AIRBUS

DEFENCE AND SPACE

Project

STR-BASED SAFE MODE FOR SCIENCE MISSIONS

Title

EXECUTIVE SUMMARY REPORT & CONFERENCE PAPER

Abstract

This document corresponds to the ESR and CP deliverables for the "STR-BASED SAFE MODE FOR SCIENCE MISSIONS" R&D (aka STEAM), (ESA-TEC-SOW-013806, contract 4000128635/19/NL/GLC).

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Technical Rater Information

This document has been assessed by the following Technical Rater:

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Acronyms

AOCS	Attitude (& Orbit) COntrol System
APS	Active Pixel Sensor (CMOS)
BASS	Bi-Axis Sun Sensor
CDF	Concurrent Design Facility
CESS	Coarse Earth and Sun Sensor
CPU	Central Processing Unit
CSS	Coarse Sun Sensor
EDAC	Error Detection and Auto-Corr* code
EKF	Extended Kalman Filter
ESR	Emergency Sun Re-acquisition
FDIR	Failure Detect* Isolat* and Recovery
FMEA	Failure Modes & Effects Analysis
FoV	Field of View
GEO	Geostationary Earth Orbit
GUI	Graphical User Interface
HIL	Harware-in-the-Loop
HW	Hardware
IRES	Infra Red Earth Sensor
JOP	Jena OPtronik
KF	Kalman Filter
LEO	Low-Earth Orbit
MAG	Magnetometer
MEO	Medium Earth Orbit
MTQ	Magnetic Torquers
MeV	Mega electron-Volt
N/A	Not Applicable
OH	Optical Head
OIRD	(ESA) Operations Interface Reqts Doc
R&D	Research and Development
RAMS	Reliab*, Availab*, Mainta*, Safety
RCS	Reaction Control Subsystem
RW	Reaction Wheel
S/W	Software
SA	Solar Array
SAS	Sun Acquisition Sensor
SEE	Single Event Effect
SEU	Single Event Upset
SGM	Safe Guard Memory
SISO	Single Input Single Output
STOS	Star Tracker Optical Stimulator
STR	Star TRacker
SW	Software/Switch (Passport)
SoW	Statement of Work
TRP	Technology Research Programme
WP	Work Package

1 STUDY MOTIVATIONS AND OBJECTIVES

Motivations

Safe modes have historically been designed for simplicity (with the minimum hardware and the simplest software), with the consequence that they are generally specific to every mission. If a safe mode design could be made generic, or at least 'more generic', we could expect the following benefits:

- Increased versatility & growth potential, allowing to consider different orbits and more diverse pointing requirements without fearing cost overruns when adapting existing designs.
- Cumulative maturity across missions, becoming more reliable than simpler but specific designs.
- Reduced development effort/time/risk when adapting to the specific needs of a new.
- Similar operation procedures, minimizing the risk of errors during these critical phases.

The choice of segregating sensors between normal and contingency modes is that STR measurements are *never used* in safe mode, even when they are available, thus depriving the system of a crucial source of attitude information during a critical phase.

The approach inspiring this study was to investigate the possibility of using star trackers as the backbone for a generic safe mode architecture (which can be instantiated *with or without* the STR). This is a major change with respect to classical designs, but it is motivated by the following expected benefits:

- Genericity: star trackers are the most generic and widely used sensors.
- Reliability: STR are fast becoming the sensor class with the most flight hours (compared to sensors dedicated to safe mode, used only for a few hours per mission).
- Trustworthiness: paradoxically, the complexity of STRs plays in favour of trustworthiness: either the quaternion provided is valid, or there is no quaternion (temporarily or permanently).

