Active Debris Removal by Vega Upper Stage adaptation

ADR Workshop
06-May-2014

System Engineering Team

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An Avio Group and ASI Company

Active Debris Removal

by

AVUM Adaption

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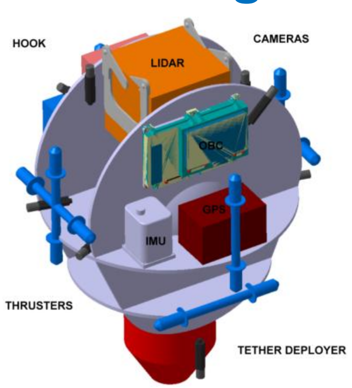
Prologue

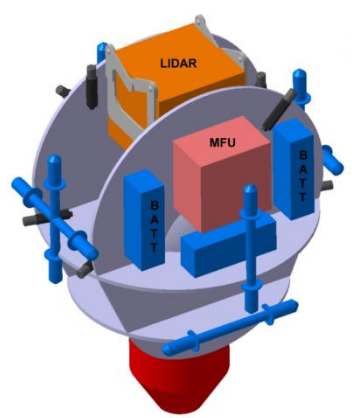
- On November 2012 ELV presented its study for an Active Debris Removal based on AVUM

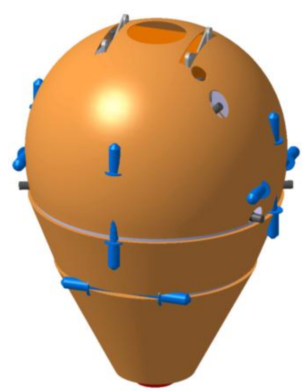
The concept was elaborated targeting to Envisat S/C

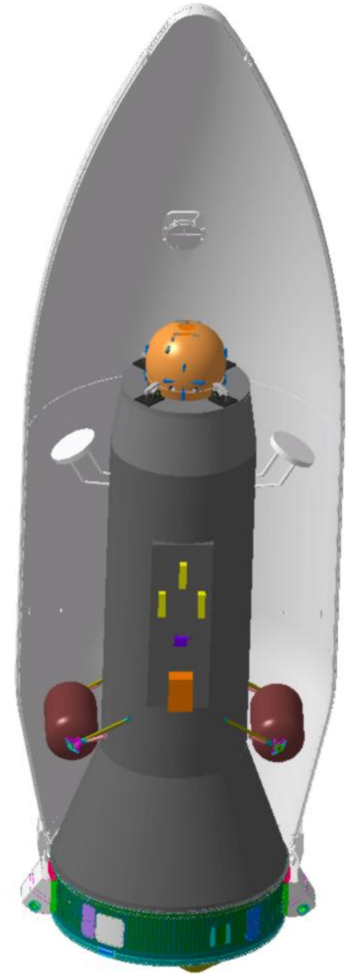
Main features

- Low impact on AVUM stage
- Modular approach
- AVUM Propulsion Runtime Extension
- Remote Controlled Probe for:
  - closing phase
  - grabbing the target



