STR-based Safe Mode

Final Presentation (long format)

DEFENCE AND SPACE

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ref. EAA.PS.000298208

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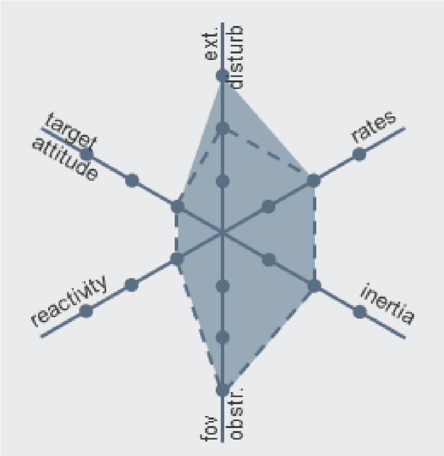
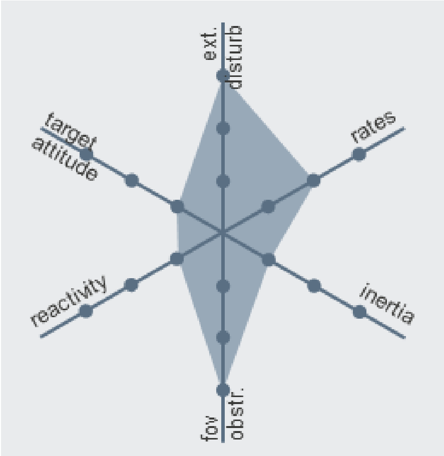
AEOLUS

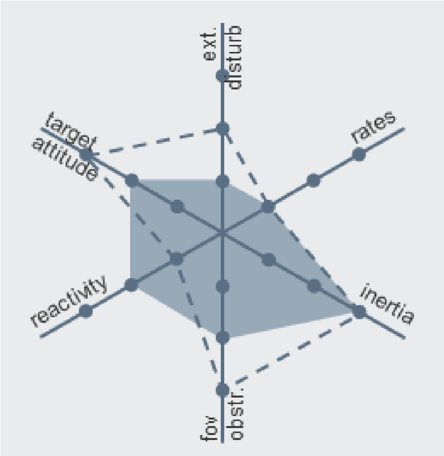


SENTINEL 5P
SPOT 6/7 --

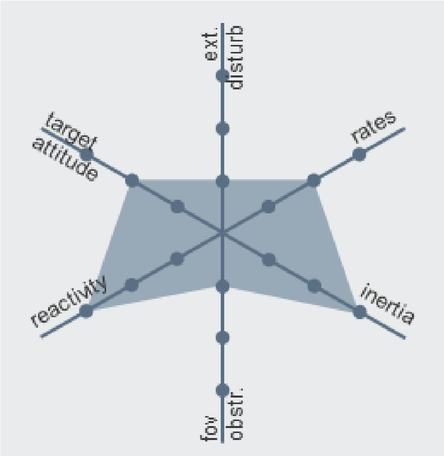


ALSAT2
(and other AS100)

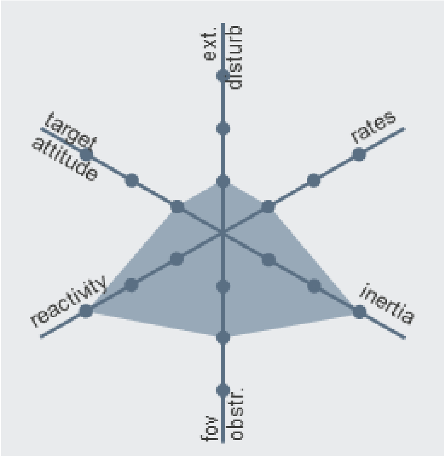
SOLO / BEPI



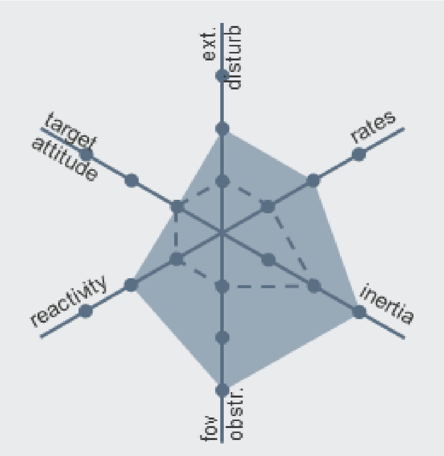
TELECOM (on station)
TELECOM (GTO/EOR) --



GAIA



XMM/INTEGRAL



LPF (composite)
LPF (on-station, science) --

Why we need more genericity in safe modes

Issues with tailor-made safe modes

- Each design = a narrow range of missions
- Limitations not corrected unless strictly needed: low growth potential
- Additional costs and development uncertainty on every new mission (incl. late HW changes)
- Low commonality between classes of missions (LEO vs GEO vs science)
- Lower maturity/reliability for individual designs
- Dissimilar operations => risk of errors

Benefits expected from generic safe mode

- Versatility & growth potential
  - new orbits,
  - complex pointing scenarios,
  - end-of-life/deorbiting concerns
- Cumulative maturity/reliablity across missions
  - higher reliability than specific designs
  - (even if each specific design appears individually simpler)
- Reduced development effort/time/risk
- Similar operations => fewer errors

Why a STR in safe mode?

Dissimilarity betw. existing safe modes is essentially sensor-related

- mission-specific safe-mode sensors

But STRs are implemented on all missions

- STRs are the most generic sensors
- STRs are fast becoming the sensor class with the most flight hours (maturity)

STR complex sensor but

- Now very mature
- Measurements can be trusted:
  – quaternion is valid // otherwise no quaternion

=> consider the penalty (performance, reliability) of *not* using the STR if available

=> a generic safe mode should (at least) *support* STR

Functional benefits

- Increased robustness/reliability
- Faster convergence
- Simpler acquisition sequence
- Increased availability (fast return to normal)
- Avoid defaulting to low-performance sensors for a critical mode
- Flexibility in pointing target
- Efficient payload protection (sun avoidance)

Industrial benefits

- Simpler overall architecture
- Maximum commonality betw. missions, better reuse, reduced recurring costs
- Lower risk from cumulative experience & validation
- Shorter development time for uncommon missions
- Easy end-to-end polarity tests
- Reduce sizing constraints
  - On battery and MTQ (shorter convergence)
  - On payload (sun avoidance)

Operational benefits

- Similarity between missions & procedures
- Increased observability for ground diagnosis
- Flexibility in pointing profiles (e.g. EOL decommissioning)
- Reduction of intermediate phases
  - (acquisition, search, etc.)
- Faster convergence
- Less dispersion

The STEAM team

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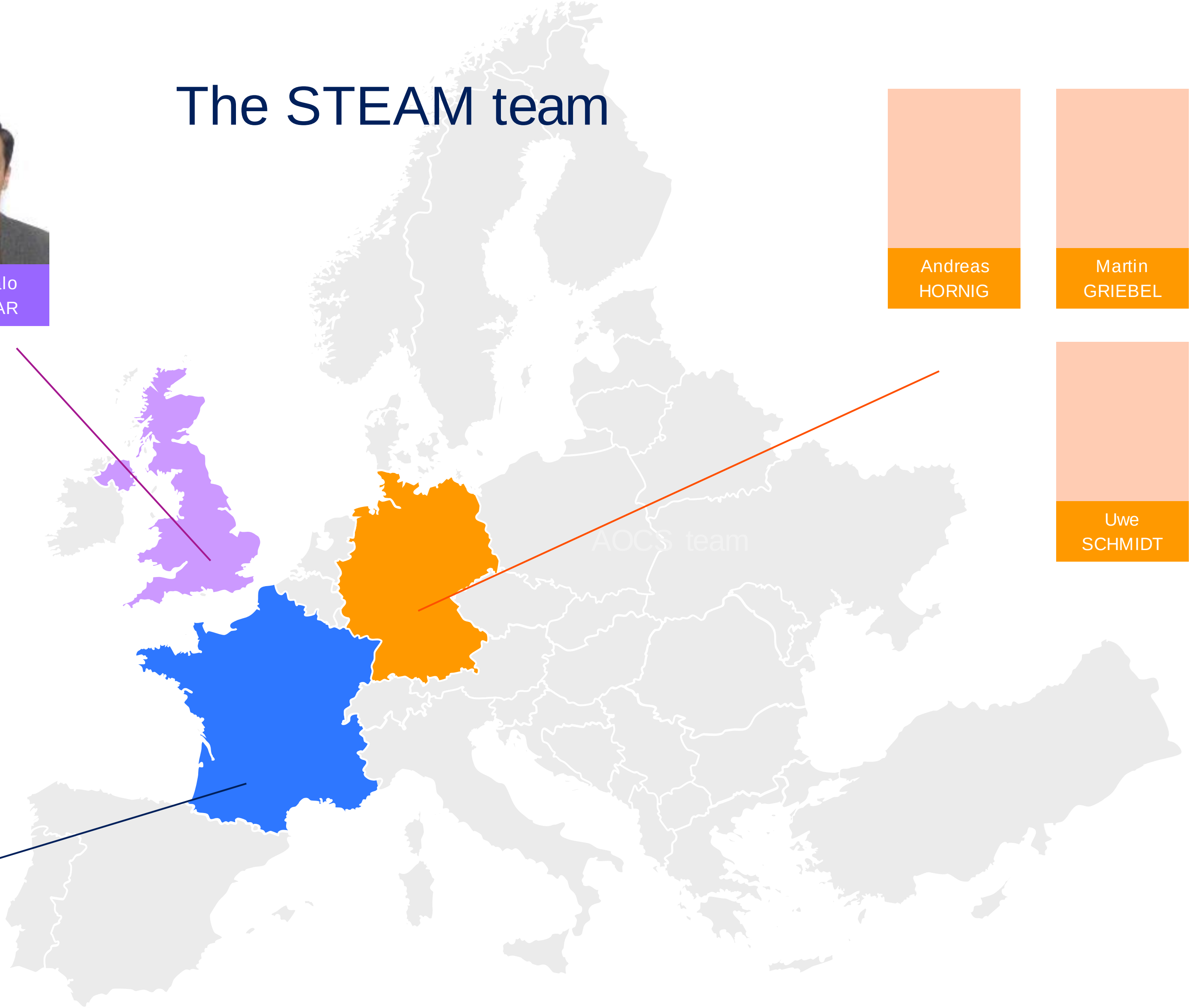

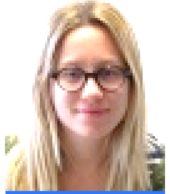

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STEAM study objectives

System
- Capture mission needs
- issue requirements for safe mode and STRs

Hardware
- Verify suitability of hardware
- Assess robustness of candidate STRs
  - (esp. high-rates & high radiations)
- Open-loop and closed-loop tests (HIL)
- Update simulation models

AOCS
- Design generic safe mode architecture
- Instantiate for 2 challenging science missions
- Verify performance and robustness to failures
  - (including STR unavailability)

FDIR & reliability
- Track record of existing star trackers
- Risks & reliability
- FDIR strategy, need/protection of context data
- Complementary attitude determination,
- De-risking

