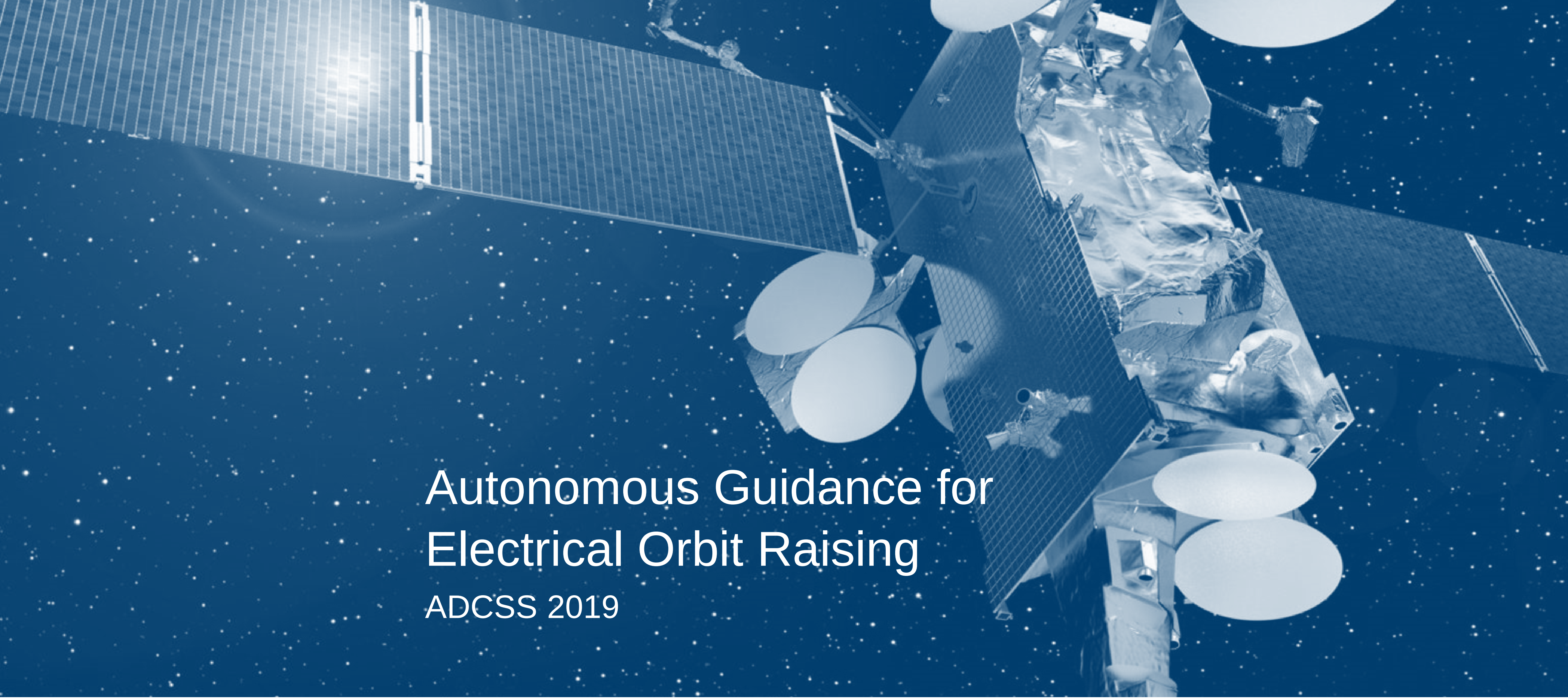

Autonomous Guidance for Electrical Orbit Raising

ADCSS 2019

DEFENCE AND SPACE

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Context and objectives of the study

CONTEXT

- ESA R&D (D/TEC) ARTES contract 4000120072/17/NL/EM
- running Q2.2017-Q1.2020
- contractor: Airbus Defense & Space FR

MOTIVATIONS

Context of Electrical Orbit-Raising

- for telecom platforms
- for large constellations in LEO

Repetitive and time consuming operations tasks during LEOP

- Duration of EOR scenarios (several months)
- Automation of tasks can decrease the cost of operations
- And reduce risk of operation bottlenecks (constellations)

Enabler = GNSS-based autonomous navigation in GTO/GEO

- e.g. GPS III and increased space service volume

OBJECTIVES

Propose appropriate autonomous guidance solutions
to be flown on the next generation of telecom platforms