Objectives and overall logic of the study

- Derive safe mode requirements and STR requirements from overall mission needs. We summarized the key requirements for the safe mode, then derived those into requirements at STR level.
- Verify STR hardware robustness of 3 star-tracker models (Sodern's Hydra and Auriga, JOP's Astro-APS respectively) to situations with combined high rates and high radiation, with the real sensor hardware, using optical stimulation test benches.
- Scrutinize reliability and FDIR/RAMS aspects. Based on a detailed census of feared events and in-flight reliability data, the study suggested an overall FDIR strategy, at STR and at the global AOCS level. Independently, solutions for protecting context data were proposed.
- Should a new/upgraded STR model be considered for use in safe mode on a future mission, the need for adequate validation and maturity is addressed, via a suitable re-risking process/strategy.
- Design a versatile AOCS architecture for a generic safe mode, with a modular design, involving in particular a versatile attitude determination filter for merging the measurements from many sensors, for filtering STR outliers (if any) and easy adaptation to new mission needs and sensors.
- Instantiate for the 2 reference science missions (at L2 and at Venus), and verify performance in simulation, in a representative simulation environment, through statistical simulation campaigns.
- Confirm findings with the real STR in open-loop and closed-loop tests with JOP's Astro-APS sensor in Airbus's optical stimulation test bench (STOS), for consolidating the model implemented in the simulator, then verifying that the overall convergence behaviour was conserved with the real STR.

Industrial setup

The study consortium was composed of the following entities:

- Airbus Defence and Space (Toulouse site) as prime contractor,
- Airbus Defence and Space (Stevenage site)
- Jena-Optronik GmbH

2 REFERENCE USE CASES AND SIMULATION SCENARIOS

Starting from a broad panorama of future ESA science missions, we selected **Ariel** and **Envision** as the reference use cases[1] for the study. From the needs of the two reference missions, we derived 4 demanding safe-mode scenarios, which served as the basis for verifying safe-mode performance:

- For the Ariel-like mission
  - A1: spin-separation. First acquisition, with high angular rates and Earth proximity
  - A2: on-station, thruster failure at L2. Representative of subsequent safe-mode events
- For the EnVision-like mission
  - E1: on-station: failure in low Venus orbit (high probability of blinding + eclipses)
  - E2: failure during the aerobraking phase (Venus proximity *and* very high aero torque)

Figure 1: representation of the ARIEL and EnVision spacecraft (from ESA CDFs)

3 REQUIREMENTS FOR USING THE STR IN SAFE MODE

From system-level to STR requirements

Three levels of requirements were considered, flowing from the top down:

- The system-level requirements mainly based on ESOC's generic OIRD.
- The requirements specific to the AOCS, cascaded down from system requirements.
- The requirements specific to the STR itself in order to be considered for use in safe mode are then derived from the AOCS requirements.

The requirements in the study are intended as a generic template which can then be declined for each mission. An important choice in the study was to follow the OIRD in distinguishing between *safe* and *survival*: the former pertains to more elaborate and more long-term capabilities while the latter refers to immediate / last resort survival functions (rates, power, thermal)

[1] Since the detailed design of those missions is not available publicly, we used the CDF definition as a reference, and extrapolated when relevant

	Safe	Survival
Power	Optimized (mission-friendly or power-friendly)	Always maximized (sun-pointing)
Thermal	Mission-friendly thermal pointing	Thermal safing
Comms	Full 3-axis	Level 0 (Omni in LEO, strobing in Interplanetary)
Instr. protec.	Full protection	Level 0 (best effort)
Other	Drag minimization Basic traj. corrections	Stand-by mode during prolonged STR outages

Table 1: safe and survival needs – system level

Requirements	Level
The STR shall achieve autonomous attitude determination ('lost in space' solution) with no attitude aiding.	N/A
STR outputs shall be refreshed at a frequency > 1 Hz	Relaxed: 1Hz Nominal/Goal: 10Hz
The absolute attitude measurement accuracy including alignment bias shall be lower than the level value.	Relaxed: 1° Nominal: 0,3° Goal: 0,1°
The presence in the FoV of false stars shall not preclude acquisition for star tracker use in safe mode.	Relaxed: 5 false stars Nominal: 20 false stars Goal: 80 false stars
The STR shall be robust (tracking as well as lost-in-space acquisition) to indicated levels of radiation.	Relaxed: GEO and LEO Nominal: worst-case solar flares Goal: Jupiter (around Ganymede).
The STR shall be robust to the maximum temperature level indicated.	Relaxed: 40°C Nominal: 60°C Goal: 80°C
The STR shall provide measurements in the worst-case dynamic conditions.	Relaxed: 1,5°/s Nominal: 6°/s Goal: 10°/s
From boot-up, the STR shall be able to provide its first attitude measurements in the worst-case conditions within the time delay indicated.	Relaxed: 100 s Nominal: 10 s Goal: 1 s
Outages (other than blinding or occultation) shall not exceed the level indicated (including power cycling and reacquisition).	Relaxed: 100 s Nominal: 10 s Goal: 1 s
The STR shall be robust to combined environmental constraints (radiation, temperature) and high dynamics conditions. (high initial angular rates).	from respective requirements
When measurements (attitude or rate) become erroneous (i.e. outside the above requirements), they shall be flagged as invalid within a fraction of the time it takes to then power cycle and reacquire.	Relaxed: 10 s Nominal: 1 s Goal: 0.1 s

