Features and critical issues for the STE-QUEST S/C Design

G. Hechenblaikner[1(*)], M.P. Hess[1], J. Beck[1], M. Williams[2], F. Beck[1] & Astrium team

1 EADS Astrium, 88039 Friedrichshafen, Germany

2 EADS Astrium, SG1 2AS Stevenage, United Kingdom

(*) Presenting author

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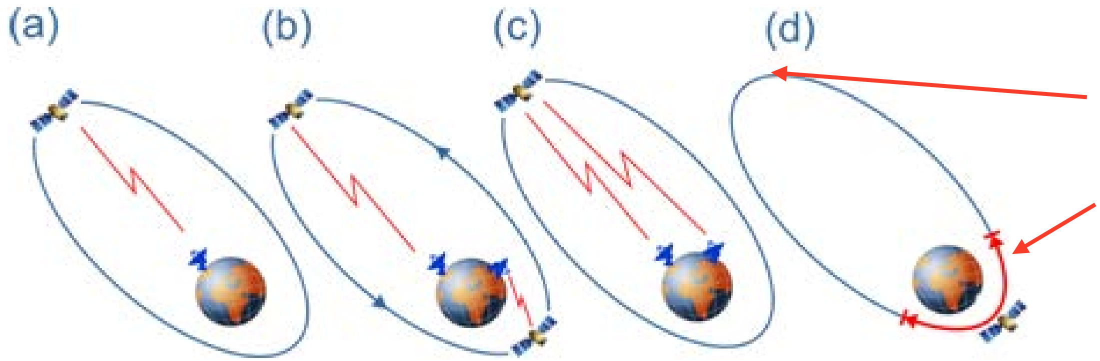
Outline

- Mission Objectives
- Spacecraft Overview & Instrument Accommodation
- Subsystems: AOCS / Thermal / Power / Critical Issues
- Time and Frequency subsystem: Science Links
- Precise Orbit Determination
- Conclusions

Scientific & Programmatic Background

- **Primary Science Objectives**

Gravitational Red-Shift Tests		
Objective 1 (a)+(b)	Earth gravitational red-shift:	shall be measured to a fractional frequency uncertainty better than 1×10^{-7}
Objective 2 (c)	Sun gravitational red-shift:	shall be measured to a fractional frequency uncertainty better than 2×10^{-6} (goal 6×10^{-7})
Weak Equivalence Principle (WEP) Test		
Objective 3 (d)	Universality of the free propagation of matter waves	shall be tested to an uncertainty in the Eötvös parameter better than $\eta=1.5\times10^{-15}$



