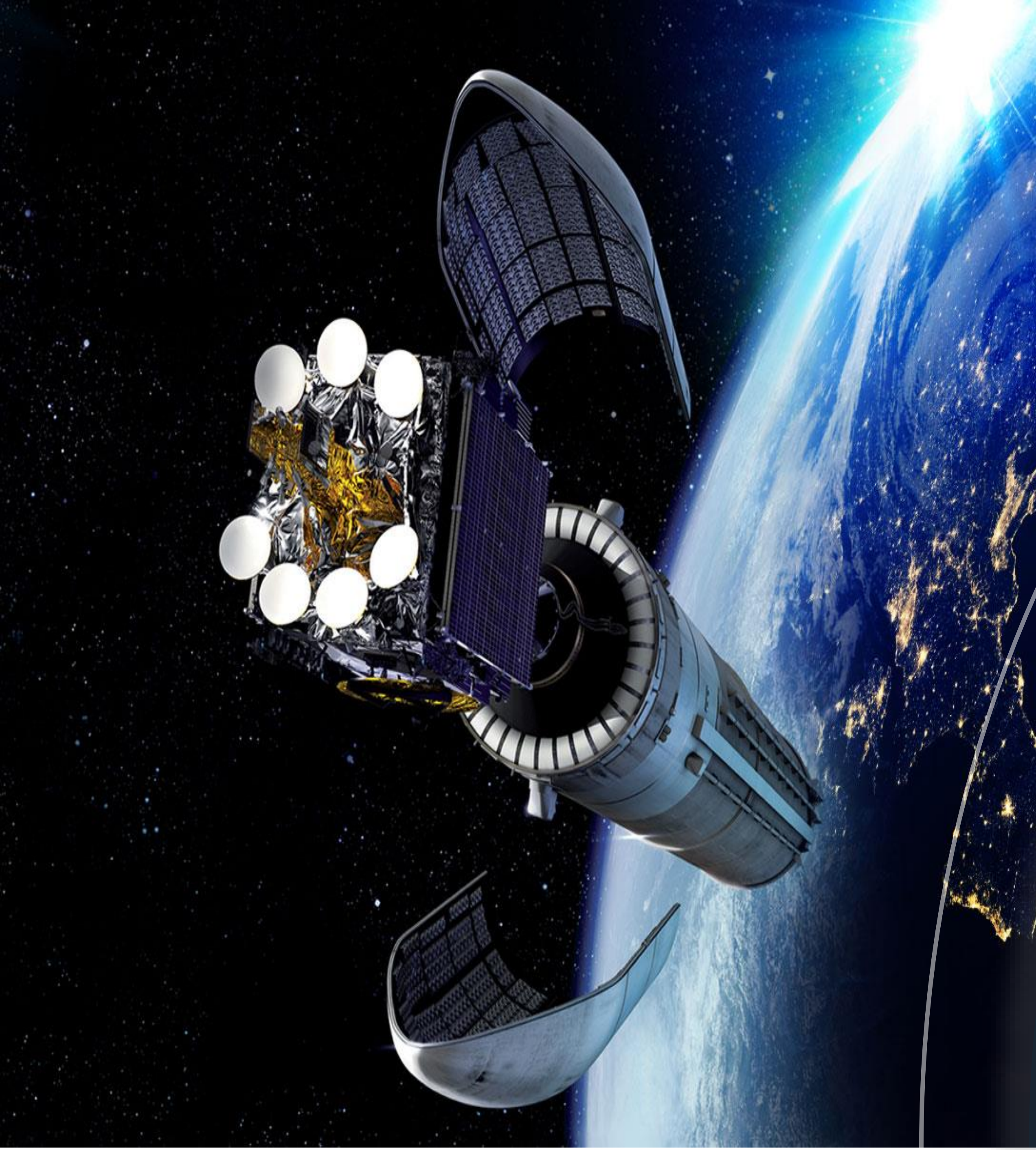


D4R
Final presentation

15 March 2017

ThalesAlenia Space
a Thales / Leonardo company

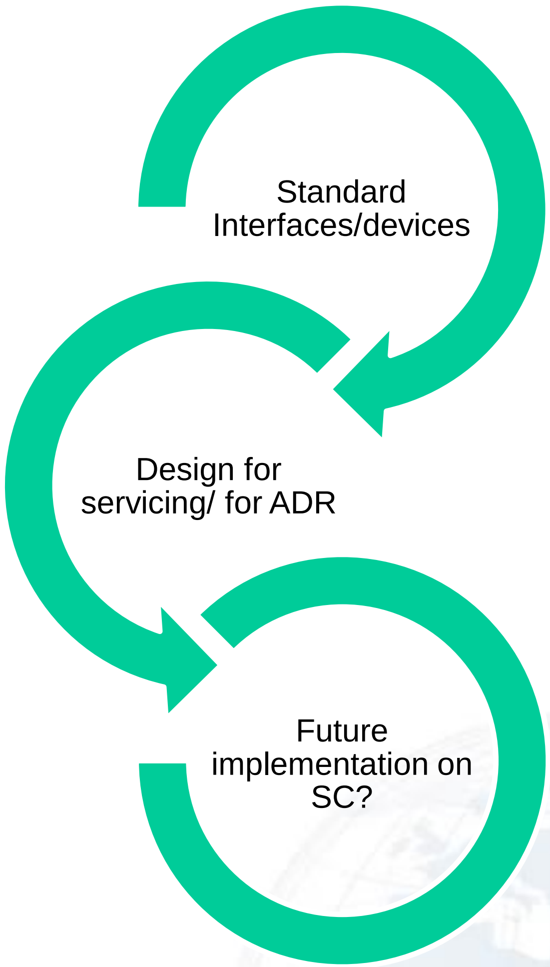
Agenda

14:00 - Organisation & Study Logic & Objectives
14:10 – Study cases definition
14:30 – Quantitative evaluation of SDRS techniques
15:00 – Selected SDRS techniques preliminary performance
15:40 – System impact
16:10 – Next steps for SDRS development
16:30 – Discussion & Conclusion
17:00 – End of Meeting

1. Organisation & Study Logic

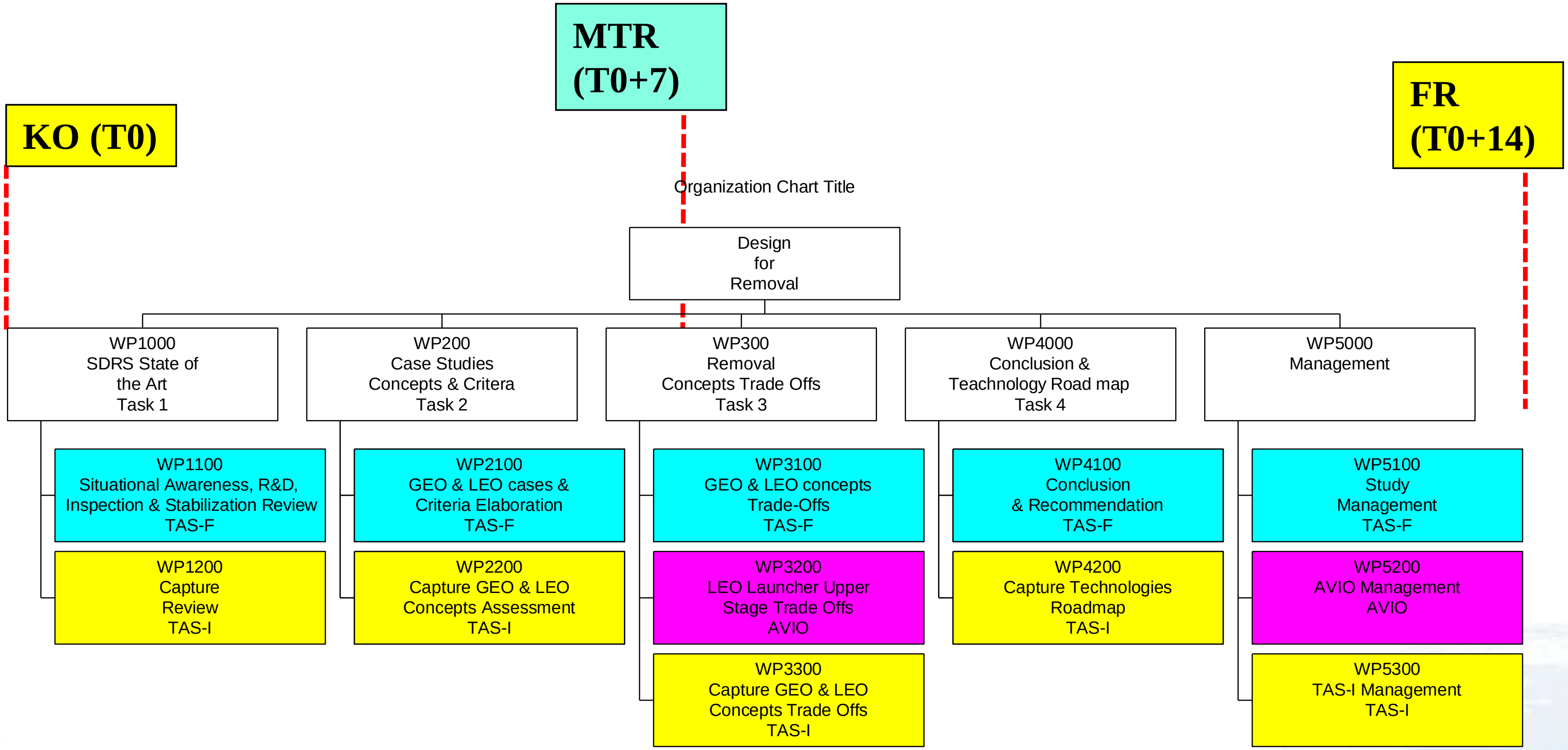
1. Organisation & Study Logic

- Perimeter
  - Characterisation and evaluation of added devices for future SC to contribute to:
    - Future ADR in case SC non-functional (during lifetime, or disposal not effective)
    - Improvement of SSA data
    - On-orbit servicing
- D4R SDRS techniques
  - SSA
  - RdV & Visions
  - Stabilization
  - Capture



1. Organisation & Study Logic

Study Work Breakdown Structure



1. Organisation & Study Logic

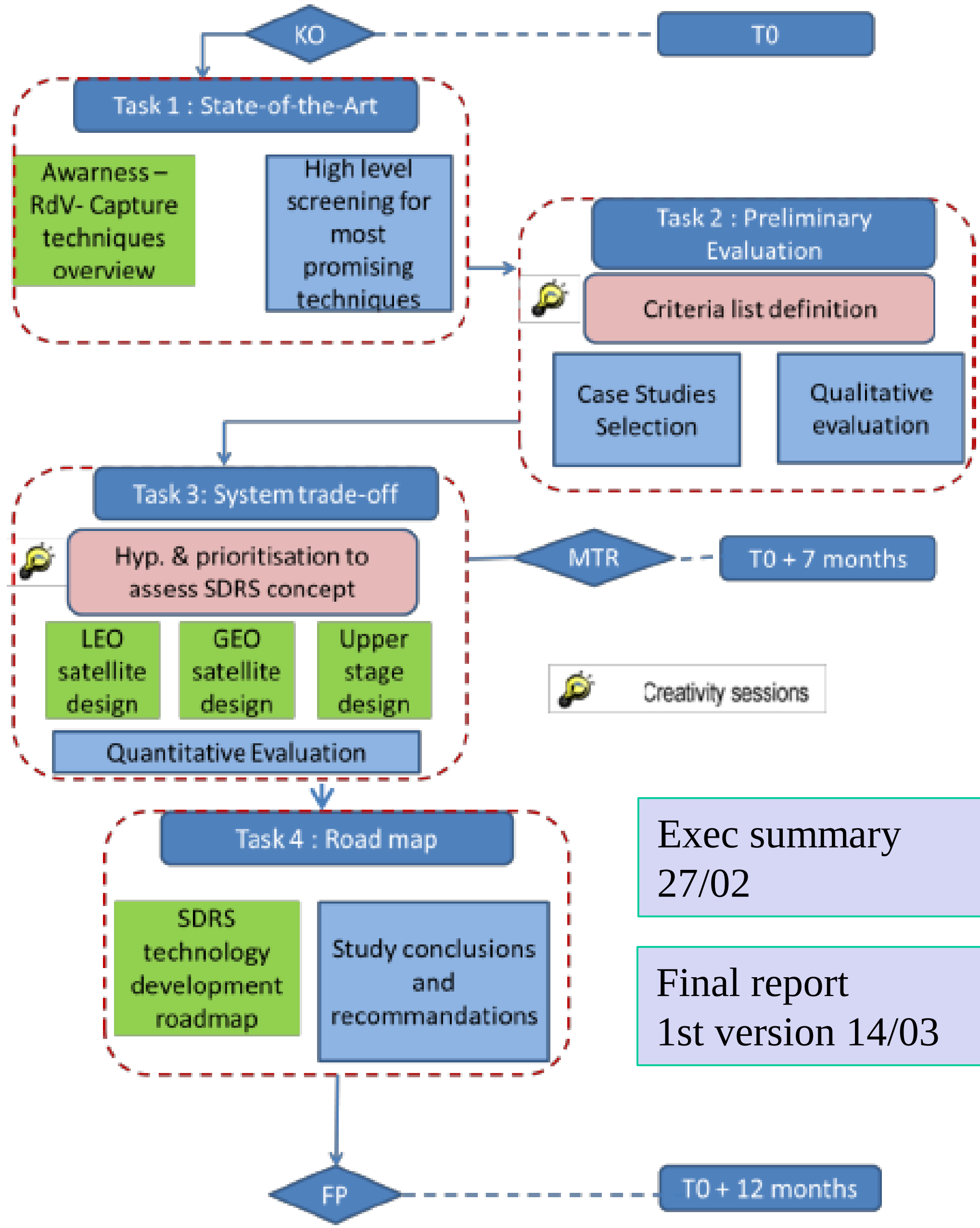
- Task 1
  - State of the art at international level
  - Identification of possible solution for satellites
  - Mapping technologies / SDRS techniques
- Task 2
  - Criteria definition
  - Choice of ref case
  - Comparison qualitative
- Task 3
  - System redesign of selected techniques
  - System impact
- Task 4
  - Road map

TN1 delivery

TN2 delivery

TN3 delivery

TN4 delivery 7/03/2017



Exec summary 27/02

Final report 1st version 14/03

- D4R addresses debris after EOL or after major failure during mission.
  - major assumption= there is no on-board capacity to react or to use on-board equipment to ease ADR capture.
- Objectives = to reduce the ADR identified risks

Ref	Failure Mode ADR	Effect	Domain
C1	Unknown debris motion	Would imply additional propellant budget and approach mode definition update in-flight for ADR Would increase ADR mission time to consider a first phase of determination of attitude motion vector and evolution to build the capture strategy	SSA device
C2	Error in the relative pose	Could lead to a collision or could induce additional in-orbit loop to support close range RdV and to secure capture process definition	RdV device

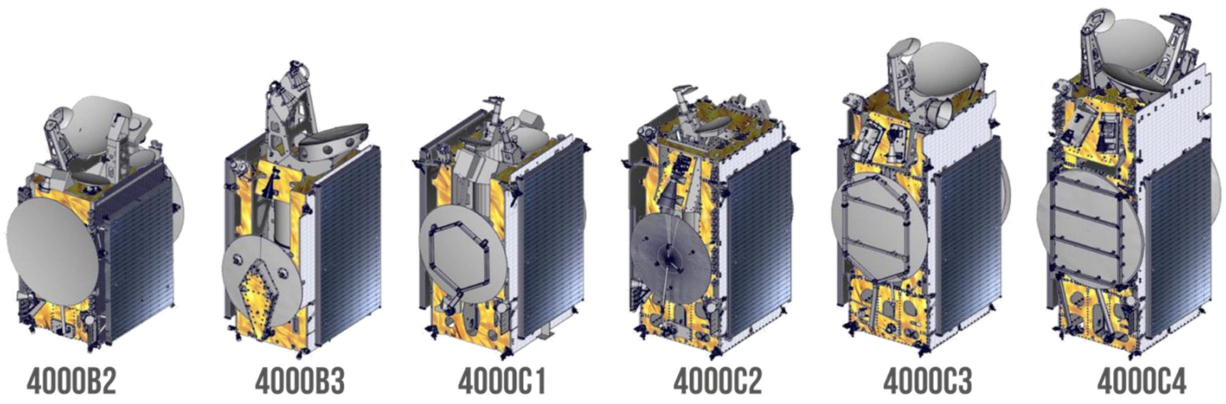
1. Organisation & Study Logic & objectives

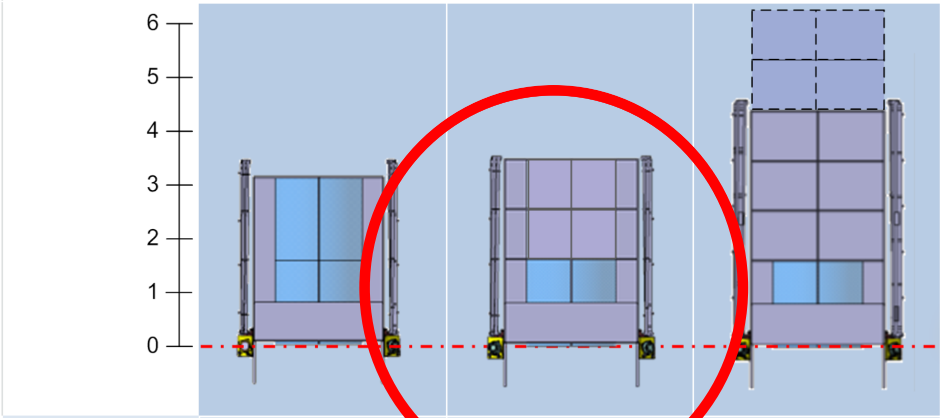
Ref	Failure Mode ADR	Effect	Domain
C3	Non-sufficient lighting condition for capture due to eclipse	Could lead to loss of vision system with no possibility to track and capture	Vision device
C4	High tumbling rate	Every capture technique (tentacle, net, harpoon, robotic arm) present a physical limit in the relative angular momentum between ADR and targe. Would induce possible non capture feasibility or additional risk	Stabilization device
C5	Rigid Capture slippery	Could result a non-correct grasping or inadvertent contact with the satellite Stiffness of the capture point on debris could not be sufficient to handle deorbiting process	Capture device
C5	Flexible capture with harpoon in bad location	Would possibly create additional debris Could result a non-correct harpooning (on pressurized vessels for example)	Capture device Stabilization device

- 2. Study cases definition
  - GEO
  - LEO
  - Constellation
  - Launcher

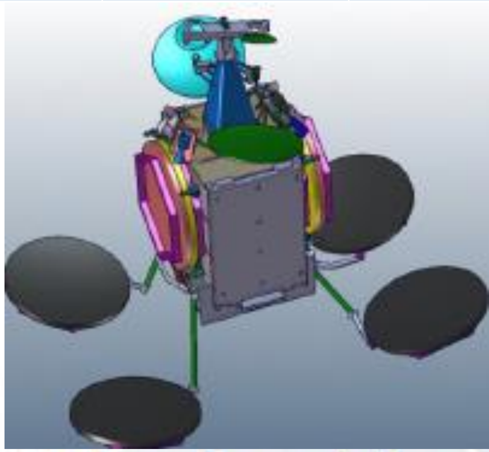
2. Study cases definition

GEO





	100 Stacked	100	200
Payload Power (kW)	3 - 9 kW	3 - 12 kW	12 - 20 kW
Payload Mass (kg)	200 - 600 kg	300 - 900 kg	700 - 2000 kg
Lateral Antennas	4	4	4 to 6
Number of Floors	N/A	3	4 to 6
Solar Array	Small 4P	Small 4P or 6P	Large 5P or 6P
Thermal	No MPL	MPL	MPL
Stacking Capability	Yes, Lower S/C	Yes, Upper S/C	No



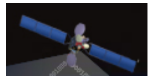
2. Study cases definition

GEO

	Propulsion	TRL	Interfaces	Advantage	Drawback
Spacebus	chemical	9	1194 mm	Large range of in-orbit satellites	-Z face cluttered with LAE engine
Spacebus NEO	electric	On-going qualification CDR 2016	1666 mm	Next GEO TAS dream product due to competitiveness High constraint in AIT schedule Interest of available area at interface due to LAE deletion	No in-orbit flight reference for programmatic issue

Eurostar E3000 full electric – SES-14
Up to 6.4 tons

16.5kW payload

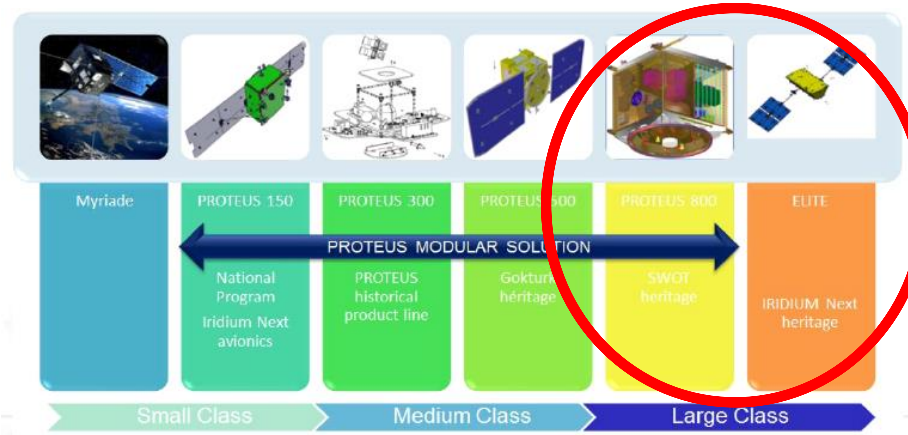
	SSL	DFH-4	Boeing 702	Orbital
Body Size	2.4 X 2.15 X 4.4m	2.36 X 2.1 X 3.6 m	2 X 2.27 X 3 m	2.1 X 2.3 X 3.9
Solar Array	2 rigid wings	2 rigid wings	2 rigid wings	2 rigid wings
Launch mass	Up to 4200 kg	5200 kg	5400 to 5900 kg	4500 kg
Propulsion	Chemical, hybrid, EP	EP	Chemical, hybrid, EP	Chemical, hybrid
Lifetime	15 years	15 years	15 years	15 years
Stabilization mode	3-axis	3-axis	3-axis	3-axis
Payload Power	15 kW	8 kW	Up to12 kW	8 KW

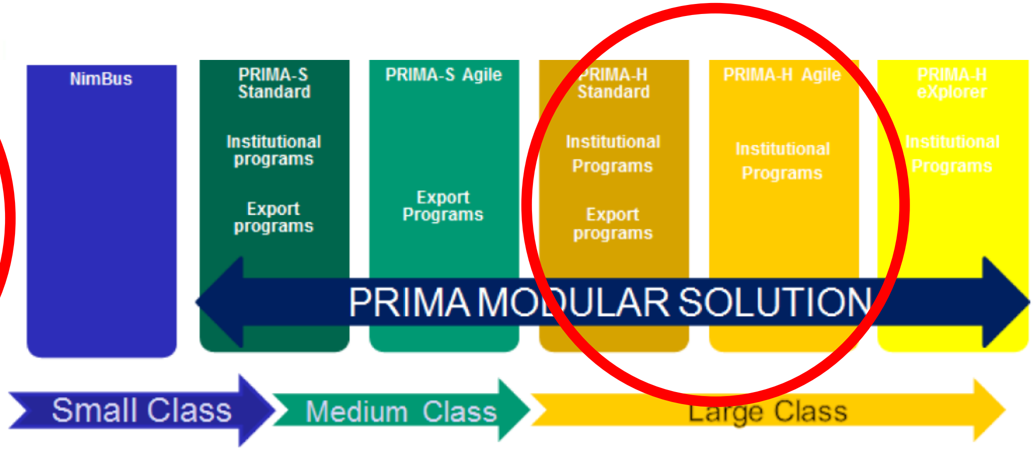
	SSTL GMP-E	ADS- SES-14 (E3000e)	Neosat
Body Size	2.8 X 2.6 X 3.2 m	1.55 x 1.75 x 2.7 m	3.72 x 3.69 x 5.64 m
Launch mass	Up to 3400 kg	4200 kg	4173 kg
Propulsion	Hydrazine or EP	EP	EP
Lifetime	15 years	15 years	15 years
Launcher Interface	A5, Soyuz, Zenith, F9	A5, F9	1666 mm, A5, F9
Payload Power	3.2 kW	16 kW	15 kW

Medium NEOSAT representative of GEO satellites for D4R

2. Study cases definition

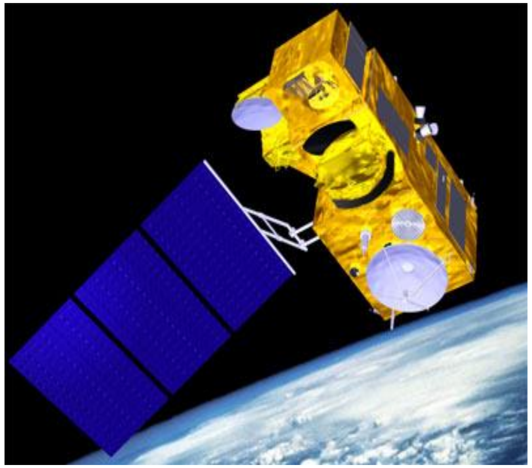
LEO

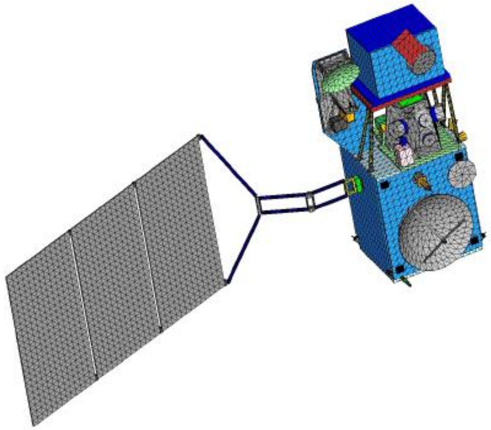




	LEO	Propulsion	conf	Advantage	Drawback
Proteus 500	SWOT	chemical	symetrical	Reference TAS-F observation P/F	Controlled re-entry implemented
Elite	03B/LEOSAT	Chemical / electric	symetrical	Refer to constellation	
Prima	Sentinel 3	Chemical	dissymetry	Just compliant to natural re-entry within 25 years Several in-orbit and in production models	

LEO





Main Satellite characteristics:

Dry Mass = 1119 kg

Dry Mass without propulsion= 1097 kg

Wet Mass = 1239 kg

Full Hydrazine

On-ground casualty risk for uncontrolled re-entry is in the range 1:13400 to 11200 (ref HTG Sentinel 3 CDR analysis with SCARAB)

Re-entry fragments were found from battery, tank and payload.