Table 2: recapitulative table for STR requirements for use in safe mode

Note about the 3 categories: nominal = *intended for the majority of science mission cases;* relaxed = *less demanding missions;* goal = *very demanding missions*

4 TESTING THE ROBUSTNESS OF STAR TRACKERS

Setup

Tests have been performed using the STOS (Star Tracker Optical Stimulator) developed and produced by Airbus DS. When coupled to the STR, the STOS can display an image of the sky, with a high refresh rate (225 Hz) allowing high representativity in high-rate scenarios.

Figure 2: A description of the STOS opto-mechanical assembly (on a Sodern SED36 sensor)

The objective of the tests was to evaluate the robustness of three STR models to combined high angular rates and high radiation levels. This was done by determining two boundaries in the rates/rad domain:

- The (combined) levels beyond which the STR fails to *acquire* within 60s
- The (combined, higher) levels beyond which the STR loses *tracking*

Two models were tested with the STOS at Airbus (Sodern's Hydra and Auriga sensors)

Results

The test results demonstrate very high robustness of the sensors to radiation, with a capability for successful acquisition mostly intact unless radiation exceeds 100k hits per cm² per second. Even at such extreme levels, the acquisition for the Hydra sensor was successful with angular rates of 3 deg/s.

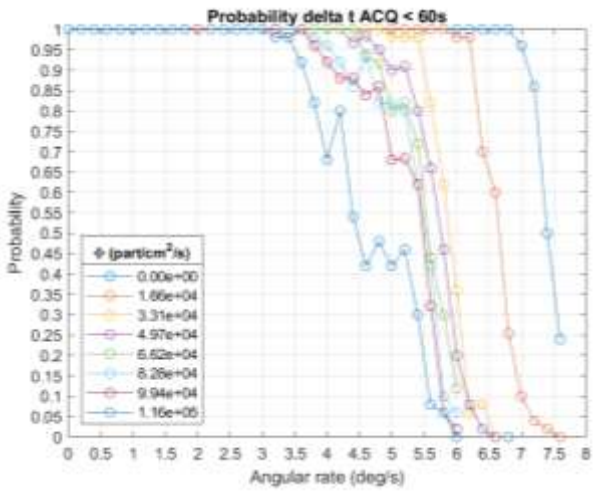

Figure 3: Hydra STR 2D – ACQ test results. Probability of entering TRK in less than 60s.

For the Auriga model the acquisition rate limit of 0.3 deg/s is essentially determined by the default SW settings, so that it is virtually insensitive to radiation: there is hardly any visible degradation up to effective flux values of 180k hits/cm²/s.

The Astro-APS sensor did not undergo the same tests but the open-loop and closed-loop tests with the STOS in task 5 confirmed that they could withstand angular rates above 3 deg/s even in pessimistic radiation environments.

The tests confirm that a mission could consider such a star tracker as the *only* sensor in safe mode, even with relatively pessimistic dynamic and environmental assumptions.

Figure 4: sensor models tested in the study

From left to right: Hydra and Auriga, by Sodern, Astro-APS, by Jena Optronik

5 RELIABILITY AND FDIR ASPECTS

Redundancy

For the safe mode in the study, we have considered a minimal redundancy situation with only 2 optical heads, with one failure. This means that the safe mode must be able to operate properly with a single STR optical head. Any additional redundancy adds to the overall safe mode performance but is not strictly required, so as to maximize reliability (fewer units are required = higher reliability).

Time storage

Even though losing the on-board time is a very low probability event, we can cover the situation with a simple solution: the current time is periodically stored in a non-volatile memory unit, so that the time retrieved from memory is recent enough and the resulting pointing error is acceptable. Even in the most demanding case (accuracy for Earth pointing at Venus), the number of write cycles over the duration of the mission is compatible with qualification levels of standard non-volatile memory technologies.

