End of Life Operations for Disposal of MegaConstellations

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Background

Recent mega-constellation concepts share critical issues w.r.t. their possible impact on the space debris environment, e.g.:

- **Large number of S/C** (significant combined mass) **deployed to high altitudes** (atmospheric decay very limited), collisions or self-induced fragmentation will lead to long-lived debris.
- **Mostly polar inclinations** where even under nominal conditions satellites of adjacent orbit planes might come as close as few tens or hundreds of kilometres.
- Large number of spacecraft, combined with **typical reliability figures → unneglectable number of S/C which fail** to reach their planned lifetime.
- **During orbit raising and orbit lowering the spacecraft traverse different orbital regimes** - in some cases a large number of satellites at a time

In order to cope with these issues **new technologies as well as new manufacturing, testing, and operational procedures need to be developed.**

Scope and Objective of Study SOW

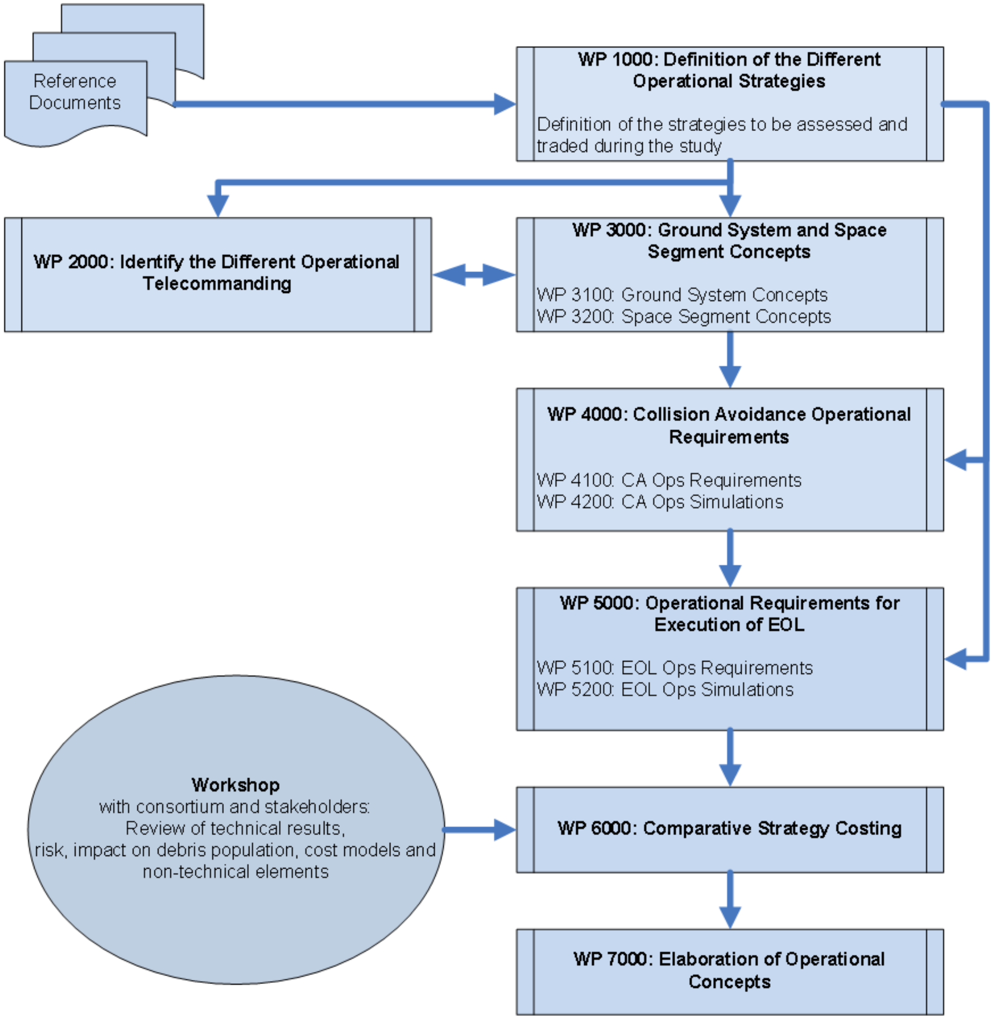
GSP funded study into the End of Life operations for disposal of Mega-Constellations.

The objective of this activity is to understand the operational complexity of large mega-constellation systems, and the potential needs to operate these, including the complexity of the collision avoidance manoeuvres (CAMS). This can be achieved by:

- **Assessing different EoL strategies** for mega-constellations of the size and complexity as foreseen for the future telecommunication mega-constellations..
- **Analysing the implications on space and ground segment design** to support execution of End of Life activities for each of the strategies identified (from the previous bullet) comparing the different ground and spacecraft conceptual architectures.
- **Analyse the execution of both debris and inter-satellite CAMs** during LEOP, orbit raising, routine phases and orbit lowering for mega-constellations.
- **Derive system and operational requirements on mega-constellations for End of Life activities** (EoL) and Space Debris mitigation.
- **Establish a baseline scenario for an operational concept** to handle Space Debris Mitigation for mega-constellations.

Structure of the Study

- ✓ Definition of the Different Operational Strategies.
- ✓ Identify the Different Operational Telecommanding.
- ✓ Ground System and Space Segment Concepts.
- ✓ Collision Avoidance Operational Requirements.
- ✓ Operational Requirements for Execution of EoL.
- ✓ Comparative Strategy Costing.
- ✓ Elaboration of Operational Concepts.



Reference Documents

WP 1000: Definition of the Different Operational Strategies

Definition of the strategies to be assessed and traded during the study

WP 2000: Identify the Different Operational Telecommanding

WP 3000: Ground System and Space Segment Concepts

WP 3100: Ground System Concepts
WP 3200: Space Segment Concepts

WP 4000: Collision Avoidance Operational Requirements

WP 4100: CA Ops Requirements
WP 4200: CA Ops Simulations

WP 5000: Operational Requirements for Execution of EOL

WP 5100: EOL Ops Requirements
WP 5200: EOL Ops Simulations

Workshop
with consortium and stakeholders:
Review of technical results,
risk, impact on debris population, cost models and non-technical elements

WP 6000: Comparative Strategy Costing

WP 7000: Elaboration of Operational Concepts

WP1000 Definition of Different Operational Strategies - Overview

Step 1
- Constellation configuration definition and trade

Step 2
- Exploration of relevant parameters for strategies elaboration

Step 3
- Assessment, trade and down selection of parameters

Step 4
- Preliminary strategies and scenarios elaboration

Step 5
- Metrics definition for short list selection and MEGACO study

Step 6
- Scenarios short list elaboration for MEGACO study

Definition of Different Operational Strategies.