Increase mass and volume of the Sentinel 3 payload with associated propellant mass in coherence to reach at EOL a final orbit insuring natural re-entry in 25 years

⇩

Sentinel3-“like”

- Diversified range of payload in LEO for observation, science, radar, meteo…

CAST-2000

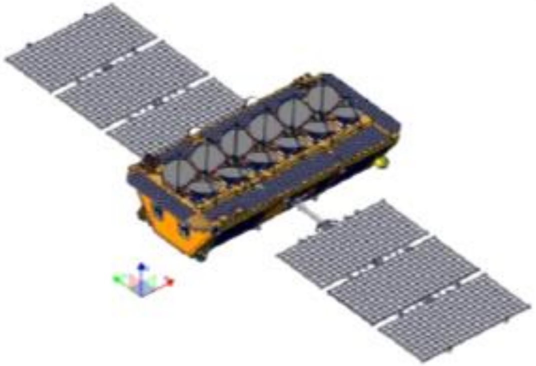
1.53 X 1.65 X 1.87 m
500 to 1000 kg
900W
5.67 m2
5 years

	Spot 6/7 Astrobus-L	D4R LEO study case
Body Size	1.55 x 1.75 x 2.7 m	1.9 x 2.18 x 4.18 m
Solar Array	3 wings for 5.4 m2	1 wing for 10.5 m^2
Launch mass	712 kg	2196 kg
Altitude	695 km - SSO	815 km SSO
TTC	S-Band X-Band PL	S-Band X-Band PL
Lifetime	10 years	7.5 years
Launcher Interface	PSLV	937 mm / Vega/Rockot
DV	80 kg propellant	313 kg propellant

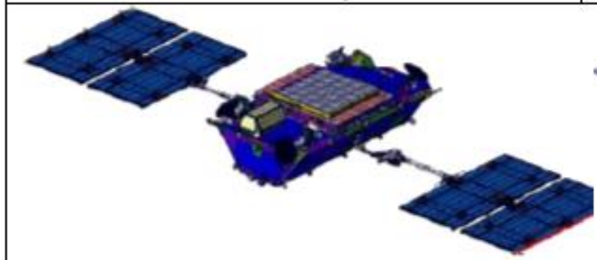
S3 enlarged to be more representative of LEO sat for D4R

Constellation

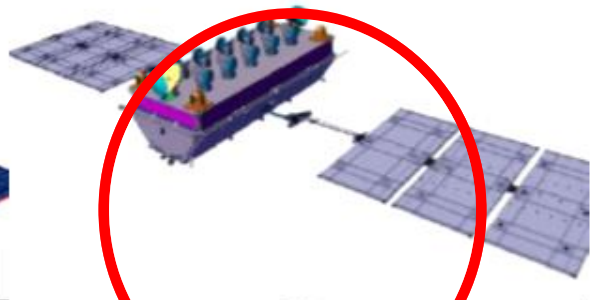
Globalstar
2010-2012- 25 satellites
LEO 1414 km, I 52°



O3B
2013-2014 - 12 satellites
MEO 8069 km, 0°

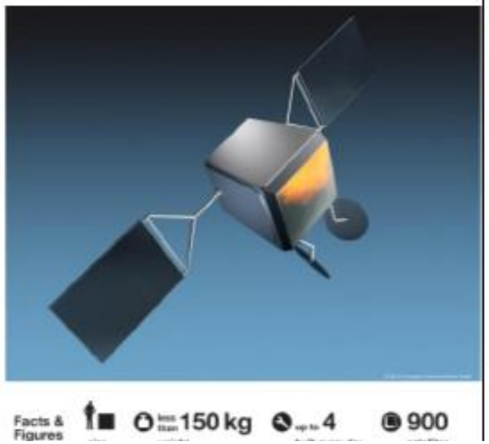


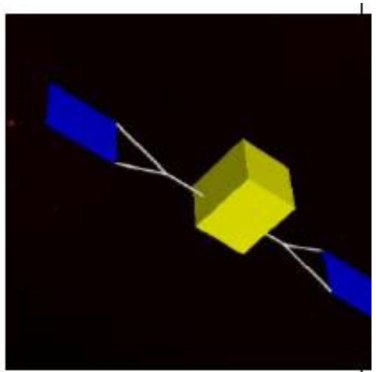
Irridium Next
2016-2017 - 62 satellites
LEO 780 km, I 86°4



LEOSAT
2019-2020, 80 satellites
LEO 1430 km, 90°

Other

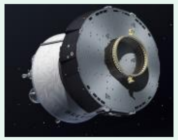




Constellation	P/F	Propulsion	Orbit	Advantage	Drawback
Irridium NEXT	Elite 1000	chemical	780 km	Large database Orbit altitude versus stability solution	2017 in-orbit
LEOSAT	Elite 2000	electric	1430 km	P/F adaptable for large domain (500-25000-i) 2020 in-orbit Natural re-entry compliant to LOS	TRL Uncontrolled re-rentry casualty risk around 2.10-4 => strategy still to define graveyard versus demise technology
ONEWEB	Dedicated P/F	electric	1200 km	900 satellites Operational date Natural re-entry compliant to LOS	TRL Dedicated design Data to be extrapolated. Programmatics concern wrt ADS status

2. Study cases definition

Launcher	VEGA	SOYUZ	ROCKOT	PSLV
Upper stage	AVUM	FREGAT	Breeze KM	PS4
				
Mass	688 kg	902 kg	1600 kg	420 kg
Dimension (m)	2.04 Height - Ø2.18	1.5 H – Ø3.35	1.3 H – Ø2.5	2.9 H X Ø2.8
Propellant	NTO/UDMH	N204/UDMH	N204/UDMH	MON/MMH
Material	Aluminium case with 4 titanium tank	Alumininum alloy	Alumininum alloy	Aluminum-lithium alloy
Reignition	Y	Y	N	Y

Launcher	ATLAS 5	DNEPR	PROTON	ARIANE 5	FALCON 9
Upper stage	2nd stage	3rd stage	Breeze M	ESC	MERLIN 2nd stage
					
Mass	2243 kg	2360 kg	2370 kg	4540 kg	3100 kg
Dimension (m)	12.7H - Ø3.05	1H - Ø3	2.61H - Ø4	4.71H - Ø5.4	10 H - Ø3.66
Propellant	LH2/LO2	UDMH/NTO	NTO/UDMH	LOX/LH2	LOX/RP1
Material	Stainless steel tank- alloy	Alloy	alloys	Aluminum alloy	Aluminum-lithium alloy
Reignition	Y	Y	Y	N	Y

- Upper stage
  - AVUM nominal re-entry into SPOUA
  - Orbital time lower than 25 years for majority of missions
  - But upper stage good candidates for D4R

Conclusion

Satellite	Symetric	Non-sym.	Electric prop.	Chemical prop.	Mass	Interface	LOS 25-years	Orbit	P/F
S-3 “like”		X		X	2196 kg	937	Controlled re-entry	LEO	PRIMA
NEOSAT	X		X		4173 kg	1666	300 km above GEO	GEO	Spacebus NEO
LEOSAT	X		X		1280 kg	Dispenser	EOL manœuvre to reach 25-years re-entry	LEO	ELITE 2000

& AVUM

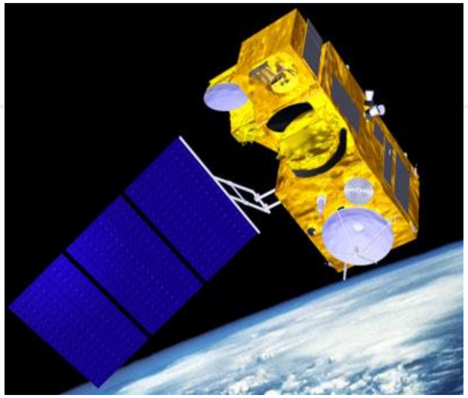
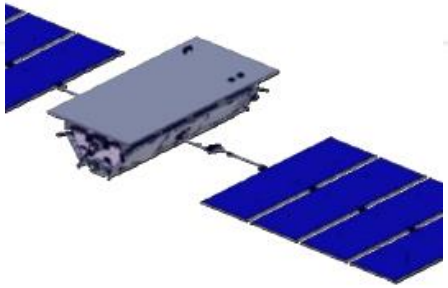
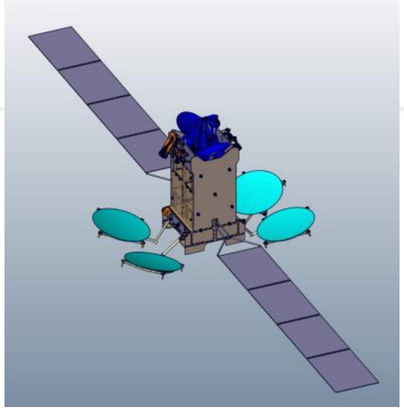
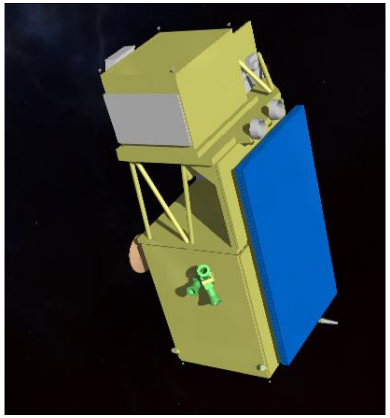
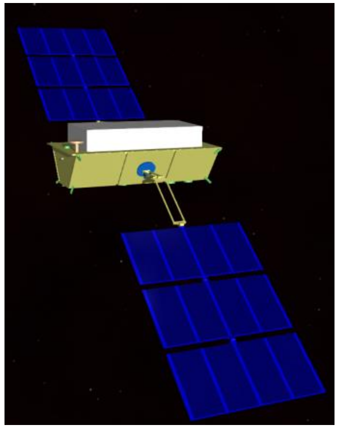
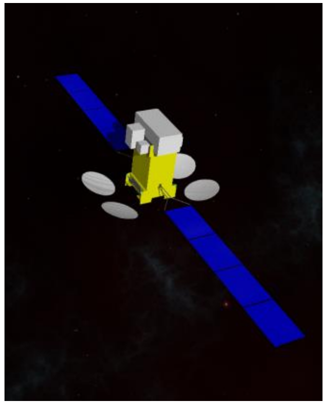
2. Study cases definition

Implementation -> IDM-CIC modelization

Sentinel 3 seen in Catia

Sentinel 3 seen in IDM

1. Collect .smg (CAO) (f)
2. Collects Budgets (Mass/Power/Thermal) (f)
3. Project Initialization
4. Complete System Structure (subsystems)
5. Define Additional Properties (f)
6. Define Elements custom Properties (f)
7. Define Coordinate System
8. Complete Equipments Summary (shape, mass, power, dissip,...)
9. Fill configuration:
   - frame/equipments
   - build geometry
10. Complete Saved configuration according to desired configurations
11. Fill Thermal Configuration (f)
12. Complete Elements Power/Dissipation Budget (f)

		
IDM Modelisation		
		
LEO satellite – PRISMA P/F	**Constellation satellite – Elite P/F**	**GEO satellite – Spacebus NEO P/F**
Main Satellite characteristics: • Dry Mass = 1886 kg • Wet Mass = 2196 kg • Tank propellant capacity 310 kg • Hydrazine	Main Satellite characteristics: • Dry Mass = 1130 kg • Wet Mass = 1280 kg • Tank capacity 150 kg • Xenon	Main Satellite characteristics: • Dry Mass = 3257 kg • Wet Mass = 4173 kg • Tank capacity 916 kg • Xenon

- 3. Quantitative evaluation of SDRS techniques
  - Criteria
  - Methodology
  - SSA
  - RdV & vision
  - Stabilization
  - Capture

3. Quantitative evaluation of SDRS techniques - Criteria

Programmatic

- Development cost
- Recurrent cost (includes manufacturing & AIT)

Technical

- Power
- Mass
- Dimensions/ accomodation
- TRL (reflecting if concept is generic or tested on ground on a descaled model for example)
- Inertia (through impact on AOCS database)

Performance

- Reduction in Mission risk (covers collision risk, debris generation risk, uncessfull detumbling, controlled re-entry, flexibility
- Increase in complexity to chaser (approach complexity, detumbling,..)
- Synergy with in-orbit servicing

Figures of merit comparison

- A is more relevant than B → +1 point awarded
- A and B are equally relevant → 0 point awarded
- A is less relevant than B → -1 point awarded

Depends on study case

- GEO, ranking of dimensions and accommodation updated

▼ this figure of merit compared to / this figure of merit ►	development cost	recurrent cost	Power	Mass	Dimensions	TRL	Inertia	Reduction in Mission Risk	Increase in Complexity to chaser	Synergy with in-orbit servicing	Total score Pi	Weighting factor Wi
Programmatic												
development cost		-1	-1	-1	-1	1	-1	-1	-1	-1	-7	**2,1**
recurrent cost	1		-1	-1	-1	1	-1	-1	-1	-1	-5	**3,1**
Technical												
Power	1	1		-1	-1	1	1	-1	-1	-1	-1	**5,0**
Mass	1	1	1		-1	1	1	-1	-1	-1	1	**6,0**
Dimensions/Accomodation	1	1	1	1		1	-1	-1	-1	-1	1	**6,0**
TRL	-1	-1	-1	-1	-1		-1	-1	-1	-1	-9	**1,0**
Inertia	1	1	-1	-1	1	1		-1	-1	-1	-1	**5,0**
Performance												
Reduction in Mission Risk	1	1	1	1	1	1	1		1	1	9	**10,0**
Increase in Complexity to chaser	1	1	1	1	1	1	1	-1		1	7	**8,9**
Synergy with in-orbit servicing	1	1	1	1	1	1	1	-1	-1		5	**7,9**
											Q = 46	

Ranking TN3 issue 3

▼ this figure of merit compared to / this figure of merit ►	development cost	recurrent cost	Power	Mass	Dimensions	TRL	Inertia	Reduction in Mission Risk	Increase in Complexity to chaser	Synergy with in-orbit servicing	Total score Pi	Weighting factor Wi
Programmatic												
development cost		-1	-1	-1	-1	1	-1	-1	-1	-1	-7	**2,0**
recurrent cost	1		-1	-1	-1	1	-1	-1	-1	-1	-5	**3,0**
Technical												
Power	1	1		-1	-1	1	1	-1	-1	-1	-1	**5,0**
Mass	1	1	1		-1	1	1	-1	-1	-1	1	**6,0**
Dimensions/Accomodation	1	1	1	1		1	1	-1	1	-1	5	**8,0**
TRL	-1	-1	-1	-1	-1		-1	-1	-1	-1	-9	**1,0**
Inertia	1	1	-1	-1	-1	1		-1	-1	-1	-3	**4,0**
Performance												
Reduction in Mission Risk	1	1	1	1	1	1	1		1	1	9	**10,0**
Increase in Complexity to chaser	1	1	1	1	-1	1	1	-1		-1	3	**7,0**
Synergy with in-orbit servicing	1	1	1	1	1	1	1	-1	1		7	**9,0**

53. Quantitative evaluation of SDRS techniques - Method

- constellation study case
  - Criteria change / LEO are
  - + mass (small launcher)
  - - in-orbit repair
  - + recurrent cost

- Power scoring reinforced for stabilization
- Pb of accomodation

▼ this figure of merit compared to / this figure of merit ▶	development cost	recurrent cost	Power	Mass	Dimensions	TRL	Inertia	Reduction in Mission Risk	Increase in Complexity to chaser	Synergy with in-orbit servicing	Total score Pi	Weighting factor Wi
Programmatic												
development cost		-1	-1	-1	-1	1	-1	-1	-1	-1	-7	**1,9**
recurrent cost	1		-1	-1	-1	1	-1	-1	1	1	-1	**5,0**
Technical												
Power	1	1		1	-1	1	1	-1	-1	1	3	**7,0**
Mass	1	1	-1		1	1	1	-1	-1	1	3	**7,0**
Dimensions/Accomodation	1	1	1	-1		1	-1	-1	-1	1	1	**6,0**
TRL	-1	-1	-1	-1	-1		-1	-1	-1	-1	-9	**1,0**
Inertia	1	1	-1	-1	1	1		-1	-1	-1	-1	**5,0**
Performance												
Reduction in Mission Risk	1	1	1	1	1	1	1		1	1	9	**10,0**
Increase in Complexity to chaser	1	-1	1	1	1	1	1	-1		1	5	**8,1**
Synergy with in-orbit servicing	1	-1	-1	-1	-1	1	1	-1	-1		-3	**4,0**
											Q = 42	

Ranking TN3 issue 3 ▼ this figure of merit compared to / this figure of merit ▶	development cost	recurrent cost	Power	Mass	Dimensions	TRL	Inertia	Reduction in Mission Risk	Increase in Complexity to chaser	Synergy with in-orbit servicing	Total score Pi	Weighting factor **Weighting factor LEO**
Programmatic												
development cost		-1	-1	-1	-1	1	-1	-1	-1	-1	-7	**2,0**
recurrent cost	1		-1	-1	-1	1	-1	-1	1	1	-1	**5,0**
Technical												
Power	1	1		1	-1	1	1	-1	1	1	5	**8,0**
Mass	1	1	-1		1	1	1	-1	1	1	5	**8,0**
Dimensions/Accomodation	1	1	1	-1		1	1	-1	1	1	5	**8,0**
TRL	-1	-1	-1	-1	-1		-1	-1	-1	-1	-9	**1,0**
Inertia	1	1	-1	-1	-1	1		-1	1	-1	-1	**5,0**
Performance												
Reduction in Mission Risk	1	1	1	1	1	1	1		1	1	9	**10,0**
Increase in Complexity to chaser	1	-1	-1	-1	-1	1	-1	-1		1	-3	**4,0**
Synergy with in-orbit servicing	1	-1	-1	-1	-1	1	1	-1	-1		-3	**4,0**

3. Quantitative evaluation of SDRS techniques - Method

- Constellation study case
  - +mass
  - - Manufacturing cost decreases due to specific process
  - + dimension
  - - in orbit servicing

	SCORES										Total score	Weighting factor
this figure of merit ► / ▼ this figure of merit compared to	development cost	recurrent cost	Power	Mass	Dimensions	TRL	Inertia	Reduction in Mission Risk	Increase in Complexity to chaser	Synergy with in-orbit servicing	Pi	Wi
Programmatic												
development cost		-1	-1	-1	-1	1	-1	-1	-1	-1	-7	2
recurrent cost	1		-1	-1	-1	1	-1	-1	1	1	-1	5
Technical												
Power	1	1		-1	-1	1	1	-1	1	1	3	7
Mass	1	1	1		1	1	1	-1	1	1	7	9
Dimensions/Accomodation	1	1	1	-1		1	1	-1	1	1	5	8
TRL	-1	-1	-1	-1	-1		-1	-1	-1	-1	-9	1
Inertia	1	1	-1	-1	-1	1		-1	1	1	1	6
Performance												
Reduction in Mission Risk	1	1	1	1	1	1	1		1	1	9	10
Increase in Complexity to chaser	1	-1	-1	-1	-1	1	-1	-1		1	-3	4
Synergy with in-orbit servicing	1	-1	-1	-1	-1	1	-1	-1	-1		-5	3
											Q = 50	

- No change post TN3

3. Quantitative evaluation of SDRS techniques - Method

- Launcher upper stage
  - Similar to LEO with no power and no servicing

▼ this figure of merit compared to / this figure of merit ►	development cost	recurrent cost	Mass	Dimensions	TRL	Inertia	Reduction in Mission Risk	Increase in Complexity to chaser	Total score Pi	Weighting factor Wi
Programmatic										
development cost		-1	-1	-1	1	-1	-1	-1	-5	**2,3**
recurrent cost	1		-1	-1	1	-1	-1	1	-1	**4,9**
Technical										
Mass	1	1		1	1	1	1	1	7	**10,0**
Dimensions/Accomodation	1	1	-1		1	-1	1	1	3	**7,5**
TRL	-1	-1	-1	-1		-1	-1	-1	-7	**1,0**
Inertia	1	1	-1	1	1		1	1	5	**8,8**
Performance										
Reduction in Mission Risk	1	1	-1	-1	1	-1		1	1	**6,2**
Increase in Complexity to chaser	1	-1	-1	-1	1	-1	-1		-3	**3,6**
									Q = 32	

- 3. Quantitative evaluation of SDRS techniques
  - 3.1 SSA

3. Quantitative evaluation of SDRS techniques - SSA

- Contributions of SSA to a Removal Mission
- Ways to improve position retrieval (and cataloguing)
- Ways to improve shape retrieval
- Ways to improve attitude (and rotation rate) retrieval
- Synthesis

3. Quantitative evaluation of SDRS techniques - SSA

- SSA contributes to a more efficient design of a Removal Mission by:
  - (Contribution 1) Maintaining a catalogue of objects in space
    - Provided information: state vector (position, velocity) at a given time and associated method to extrapolate the trajectory
  - (Contribution 2) Giving information on the shape of the objects to be removed
    - Provided information: general shape, deployed appendices
  - (Contribution 3) Giving indications on the attitude
    - Provided information: axis of rotation, rotation rate (when rotating)
  - (Contribution 4) Giving the status of objects to plan its removal
    - Provided information on: Object compliance with its nominal design functions

- This helps to identify the objects for which the removal is possible and reduces the most the risk of large fragmentations in space

3. Quantitative evaluation of SDRS techniques - SSA Contribution 1: Maintaining a catalogue of objects in space (1/4)

- Observations contributing to the catalogue maintenance can be made from space or ground, with optical or radar means:
  - Ground radars are most suited for Low Earth Orbits (because of link budget)
  - Laser tracking provides accurate measurements (in LEO only)
  - Optical telescopes are used for higher orbits (MEO or GEO), from ground or space

- Existing assets on ground belonging to large space fairing nations are sufficiently sensitive to observe the candidate objects for a removal mission (>m in LEO and GEO)

- Ways to increase their detection are (see next page):
  - Use of reflectors for laser tracking
  - Reflective surface for optical or RF waves

3. Quantitative evaluation of SDRS techniques - SSA Contribution 1: Maintaining a catalogue of objects in space (2/4)

- A more frequent observation of the objects is also beneficial for the maintenance of the catalogue
  - Less erroneous correlations between observations at different times
  - More chance to have on a given time a favorable observing geometry

- Observation from space is favorable in terms of detection (closer to the objects) but offers quicker observation duration (since both objects move fast), except if
  - Both objects are on close orbits
  - Or the observing asset is far from the observer (smaller relative motion)

- Space based optical means offers longer observation time (less energy consuming)

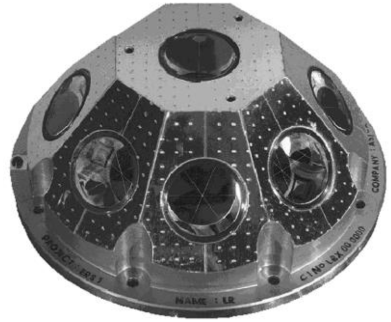
3. Quantitative evaluation of SDRS techniques - SSA Contribution 1: Maintaining a catalogue of objects in space (3/4)

- A cooperative tracking system can be envisaged on future spacecraft where the object in space broadcasts its position (like AIS for ships or ADSB for aircraft)
  - Would help the correlation between catalogued objects and physical objects
  - Need to be reliable and working even after object end of operational lifetime (objects to be removed are usually defunct)

- It would only concern the objects to be launched in the future, a small fraction of the potential candidate objects for a removal mission
  - Not really significant to change the name of the game of the cataloguing in space.
  - NB: The beacon can also be used for proximity operations in space

Contribution 1: Maintaining a catalogue of objects in space (4/4)

- Ways to improve the tracking of spacecraft by SSA assets
  - Embark retro-reflector arrays to ease satellite laser ranging (also on spacecraft not devoted to ILRS)



Retro reflector for ILRS. Should be downsized for larger use

NB: other means of observation (optical and RF) are already efficient on spacecraft potentially concerned by a removal mission

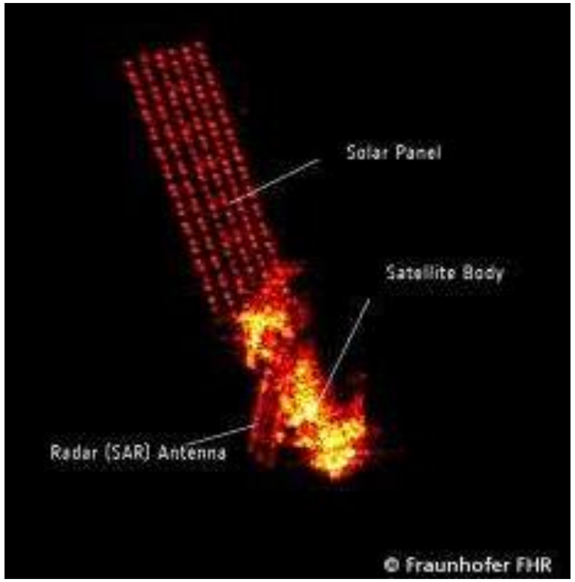
  - Alternatively, promote in Europe the development of laser tracking system on non cooperative objects (with performances similar to what is achieved by EOS in Australia)
    - This would require the use in space of more powerful laser (may be seen as a weaponization of space). Need for international cooperation and exchange on the subject

3. Quantitative evaluation of SDRS techniques - SSA Contribution 2: Giving information on their shape (1/3)

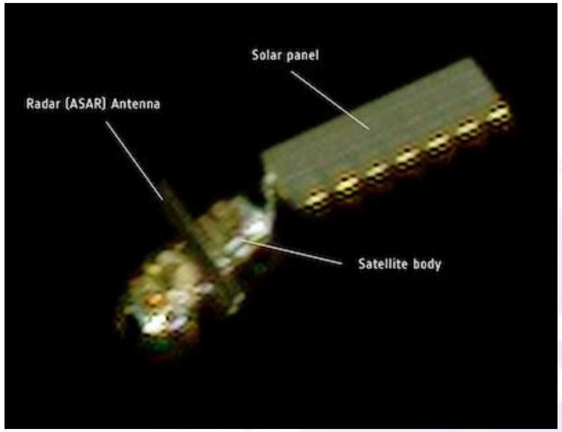
- The shape of the object is important to design a removal mission (choice of the system to « grasp » the object)
  - It provides indications on the mass of the object (if not provided by the owner of the object)
  - It gives indications on the inertia of the object (with assumptions on the used materials)

- The shape can be retrieved by different methods
  - The most straight forward is imagery (from the ground or space)
  - Indirect methods are based on the sensing of a parameter that depends on the shape of the object
    - e.g. the variation of the radar cross section (RCS)/reflected light during a pass over a ground radar or optical sensor
    - the variation of RCS/ reflected light, in particular due to speckle/specular reflection gives indication on object surface orientation

- For imagery, low image resolution (of the order of 1/10th of the object size) is sufficient for overall shape
  - Optical or radar means can be used, from space or ground
    - Optical imaging in LEO from the ground at such resolution requires active optics to mitigate the degradation of the resolution coming from the turbulence of the atmosphere
    - Radar imaging in LEO from the ground is possible with large radars (e.g. TIRA in Germany)
    - Space to space imaging is possible, but rare (due to high relative velocity)



Ground radar imagery with TIRA

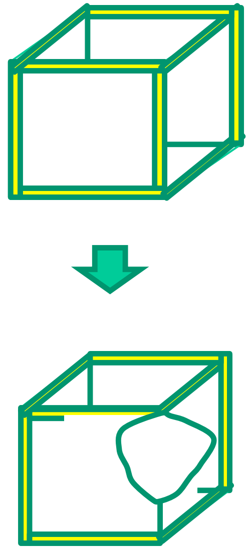


Space optical imagery with Pleiades

ThalesAlenia Space
A Thales / Finmeccanica Company

3. Quantitative evaluation of SDRS techniques - SSA Contribution 2: Giving information on their shape (3/3)

- Ways to improve the quality of the imaged objects
  - Use reflective material at the limit of the object
    - This would be particularly useful to investigate the integrity of an object (e.g. change of the structure after a mission loss)
    - Low cost solution with little impact on the mass and design of the spacecraft (use of highly reflective adhesive bands)



- Use contrasted colors on the spacecraft (e.g. black MLI instead of gold MLI around white reflective surface)
  - The resolution (capacity to interpret an image) depends on the contrast in the image
  - This may be unbeneficial for the detection of the object (less reflectivity of the black MLI versus the golden one)

3. Quantitative evaluation of SDRS techniques - SSA Contribution 3: Giving indications on the attitude (1/2)

- The rotation rate of the object is important to know to design a removal mission (choice of the system to « grasp » the object)
  - Only « low rotating » objects can be grasped

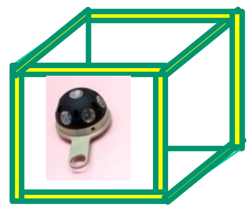
- The rotation rate of the object can be retrieved by
  - looking at the frequency of the information collected during the observation
    - e.g. Light curves collected by a telescope, evolution of the Radar Cross Section
  - Imaging at high frequency a space object (at least twice the rotation rate)

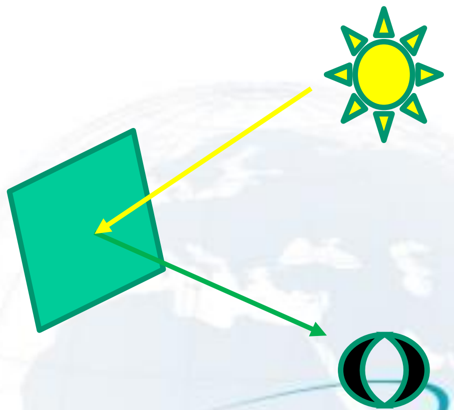
- Not so easy to achieve since
  - The shape impacts the estimation of the frequency
  - The face exposed to the observed may change with time (due to relative geometry)

3. Quantitative evaluation of SDRS techniques - SSA Contribution 3: Giving indications on the attitude (2/2)

- Impact on the sensor side
  - To retrieve the frequency of the collected signal, the acquistion shall be fast (e.g. use of CMOS technology instead of CCD at optical sensor level to shorten read-out time)