Ephemeris protection

Alongside time protection, the ephemeris must be guarded against corruption and operator errors:

- For the former, redundancy, voting and consistency checks with a backup ephemeris can help minimize the risk.
- For the latter, implementing strict ground procedures for uploads/updates is nothing new and can easily be included in the overall ground segment design

Feared Event	Potential mitigation
STR HW failure	Higher class grade components *Redundancy and FDIR strategy (reconfiguration)*
STR SW design errors	*Software Design Assurance Level: category B required for safe mode* *FDIR strategy: power-cycling and retry* Diversification (use of different STRs)
STR SEE / Transient failure	Equipment level: hardening and tolerance / performances *Equipment level: hot restart capability* *AOCS level: tolerance to STR outages* *FDIR strategy: power-cycling and retry*
STR erroneous Star Catalogue	*Validation process: characterization/functional tests with STOS* Diversification (use of different STRs)
STR erroneous parameterization	*Validation process : characterization/functional tests with STOS*
STR Undetected failure	*Failure Detection coverage requirement and verification* *AOCS level: robustness to outliers* FDIR strategy: functional, consistency monitoring, higher level alarms
Blinding / Object in FoV	Redundancy (e.g. multiple optical heads) STR performances / tolerance *FDIR strategy: deobstruction manoeuvre*
Solar flare	*STR robustness tests with STOS* *AOCS strategy: interim pointing during STR outages* FDIR strategy: unlimited retries
Operational errors (no or erroneous ephemeris)	*Safe procedures* *FDIR strategy: validity checking of ephemeris data, alarm against expiration, consistency monitoring, backup profile*
SGM failure (corrupted ephemeris)	Redundancy FDIR strategy: EDAC, CRC check, scrubbing, reconf., backup profile
Onboard time failure	Redundancy *FDIR strategy: periodic onboard time saving*
FDIR False triggering	*FDIR tuning validation, FDIR disabling after triggering*
STR performances in worst case condition (power, thermal, rates)	*STR robustness tests with STOS* STR delta qualification

Table 3: STR feared events and possible mitigation options

In-flight track record and STR anomalies

Based on a complete review of in-house and public reports about in-flight STR-related anomalies, we established that:

- 21% of STR anomalies were triggered by SEU, hence transient and recoverable with a retry
- 73% of STR anomalies were recovered from with a reset (59%) or without any specific recovery action (14% - transient failures)
- Only 3% of STR anomalies had a final impact at mission-level (after recovery)

A very important finding was the absence of a visible trend in the yearly rate of anomalies. It proves that the reliability of star-trackers is improving faster than the (fast growing) number of units flying.

Derisking process when considering a new STR for safe mode

Depending on the objective robustness and subjective 'newness' of the STR; and on the objective cost and subjective criticality of the mission, we suggested steps that can be taken to improve trust in a new STR, to the level required for a given mission:

- High rate tests on real sky (by supplier)
- Robustness tests (rates, radiation, artefacts) with optical stimulation (on independent test bench)
- Open-loop tests with optical stimulation, with realistic high-rate scenarios
- Validation according to the requirements in ECSS-Q-ST-80C for category *B* (mission-critical SW/)
- Early and thorough characterization tests with the help of optical stimulation, testing all functional modes of the STR, in as many operating conditions as possible (attitudes, rates, radiation, artefacts)
- Closed-loop tests, for checking the STR's detailed real-time behaviour, especially when coupled with the AOCS closed loop.
- Specific review of the STR's fault tree analysis about the conditions/scenarios that might cause a faulty measurement to be flagged as valid for a prolonged period of time.
- Polarity checks[2] on the assembled satellite, with an independent path for determining the orientation of the optical stimulator and the orientation of the STR optical head.

The general characterization checks and the closed-loop tests with an independent optical stimulation setup are a key to early identification of issues with the STR, allowing efficient iterations with the supplier. By increasing the variety and coverage of operation cases, they reduce the risk that an interface mis-match or SW glitch could cause the STR to malfunction when first switched-on in flight.

