance to the micro-vibration requirements and the limitation on the RPM range, this approach is considered risky, with limited fall-back capability in case of problems identified in later phases.

Astrium has selected the use of a micro-propulsion system to perform the attitude control, implying a more complex design, but a much better compliance to the micro-vibration requirements.

The AOCS baseline has to be consolidated in the next phase. The PRR team considers that the micropropulsion systems based on cold gas provides increased margin towards the requirements and is consequently a preferable approach at this stage of the mission design.

Flexible modes resulting from the extensive solar arrays or fuel sloshing have been analyzed, but only in a preliminary way. Both study teams indicate the need for a sufficient “settling phase” after the large attitude manoeuvres along the orbit, but its duration (and hence its compliance with the mission requirements) was not fully assesssed. However, the current estimate of the maneuver duration of 900 seconds leaves ample margin to the 30 min requirement listed in the MRD.

The propulsion system presented by the TAS study team is marginal with respect to the proposed propellant tank capacity. Due to lack of details on the propellant sizing analysis, there is a risk that a bigger propellant tank may be needed. Implications on the spacecraft design need to be verified.

Analysis of the feasibility of performing orbit determination based on GNSS measurements along the orbit showed that the orbit determination based on detailed post-processing of the GNSS measurements, in combination with propagation for the part orbits not covered by the measurements due to the highly elliptical nature of the orbit, is reliably compliant with the science requirements. It is noted that the removal of the ATC will lead to a relaxation of this requirement.

5.2.1.8 Compliance with space environment

The STE-QUEST satellite operates in a highly elliptical orbit with high level of radiation doses. The applicable environment has been established by the ESA project team and was made applicable to the study teams. Both study teams have analyzed compliance of their satellite designs with this radiation environment, more specifically regarding total dose. Although some doubts were raised concerning the correctness of the results presented by the TAS study team, it was found that radiation total doses for units inside the spacecraft could be reduced to acceptable levels by means of the overall satellite shielding.

In the case of the TAS design, it is expected that additional shielding will be required for the Atom Interferometer instrument due to its outboard location, leading to a mass penalty.

In addition, the situation for the external units (which receive high level of radiation dose), such as star tracker optical heads, needs to be further assessed to demonstrate the suitability of the design. Suitability to SEE/SET requirements has to be demonstrated once more detailed unit level designs are available.

5.2.1.9 De-orbit compliance

The panel notes that both study teams proposed a satellite design capable of performing controlled de-orbit at the end of the mission, considerably simplifying compliance with the applicable debris mitigation requirements.

5.2.1.10 Budgets

Both study teams present a mass budget, including the required margin philosophy that is compliant to the launcher capacity. The TAS satellite design has a considerably lower mass than the Astrium one, however, as highlighted above, the TAS design is marginal with respect to quite a number of aspects, which will nearly certainly lead to a “design-growth” in several areas. Consequently the Astrium mass budget is considered more realistic.

It is noted that the removal of the onboard atomic clock will have a considerable positive impact on the overall mass budget.

5.2.1.11 Technological maturity

Both study teams present a platform design based on state- of- the- art equipment which is either already off-the-shelf or expected to fly considerably before the planned flight of STE-QUEST (examples of the latter are: GPS (Astrium), solar cells (Astrium), proposed 2-DOF solar array drive (TAS), proposed CDMU (TAS)). Whilst this is positive, detailed compliance of the off-the-shelf equipment to the STE-QUEST requirements is required (it is typically performed in later project phases) to identify delta-qualification activities.

Compliance to the STE-QUEST radiation environment has to be verified in detail at equipment level.

5.2.2 Payload

5.2.2.1 General

The revised baseline of the payload complement, i.e. atom interferometer, time-frequency comparison science ground segment together with the microwave link, was reviewed and produced the following findings.