- Impact on the spacecraft design
  - Differentiate the faces of the satellite as seen by the sensor, e.g. put a retro reflector on only one side
    - to know when/whether this face is toward the laser tracking system
    - to have an reliable indication of the rotation rate (and not a multiple)
  - Use/introduce material with high specular reflections and of different colors (to know which one is reflecting from the spectrum analysis)





- Spacecraft design can ease the supporting functions of SSA for a Removal Mission through

  - Change/increase of the reflectivity of the spacecraft
    - With a dedicated device (typically retro-reflector arrays)
    - With a modification of the external surface properties (highly reflective materials)

  - Introduction of a difference in the reflectivity/spectrum response between the faces of the satellite
    - To know which face is directed towards the sensing asset of the SSA
    - To estimate the rotation rate

  - Introduction of a difference in reflectivity/spectrum response <u>within</u> a face of a satellite (to ease imagery by increasing the constrast)

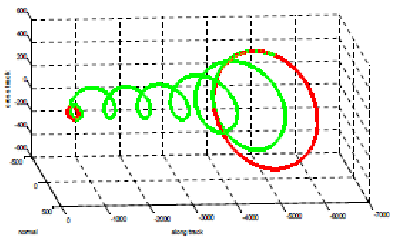
3. Quantitative evaluation of SDRS techniques - SSA

		development cost	recurrent cost	Power	Mass	Dimensions	TRL	Inertia	Reduction in Mission Risk	Increase in Complexity to chaser	Synergy with in-orbit servicing	Total
	LEO Pounderation	1,9	5,0	7,0	7,0	6,0	1,0	5,0	10,0	8,1	4,0	
SSA												
SDRS-1-1	Reflector for laser tracking	3	3	3	3	2	3	3	3	2	3	150,9
SDRS-1-2	In-situ RF device tracking	2	1	1	1	1	2	1	3	1	3	85,9
SDRS-1-3	reflective material	3	3	3	3	3	3	3	2	2	3	146,9
SDRS-1-4	CMOS techno	1	2	1	2	2	2	3	2	1	2	98,0
	GEO Pounderation	2,1	3,1	5,0	6,0	6,0	1,0	5,0	10,0	8,9	7,9	
SSA												
SDRS-1-1	Reflector for laser tracking	3	3	3	3	2	3	3	1	2	3	130,1
SDRS-1-2	In-situ RF device tracking	2	1	1	1	1	2	1	3	1	3	85,9
SDRS-1-3	reflective material	3	3	3	3	3	3	3	2	2	3	146,9
SDRS-1-4	CMOS techno	1	2	1	2	2	2	3	2	1	2	98,0
	Constellation Pounderation	2,0	5,0	7,0	9,0	8,0	1,0	6,0	10,0	4,0	3,0	
SSA												
SDRS-1-1	Reflector for laser tracking	3	3	3	2	2	3	3	3	2	3	144,0
SDRS-1-2	In-situ RF device tracking	2	1	1	1	1	2	1	3	1	3	85,9
SDRS-1-3	reflective material	3	3	3	3	3	3	3	2	2	3	146,9
SDRS-1-4	CMOS techno	1	2	1	2	2	2	3	2	1	2	98,0
	Launcher upper stage	2,3	4,9	0,0	10,0	7,5	1,0	8,8	6,2	3,6	0,0	
SSA												
SDRS-1-1	Reflector for laser tracking	3	3	3	3	2	3	3	3	2	3	121,8
SDRS-1-2	In-situ RF device tracking	2	1	1	1	1	2	1	3	1	3	60,0
SDRS-1-3	reflective material	3	3	3	3	3	3	3	2	2	3	123,1
SDRS-1-4	CMOS techno	1	2	1	2	2	2	3	2	1	2	91,5

- 3. Quantitative evaluation of SDRS techniques
  - 3.2 RdV & vision

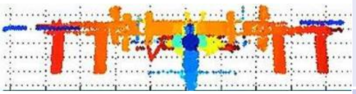
3. Quantitative evaluation of SDRS techniques - RdV

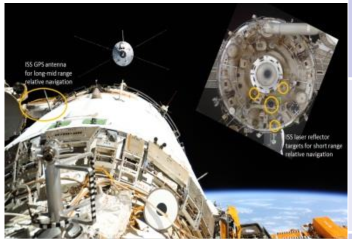
Rendez-vous



Solutions	In D4R scope	Type of solution at debris level	Rendez-vous: Long range approach	Inspection: close range approach	Reference
Radar on chaser	No	NA	X		Space Schuttle Ku-band rendezvous radar
Monocular monochromatic camera on chaser with spiral approach and reflective surface coatings (gold MLI) / sparkling ionized materials on debris	Yes	Passive	X		ADS E-deorbit study: Close Range GNC approach for a rendezvous with a tumbling target
Laser ranging with reflectors on debris	Yes	Passive	X		None
GPS & RF communication on debris	Yes	Active	X		ISS relative GPS for rendezvous
RF Beacon on debris	Yes	Active	X		None
LED or light emission on debris with autonomous power system and spiral approach	Yes	Passive	X		None

Inspection:



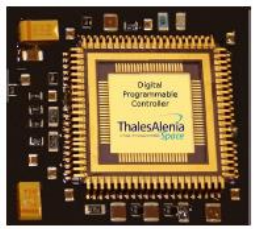


Solutions	In D4R scope	Type of solution at debris level	Rendez-vous: Long range approach	Inspection: close range approach	Reference
Radar on chaser	No	NA			Car radars for collision avoidance
LIDAR / 3D / TOF camera on chaser & illumination	No	NA		X	ATV5 LIDAR
Videometers and telegoniometers with reflectors on debris	Yes	Passive		X	ATV and ISS rendezvous sensors
Pose estimation with reflective tapes / markings on debris	Yes	Passive		X	STORRM planar reflectors
Pose estimation with LED with autonomous power system on debris	Yes	Passive		X	Tango / Mango rendez-vous (Prisma mission)
Multi-chromatic camera on chaser & Surface coatings / MLI with a color per side on debris to detect damages	Yes	Passive		X	None
Gyroscope & RF communication on debris	Yes	Reactivated		X	None

3. Quantitative evaluation of SDRS techniques - RdV

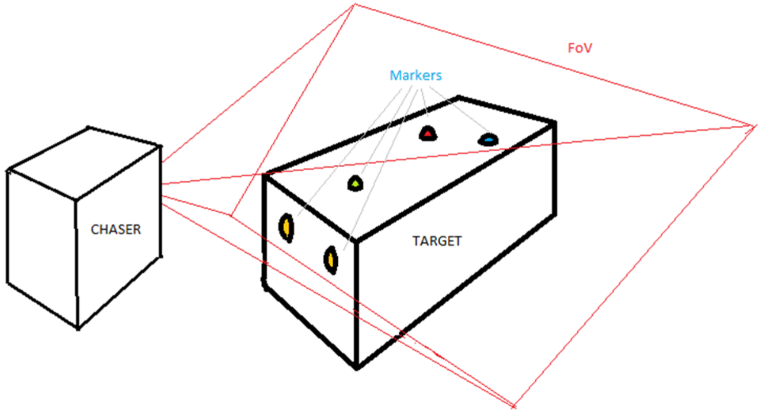
- Reactivated solutions
  - Solutions including:
    - A ‘wake-up system’
    - And a system with independent power system for possibly: passive/active Stabilization, active Docking or direct Removal
  - Solutions based on a ‘Button wake-up system’:
    - Activated by a projectile thrown by the chaser
  - Solutions based on a ‘Telecommand wake-up system’:
    - Activated by close range RF system with multiple standby mode activation of limited time (could be at a monthly frequency TBC to save power)
    - ISIS TXS S-band transmitter

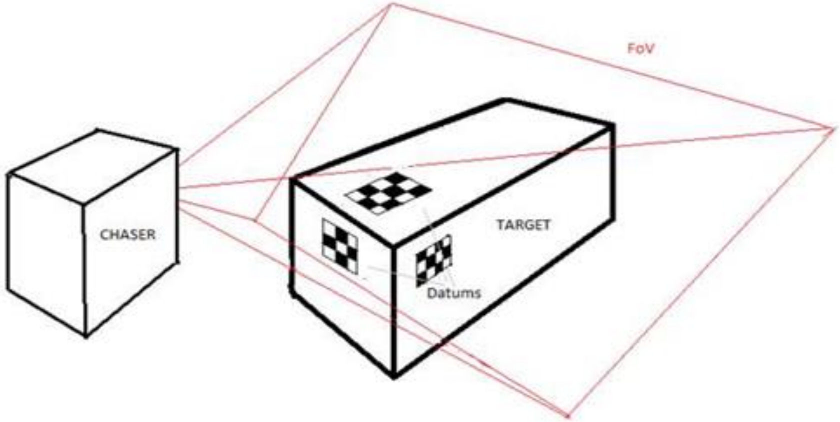
  - Large constraints on power and thermal design
  - For stabilization:
    - Possibility to use Possible use of DPC Micro-controller

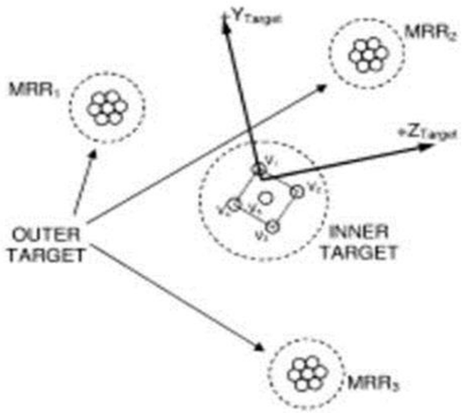


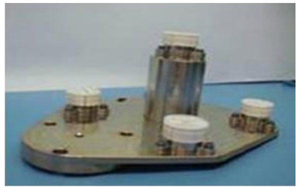
3. Quantitative evaluation of SDRS techniques - RdV

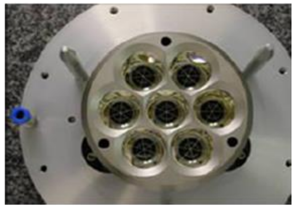
- Markers
  - Punctual
    - On several faces
    - Limited benefit at very short range
  - 2D markers / reflective tapes
    - Same constraints
  - 3D markers
    - Adapted to close range

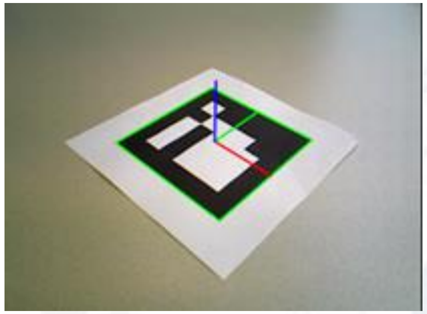












3. Quantitative evaluation of SDRS techniques - RdV

		development cost	recurrent cost	Power	Mass	Dimensions	TRL	Inertia	Reduction in Mission Risk	Increase in Complexity to chaser	Synergy with in-orbit servicing	Total
	LEO Pounderation	2,0	5,0	8,0	8,0	8,0	1,0	5,0	10,0	4,0	4,0	
RdV												
SDRS-2-1	retro-reflectors	3	3	3	3	2	3	3	3	2	3	153,0
SDRs-2-2	punctual markers or reflective tapes	2	3	3	3	3	2	3	2	2	3	148,0
SDRS-2-3	2D or 3D markers	2	3	3	3	3	2	3	3	2	3	158,0
SDRS-2-4	LED passive or reactivated	2	3	2	3	3	2	3	3	2	3	150,0
SDRS-2-5	gyro & RF	2	1	1	1	1	2	1	2	1	3	76,0
SDRS-2-6	Formation flying RF	2	2	1	2	1	2	2	1	1	2	80,0
	GEO Pounderation	2,0	3,0	5,0	6,0	6,0	1,0	5,0	10,0	8,0	9,0	
RdV												
SDRS-2-1	retro-reflectors	3	3	3	3	2	3	3	3	2	3	151,0
SDRs-2-2	punctual markers or ref lective tapes	2	3	3	3	3	2	3	2	2	3	144,0
SDRS-2-3	2D or 3D markers	2	3	3	3	3	2	3	3	2	3	154,0
SDRS-2-4	LED passive or reactivated	2	3	2	3	3	2	3	3	2	3	149,0
SDRS-2-5	gyro & RF	2	1	1	1	1	2	1	2	1	3	86,0
SDRS-2-6	Formation flying RF	2	2	1	2	1	2	2	1	1	2	81,0
	Constellation Pounderation	2,0	5,0	7,0	9,0	8,0	1,0	6,0	10,0	4,0	3,0	
RdV												
SDRS-2-1	retro-reflectors	3	3	3	3	2	3	3	3	2	3	153,0
SDRs-2-2	punctual markers or ref lective tapes	2	3	3	3	3	2	3	2	2	3	148,0
SDRS-2-3	2D or 3D markers	2	3	3	3	3	2	3	3	2	3	158,0
SDRS-2-4	LED passive or reactivated	2	3	2	3	3	2	3	3	2	3	151,0
SDRS-2-5	gyro & RF	2	1	1	1	1	2	1	2	1	3	74,0
SDRS-2-6	Formation flying RF	2	2	1	1	1	2	2	1	1	2	72,0

3. Quantitative evaluation of SDRS techniques

3.3 Stabilization

3. Quantitative evaluation of SDRS techniques - Stabilization

- Stabilization
  - Pb : most of stabilization technique needs to deploy a device
  - 1/ Not applicable to D4R for a satellite in failure mode
    - Or device to implement on the satellite to support ADR action for stabilization before capture
    - Focusing on solutions
      - Passive = by design
      - Embedded passive = activated by high tumbling without any support
      - Embedded active = transferred from ADR, or activated by TC
  - 2/ For in-orbit servicing, satellite will be controlled

3. Quantitative evaluation of SDRS techniques - Stabilization

- Stabilization
  - Different types:
    - Active control or passive (no control)
    - Active with actuators or with interactions
    - Active or passive control With embedded or transfered system
  - Different actuators
    - Orientable surfaces
    - MTB seem more reliable and robust

Embedded passive CTL (or activated)

Transfered passive CTL

Contactless interactions

Embedded actuators

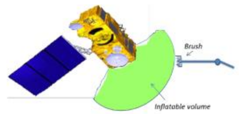
Transfered actuators

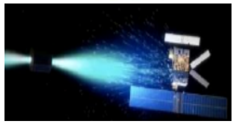
Contact interactions

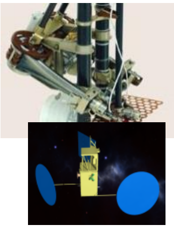
More complexity at chaser lever

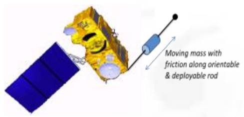
3. Quantitative evaluation of SDRS techniques - Stabilization

Stabilization









Solutions	In D4R scope	Type of solution at debris level	Type of stabilization	Reference
Brush based rate damping with inflatable surface on debris	Yes	Pseudo active	Contact interactions	None
Chaser blowing / with ion beam on deployable/inflatable debris surfaces	Yes	Passive / Pseudo active	Contactless interactions	IBS
Magnetic rate damping with or without deployable dipole/magnets on debris	Yes	Pseudo active or passive		Truck brakes
Deployable mast on debris for gravity gradient stabilization	Yes	Pseudo active	Embedded passive	None
Deployable surfaces on debris for solar pressure stabilization	Yes	Pseudo active		None
Debris mechanical design optimized for gravity gradient / aerodynamic / solar pressure stabilization	Yes	Passive		None
Spin of the debris before passivation	Yes	Pseudo active		None
Energy dissipation system released on debris or Fluid damping	Yes	Pseudo active		None
Embedded AOCS on debris	Yes	Reactivated	Embedded actuators	None
Projectile with AOCS & interface for projectile reception on debris	Yes	Passive	Transferred actuators	**EASE**
Projectile with deployable mast & interface for projectile reception on debris	Yes	Passive	Transferred passive	None

3. Quantitative evaluation of SDRS techniques - Stabilization

		development cost	recurrent cost	Power	Mass	Dimensions	TRL	Inertia	Reduction in Mission Risk	Increase in Complexity ot Chaser	Synergy with in-orbit servicing	Total
	GEO	2,0	3,0	5,0	6,0	6,0	1,0	5,0	10,0	8,0	9,0	
RdV Stab												
SDRS-3-1	friction by contact	3	3	3	1	1	1	2	1	1	1	80
SDRS-3-2	Blowing from chaser / laser ablation	3	3	3	2	3	1	3	2	1	1	113
SDRS-3-3	IBS / Plume inpingement	3	3	3	2	3	1	3	2	1	1	113
SDRS-3-4	magnetic damping (deployed magnets)	2	2	1	2	3	1	2	1	1	1	83
SDRS-3-4	magnetic damping (MTB short circuit)	3	3	3	3	3	2	3	1	1	1	110
SDRS-3-5	tether	2	2	2	2	2	1	2	1	1	1	82
SDRS-3-6	fluid damper	1	2	3	2	2	1	2	3	3	3	139
SDRS-3-7	deployable mast	2	2	2	1	1	2	1	1	1	1	66
SDRS-3-8	solar sail	1	2	2	1	1	1	1	2	2	1	81
SDRS-3-9	spin function of velocity	2	3	1	3	3	1	3	1	1	1	97
SDRS-3-10	design	1	2	3	2	2	1	3	3	1	2	119
SDRS-3-11	embedded AOCS	2	1	1	2	1	2	2	3	3	3	123
SDRS-3-12	passive interface for transferred AOCS	2	3	3	2	2	2	2	3	1	1	111
SDRS-3-13	passive interface for fixation of deployable mast	2	3	3	2	2	2	1	2	1	1	96
SDRS-3-14	Stack	3	3	1	3	3	3	3	1	3	3	135

3. Quantitative evaluation of SDRS techniques - Stabilization

		development cost	recurrent cost	Power	Mass	Dimensions	TRL	Inertia	Reduction in Mission Risk	Increase in Complexity ot Chaser	Synergy with in-orbit servicing	Total
	LEO Pounderation	2,0	5,0	8,0	8,0	8,0	1,0	5,0	10,0	4,0	4,0	
RdV Stab												
SDRS-3-1	friction by contact	3	3	3	1	1	1	2	1	1	1	90
SDRS-3-2	Blowing from chaser / laser ablation	3	3	3	2	3	1	3	2	1	1	129
SDRS-3-3	IBS / Plume inpingement	3	3	3	2	3	1	3	2	1	1	129
SDRS-3-4	magnetic damping (deployed magnets)	2	2	1	2	3	1	2	2	2	1	105
SDRS-3-4	magnetic damping (MTB short circuit)	3	3	3	3	3	2	3	2	3	2	150
SDRS-3-5	tether	2	2	2	2	2	1	2	1	3	1	99
SDRS-3-6	fluid damper	1	2	3	2	2	1	2	3	3	3	133
SDRS-3-7	deployable mast	2	2	2	2	1	2	1	2	2	1	93
SDRS-3-8	solar sail	1	2	2	2	1	1	1	2	2	1	90
SDRS-3-9	spin function of velocity	2	3	1	3	3	1	3	1	1	1	109
SDRS-3-10	design	1	2	3	2	2	1	3	3	1	2	126
SDRS-3-11	embedded AOCS	2	1	1	2	1	2	2	3	3	3	107
SDRS-3-12	passive interface for transferred AOCS	2	3	3	2	2	2	2	3	1	1	125
SDRS-3-13	passive interface for fixation of deployable mast	2	3	3	2	2	2	1	2	1	1	110
SDRS-3-14	Stack	3	3	1	3	3	3	3	1	3	3	129

- 1/ Fluid damper 2/ Stack for servicing for GEO 3/ Magnetic damping
- 4/ Transferred AOCS 5/ Design 6/ Blowing/plume/laser

3. Quantitative evaluation of SDRS techniques

3.4 Capture

3. Quantitative evaluation of SDRS techniques - Capture

- A review of the current capture techniques and mechanisms, including some new concepts, have been assessed.

  The solutions have been collected in two families depending on the main dynamic behavior of the chaser/target connection element:

  - the Rigid Capture family encompasses the techniques relying on robotic arms and/or docking interfaces. Robotic arm technique has been considered in the stand-alone solution and with a docking/clamping mechanism to stiff engagement of the composite
  - the Flexible Capture family collect all the techniques that involve connection elements mainly exchanging forces along their line of action of the connection element (e.g. tethers).

An SDRS assessed solution seems promising for debris removal, mainly if mounted before launch. This solution, shown later in the presentation, is a bit out of the capture technique scenarios (decommissioning only).

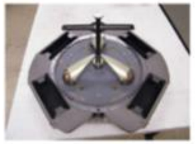
3. Quantitative evaluation of SDRS techniques - Capture

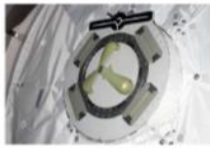
State of the art Review

1 **Canadarm 2**

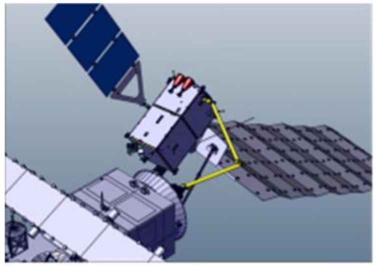

FRGF

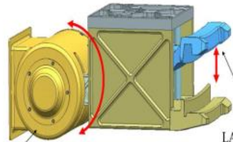

PDGF

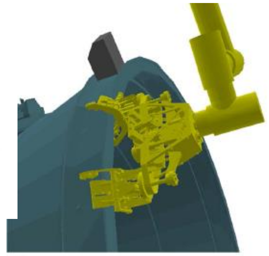

LGF


PVGF (grapple shaft not shown)

4 **ESA E-DeOrbit study concept**

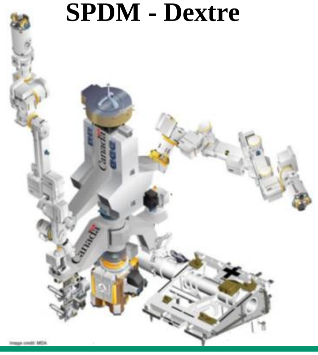



Alignment Mechanism (Rotary Joint)
LAR Clamping Mechanism (Vise)

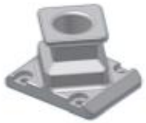


Credits: MDA

2 **SPDM - Dextre**



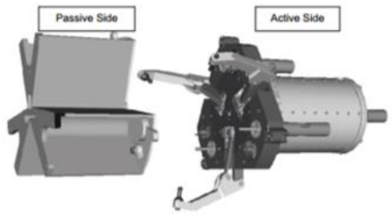

H-Fixture


Micro-fixture


Micro-Conical Fitting (MCF)

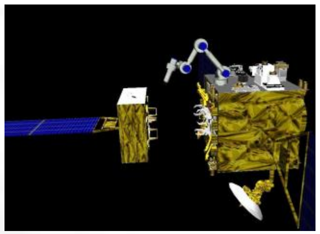
Credits: MDA

5 **Orbital Express Demonstration System**



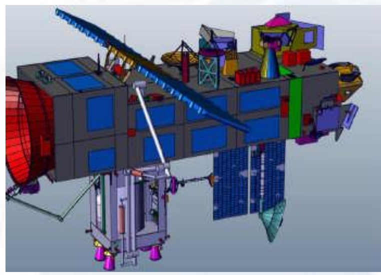
Credits: DARPA

3 **Engineering Test Satellite VII**



Credits: NASDA

6 **ESA E-DeOrbit study concept**



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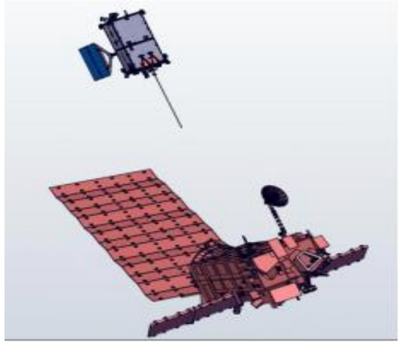
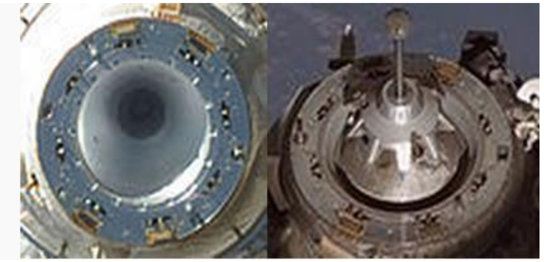
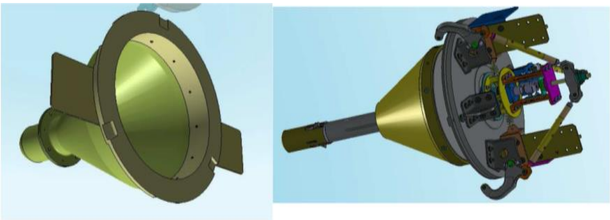
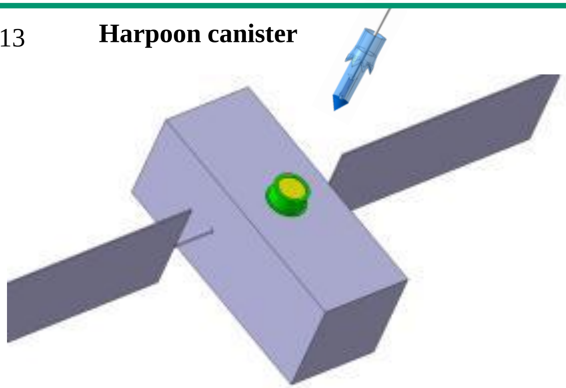
State of the art Review

7 **IBDM (Androgynous)** 	10 **Harpoon** 
8 **Modern Russian probe and drogue docking system** 	11 **APAS-95** 
9 **TAS-I docking mechanism** 	12 **Thurster for removal** 

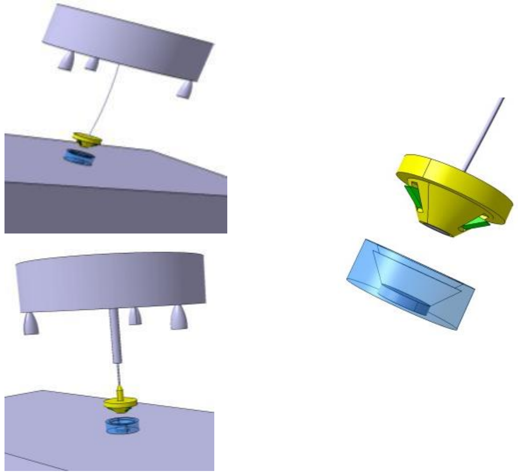
3. Quantitative evaluation of SDRS techniques - Capture

New ideas

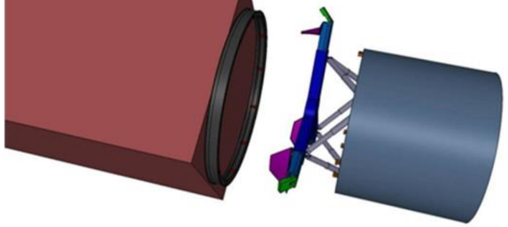
13 **Harpoon canister**



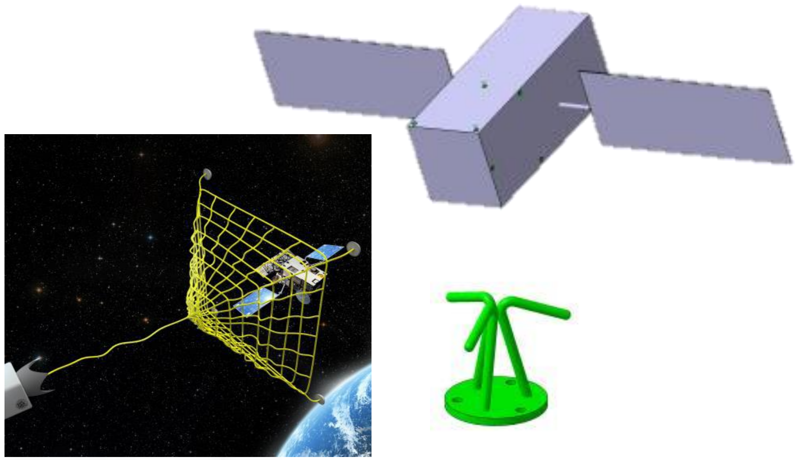
15 **TAS-I semi-rigid tether magnetic capture**



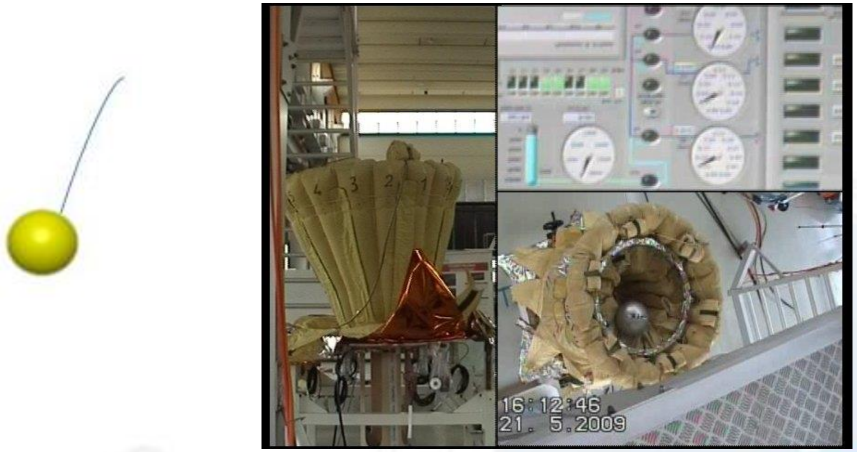
16 **TAS-I Soft/Stiff Clamping Mechanism Hard docking capability**



14 **Tether - Net**



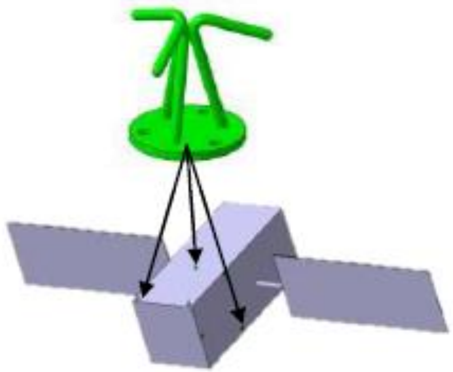
17 **TAS-I Inflatable Capture Mechanism**



Capture Technique: Flexible Capture – Net

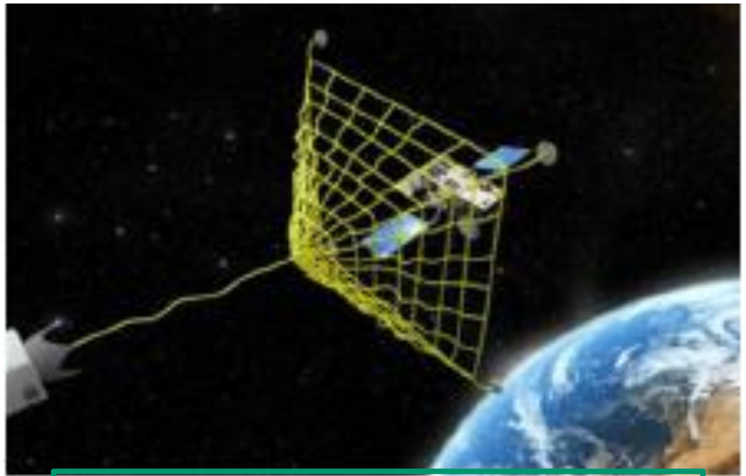
Solution based on the deployment of a net toward the target to allow its capture; the link is made through a tether

- Dedicated interfaces "hook style" to facilitate the net capture needed on Target



- Reflectors to align the target and the chaser prior the net launch.