- Development of on-board orbit/attitude guidance algorithms
  - For efficient and autonomous EOR
  - Explore hybrid analytical/numerical methods
  - Consider limited on-board processing power

- Validation of the SW implementation
  - On a representative processor in the loop setup

- Ground station and control center use reduction target > 80%

- Extension to LEO missions

On-board, full autonomy concept

Key characteristics

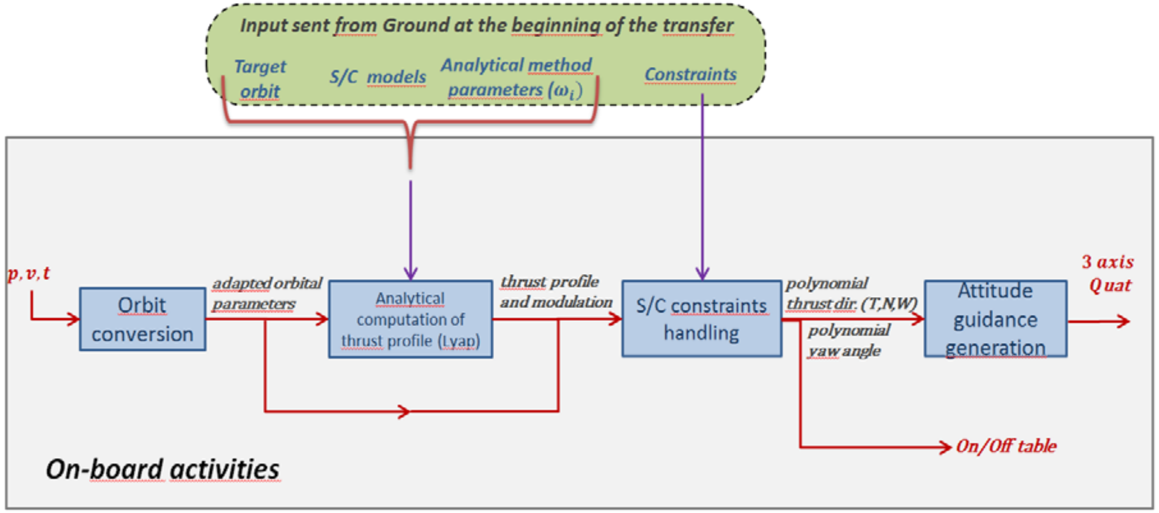
- The ground only uploads the target orbit + slot
- Thrust scenario & attitude profile entirely calculated on board
- Methods applicable to all kinds of transfer (LEO or GEO)

Challenges

- On-board optimization shall be simple but “good enough” compared to ground based solutions (in terms of ΔV)
- AOCS and other S/C constraints must be met
- Need to handle final phasing (longitude rendezvous)

Decoupling assumption

- thrust profile optimized independently of attitude constraints
  - allows simple optimizer for onboard implementation
- then attitude profile is computed to meet AOCS constraints
  - might cause deviations from optimum thrust profile
  - deviations from optimum thrust profile are only transient
  - errors are then compensated by closed loop
  - additional cost wrt. ground optimum is acceptable



On-board, full autonomy concept: thrust profile computation

Lyapunov feedback law, allowing a simple closed-loop formulation of the guidance problem

- Control feedback algorithm designed to decrease a scalar function L representing of how far the S/C is from its target.

$$\boldsymbol{L(\underline{x}, t) \overset{\text{def}}{=} \frac{1}{2}\sum_{i=1}^{N} w_i\left(x_i(t) - x_{i,target}(t)\right)^2}$$

- The method is simple, with very few tuning parameters and offers a good mix between stability and optimality
- Many mathematical expressions have been derived in the literature to describe such a Lyapunov function.
  - In most expressions, the coupling of the orbital parameters is ignored
  - however, this coupling needs to be considered for GTO to GEO, in order to really minimize propellant consumption

Innovative Lyapunov Feedback Control algorithm improved from Q-law

- Uses a new formulation for the Lyapunov function
- Enables to target a, e, i, RAAN
- The calculations involved (such as the derivatives) are derived analytically and rather simple
- Minimum mass transfers, eclipses (for EPS constraints) are included.
- Perturbations: J2, Moon + Sun, SRP (can be extended)
- Requires very few tuning parameters (typ. between 2 to 4 for a GTO to GEO transfer)

