DEFENCE AND SPACE

Aeolus Assisted Reentry

From early concept to consolidated design

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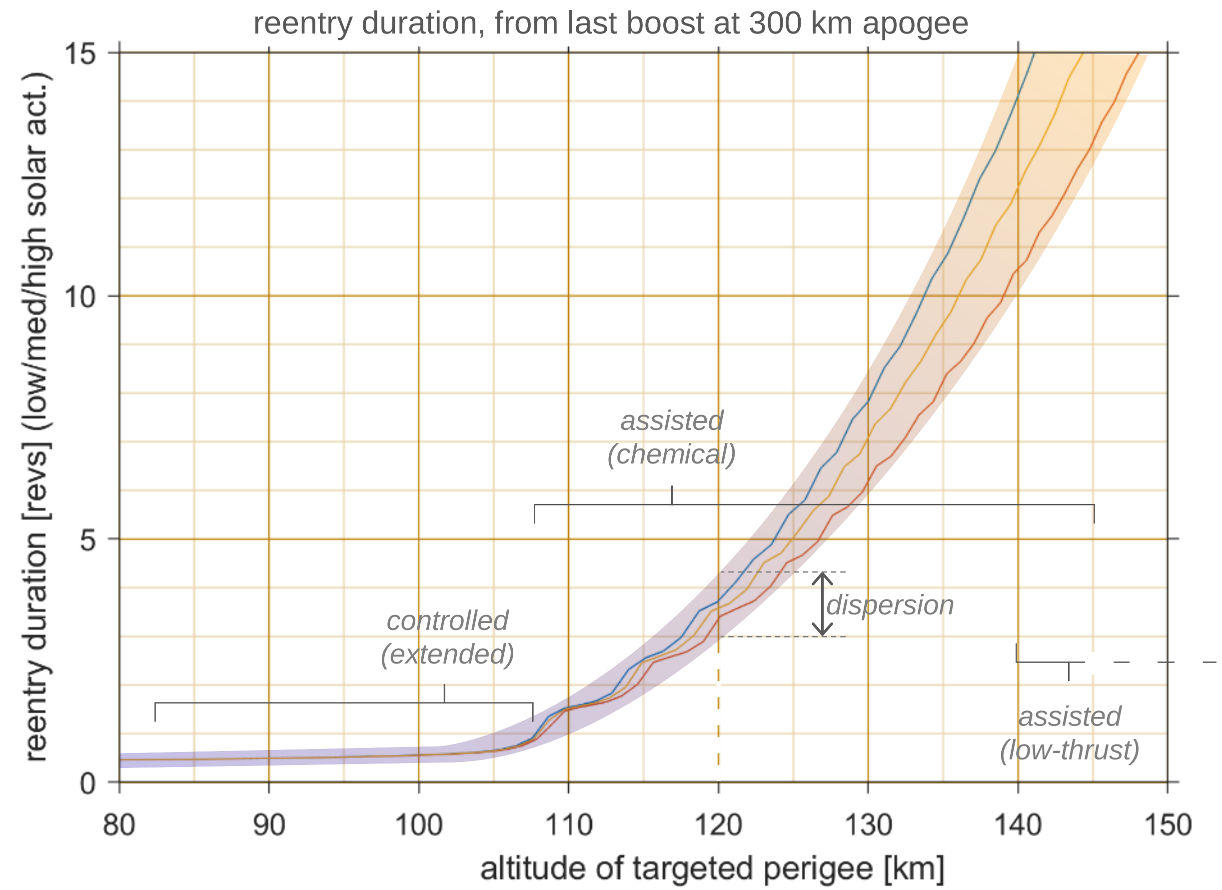
Rationale: why an assisted reentry option for Aeolus?

- **Controlled reentry not mandatory for Aeolus**
  - (Satellite design predates entry into force of regulation)
  - But expected risk slightly above regulatory limit if uncontrolled

- **Aeolus thrust capacity insufficient for controlled reentry**
  - need to lower perigee by >160 km in one boost
  - whereas Aeolus could do only 35 km (4x5N thrusters, 1.1 tons)

- **Alternative = assisted reentry**
  - prepare orbital phasing wrt. the Earth's rotation
  - lower perigee to 150 km
  - large last burn drops perigee to 120 km
  - then the satellite is left uncontrolled
  - reentry occurs after ~2.5 revolutions
  - short enough to limit dispersion < 0.5 revs
    - potential reentry locations confined to oceans



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- Aerodynamic modelling / equilibrium attitude
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- Uncertainty budgets and preliminary performance predictions
- Detailed simulation and statistical performance campaigns