Two classes of requirements: *safe* vs *survival*

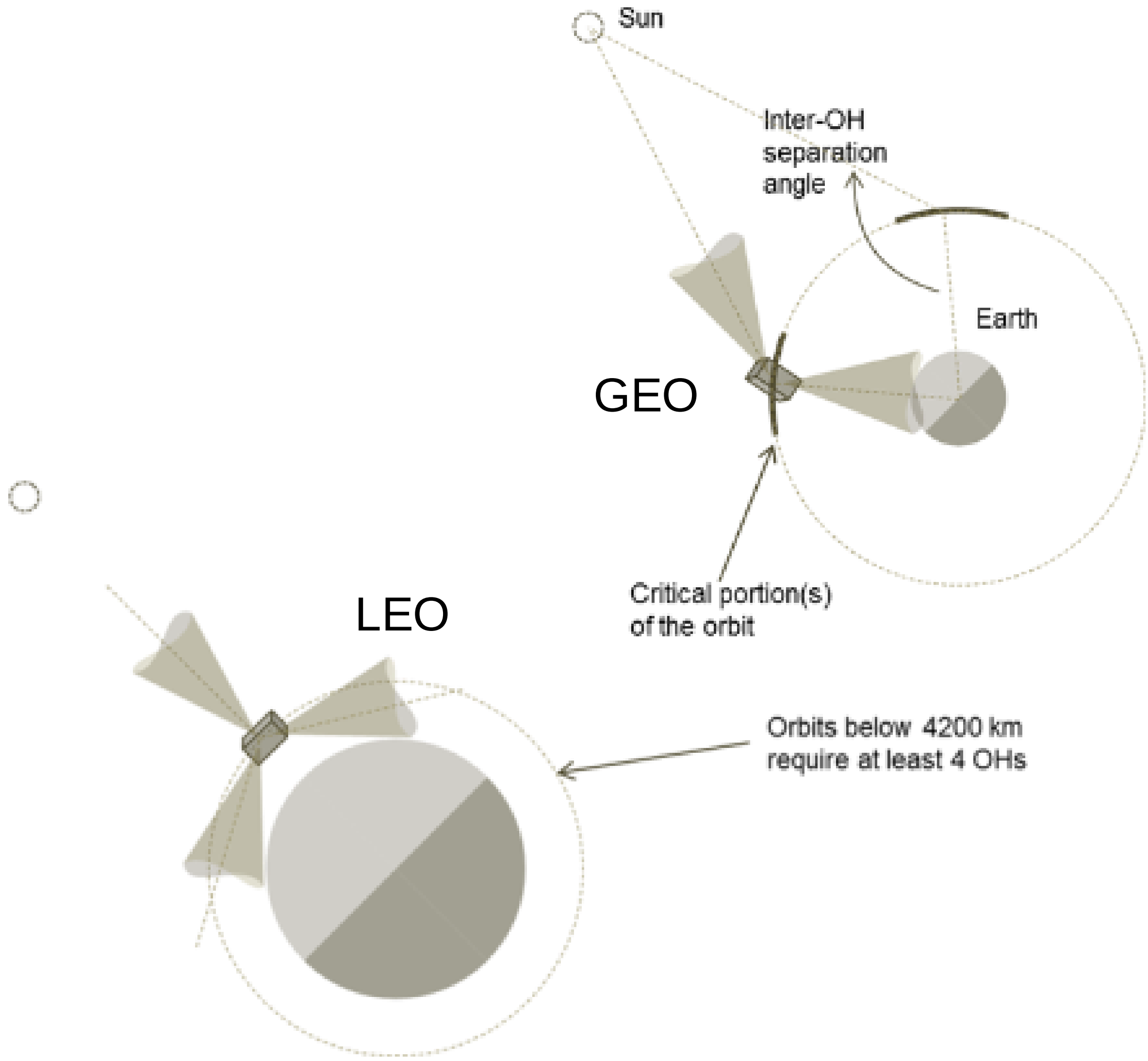
Following distinction in ESA's OIRD

- Safe Mode (more functionality, optimized for steady-state)
- Survival Mode (last resort, minimal functionality, ideally transient before converging to *safe*)

STR requirements (relaxed vs nominal) are derived from that classification

	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 minimisation / Basic traj. corrections	Stand-by mode during prolonged STR outages

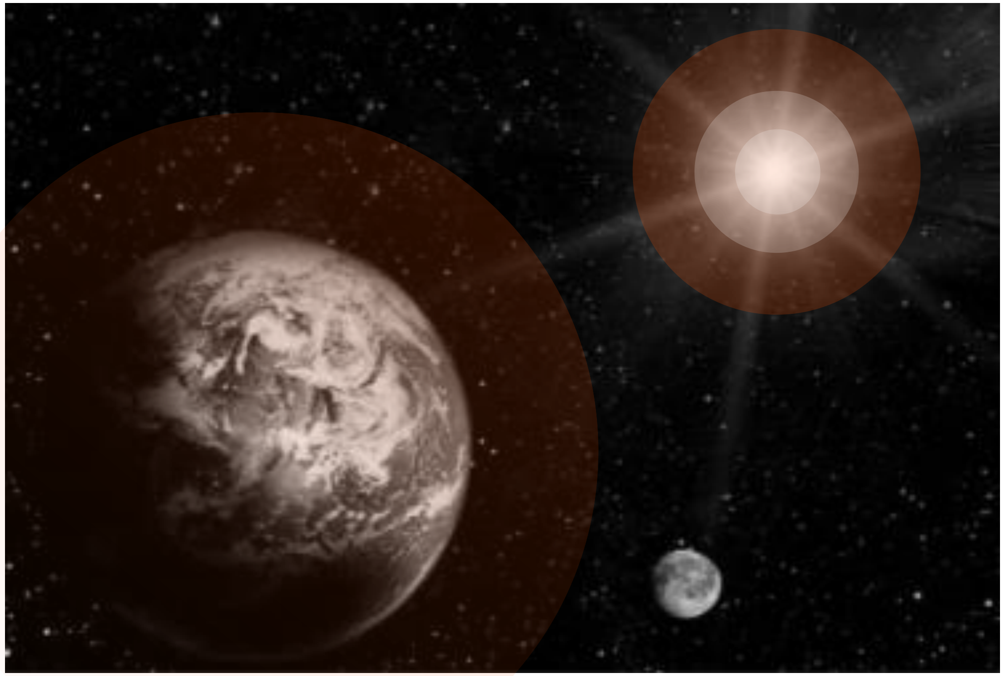
Safe-mode needs to work with a single optical head, with intermittent gaps



Rationale

- Many missions have only 2 parallel OHs
- Safe-mode needs to tolerate 1 failure
- Except for deep space, the number of OHs required for permanent visibility (including redundancy) is ‘too many’

Statistics for 1-OH STR lost-in-space visibility



Orbit	Probability of initial STR visibility
GTO @ perigee (250 km)	40%
600-km orbit	47%
1000-km orbit	56%
23000-km MEO	91%
GEO orbit	93%
beyond	95%

STR level requirements

Three categories of robustness:

Relaxed

STR that would correspond to most missions* but not some science missions

*and would require a working survival mode for backup

Nominal

STR with a higher level of robustness to be used in safe mode of more demanding missions

Goal

STR with the highest robustness level. Survival mode would not be necessary.

Requirements	Relaxed	Nominal	Goal
Absolute measurement accuracy incl. alignment bias	1°	0.3°	0.1°
Angular rates	1.5°/s	6°/s	10°/s
Radiation levels	GEO and LEO	worst-case solar flares or Van Allen	Jupiter or worst case interplan. radiations
Combined rates and radiation	from respective requirements above		
False stars in FoV for acquisition	5	20	80
Temperature	40°C	60°C	80°C
Boot-up to tracking	100 s	10s	1s
Delay from failure to measurement flagged as invalid	10s	1s	0.1s

STR robustness tests

Evaluation of the effects of:

- **Angular rate**, Ω
- **Radiation**, Φ (particle flux)

on the capacity of the start tracker to enter / maintain Tracking Mode.

Tests

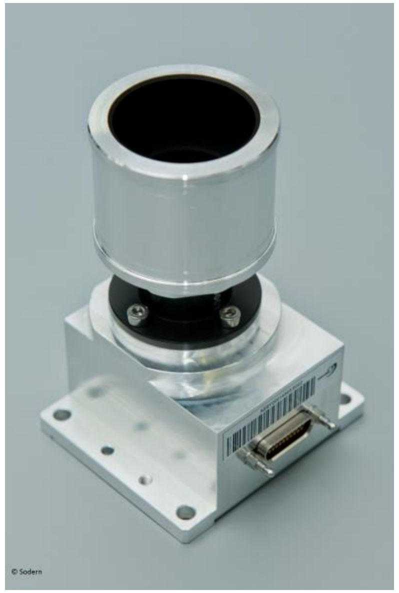
- Test **ACQ**[1]: obtain the probability of the STR to enter TRK in delta_t < 60s for a given set [Ω,Φ]
- Test **TRK**[2]: explore the limit conditions [Ω,Φ] in which the TRK mode can be maintained.

[1] ACQ for "Acquisition Mode"
[2] TRK for "Tracking Mode"

STR tested:

- HYDRA (Sodern)
- AURIGA (Sodern)

Hydra



Auriga

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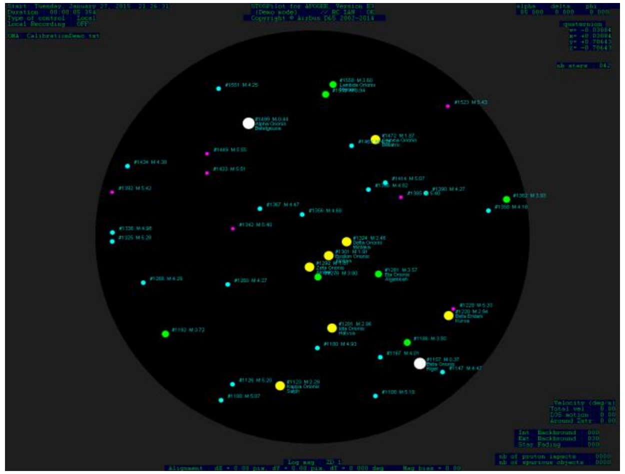
Test bench: STOS

STOS (Star Tracker Optical Stimulator)

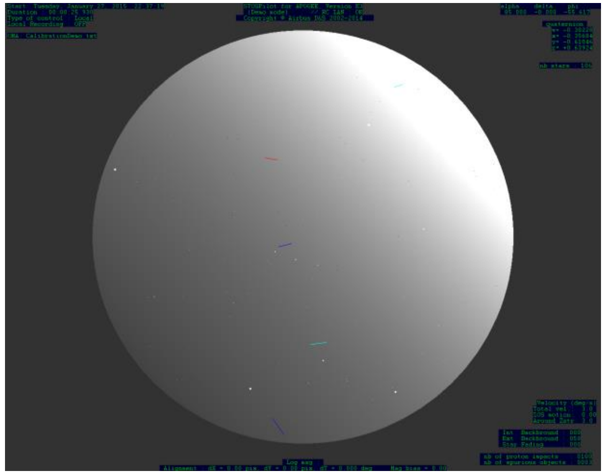
- Developed and commercialized by Airbus DS
- Opto-mechanical assembly (OMA) + Software (STOSPilot)
- Open loop and closed loop simulations (together with an environmental processor).

OMA-D model
to test HYDRA
- FOV 23°
- Displayed image rate of 225Hz allowing to simulate fast dynamics

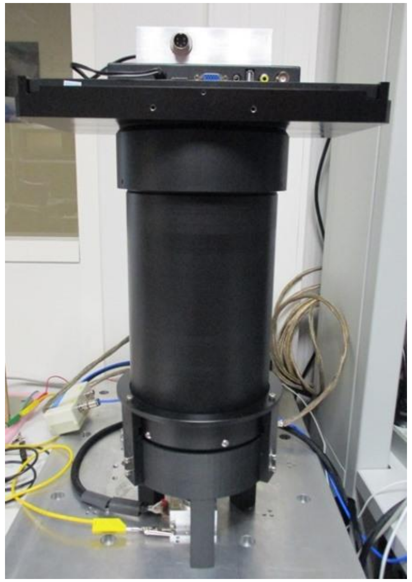
OMA-SL30 model
to test AURIGA
- FOV 30°
- Displayed image rate of 60Hz



Constellation displayed in demo mode for illustration purposes. Enhanced stars and catalog information



Simulation of different artefacts: stray light, proton impacts, moving objects, false/additional stars.



Test setup

Initial conditions

- q, attitude quaternion: random
- [Ω,nP] :
  - The direction of Ω is perpendicular to q (Ω in the STR image plane)
  - nP: simultaneous particle impacts
    - Life duration of an impact: from 0 ms to 20 ms
    - Ratio streaks vs punctual impacts: 10%
    - nP → Φ « effective » particle flux (part/cm^2/s)
      - T simulation image refresh (*)
      - Sensor detector surface

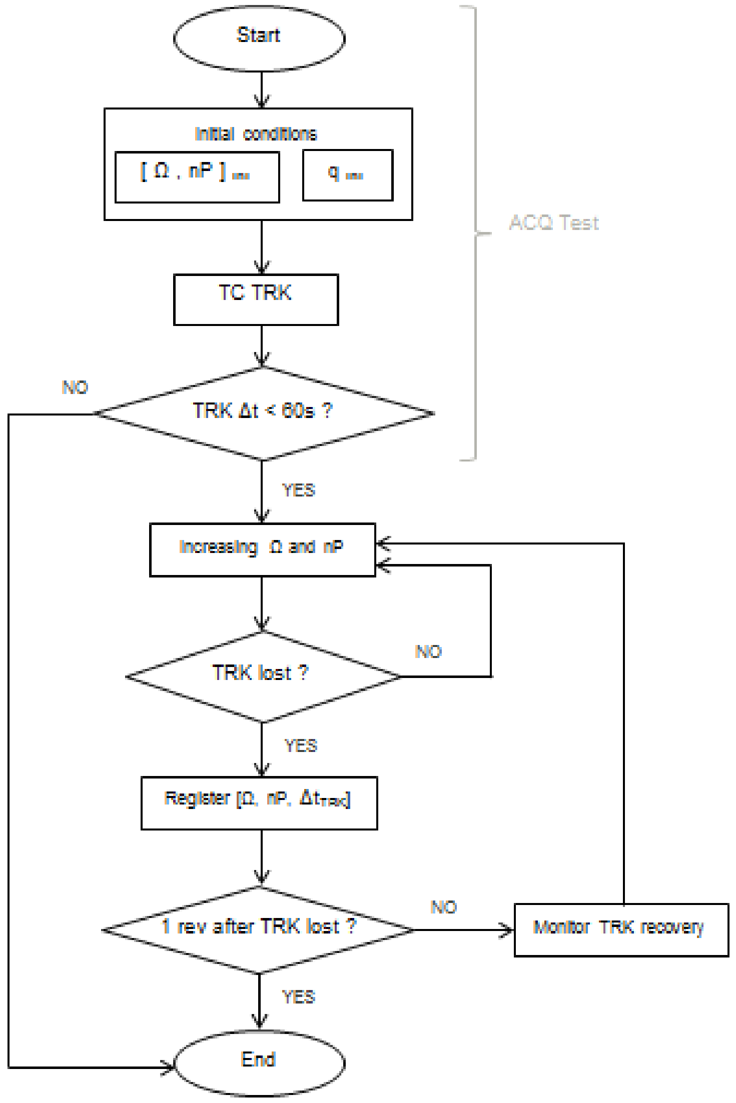
Notes:

Φ « effective » particle flux: flux of particles that can arrive to the detector

Φ « effective » → **Φ** environment

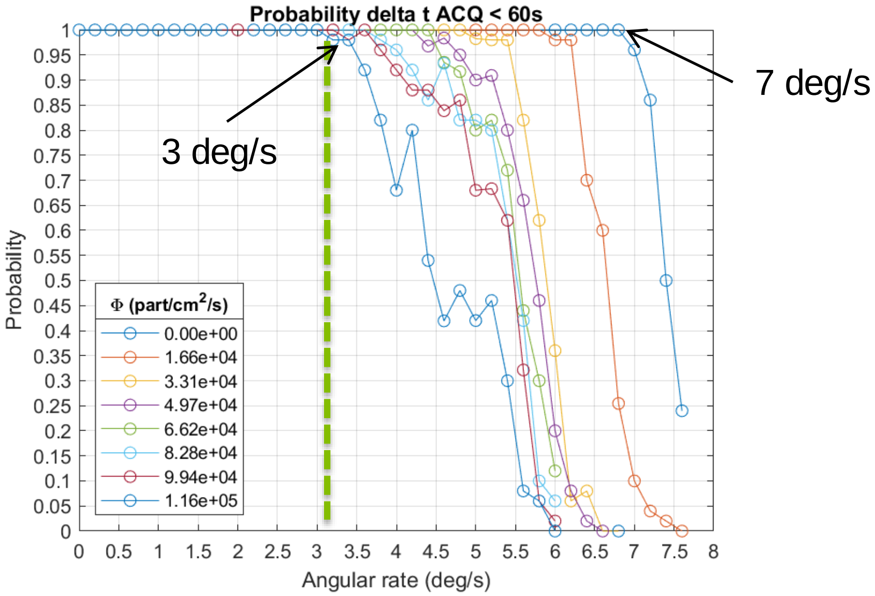
- Detector technology
- Shielding

(*) STOS Image display

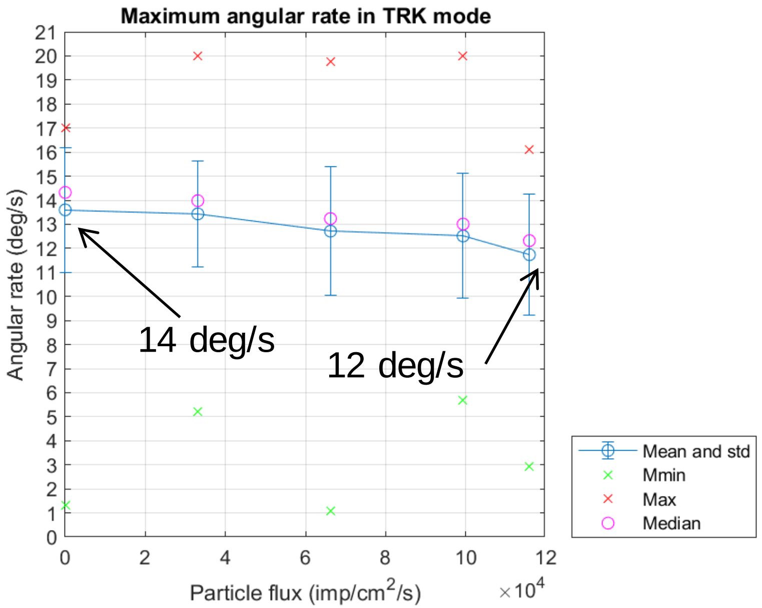


Test results - HYDRA

ACQ test (~15000 measurements)



TRK test (~800 measurements)



99% Prob t < 60s

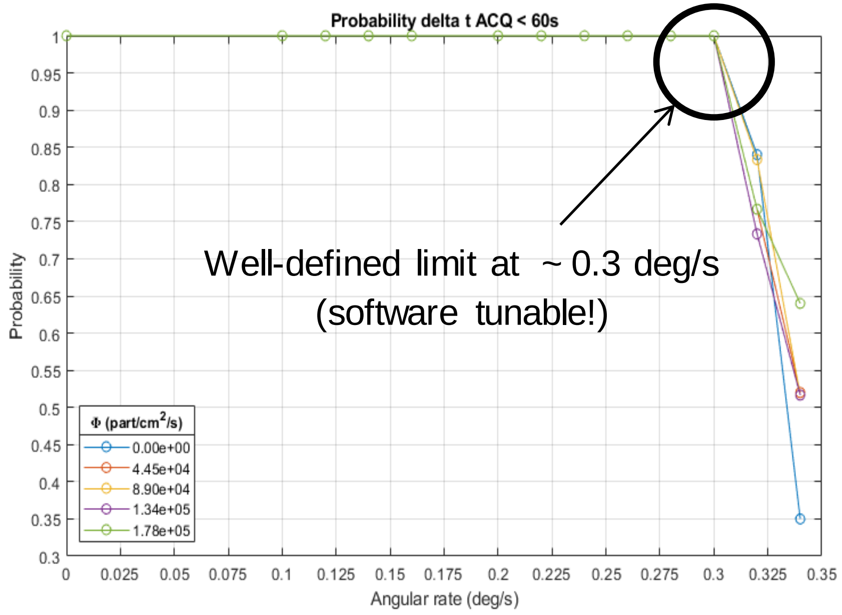
~ Ω (deg/s)	Φ (part/cm2/s)
6.85	0
5.90	1.66 e4
4.91	3.31 e4
3.10	1.16 e5

For reference/comparison: considering the flux for protons above 1 MeV in the CREME96 model flare worst 5 minutes and 10mm of shielding, we would have 13500 p+/cm2/s at detector,.

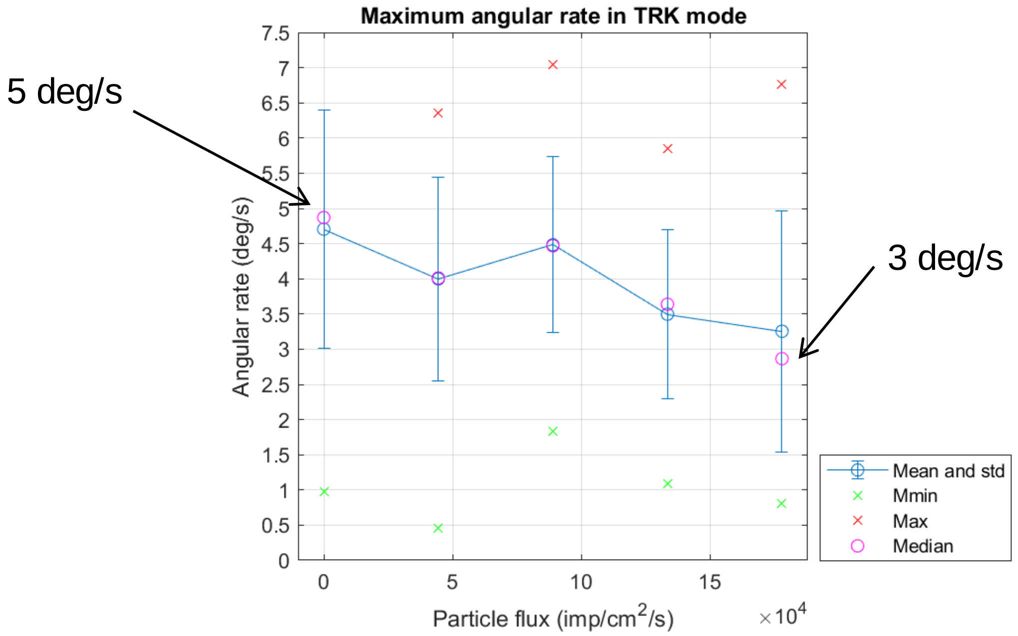
Φ (part/cm2/s)	$\Omega_{max\ TRK}$ (deg/s)			
	Mean	Std	Max	Min
0	13.6	2.6	17.0	1.3
3.31 e4	13.4	2.2	20.0	5.2
1.16 e5	11.7	2.5	16.1	2.9

Test results - AURIGA

ACQ test (~3400 measurements)

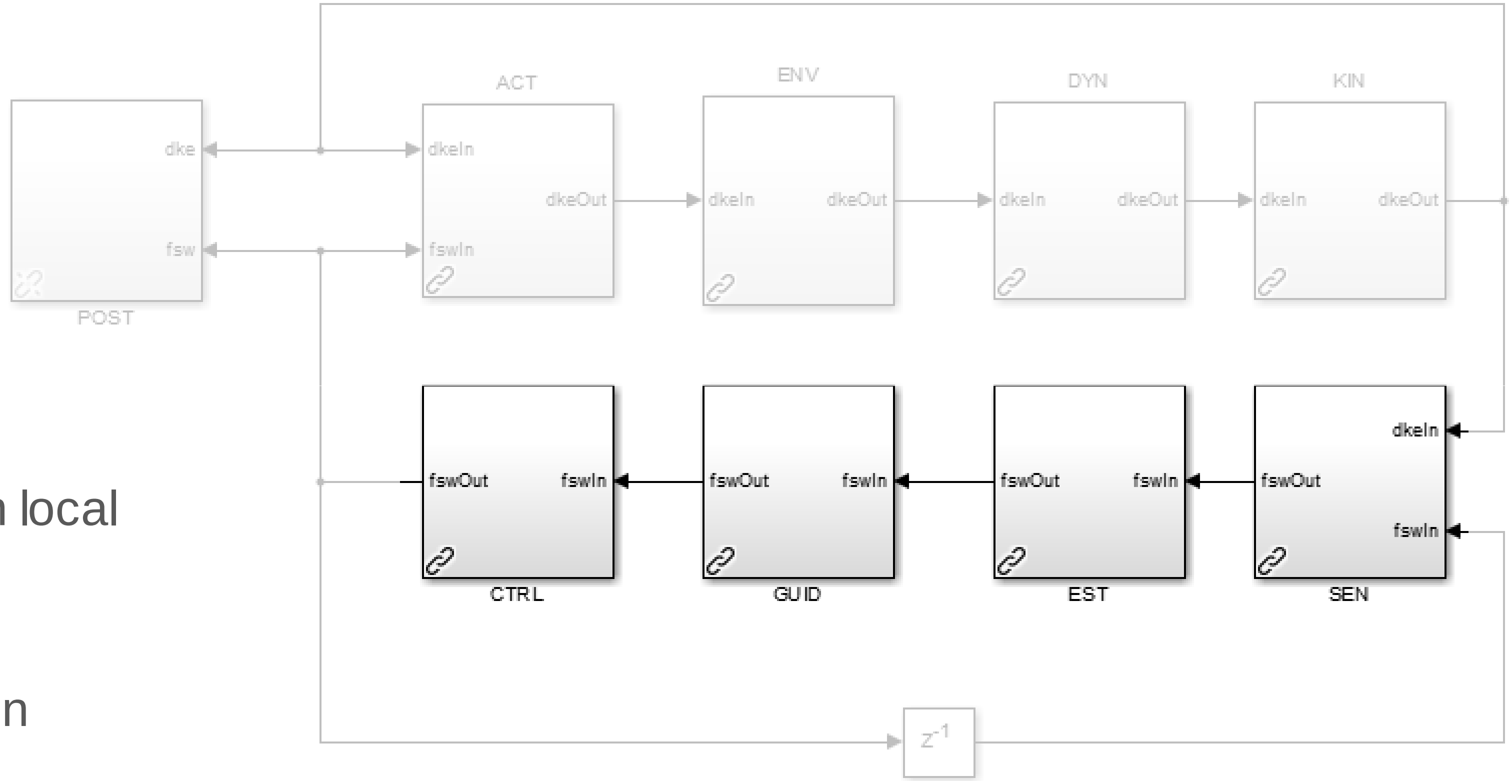


TRK test (~150 measurements)



Φ (part/cm2/s)	$\Omega_{max\ TRK}$ (deg/s)			
	Mean	Std	Max	Min
0	4.7	1.7	7.7	0.9
4.45 e4	4.0	1.4	6.4	0.5
1.78 e5	3.2	1.7	6.8	0.8

Basic principles for architecture definition



- modular, with standard interfaces
  - SEN, EST, GUI, CTR modules
  - upgrades to a module should remain local
- sensor- and actuator-agnostic
  - not tied to STR-based implementation
- can be instantiated for all orbits
  - should not rely in principle on specific environments/geometry

Generic estimation module

Principle
- Kalman filter using all sensors
  - can determine 2-axis attitude + 3-axis angular rates with only CSS measurements (based on 1996 ADS patent)
- when STR is available, KF helps to discard outliers
- filter structure also compatible with other sensors
  - straightforward data fusion (for e.g. MAG, IMU)