5.2.2.2 Atom Interferometer Instrument (ATI)

The design concept is based on existing atom interferometer systems and includes several components already used in ongoing developments and experiments, so that the expected performance at component or unit level has a consolidated benchmark. The atom interferometry measurement on a dual (85Rb-87Rb) atomic source however has not been proven yet and the consortium proposes a demonstrator model to be built in the next phase to demonstrate the measurement concept. This approach is judged adequate. Risks are inherent in the qualification of the sub-systems of the ATI and of the instrument as a system. These are identified by the consortium, although the mitigation actions lack detail that needs to be provided in the next phase.

The definition of the interfaces to the spacecraft was judged adequate, but requiring consolidation for the data interfaces, as indicated earlier.

The presented budgets are derived from a finite element model, a thermal model and a CAD model that have been developed and used for the analyses described in the design report. These budgets are corroborated by similarity with existing developments and experiments, and were considered credible.

In the design and development plan the critical technologies are identified and assessed together with the readiness level. Roadmaps toward TRL 5 are also presented. This includes the already mentioned development of a laboratory demonstrator model of the physics package and the laser system. This is considered a sound approach to mitigate the risk inherent in such a new development. The development plan includes also the manufacturing and testing of an EM, its upgrade to EQM and a ProtoFlight Model. While the planning of the demonstrator is very detailed, the planning for the subsequent models is only described at top-level.

Subsystem		**TRL 2013**	**TRL 2014**
ATI		(3)	
	Physics Package	3-4	4-5
	Laser Package	3-4	4-5
	Electronics	3-4	4-5
MWL		3-4	3-4

The risk register ranks the laser system quite optimistically. The laser system is complicated and the space compatibility not fully demonstrated yet. The Laser TRL reported in the design report is largely based on similarity with Telcordia qualification standard (that are not for space applications) and the need for a proper space qualification is indicated only in broad terms, consequently the actual amount of delta testing and effort is not fully assessed. Despite clarification received by the ATI team that radiation tests and a delta qualification for shock are the only activities required by a Telcordia-qualified component to achieve full space qualification, the panel is of the opinion that this point will need to be thoroughly addressed in the next phase.

Also, the laser TRL is given for individual items and sometimes for the laser technology. The full laser system for STE-QUEST has not yet been assembled, so other technology problems might arise due to different interface requirements. The TRL has to be referenced to the complete system (i.e. lasers + stabilization + switching system, etc.) and not only to components. The roadmap for the demonstration of the laser system TRL 5 by mission adoption is judged incomplete.

5.2.2.3 Atomic Clock Instrument / Time and Frequency Comparison (ATC/TFC)

Removal of the onboard atomic clock still leaves the TFC/SGS measurement based on time and frequency comparisons between ground clocks.

The panel notes that the current accuracy of the ground clocks still needs an improvement by up to 1 orders of magnitude, to be compatible with the STE-QUEST requirements, which is believed to be achievable in time.

5.2.2.4 Microwave Link

The proposed design for the Microwave link electronics is based on the one used on ACES. However, some modifications need to be implemented in order to meet the STE-QUEST requirements:

- Specific improvements of the ACES MWL design
- Increase of clock rate and modulation rate from 100 MHz to 250 MHz
- Increase of frequency bands from Ku to Ka band for up- and downlink and from S- to X-band for the additional downlink to mitigate ionosphere errors
- Increase in transmit power by 1 order of magnitude as well as change in antenna design, including antenna switching, to compensate for the larger free space losses (due to higher orbital altitude) as well as for the larger atmospheric losses in the Ka band.

These modifications are not considered very critical in terms of feasibility and risk and an acceptable development approach, based on breadboards, EQM and FM is presented. However, considering the fact that the system is very sensitive and operates at the limits of what is technologically feasible, there is a remaining risk that problems may be encountered during the development. Therefore, the MWL development should be started as soon as possible (early 2014) to mitigate the remaining risk on the overall project and to ensure timely availability of the flight units. The panel notes that technology development activities for the full on-board microwave link system are about to be started by ESA and scheduled to arrive at TRL 5 before the end of 2015.