Altitude separation vs Walker "star" configuration

Altitude separation option provides significant improvement of safety distances between satellites versus moderate mission impacts

Especially compared to a conventional circular tiling configuration

⇒ Trade done by mega constellation operators: Reduction of complexity of operations/collision risks (and associated impact on business) vs moderate Capitol Expenditure penalty.

=> Altitude separation option is selected for MEGACO study.

System and operator profiles

Profile 1:

A high end system, operated by a major “established” telecom operator, supported by a major space agency and governmental organization, taking full benefit of the most advanced available space technologies

Profile 2:

A low cost and low quality of service (low end), developed in a low cost of operations and access to space country, with medium to low sensitivity to space debris issues

Profile 3:

A medium to high quality of service, based on “more than proven” technologies, developed in an “easy” access to space country

Profile 4:

A very high quality of service system, also operated by an established telecom operator, developed according to a comprehensive approach for new technologies implementation on each successive satellite generation

Profile 5:

A high quality of service system developed by a powerful “new space /GAFA like ” actor, implementing as much as possible advanced technologies and innovative concepts

Profile 6:

A medium quality of service system, with “medium” attributes for all dominant profile characteristics

Definition of Different Operational Strategies.

Summary of the 6 profiles characteristics:

Operator & program "profiles"	**1**	**2**	**3**	**4**	**5**	**6**
Quality of Service	Very High	Low	Medium to High	Very High	High	Medium to High
Satellites capacity & oversizing	Very High	Low	Low	Very High	Medium	Medium
Technological maturity	Very High	Very Low	Low	Very High	Very High	Medium
Techno risks aversity	Low	High	High	Progressive approach	Very Low	Medium
Cost of access to space	High	Low	Low	High	High	Medium
Cost of system operators	Very High	Very Low	Moderate	Very High	High	Medium
Sensitivity to debris matters	Very High	Low	Low	Very High	High	Moderate

Definition of Different Operational Strategies.

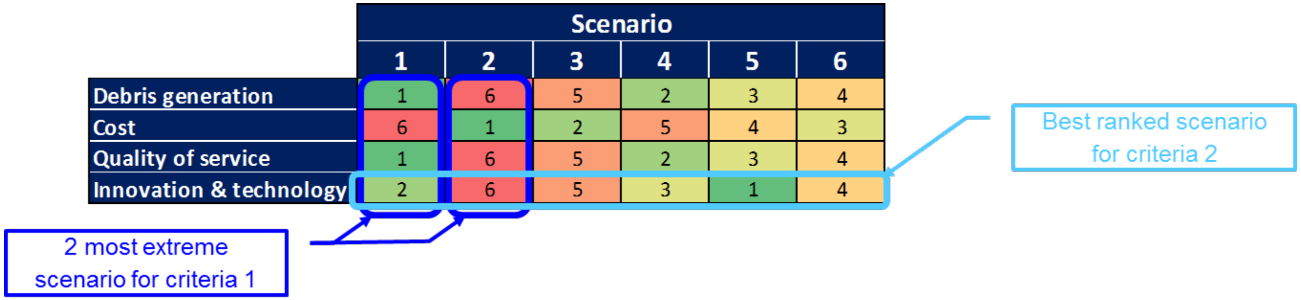
Salient points of the different profiles

= major technical decisions made for each scenario in accordance with each system/operator profile.

Major features	1	2	3	4	5	6
Propulsion	Electrical with advanced options	Electrical "basic"	Chemical	Electrical with progressive options	Electrical "basic"	Electrical "basic"
Nominal Post Mission Disposal (PMD) Reliability	Very high 95%+	Medium 85%	High 90%+	Very high 95%+	High to very high 90%+	High 90%+
Accepted Collision Probability Level (ACPL)	10-4 to 10-5	10-3	10-3	10-4 to 10-5	10-4	10-3 to 10-4
Re entry orbit after PMD	Fast re-entry (0.5 yrs)	Long re-entry (25 yrs)	Fast re-entry (0.5 yrs)	Fast re-entry (0.5 yrs)	Fast re-entry (0.5 yrs)	Fast re-entry (0.5 yrs)
Injection orbit	Low altitude transfer orbit	Direct injection	Direct injection	Low altitude transfer orbit	Low altitude transfer orbit	Direct injection
Spare satellites management philosophy	0 spare (oversized) + on ground spares	In plane + under plane (close) spares	Under plane (close) spares	0 spare (oversized) + under plane (close) spares	In plane spares	In plane + under plane (close) spares
Additional PMD means	Degraded propulsion advanced modes	*Nothing*	*Nothing*	Degraded propulsion mode + space tug	Degraded propulsion mode + shepherd	De orbit kit
Conjunction Assessment (CA) means	Extra tracking + fencing facilities	CDM analysis	CDM analysis	Progressive: CDM only -> Tracking means -> Fencing means	Extra tracking facilities	CDM analysis
Autonomy	Advanced	*No autonomy*	Ground Segment automation	Progressive: GS automation -> Improved -> Advanced	Advanced	Ground Segment automation
Inter Satellite Links (ISL) & Ground Stations (GS)	Endogenous ISL + polar station	*No ISL* GateWay stations	*No ISL* polar station	Progressive: GS only -> Endogenous ISL	Endogenous ISL + polar station	GEO ISL + polar station

Scenarios short list down selection.