HIGHLY ELLIPTICAL ORBIT

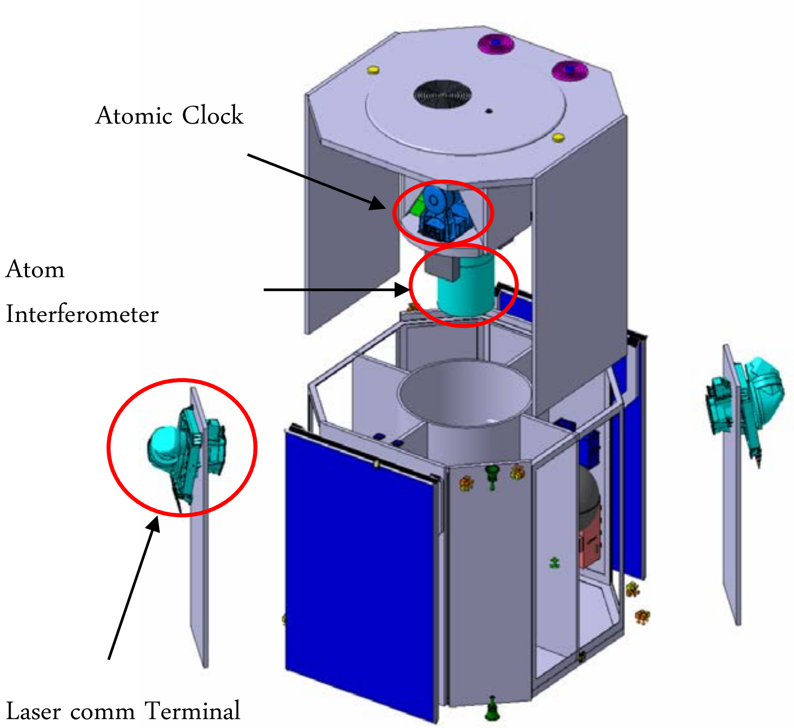
Apogee altitude approx 50 000 km

Perigee altitude 690-2500 km

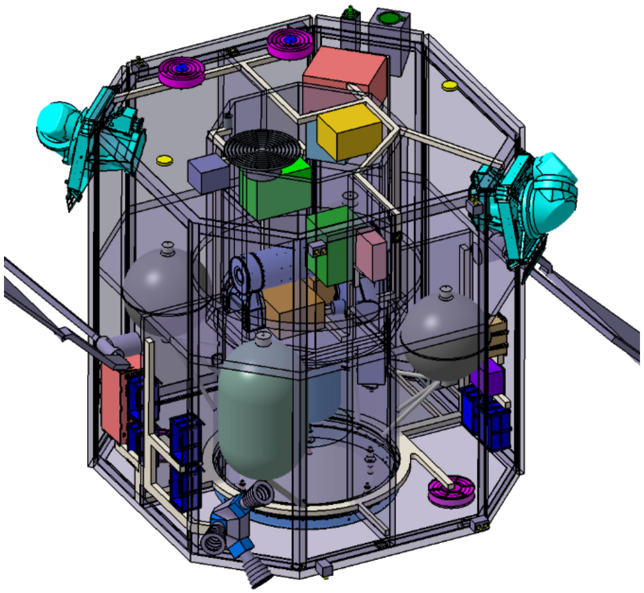
- **Objective 1 & Objective 2:** use Atomic Clock (PHARAO NG) & bi-directional microwave & optical links during apogee or perigee passage.
- **Objective 3:** use Atom Interferometer during perigee passage (<3000 km) No science communication links required.

Spacecraft Overview

- Instrument accommodation
  - Inside protected central region of S/C
  - Close to center-of-mass → minimize accelerations
  - Sensitive to micro-vibrations → **Micro-propulsion** system for attitude control (instead of reaction wheels)

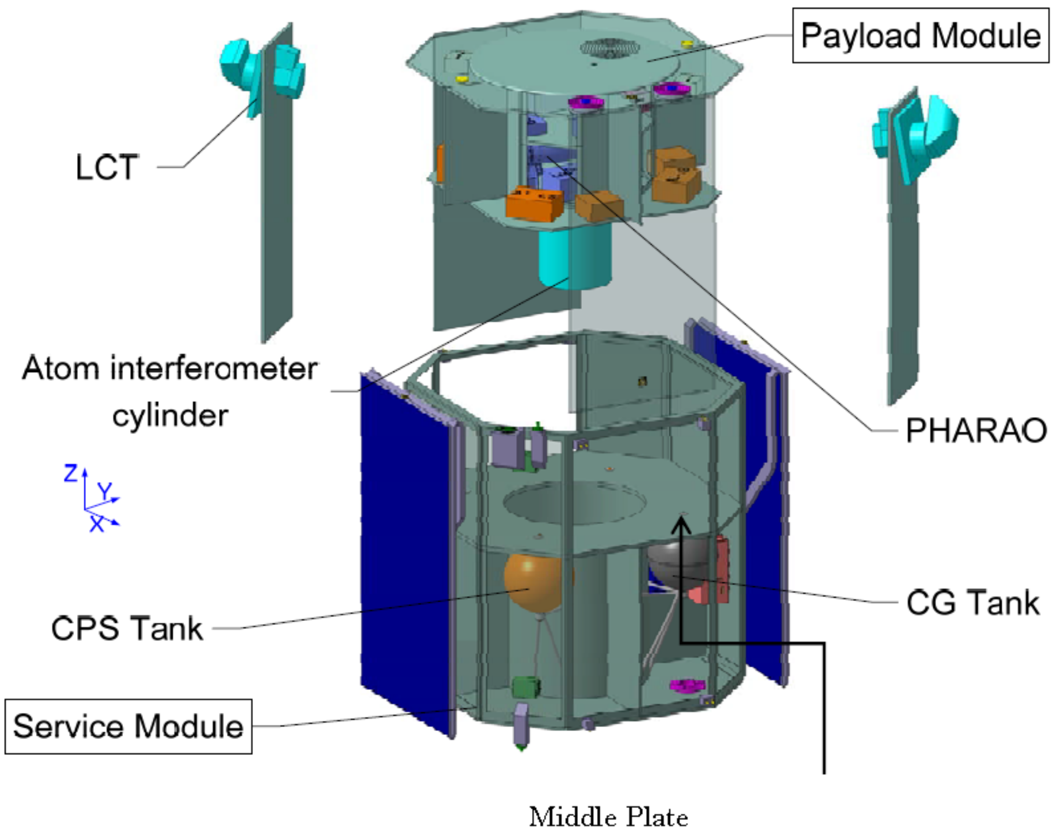


- Some Spacecraft features ...
  - **Microwave Link:**
    S/Ka-band antennae: 2 each on nadir panels
  - **Optical link:**
    2 LCTs on opposite shear panels
  - **GNSS equipment:**
    1 receiver + 2 antennae on nadir and zenith panels
  - **Chemical Propulsion:**
    orbit manoeuvres and de-orbiting



Instrument Accommodation

- The instrument are accommodated in the central part of the spacecraft, i.e. the Payload Module
- All requirements in terms of orientation, alignment and self-gravity are met in this configuration
- The spacecraft is able to support the presently defined resources of the instrument (mass, envelope, power, thermal dissipation, data rate)