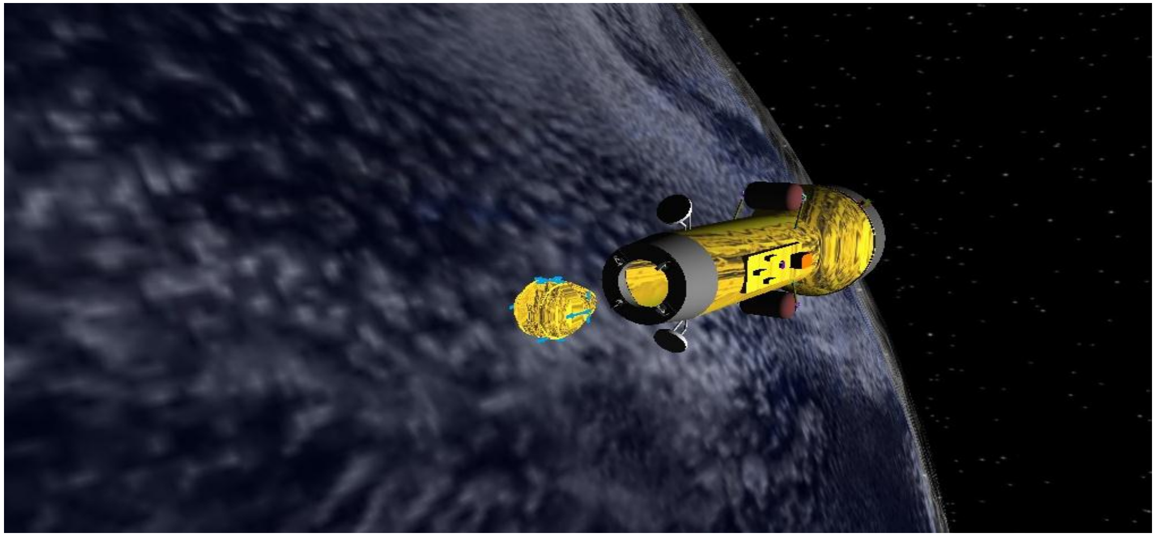




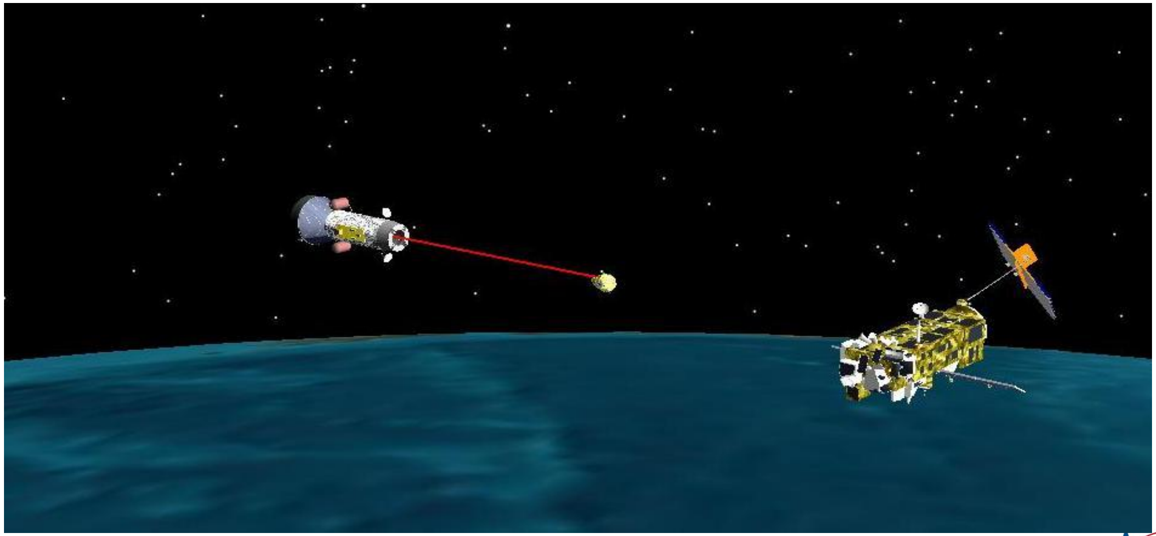


ENVISAT Capture and De-orbiting

Avum attitude aiming to target



Remote Probe Deployment



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ADR by Vega Upper stage Adaption

Beginning 2013 a RFQ from ESA for a feasibility study was receipt:

"Active Debris Removal by Adaption of Vega Upper Stage"

1. **System level conceptual design for two capture scenarios:**
   - **Net capture**
   - **Tentacles**

2. **The design had to include**
   - **Capture device(s)**
   - **GNC functions and requirements**
   - **Sensors' suite**
   - **Power Budget**

3. **Trade-off among different mission profiles with associated VEGA launcher performance.**

4. **Demonstrate the feasible of de-orbit scenario through analysis and simulations.**

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AO-13780 - The Team

Industrial Team

ELV
Prime Contractor
System design
Mission Analysis

MDA
Sensor Suite S/S selection and trade-off
Robotic grabbing device S/S design

PoliMi
Net grabbing device S/S design
Tether supports design

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ELV Team Roster

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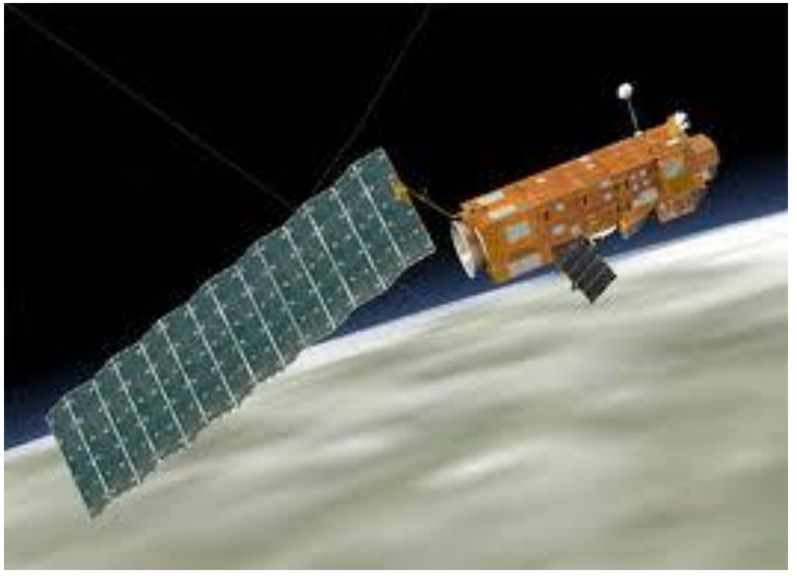
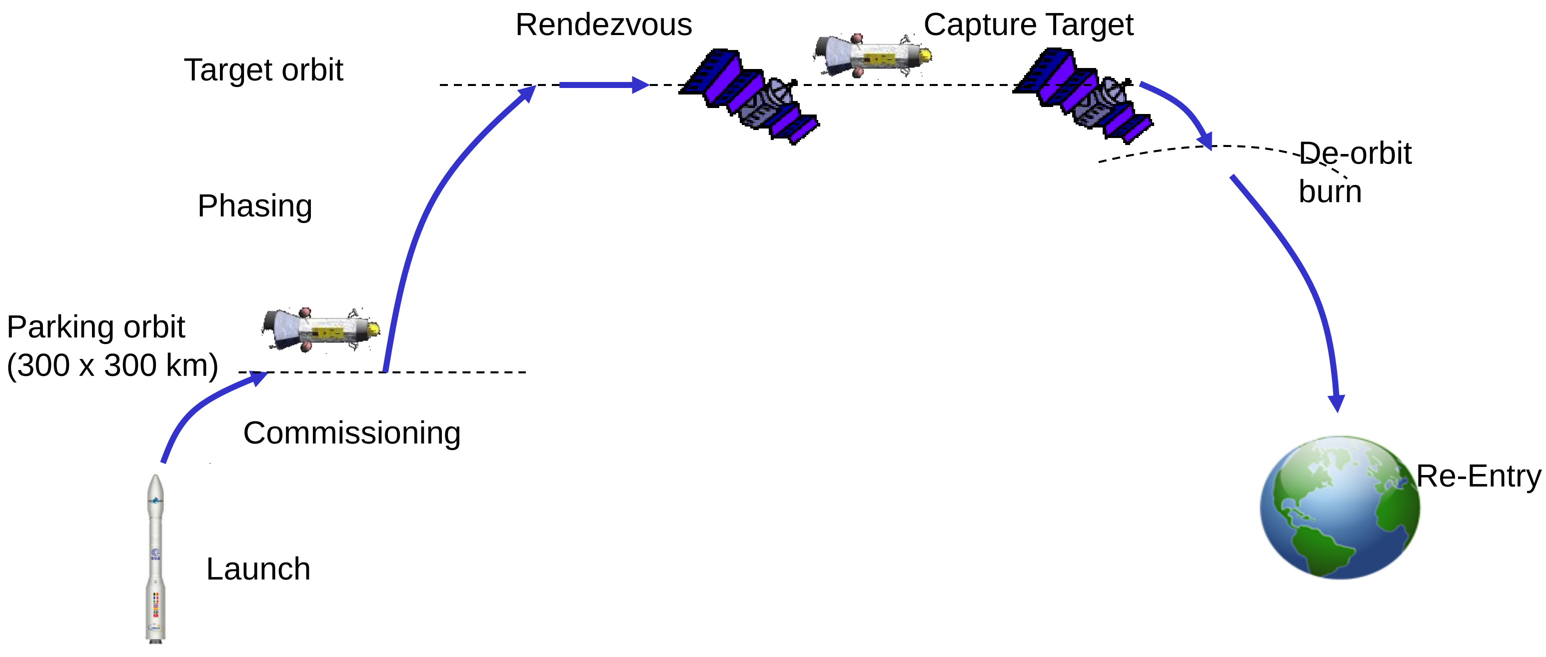
Target Selection