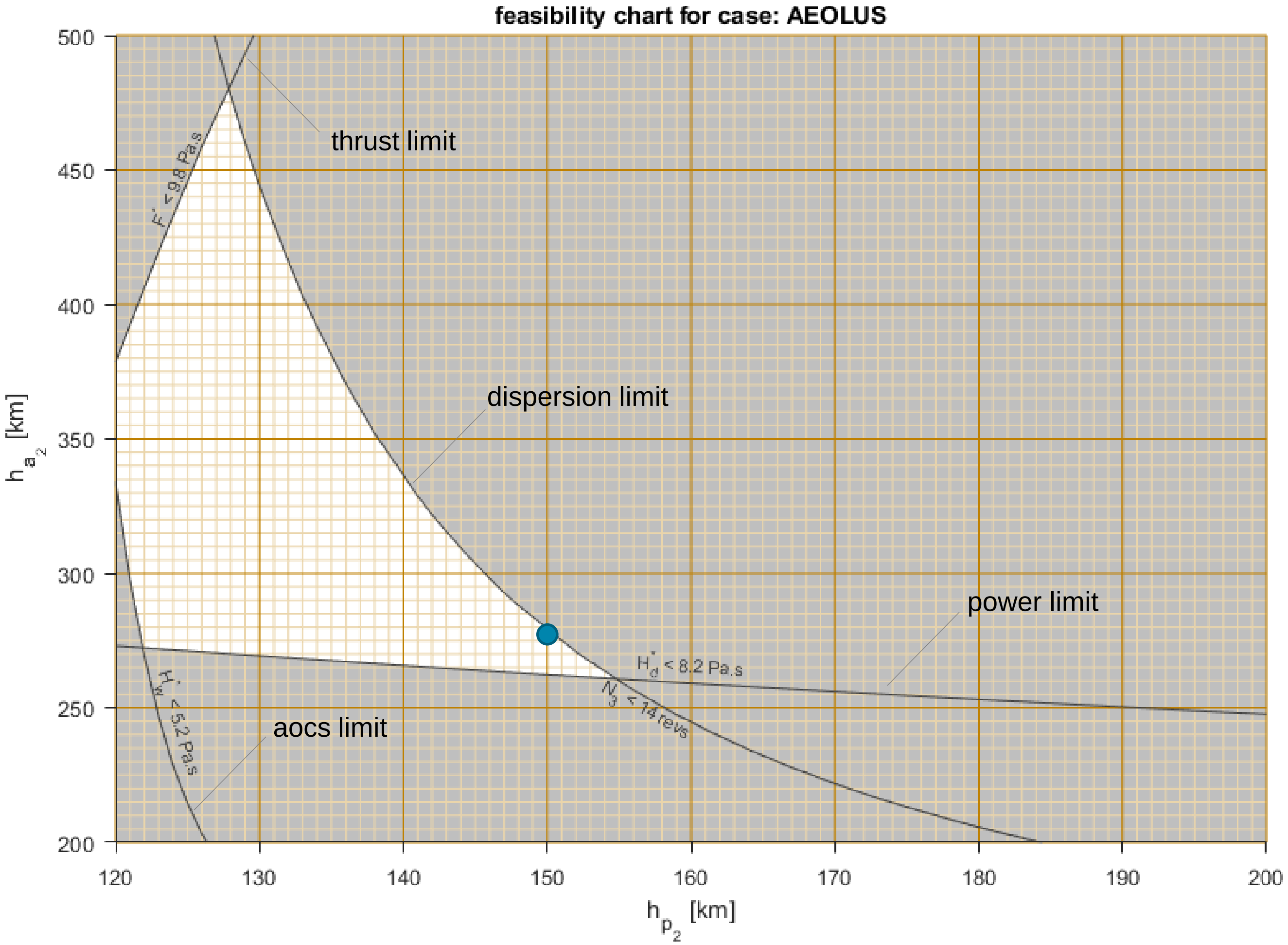
JUN 2021	First analyses
DEC 2022	Final report
FEB 2023	GO decision by ESA
MAR 2023	Earliest reentry date
JUL 2023	Actual reentry date

Early feasibility assessment

- Preliminary feasibility
  - Tool from our 2017 R&D for ESA
  - Analytical + tabulations
  - Assesses the constraints in terms of last controlled orbit (h_a, h_p at last boost)

- Results appeared promising
  - Pending confirmation of aerodynamics
  - Target for last controlled orbit ~280x150

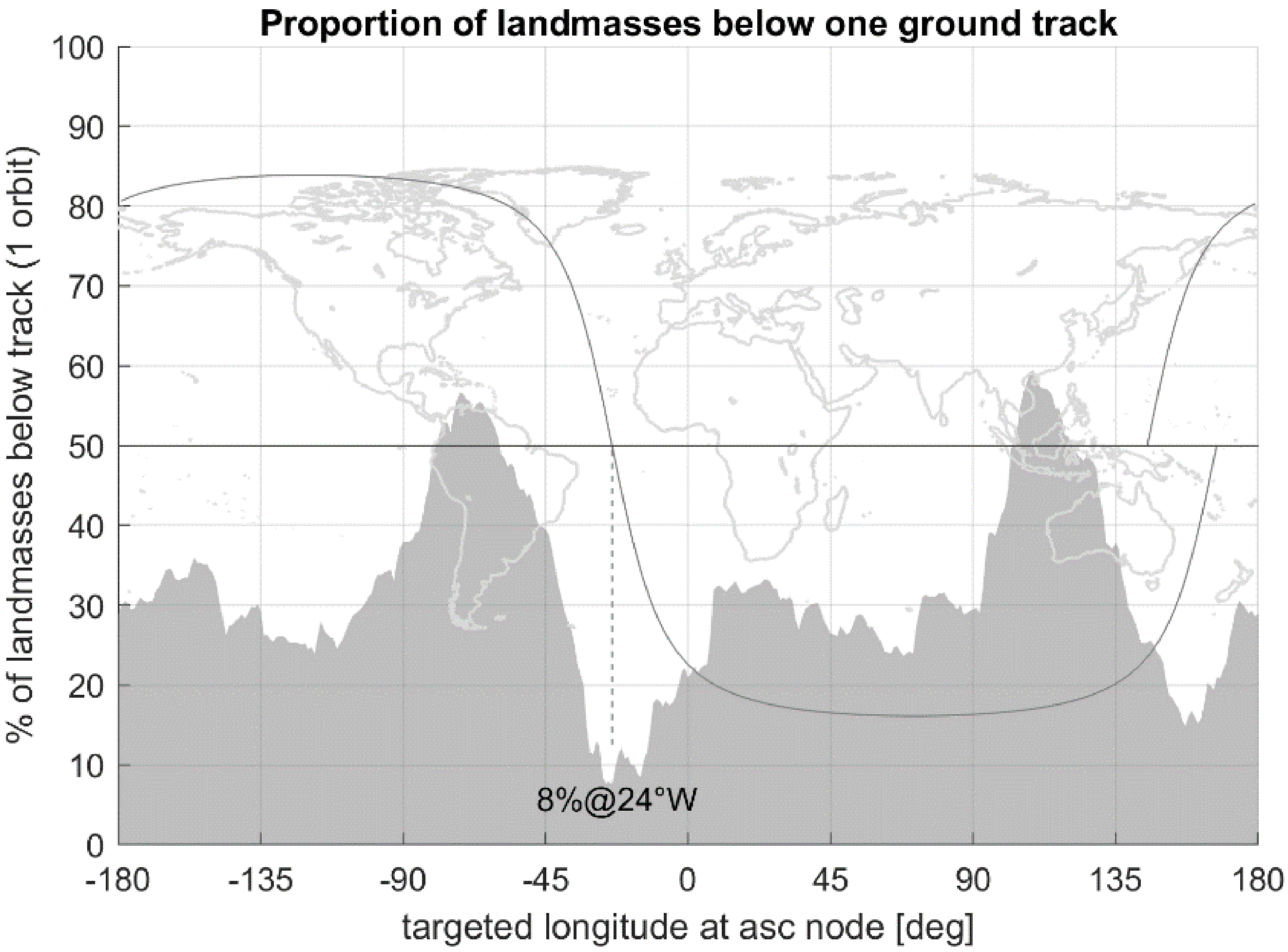
  - Then last boost will lower first uncontrolled perigee to 120 km
  - Resulting in very short uncontrolled phase
  - And narrow final dispersion