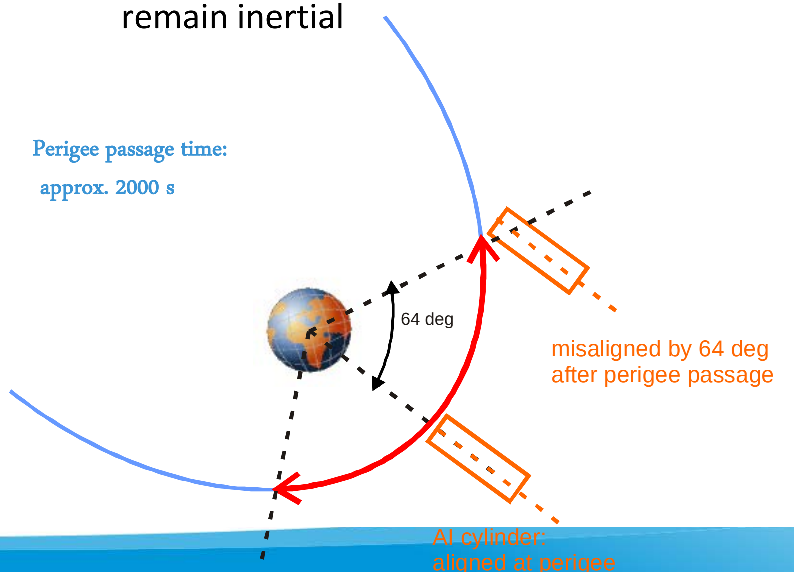


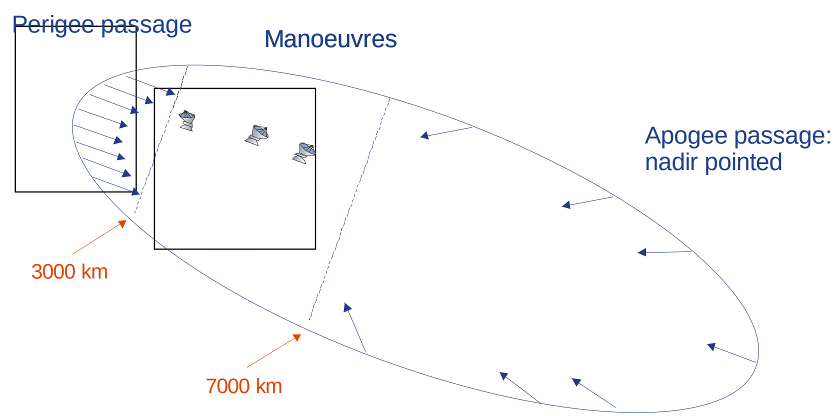
Attitude and Orbit Control

- Atom Interferometer measurements:
  - performed at low altitudes (<3000 km) with sufficiently high gravity gradients
- Angular Accelerations during orbit:
  - Atom interferometry requires: rotational accelerations $< 10^{-6}$ rad/s
  - For baseline orbit & nadir pointing: rate **> 2 x 10^{-5} rad/s** at all times, and much faster at perigee!
  - Therefore, during AI measurements S/C must remain inertial

Pointing Strategy

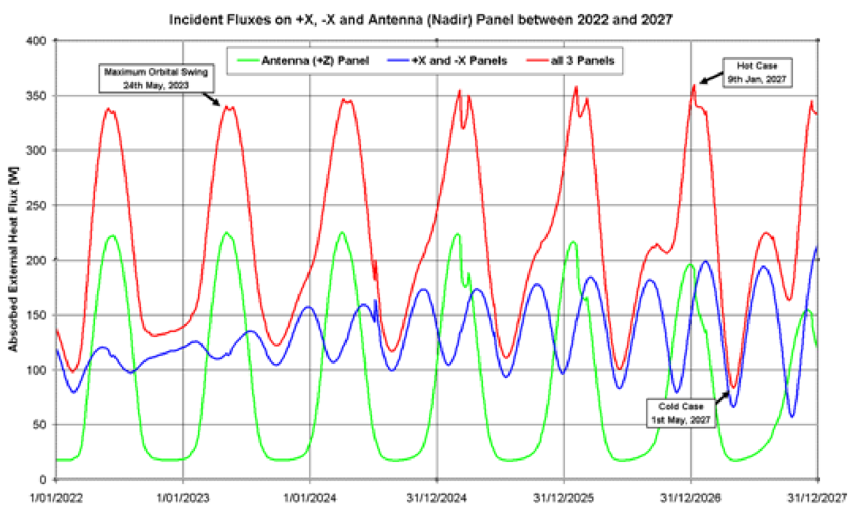
- Perigee Passage:
  - S/C remains inertial for altitudes< 3000 km.
  - Sensitive atom interferometer axis is aligned with nadir at perigee and 64 degrees rotated from nadir at 3000 km altitude.
  - Solar array frozen to avoid vibrational noise.
- Transition Period:
  - Between 3000 km and 7000 km altitude the
  - S/C is rotates in a nadir pointing direction.
- Remaining Orbit:
  - S/C keeps pointing nadir.
  - Rotations much slower than during perigee