States in estimator
- Attitude quaternion (valid for sun-pointing even if axial component undefined when only sun sensor available)
- Angular rates
- Right ascension of sun (if context not trusted)
  - (to convert STR measurements in reference frame)

Inputs
- STR measurements and associated validity flags
- CSS measurements
- Magnetometer measurements (LEO variant)
- Gyro measurements (gyro variant)
- Torque commanded at previous sample time

Outputs
- estimated quaternion + 3 validity flags (roll, pitch, yaw)
- estimated angular rate vector + 3 validity flags
- right ascension of sun + validity flag

Sensors/Actuators in the baseline architecture (for science missions)

- Star Tracker is the main sensor
  - with at least one optical head (to cover degraded cases)
  - considered robust to angular rates, radiation, temperature
- No gyro required
  - but can be added if available (improves observability)
- CSS with (near-)full-sky coverage
  - e.g. 2 BASS
  - rationale = need for gyroless STR deobstruction maneuver
  - additionally: can ensure rate reduction & sun pointing upon persistent STR unavailability (contingency)

- Thrusters are used as main/sole actuation system
  - (generic baseline, compatible with all orbits)
- Optionally: transverse momentum from RW
  - improves observability of angular rates around sun

LEO variant

- magnetometer added
  - simplifies rate reduction and deobstruction
  - second sun sensor no longer needed
- magnetorquers (+reaction wheels) replace thrusters
  - no use of propellant

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STR reliability: STR feared events and mitigations

Feared Event	Potential mitigation
STR HW failure	Redundancy and FDIR strategy (reconfiguration)
STR SW design errors	Software Design Assurance Level: category B required for safe mode Diversification (use of different STRs) FDIR strategy (power-cycling and retry)
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 Undetected failure	Failure Detection coverage requirement and verification 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 increased robustness AOCS (stable Sun pointing during STR outages) and FDIR (unlimited retries) strategies
Operational errors	Safe procedures FDIR strategy (validity checking of ephemeris data, alarm against expiration, consistency monitoring, backup profile)
DHS SGM failure (loss or erroneous ephemeris)	Redundancy and FDIR strategy (CRC check, OBT check, reconfiguration)
FDIR False triggering	FDIR tuning validation, FDIR disabling after triggering
STR performances in worst case condition (power, thermal, rates)	STR increased robustness STR delta qualification

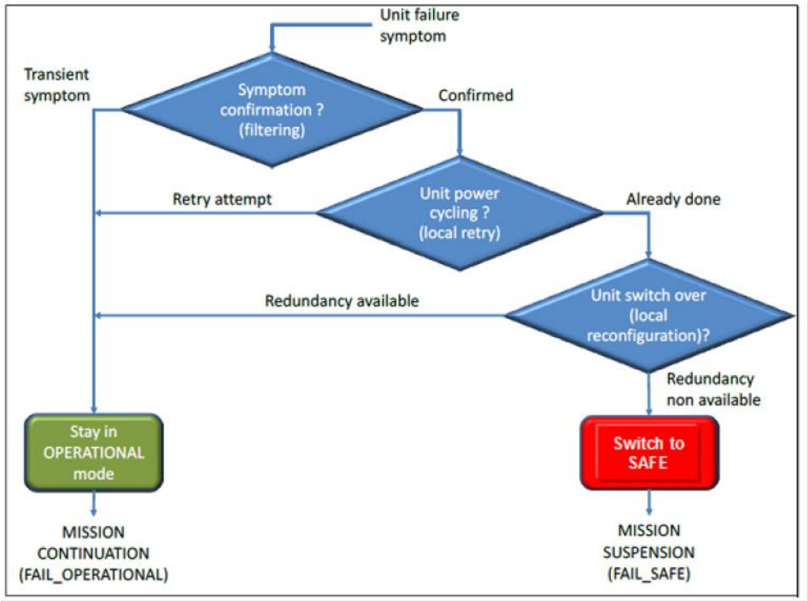
Equipment-level FDIR: STR

STR usually performs own health self-assessment, so that FDIR is performed at 2 levels

- L1 FDIR: STR internal failure detection mechanisms based (e.g. memory / processor error), and recovered at unit level
- L2 FDIR: CSW monitoring of STR HK TM (e.g. health status, temperature, secondary voltages, communication check) and quaternion validity flag
- The following focuses on L2 FDIR

L2 FDIR overall recovery strategy:

- STR being sensitive to non-permanent failures (e.g. SEU) or external transient phenomena (solar flares, blinding), retries (e.g. power cycle) may be sufficient to recover from many failure occurences
- Therefore, except in case of confirmed risk of failure propagation (e.g. over-temperature) or confirmed permanent failure, and as long as STR outage can be tolerated, FDIR shall attempt to recover STR failures with retries



Retry and switchover strategy

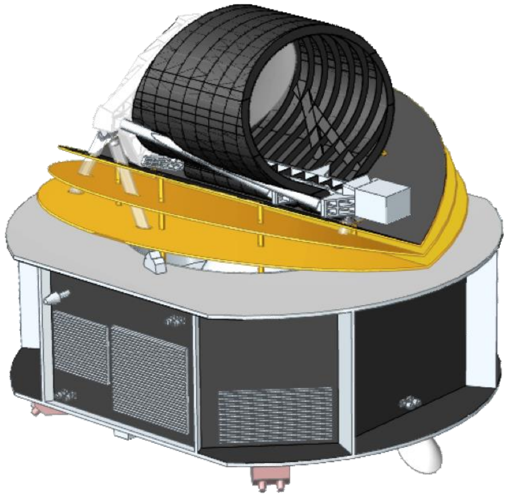
Loss of tracking: FDIR strategy

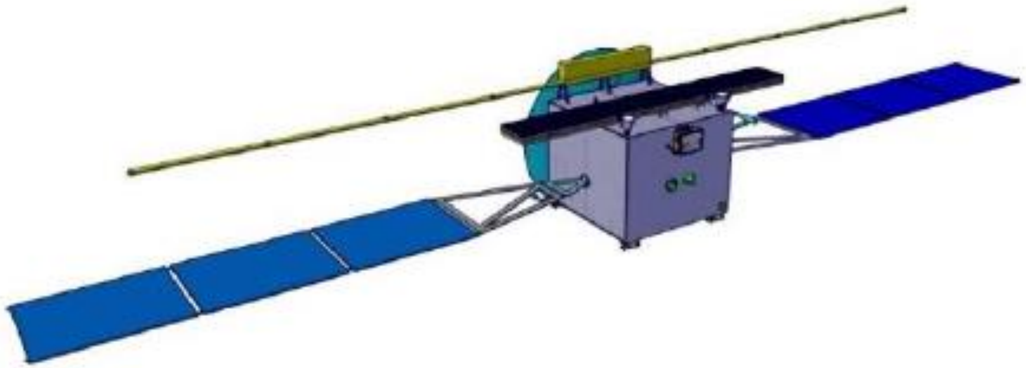
Analysis of possible STR final status based on proposed FDIR strategy and for all possible root causes leading to loss of tracking

- Tracking is recovered in all cases
- Although temporary loss of quaternion information is possible, up to worst case solar flare / deobstruction duration
- Safe mode robust by design to such outages (Sun pointing remains uninterrupted thanks to CSS)

Scenario (root causes)	Detection	Recovery(ies)	Final status
Failure on a single OH (not detected by other monitorings)	No valid quaternion on single OH	Permanent retries on failed OH	AOCS uses quaternion from hot redundant OH ; no quaternion loss
Failure on a single EU (not detected by other monitorings)	No valid quaternion on any OH	Retry on failed EU, then swap to redundant	AOCS uses quaternion on cold redundant EU ; temporary quaternion loss
SEU on a single OH	No valid quaternion on single OH	Retry on failed OH	AOCS uses quaternion from hot redundant OH ; no quaternion loss
SEU on a single EU	No valid quaternion on any OH	Retry on failed EU	AOCS uses quaternion from recovered EU ; temporary quaternion loss
Solar flare	No valid quaternion on any OH	Successive retry / swap on EU (or successive retries on OH depending on STR HW configuration), deobstruction maneuver	Quaternion loss until solar flare end, then recovered on currently used EU
Blinding	No valid quaternion on any OH	Successive retry / swap on EU (or successive retries on OH), deobstruction maneuver	Quaternion loss until deobstruction is complete, then recovered on currently used EU

Use cases for the STEAM study





Rationale = 2 missions, 4 ambitious cases for stress-testing

- same architecture for all cases
- (only minor parameter changes)
- high radiation levels considered in all cases

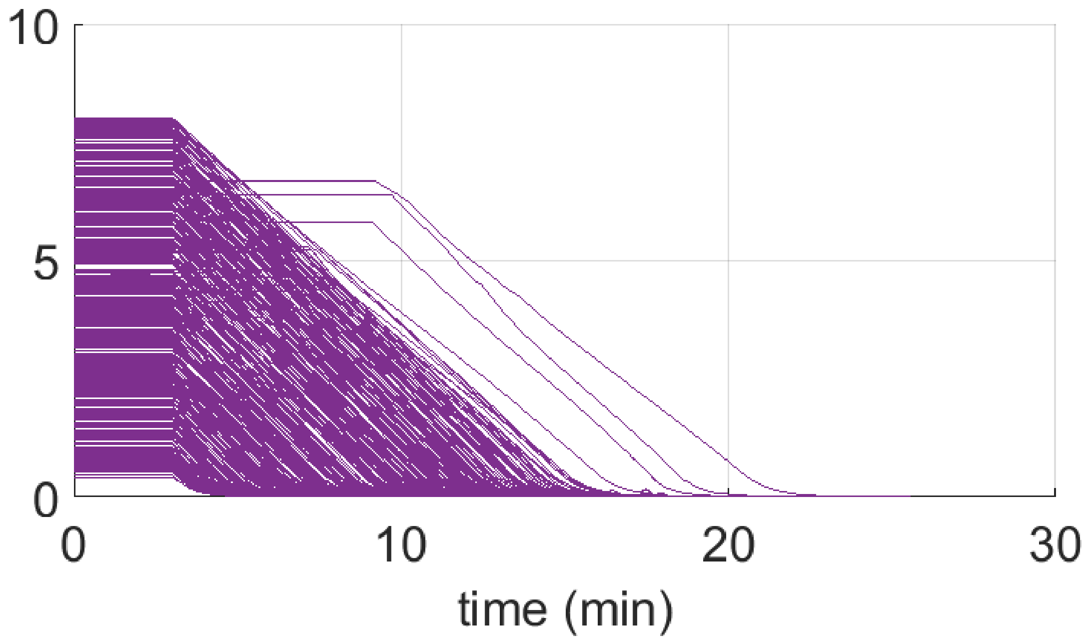
- ARIEL-like: (fictitious) spin separation
  - initial yaw rate up to 8 °/s (above STR acquisition limit)
  - narrow allowed attitude range (payload protection)
- ARIEL-like: failure on-station
  - narrow allowed attitude range

- ENVISION-like: failure at low Venus orbit
  - closeness to Venus (STR blinding + long eclipse)
  - random season (sun angle wrt. orbital plane)
  - lost-in-space (random initial attitude and rates)
- ENVISION-like: failure during aerobraking
  - extreme aerodynamic torque at periapsis
  - (up to 10 Nm > thruster authority)

Results of performance campaigns – ARIEL-like cases

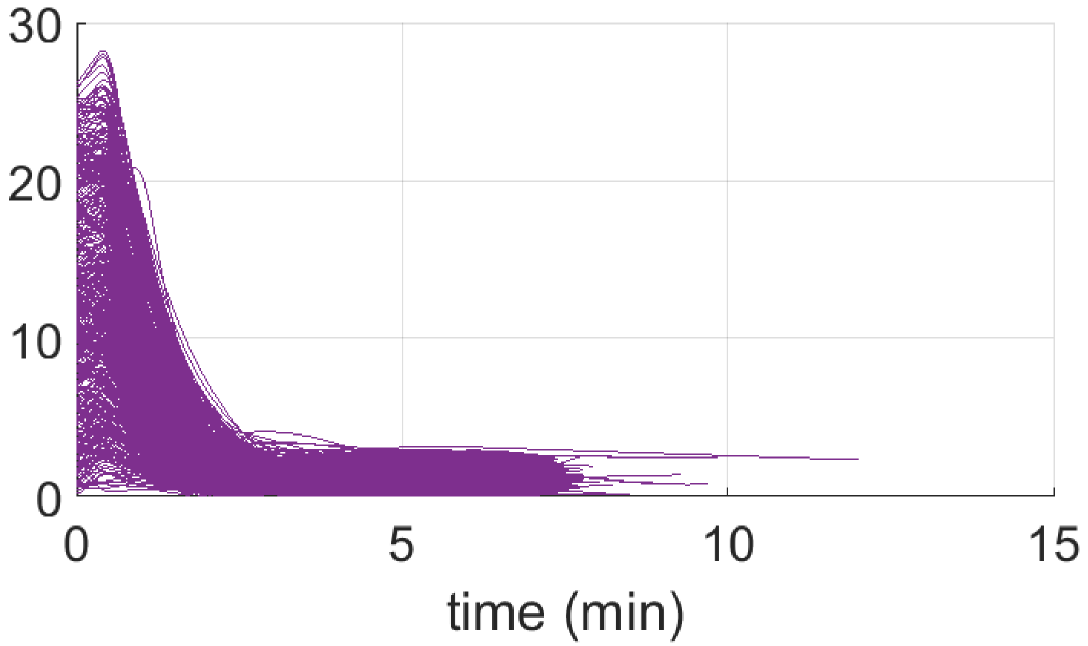
Spin separation, Angular rate history, deg/s