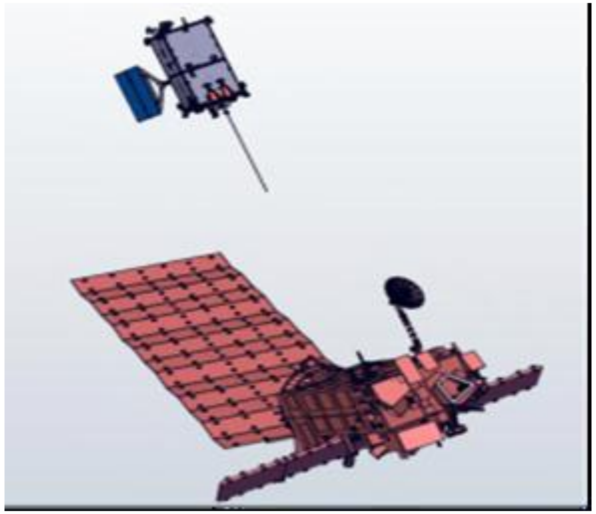
- Post-capture stabilisation: Further target stabilisation after capture and the successive orbit manoeuvres are a challenging control task because the relative chaser/target position must be maintained relying on a tether that acts simply along its straight line and in stretching. Anyway, after contact, the net acts as a passive damper in case of residual target/chaser relative rotational motion.



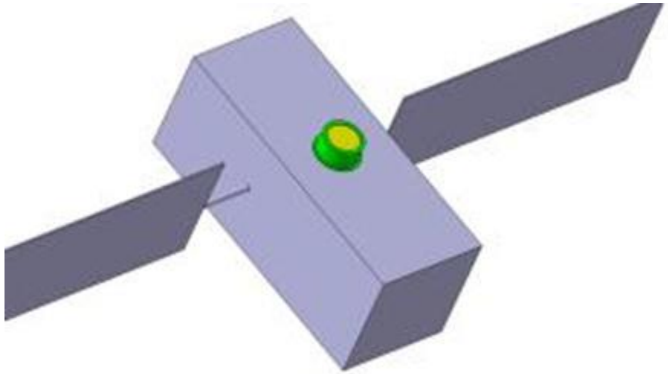
http://www.esa.int/gsp/ACT/doc/MAD/pub/ACT-RPR-MAD-2013-04-KW-CleanSpace-ADR.pdf

Capture Technique: Flexible Capture – Harpoon

Solution based on the Harpoon launched from chaser to target for generating a flexible link between the S/C.

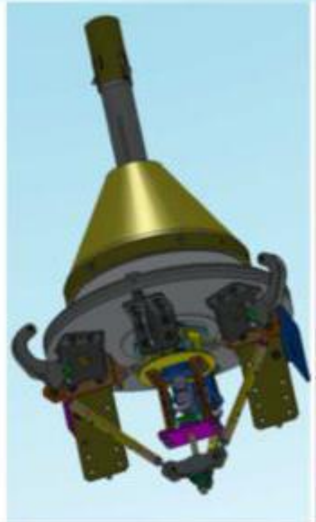


- Dedicated harpooning interface on target to eliminate risks of debris generation due to the harpoon impact.
- Reflectors to align the target and the chaser prior the harpoon launch.
- Post-capture stabilisation: Further target stabilisation after capture and the successive orbit manoeuvres are a challenging control task because the relative chaser/target position must be maintained relying on a tether that acts simply along its straight line and in stretching. Anyway, after contact, the net acts as a passive damper in case of residual target/chaser relative rotational motion.



Capture Technique: Rigid Capture – TASI probe and drogue

Solution based on docking mechanism; the probe is engaged for soft docking and retracted in order to fix rigidly the two vehicles by a second mechanism for the hard docking.



- Dedicated passive drogue on target.
- 2D markers or QR-like markers to be compliant with monocular camera. 3D Markers to be compliant with ToF Camera. Markers should be placed near the docking I/F in a way that are visible from very short distance to ensure proper alignment before docking. Known mechanism shapes can be used in place of 2D/3D markers at cost of higher complexity on IP algorithms on the chaser
- Post-capture stabilisation: No particular further stabilization after locking is required apart from some attitude recovery at the end of the stiffening phase likely followed by a settling time interval in case of presence of sloshing and/or flexible appendages

Capture Technique: Thrusters for Removal

Solution based on use of thrusters;

Post-capture stabilisation: the post-capture stabilisation is fully in charge of the device itself.

- Solution customizable for LEO, GEO and Constellation ADR removal missions
- Possible to assemble the system on S/C before launch.

- Capture Technique: Thrusters for Removal Manufacturer Infos
- Designed assuming the following Reference Missions:
  - Satellite Mass properties
    - mass=1400 [kg], max.inertia=2000[kgm2]
    - Maximum acceleration during Hohmann firings: 0.4 [m/s2]
    - First frequency: 0.25 [Hz]
  - LEO Orbit altitude: 750 [km]
    - Decommissioning strategies: Single Impulse/25 years re-entry
    - On-orbit lifetime: 10 years
  - MEO Orbit altitude: 23222 [km]
    - Decommissioning strategies: Hohmann transfer to a graveyard orbit 300 [km] above the nominal orbit
    - On-orbit lifetime: 20 years

- If mounted on-orbit, dedicated interfaces required

Thrusters on-orbit assembly requires a chaser equipped probably mechanisms (e.g. robotic arm), capable to reach the target and maintain required position and attitude

Thrusters for Removal dimensions can be an issue for the ADR configuration, mainly in case of on-ground installation

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Robotic ARM: Hints on the post-capture stabilization

The capturing phase involves physical interception and thus is highly risky. The goal would be to capture the moving target without destabilizing the attitude of the base spacecraft. Once the target is successfully captured, the combined system must be stabilized as soon as possible.

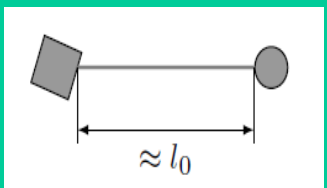
Usually in space applications the robotic arms are considered linked to bases that can be assumed:
Free-flying: case in which the base is actively controlled in position and rotation so that the servicing system is capable of being transferred and orientated arbitrarily in space, or actively controlled in rotation only;
Free-floating: case, in which the control of the base is inactive and thus, the base is completely free to translate and rotate in reaction to the manipulator motion

Free Floating: since it is difficult to sense the impact force precisely because impact is very high speed phenomenon and force sensor signal is very noisy, some Authors modeled the Collision dynamics, without sensing the impact force. They formulated the collision problem focusing on the velocity relationship just before and after the impact considering the momentum conservation law. Impedance control law is exploited for controlling the dynamic interaction of manipulators with the environment. Using estimated contact force and the observed target motion, an optimal capturing time and location are determined such that the resulting physical contact for capturing cause minimal attitude impact to the base spacecraft

Free Flying: To control the system after grasping the object, an adaptive approach could be employed considering the flexibility of the transported object. With the objective of reducing the disturbances on the base spacecraft during contact with the target, a control scheme of multi-arm cooperating manipulator has been proposed. Grasping a target satellite without considering its momentum imposes difficulties for the post-impact control, and most likely the capturing operation will fail. Once a manipulator has captured a target satellite, the manipulator and the target become a single system with combined mass properties and dynamics characteristics. In order for the controller to handle these changes, an adaptation law is preferable. Several Researchers proposed an adaptive controller for this purpose. They focused on the uncertainty of kinematic mapping, which included the dynamic parameters of the system. To achieve the desired input torques, a velocity-based-closed-loop servo control is used.

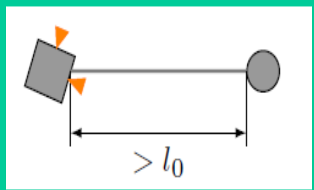
3. Quantitative evaluation of SDRS techniques - Capture

- Tether and Harpoon removal ask for a chaser able to guarantee stability along over the all deorbit maneuver:
  - The chaser to maintain the needed attitude during the burns
  - The chaser to ensure chaser-target safe relative position
- Main phases:



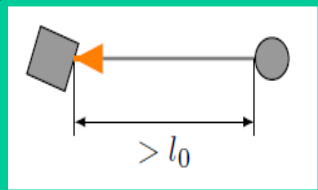
Parking

Chaser/target stack is maintained at a distance so that the tether is slack just to avoid it tangling around the target



Pre-tensioning

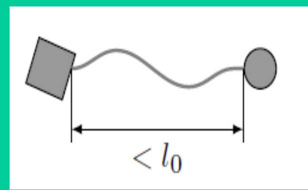
The chaser RCS pre-tensions the tether to avoid discontinuities in the exchanged forces when starting the de-orbit burn



Deorbit burn

Main engine is activated and the control must:

1. damp tether oscillations
2. maintain the target on the LVLH x-axis
3. the chaser to maintain the thrust direction



Stabilisation

Engine switch-off causes chaser target approach each other due to the tensioned tether and control must:

1. maintain the target on the LVLH x-axis
2. Maintain target in the camera FOV

3. Quantitative evaluation of SDRS techniques - Capture

		development cost	recurrent cost	Power	Mass	Dimensions	TRL	Inertia	Reduction in Mission Risk	Increase in Complexity to chaser	Synergy with in-orbit servicing	Total
	LEO Pounderation	1,9	5,0	7,0	7,0	6,0	1,0	5,0	10,0	8,1	4,0	
capture												
SDRS-4-1	Robotic arm ISS	2	2	3	2	3	3	2	2	1	3	119,9
SDRS-4-2	Robotic arm SPDM Dextre	3	3	3	3	3	3	3	2	1	3	138,8
SDRS-4-3	Robotic arm Frend	3	3	3	3	3	3	3	2	1	3	138,8
SDRS-4-4	Robotic arm eDeorbit	3	2	3	3	3	3	3	2	1	3	133,8
SDRS-4-5	Robotic arm ETS VII	3	2	3	2	1	3	3	2	1	3	114,8
SDRS-4-6	Robotic and clamp Orbital Express	3	2	3	2	1	3	2	2	1	3	109,8
SDRS-4-7	Rigid Peripheral attach system	2	2	3	2	2	3	2	3	2	2	128,0
SDRS-4-8	IDBM docking & berthing	2	2	3	2	2	3	2	3	2	2	128,0
SDRS-4-9	Russian probe and drogue	2	2	3	2	2	3	2	3	2	2	128,0
SDRS-4-10	TASI probe and drogue	2	2	3	2	2	3	2	3	2	2	128,0
SDRS-4-11	Hard clamping on launcher IF	3	3	3	3	3	3	3	1	1	2	124,8
SDRS-4-12	ASSIST	2	2	3	2	2	2	2	2	2	3	121,0
SDRS-4-13	Rigid capture tentacles	3	3	3	3	3	2	3	2	1	3	137,8
SDRS-4-14	Harpoon	3	3	3	2	3	2	3	2	3	1	135,0
SDRS-4-15	Net	3	3	3	3	3	2	3	2	3	1	142,0
SDRS-4-16	Inflatable capture mechanism	1	1	2	2	2	2	2	2	1	1	91,0
SDRS-4-17	Semi-rigid tether	2	2	3	3	2	1	2	1	3	1	117,1
SDRS-4-18	Rigid tether hybrid capture	2	2	3	3	2	1	2	1	2	1	113,0
SDRS-4-19	Balloon & net	3	3	3	3	3	2	3	2	2	1	137,9
SDRS-4-20	Deorbit system	2	2	3	2	1	2	2	2	1	1	98,9
SDRS-4-20-1	Deorbit system- on ground installation	3	3	1	3	1	3	2	3	3	1	126,0

3. Quantitative evaluation of SDRS techniques - Capture

		development cost	recurrent cost	Power	Mass	Dimensions	TRL	Inertia	Reduction in Mission Risk	Increase in Complexity to chaser	Synergy with in-orbit servicing	Total
	GEO Pounderation	2,1	3,1	5,0	6,0	6,0	1,0	5,0	10,0	8,9	7,9	
capture												
SDRS-4-1	Robotic arm ISS	2	2	3	2	3	3	2	2	1	3	121,0
SDRS-4-2	Robotic arm SPDM Dextre	3	3	3	3	3	3	3	2	1	3	137,2
SDRS-4-3	Robotic arm Frend	3	3	3	3	3	3	3	2	1	3	137,2
SDRS-4-4	Robotic arm eDeorbit	3	2	3	3	3	3	3	2	1	3	134,1
SDRS-4-5	Robotic arm ETS VII	3	2	3	2	1	3	3	2	1	3	116,1
SDRS-4-6	Robotic and clamp Orbital Express	3	2	3	2	1	3	2	2	1	3	111,1
SDRS-4-7	Rigid Peripheral attach system	2	2	3	2	2	3	2	3	2	2	126,0
SDRS-4-8	IDBM docking & berthing	2	2	3	2	2	3	2	3	2	2	126,0
SDRS-4-9	Russian probe and drogue	2	2	3	2	2	3	2	3	2	2	126,0
SDRS-4-10	TASI probe and drogue	2	2	3	2	2	3	2	3	2	2	126,0
SDRS-4-11	Hard clamping on launcher IF	3	3	3	3	3	3	3	1	1	2	119,3
SDRS-4-12	ASSIST	2	2	3	2	2	2	2	2	2	3	122,9
SDRS-4-13	Rigid capture tentacles	3	3	3	3	3	2	3	2	1	3	136,2
SDRS-4-14	Harpoon	3	3	3	2	3	2	3	2	3	1	127,8
SDRS-4-15	Net	3	3	3	3	3	2	3	2	3	1	133,8
SDRS-4-16	Inflatable capture mechanism	1	1	2	2	2	2	2	2	1	1	88,0
SDRS-4-17	Semi-rigid tether	2	2	3	3	2	1	2	1	3	1	111,0
SDRS-4-18	Rigid tether hybrid capture	2	2	3	3	2	1	2	1	2	1	106,5
SDRS-4-19	Balloon & net	3	3	3	3	3	2	3	1	2	1	119,3
SDRS-4-20	Deorbit system	2	2	3	2	1	2	2	2	1	1	92,2
SDRS-4-20-1	Deorbit system- on ground installation	3	3	1	3	1	3	2	3	3	1	122,2

3. Quantitative evaluation of SDRS techniques - Capture

		development cost	recurrent cost	Power	Mass	Dimensions	TRL	Inertia	Reduction in Mission Risk	Increase in Complexity to chaser	Synergy with in-orbit servicing	Total
	Constellation Pounderation	2,0	5,0	7,0	9,0	8,0	1,0	6,0	10,0	4,0	3,0	
capture												
SDRS-4-1	Robotic arm ISS	2	2	3	2	3	3	2	2	1	3	125,0
SDRS-4-2	Robotic arm SPDM Dextre	3	3	3	3	3	3	3	2	1	3	147,0
SDRS-4-3	Robotic arm Frend	3	3	3	3	3	3	3	2	1	3	147,0
SDRS-4-4	Robotic arm eDeorbit	3	2	3	3	3	3	3	2	1	3	142,0
SDRS-4-5	Robotic arm ETS VII	3	2	3	2	1	3	3	2	1	3	117,0
SDRS-4-6	Robotic and clamp Orbital Express	3	2	3	2	1	3	2	2	1	3	111,0
SDRS-4-7	Rigid Peripheral attach system	2	2	3	2	2	3	2	3	2	2	128,0
SDRS-4-8	IDBM docking & berthing	2	2	3	2	2	3	2	3	2	2	128,0
SDRS-4-9	Russian probe and drogue	2	2	3	2	2	3	2	3	2	2	128,0
SDRS-4-10	TASI probe and drogue	2	2	3	2	2	3	2	3	2	2	128,0
SDRS-4-11	Hard clamping on launcher IF	3	3	3	3	3	3	3	1	1	2	134,0
SDRS-4-12	ASSIST	2	2	3	2	2	2	2	2	2	3	120,0
SDRS-4-13	Rigid capture tentacles	3	3	3	3	3	2	3	2	1	3	146,0
SDRS-4-14	Harpoon	3	3	3	2	3	2	3	2	3	1	137,0
SDRS-4-15	Net	3	3	3	3	3	2	3	2	3	1	146,0
SDRS-4-16	Inflatable capture mechanism	1	1	2	2	2	2	2	2	1	1	96,0
SDRS-4-17	Semi-rigid tether	2	2	3	3	2	1	2	1	3	1	116,0
SDRS-4-18	Rigid tether hybrid capture	2	2	3	3	2	1	2	1	2	1	114,0
SDRS-4-19	Balloon & net	3	3	3	3	3	2	3	1	2	1	134,0
SDRS-4-20	Deorbit system	2	2	3	2	1	2	2	2	1	1	102,0
SDRS-4-20-1	Deorbit system- on ground installation	3	3	1	3	1	3	2	3	3	1	123,0

3.5 Quantitative evaluation of SDRS techniques for Launcher upper stage

Defined study case for launcher Upper Stages (US) is the present Vega commercial flight configuration.

It is based on Direct Re-Entry and, even in case of (full) failure, it does not generate any major concern since its uncontrolled re-entry max casualty is < 1 E-4, and orbital time (large amount of missions) is < 25 years.

In case a back-up re-entry system should be considered for Vega, the SDRS 4-20 (Deorbit System appoach) is preferred and can be based on a STANDARD «add-On» **deorbit module** integrated, on ground, between the PL Adapter and the PL (→ no need od RdV and docking mission)

Since such «add-On» **deorbit module** is characterised by using the STANDARD PL-Adapter interface flange, it will be suitable for utilisation even on other Launchers than Vega, as **BASELINE** actuator for a direct re-entry.

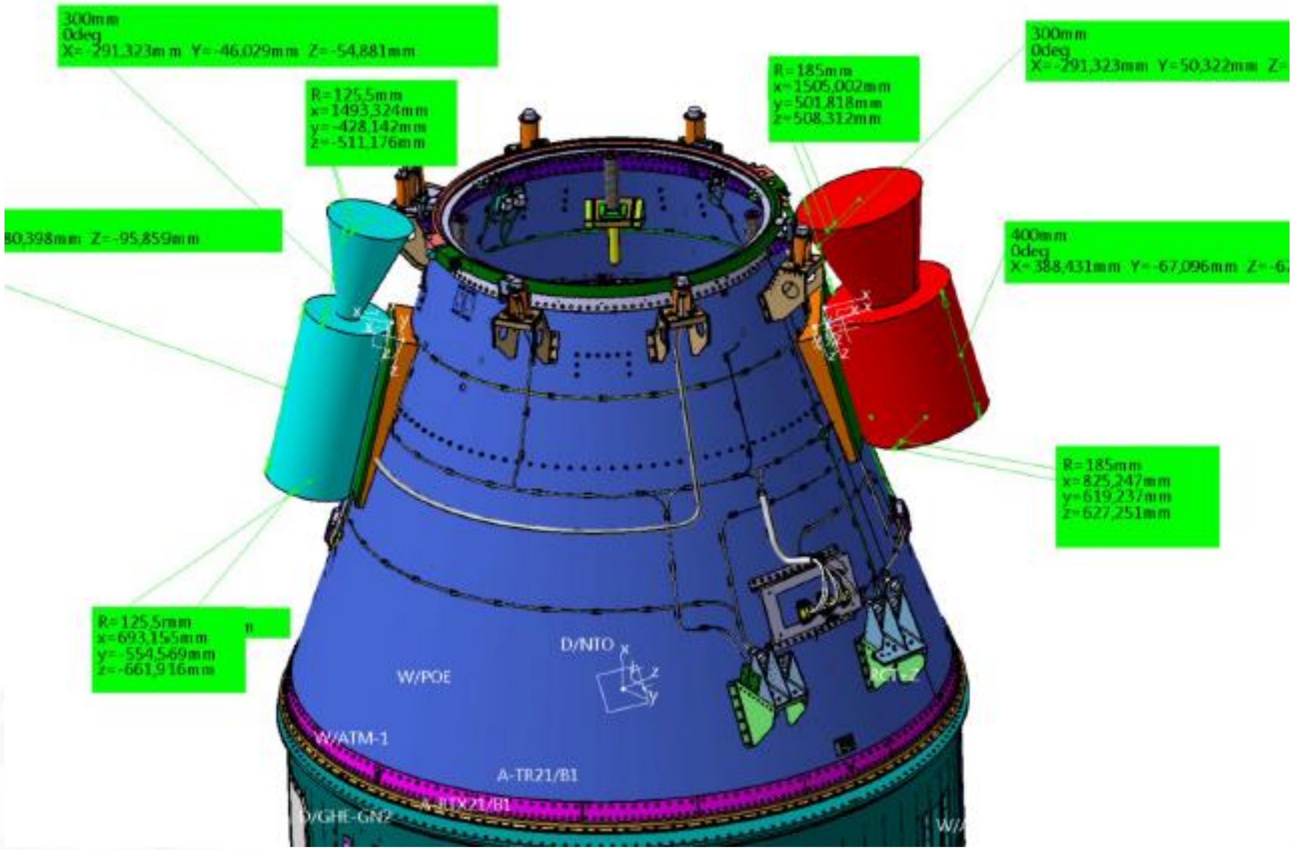
The scenario of integrating the module above on **an already orbiting US** seems not attractive from a cost/benefit ratio point of view since there are not INDIVIDUAL upper stages (over the several hundreds in orbit for several LV USSR and USA upper stage families) that constitute a major risk, so justifying a dedicated complex rendezvous and docking mission

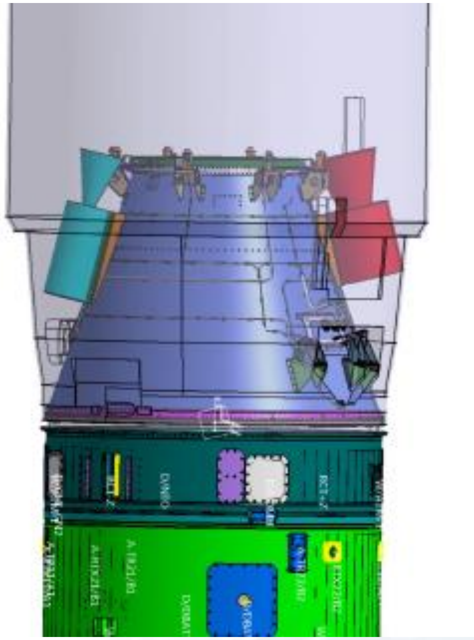
D3-LEO

1,000kg-Class LEO Platform, 649km Orbital Altitude, 10 Years Nominal Operational Life

	Single-Pulse Direct Controlled Re-Entry*	Dual-Pulse 1-Year Controlled Re-Entry	Dual-Pulse 25-Year Controlled Re-Entry
D3 Mass	85.5kg	75kg	41kg
Final Orbit After De-Orbiting Maneuver	80km x 694km	80km x 375km	80km x 540km
Motor Specific Impulse	280s		
ΔV Necessary For Disposal Maneuver	172.32m/s	87m/s + 36m/s	41m/s + 36m/s
Satellite Life Extension	3.6 years	3.8 years	4 years
Motor Diameter	370mm	319mm	251mm
Motor Length, Excluding Nozzle	400mm	527mm	524mm
Maximum Thrust	19.4kN	7.1kN	7.1kN
Time to Re-Entry	< 90 minutes	< 1 year	25 years
Re-Entry and Impact Zone	Controlled	Controlled	Controlled

Baseline design





26/04/2017

SRM support bracket design

Input	Value	comment
T : SRM max thrust force (N)	19400	worst case
b: thrust force moment arm (m)	0,5	conservative
W: bkt width (m	0,37	parallel to the thrust force
L: bkt lenght (m)	0,2	perpendicular to the thrust force
H: bkt height (m)	0,2	
t1: bkt panel thickness (m)	0,001	along L
t2: bkt panel thickness (m)	0,002	along W
Material:	Al 7075	pessimistic; will be probably utilized a fiber composite
Ro: density (Kg/m3)	2,80E+03	
Sy: yield strenght (N/m2)	4,48E+08	

Mass 1 kg / bracket

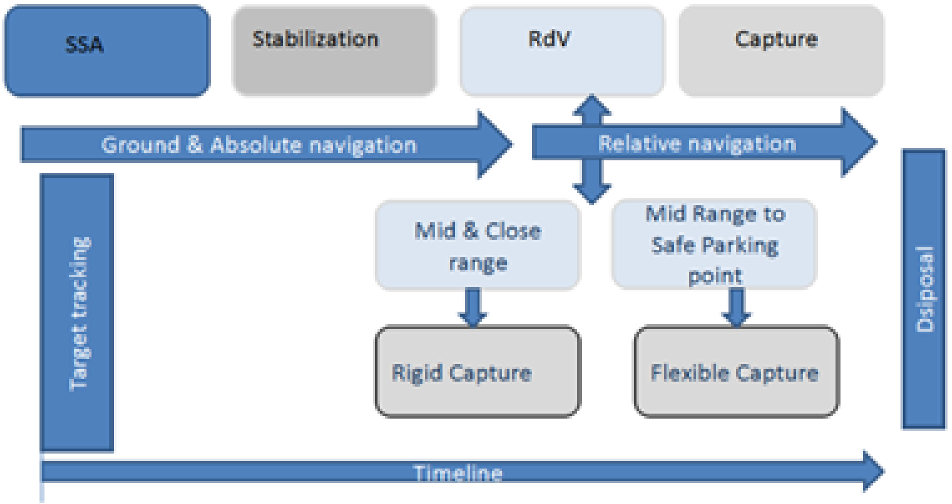
Impact mainly due to mechanical design loads on US during deorbiting