The ranking according to metrics defined for scenario assessment is summarized in following table:



	Scenario					
	1	2	3	4	5	6
Debris generation	1	6	5	2	3	4
Cost	6	1	2	5	4	3
Quality of service	1	6	5	2	3	4
Innovation & technology	2	6	5	3	1	4

Best ranked scenario for criteria 2

2 most extreme scenario for criteria 1

Criteria for short list selection:

- ➢ **Criteria 1. Sensitivity** : select the **2** “extreme” scenarios in terms of ranking according to the above metrics

⇒ **Scenarios selected according to criteria 1 are scenario 1 and scenario 3 (Scenario 2 is considered non realistic in the scope of this study).**

- ➢ **Criteria 2. Technology & innovation : s**elect the most “innovative” approach as the 3rd short listed scenario

⇒ **Scenario selected according to criteria 2 is scenario 5.**

Short list summary and definition of reference parameters.

- ✓ **Scenario 1**: The high end system, operated by a major “established” telecom operator, supported by a major space agency and governmental organization, taking full benefit of the most advanced available space technologies.
- ✓ **Scenario 3**: The system based on “more than proven” technologies (e.g. chemical propulsion) and robust concepts, developed in an “eased” access to space environment.
- ✓ **Scenario 5**: The system developed by a powerful “new space /GAFA like” actor, implementing as much as possible advanced technologies and innovative concepts.

WP2000 Identify different operational commanding.

Study logic used for WP2000

Assess impact of autonomy and large constellations on ground segment design (through the needed TM and TC).

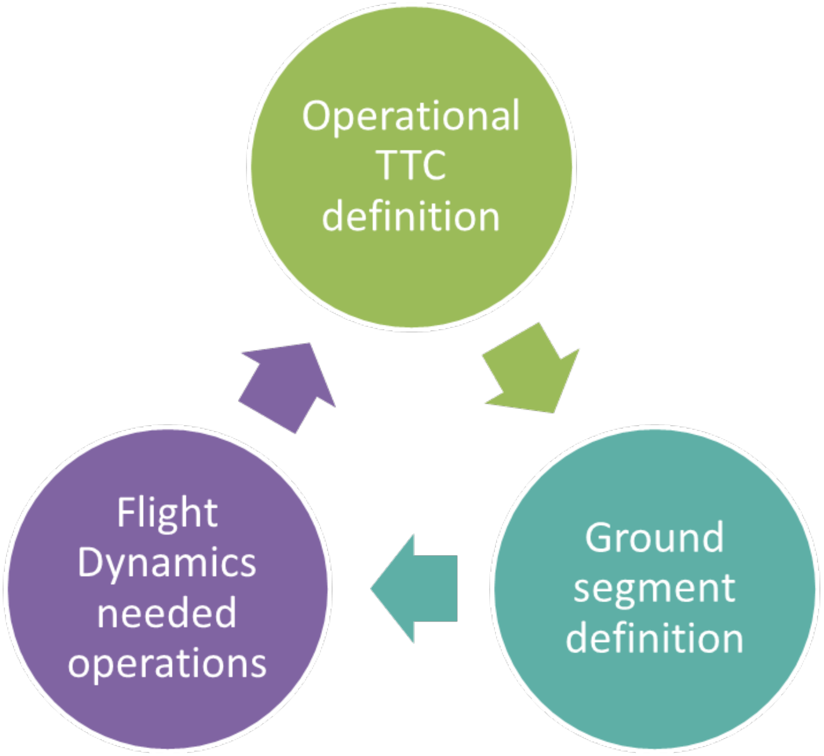
Reference scenarios

- Gather needed commands and telemetry
- Gather mission phases and needs

Airbus Background

- Define typical TC and TM to meet scenarios TTC needs
- Derive typical volume to TC and TM

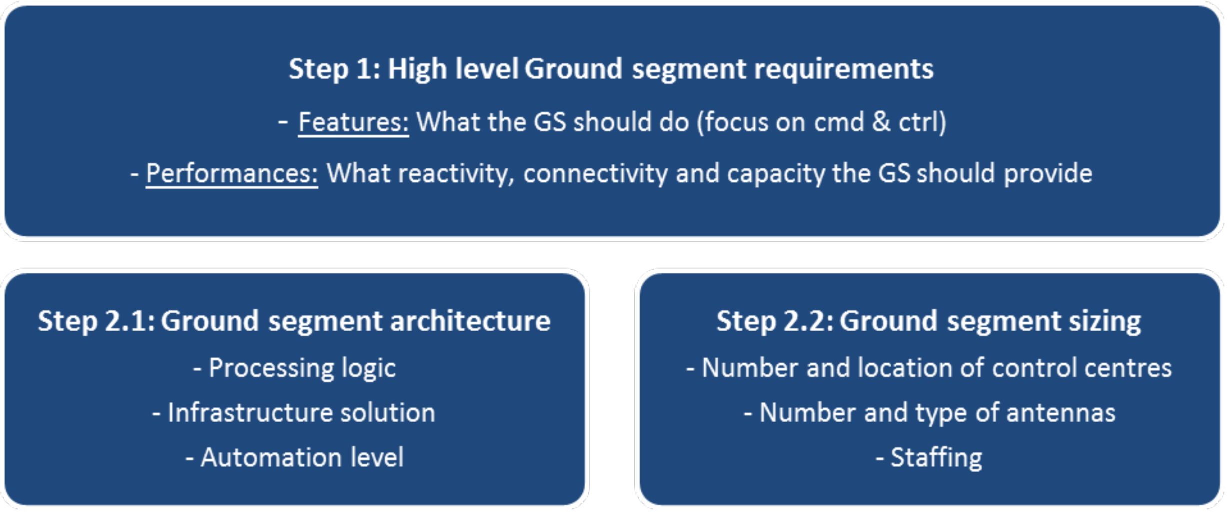
- Provide TC and TM par phase to WP3100
- Iterate with WP3000 & WP4100 (FDS)



Needed iterations between Ground segment design, Flight Dynamics (operations) needs and Operational TTC to assess benefit of autonomy & automation.

WP3000 : Ground system and Space segment concepts.