6 ARCHITECTURE OF GENERIC SAFE MODE

Genericity vs versatility

Our rationale is to organize architecture genericity around:

- a simple, common algorithmic core that can cater to a majority of missions,
- a set of variants to fulfil less-frequent mission needs

[2] Note that although erroneous alignment parameters for the STR in the AOCS S/W database can indeed lead to erroneous quaternions flagged as valid, this feared event is not restricted to new sensors: the polarity tests with the STOS are recommended for all sensors on all missions

- and full versatility in terms of sensors and actuators (i.e. the safe mode design imposes minimum constraints in terms of sensor/actuator setup)

Primary sensor = Star-Tracker

The fact that Star Trackers are implemented on all missions and that they can provide absolute attitude measurements in all orbital contexts makes them a straightforward choice as the backbone for a generic safe mode. This is the central tenet of the study.

Secondary sensors = mission-dependent

Since protecting the system against all possible blinding events at launcher separation would require more than 5 optical heads, a function ensuring deobstruction of the STR is needed, by scanning it across the sky. Such manoeuvres can be performed in two ways:

- with secondary sensors, in closed loop – this is the preferred approach. Depending on the mission opportunities and constraints, these sensors can be sun sensors, magnetometers or gyros.
- without additional sensors, in open-loop – this approach is a bit more risky, esp. with thrusters

Primary sensor		
Star Tracker	same Star-Tracker as the one used for normal mode (optionally: additional/dedicated low-cost STR)	
Secondary sensor		**Name for variant**
Coarse sun sensors	Inexpensive & generic, all orbits	STEAM-S (study baseline)
Magnetometer	Recommended for LEO orbits (generally with +1 CSS)	STEAM-M
Gyro[3]	Generic choice but more expensive/complex (interesting if the mission already needs a gyro)	STEAM-G
Earth sensors	Not recommended (too narrow application domain)	
None	Requires open-loop deobstruction manoeuvres	STEAM-D

Table 4: Recapitulation of sensor choices

Rationale for a modular structure

A modular architecture with standard interfaces minimizes mission-specific adaptation and validation efforts. The modules are made of reusable building blocks, with add-ons confined within modules.

[3] Note that when a truly inexpensive gyro becomes available, it will be a game changer and will certainly be baselined for safe mode

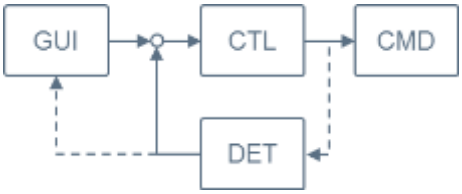

Figure 5: Flow-chart of the modular architecture

This architecture includes the following modules:

- *Attitude determination* (DET) – computes attitude and rate estimates from all available measurements (and sensor validity flags) – this is the most generic module
- *Guidance* (GUI) – computes attitude and angular rates target (from time and ephemeris data)
- *Control* (CTR) – computation of control torques to be achieved by the actuators
- *Actuator management* (CMD) – converts high-level AOCS commands (e.g. torque, momentum) into low-level actuator input signals (e.g. magnetic moment, thruster on-times)

module	Main functionality/algorithms
DET	Extended Kalman filter, (optimized for robustness and CPU, not performance) - for merging measurements from all available sensors - for robustness against STR measurement gaps and outliers
GUI	Relevant ephemeris for computing sun-pointing and Earth-pointing target attitudes Computation of target attitudes and associated angular rate profiles
CTR	Proportional-Derivative controller with quaternion feedback The derivative branch also serves for rate reduction
CMD	Generic thruster allocation function Low level reaction wheel steering

Table 5: Summary of modules and functions in baseline architecture

Although the estimation filter is not strictly needed when the STR measurements are available, it offers many valuable features:

- smooth-out large updates at the end of STR measurement gaps
- naturally filter-out outliers without requiring specific monitoring logics
- FDIR capability, by detecting large update residuals
- A key feature of the filter is its capacity to extract 3-axis rate observability based only on 2-axis sun sensor data (thanks to gyroscopic coupling effects, after Airbus patent [FR96 06162, B. Polle], implementing a specific heuristic. Even when the STR is not available, this allows to:
    - perform rate reduction,
    - start sun-rallying and maintain sun-pointing
    - and achieve STR deobstruction.