ENVISAT S/C assumptions made for the study

- **Launched in 2002 it was the largest civilian Earth observation mission**
- **Sun-synchronous polar orbit (SSO):**
  - Nominal reference orbit of mean altitude 800 km
  - 35 days repeat cycle, 10:00 AM MLST descending node
  - Inclination 98.55 deg
- **Dimensions: 23 m x 5 m**
- **Mass is ~8000 kg**
- **Probable attitude:**
  - Less than 1 deg/s spin around X axis
  - X axis pointing towards Nadir



Typical Mission Profile



Note: ESOC courtesy

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ADR Mission Scenario

The overall mission can be divided in several arcs:

- **Ascent phase ➔ injection of the chaser into a parking orbit**
- **Far Range Rendezvous**
  - phasing of the chaser and transfer to an orbit close to the target (≈30/50km)
- **Close Range Rendezvous**
  - close approach (few meters)
- **Capture by the selected grabbing device: net or tentacles**
- **De-orbiting**
  - Pulling the Debris linked by the tether (grabbing by net)
  - Pushing the Debris firmly connected by tentacles

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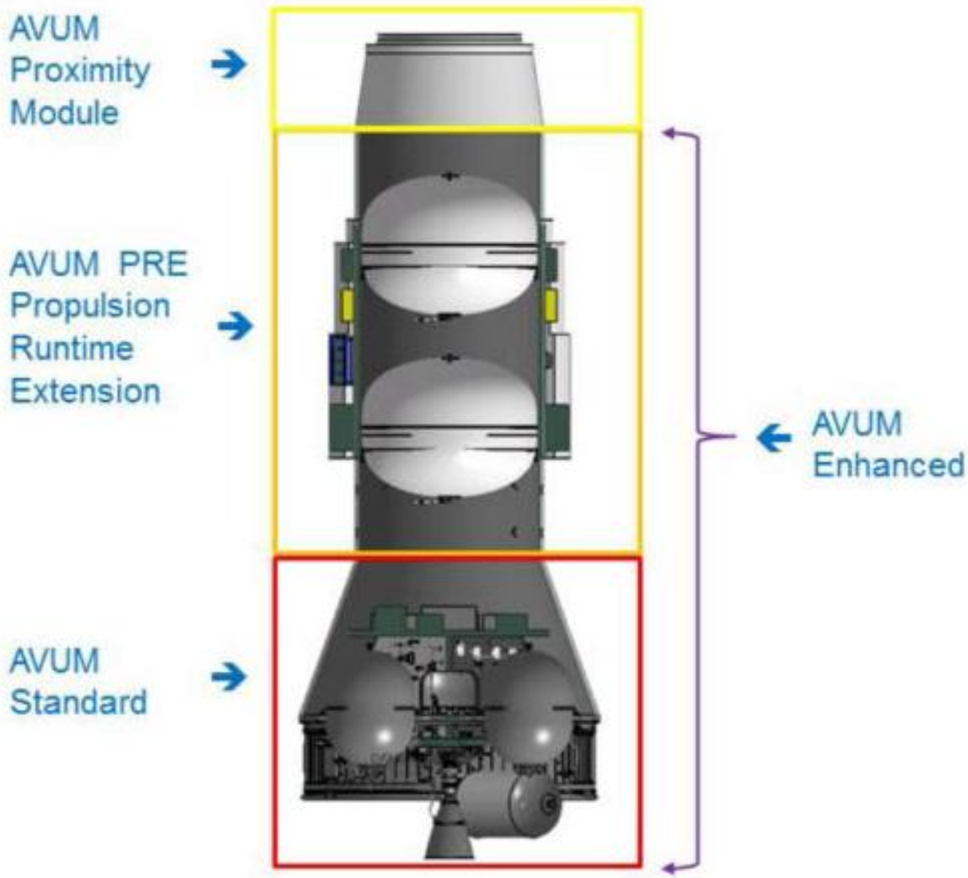
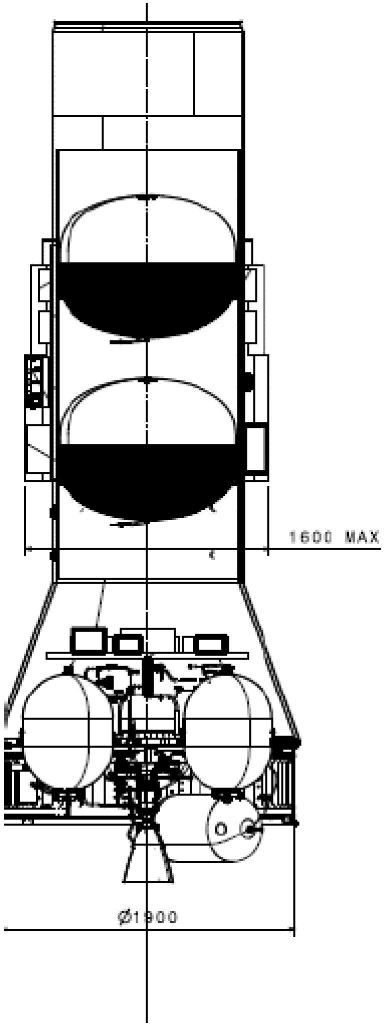
Modular approach