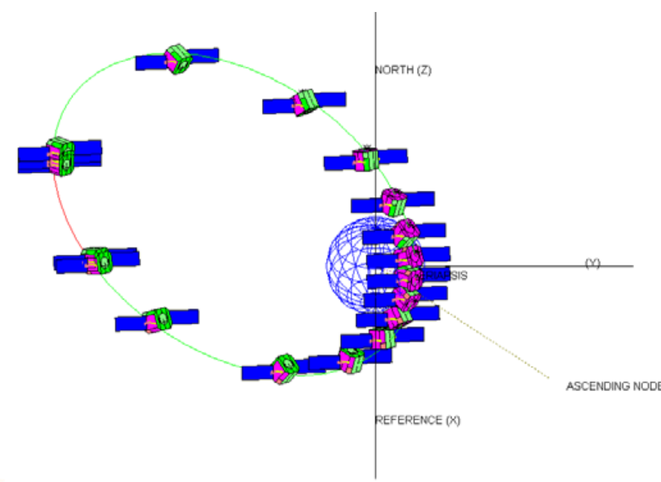


Thermal Subsystem

- Baseline orbit implicaiton for thermal system:
  - **High variations of sun illumination** on S/C external surfaces over one orbit (see Figure below)
  - Sesonal variations→ the sun is incident on the S/C from all sides over one year.
  - Long term variation of the incident heat flux calculated → determine hot & cold case, and maximum orbital swings
  - **Stability requirements** (+/-3 K) and **operating range** (10°C to 30°C) could be met for all instrument units
- Power requirements
  - Instruments and S/C units dissipate a lot of power (> 1.8 kW with margins) --> extensive use of heat-pipes
  - Solar array pointing strategy is complex, SA efficiency degrades over mission

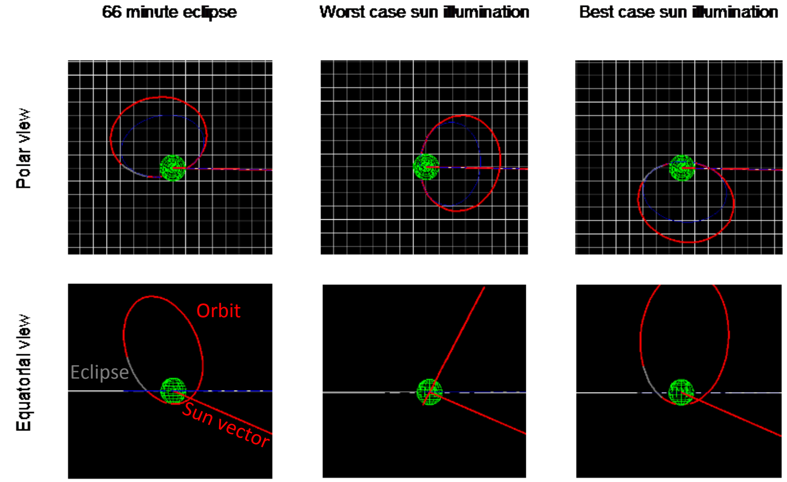


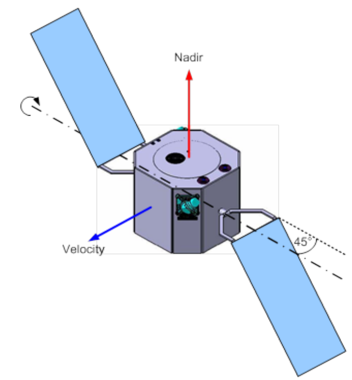
The incident solar flux (old baseline orbit)

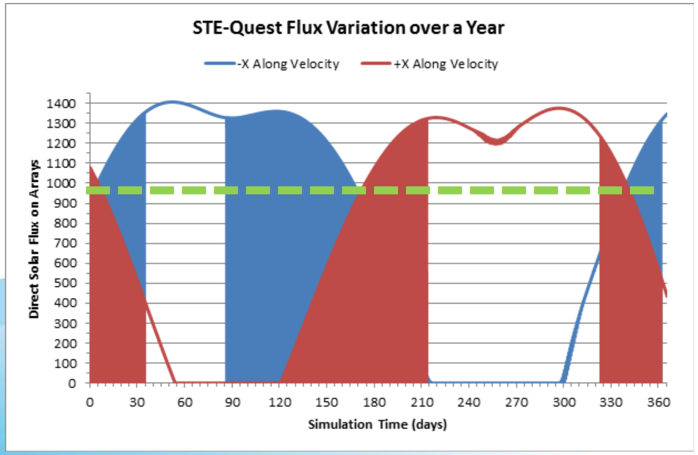


Electrical Design – Power Subsystem

- What are the main drivers for the EPS subsystem design?
  - Spacecraft total power (incl. margins) > 2kW
  - Inclined orbit and nadir pointing create large variation in sun incidence angle over an orbit
  - Nearly 2000 eclipses of 30-60 minutes over 5 year mission
  - Must also be mindful of drag forces during ATI science phase
  - Instrument 50 V bus stability requirement +/- 10 %
- Architecture proposed
  - Separate buses for platform (28 V) and payload (50 V)
  - 2 solar array wings 'canted' at 45 degrees rotate during each orbit to maintain constant flux