- convergence time correlated to highest initial spin rate



Failure on-station, Sun aspect angle history, deg

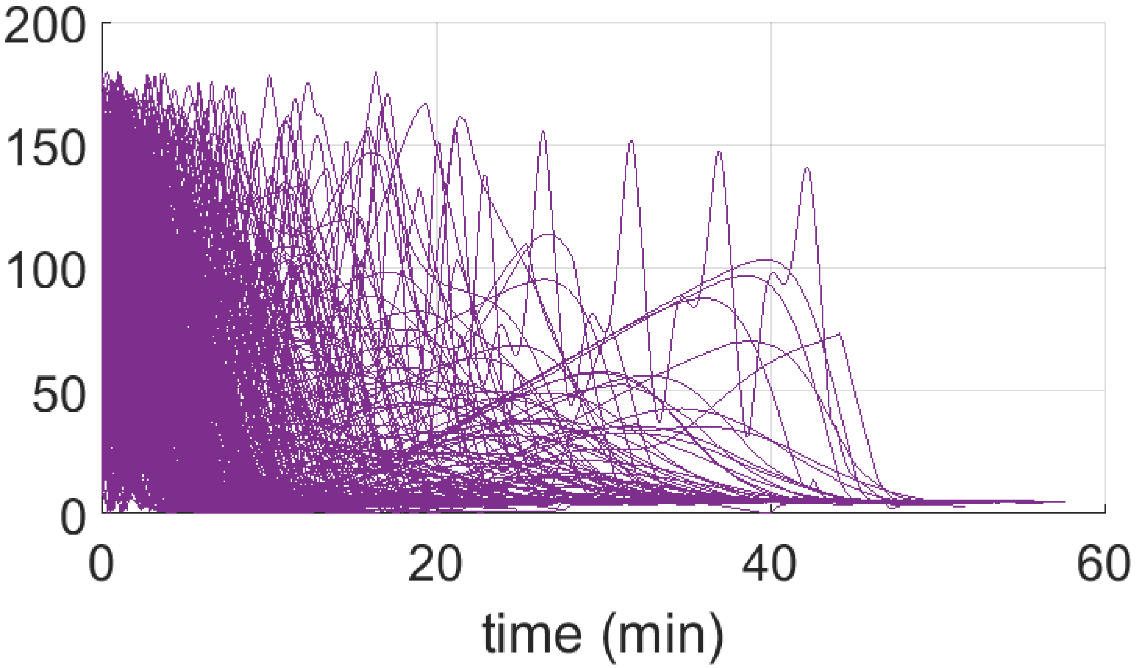
- immediate STR tracking => rapid convergence in all cases



Results of performance campaigns – Envision-like cases

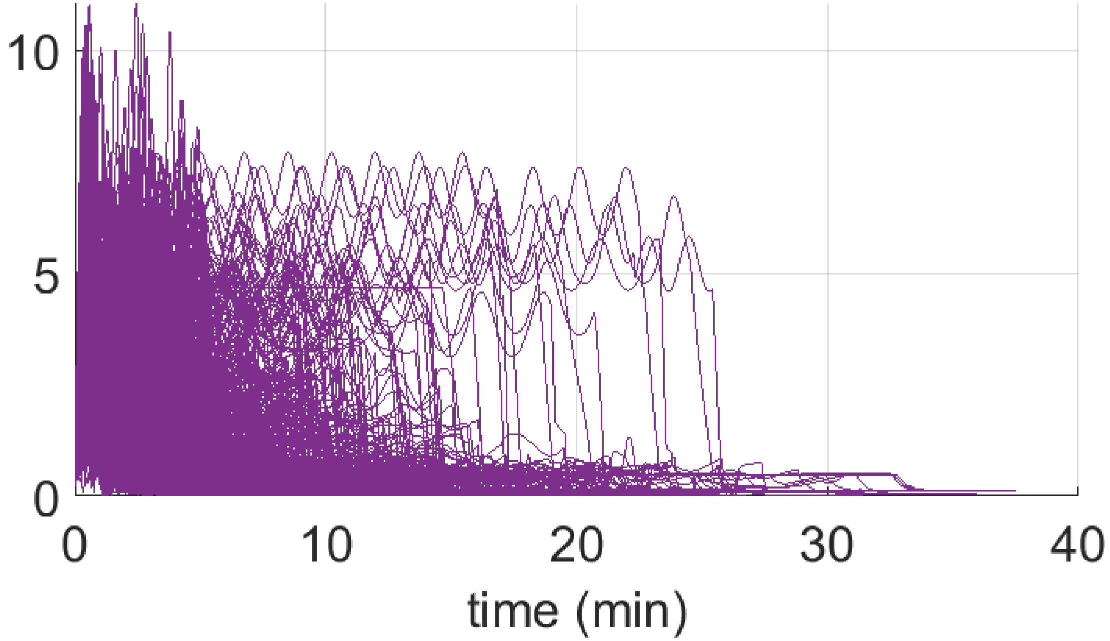
Failure at low Venus orbit, sun aspect angle history, deg

- worst-case corresponds to worst phasing with eclipse



Failure on-station, angular rate history, deg/s

- similarly, rates cause by aerodynamic torque at perigee cannot be corrected until they are obseved (out of eclipse)



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Conclusions on performance campaigns

Baseline safe mode architecture feasible even in very demanding cases

- considering only 1 STR optical head and 2 SAS

- Including for cases when STR is unavailable for significant amount of time
  - high initial spin rate (ARIEL-like case)
  - long occultations by Venus (Envision-like case)

- Including severe environmental stress
  - high rad. (lower angular rate limit for STR ACQ)
  - high disturbance torque (aerobraking case)

Main take-away message

- reference architecture suited to very demanding science missions
- should perform even better for less demanding cases
- expected to perform better in LEO (adding magnetometer improves observability of angular rates while STR is unavailable)

Additional message

- mode design can converge to and maintain sun pointing despite prolonged STR unavailability
- design can thus ensure survival even if STR is permanently unavailable => ultimate safety
  - e.g. first flight of new STR model
  - e.g. extreme radiation events

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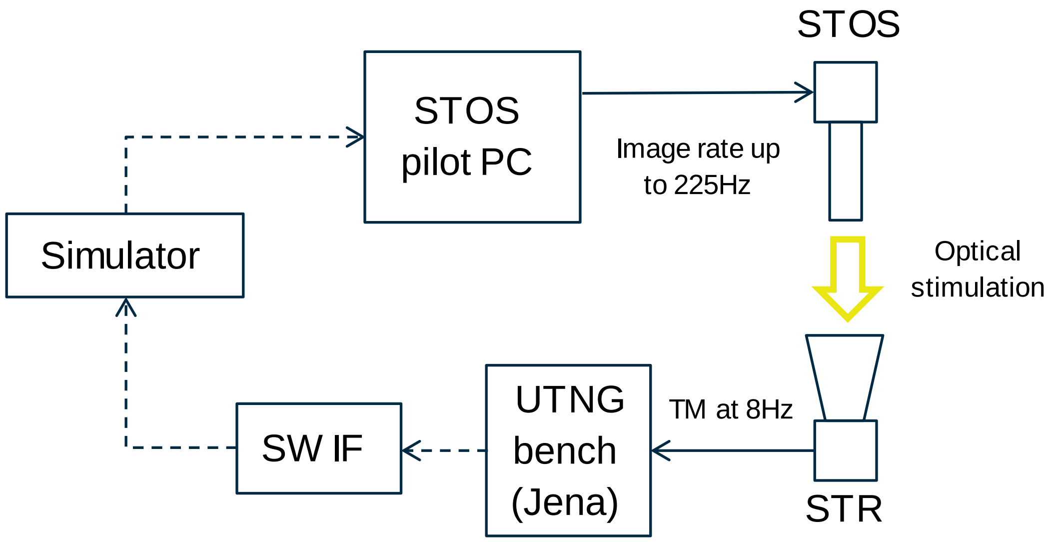
Open-loop and closed-loop tests with real STR in-the-loop

OBJECTIVES

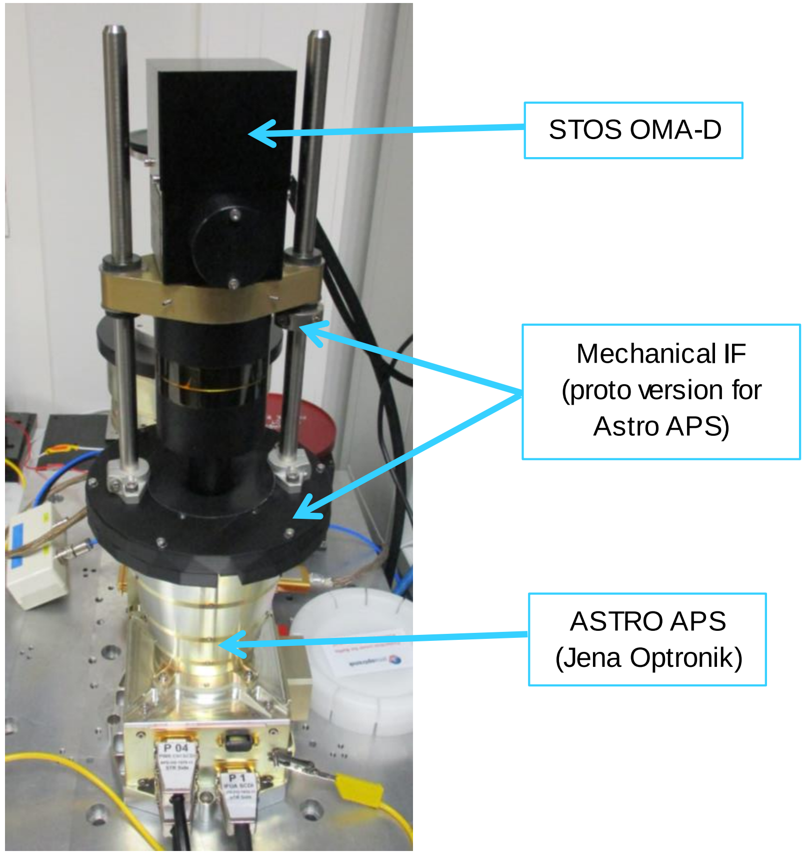
- verify similar functional behaviour than in simulations
- for open-loop tests: STR should not lose tracking when simulation believes it should be tracking
- for closed-loop: convergence behaviour should be the same or better than in simulation

SETUP of closed-loop tests



STR tested:

- ASTRO APS (Jena Optronik)



Open Loop with STR-in-the-loop

SELECTED CASES

from Monte Carlo campaign with simulator. Selection criterion:

For Ariel-like spin separation scenario (A1)

- Max norm of angular rate projection to STR image plane $(x,y)_{OH}$: $W_{OH\,t}$
- Blinding near angular rate for transition to Tracking mode (ACQ→TRK)

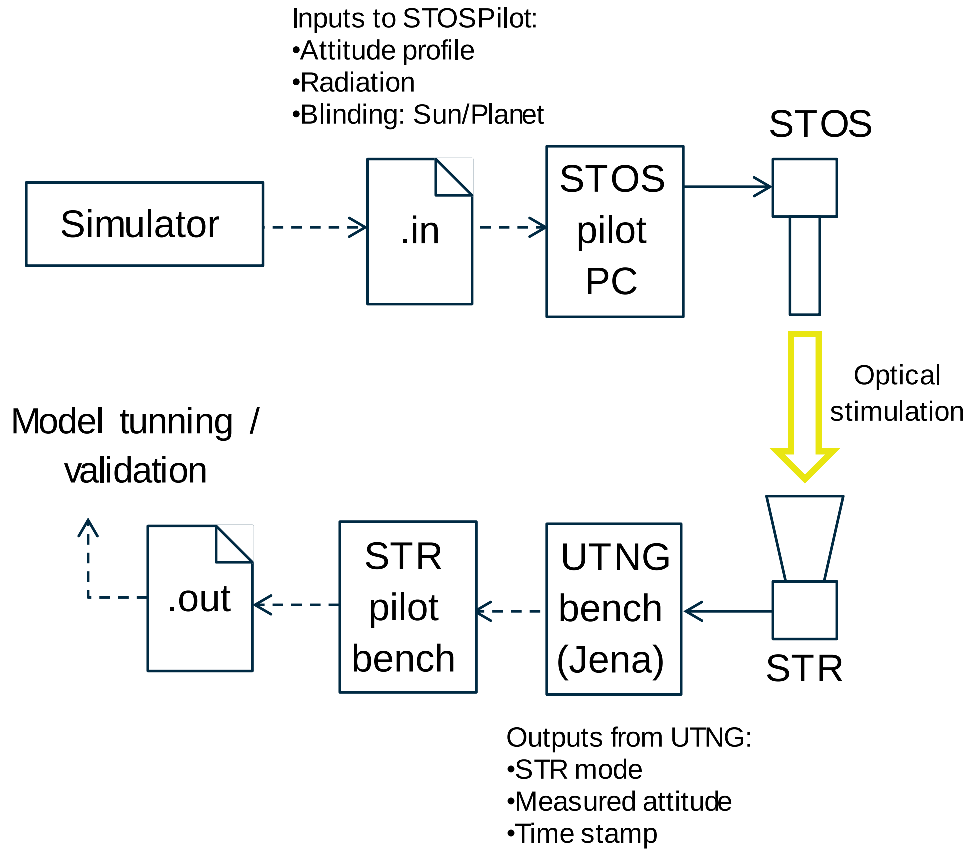
For Envision-like near Venus scenario (E1)

- Near max simulated* $W_{OH\,t}$ with blinding transitions *(2.49 deg/s)

Obtain a rough estimate of:

- Angular rate in which the STR enters TRK mode: $W_{OH\,TRK}$
- Time to enter TRK mode after a blinding period (or after commanding TRK mode): t_{TRK}

SETUP for Open loop



Open Loop results

Maximum angular rate $W_{OH\,t}$ for transition to TRK mode

- Transition ACQ→TRK occurs for max WOH t :

  3.0 deg/s < max $W_{OH\,t}$ < 3.9 deg/s

- No observed relationships wrt tested radiation level.