This unique property of the safe mode KF thus allows to minimize the need for additional sensors.

7 SIMULATION CAMPAIGN FOR PERFORMANCE

Instantiation of the safe mode for the 2 reference science missions

The complete safe mode logics and algorithms have been instantiated from the generic template (of the STEAM-S variant), with minor adaptations to the specificities of each mission:

- For the Ariel-like case, only 1 CSS is considered, considering the very narrow allowed attitude domain; there is no need for a specific deobstruction manoeuver for the on-station simulation scenario, because the Earth will not be blocking the STR's field-of-view in L2.
- For the Envision-like case, the guidance module implements a smart guidance function to prevent STR re-obstruction (Venus limb avoidance) once it has acquired.

The safe mode software was then implemented within a representative simulation environment including detailed models for:

- Sensors (STR, CSS)
- Actuators (Thrusters, reaction wheels)
- Disturbances (aero for Venus aerobraking, gravity gradient, solar radiation pressure)
- Trajectories and ephemeris (positions of Earth, Sun, Venus and the satellite)

Simulation campaigns

For each case we performed a small Monte-Carlo campaign, with 250 runs per case. The performance indicators and success/fail criteria were the following:

- Time to acquire (sun pointing error < threshold) and converged sun-pointing performance
- Max Sun aspect angle (Ariel) in pitch and roll over whole simulation duration
- Propellant cost until acquisition and in converged state (to detect pathological thruster activity)
- Total time spent with STR obstructed

Summary of results

- For case A1 (ARIEL, spin separation): all cases converged within 20 minutes, with the STR at most unavailable (due to initial rates above its acquisition capacity) for 14 minutes. The maximum attitude roll excursions are within the narrow allowed domain.
- For case A2 (ARIEL, thruster failure, on-station), the STR is always available immediately, the transition to sun-pointing phase occurs in less than 1.5 min and the sun aspect angle converges to less than 5 deg within 3 minutes.

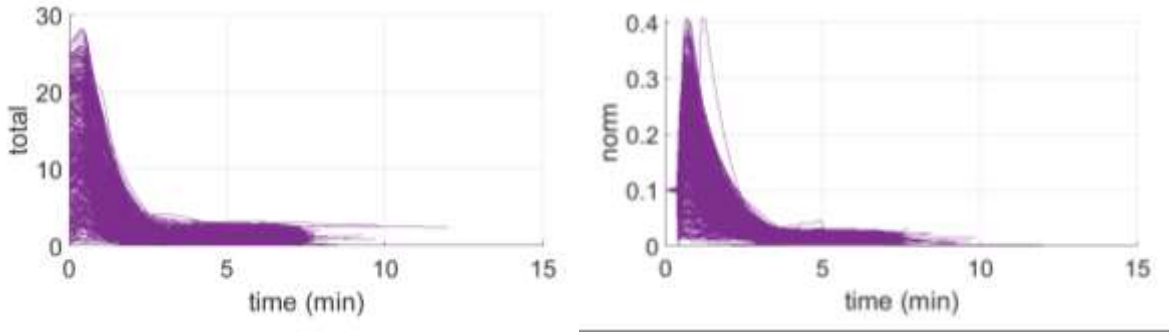

Figure 6: ARIEL-like, case A2 - convergence of sun aspect angle (deg) and angular rate (deg/s)

- For case E1 (EnVision, failure in low Venus orbit), the STR is initially unavailable in 57% of the simulations, which reflects the proximity to Venus, and convergence can also be delayed if the safe mode starts in eclipse (no sun sensor measurements). Still, convergence takes less than 50 min in all cases, meaning the spin rate is reduced and the star tracker becomes predictably available within that time; the smart guidance law add-on efficiently prevents re-obstruction of the STR.
- For case E2 (EnVision, failure during aerobraking, near periapsis), the STR is initially unavailable in 57% of the simulations; regardless, convergence to sun pointing occurs within 30 min in all cases, despite transient rates of up to 11 deg/s because of the large aerodynamic torque around periapsis, showing how challenging this case is.