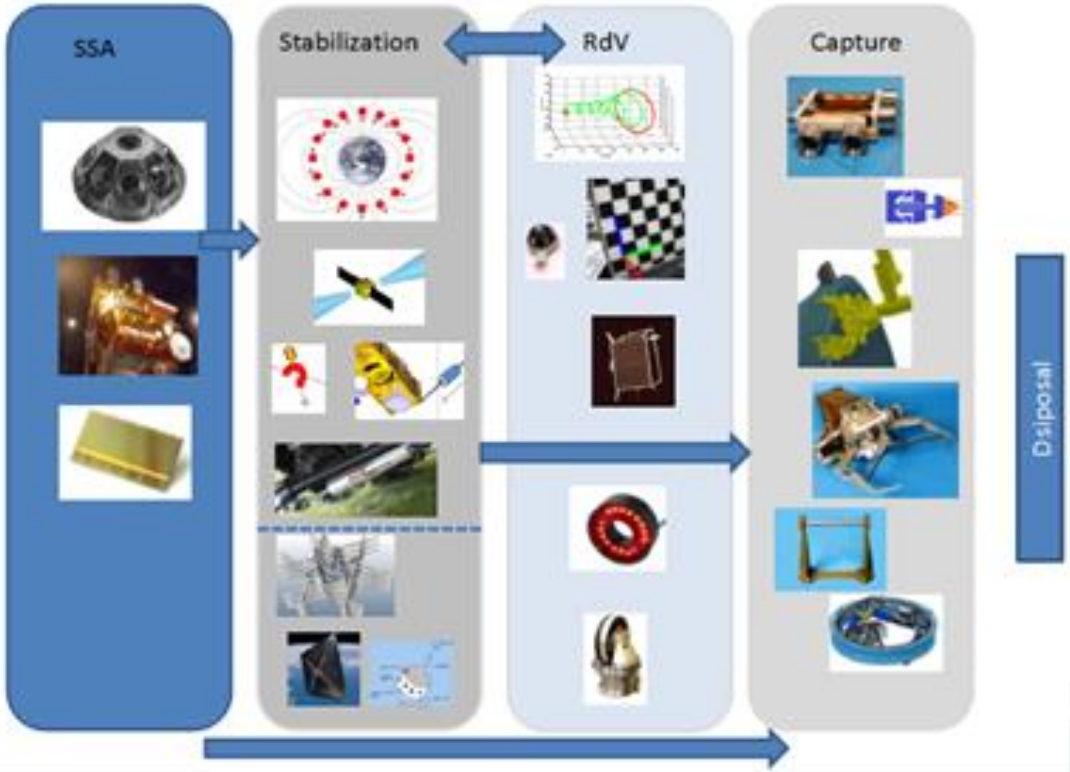
Risk of installation by ADR

- 4. Selected SDRS techniques preliminary performance
  - 4.1 SSA
  - 4.2 RDV & Vision
  - 4.3 Capture

4. Selected SDRS techniques preliminary performance

- Mix based on mission scenario timeline





- => mapping

4. Selected SDRS techniques preliminary performance

- SSA – Laser retro reflector
- For GEO
- Interference risk very low (narrow beam, no interferences)
- Preliminary sizing
  - Wavelength: Optimized at 532nm
  - Cross Section 1.68E-8 m^2
  - Mass <3kg
  - Cube Diameter: 40.6mm
  - Reflectors: 36
  - Reflectivity >75%
  - Size: 26cm x 30cm x 5cm (within an envelope)
- No power
- Passive

GPS 35/36 (US)	COMPASS / BEIDOU (China)	GIOVE (ESA)
Design of LRR in GEO		

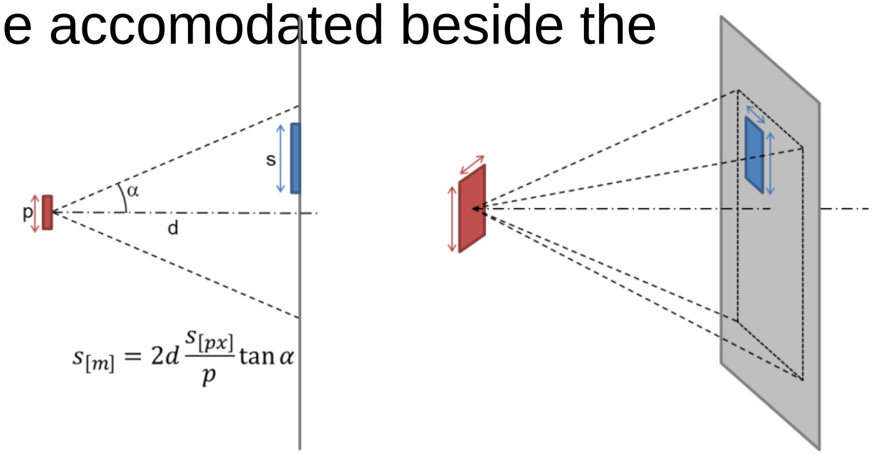
4. Selected SDRS techniques preliminary performance

- SSA – Radar corner reflector
- For LEO
- RF corner reflector for Mono-static radar (TIRA)
- Reflective surface for bi-static radar (Graves)
- Preliminary sizing for TIRA
    - L-band tracking aluminum cube
    - 4 cm for a satellite orbing at 800 km (length of the side edges)
    - 5 cm for a satellite orbing at 1000 km
    - Mass ~ 100g
  - No power
  - Passive

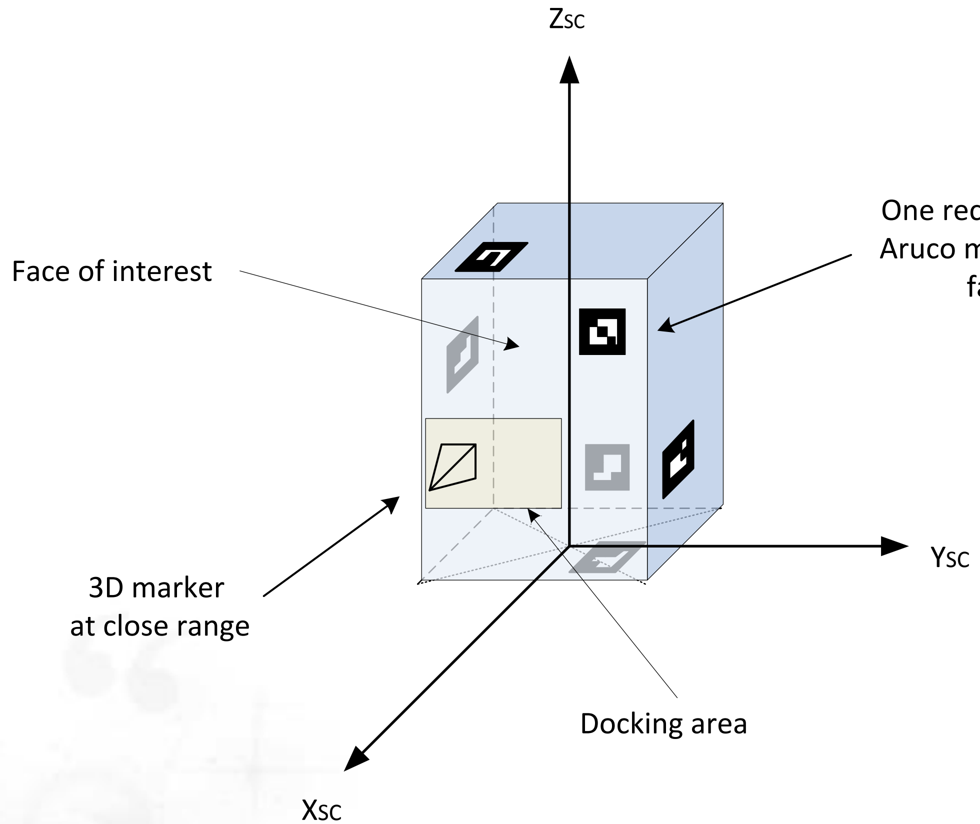
- 4. Selected SDRS techniques preliminary performance
  - 4.2 RDV & Vision

RDV in LEO : 2D/3D Marker

- Baseline design consists in the accommodation of Aruco makers on each face of the spacecraft plus a 3D marker that will be accomodated beside the docking/capture area at very close range.



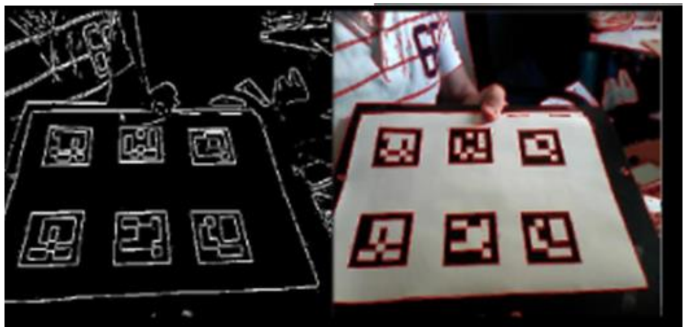
$$s_{[m]} = 2d\frac{s_{[px]}}{p}\tan\alpha$$



Property	Value
FoV [deg]	50 x 50
Rsolution [pixel]	1024 x 1024
Pixel size [µm]	24.5 x 24.5
Camera size [cm]	13.6 x 13.6 x 6.8 (without baffle)
Mass [g]	875
Power [W]	10

Chaser camera properties hypothesis

- RDV in LEO : 2D/3D Marker
  - The sizing of the markers depends highly on the chaser navigation architecture (camera FoV, detector resolution) and the approach strategy for RDV.
  - Aruco markers consist in 2D code included in a black border. In order to distinguish the 6 S/C faces, at least 3x3 elements code shall be considered.

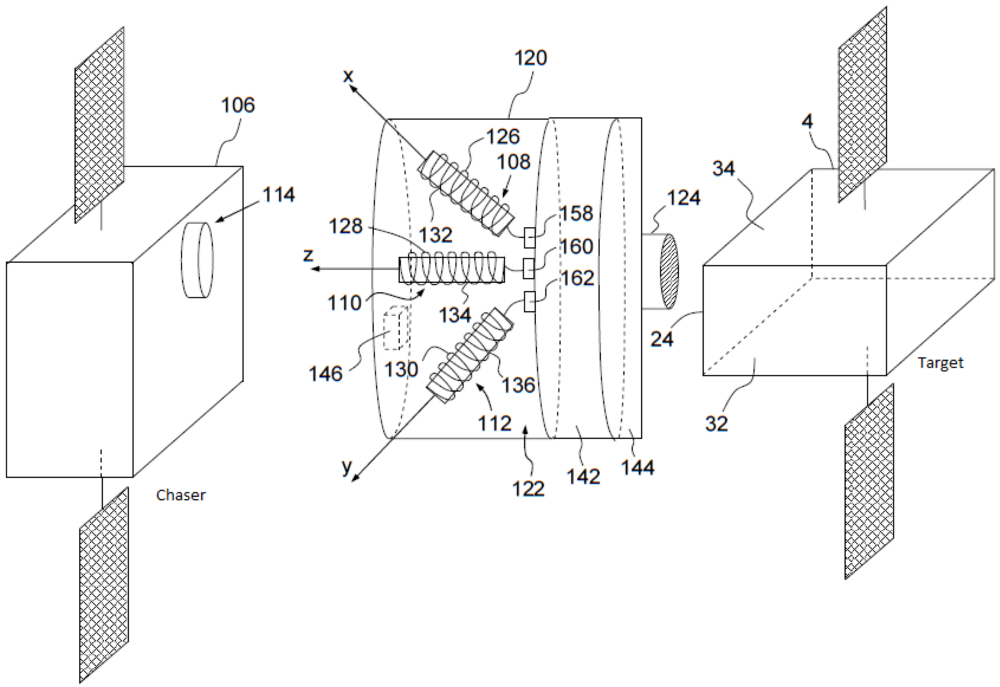


  - Aruco marker shall then be at least 5x5 elements.
  - Each element to be 2 pixels resoluted in the camera chaser detector frame.
  - Overall marker size in camera detector frame shall be at least 10x10 pixels.

4. Selected SDRS techniques preliminary performance

- RDV in LEO : 2D/3D Marker
  - Assuming a 30deg FoV camera and the objective of pose estimation at 10m distance, the size of the 2D Aruco maker shall be 11x11cm
  - At very close distance (1m assumed), the 2D Aruco marker may not stay inside the camera FoV. Hence, accomodation a 3D trihedric shape marker is proposed. Assuming the same camera chaser charateristics, a 2cm square device can be used.
  - Assuming a 2mm thickness device made of aluminium, the weight of the D4R device would be 400g per marker plus 70g for the 3D shape marker.
  - Starting from these assumptions, the overall mass budget for the concept is 2.07kg

- Stabilization in LEO: transferred AOCS
  - The proposed concept consists in the accommodation, via a capture device (harpon), of an AOCS device composed of 3 MTB, a battery used to power the MTB and a DPC controller used to command the MTB from the chaser.

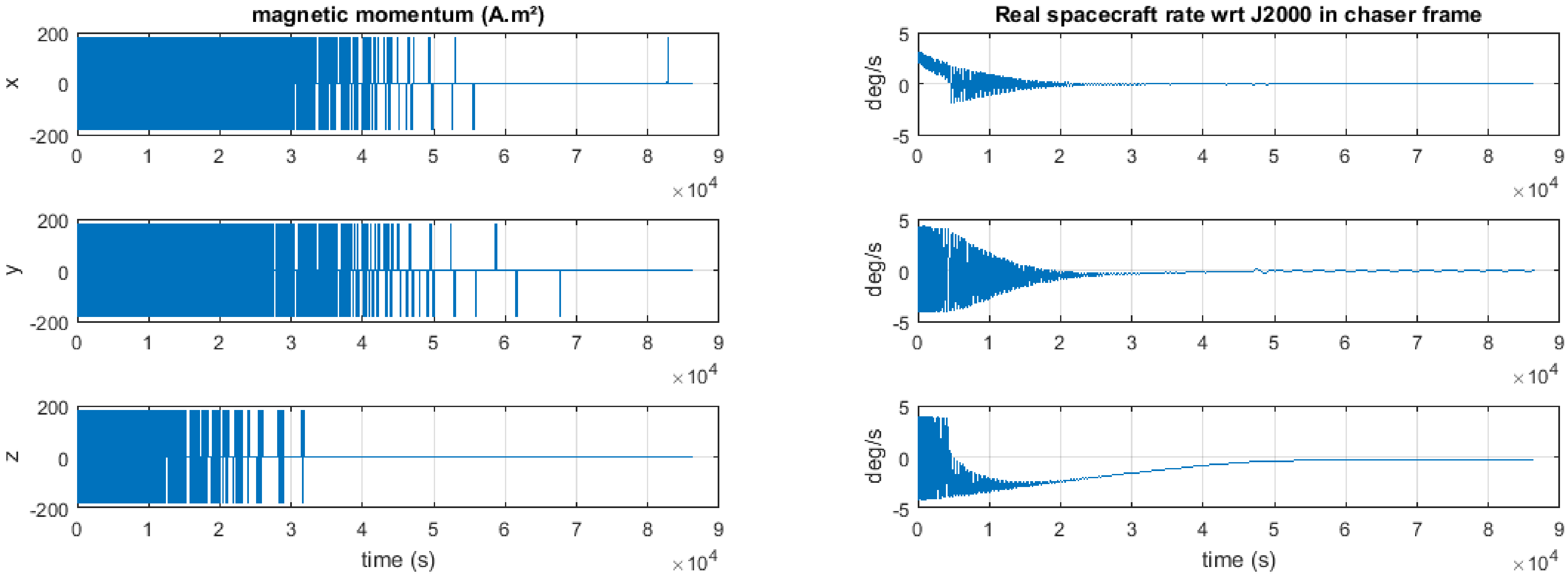


TAS-F pattented

4. Selected SDRS techniques preliminary performance

Stabilization in LEO: transferred AOCS

- No specific D4R device is needed on the Target spacecraft except the capture device already detailed in the dedicated section.
- Assessment of the stabilization concept has been done considering 180Am² MTBs (2.5kg, 7.3W consumption) and initial Target spacecraft angular rates of 5deg/s



4. Selected SDRS techniques preliminary performance

- Stabilization in LEO: transferred AOCS
  - The stabilization concept allows an overall rate damping duration of about 14h, including 9.65 hours of effective MTB actuation
  - A 70Wh battery capability shall be used. By analogy with devices currently available, the battery would have a 0.7kg mass and a 0.7dm3 volume.

- Stabilization for constellation: magnetic damping
  - Magnetic damping concept assessment
  - The method consists in assimilating the overall system to an asynchone machine in which:
    - The stator rotating magnetic field is the Earth magnetic field with a rotation velocity corresponding to the spacecraft angular velocity.
    - The rotor is the MTB coil set in short circuit in which a current is induced by the rotating magnetic field.
    - The magnetic moment of the rotor is then submitted to a torque equals on average:

$$\Gamma = \frac{1}{2}\left(\frac{R_r g \omega_s}{R_r^2 + L_r^2 g^2 \omega_s^2}\right) S^2 B_s^2$$

    - Numerical application provides an induced torque of 4^{e}-20Nm, which is far away from the actual needs for stabilization (H_rw_init = 130Nms).

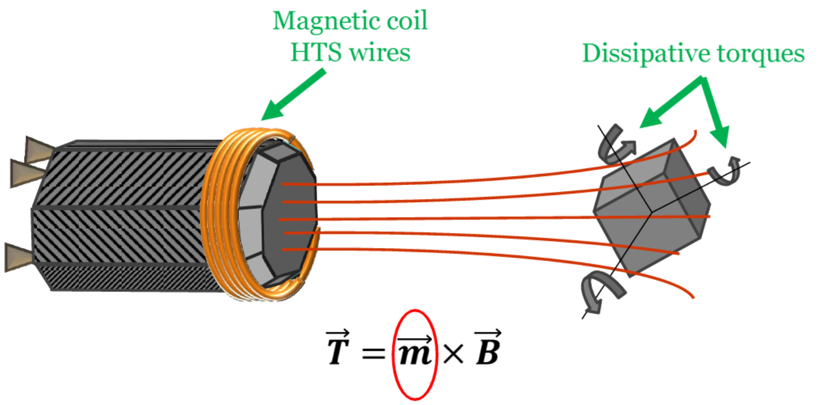
- Magnetic damping
  - MTB in short circuit

The concept is completly passive and requires the short circuit set-up of the Target spacecraft MTB.

The short-circuit set-up does not require specific device to be accomodated on the Target. The short-circuit set-up can be pre-programmed in the Target PCDU and be commanded at the end of the Target end-of-life passivation procedure

- Only passive solution is to increase by ADR

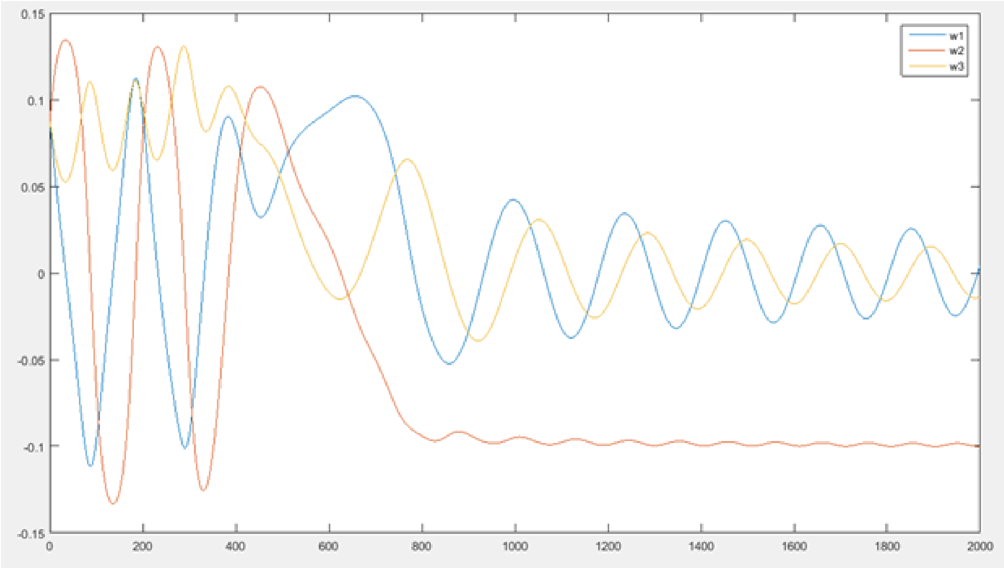
Need additional magnetic field increase



Need magnetic coil for detumbling
Credit AUAA SciTech Forum

- Fluid damping
  - Passive solution
  - Small steel balls in viscous fluid

Convert tumbling into spin around principal inertia axis



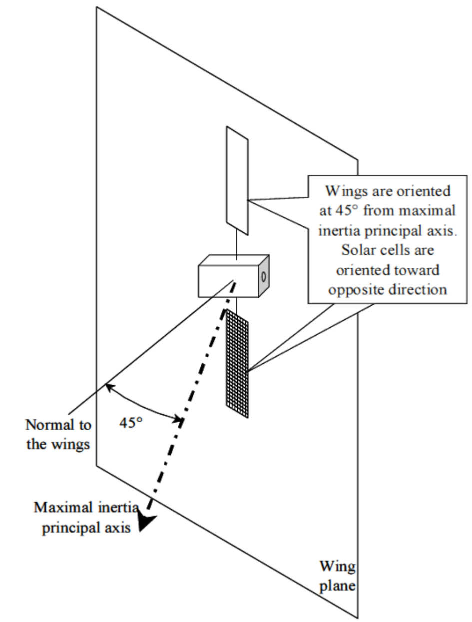
Fluid damping first evaluation for LEO case

  - Need consolidation of stabilization operations, selection of system parameters and mass control law

4. Selected SDRS techniques preliminary performance

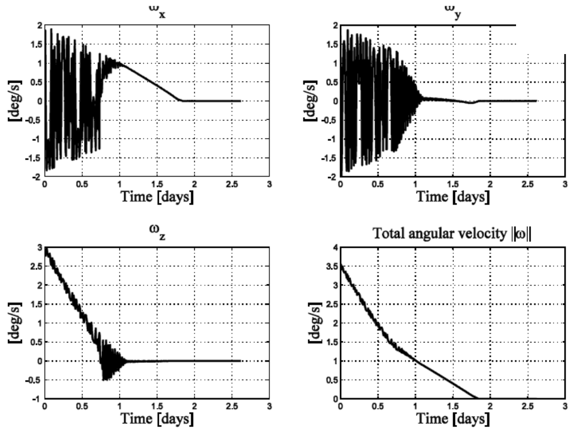
- Per Design
  - Use of eddy current effect
  - SA windmill

Efficient for PMD management



Satellite despin using solar sailing
Spin direction toward sun direction TBC in long term

- Blowing
  - IBS / Plume / Laser
  - ADR solution



Laser detumbling ablation – 100W
Material patches on debris
Remote control of the attitude
(credit IEEE conference 2015)

- 4. Selected SDRS techniques preliminary performance
  - 4.3 Capture

Capture Device - Robotic Arm

Baseline design

- Capture Device for Removal is based on two possible solutions:
  1. **Mechanical I/Fs (e.g. similar to the FRGF)**
  2. **LAR (Launch Adapter Ring –** e.g. Dia. 937 mm, 1194 mm**)**

Mechanical I/Fs are surely required for S/C which does not have a LAR (e.g. launched by dispenser) but a reasonable solution can be also having the mechanical interface used for berthing and the LAR used for final docking.

The proposed concept is similar to the FRGF device.

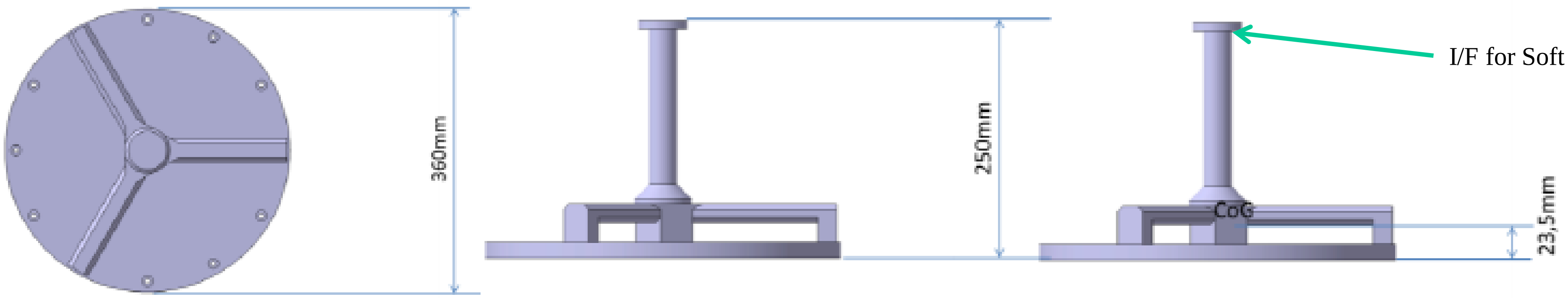
Reference data for Mechanical I/F conceptual sizing:

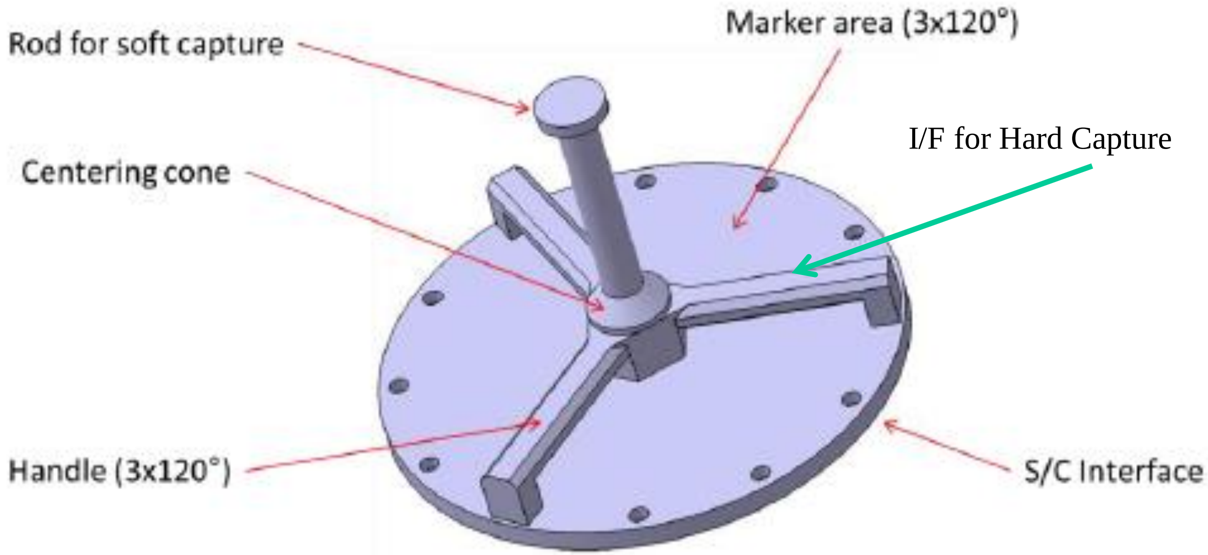
Spacecraft Masses and thrusters performance are:

• Target mass	1280Kg
• Chaser mass	2500Kg
• Thruster force (providing required DV)	750N
• Torque load (doc. eDeorbit-TAS-TN-DJF-0005-0005161114)	232 Nm

Material: Titanium

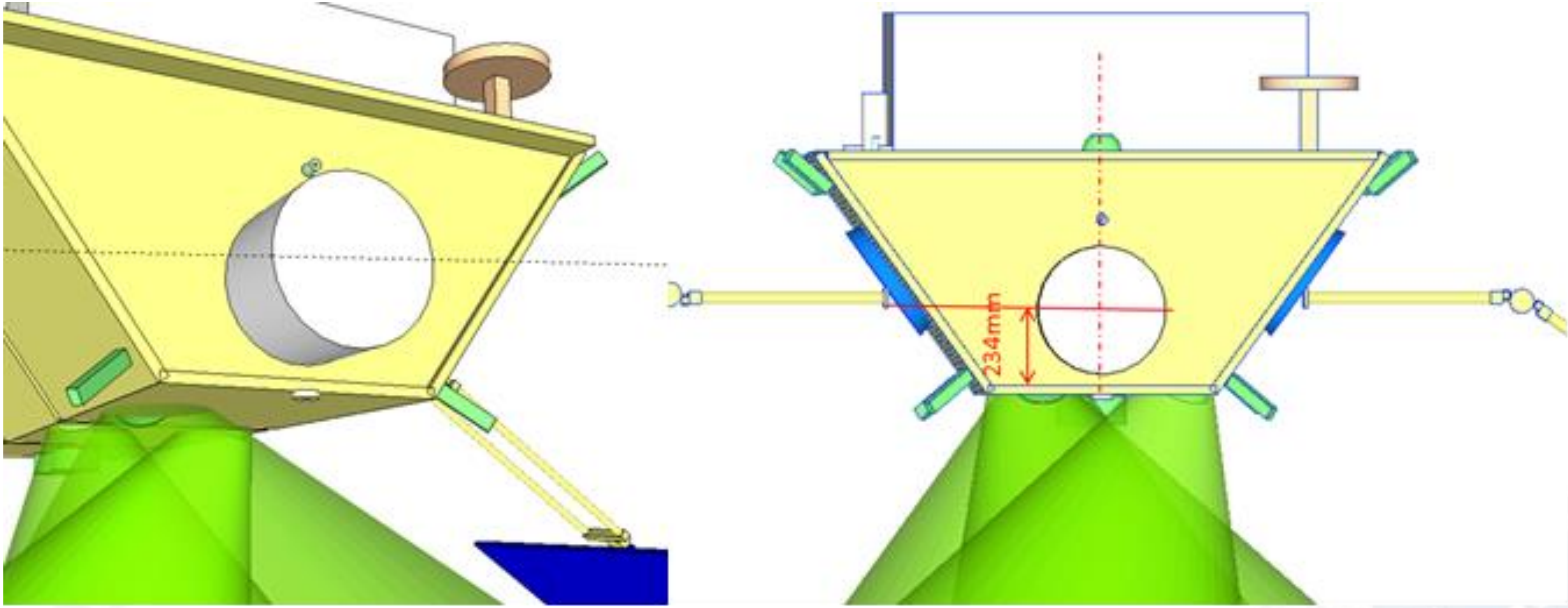
Mechanical I/F: Concept functionally similar/equal to the FRGF device





- Mass around 3.6 Kg. No power required target S/C removal mission.
- Marker area is about 1/3 of the S/C inter area, meaning ~0.14m^2. The area is suffi accommodate one or more 8.4 x 8.4 cm (0.007m^2) marker per side, therefore no additional dedicated brackets are needed.