Additional functionality for autonomous longitude targeting

Problem statement

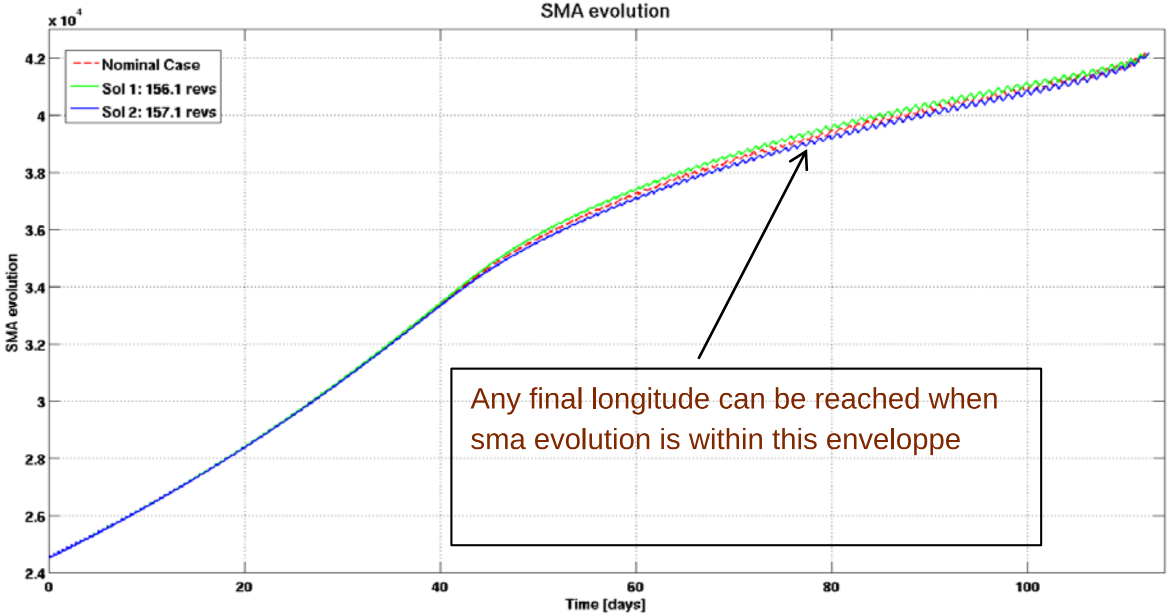
- total time/longitude is not covered by Lyapunov optimizers
  - optimizer might reach the right orbit, but not at the right time
  - therefore not the right longitude
- a separate functionality is needed, for longitude targeting

Solution uses two main modules

- periodic prediction of final longitude
  - from current orbital state + time
- adjustments of thrust profile to correct final error

Computational aspects

- on-board prediction of final longitude error is CPU-intensive
- but it is only needed from time to time
- expected to be the largest contributor to CPU load



Any final longitude can be reached when sma evolution is within this enveloppe

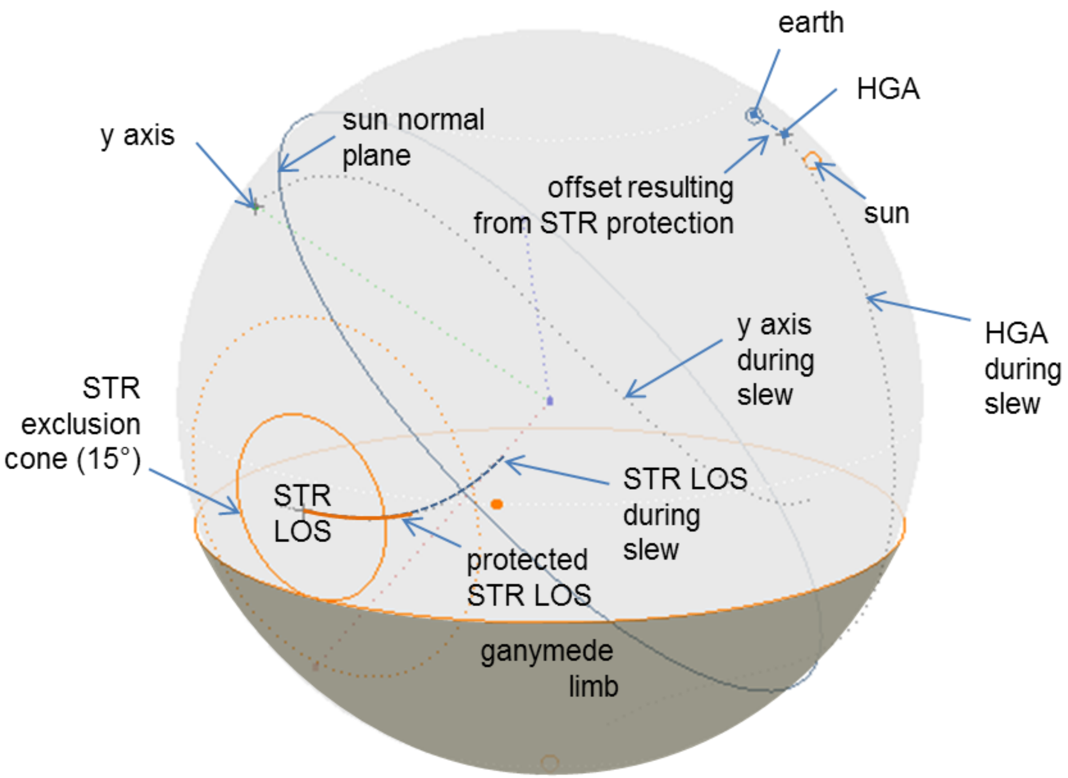
Autonomous attitude profile computation: 3-axis Lyapunov attitude guidance