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Phases and Functions

Ascent Phase ➔ Avum Std

- Standard Vega ascent to parking orbit

Far Range RDV ➔Avum enhanced

- Parking orbit/Phasing
- PRE ➔ Propulsion Runtime Extension
- Patchable FPS ➔ Mission Data uploaded to acquire target orbit

Close Range RDV➔ Proximity Module with its own dedicated GNC

- Sensor Suite/Avionics ➔ Relative Navigation
- Dedicated ACS sized for proximity operations

Grabbing Phase ➔ Grabbing Device (Net or Robotic Arm/Clamp)

De-orbiting ➔ Avum enhanced

- PRE/Patchable FPS ➔ Safe de-orbit

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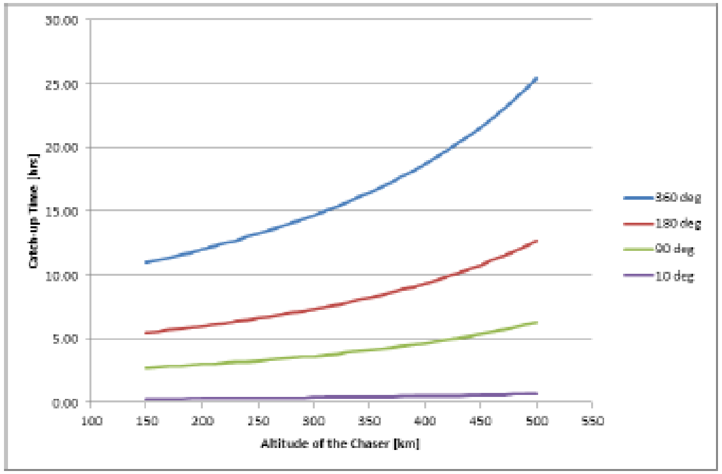
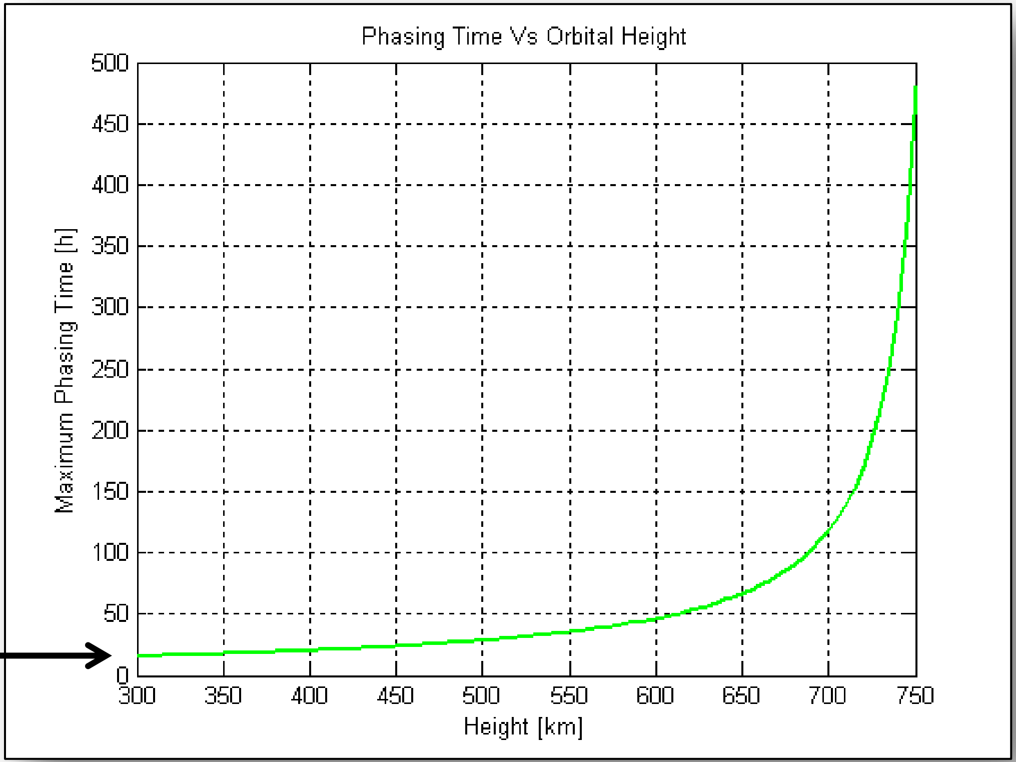
Avum Parking Orbit Choice





Phasing Time (h=300 km) =T14.7 hours

The 300 km @98.55° orbit is attractive for Vega ➔ direct injection in the circular parking orbit by only 1 Avum boost (AV1)

AV2 and AV3 will perform the transfer to the Target orbit
AV4 and AV5 could be used for a two boosts re-entry