Capture Device on ELITE Satellite - Constellation



Reduction in the risk to an ADR mission

- Assessment on risk reduction of the device implementation to a future ADR mission (with identification of increase in complexity to the chaser, if any):
  - Implementing appropriate system on mechanical I/F to be consistent with the Robotic arm capture system performance, considering Target configuration and flying Target/Chaser Satellite constraints.
  - Need of estimation of the relative dynamic state vector (Target/Chaser S/Cs)
  - Removal throughout robotic arm alone requires a stiff arm in the composite. An additional clamping mechanism can be considered latching also the LAR.
  - Pending the selected I/F and generally the overall removal approach, a complex Control S/W due to the management of entire composite (combined Chaser and robotic arm + Target) is required.
  - The approach with the robotic Arm can be compatible with various missions scenarios also concerning servicing purpose
    - Refueling/Maintenance
    - Equipment Replacement
- Device Technology well known (high TRL) for Capture and Servicing.

Risk impact of implementation of such device on the satellite.

- No risk expected

4. Selected SDRS techniques preliminary performance “Drogue”

Capture Device - Drogue

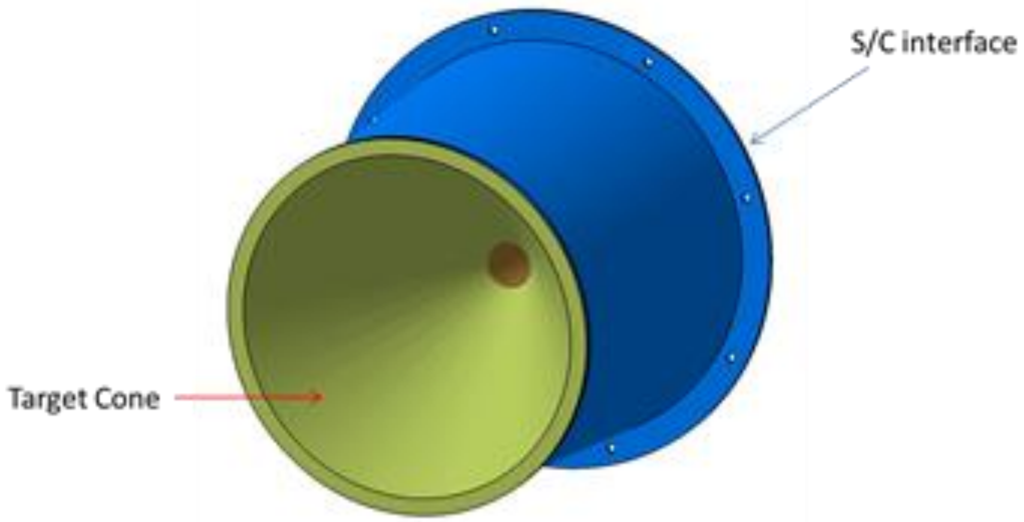
- Baseline design

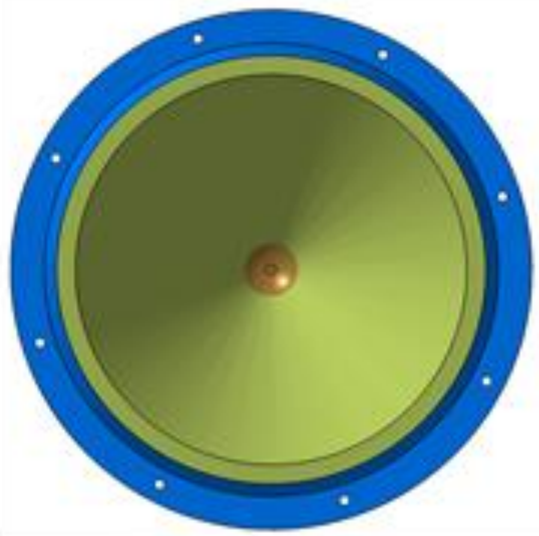
  Capture Device for Removal for **GEO** is based on a drogue solutions:

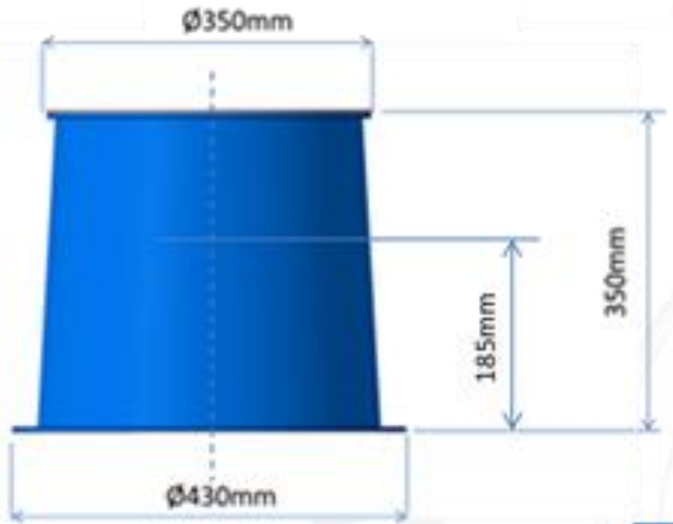
  - The proposed Drogue Capture Device is a passive mechanical part, conically shaped.
  - The conical part is supported by a bracket to interface with the target and is fastened via a set of screws.
  - A thermal control could be required pending thermal analysis results.
  - Capture device material is assumed to be aluminum.
  - Mass is expected less than 10 kg
  - Main dimension: Ø = 430mm (TBC), h = 350mm (TBC) which is considered consistent with expected docking errors
  - No power need.

Note: The cone dimensions depends from the misalignments between the two spacecraft that need to be recovered at the end of the RVD phase (i.e. S/C GNC performances)

Mechanical I/F: Concept based on typical passive docking mechanism device



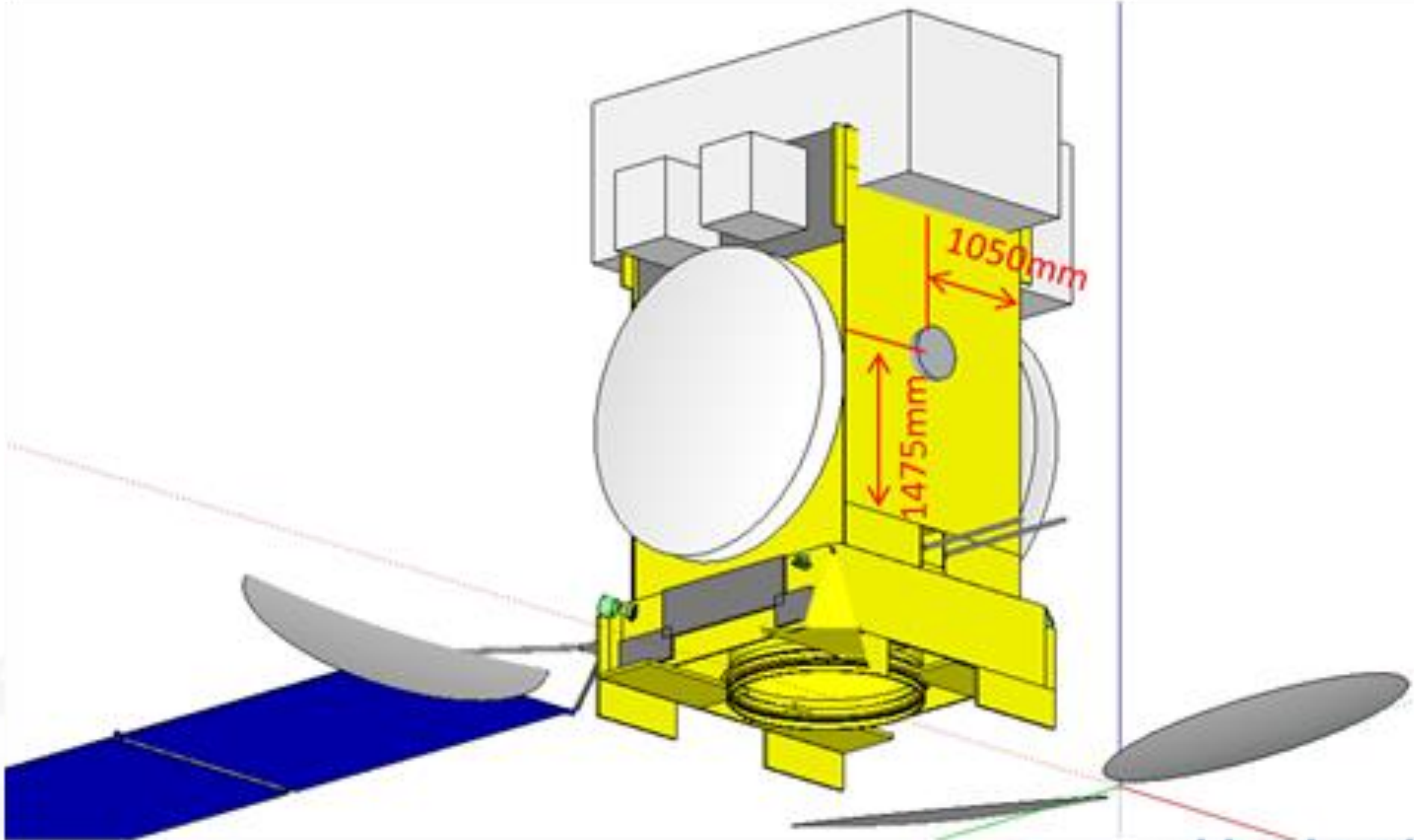




Drogue I/F flange can be moved toward the target cone external flange pending to the S/C configuration

4. Selected SDRS techniques preliminary performance "Drogue"

GEO - Drogue I/F Neosat



4. Selected SDRS techniques preliminary performance “Drogue”

- ***Reduction in the risk to an ADR mission***
  - Analysis of risk reduction of the device implementation to a future ADR mission (with identification of increase in complexity to the chaser if any.)
    - Need of locating the Capture Device axis in a position as much as possible in line with the Target CoG in order to minimize disturbances.
    - A free volume around the Capture Device shall be foreseen for a safe docking phase. Expected volume dimensions is TBD.
    - Dimensions linked to:
      - Lateral and longitudinal relative velocities
      - Relative angular rates
    - Drogue capture device allows multiple S/C removal and can assure a stable composite (target + chaser and arm) for servicing and safer removal (hard docking)

      Note: Stable composite (docked target and chaser) requires a standard robotic arm control for servicing (already available techniques)
    - Device Technology well known (high TRL) for Capture and Servicing.

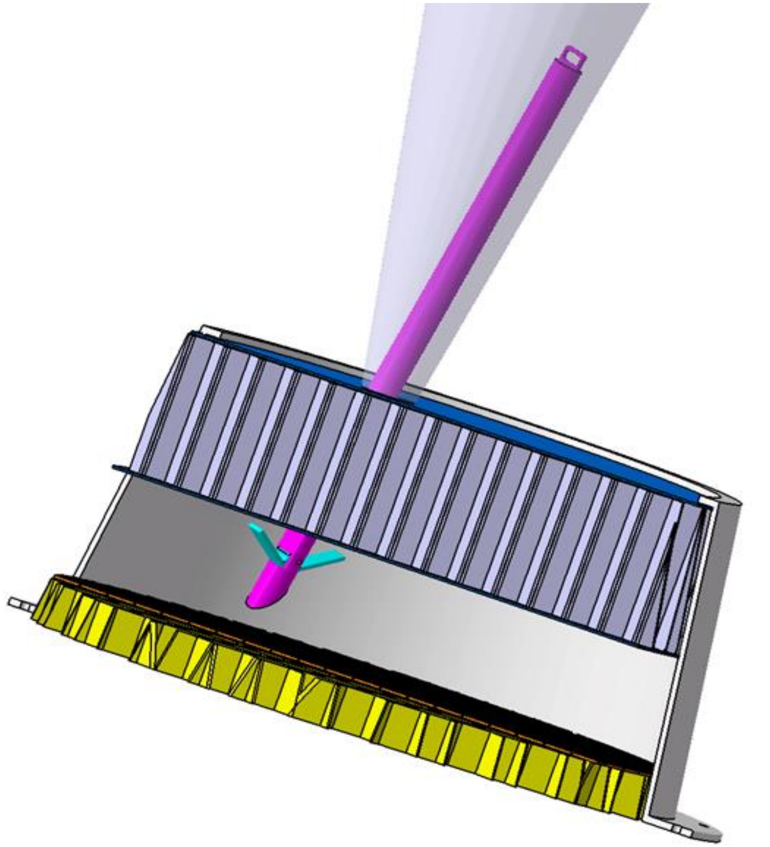
- **Risk impact of implementation of such device on the satellite.**
    - No risk expected

Capture Device for LEO - Harpoon

Baseline design

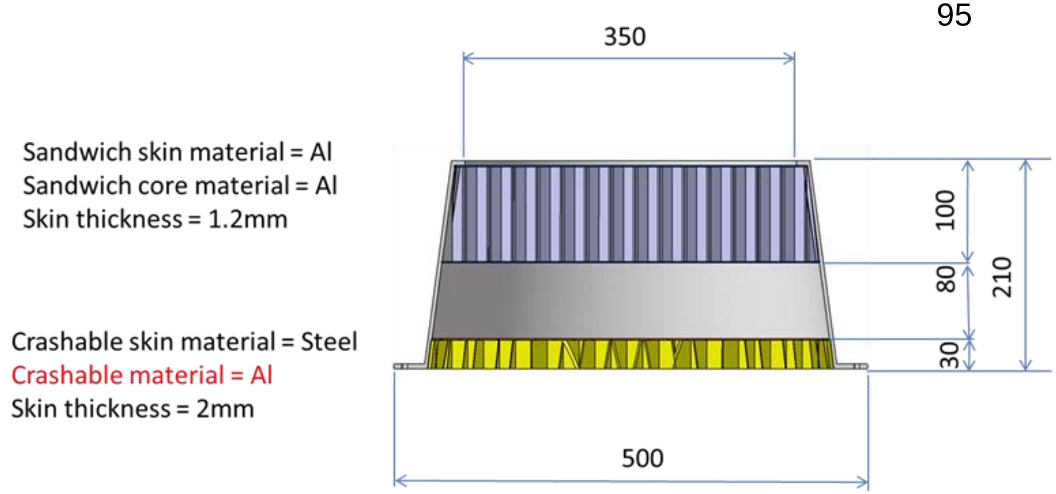
Although the debris generation in space is declared to be "virtually zero", in order to guarantee a more reliable behaviour from this point of view, it is proposed to mount on new satellites a dedicated receptacle especially designed to receive and lock the harpoon guaranteeing no debris generation during the capture and removal phases.

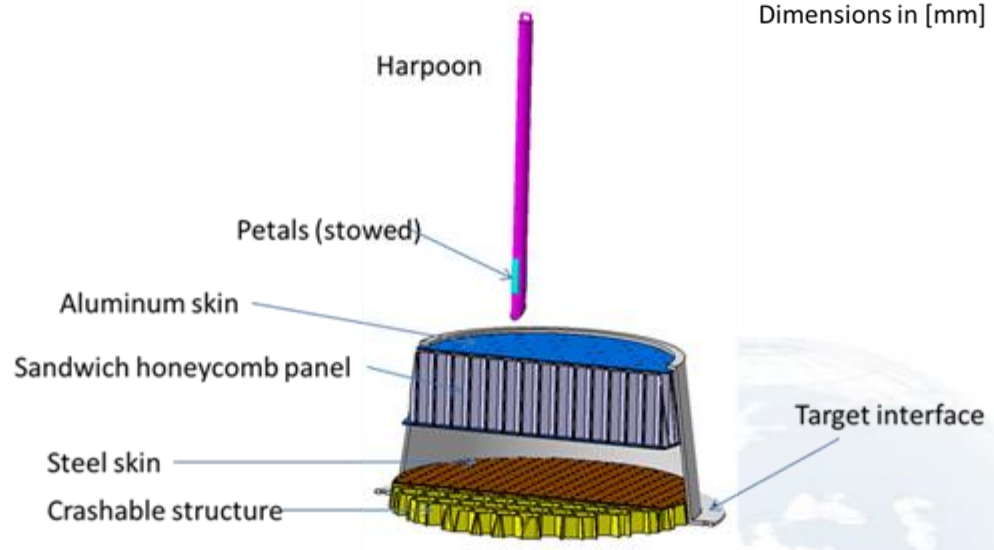
- Assumptions:
  - the Chaser is supposed to be able to estimate the target relative attitude with errors <= 0.2 [deg], angular velocity with errors <= 0.1 [deg/s] and estimation of the optimal time of firing.
  - Impact energy (70J), stabilization/ removal force (1600 N) and harpoon accuracy (80 mm 1σ radius) are based on the values defined in RD[4] and considered coherent with the Removal mission scenario.
  - Harpoon diameter of 20 mm



4. Selected SDRS techniques preliminary performance "Harpoon"

- Capture Device is a canister composed by:
  - Sandwich honeycomb panel covered on top and bottom by an Aluminum skin;
  - Crushable Structure covered on the top by a Steel skin.
  - Under assessment the need of applying a further layer on the external skin dedicated to assure the containment of debris due to the impact of the harpoon to the skin (soft material TBD)
  - A thermal control could be required as result of a dedicated thermal analysis





The harpoon canister mass is expected around 15 kg. No power required .

4. Selected SDRS techniques preliminary performance “Harpoon”

Capture Device – Harpoon

<u>Preliminary Harpoon canister design assessment:</u>

Sandwich panel:

- Sandwich Skin material: Al
- Distance between skins = 100mm
- Skin thickness: t= 1,2mm
- τ_{RAL}=70 ÷ 160 N/mm^2

Harpoon diameter = 20mm

Harpoon circumference: C= 2*π*r=62,8m

Force required to shear off the two skins= τ_{RAL} *C*t*1.2

(1.2 is a coefficient to take in account the friction)

F= 160*62,8*2,4*1,2= 28938,2N

Required energy:

Lteor=F*t= 28938,2*2,4=69,45J

Energy required to shear off the sandwich panel = about 70J

Traction force = 1600N

Harpoon length = 350mm

α= 30°

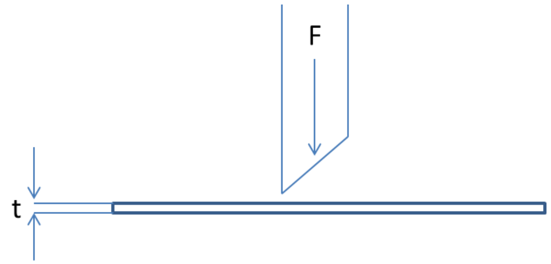
Part of harpoon external to the interface=200mm

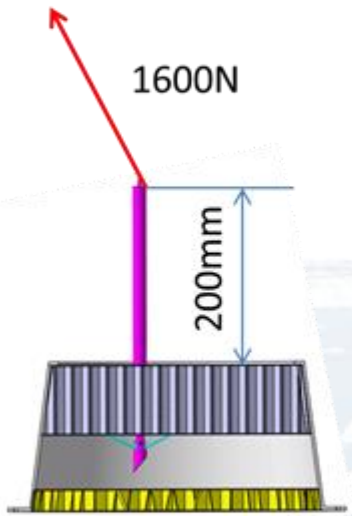
M=1600*sin30*0,2=160Nm

Thikness panel is compatible with applied shear load due by the momentum

Sl=160/0.1=1600 N

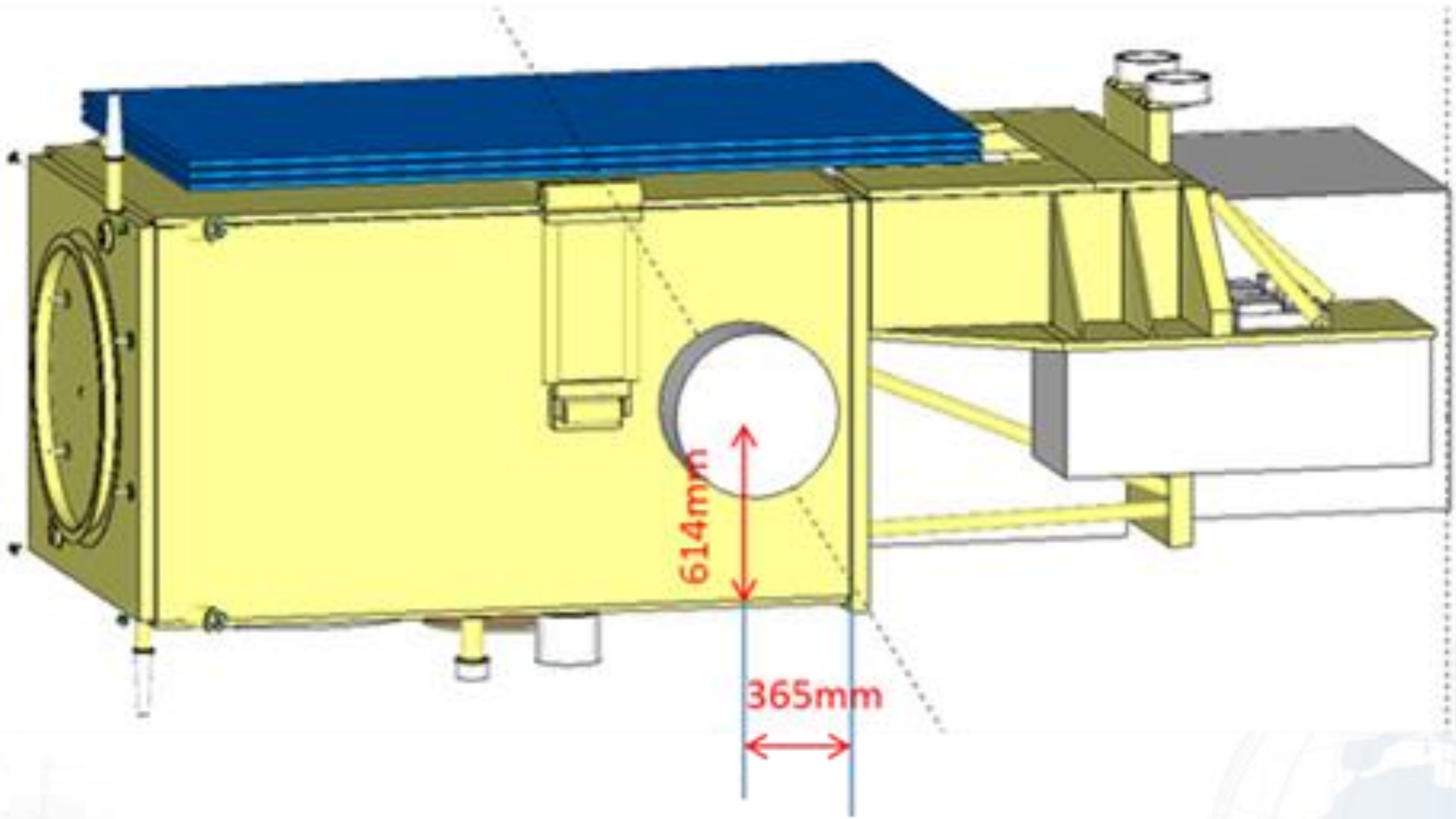
Tau=1600/(1.2*20)=66 N/mm2





4. Selected SDRS techniques preliminary performance “Harpoon”

LEO -Sentinel + Harpoon I/F



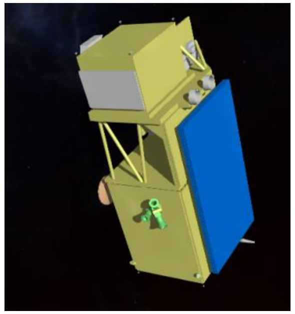
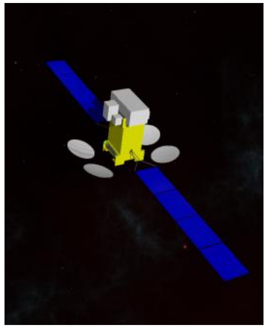
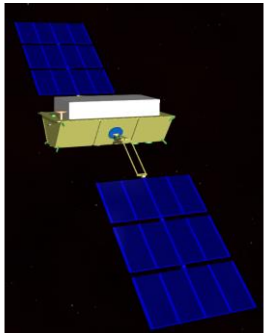
4. Selected SDRS techniques preliminary performance “Harpoon”

- ***Reduction in the risk to an ADR mission***
  - Analysis of risk reduction of the device implementation to a future ADR mission (with identification of increase in complexity to the chaser if any.)
    - The concept and the realization of the device are simple and straightforward so guaranteeing reliability and low risks from the target point of view.
    - The AOCS and the relative navigation system on board to the chaser will face complex tasks:
      - Identification of the chaser/target relative pose, velocity (linear & angular) and, in case, estimation of the inertia properties
      - Chaser/target composite stabilization after capture and during the deorbiting maneuvers in case of simple harpoon is shot.
    - The capture device dimensions compatibility with target configuration..
    - The device must be accommodated on the target satellite as nearest as possible to the satellite CoG.
    - The perpendicular to the device surface grasping the harpoon must be as much as possible co-aligned with the satellite maximum principal inertia axis to guarantee stable motion in case of slow target.
    - The capture device cannot comply with servicing need
    - Risk of wrong shot with the target hooked in a wrong place or bounced.
    - Technology to be developed; TRL is TBD. Canister testing (shooting test characterization) considered mandatory.
- **Risk impact of implementation of such device on the satellite.**
  - No risk expected