- Derived from a function under development for JUICE

- a Lyapunov function includes
  - – thrust direction error (weighted)
  - – sun pointing error (weighted)
  - – forbidden cones (e.g. STR blinding in LEO)

- computes direction of steepest descent
  - – for maximum decrease of L function
  - – saturated by dynamic limitations (torque, momentum)
  - – to obtain commanded quaternion step

- smart avoidance of forbidden directions
  - – adjust radial component of angular rate
  - – circulate around forbidden cones
  - – avoid stalling when approaching normally
  - – avoid locking when constraint not convex



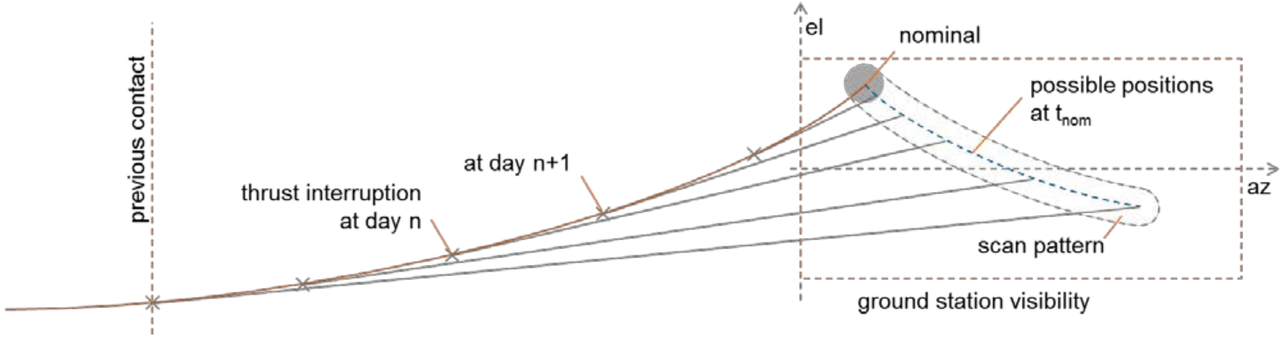
FDIR aspects

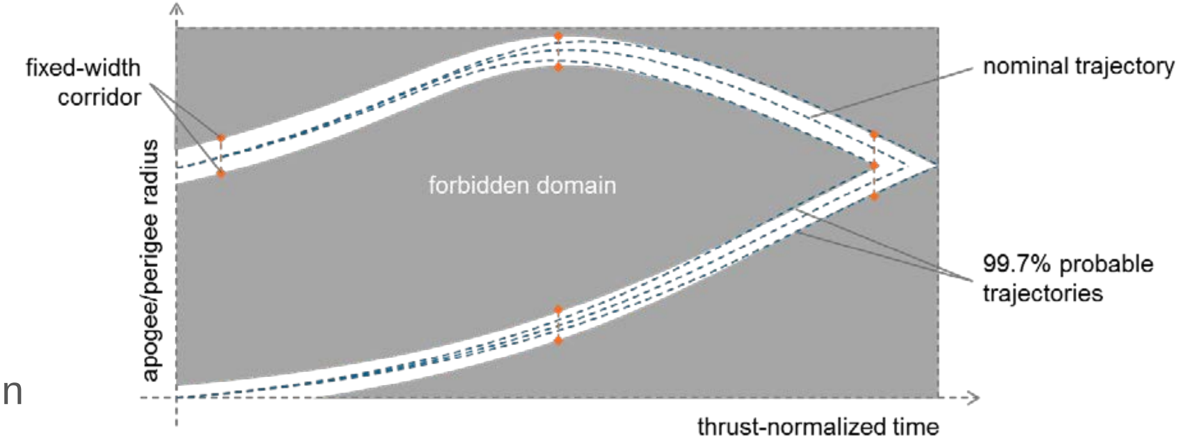
Current architecture already autonomous wrt. anomalies