Launch Opportunities without Phasing

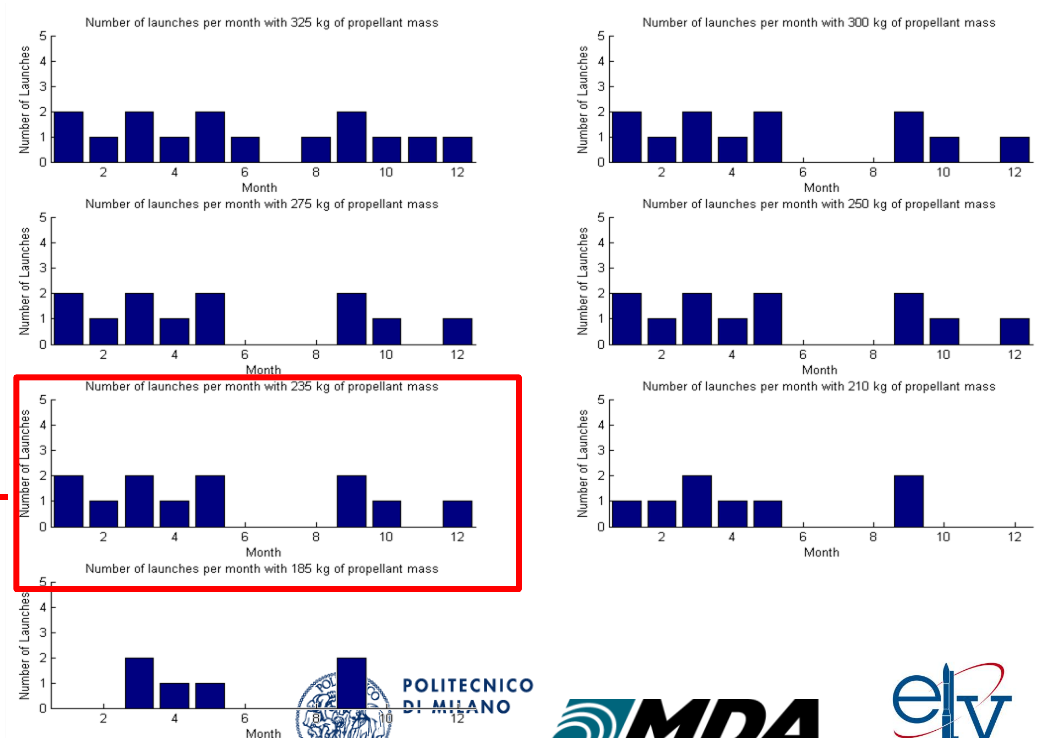
Hohmann transfer manoeuvre RESULTS:

- Zero direct launches

Lambert transfer maneuver RESULTS:

-Burned propellant mass sensitivity

mp [kg]	Launches per year
325	15
300	12
275	12
250	12
235	12
210	8
185	6



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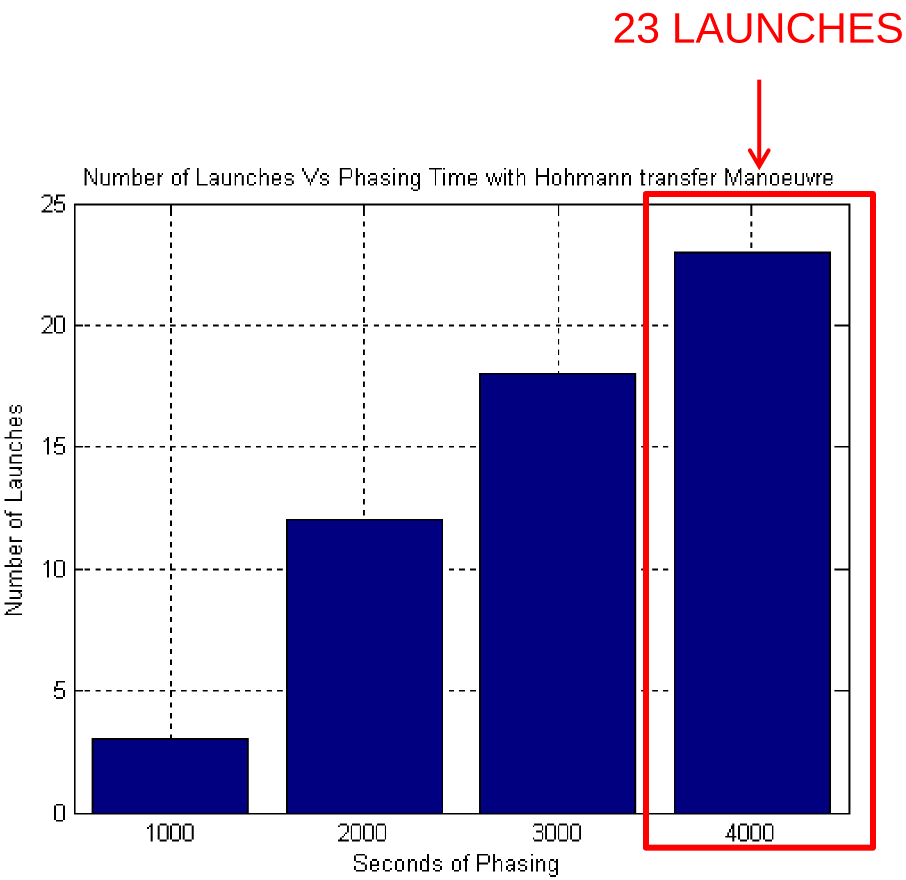
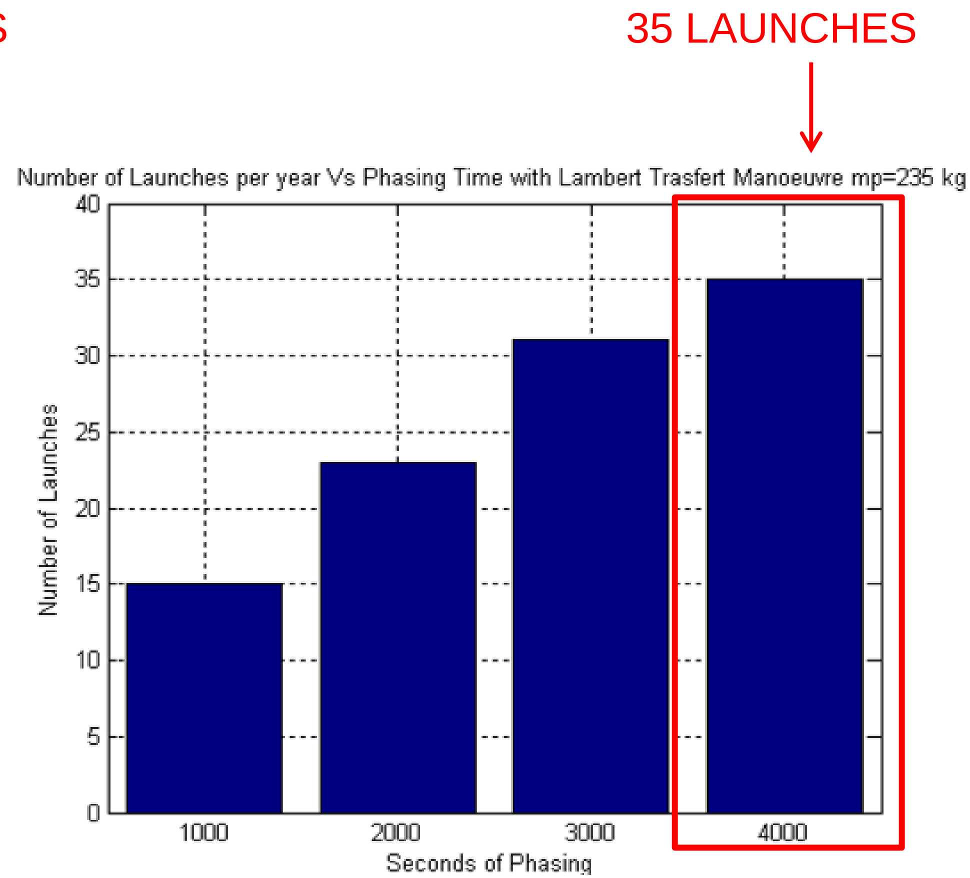
Launch Opportunities with Phasing