Study logic used for WP3100



Step 1: High level Ground segment requirements

- Features: What the GS should do (focus on cmd & ctrl)
- Performances: What reactivity, connectivity and capacity the GS should provide

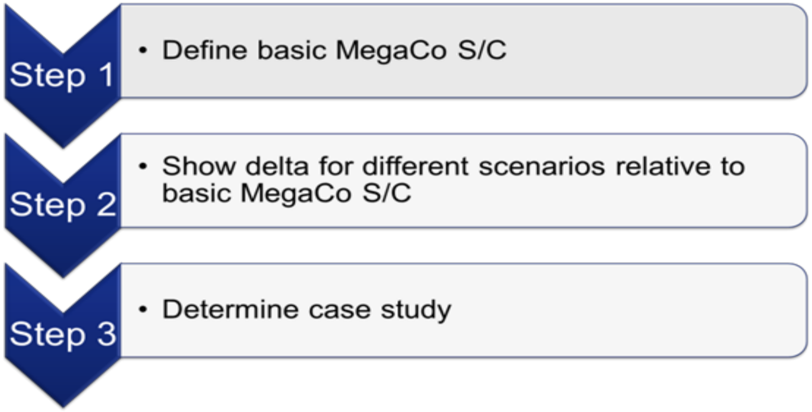
Step 2.1: Ground segment architecture

- Processing logic
- Infrastructure solution
- Automation level

Step 2.2: Ground segment sizing

- Number and location of control centres
- Number and type of antennas
- Staffing

Study logic used for WP3200



Step 1
- Define basic MegaCo S/C

Step 2
- Show delta for different scenarios relative to basic MegaCo S/C

Step 3
- Determine case study

WP3100 : Ground segment concepts.

Conclusions

Impact of ISL

- Simpler TC distribution with less antennas during mission. ☺
- Still need for direct links during orbit transfers (most demanding phase with current strategies). ☹

NB: Need for management and monitoring of ISL network at GSegment level.

Impact of automation

- Significant reduction of operators. ☺

Impact of electrical propulsion

- Lead to very long orbit transfers with complex management of collision risk.
- Current strategy implies many antennas and operators during such phases. ☹

Other parameters

- Need for a cost model before impact assessment (WP6000)

Huge number of antennas and staffing required for orbit transfer in scenarios 1 & 5.

=> **Need for mitigation solutions.**

WP3200 : Space segment concepts.

Determine Space Segment Case Study

1. PMD is the major driver for the satellite mass and thus the satellite costs.
2. Autonomy aspects (e.g. enhanced intelligence of on-board computing capabilities) are major driver for operational costs.

Scenario 5 : Proposed as case study for EOL analysis:

- Low mass due to the decrease of power demand with a less demanding HET.
- re-morphing of orbit + increase of P/L power to close the gap in case a satellite fails.
- P/L and prop. system do not work in parallel .
- Prop. system does not work during eclipse.
- BUT: additional satellites needed as PMD back-up strategy (shepherd).

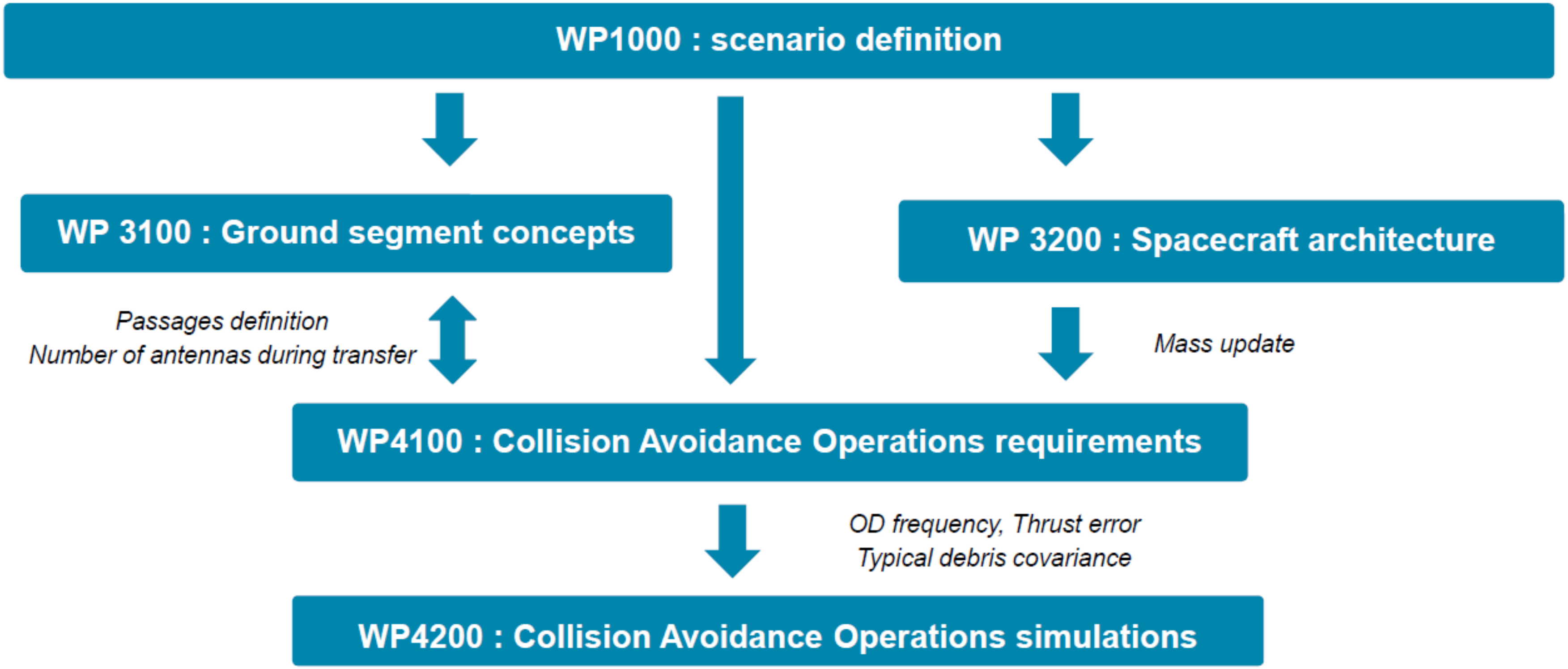
	Baseline	Scen. 5
Propulsion subsystem	Electric prop., HET	Electric prop., HET
Dry mass	187 kg	183 kg
Fuel	9 kg	20 kg
Wet mass	197 kg	**203** kg

Scenario 5 offers:

- relatively low mass,
- possibility to launch many satellites with one launcher,
- reliable back-up PMD strategy,
- innovative technologies.