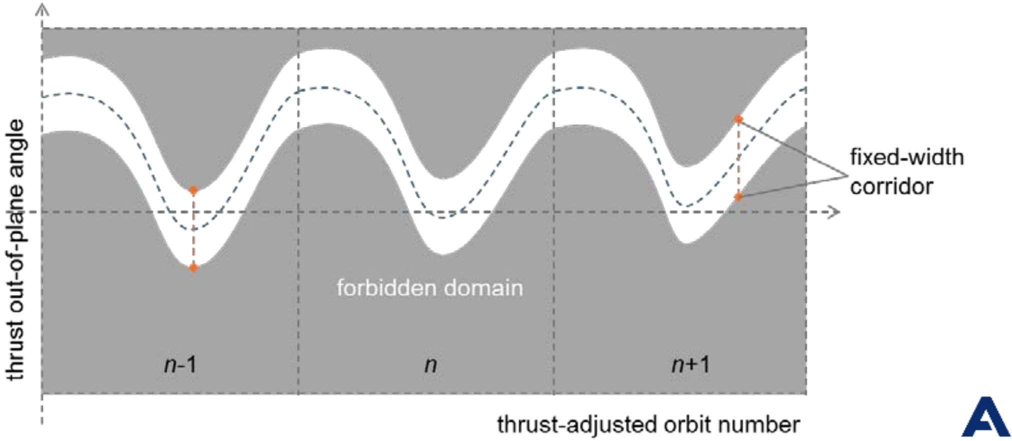
- autonomous reconfiguration / safing
- default strategy
  - interrupt thrust
  - go to safe configuration
  - wait for ground input
- 24-48h delay in EOR scenario

Specific changes introduced in suggested architecture

- Reduced frequency of ground contacts
  - antenna search patterns after 1 week of thrust interruption
  - (see top-right figure)
- Autonomous navigation
  - option: protect against corrupt navigation inputs
  - (see middle-right figure)
- Autonomous guidance
  - option: protect against corrupt guidance inputs
  - (bottom-right figure)