Requirements: optimum phasing

- Maximize oceans under the last few ground tracks
  - example for dispersion range = 1 revolution
    - optimum target longitude of asc. node = 24W
    - only 8% of ground track over landmasses
    - reentry will statistically occur mosly over oceans

  - substantial reduction of casualty risk

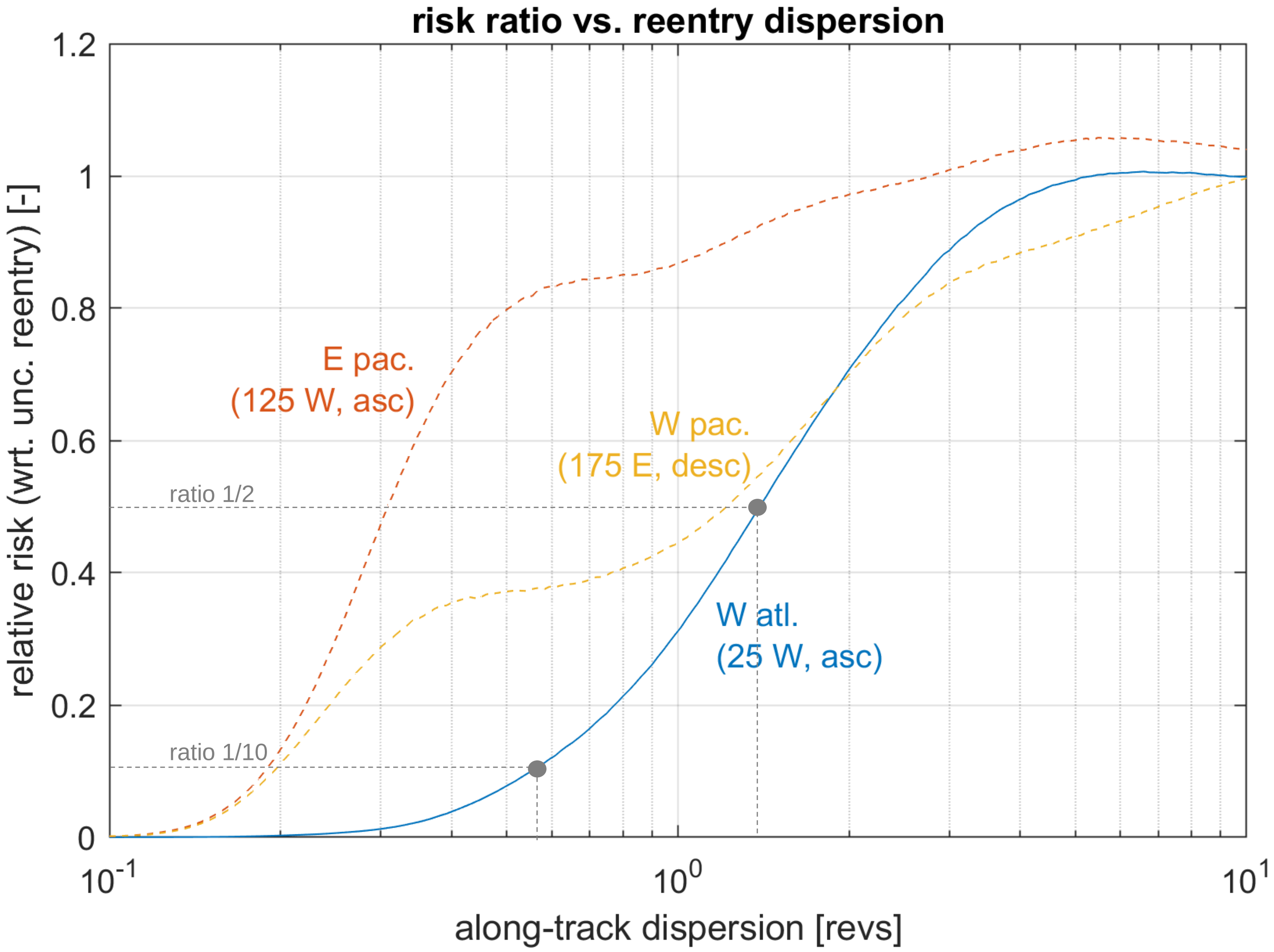


Requirements: risk vs dispersion

- What target value for dispersion?
  - In order to comply with 1/10,000 risk
    - Need to reduce risk by a factor at least 2
  - At optimum longitude
    - Dispersion 1 rev (1σ) reduces risk x2
    - Dispersion 0.5 rev (1σ) reduces risk x10