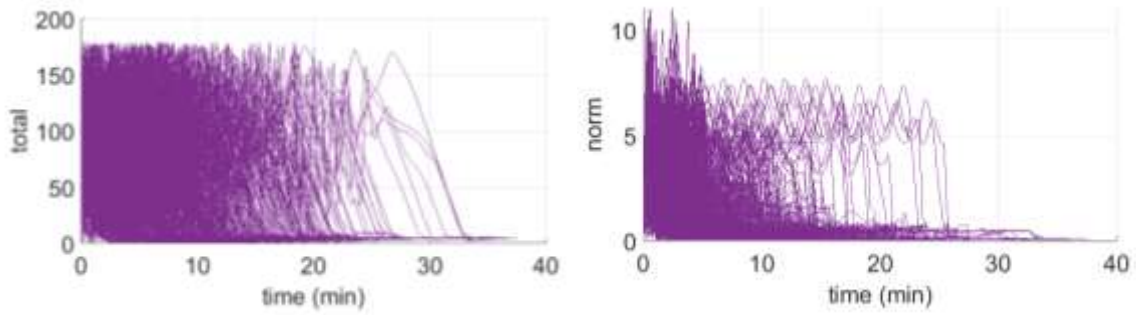

Figure 7: Convergence of sun aspect angle (deg) and angular rate (deg/s)

8 OPEN- AND CLOSED-LOOP TESTS WITH THE REAL STR

For further consolidation of both the simulation results and the STR functional representativity , we have conducted two series of tests with the real star tracker (Jena Optronik's Astro-APS) in the loop, thanks to optical stimulation with the STOS.

The main goal of the open-loop tests was to evaluate the consistency between the STR model used in the simulations and the real sensor, adapting the parameters in the simulation if required.

The closed loop tests were beyond the strict requirements in ESA's SoW but were considered a key step for consolidating the maturity of the safe mode design:

- to weed-out any low-level interface and functional issues that might be overlooked when operating in open-loop, due to the more demanding real-time conditions;
- to confirm that the performances predicted from the simulation campaign were conserved when using the real hardware in the loop;
- to verify that no pathological behavior arose from the coupled nature of the closed-loop, when the output of the STR feeds back to its input, after being processed by the AOCS software and the simulated satellite dynamics.

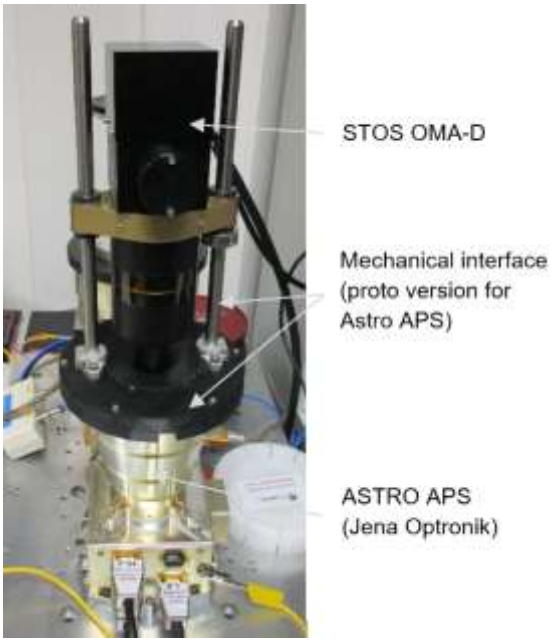

Figure 8. STR Astro APS mechanically coupled with STOS OMA-D.

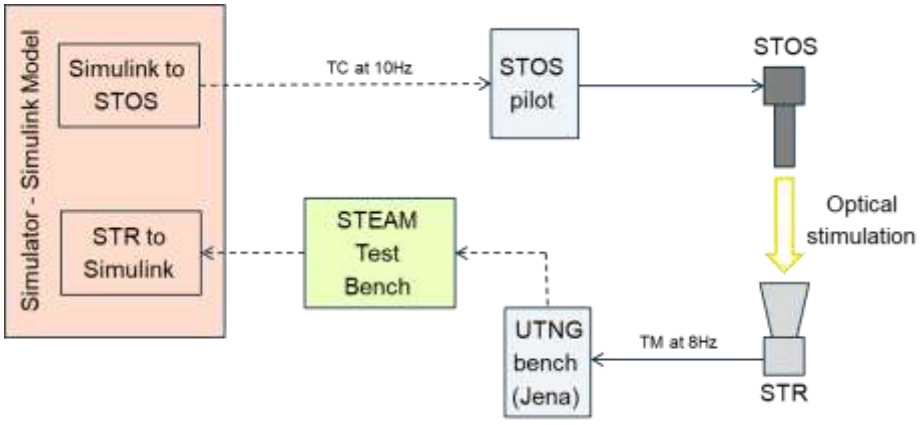

Figure 9. Closed loop setup.