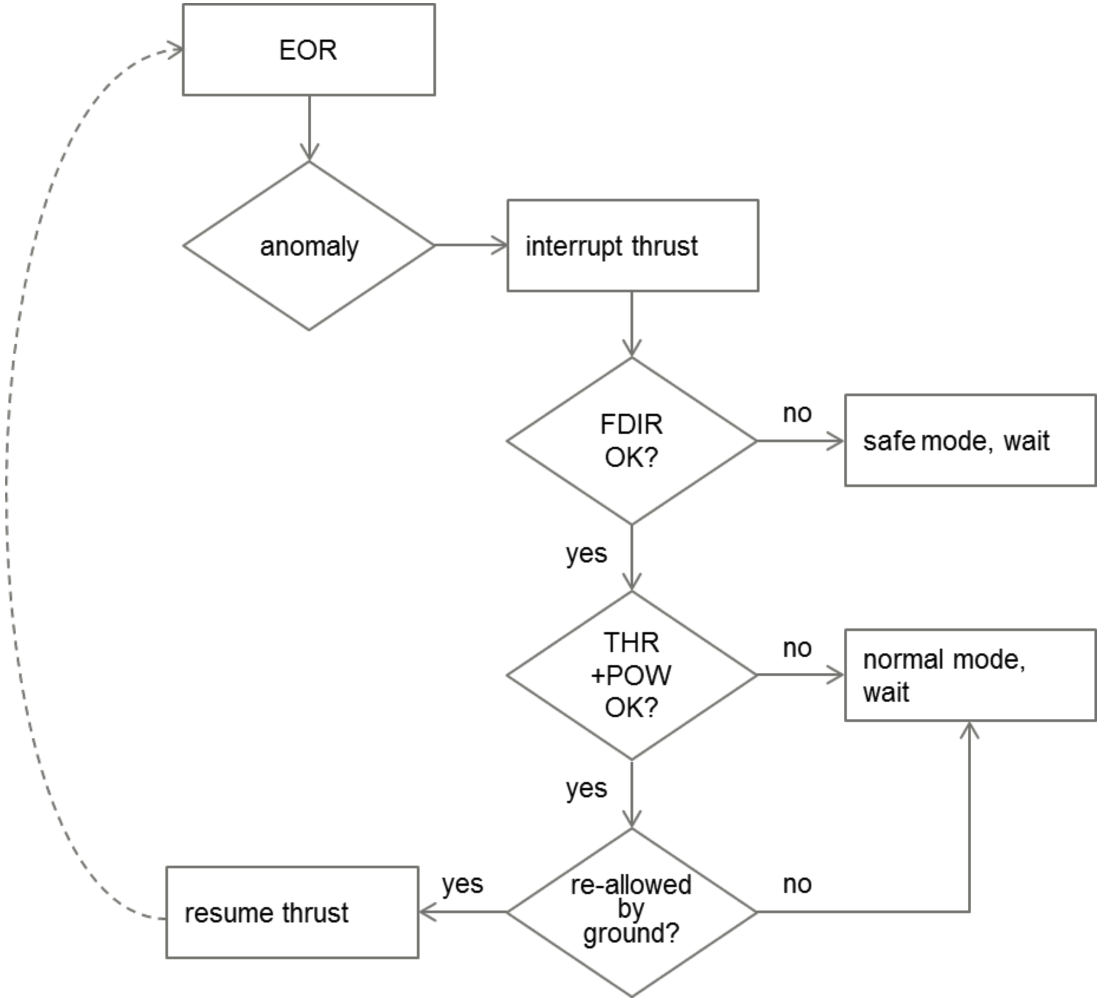
Option: autonomous resumption of thrust scenario

Objective = avoid long interruptions
- especially upon spurious anomalies
- simple and safe approach proposed

Description of the (optional) strategy
- upon anomaly, interrupt thrust
- isolate failure and reconfigure

then:
- if not back to nominal, go to safe mode and wait for ground
- if failure related to propulsion system, wait for ground
- if ground has not re-allowed autonomous thrust resumption since previous anomaly, wait for ground

- otherwise, restart thrust and resume the EOR closed-loop



Routine operations

Telemetry slots

- every 7 days, TM link is established
  - to receive satellite data (health check)
  - satellite orbit (nav check)

Ground tasks

  - general monitoring
  - thrust calibration
  - collision risk monitoring

Telecommand slots

- the autonomous guidance does not need TCs
- however, TCs required every ~28 days
  - to monitor TC link health (dead man’s switch)
  - (upload updates to guidance parameters if relevant)
    - (e.g. calibrated thrust, if significant deviation)

Contingency cases

On-board failure

- interrupt thrust if degraded configuration
- if FDIR = OK, EOR resumes autonomously (if pre-allowed)
- if satellite not found immediately, start search pattern
- on-demand TC: upload new conf. / re-arm auto-resume flag

Navigation function failure

- (self-detection by GPS or inconsistency in guidance function)
- decision = thrust interruption

Collision risk

- detected: book on-demand TMs to refresh nav information
- confirmed: on-demand TC, temporary override of guidance

TC link failure (if no TC received after 28 days)

- cut thrust to facilitate ground search if issue is nav-related
- if still no TC after P days: autonomous transfer to safe orbit
  - avoiding GEO arc if middle of transfer
  - reorbiting to graveyard orbit if end of transfer

Prototyping, performances, and results of real-time PIL tests

Autonomous guidance SW prototyped

- longitude rendez-vous (asynchronous, from time to time)
- thrust/attitude guidance computation (@each orbit)
- attitude profile unpacking (synchronous @AOCS cycle)

Performances and functional validation in MATLAB/Simulink

- sub-optimality wrt. ground optimum < 1% extra ΔV
- performances and behaviour confirmed in FAME simulator

Automatic code generation => real-time SW prototype

- following standard AOCS/SW practices

PIL testing on LEON3 board (50 MHz)