- But what if we underestimate our dispersion?
  - No increased risk wrt. uncontrolled reentry
  - Especially for Atlantic corridor
    - Monotonic evolution of risk vs dispersion, from 0 to *same-as-uncontrolled*

  - Not true of other target reentry locations
    - e.g. SPOUA



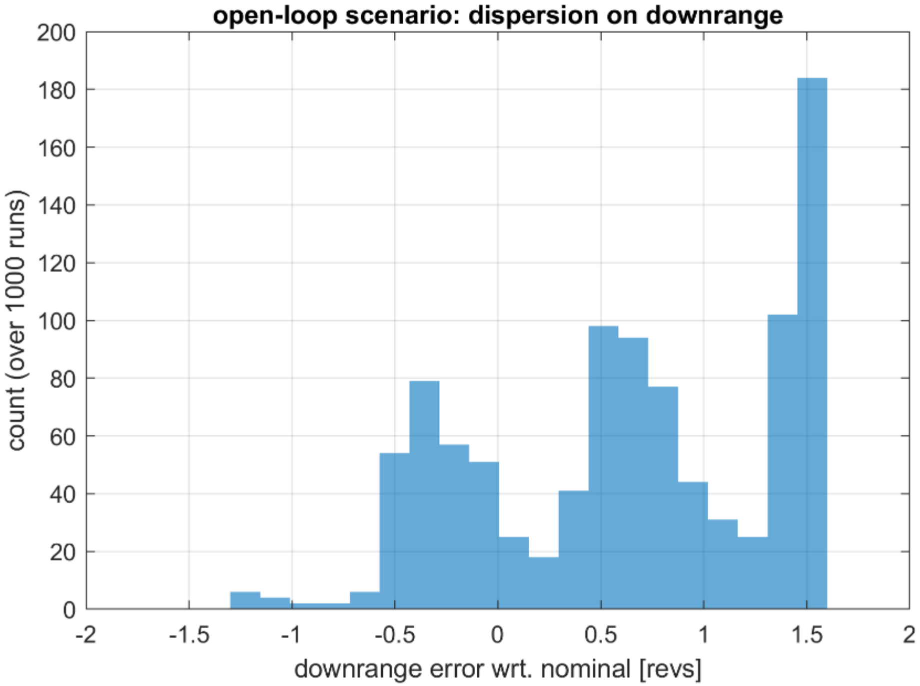
Descent control strategy

- Descent control is needed
  - (Too much final dispersion if open-loop descent)
  - It is sufficient to adjust only the last boost (by an amount dV)
    - (thanks to the large control authority)
    - To correct for aerodynamic/atmospheric errors
    - To target the nominal reentry location

- *Simplified* approach (by ADS, for performance analyses)
  - Establish 1st-order sensitivities between duration of uncontrolled phase and the major error terms (ha, dha/dt, dV)
  - This is done via simulation campaigns

  - Then, given the errors observed at last OD:
    - Determine dV correction for last manœuvre

$$\delta\Delta V = -\frac{1}{\frac{\partial N_3}{\partial \Delta V}}\left(\frac{\partial N_3}{\partial \dot{h}_a}\delta \dot{h}_a + \frac{\partial N_3}{\partial h_a}\delta h_a\right).$$



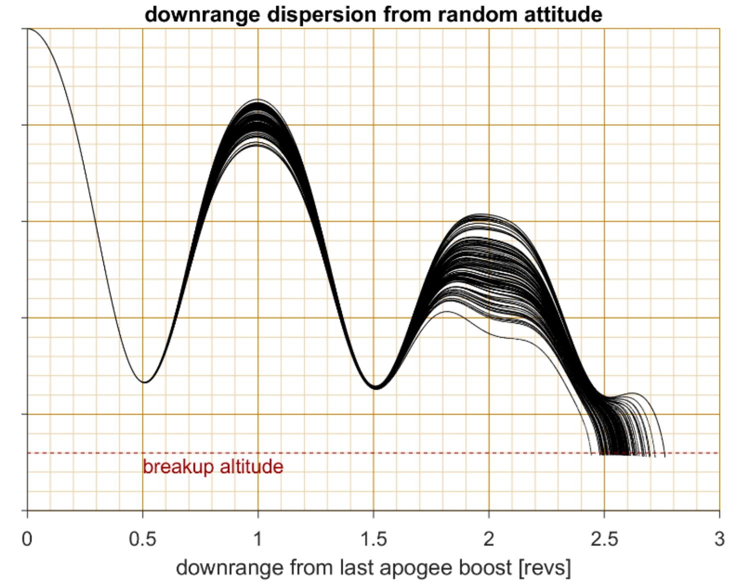
- *Optimization* approach (developed by ESOC)
  - Predict reentry location by propagating from last OD
    - Considering solar activity observations and predictions
    - Including last manoeuvre
  - Optimize dV so that prediction matches target