Time to TRK mode

- Max time ACQ→TRK after blinding near max $W_{OH\,t}$:

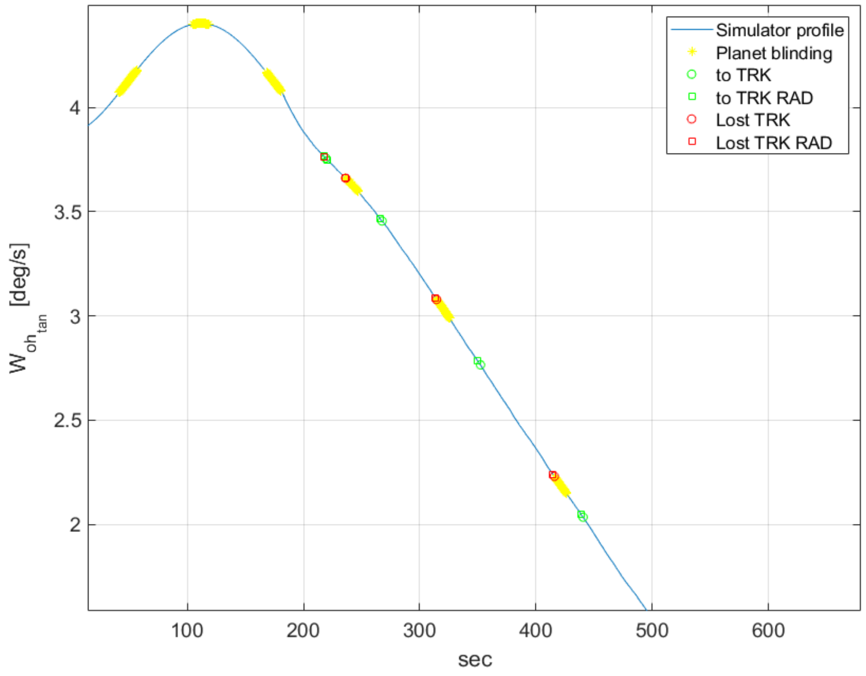
  10 s < t_{max} for max W_{OHt} < 25 s

- Max time ACQ→TRK after blinding for $W_{OH\,t}$ < 2deg/s :

  3 s < t_{max} for (W_{OHt}< 2deg/s) < 7s

- No observed relationship wrt tested radiation level.

A1 case for illustration



STR trust classes and required AOCS backup functionality

Three broad categories for trusting the STR

- objective robustness / subjective 'newness' of the STR
- objective cost / subjective criticality of the mission

Note that the trust classes are not intrinsic to a sensor model but depend on *both the STR and the mission*

STR trust category	Feared event			Complementary solution needed for:		
	Sensitivity to rates	Sensitivity to radiation	Serious glitch (SW or HW)	deobstruct	rate reduction	sun-pointing
High		low		X		
Medium	X	medium		X	X	
Low	X	high	X	X	X	X

Important note: deobstruction is required in all cases

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Secondary sensors and complementary attitude determination

Deobstruction is required *regardless of STR trust class*

- (because we would need too many optical heads to ensure permanent visibility)

Deobstruction manoeuvres can be done in two ways:

- open-loop (after a time-out) – this was the baseline in the previous study
  - – requires no additional sensors
  - – but more risky (esp. if thrusters are used)
- closed-loop – baseline in this study
  - – requires additional sensors (gyro, magnetometer or sun sensor)
  - – less risky

the baseline architecture (STEAM-S)
in this study relies on sun sensors
for complementary attitude/rate determination

If additional sensors (for deobstruct), they can provide *additional benefits*

- rate reduction (for all sensors)
- sun rallying and sun pointing (if sun sensors are used)

This can help to reduce risks even further (lower STR trust class required)

Decision tree and architecture variants

Decision tree

- STR trust class
  - – choice of the STR
  - – vs criticality of the mission
  - – and derisking effort
- LEO vs non-LEO
  - – magnetometer usable only in LEO
- Accommodation constraints
  - – sun sensors require wide field of view
- Availability of a gyro
  - – either the normal mode's gyro
  - – or a low-cost dedicated unit

Two variants cover all situations

- STEAM-S for non-LEO (study baseline)
- STEAM-M for LEO

Mission orbit	Complementary sensors	STR trust category		
		High	Medium	Low
LEO	**MAG+CSS**	**STEAM-M**		
	MAG	STEAM-M'		
Non-LEO	none	STEAM-D		
	CSS	**STEAM-S**		
	Gyro	STEAM-G		

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Description of STEAM variants

STEAM-S: STR + sun sensor(s)
- estimation filter can observe 2 attitude angles and 3 rates
- from sun sensor measurements only
- A second sun sensor (or individual cells) is required for covering full 'lost-in-space' attitude domain
- can ensure deobstruction, rate reduction, sun pointing
  – STEAM-S can guarantee survival until STR available
  – compatible with trust class L

STEAM-M: STR + magnetometer (+ sun sensor)
- derivative of mag field used as proxy for angular rates
- allows rate reduction and deobstruction

- if sun sensor is used, then sun-pointing is possible as well
  – can then guarantee survival until STR available
  – compatible with trust class L

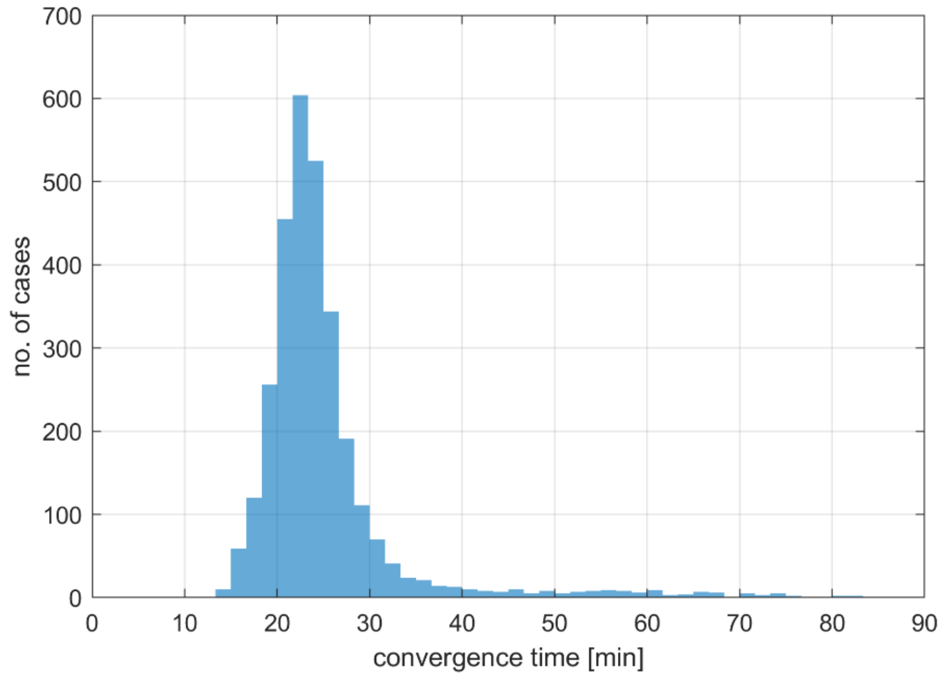
STEAM-G: STR + gyro
- estimation filter naturally behaves as gyro-stellar estimator
- Rate reduction and deobstruct thanks to gyro measurements
  – but then STR needs to acquire for going to sun-pointing
  – requires trust class M or H

STEAM-D: STR alone
- minimialistic architecture
- deobstruction maneuver performed in open-loop after time-out
- no rate reduction capacity
- STR must be able acquire once deobstructed
  – requires trust class H

Simulation campaign for STEAM-S backup survival

- Extension of the baseline simulation campaigns
- STR not available
- Only sun sensor measurements are used
  – 1 BASS + 4 cells in the back, for coverage of lost-in-space cases
- Random orbit altitude between 500 and 36000 km (e.g. GTO)
- Random inertia matrix (including cross-products of inertia)
- Random initial rate 7.5 deg/s 3-sigma
- Random initial attitude
- Random position along the orbit (prob. eclipse >0)
- Pessimistic external disturbances (0.01 Nm 1-sigma @0.1 Hz)
- 3000 cases

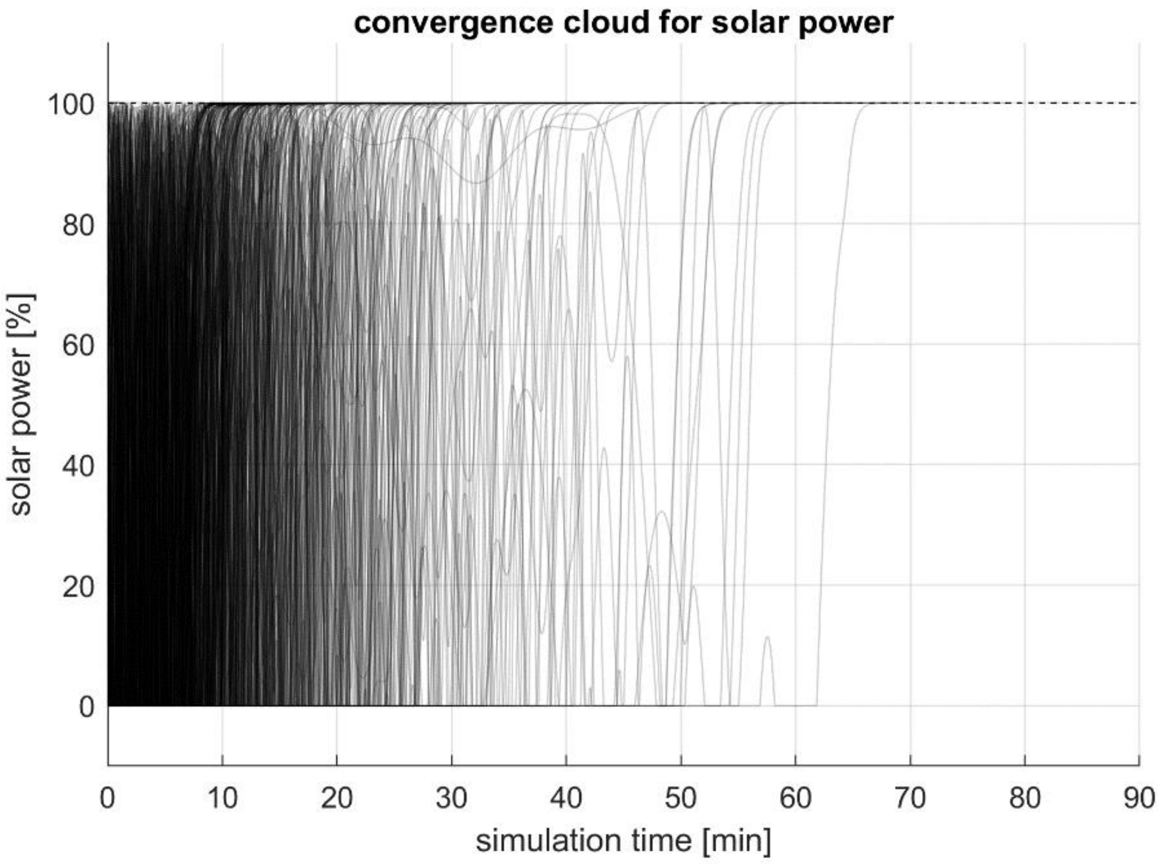
- Success/stopping criteria:
  – pointing error < 10 deg over 20 minutes
  – and angular rate < 1 deg/s for 20 minutes