Hohmann Transfer



Lambert Transfer

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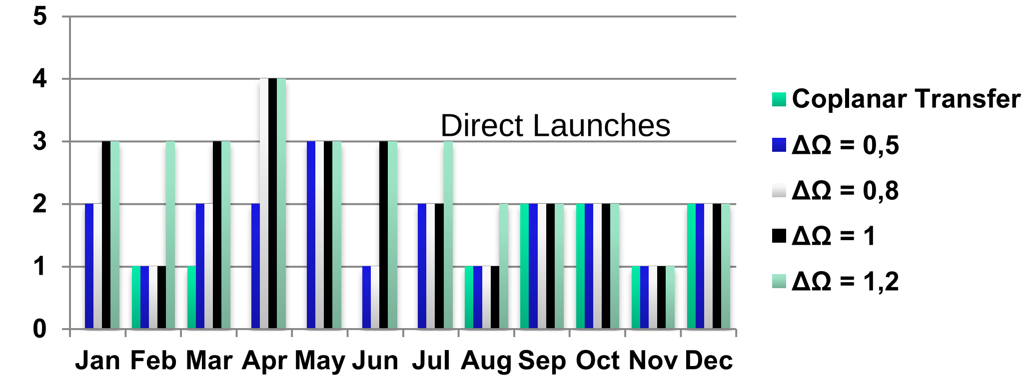
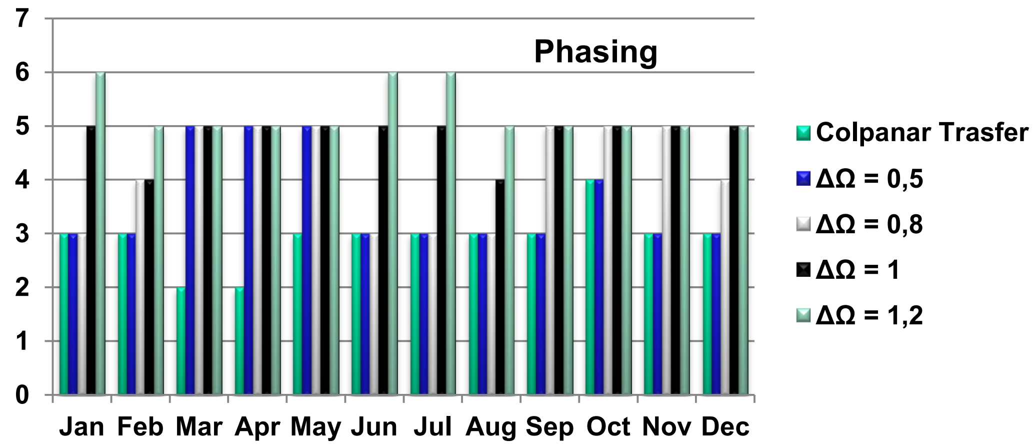
Launch Opportunities with ΔΩ