WP4000 : Collision avoidance operational requirements.

Study logic used for WP4100



WP1000 : scenario definition

WP 3100 : Ground segment concepts

WP 3200 : Spacecraft architecture

Passages definition
Number of antennas during transfer

Mass update

WP4100 : Collision Avoidance Operations requirements

OD frequency, Thrust error
Typical debris covariance

WP4200 : Collision Avoidance Operations simulations

WP4000 : Collision avoidance operational requirements.

WP4100 conclusions

1. **LEOP / IOT / SK phases** can be managed as usual.

For **all kinds of propulsion**, the insertion into the final orbit can be done safely thanks to a classical phasing.

2. **Chemical** propulsion: **Orbit raising / PMD** phases can be managed as usual.

3. **Electrical** propulsion with **automated FDS orbit raising / PMD** phase:

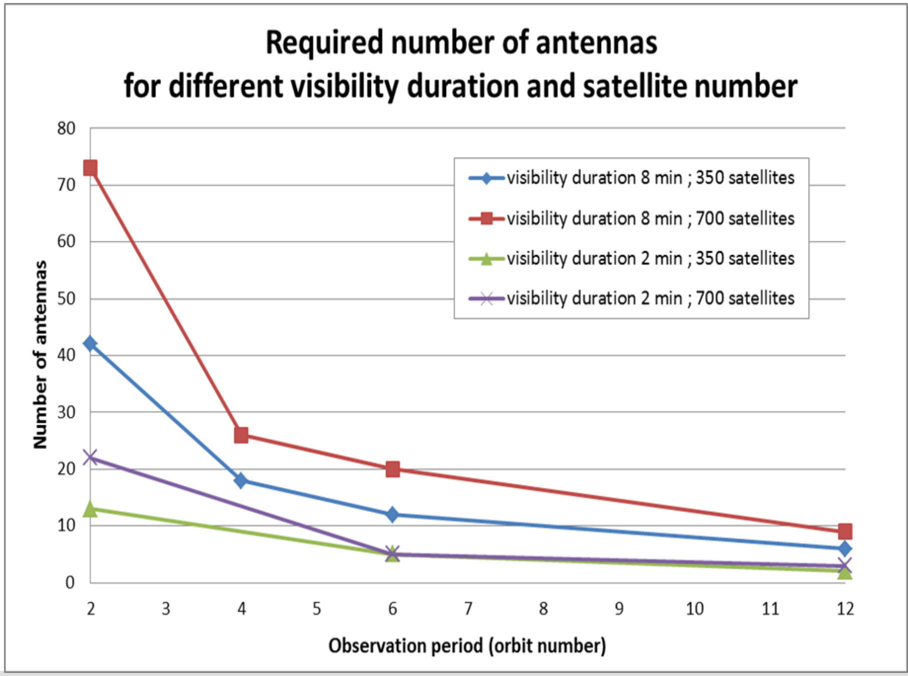
Orbit determination frequency driven by 3 constraints, 1 visibility needed every 4 orbits, intra-constellation collision risk can be reduced by design.

4. **Electrical** propulsion with **advanced autonomy orbit raising / PMD** phase:

On board closed loop trajectory control and CAM computation, intra-constellation collision risk is managed by the ground, 1 visibility every day. Two possible timelines:

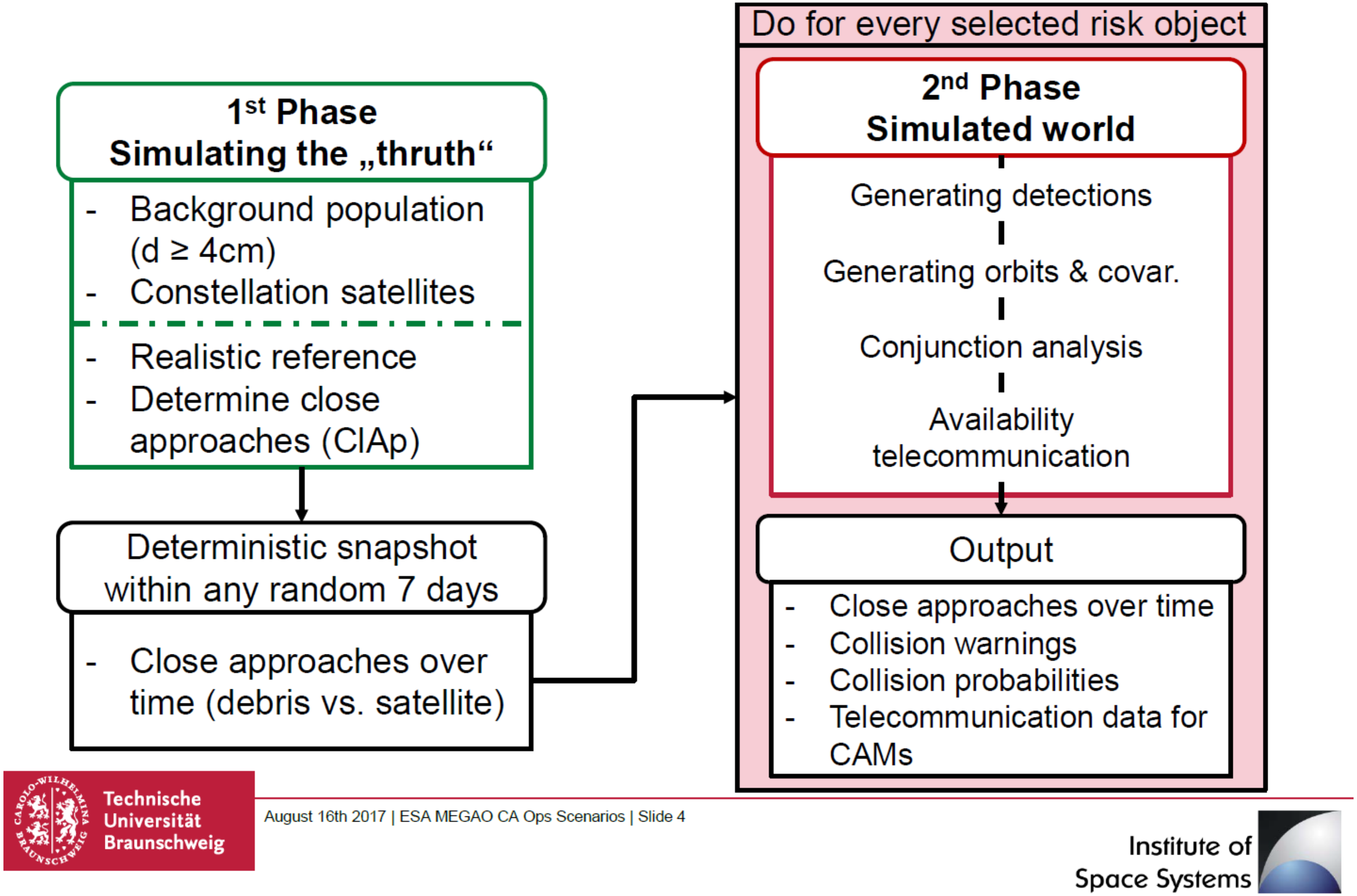
i. On-board maneuvers planning + Ground control confirmation,