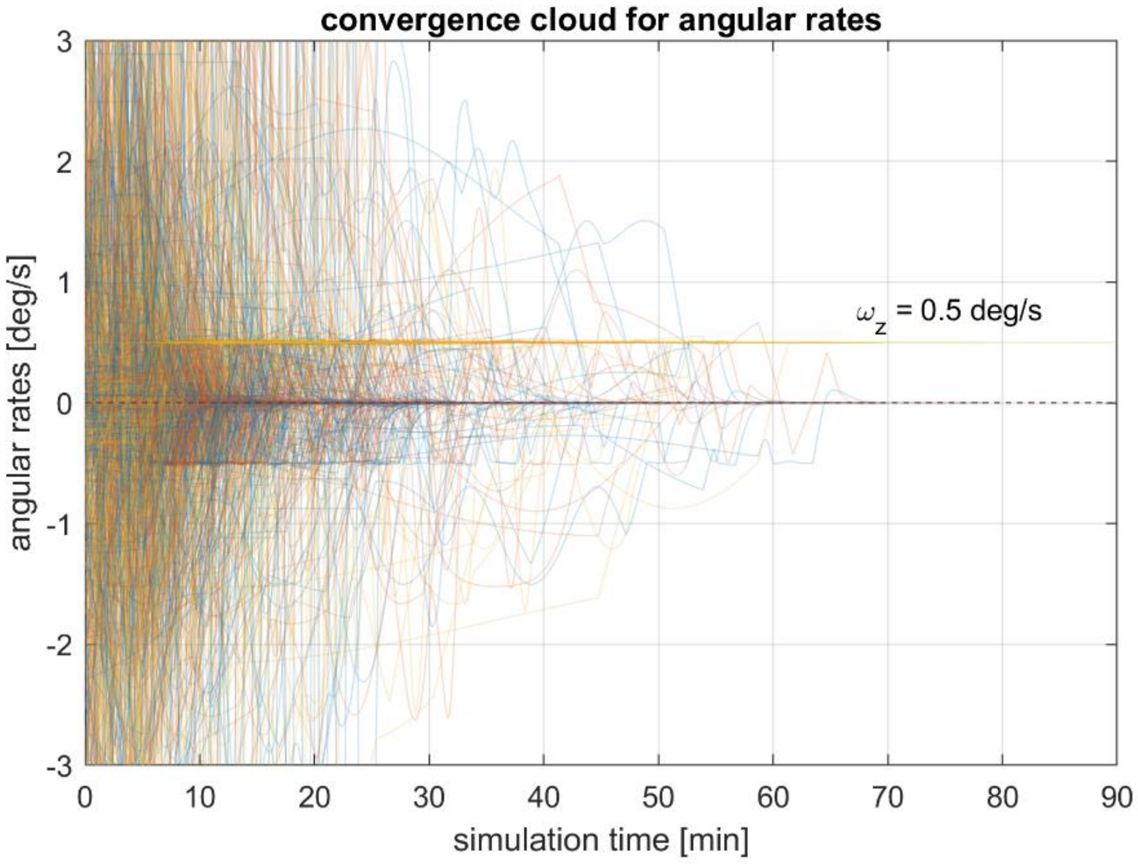


quantiles	68%	90%	95%	99.7%
Convergence time	25 min	30 min	39 min	74 min

note: worst-case eclipse = 70 min

Additional outputs: convergence clouds (300 cases)





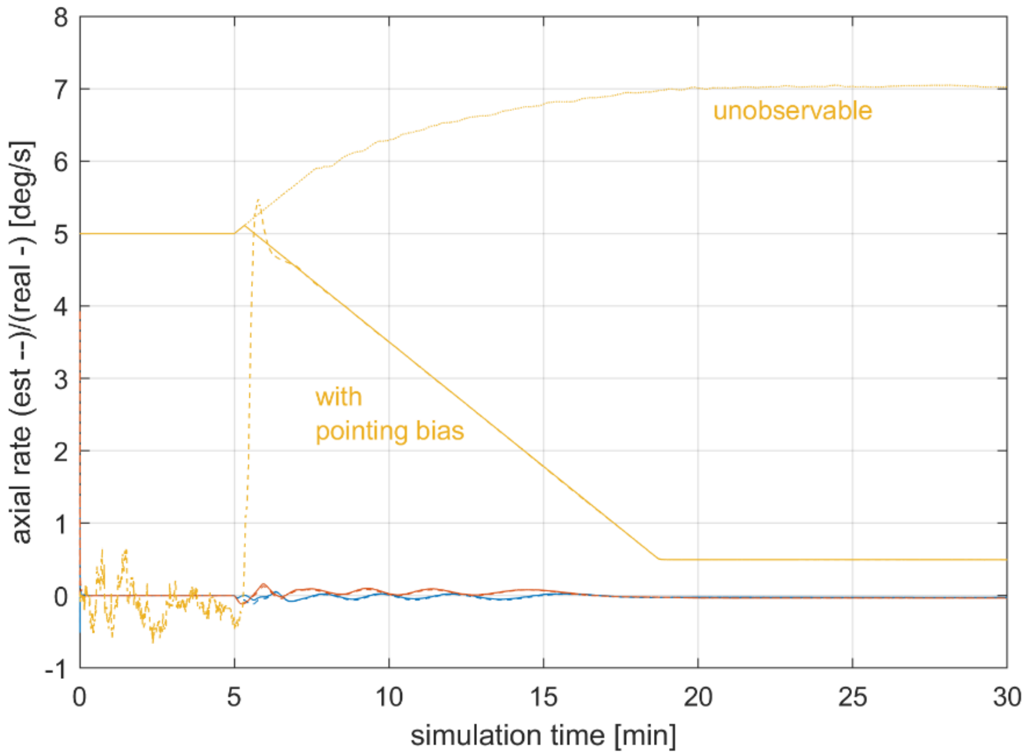
About inobservable cases (rarity and workarounds)

No convergence issues observed among 3000 random cases

No convergence issues even among 300 special-made worst cases
- spherical inertia
- or axisymmetrical inertia, with principal axis aligned with sun sensor
- random initial attitude and rates

Divergence of axial rate estimate only detected with perfect conditions
- angular rate aligned with sun direction
- sun sensor aligned with sun direction
- angular rate aligned with principal axis of inertia

Simple workarounds to recover observability (if deemed necessary)
- Introduce a small transverse momentum bias (1 Nms)
- Or impose an offset in sun-pointing target attitude
  – 6 deg appears to be sufficient



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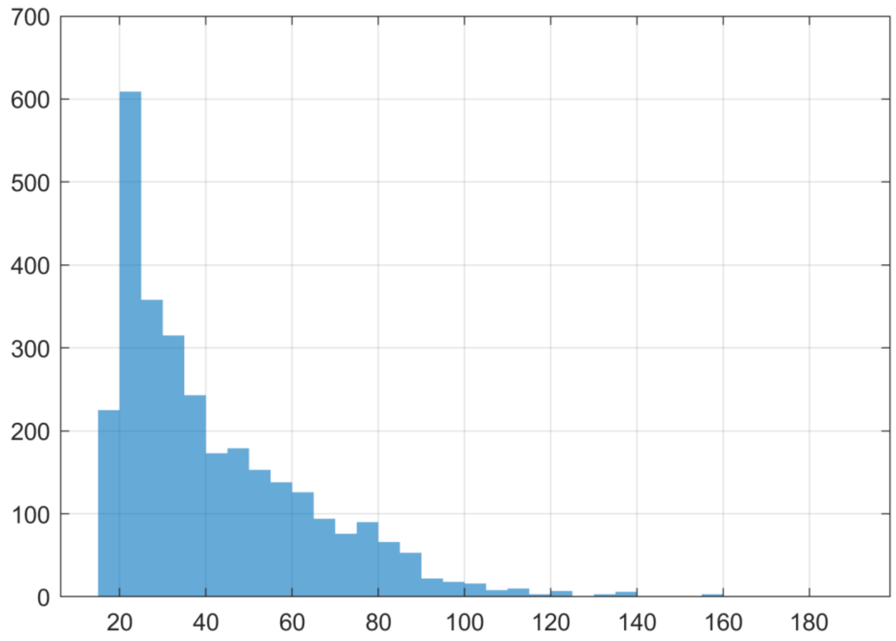
Simulation campaign for STEAM-M backup survival

- Proof-of-concept campaign for LEO (outside study scope)
- Estimator instantiated for MAG + CSS + STR (but STR no available)
- Only magnetometer and sun sensor measurements are used
  – 1 MAG + 1 BASS (i.e. same architecture as other LEO safe modes)
- Orbit altitude = 800km, incl 60 deg, random raan (drifting orbit)
- Random inertia matrix (including cross-products of inertia)
- Random initial rate 3 deg/s 3-sigma
- Random initial attitude
- Random position along the orbit (prob. eclipse > 30%)
- Pessimistic external disturbances (0.01 Nm 1-sigma @0.1 Hz)
- Actuators = MTQs + RWs
- 3000 cases



- Success/stopping criteria:
  – pointing error < 10 deg over 20 minutes
  – and angular rate < 1 deg/s for 20 minutes

quantiles	68%	90%	95%	98%	99.7%
Convergence time (minutes)	50	75	85	100	140
Convergence time (orbits)	0.5	0.8	0.9	1.0	1.4

note: existing magnetic modes converge within typ. 2 orbits = 200 minutes

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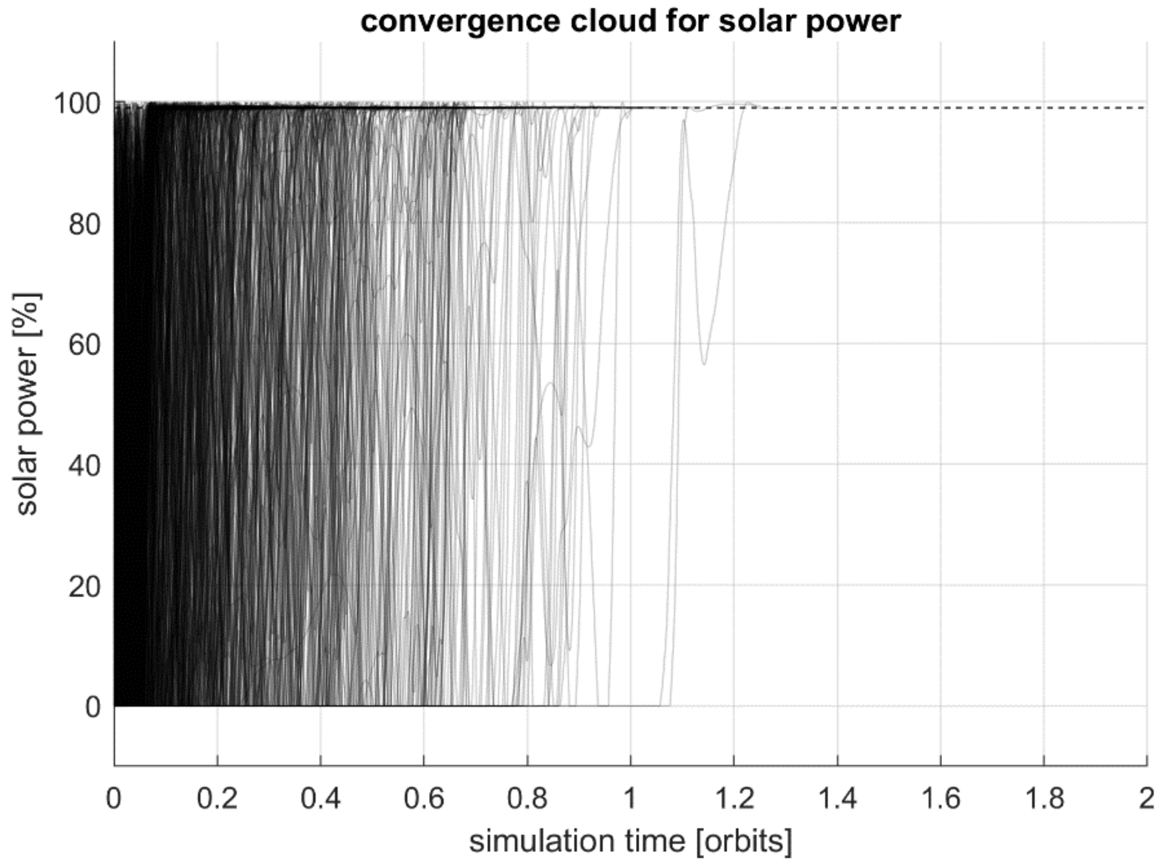
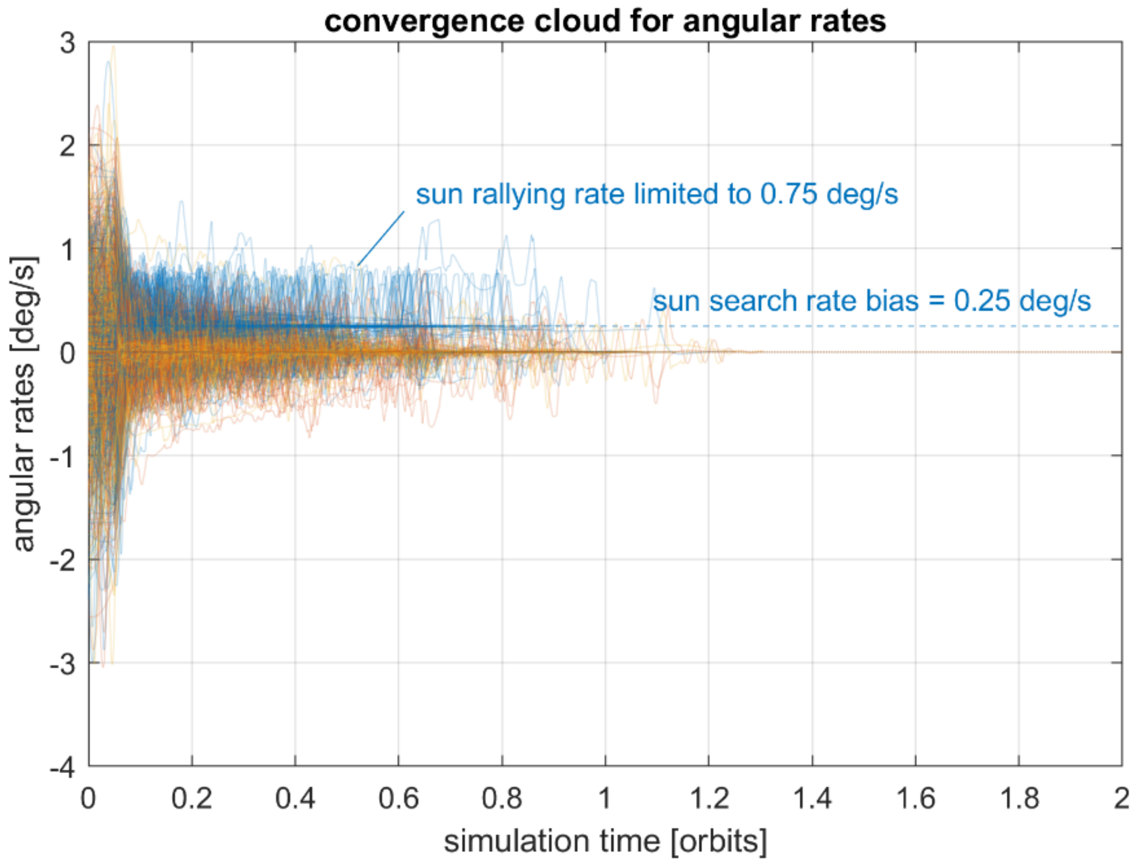
Additional outputs: convergence clouds (600 cases)