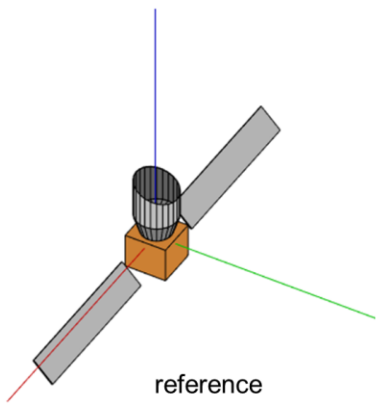
  - This is the solution that was implemented for operations

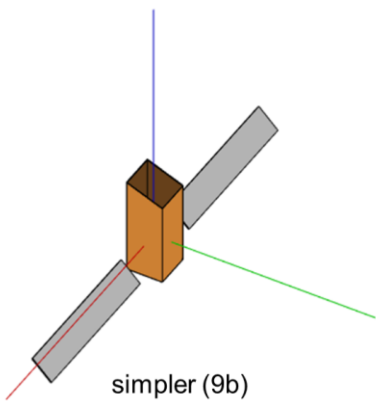
Aerodynamic modelling + 6-dof simulations

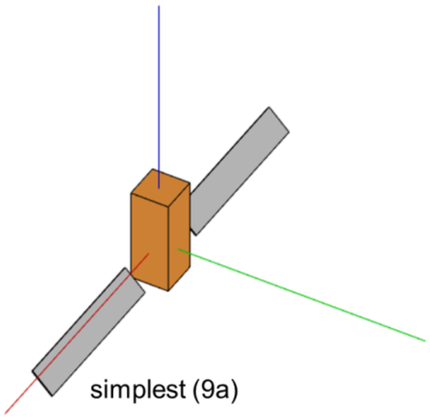
- Predicting drag is key to final accuracy
  - To propagate the descent until the reentry
  - To adjust the last manœuvre

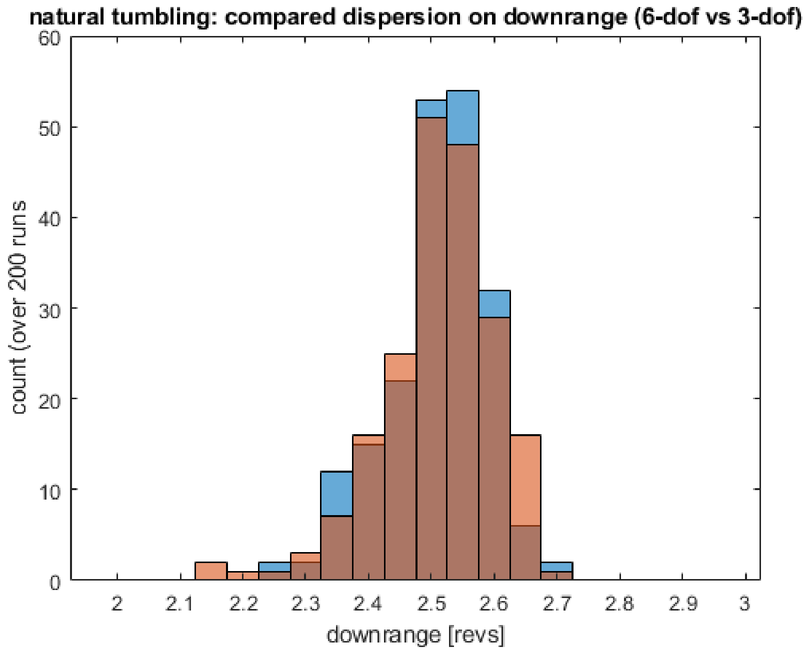
- Two main challenges
  - Aero modelling is not very accurate
    - additional in-flight calibration is possible
  - Random tumbling during uncontrolled phase
    - Average drag and dispersion assessed via 6-dof simulation




reference


simpler (9b)

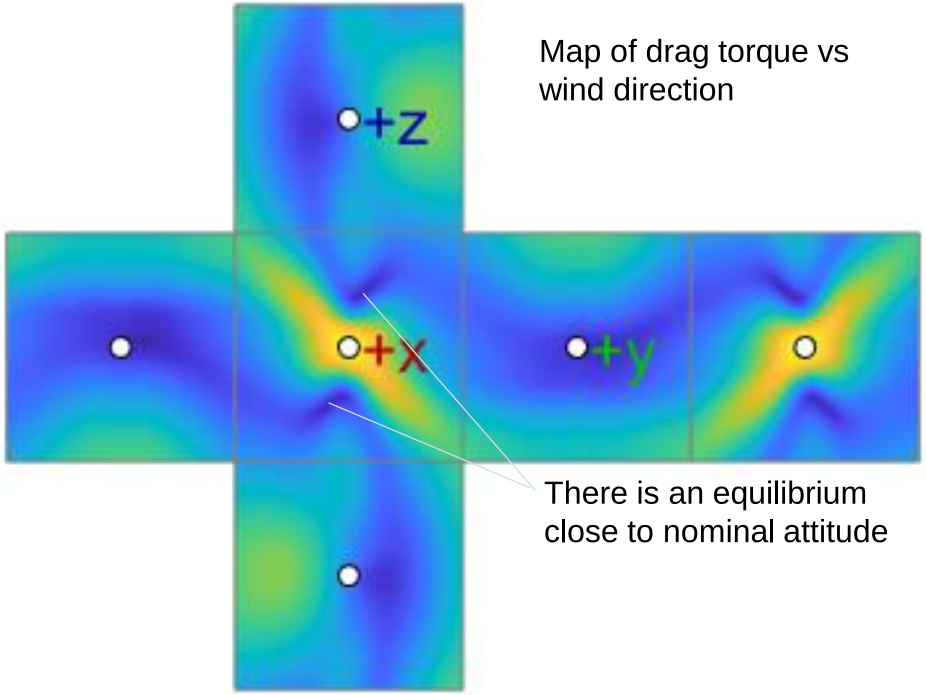

simplest (9a)