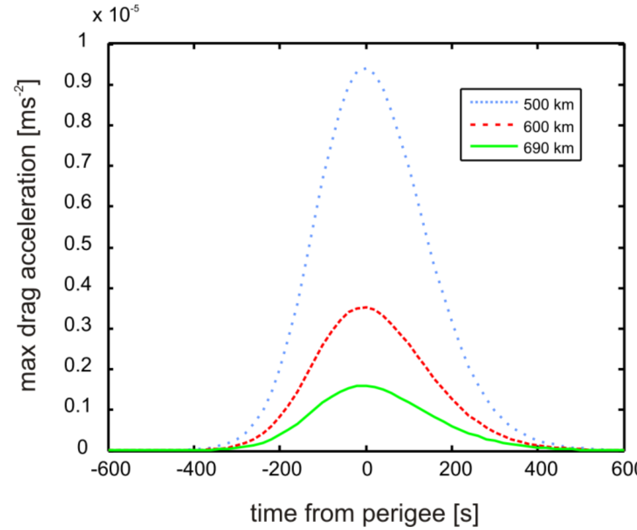




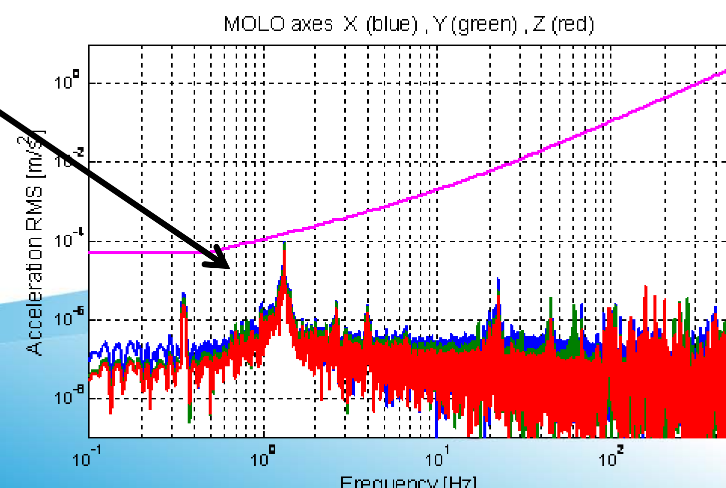


Critical issues

- Center-of-mass accelerations
  - should not exceed 10^{-6} ms^{-2}
  - Drag forces at perigee might violate this requirement
- Micro-vibrations
  - From reaction wheels →
    - preferable to use micro-propulsion system (MPS) for attitude control
    - MPS also allows to compensate drag, if needed
  - From solar array driving mechanism →
    - use proper SADM, accurately model its acceleration noise through the S/C onto instrument interface
- Pointing stability
  - Better than 15 μrad in 15 s (RPE)
  - Perturbations
    - External (drag, magnetic & solar torques, etc.)
    - Reaction wheels



Reaction wheel on Kistler table

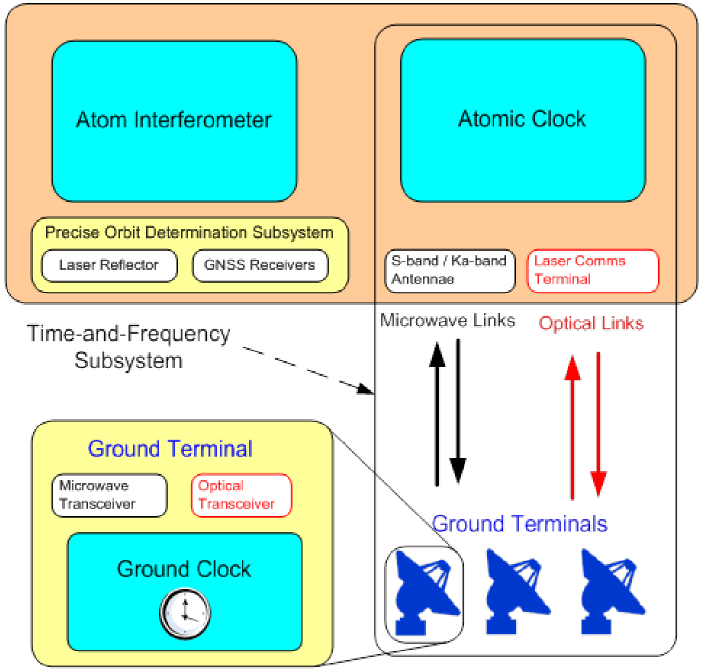


Time & Frequency Measurement Requirements – Objectives 1&2

- Space-clock:
  - Fractional frequency inaccuracy & instability (10^5 s integration) : 1×10^{-16}
- Ground clocks:
  - Fractional frequency inaccuracy & instability (10^5 s integration) : 1×10^{-18}
- Science Links:
  - Microwave instability (10^5 s): 2×10^{-18}
  - Optical Link instability (10^4 s): 1×10^{-18}