ii. Ground maneuvers planning + On-board closed loop trajectory control.



WP4000 : Collision avoidance operational requirements.

Study logic used for WP4200 : Collision Avoidance operations simulations



Do for every selected risk object

1st Phase
Simulating the „thruth“

- Background population (d ≥ 4cm)
- Constellation satellites

- Realistic reference
- Determine close approaches (ClAp)

Deterministic snapshot within any random 7 days

- Close approaches over time (debris vs. satellite)

2nd Phase
Simulated world

Generating detections

Generating orbits & covar.

Conjunction analysis

Availability telecommunication

Output

- Close approaches over time
- Collision warnings
- Collision probabilities
- Telecommunication data for CAMs

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August 16th 2017 | ESA MEGAO CA Ops Scenarios | Slide 4

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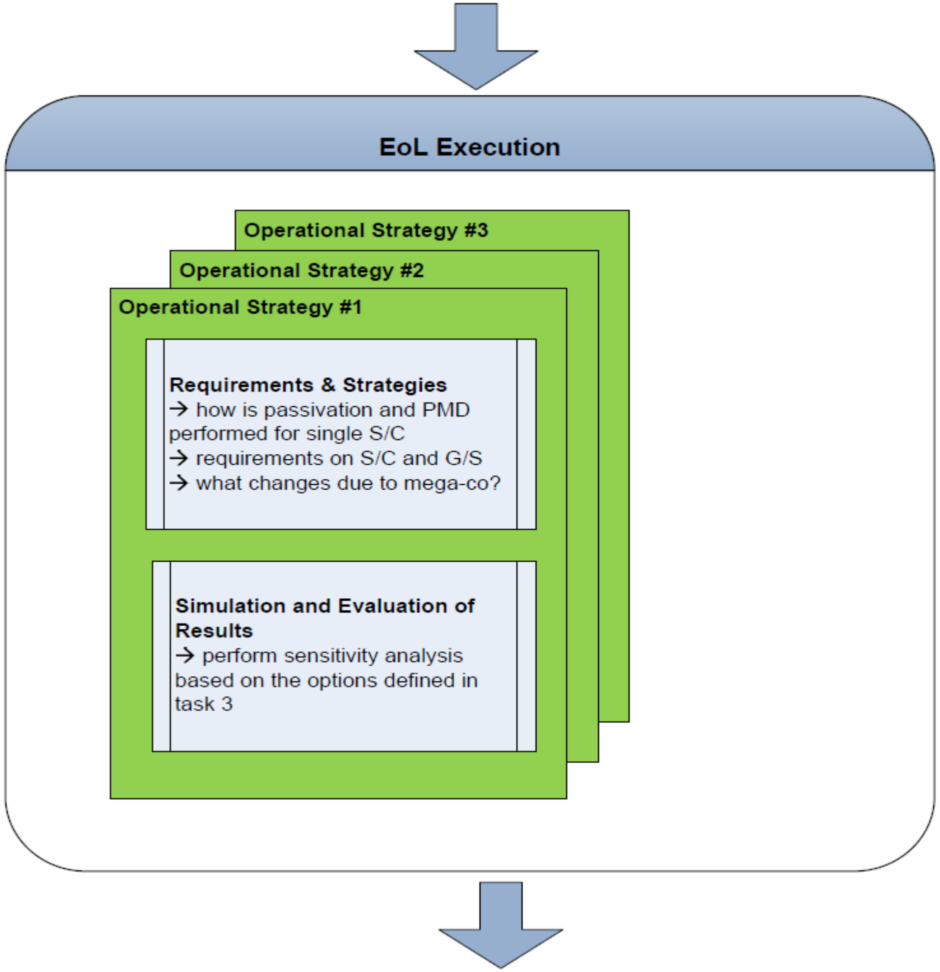
WP5000 : EOL Operations Requirements and Simulations.