Existence and characterization of equilibrium attitude

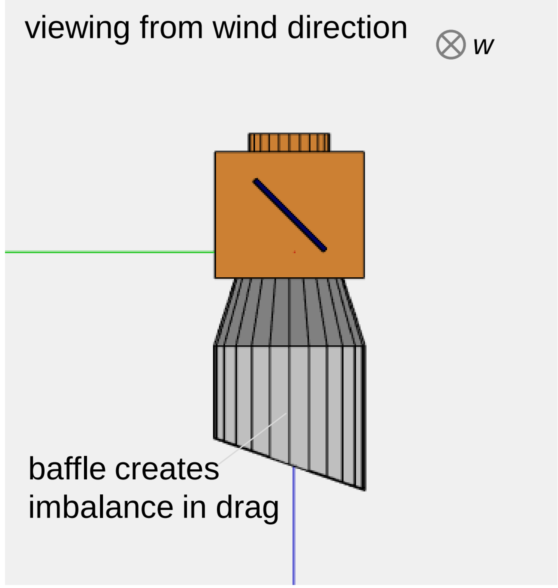
- Torque-free attitude thanks to pitch bias
  - large pitch torque from baffle in normal flight attitude
  - can be balanced by SA wing with small pitch offset
  - this is confirmed by modelling

- Confirmed in orbit during end-of-life activities (June 2023)
  - Various pitch bias values tested
  - Observation of RW momentum telemetry
  - x3 torque reduction for ~25 deg in pitch



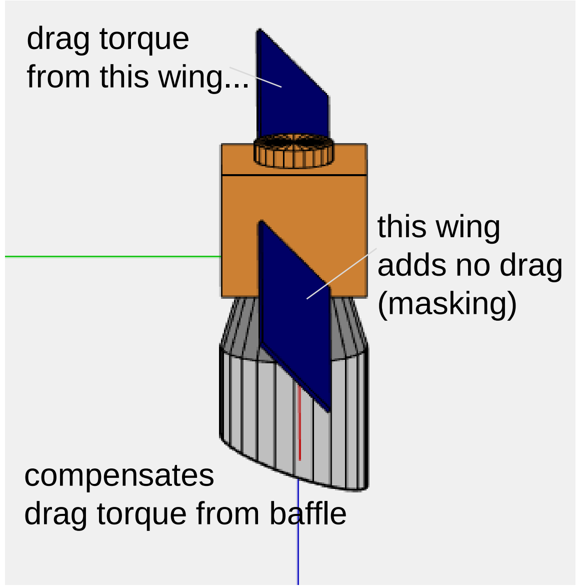
Map of drag torque vs wind direction

There is an equilibrium close to nominal attitude



viewing from wind direction

baffle creates imbalance in drag



drag torque from this wing...

this wing adds no drag (masking)

compensates drag torque from baffle

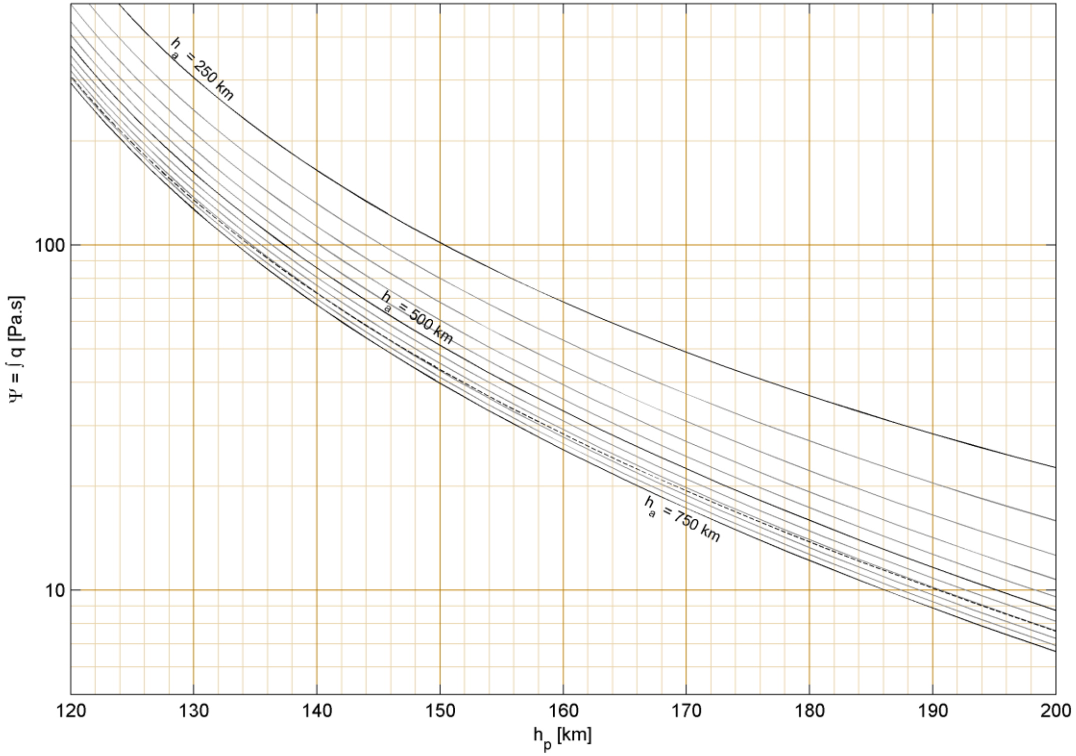
Inputs to reference scenario: apogee decay rate vs perigee altitude

(how time-constrained is the descent scenario?)