5.2.2.5 Optical Link

The presented industrial baseline designs include the use of a laser communication terminal (LCT), as available from Tesat. However, due to the fact that this has been removed from the baseline, no specific review of the LCT related aspects was performed.

5.3 Confirmation of the mission programmatic feasibility:

5.3.1 Spacecraft Model Philosophy

The model philosophy proposed by both study teams is primarily based on:

- A structural and (partial) thermal model (STM)
- An Avionics Test Bench (ATB - Electrical Functional Model - EFM) of the satellite, including payload EM (ATB)

- A Protoflight Model of the satellite (PFM)
- Completed with a number of lower level models and simulators.

This approach can be acceptable, considering the level of maturity of the proposed platform concepts. However, care has to be taken to ensure sufficient level of representativity of the ATB in terms of functionality, redundancy and availability (for instance it is recommended to ensure that no re-use of ATB units into the PFM is foreseen, in order to ensure availability of a completely representative ATB throughout the complete AIT phase).

Potential re-use of the STM structure as PFM structure was suggested by the TAS consortium, for cost reasons. However, care has to be taken to avoid any potential schedule conflict between the STM and the PFM.

Specific comments on the test matrices were made. The lack of a service module thermal model as proposed by the TAS study team could be acceptable if recurrence with previous platforms can be demonstrated. However, this should be carefully re-assessed once the final design baseline is consolidated.

5.3.2 Payload Model Philosophy

The development of the Time and Frequency Science Ground Segment (TFC SGS) of the ATC is briefly described. A more detailed definition is required in the following phase.

For ATC ground clock comparisons obviously no hardware models are expected to be developed.

The model philosophy proposed by the ATI consortium is based on:

- Laboratory development model
- EM
- EQM
- Proto-flight (PFM)

The Instrument EM model is used by the consortium for the drop-tower test and is later refurbished to an EQM that includes redundancy and can withstand environmental tests.

After instrument qualification, the EQM is delivered to the mission prime for inclusion within the Electrical Functional Model/ATB.

The laboratory demonstrator activities are fully detailed whilst plans for development and testing of the later models are very preliminary and lack details; a potential impact on cost and schedule could therefore not be assessed by the panel.

The instrument performance verification is made on the EM model using the drop-tower test, the duration of which is limited, but which, according to the consortium, will still allow the short-term sensitivity to be verified to almost full performance. Performance verification on EQM and FM models is generically planned to be performed in the laboratory prior to delivery, but no specific information is provided.

A concern was raised by the panel relative to the ATI different delivery responsibility of the EQM and FM models, as indicated in the documentation. The consortium, though, confirmed that the responsibility will be with the same industrial contractor, which is considered a sound approach by the panel.

Once the payload is delivered to the spacecraft prime for integration, the payload activities are limited to functional testing, for which no detailed information is provided. This shall be elaborated.

5.3.3 Payload Schedule

The P/L schedule proposed by the ATI consortium is very aggressive and is based on (ongoing) technology development activities lasting 23 months, which the panel considers very tight, as is the time allocated for the upgrade of the EM to EQM (4 months). For the EQM delivery however, a considerable slack with respect to the need date (almost one year) is present in the schedule, so the risk involved is considered manageable.

The P/L PFM manufacturing is scheduled to last less than one year, which is considered far too short, followed by one year of integration and testing. The P/L PFM development schedule presented is therefore considered non-credible. The panel noted, though, that the duration between the end of EM testing campaign and P/L FM need date by the prime contractor is 32 months, which could be considered a reasonable duration for the P/L PFM development schedule. The EM design update runs in parallel to the EM testing campaign, which is considered a risk. It is therefore recommended to add a margin in the order of 4 month for safety.

ATI does not explicitly identify a critical path, but on the basis of what stated above, the delivery of the FM constitutes the critical path.

In terms of schedule harmonization between the P/L and the S/C, it is noted that the P/L development and the models production (both EM and FM) start very early with respect to the Platform activities. Specifically, the P/L EM design and manufacturing begins in the second quarter of 2015, halfway through the SC phase B1. The P/L EQM testing will be almost completed when the S/C CDR will be held, in January 2018, and the P/L FM manufacturing will start one year before the S/C CDR.