Study logic used for WP5000 : EoL Execution. (still under study)



EoL Execution

Operational Strategy #3

Operational Strategy #2

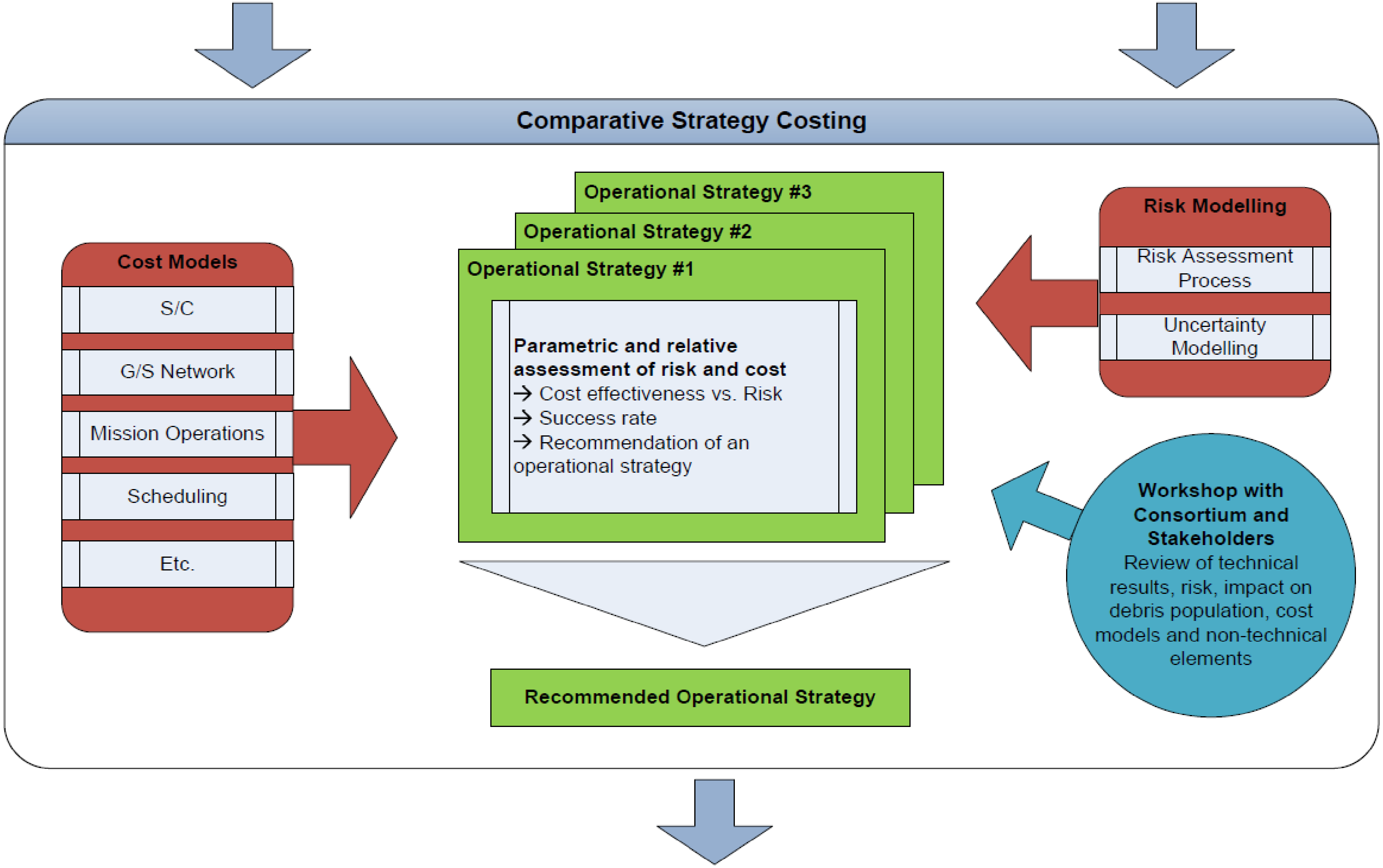
Operational Strategy #1

Requirements & Strategies
→ how is passivation and PMD performed for single S/C
→ requirements on S/C and G/S
→ what changes due to mega-co?

Simulation and Evaluation of Results
→ perform sensitivity analysis based on the options defined in task 3

WP6000 : Comparative Strategy Costing.

Study logic used for WP6000 : Comparative Strategy Costing (still under study)



Comparative Strategy Costing

Cost Models

- S/C
- G/S Network
- Mission Operations
- Scheduling
- Etc.

Operational Strategy #3

Operational Strategy #2

Operational Strategy #1

Parametric and relative assessment of risk and cost

→ Cost effectiveness vs. Risk

→ Success rate

→ Recommendation of an operational strategy

Risk Modelling

- Risk Assessment Process
- Uncertainty Modelling

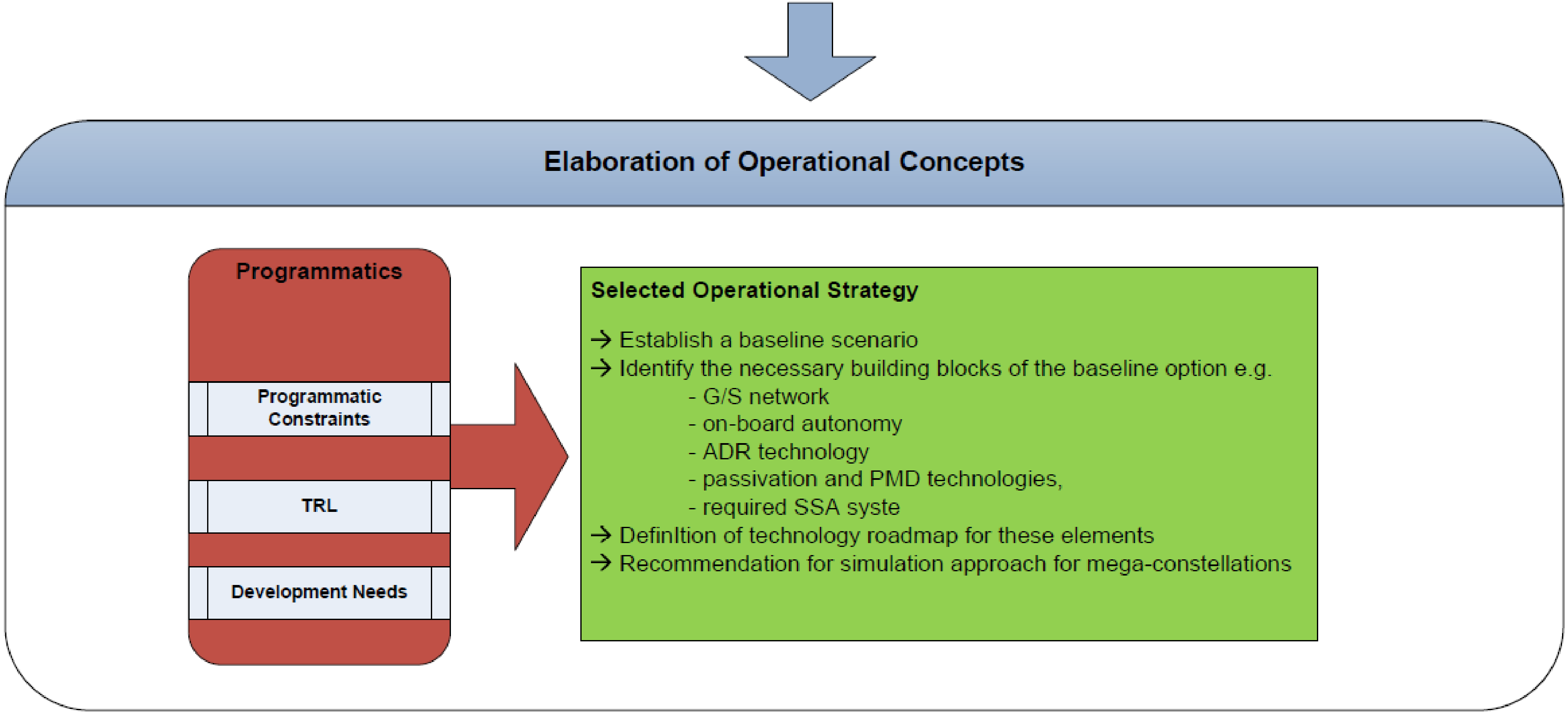
Workshop with Consortium and Stakeholders