In this setup, the input and output files have to be replaced with real-time data exchanges (via TCP/IP link to STOSPilot / from UTNG) with the simulator running in real time.

Test Scenario	Φ (p+/cm²/s)	Simulated events per second for a HAS2 detector	Simulated event per STOS frame for HAS2 detector[4]
A1	13500	~4000	~200
E1	27000	~8000	~400

Table 6. Effective proton flux considered for A1 and E1 scenarios.

These levels correspond to the worst 5-min solar flare in the CREME96 model for particles above 1 MeV in LEO, considering 10mm shielding.

Results and conclusions for the open-loop tests

The objectives of the tests were fully reached, confirming that the simulation model was representative of the real hardware.

- The Astro-APS star tracker manages to start tracking for transverse angular rates between 3.2 deg/s and 3.9 deg/s (note that this limit is dependent on STR SW parametrization).
- Angular rate capability appears unaffected by the level of radiation, up to the high levels tested (27000 hits/cm²/s).
- Acquisition occurs in less than 40s (can be as early as 2s).

Results and conclusions for the closed-loop tests

The sensor-in-the-loop tests with the complete feedback loop have achieved all the key objectives:

- They have demonstrated that the behavior is very similar in simulation and with the real STR.
- The design of the safe mode itself (and the attitude determination filter in particular) is robust to the switch between simulation conditions/model and HIL tests conditions/hardware (even in extreme cases with large angular rates or frequent blinding).

9 CONCLUSIONS, RECOMMENDATIONS, PERSPECTIVES

Key take-away messages

STRs are mature

- in-orbit experience shows excellent reliability
- most anomalies can resolve through power-cycling
- no anomalies causing persistent false quaternions

STRs are robust

- Three STR models tested
- Two models robust to rates above 3 deg/s
- Despite very high levels of radiation (10 x worst-case flares)

Straightforward FDIR solutions

- context (time/ephemeris) protection
- redundancy/reconf. management
- template FDIR architecture (for tailoring)

[4] HAS2 detector surface of 3.397cm². STOS image stimulation at 225Hz.

Optical stimulation = key enabler

- functional validation
- polarity testing
- robustness tests
- open-/closed-loop tests on realistic scenarios

Safe-mode architecture with demonstrated performance

- adaptable to all missions with minor adaptations
- instantiated for 2 very different reference science missions
- successful simulation campaigns

Pivotal role of versatile estimator

- for merging sensors
- for smoothing STR gaps and outliers
- 5-dof state determination from sun sensor alone

Complementary sensors are needed

- MAG or CSS or gyro
- for deobstruction at least (in case STR initially blinded)
- can also be exploited for ensuring survival (even without STR)

Four main architecture variants described

- STEAM-S (baseline, on-LEO) – all STR trust classes
- STEAM-M (recommended in LEO) – all STR trust classes
- STEAM-G (if gyro available) – STR trust classes M or H
- STEAM-D (STR alone) – STR trust class H

Perspectives

We believe that the concept is ready for the detailed development phase, within actual projects, in two types of circumstances:

- Adoption by future missions: indeed, it looks like many projects are only waiting for a confirmation that the technology is mature and there are no hidden risks in taking that promising step.
- Retrofitting existing missions: if allowed by avionics, this could improve functionality in missions already flying, with less risk because the STR is already known. The benefits could be:
    - Faster return to normal operations, drastically reducing downtime
    - More predictable behavior in the vast majority of safe mode events
    - More versatility for end-of-life operations, deorbiting, servicing, in-orbit demonstrations

> In the long run, this next step of using a STR in safe mode will further erode the historical approach of segregation and dissimilarity between safe and normal mode. This highlights a global trend away from segregation and dissimilarity, towards rigorous validation and FDIR, with a philosophy of graceful degradation in case of an anomaly, following the successful path of flight control architectures in military and commercial aviation.