With this approach, the SVM and PLM design will be driven by the P/L, which will limit the flexibility of the industrial prime contractor. Whilst this approach is considered positively by the review panel, as it contributes to reduce the risk related to P/L delivery, it also mandates for a tight schedule control of the ESA activities (industrial phase B1, implementation ITT process, adoption) and the existence of an early project team during phase B1 to define the interfaces for the S/C phase B1 and the P/L EM phase and to take into account the outcome of the P/L EM phase when preparing the documentation for the implementation phase ITT.

The Panel highlights the absolute necessity of early funding (starting in 2015) for the payload EM activities to support the above plan.

5.3.4 *Spacecraft Schedule*

Both contractors indicate a development schedule from the start of B2 of less than 6.5 years, for a launch in late 2022.

For Astrium, this includes a phase B2 duration of 15 months, a phase C/D of 18+41 months (including 3.5 months of contingency) and a 3–month launch campaign.

For Thales, the duration of phase B2 is 12 months, phase C/D lasts 24+36 months (including 6 months of contingency), and 3–month launch campaign.

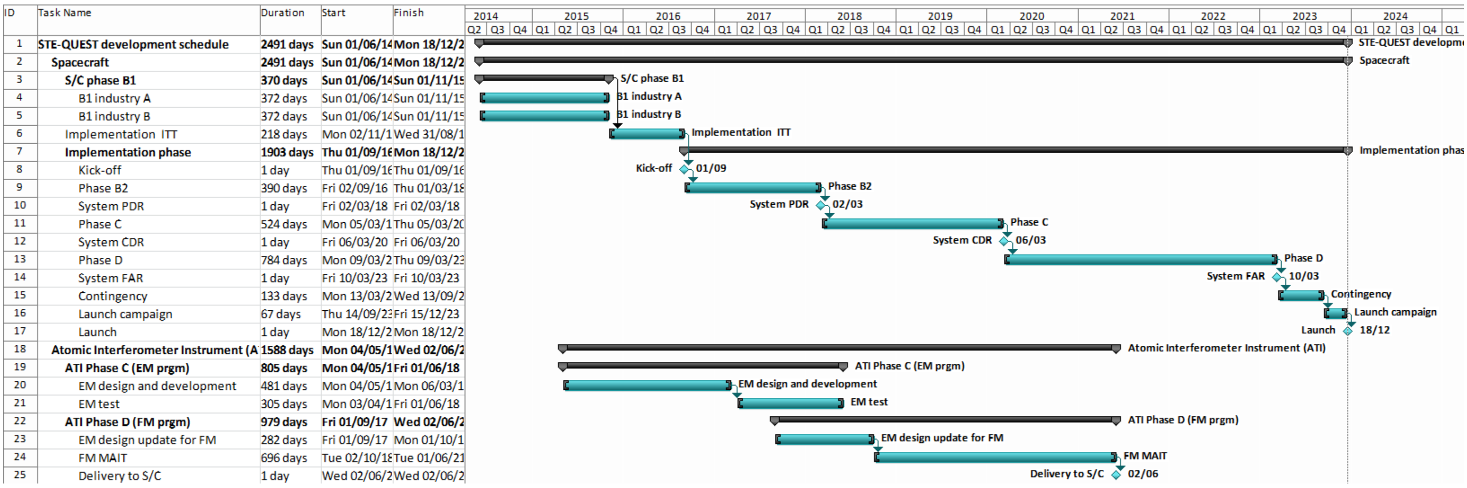
The panel considers the duration of phase B2 for Thales too short and the Astrium duration of B2 marginal for a thin prime approach.

At satellite level, the time available to perform the AIT on the complete satellite (i.e. service module and payload module) is rather limited and, especially in the Thales case, not judged sufficient.