- **Mission feasibility increases:**

  ΔΩ gives higher flexibility in terms of launch opportunities





ΔΩ [°]	Direct Launches	Phasing
0	10	35
0,5	21	43
0,8	23	50
1	27	58
1,2	31	63

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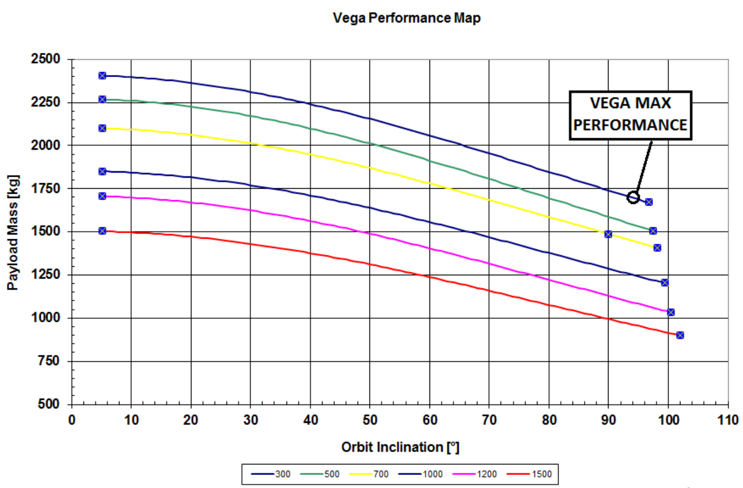
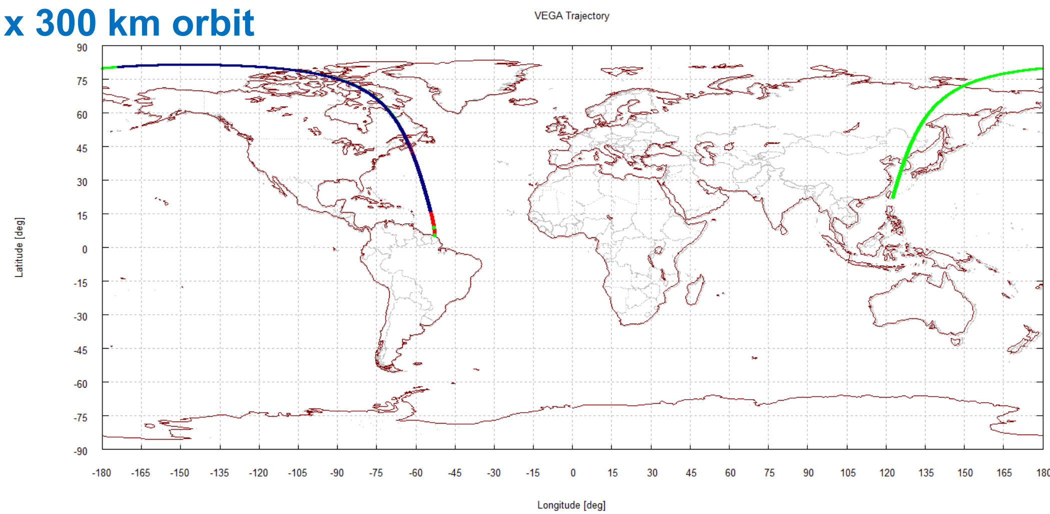
Vega Mission Analysis

VEGA Maximum Performance on 300 km x 300 km orbit





Maximum performance is limited to 1500 kg by CSG constraints (Vega C > 1600kg)

	ΔV [m/s]	
	Short Mission	Long Mission
SRMs	8790	
To Parking Orbit	545	
Rendez-Vouz	385	265
Approaching	16	
Deorbiting	223	
TOTAL	9959	9839

NTS

	TIME [s]	REL.SP. [m/s]	ALT. [km]	WEIGHT [kg]	MACH [-]	P.DYN [Pa]	(T-D)/M [m/s2]	GAM.R [°]	ALPHA [°]	DVprop	DVgrav	DVaero [m/s]	DVdis	DVinert
1 IMU Start	0.0	0.0	0.0	138486.3	0.0	0.0	0.00	90.0	0.0	0.0	0.0	0.0	0.0	0.0
1 Motor Start	0.0	0.0	0.0	138486.3	0.0	0.0	0.00	90.0	0.0	0.0	0.0	0.0	0.0	0.0
1 Lift-off	0.3	0.0	0.0	138435.3	0.0	0.0	9.86	90.0	0.0	0.0	0.0	0.0	0.0	0.0
1 q*alpha max	17.0	169.9	1.3	120934.6	0.5	15115.3	21.56	74.6	3.8	(57900.2 Pa*°)				
1 Pitch-Over	4.5	31.2	0.1	134381.2	0.1	567.2	18.62	89.9	0.3	72.4	-1.3	0.0	-70.1	1.0
1 GravityTurn	20.5	212.3	1.9	117305.5	0.6	22133.9	21.25	70.7	0.1	409.7	-38.5	-0.7	-326.7	43.8
1 Mach 1	31.5	332.1	4.7	107208.9	1.0	40541.3	17.55	61.7	0.0					
1 P.dyn. max	57.0	647.7	13.8	86020.7	2.2	55793.4	25.06	42.7	0.1					
1 (T-D)/M max	92.5	1627.2	34.8	54759.0	5.2	11579.3	38.66	27.2	0.1					
1 AT Det.	114.5	1762.1	50.5	50232.9	5.4	1590.5	0.72	21.1	0.2	2658.3	-486.7	-98.7	-730.4	1342.6
1 Separation	114.8	1761.2	50.7	50228.6	5.4	1553.9	0.70	21.1	0.2	2658.6	-487.7	-98.7	-730.4	1341.8
2 Coasting														
2 Motor Start	115.6	1758.3	51.3	41727.6	5.4	1454.1	-0.06	20.8	0.0	2658.6	-487.7	-98.7	-730.4	1338.9
2 (T-D)/M max	160.0	3036.4	79.7	25352.1	11.1	101.4	35.85	13.1	7.4					
2 AT Det.	193.5	3936.7	103.7	17855.9	13.7	2.1	1.39	10.3	0.0	5036.5	-669.8	-100.1	-810.8	3452.8
2 Separation	218.4	3903.9	119.1	17828.6	10.4	0.2	0.00	7.8	0.0	5040.6	-706.9	-100.1	-810.9	3419.7
3 Coasting														
3 Motor Start	235.5	3884.6	127.0	15060.5	8.3	0.1	0.00	6.0	2.4	5040.6	-706.9	-100.1	-810.9	3400.4
3 HS Jettison	241.0	3942.8	129.2	14738.2	8.1	0.1	13.88	5.5	21.0	5104.3	-712.0	-100.1	-811.8	3458.0
3 alpha max	241.0	3942.8	129.2	14738.2	8.1	0.1	13.88	5.5	21.0					
3 (T-D)/M max	342.0	7074.1	168.6	4514.9	10.9	0.0	47.34	4.3	8.8					
3 AT Det.	353.5	7461.2	175.1	3912.3	11.2	0.0	1.32	4.5	3.5	8781.8	-791.8	-100.1	-953.6	6914.0
3 Separation	378.3	7448.3	189.2	3905.9	10.7	0.0	0.03	4.3	3.5	8786.4	-809.3	-100.1	-953.6	6901.0
4 Coasting														
4 Motor Start	461.3	7395.6	231.7	2521.5	9.7	0.0	0.00	3.6	6.9	8786.4	-809.3	-100.1	-953.6	6848.4
4 (T-D)/M max	977.6	7793.3	330.0	2112.0	9.1	0.0	1.16	0.2	14.9					
4 Cut-off	977.6	7793.3	330.0	2112.0	9.1	0.0	1.16	0.2	14.9	9333.1	-921.9	-100.1	-982.8	7253.3