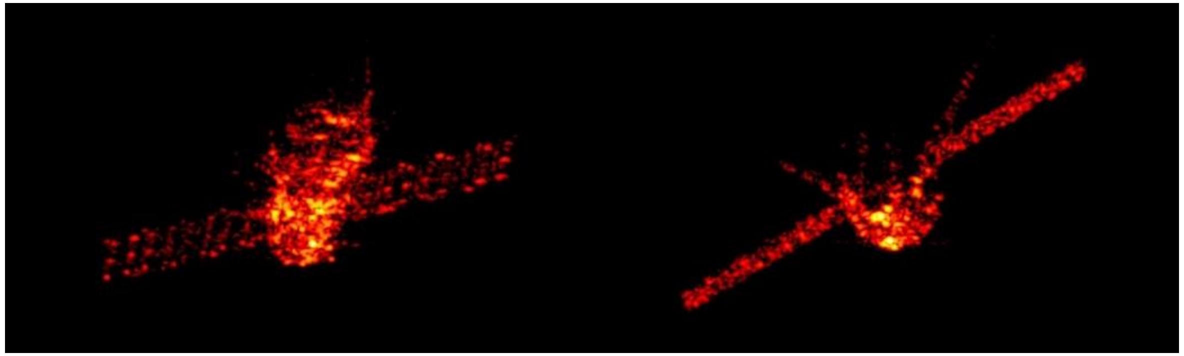
About ground-based recovery options

Functions to perform
- rate estimation for rate reduction
- attitude estimation for sun-pointing

Technology options
- Optical systems
- Radar systems
  – classical (with doppler)
  – imaging (synthetic aperture, e.g. TIRA)
- Antenna tracking

Limitations
- timeliness: reactivity (incl. on-call operators) >> battery autonomy
- measurement frequency (orbits or days) >> control bandwidth
- range sufficient only for LEO
  – (where backup survival with MAG is inexpensive)

Recom.: niche situation (await concrete use case before further effort)



tiangong-1 space station, acquired by TIRA from 800km distance

TIRA facilities in Germany: 50m radome for 34-m antenna

Derisking strategy for new STRs – trust classes (recap)

Trust class needed vs safe mode architecture

- STEAM-M (STR+MAG+CSS) or STEAM-S (STR+CSS+CSS)
  - can ensure survival without STR measurements
  - trust class Low is sufficient
- STEAM-G (STR+RMU)
  - can ensure rate reduction without STR measurements
  - trust class Medium is needed
- STEAM-D (STR+ø)
  - only performs deobstruction
  - needs trust class High

STR trust category	Feared event			Complementary solution available for:		
	Sensitivity to rates	Sensitivity to radiation	Serious glitch (SW or HW)	deobstruct	rate reduction	sun-pointing
High		low		X		
Medium	X	medium		X	X	
Low	X	high	X	X	X	X

Suggested de-risking steps

For high rates (class H)

- High rate tests on real sky (by supplier)
- Robustness tests with optical stimulation (on independent test bench, as was performed with the STOS during this study)
- Open-loop tests with optical stimulation, with realistic high-rate scenarios (again, on an independent test bench)

For high radiation (classes M or H)

- Fault tree analysis, check that false positives are transient
- Radiation robustness tests in SW simulation (by supplier)
- Radiation robustness tests with optical stimulation (on independent test bench, e.g. STOS)
- Open-loop tests with optical stimulation, with realistic high-rate scenarios (on independent test bench), including high radiation levels

For persistent false quaternions (all classes)

- Fault tree analysis (artefact patterns causing spurious acq.)
- Robustness campaign with optical stimulation
  – (generation of random and/or realistic patterns of false stars, extended objects, dust particles)
- Polarity checks with STOS in AIT

SW and functional issues (classes M or H)

- S/W validation cat B
  – ongoing at JOP, planned at Sodern
- Early characterization tests with STOS
- Closed-loop simulations with STR in the loop

Polarity tests thanks to STOS setup in AIT

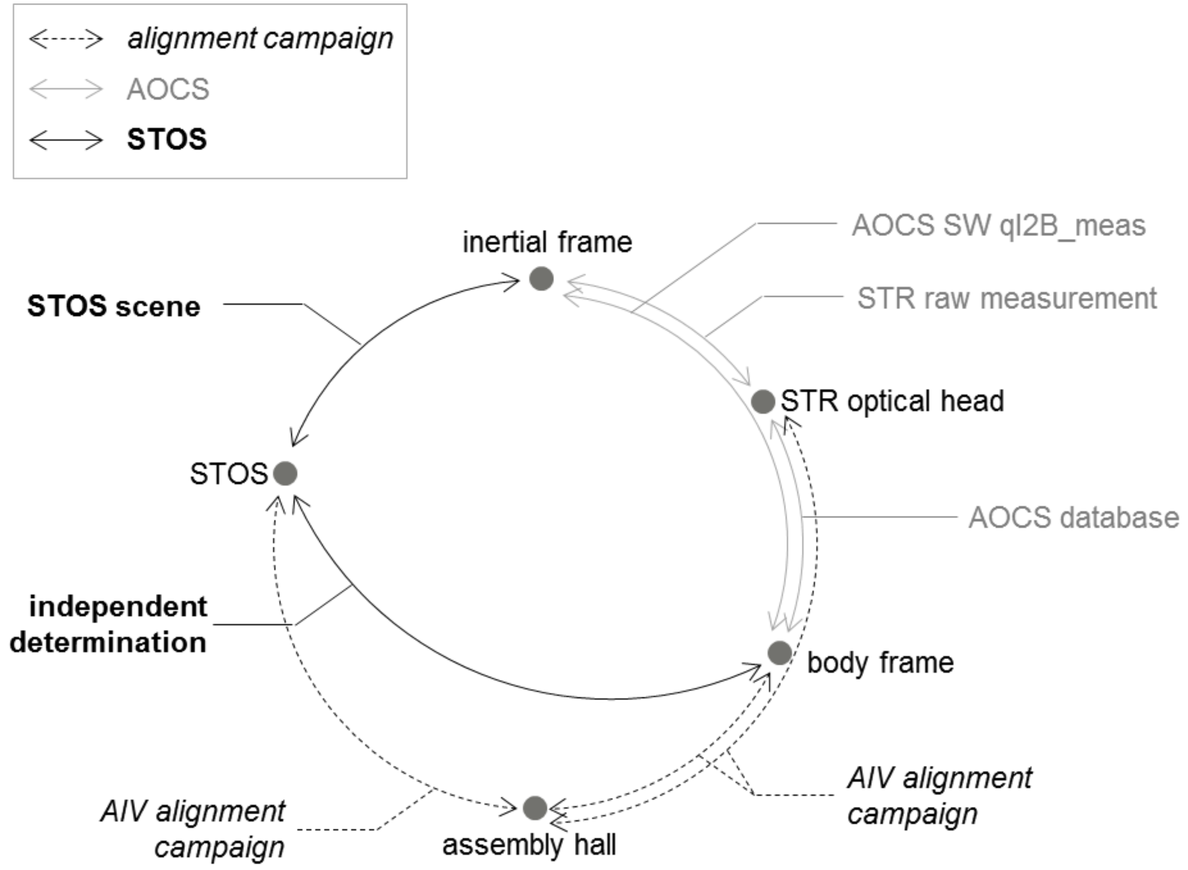
Feared event specific to STR = wrong attitude reading

- erroneous STR orientation parameters in database
  - – quaternion bias between STR measurement and reality
  - – causes attitude bias and coupling between axes (for rates)
  - – can destabilise rate control if error > 90 deg

Needs for polarity testing

- – verify STR orientation parameters in database
- – with independent verification system

- STOS in AIT (static OMA is sufficient)
  - – test can be added to current AIT process
  - – (STOS already implemented in AIT)
- Independent verification of STR/STOS alignments
  - – by coupling STOS on STR (without exchanging data)
  - – comparing STR quaternion with STOS orientation



Functional tests with independent optical stimulation (e.g. STOS)

Using the STOS will be key to improving safe STR use.
Independent setup wrt. supplier has many benefits:
- no additional data supplied to sensor (just photons)
- No unconscious influence from supllier skills
- Hidden assumptions need to become explicit
- Early detection and correction of interface issues

STOS setup is versatile and inexpensive
- compatible with
  – lab setup
  – flatsat
  – AIT
- easy to ship for tests outside Airbus
- easy to operate (STOSPilot S/W)

Categories of tests (indicative target trust classes in brackets)
- Functional characterization and acceptance tests (L,M,H)
  – mechanical/ electrical integration
  – functional checks
  – test of auxiliary functions
- Robustness tests
  – angular rates (H)
  – radiation levels (M)
  – straylight and background level (H,M)
  – artefacts (H)
- Open-loop tests (M,H)
  – representative attitude/rate scenarios
  – verification of STR simulation model parameters
- Closed-loop tests (H)
  – low-level interfaces, real-time behaviour
  – coupled behaviour STR + AOCS

1. The STEAM study for ESA: motivations and objectives
2. Requirements for using the STR in safe mode
3. Robustness tests with real STR hardware
4. Overall architecture of generic safe mode (STR-based or not)
5. Reliability and FDIR aspects
6. Implementation and performance for 2 challenging science missions
7. Open-loop and closed-loop tests with real STR
8. Complementary attitude determination
9. Derisking new Star Trackers
10. **Conclusions**

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)

Optical stimulation = key enabler
- functional validation
- polarity testing
- robustness tests
- open-/closed-loop tests on realistic scenarios

Safe-mode architecture with demonstratef 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

Recommendations

Widespread adoption of the new safe mode architecture, with or without the STR: the modular structure makes it simple to decline the safe mode for various missions. The decision of allowing STR measurements in safe mode can be taken at any moment (even after the start of the mission)

Systematic use of optical stimulation test benches for validating all aspects of the interaction between the STR and the AOCS, from early iterations to late tests on the assembled satellite

Reliance on complementary sensors when required or relevant (STEAM-S or STEAM-M), so that survival can be ensured even if the STR is unavailable

Adoption of STR-only ‘minimalistic’ variants (STEAM-G or STEAM-D) when a high level of trust can be placed in the STR

Perspectives

Adoption by future mission(s)

- many projects in dev. could immediately benefit

Retrofitting existing missions

- less risk because STR already known
- immediate benefits (lower downtime, more predictable, more versatile attitude options)

Suggestion for follow-up R&D = PIL tests of estimation filter

- novelty + central role in the STEAM architectures
- generic, all missions/variants
- straightforward process (autocoding / porting)

In the long run

- trend away from segragation / dissimilarity
- blurred line between normal and safe modes
- graceful degradation philosophy (e.g. commercial aviation)


THEOS
satellite

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