The overall schedule contingency margin with respect to a launch date in 2022 presented by the Astrium study team is judged too small, even without taking into account the suggested additional slack in the payload schedule. The schedule margin of 6 months presented by TAS is considered not credible since it is based on an earlier (and hence not very realistic) need date for the payloads and it includes an increased schedule risk due to early start of activities (for instance start of PFM manufacturing and AIT activities before finalization of ATB verification activities). The TAS duration of Phase C/D is thus judged too short.

In consideration of what stated above on the P/L and satellite schedules, the panel considers the launch date of 2022 not realistic.

A launch date in June 2023 is considered the earliest credible launch date, to be confirmed by a detailed analysis of updated P/L development and test plan and of S/C development schedule. This date is success oriented, in that it is based on the assumption of early availability (starting in phase B1) of funding for the payload elements from Member States and successful technology development activities. Adding the 6-month contingency between FAR and Launch brings the launch date to December 2023, as indicated in the schedule below.



ID	Task Name	Duration	Start	Finish
1	**STE-QUEST development schedule**	**2491 days**	**Sun 01/06/14**	**Mon 18/12/2**
2	**Spacecraft**	**2491 days**	**Sun 01/06/14**	**Mon 18/12/2**
3	**S/C phase B1**	**370 days**	**Sun 01/06/14**	**Sun 01/11/15**
4	B1 industry A	372 days	Sun 01/06/14	Sun 01/11/15
5	B1 industry B	372 days	Sun 01/06/14	Sun 01/11/15
6	Implementation ITT	218 days	Mon 02/11/1	Wed 31/08/1
7	**Implementation phase**	**1903 days**	**Thu 01/09/16**	**Mon 18/12/2**
8	Kick-off	1 day	Thu 01/09/16	Thu 01/09/16
9	Phase B2	390 days	Fri 02/09/16	Thu 01/03/18
10	System PDR	1 day	Fri 02/03/18	Fri 02/03/18
11	Phase C	524 days	Mon 05/03/1	Thu 05/03/20
12	System CDR	1 day	Fri 06/03/20	Fri 06/03/20
13	Phase D	784 days	Mon 09/03/2	Thu 09/03/23
14	System FAR	1 day	Fri 10/03/23	Fri 10/03/23
15	Contingency	133 days	Mon 13/03/2	Wed 13/09/2
16	Launch campaign	67 days	Thu 14/09/23	Fri 15/12/23
17	Launch	1 day	Mon 18/12/2	Mon 18/12/2
18	**Atomic Interferometer Instrument (A**	**1588 days**	**Mon 04/05/1**	**Wed 02/06/2**
19	**ATI Phase C (EM prgm)**	**805 days**	**Mon 04/05/1**	**Fri 01/06/18**
20	EM design and development	481 days	Mon 04/05/1	Mon 06/03/1
21	EM test	305 days	Mon 03/04/1	Fri 01/06/18
22	**ATI Phase D (FM prgm)**	**979 days**	**Fri 01/09/17**	**Wed 02/06/2**
23	EM design update for FM	282 days	Fri 01/09/17	Mon 01/10/1
24	FM MAIT	696 days	Tue 02/10/18	Tue 01/06/21
25	Delivery to S/C	1 day	Wed 02/06/2	Wed 02/06/2

5.3.5 *Procurement Approach:*

The procurement approach proposed by TAS is not fully compliant with the thin prime approach, as the majority of tasks are shared between TAS-I and TAS-F in a sort of co-prime arrangement, significant manpower is held at prime level for engineering and AIV tasks and apparently only S/S units are procured.

The panel notes that the subcontracting of AIV/T activities, as foreseen in the thin prime approach, is considered an element of risk.

The procurement approach proposed by Astrium is fully compliant with the thin prime approach, with AIV and major S/Ss subcontracted. The panel noted that no manpower is allocated at prime level for AIV planning and coordination tasks.

5.3.6 *Risk assessment:*

The development of the payload requires significant effort before adoption and the panel judges the risk of insufficient funding from national budgets for these activities to be **high**. This funding is essential to meet the payload delivery date.