5. System impact

- 5.1 GEO
- 5.2 LEO
- 5.3 Constellation
- 5.4 Launcher Upper stage

Implementation on representative satellites

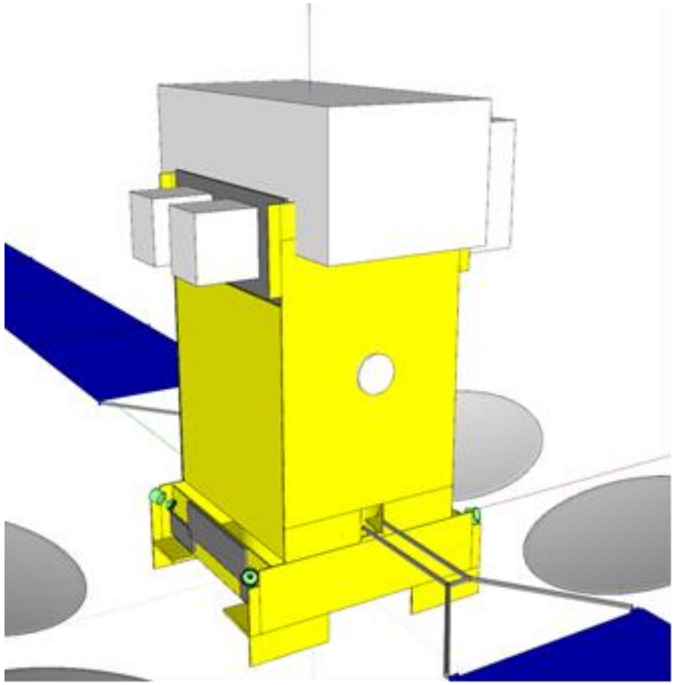
satellite	S-3 “like”	NEOSAT	LEOSAT	AVUM
				
Mass (kg)	2196	4173	1280	688
Interface (mm)	937	1666	Dispenser	
LOS	Controlled re-entry	300 km above GEO	EOL manœuvre to reach 25-years re-entry	Controlled re-entry
Orbit	LEO	GEO	LEO	LEO
Platform	PRIMA	Spacebus NEO	ELITE 2000	NA

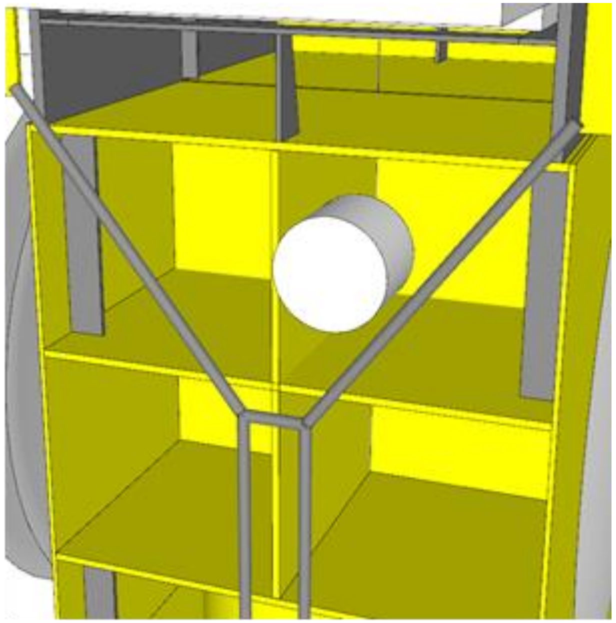
5. System Impact - GEO

SST	RdV & Vision	Stabilization	Capture Technique
Laser Retroreflector	retro-reflectors	Stack (for in-orbit servicing)	Functional = servicing, Drogue device

5. System Impact - GEO

Accommodation on Neosat





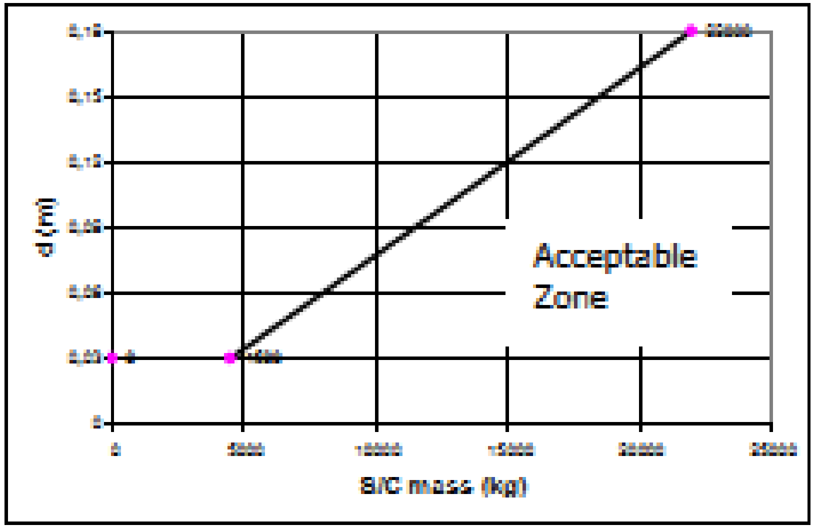
In line with databanck except for mass

AOCS modes and control laws still valid

Configuration	Mass [kg]	COG			Inertia matrix at system origin					
		x [mm]	y [mm]	z [mm]	Ixx [kg.m²]	Ixy [kg.m²]	Iz [kg.m²]	Iyy [kg.m²]	Iyz [kg.m²]	Izz [kg.m²]
Stowed BOL (ref)	**4173,0**	**22,4**	**15,2**	**1662,8**	**19937,3**	**-159,5**	**-271,3**	**18703,7**	**-151,2**	**3147,9**
Stowed BOL (D4R)	**4191,5**	**22,9**	**12,9**	**1662,7**	**59628,7**	**-157,6**	**-285,0**	**18628,8**	**-77,5**	**42917,6**
Deployed BOL (ref)	**4173,0**	**22,4**	**14,1**	**1580,6**	**58421,8**	**-159,7**	**-271,3**	**17433,4**	**-95,6**	**42902,7**
Deployed BOL (D4R)	**4191,5**	**22,9**	**11,8**	**1580,8**	**58515,3**	**-157,5**	**-277,1**	**17515,5**	**-66,0**	**42917,5**

5. System Impact - GEO

Accommodation on Neosat



In line with static unbalance requirement

Major impact is launch mass cost

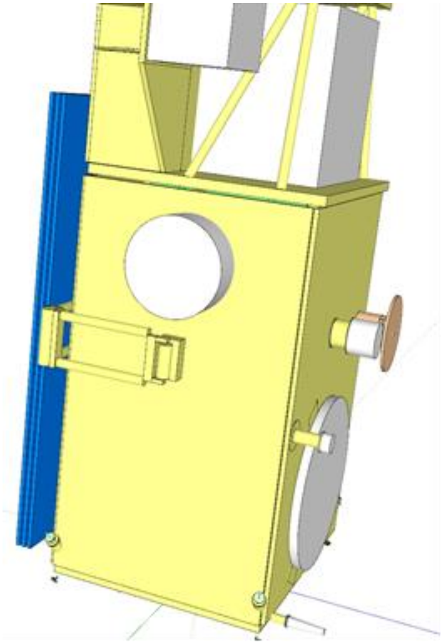
To be analyzed versus ASSIST

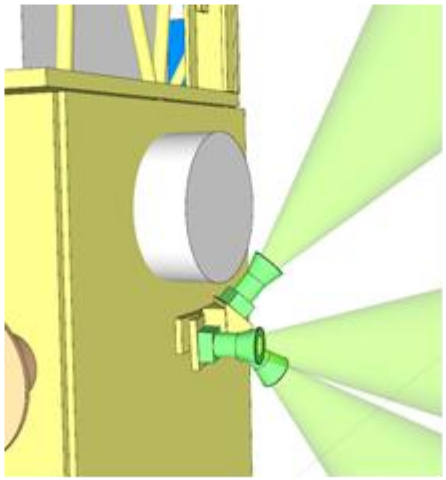
5. System Impact - LEO

SST	RdV & Vision	Stabilization	Capture Technique
Radar corner reflector	2D-3D markers	Passive interface for transferred AOCS	Harpoon device

5. System Impact - LEO

Accommodation on « S3-like »



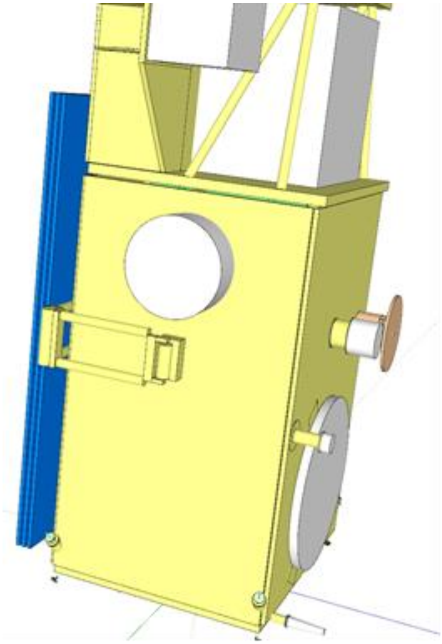


More opportunity for accomodation on –Y panel, no interference with STR

LEO medium satellite not similar generic P/F

No power considered for SSA optics decontamination (timeframe..)

Accommodation on « S3-like »



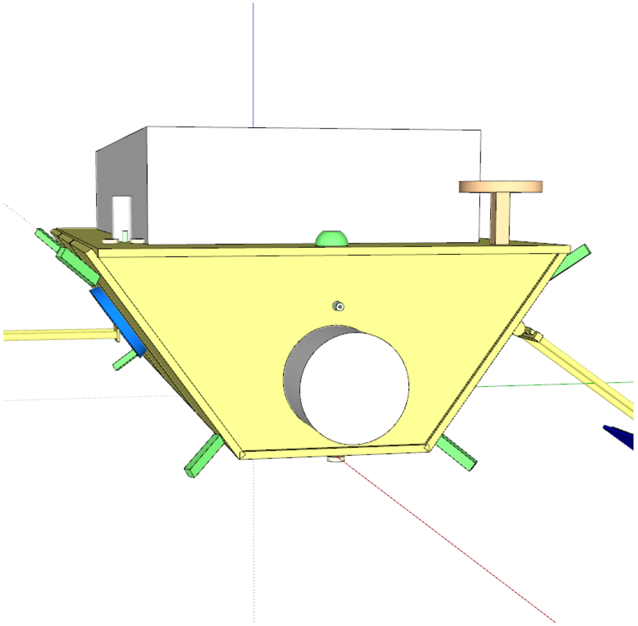
Configuration	Mass [kg]	COG			Inertia matrix at system origin					
		x [mm]	y [mm]	z [mm]	Ixx [kg.m²]	Ixy [kg.m²]	Iz [kg.m²]	Iyy [kg.m²]	Iyz [kg.m²]	Izz [kg.m²]
Stowed BOL (ref)	2199,5	1789,9	54,8	-92,5	735,5	-325,2	521,6	10818,0	33,7	10913,4
Stowed BOL (D4R)	2220,7	1787,9	59,7	-91,6	738,1	-345,3	519,2	10833,6	34,6	10930,7
Deployed BOL (ref)	2199,5	1789,9	247,6	-57,8	853,0	-1089,1	384,0	10806,5	54,2	11042,6
Deployed BOL (D4R)	2220,7	1787,9	250,6	-57,2	858,3	-1103,4	382,6	10822,2	54,3	11062,3
Deployed EOL (ref)	1905,0	1903,3	285,9	-66,7	900,7	-1313,1	436,3	11743,4	64,7	12022,2
Deployed EOL (D4R)	1923,3	1902,0	289,4	-66,0	907,2	-1330,5	434,4	11759,4	64,9	12043,5

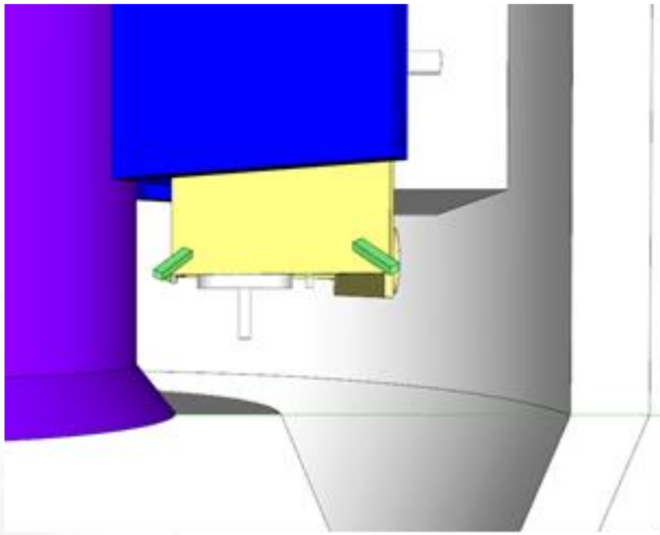
No pb with AOCS databanck anticipated

No impact on power

5. System Impact - Constellation

SST	RdV & Vision	Stabilization	Capture Technique
Radar retro reflector	2D/3D markers	Fluid damping	Functional = Rigid link on FGRF-like concept

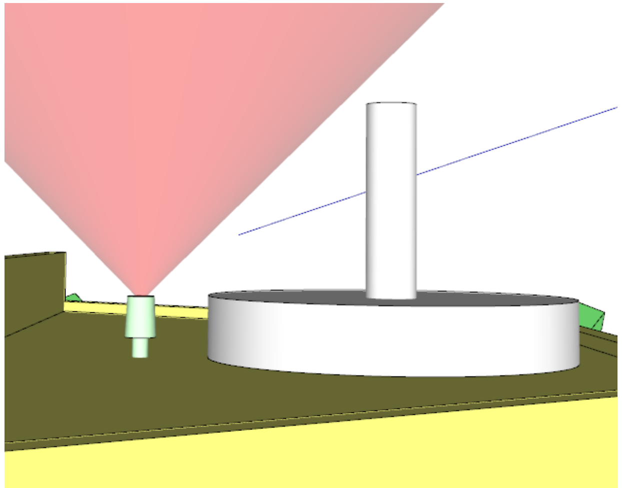




No interference with current dispenseur accomodation

Conclusion is specific to Irridium next P/F

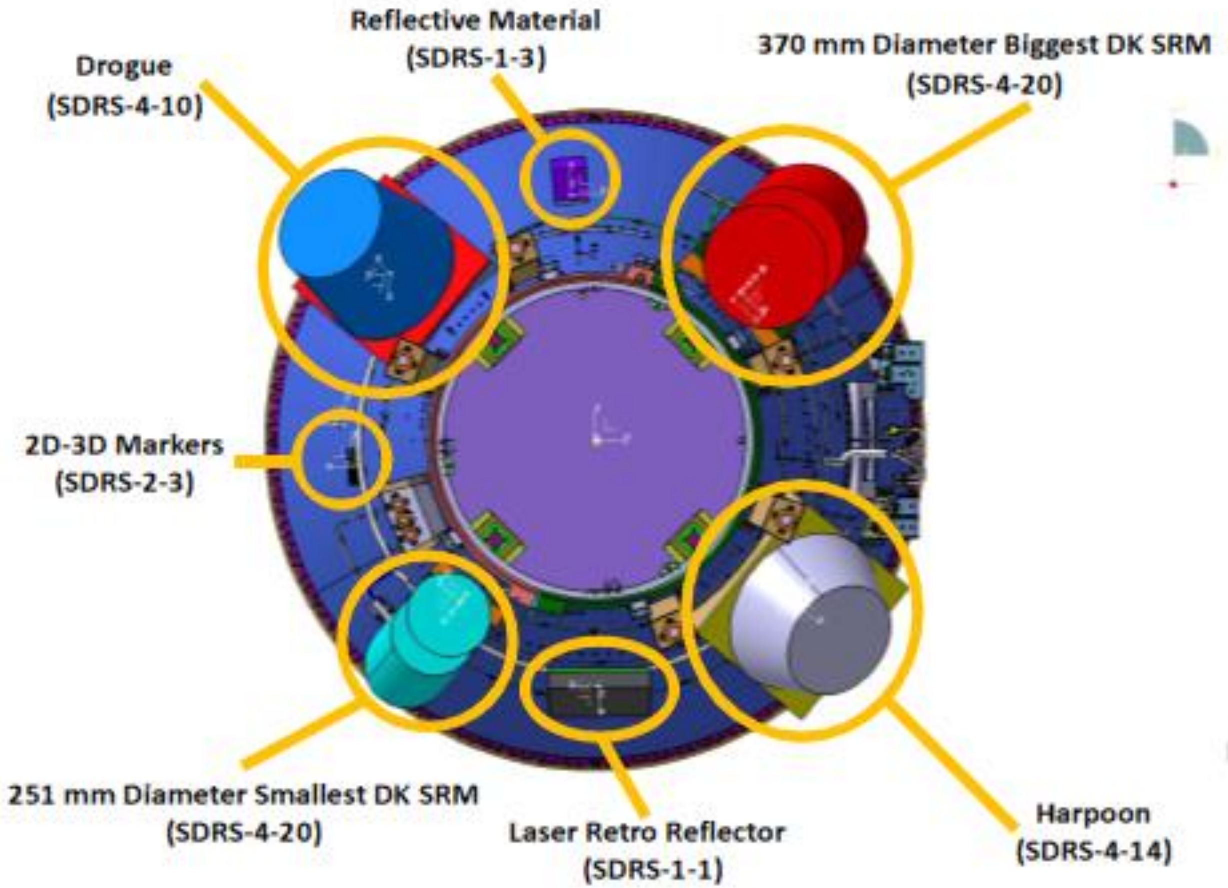
Major impact is mass and accommodation and ADR capture reference concept questionnable.
-> no LAR capability specific



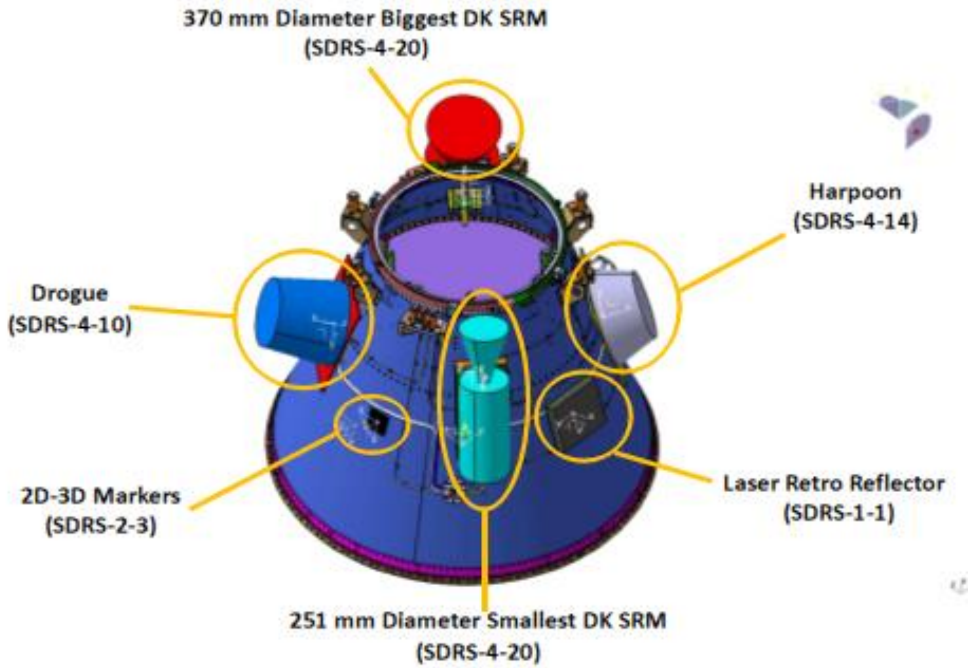
Mass evolution estimation

Configuration	Mass [kg]	COG			Inertia matrix at system origin					
		x [mm]	y [mm]	z [mm]	Ixx [kg.m²]	Ixy [kg.m²]	Iz [kg.m²]	Iyy [kg.m²]	Iyz [kg.m²]	Izz [kg.m²]
Stowed BOL (ref)	1077,0	32,1	7,4	591,2	2297,9	2,9	-12,2	1379,3	642,7	2042,6
Stowed BOL (D4R)	1083,9	37,8	7,4	589,2	2299,5	2,9	-13,9	1392,7	642,7	2055,7
Deployed BOL (ref)	1077,0	32,1	8,3	593,6	2301	2,8	-12,3	1382,3	642,1	2042,6
Deployed BOL (D4R)	1083,9	37,8	8,2	591,5	2302,5	2,8	-14	1395,7	642,1	2055,7
Deployed EOL (ref)	934,5	36,9	9,5	630,6	2349,7	2,7	-16,9	1431,4	641	2043
Deployed EOL (D4R)	940,5	43,5	9,5	628,2	2351,1	2,7	-19,4	1444,7	641	2056,2