- Assess daily apogee decay rate
  - Determine cumulated dynamic pressure from chart
  - Deduce apogee drop at each perigee pass

$$\Delta h_a \approx \frac{4\Psi}{\omega_0 B}$$

Perigee altitude	200 km	186 km	174 km	164 km	154 km
Cumulated Dyn. Pressure	16	23	32	45	64
Apogee drop each orbit	600 m	900 m	1200 m	1700 m	2400 m
Daily apogee decay	10 km	14 km	20 km	28 km	40 km
(figures provided for h_a = 300 km / add 25% for h_a = 250 km) Ballistic coefficient for wind near y axis: B ~ 90 kg/m²					

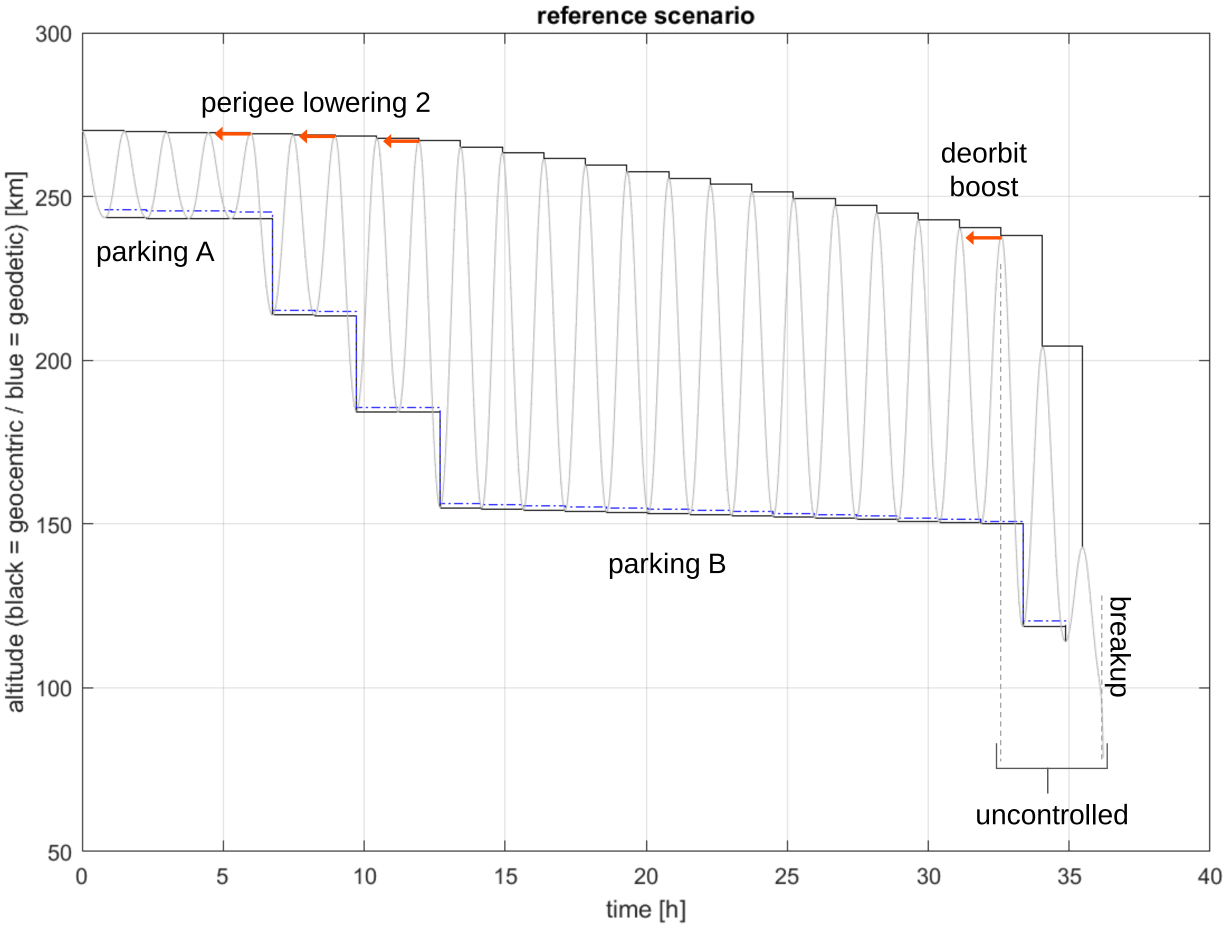


- Descent scenario is quite time-constrained
  - Need to avoid premature circularisation

Reference descent scenario (from ESOC)

Phase or event	h_a [km]	h_p [km]	Details	Lasts	Start time
Initial orbit	270	270	At end of decay		
Perigee lowering 1	270	270 → 250	arg. of perigee ~ +6 deg		T – 32 – TBD h
Parking A	270	250		TBD hours	T – 32 – TBD h
Perigee lowering 2	270	250 → 155	3 apo. boosts, ~ 27 m/s total	6 orbits	T – 32 h
Parking B	270 → 250	155 → 150	For last orbit determination	20 hours*	T – 24 h
Deorbit boost	250	150 → 120	~ 9 m/s + correction	30 min	T – 4 h
Uncontrolled phase	250 → 80	120 → 80	Uncontrolled, tumbling	2.5 revs	T – 3.5 h
Breakup	80	80	At ascending node		T