Errors in POD also affect calculated frequency shift through ΔU and relativistic Doppler shift between space&ground

- POD Requirement:
  - Space-clock: fract. frequency uncertainty for red-shift due to POD errors $< 3 \times 10^{-17}$
    → specified position error < 2 m
    → specified velocity error < 0.2 mm/s
  - More precise requirements for the accuracy of POD to support relativistic clock comparison were derived for ACES

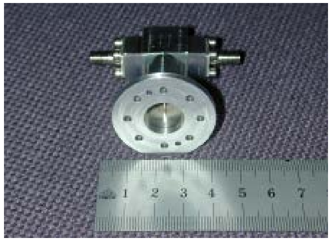


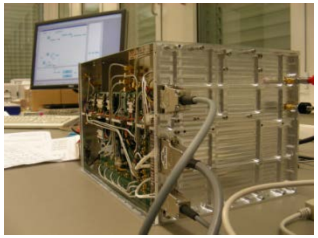
L. Duchayne, F. Mercier, and P. Wolf, Orbit Determination for the next generation space clocks, Astronomy & Astrophysics 504, 653-661 (2009)

Science Links

- Microwave Link (MWL)
  - STE-QUEST MWL link design → derived from the ACES (Atomic Clock Ensemble in Space) MWL
  - Modification are due to the change in transmit frequency, increased range and performance
  - Critical point: thermal sensitivity→ driver in the end-to-end performance budget

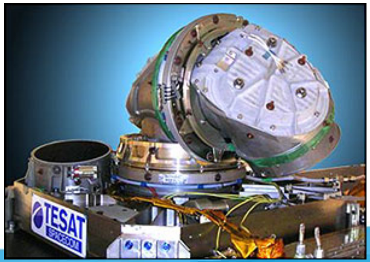
ACES MWL Ground Terminal



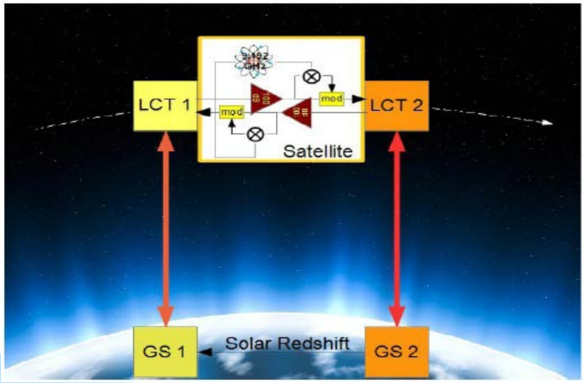


ACES MWL Flight Segment – Electronics & Antenna

- Optical Links (OSL)
  - Several link configuration were traded → detailed link budgets and performance error assessments
  - OSL optimized for common view measurement at apogee → the Sun redshift measurement (objective 2)
  - Mitigations for critical areas identified → further assessment
    - Link stabilisation and cycle slips due to atmospheric turbulence
    - Demonstration of link stability for long, period (10^4 s)
    - OSL availability dependent on local weather conditions



TESAT LCT



STE-QUEST OSL Configuration

Precise Orbit Determination

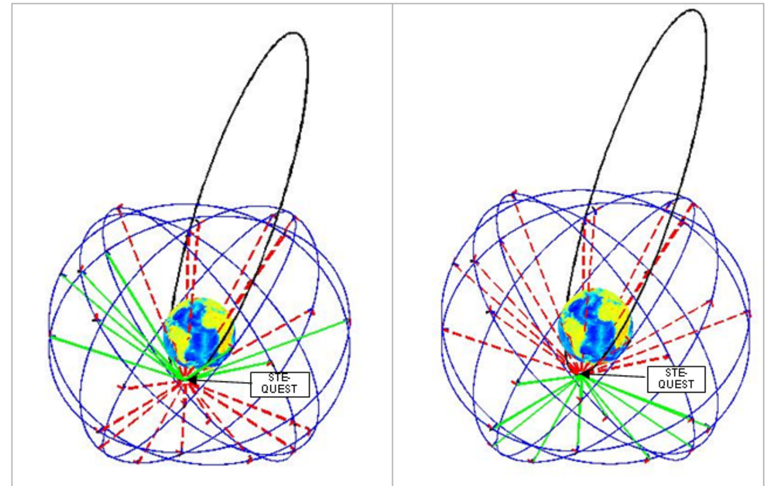
GNSS Receiver Characteristics:

- Tracking of all available GNSS signals (GPS,Galileo,…)
- Tracking loops optimized for orbit dynamics (v up to 10 km/s), support of side-lobe tracking.
- Signal-to-noise (C/N0): 30 dB-Hz (standard),25 dB-Hz (high-end),
- Nadir- and zenith-pointing atennas are used

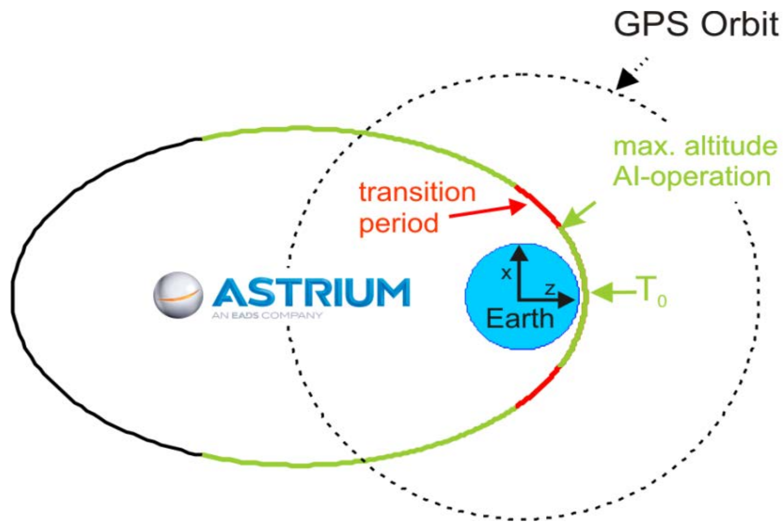
Results:

- The specified accuracies in position and velocity (<2m,< 0.2 mm/s) during GNSS visbility phases
- At apogee accuracies are singificantly lower if uncertainties in external perturbations are considered (solar radiation pressure
- The flyby anomaly (anomalous momentum transfer of S/C careening around earth) could be tested with the STE-QUEST mission →

J. Paramos and G. Hechenblaikner, Planetary and Space Science 79, p.p.76 (May 2013)



GPS-STE QUEST Visibility (NP) | GPS-STE QUEST Visibility (ZP)



Conclusions

- STE-QUEST has a strong scientific case. It is intended to test the foundations of Einstein's Equivalence Principle, addressing the three cornerstones in one combined mission. It also complements the ACES and MICROSCOPE missions.
- The payload comprises two instruments, one of which (Atomic Clock) has a strong heritage from the ACES mission. The other instrument (Atom Interferometer) is subject to a series of comprehensive campaigns on a zero-g aircraft and sounding rocket to mature the design.
- The spacecraft and mission design is s challenged by the mission objectives and the related performance requirements. Whereas several critical issues have been identified, none of them currently seems to pose an unsurmountable obstacle.

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  (*) The presentation itself is not part of the contract and has not been supported by ESA

- Disclaimer: The view expressed herein can in no way be taken to reflect the official opinion of the European Space Agency.

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BACKUP Slides

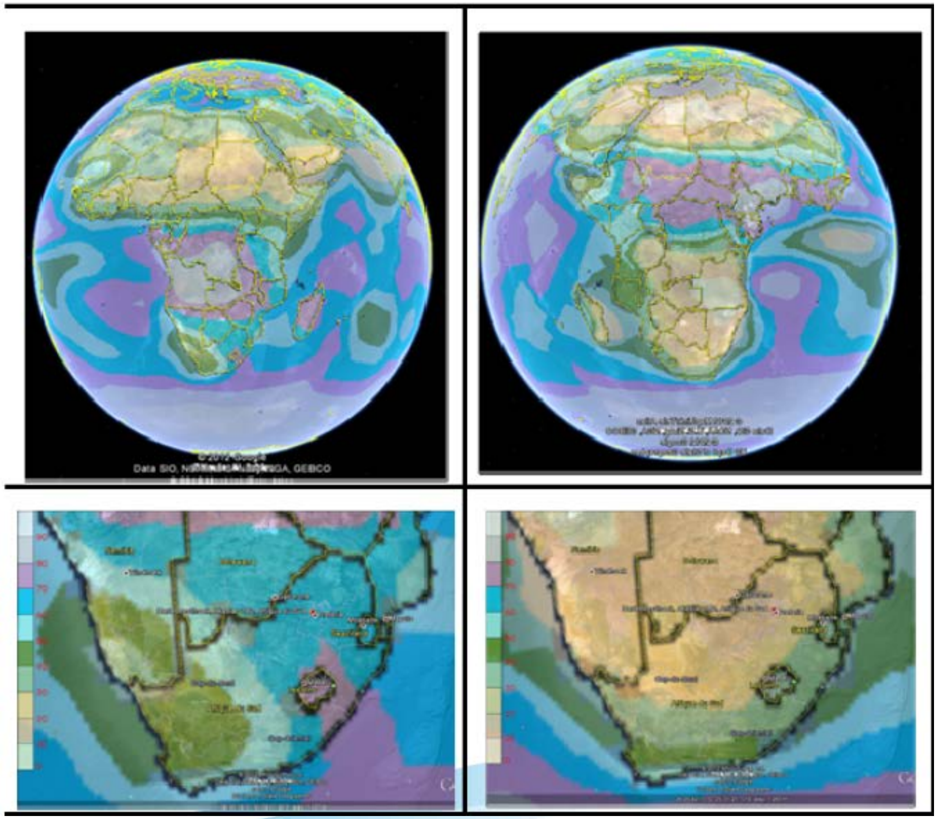
Instrument Accommodation (2)