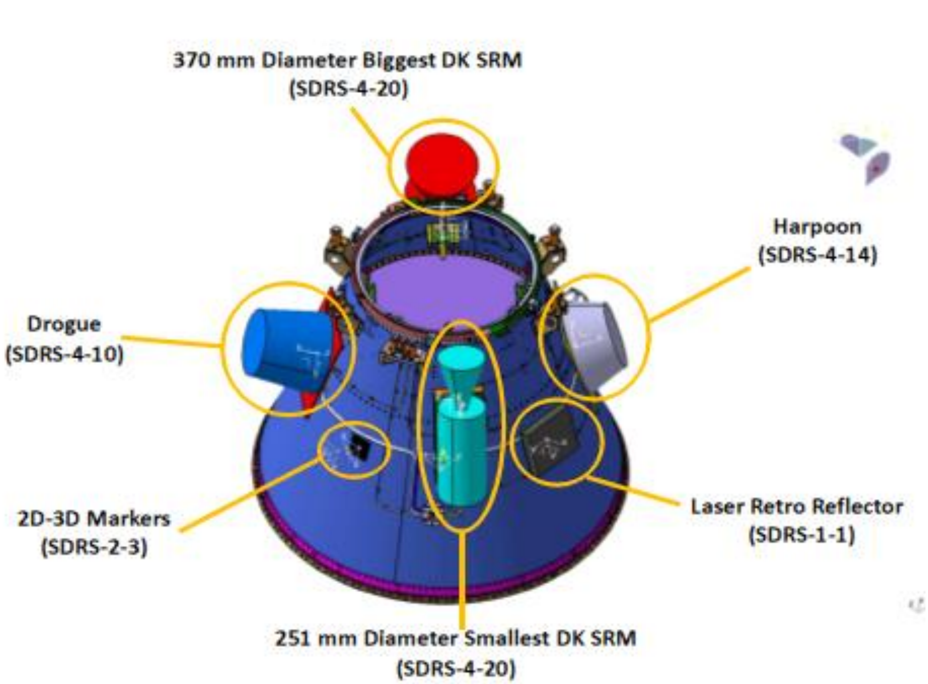
5. System Impact - Launcher

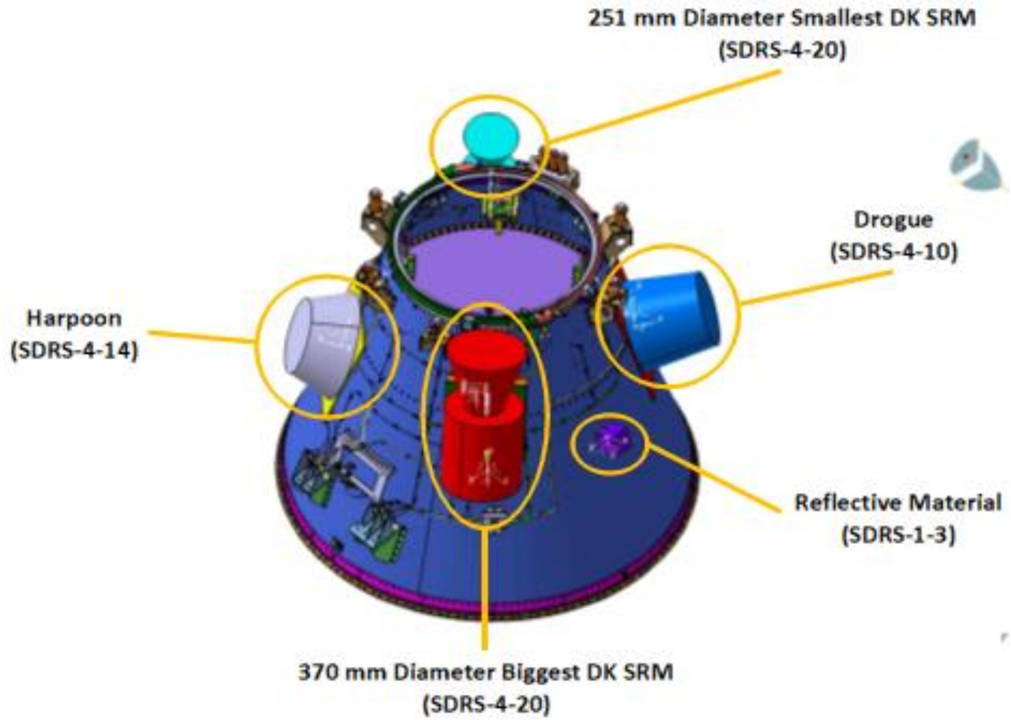


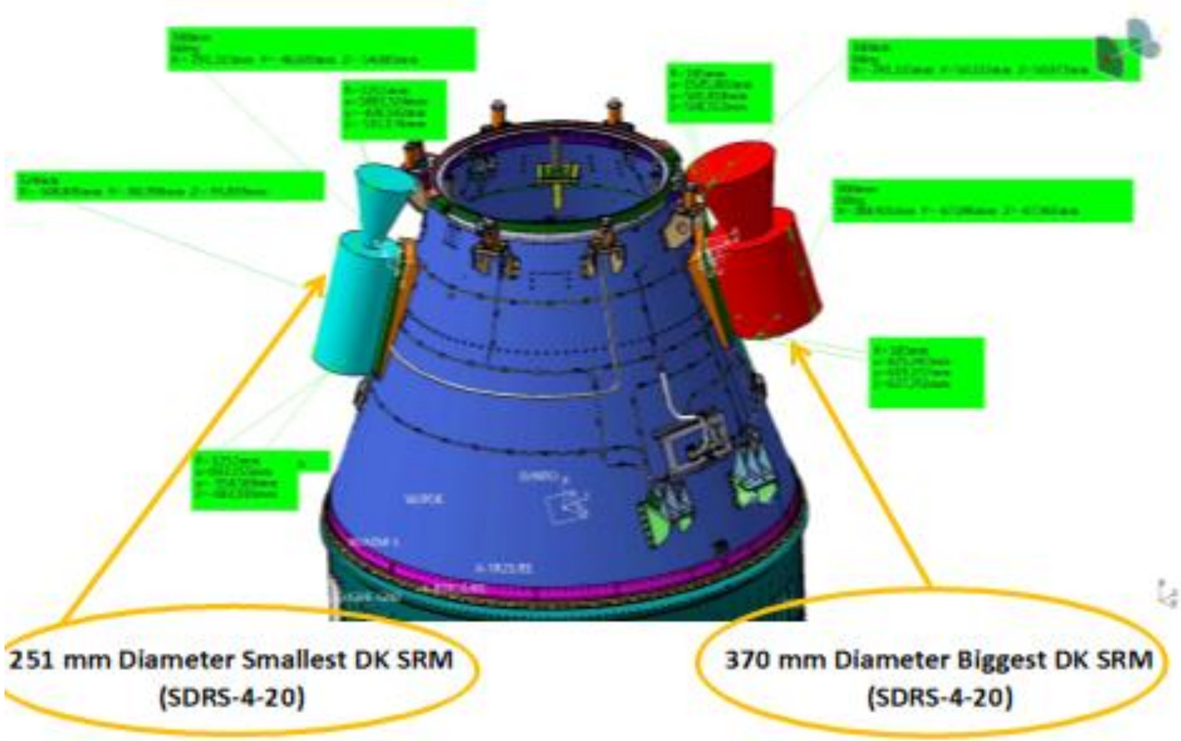
5. System Impact - Launcher

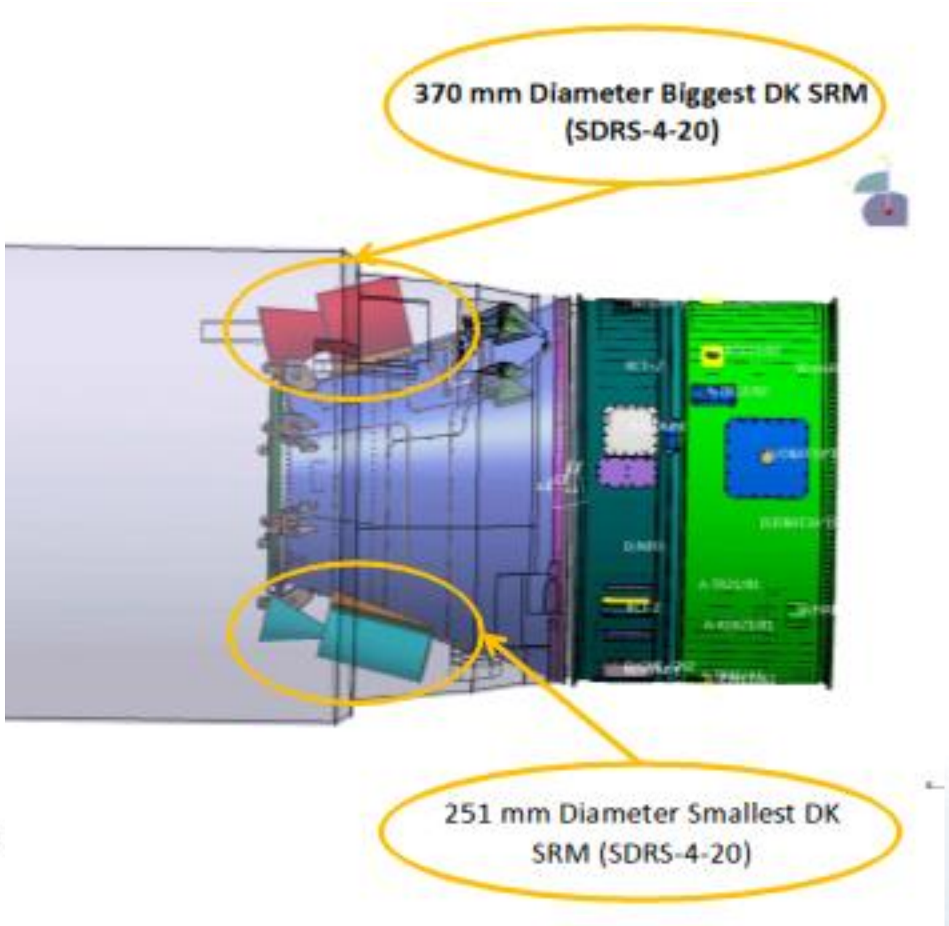


5. System Impact - Launcher



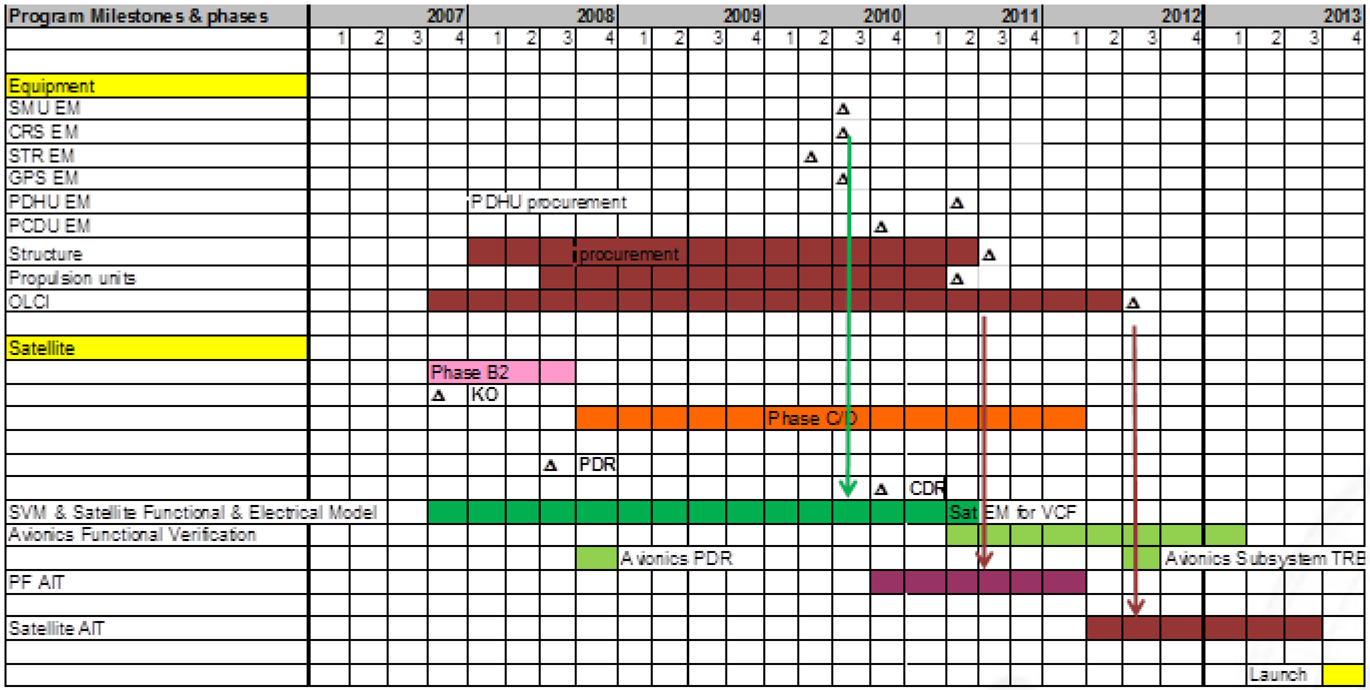



251 mm Diameter Smallest DK SRM (SDRS-4-20)
370 mm Diameter Biggest DK SRM (SDRS-4-20)


370 mm Diameter Biggest DK SRM (SDRS-4-20)
251 mm Diameter Smallest DK SRM (SDRS-4-20)

5. System Impact - programmatic

- Programmatic
  - SDRS concept screwed and accomodation of panels (and support for Neosat) => To be done at manufacturing level. Possibly to be decided late in the process if dummy
- Other: additive manufacturing marking…(relief on metallic pieces)



26/04/2017

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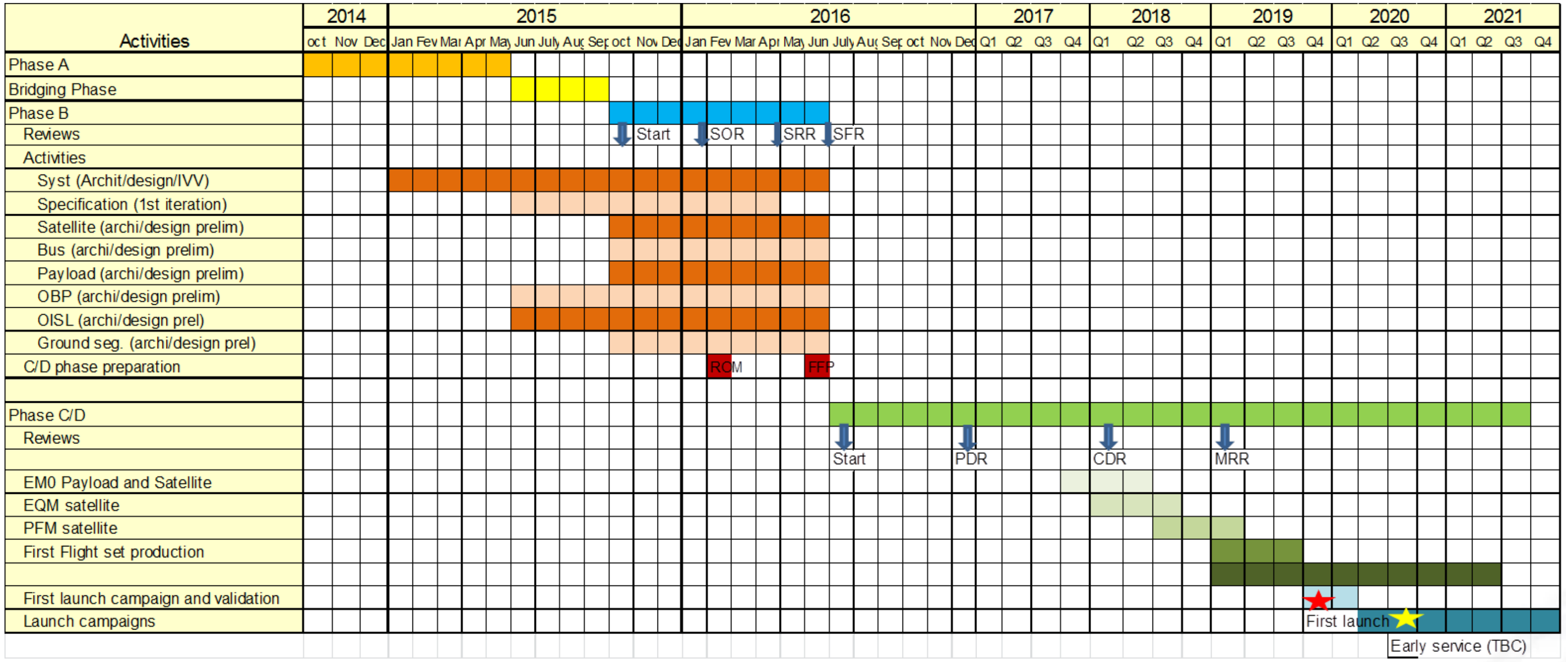
5. System Impact - programmatic

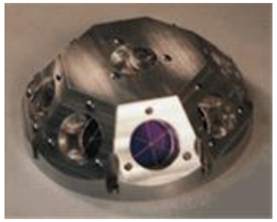
- Same exercice for typical constellation schedule
  - SDRS concept implementation during architecture design activity
    - = 4.5 years before launch 1st batch
  - Interface for SDRS deviced to be mounted on panels at PDR



- For launcher upper stage, SDRS devices proposed to be integrated at CASA before final acceptance

6. Next steps for SDRS development

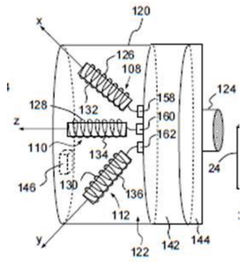
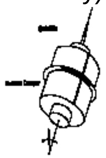
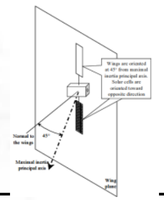
Some elements have already a high TRL

Element	Concept TRL	Previous TRL achieved in Similar System	Notes
Laser Retro Reflector 	TRL7	TRL9 - Various design exist for LEO, MEO and GEO satellites	No additional TDA is proposed at this step Additional activity is needed to cover the long term reliability of ADR mission Recurrent cost for one LRR between 500k$ and 1M$ (refer to TN3)
Retroreflectors 	TRL7	TRL9 Demonstration done on ISS with laser ranging	No additional TDA is proposed at this step
2D/3D Markers 	TRL7	TRL9 Demonstration on Tango-Mango	No additional TDA is proposed at this step. Surface marking (datecode) with AM is easy.

Some high TRL – additional study proposed

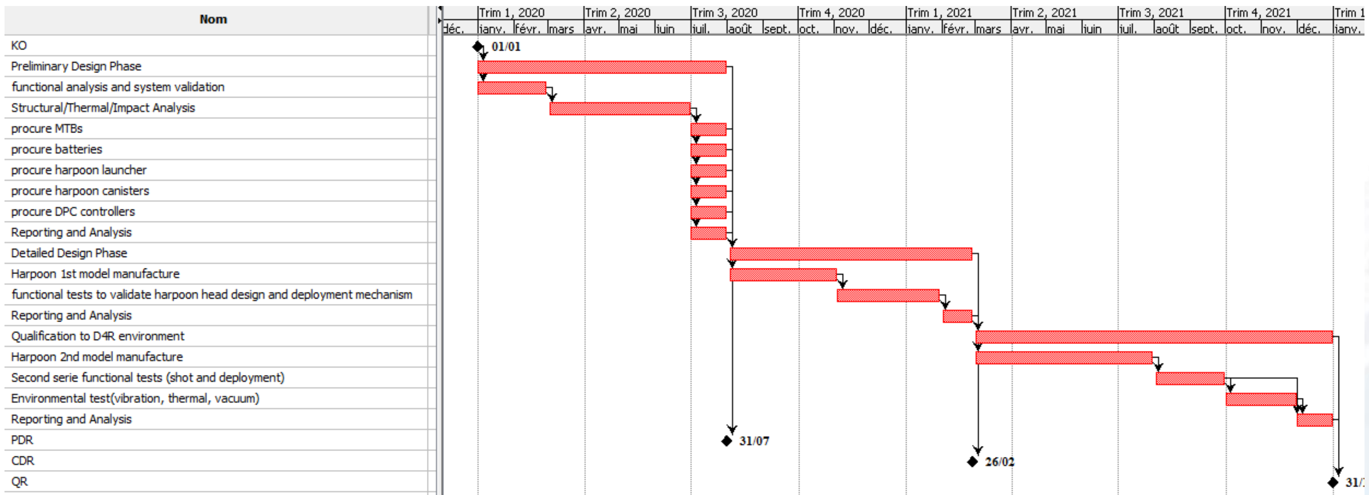
Element	Concept TRL	Previous TRL achieved in Similar System	Notes
Radar corner reflector 	TRL7	TRL9 for reflective surface of TIRA radar	No additional TDA is proposed at this step A study analysis is proposed to assess the possibility to rely on smaller radar than TIRA for similar performance
Reflective material 	TRL7	TRL9 for Kapton or black-kapton MLI. Not compatible with the specified lifetime duration (> 30 years).	No additional TDA is proposed at this step. Feasibility is achieved for stripped MLI. A study analysis is proposed to assess the impact and the potentiality of alternative concept such as aerogel

Some technics need maturation

Element	Concept TRL	Previous TRL achieved in Similar System	Notes
Stabilization by transferred AOCS device 	TRL2		AOCS concepts is well-known. Harpoon demonstration has been demonstrated on-ground (refer to on-going GSTP) TDA is proposed for Concept of implementation around a harpoon and performances assessment to raise to TRL5 This type of stabilization fits to flexible link capture, eventually also before capture by net.
Stabilization by fluid damping (credit Nathaz Modelling Laboratory) 	TRL2	TRL9 on ISS	TDA is proposed for design and interest of such solution for debris stabilization to raise TRL4.
Stabilization by SA windmill 	TRL6	TRL9 on previous Spacebus satellite use as active process for stabilization and PMD management	A study analysis is proposed to assess FDIR solution and capability to use this solution as passive one on long term stabilization

6. Next steps for SDRS development

Objectives:
This consists in a passive interface allowing an AOCS device to be transferred on the Target spacecraft via a flexible link (harpoon). Once the Target has been reached, the flexible link shall be cut.
Description:
1. Procure 6 MTBs, remote controls, DPC controllers, 2 batteries, and AOCS interface, 2. Functional analysis and system validation 3. Functional tests with simulation of debris tumbling motion and harpoon impact with AOCS transferred 4. AOCS transfer device assembly: integration of MTBs+DPC controller+battery on harpoon-like 5. Test of stabilization in different configurations
Deliverables:
Test report
Remarks:
No full qualification with system tests. No zero-g activity is included. Harpoon is CFE (not quoted). The upper range of preliminary ROM evaluation covers the low definition of test bench at this stage



6. Next steps for SDRS development

Description:

The fluid damping canister consists of:

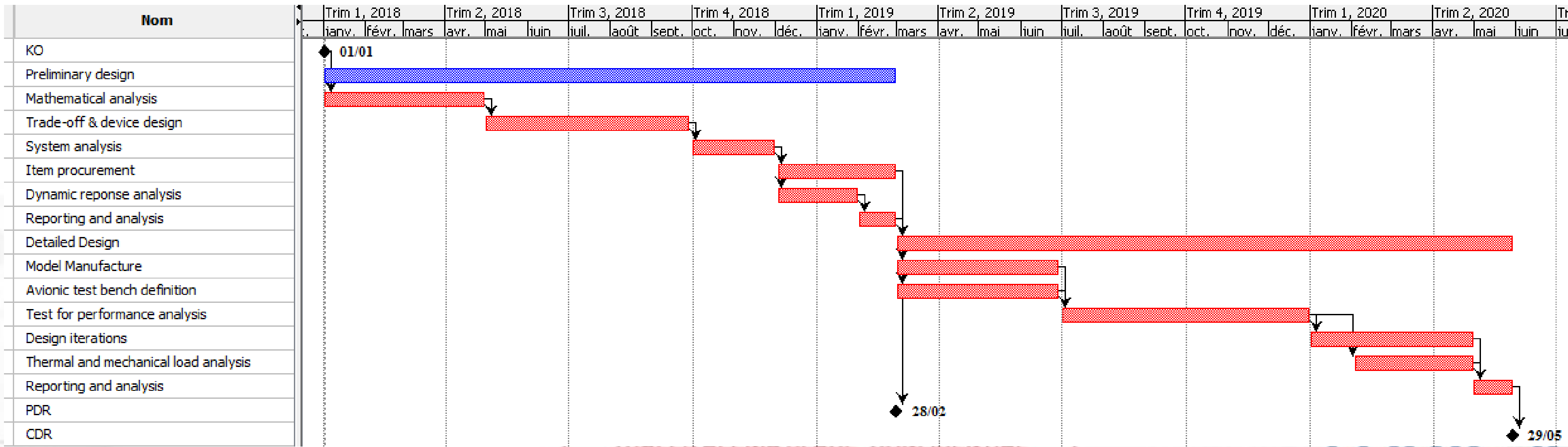
- A steel ball
- Oil bath
- Support structure for accommodation on the satellite
- A liberation system operated by FDIR at EOL or end of mission of by external TC

The planned activity consists of a definition, design, development and verification phases. The design phase consists of the following tasks:

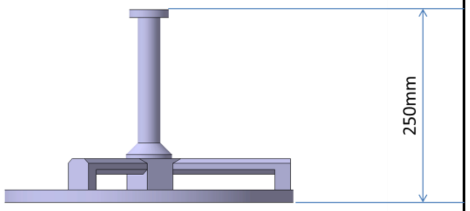
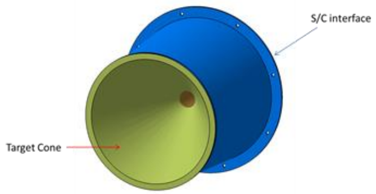
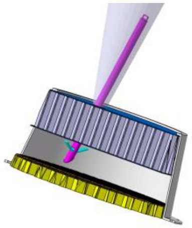
- Mathematical and trade-off analysis to define best solution (1 or 2 devices and orientation and location wrt inertia axis, damping parameters mass, k, c,d)
- device design (including 3D model and drawings)
- system analysis for representativeness
- definition of avionic test bench to represent the full system
- dynamic response analysis
- Thermal and mechanical / loads analysis
- Mathematical model and Performance analysis
- Liberation system requirements

The following tests will be considered as a minimum:

- One cube representative for mathematical model correlation
  - Canister with steel ball and oil
  - Strength test of the device (capability to withstand launch loads)
  - Test bench to simulate the concept
  - Functional & performance test
  - Extrapolation to 0g



Some technics need maturation

Element	Concept TRL	Previous TRL achieved in Similar System	Notes
Device similar to FRGF or robotic capture 	TRL2	TRL9 for ISS (FRGF) the capture mechanism is to be considered as designed by the chaser authority. The proposed concept need to fit with the robotic capture interface.	The proposed activity is a qualification of the device to rise TRL5. A preliminary design phase has to consider similarity with ASSIST interface, which is dedicated to servicing and not to ADR mission
Drogue for servicing 	TRL3	Some reference to standard docking mechanism but with new functionality and dimension (is expected around 350 mm dia). The capture mechanism is to be considered as designed by the chaser authority.	The proposed activity is a qualification of the mechanism to rise TRL5. A preliminary design phase has to consider similarity with ASSIST interface, which is dedicated to servicing and not to ADR mission
Harpoon canister for flexible capture 	TRL2	TRL5	The designed canister is conceptually sized and implemented on the external panel. Dedicated analysis and breadboard of potential integration in the panel design would be more optimized. TDA is proposed

6. Next steps for SDRS development

Description:

The harpoon canister consists of:

- Sandwich honeycomb panel covered on top and bottom by an Aluminum skin;
- Crashable Structure covered on the top by a Steel skin.
- Further layer, if needed, on the external skin dedicated to assure the containment of debris due to the impact of the harpoon to the skin (e.g. soft material)
- A thermal control according to the needs of the thermal analysis.

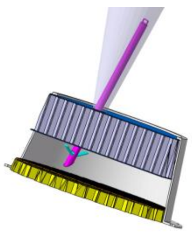
The planned activity consists of a design, development and verification phases. The design phase consists of the following tasks:

- Harpoon canister design (including 3D model and drawings)
- Structural analysis/dynamic response analysis
- Thermal analysis
- Impact analysis
- Functional analysis

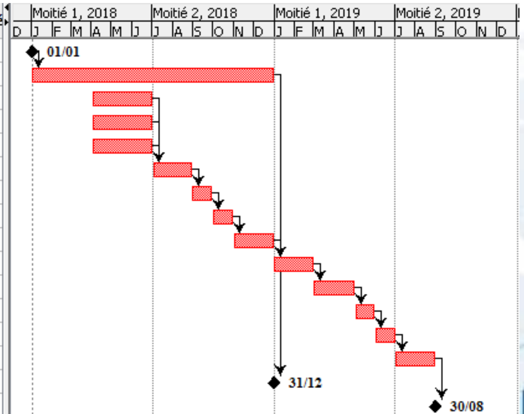
The following tests will be considered as a minimum:

- One model for development tests:
  - by a series of shots (10X) of the harpoon against the canister to freeze the design - shot tests
  - Strength test to verify the capture performances (capability to withstand loads applied on the harpoon)
- One model for qualification tests
  - Mass and dimensions measurements
  - Random Vibration
  - Thermal vacuum (to be assessed)
  - Functional test with the harpoon (3X) - shot tests
  - Strength test to verify the capture performances (capability to withstand loads applied on the harpoon)

Note: Harpoon male part considered provided by chaser responsible authority for test campaign and provided as CFE



		Nom	Durée	Début	Fin	Pré
1		KO	0 jours?	01/01/18 08:00	01/01/18 08:00	
2		CAD design	261 jours?	01/01/18 08:00	31/12/18 17:00	1
3		Structural model	66 jours?	01/04/18 08:00	02/07/18 17:00	
4		Thermal Model	66 jours?	01/04/18 08:00	02/07/18 17:00	
5		Impact model	66 jours?	01/04/18 08:00	02/07/18 17:00	
6		1st Model manufacture	43 jours?	03/07/18 08:00	30/08/18 17:00	3;4;5
7		Shock tests to freeze design	21 jours?	31/08/18 08:00	28/09/18 17:00	6
8		Strength tests	23 jours?	01/10/18 08:00	31/10/18 17:00	7
9		Test report 1	43 jours?	01/11/18 08:00	31/12/18 17:00	8
10		2nd Model manufacture	43 jours?	01/01/19 08:00	28/02/19 17:00	2;9
11		Qualification to D4R environment (vibration, thermal vacuum)	45 jours?	01/03/19 08:00	02/05/19 17:00	10
12		Shock tests	21 jours?	03/05/19 08:00	31/05/19 17:00	11
13		Strength tests	22 jours?	03/06/19 08:00	02/07/19 17:00	12
14		Test report 2	43 jours?	03/07/19 08:00	30/08/19 17:00	13
15		MTR	0 jours?	31/12/18 17:00	31/12/18 17:00	9
16		FR	0 jours	30/08/19 17:00	30/08/19 17:00	14



6. Next steps for SDRS development

Description:

The Drogue for capture interface is the female part of a docking mechanism to be accommodated on the target vehicle of a rendezvous and docking mission between two spacecraft. The drogue for capture interface is a structural part of conical shape (Ø 430mm, H 350mm) completely passive. The drogue for capture interface could be interfaced to the target vehicle by means of a dedicated flange on its body or a dedicated support structure (tubular or conical shape) to expose the interface pending the configuration of the composite. The drogue for capture interface is currently considered of metallic material (TBC by design).

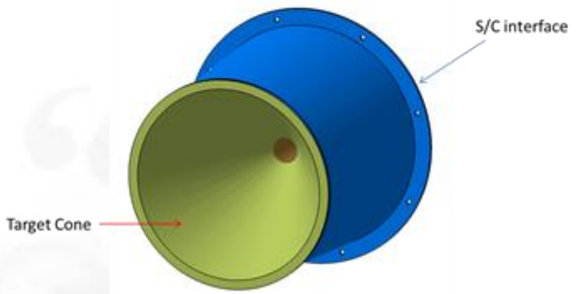
The planned activity consists of a design, development and verification phases. The design phase consists of the following tasks:

- Drogue device design (including 3D model and drawings)
- Structural analysis/dynamic response analysis
- Thermal analysis
- Functional analysis

The following tests will be considered as a minimum:

- One model for Development tests:
  - Functional test with the active part of the docking mechanism (active mechanism mounted on rigid bench with a COTS robotic arm testing the capture feasibility by using the drogue female – capability of "soft" capture and final docking)
  - Stiffness test (docked configuration)
- One model for Qualification tests (could be the development model properly refurbished)
  - Mass and dimensions measurements
  - Random/sine Vibration
  - Thermal vacuum (to be assessed)
  - Functional test (3X) mechanism (active mechanism mounted on rigid bench with a COTS robotic arm testing the capture feasibility by using the drogue female – capability of "soft" capture and final docking)

Note: Mechanism male part with relevant actuation system, considered provided by chaser responsible authority for test campaign



Drogue female part should be developed and verified by the docking mechanism design authority. The responsible of target design should have in charge the verification of I/F and environment compatibility

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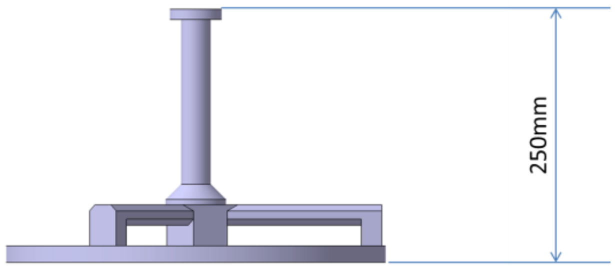
6. Next steps for SDRS development

Description:
The proposed concept of Robotic device for capture is a concept similar to the FRGF device. The device is made of metallic material and is composed by a circular baseplate (about Ø360mm x10mm) supporting three handles at 120° and a central Rod (Height about 250mm) for soft capture.
The planned activity consists of a design, development and verification phases. The design phase consists of the following tasks: •Robotic device design (including 3D model and drawings) •Structural analysis/dynamic response analysis •Thermal analysis •Functional analysis The following tests will be considered as a minimum: •One model for Development tests: o Functional test with the active part of the end effector (mechanical I/F mounted on rigid bench with a COTS robotic arm testing the capture feasibility by using the provide end effector – capability of e.g.“soft” capture and final grasping) o Stiffness test (grasped configuration) •One model for Qualification tests (could be the development model properly refurbished) oMass and dimensions measurements oRandom/sine Vibration oThermal vacuum (to be assessed) oFunctional test (3X) (mechanical I/F mounted on rigid bench with a COTS robotic arm testing the capture feasibility by using the provided end effector – capability of “soft” capture and final grasping) Note: end effector with relevant actuation system, considered provided by chaser responsible authority for test campaign



Mechanical I/F male part should be developed and verified by the capture mechanism design authority. The responsible of target design should have in charge the verification of I/F and environment compatibility

7. Discussion & Conclusion

Deliveries

Doc. Id	*Title*	*Time*	*Format*
CS-D4R-TN1	SDRS Supporting Technologies / Device (State of the Art)	T0+3 months	Word + PDF
CS-D4R-TN2	Case Studies and Preliminary Evaluation	T0+6 months	Word + PDF
CS-D4R-TN3	D4R Concepts: System trade-off	T0+9 months	Word + PDF
CS-D4R-TN4	Technology Roadmaps and Recommendations For Future Spacecraft Chaser Design	T0+11 months	Word + PDF
CS-D4R-ESR	Executive Summary Report	T0+12 months	Word + PDF

Draft Final report

Doc. Id	*Title*	*Time*	*Format*
CS-D4R-FR	Final Report	T0+12 months	Word + PDF
CCS	Contract Closure Summary	Contract Closure	Word + PDF

7. Discussion & Conclusion

- Some SDRS device have been proposed with maximum potential added value
- Some technics needs to raise TRL
- Satellites on-going program managers would be reluctant for modification
  - Satellite will be compliant to SDM requirements
  - D4R effort covers failure case
  - And not mandatory
- Roadmap to build in coherence with ADR definition

Thank You