Review of technical results, risk, impact on debris population, cost models and non-technical elements

Recommended Operational Strategy

WP7000 : Elaboration of Operational Concepts.

Study logic used for WP7000 : Elaboration of Operational Concepts (still under study)



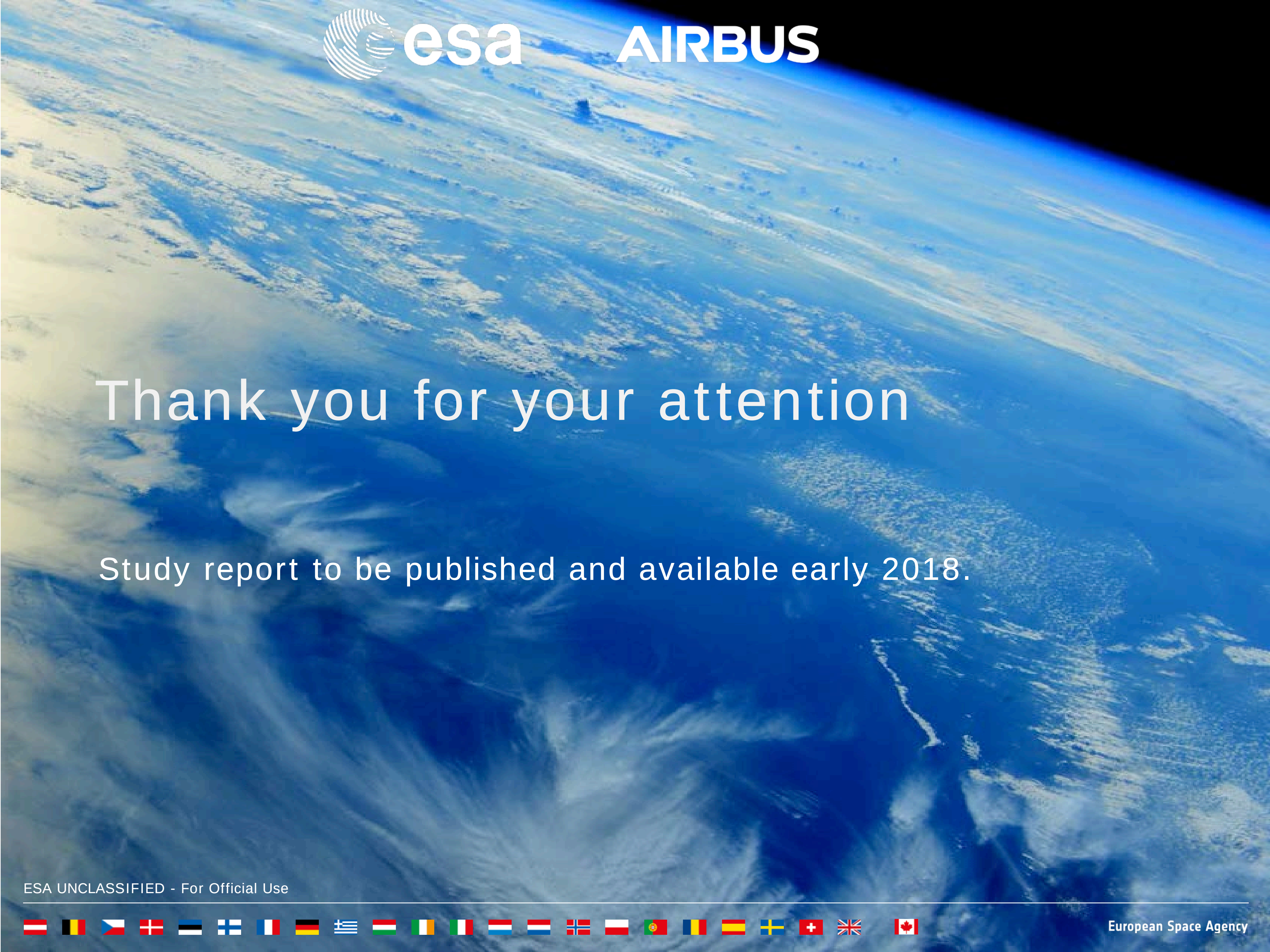
Elaboration of Operational Concepts

Programmatics

- Programmatic Constraints
- TRL
- Development Needs

Selected Operational Strategy

→ Establish a baseline scenario
→ Identify the necessary building blocks of the baseline option e.g.
  - G/S network
  - on-board autonomy
  - ADR technology
  - passivation and PMD technologies,
  - required SSA syste
→ DefinItion of technology roadmap for these elements
→ Recommendation for simulation approach for mega-constellations



Thank you for your attention

Study report to be published and available early 2018.