* 12 hrs in later definition



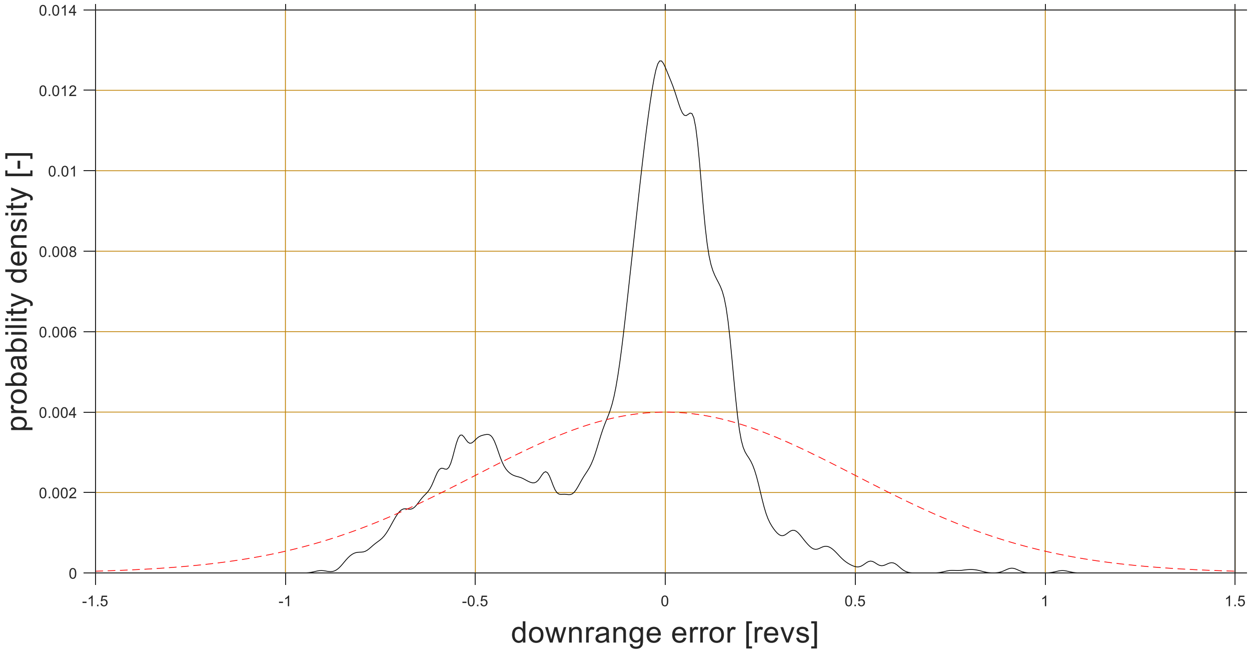
Uncertainty contributors and preliminary performance budget

Parameter (U/V)	Cause	Model	Contrib. 1σ
Atmospheric density variations (V)	Changes in solar activity	Historical solar activity records (10% 3σ 5-day variability @120km)	~ 0.05 rev
Atmospheric model uncertainty (U)	Inaccuracy of model used for the reference scenario	Gaussian, 0-mean, 3σ = 20%, i.e. σ = 6.7%	~ 0.10 rev
AOCS thruster activity (U)	Uncertainty on drag torque prediction, from aerodynamic model errors	Covered by atmospheric model uncertainty, and irrelevant after last boost	
Aerodynamic model uncertainty (U)	Uncertainty on the aerodynamic model used for reference scenario	Considered covered by uncertainty in atmosphere model	
Ballistic coefficient variability (V)	Natural tumbling causes the attitude to vary ~randomly	Gaussian, mean = 43 kg/m², σ = 2.7 kg/m² (i.e. 6.3% 1σ)	~ 0.09 rev
Thrust realization errors (U)	Uncertainty in the propulsion system for a long boost in EOL conditions	Gaussian, 0-mean, 3σ = 15%, i.e. σ = 0.05×8 m/s = 0.4 m/s	~ 0.24 rev
Navigation errors (U)	Errors in the last orbit determination, especially on apogee decay rate	Gaussian, 0-mean, σ = 100 m/rev	~ 0.13
		TOTAL (RMS)	~ 0.31 rev
		REQUIREMENT (RMS)	1 rev

Detailed performance campaigns: statistical results

- Dispersion of reentry locations
  - 68% of samples within 0.23 revolutions of target
  - (99.7% of samples within 0.84 revs. of target)
  - requirement: 1-sigma < 0.5 revolution
    - for reducing risk by a factor > 10

- Global casualty risk over 2000 cases
  - 4×10^{-6}
  - considering a casualty area of 15 m²
    - (source = HTG)



We can reduce the casualty risk for Aeolus by a factor >20 compared to uncontrolled reentry (Despite conservative assumptions and a simple control strategy)

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Take-away messages for Aeolus

- Feasibility and performance demonstrated
- Key design elements and drivers documented
- Allowing ESOC to develop own detailed implementation
- Very fruitful teamwork atmosphere & organisation

Broader perspectives

- Practicality of Assisted Reentry techniques
  - fill the continuum between controlled and uncontrolled
  - more design flexibility to comply with safety regulations

- Potential avenues for implementation
  - for medium-size satellites
    - that are marginally non-compliant with the 10^{-4} limit
    - especially all-electrical platforms
      - (avoids adding chemical propulsion)

  - for mission extension
    - (switching from controlled to assisted can save > 30 m/s)

  - for retrofitting currently flying satellites, best-effort basis
    - e.g. applicable to Aeolus (with simplifications)

Thank you