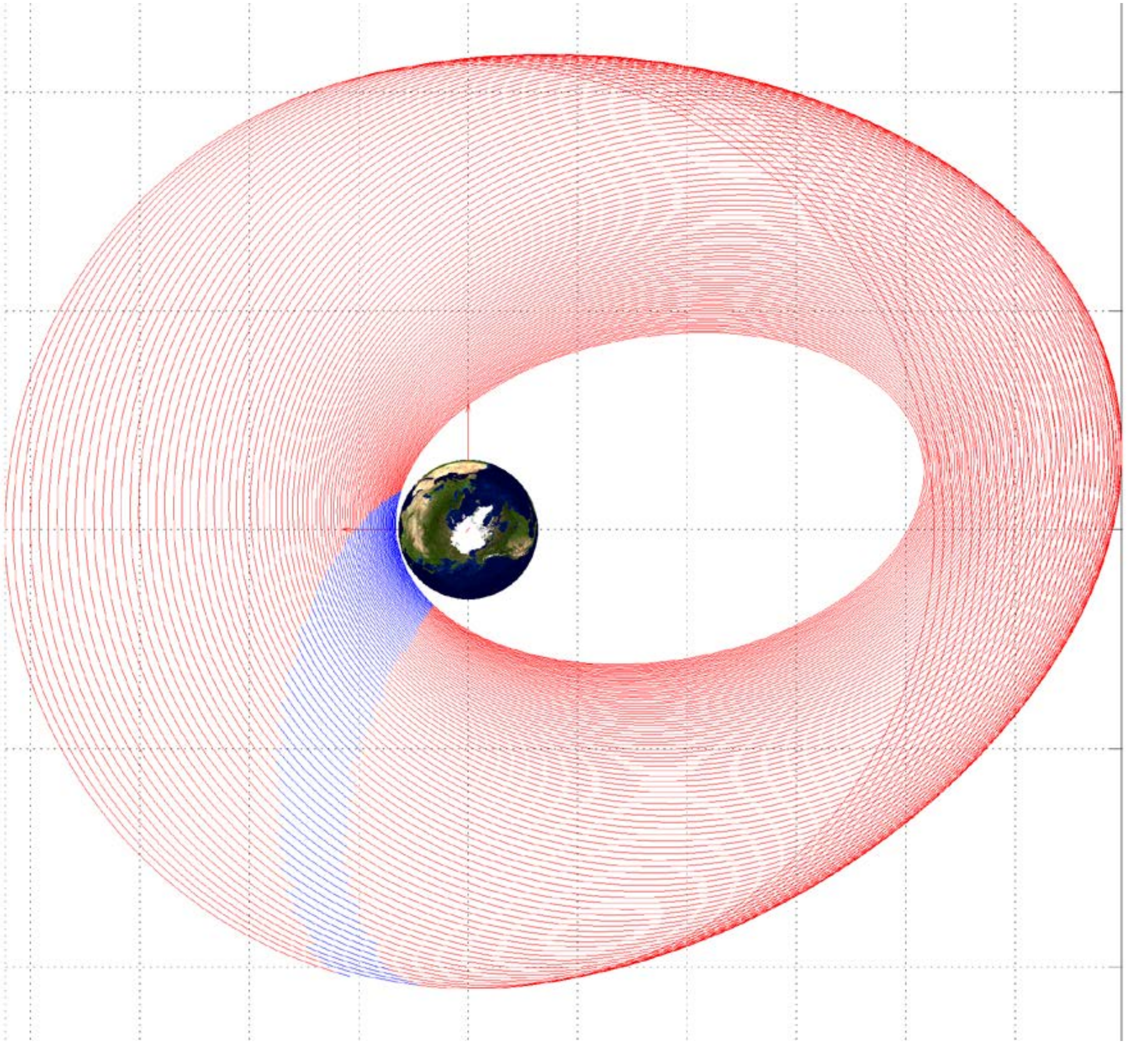
- measurement of worst-case execution times (WCET)
- alls functions tested on sizing case (early transfer)
- new cyclic task compared to current NEOSAT task

	longitude	**guidance**	**unpack (new – current)**
WCET (measured)	300 s	800 ms	110–100 = 10 µs
Time allocated to task	1 orbit	5 minutes	100 ms
relative overhead	0,7%	0,25%	<0.01%

Conclusions

Compatibility with on-board implementation is confirmed

- Fully autonomous EOR solution
- Ready for adoption by future missions
- Compatible with GEO as well as LEO cases



Thank you