- The instrument accommodation takes into account unique constraints imposed by the instrument, including
  - Magnetic cleanliness, for which specific guidelines for both instruments and spacecraft have been established and are implemented
  - Micro-vibration environment, where dedicated, detailed analysis was performed to ensure that the instruments can be offered an environment adequate for achieving the full level of performance
  - Assembly, integration and test, which is considered from the onset in the design process to ensure constraints of the instruments (in particular on-ground) are considered, testability is provided throughout the AIT process and schedule risks out of mutual dependencies are minimised

Science Links

- The science links have been extensively studied in the initial mission assessment phase, including in particular a thorough analysis of the mutual constraints between link design, link performance, POD performance, orbit and spacecraft configuration

  - Apart from the flight segment elements of the link, the ground terminal locations and availability were assessed
  - Local weather conditions are a major and critical parameter in optical link common-view availability
  - It should be noted that with the ESA defined orbit and ground terminal placement, no links can be established at altitudes roughly below 6000 km, impacting the science objective related to AC measurements of the Earth redshift



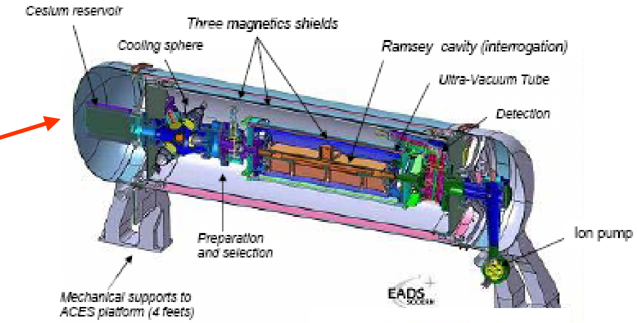
Payload Overview

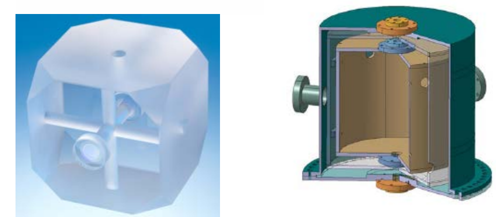
1. Atomic Clock:
   - **PHARAO** Next Generation:
     rebuilt of clock used on ACES
   - **MOLO (**Microwave-Optical Local Oscillator):
     reference laser, frequency comb, highly stable cavity
   - **MSD** (Microwave Synthesis and Distribution):

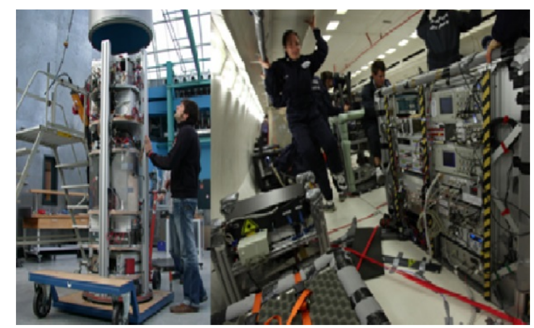
2. Atom Interferometer
   - **Physics Package**:
     Vacuum chamber. Magnetic shielding, Atom source, coils,
   - **Laser subsystem:**
     cooling, repumping, detection, Raman, dipole trap
   - **Electronics and Detection Units**

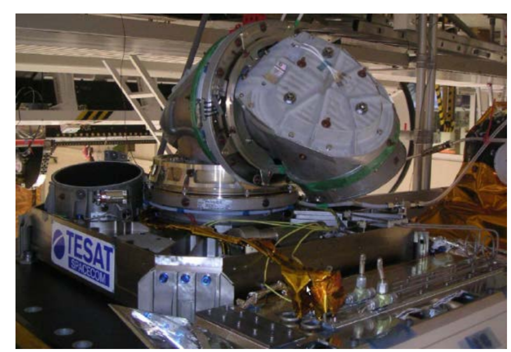
3. Science Link Equipment
   - **Microwave:** Ka-band and S-band antennae
   - **Optical:** Laser Communication Terminals (LCTs)

4. Auxiliary Equipment
   - **POD** (Precise Orbit Determination): GNSS-receiver




MOLO cavity+ chamber,NPL


QUANTUS & ICE Atom Interferometers



TESAT Laser Communication Temrinal