The risk in the overall payload development schedule is considered **medium-high**, due to the uncertainties inherent to the timely achievement of the required technology readiness level.

Risks relative to the spacecraft are considered **low** and all manageable.

6 ACHIEVEMENT OF REVIEW GOALS

6.1 Confirmation of the Mission and System requirements

The present set of mission requirements established for STE-QUEST was found complete and their level of detail adequate.

6.2 Confirmation of the mission technical feasibility

The proposed mission is considered feasible, without major concerns on the required technology on the spacecraft side, but with a specific reservation regarding the laser system on the payload side and assuming successful completion of the technology development activities. Redesign of the spacecraft to cope with the removal of the on-board atomic clock will require extra effort in the definition phase but is not likely to change the panel judgment on feasibility.

6.3 Confirmation of the mission programmatic feasibility

The schedule proposed by both contractors was considered too optimistic. The panel introduced some additional schedule margin and appropriate phase durations, resulting in an earliest expected launch date in June 2023 that becomes December 2023 with the required 6-month margin between FAR and Launch.

The early start of Instrument detailed design and production w.r.t. the spacecraft schedule is considered positive but it requires availability of substantial funds to support the EM phase as of mid-2015.

The ECaC is addressed in the Cost Report.

7 CONCLUSIONS AND RECOMMENDATIONS

The mission, payload, and ground segment requirements complete and traceable to the science requirements

The interface between instruments and platform is well defined

The spacecraft platform design concept is considered technically feasible, no technical “show-stoppers” have been identified by the review panel, however the removal of the onboard atomic clock will likely modify the current approach, requiring an extended reassessment during phase B1.

On the thermal side, the use of heat-pipes introduces complications at mechanical level and during integration that have to be addressed in detail.

The micro-vibrations requirement is a driver in particular for the AOCS, which is based on the use of reaction wheels that have to be operated within a limited rotational range. The performance in this regime has not been fully demonstrated.

Compliance to the radiation requirements has to be assessed in detail for some units, in particular those located on the outside of the spacecraft.

Compliance of the off-the-shelf proposed units to the specific STE-QUEST requirements has to be demonstrated.

The payload design does not present any technical “show stoppers”, but the interferometric measurement concept using the dual atomic source still has to be demonstrated. The development plan for the ATC EM, EQM, PFM models is limited to top-level considerations.

The Microwave Link units, albeit derived from ACES, require modifications to fulfil the STE-QUEST requirements that are not considered critical but that carry an inherent element of risk.

The P/L schedule proposed by the ATI consortium is very aggressive and is based on successful result of ongoing technology development activities lasting 23 months, which the panel considers very tight.

The risk analysis of the payload elements provided by the consortium is too optimistic and is very much success-oriented for what regards the technology demonstrations.

Subsystem	**TRL 2013**	**TRL 2014**
ATI	(3)	
Physics Package	3-4	4-5
Laser Package	3-4	4-5
Electronics	3-4	4-5
MWL	3-4	3-4

Delays in the delivery of payload elements by the consortium to ESA constitute a risk that could be largely mitigated by re-organising the ESA activities but that will afterwards translate into a financial liability.

The mission is considered feasible, with an earliest launch date in December 2023, including the nominal six months margin. This date is success oriented, in that it is based on the assumption of early availability (starting in phase B1) of funding for the payload elements from Member States and successful technology development activities.

The risk on the payload schedule was considered medium-high by the Review Panel, due to the technology readiness.

The panel judged the risk of unavailability of sufficient, early national funding to support developments efforts on the instruments high.

The risks on the spacecraft development and schedule are judged low (excluding the payload).

The review panel has identified a number of points that require attention in the next phases, should the mission be selected:

- Extended industrial phase B1 to cope with the required re-design

- Early start of payload development after mission selection with sufficient national funding
- Consolidation and timely implementation of the technology roadmap
- Detailing of payload verification activities for the EQM and PFM
- Early establishment of project team during phase B1