(DVprop, DVgrav, DVaero, DVdis, DVinert: DV_BALANCE)

MISSION SUMMARY - ORBIT ELEMENTS	h_p[km]	h_a[km]	om_n[°]	i[°]	om_p[°]	theta*[°]
Last SRM Stage	-1214.948	321.665	-50.332	98.459	-133.140	154.904
Transfer (before coasting)	316.000	316.000	-50.329	98.465	3.425	51.478

LAST STAGE PROPELLANT BUDGET	DV[m/s]	DW[kg]	tb[s]	Marg.[kg]	Wp[kg]
Motor Ignition	-	-	-	-	1477.300
Perigee Firing	546.693	409.456	516.238	0.000	1067.844
Unusable Propellant	-	-	-	38.500	1029.344

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Vehicle Configuration – Short Mission

Short Mission → Maximum Phasing Time on Parking orbit = 5000 s

	Short Mission (Batteries)		
	Time [s]	Time [h]	Mp [kg]
H0	0	0	1477
Parking Orbit (300km x 300km)	977.6	0.27	1068
Phasing (Max)	5000	1.39	1068
Final Orbit (800km x 800km)	3000	0.83	818
Avvicinamento Target	1000	0.28	818
Aggancio + CCAM	5000	1.39	818
Deorbiting Boost 1 + Coasting	5800	1.61	50
Deorbiting Boost 2 + Coasting	2780	0.77	
TOTAL	**23560**	**6.5**	

Extra On Board Battery* needed to cover full mission → 1

Extra TVC Battery* needed to cover overall AVUM burning time → 1

OBB Duration [s]	12000
Extra OBB needed for mission	**1**
Total OBB weight [kg]	14.3

AVUM Burning Time [s]	1170
Extra ACTB needed for mission	1
TOTAL ACTB weight [kg]	10.9

*** With respect to VEGA generic configuration**

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Vehicle Configuration – Long Mission

Long Mission → Maximum Phasing Time on Parking orbit = 14 hours

	Long Mission (Solar Array)		
	Time [s]	Time [h]	Mp [kg]
H0	0	0	1477
Parking Orbit (300km x 300km)	994.5	0.28	1068
Phasing (Max)	50400	14	1068
Final Orbit (800km x 800km)	3000	0.83	898
Avvicinamento Target	1000	0.28	898
Aggancio + CCAM	5000	1.39	898
Deorbiting Boost 1 + Coasting	5800	1.61	70
Deorbiting Boost 2 + Coasting	2780	0.77	
TOTAL	**68975**	**19.2**	

Power provided By Body Mounted Solar Array

Power Budget

	V	I [A]	Charge Power [W]	Charge Time [s]
ACTB	63	3.7	30	3000
Reduced Capacity OBB	33	9.1	300	3000
Avionics Power			200	
Extra Power			180 (35% Margin)	
POWER NEEDED			**710**	

Sizing

Solar Array	
Height [m]	3
Radius [m]	0.6
Surface [m^2]	11.2
Clean Surface [m^2]	10.1
Power Density [W/m^2]	70.3
Power [W]	**711**

Solar Cell Density [kg/m2]	0.84
Solar Cells Weight [kg]	8.5
Integration Masses [kg]	17.0
Solar Panel Weight [kg]	**25.5**

Margin Policy on Known Losses	
Temperature losses	15%
Array losses	30%
Solar incidence	20%
Geometry losses	70%

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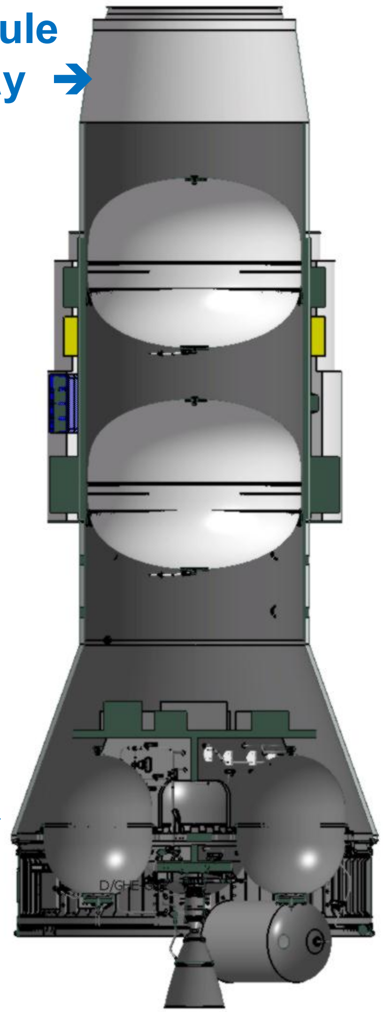
AVUM SM preliminary layout

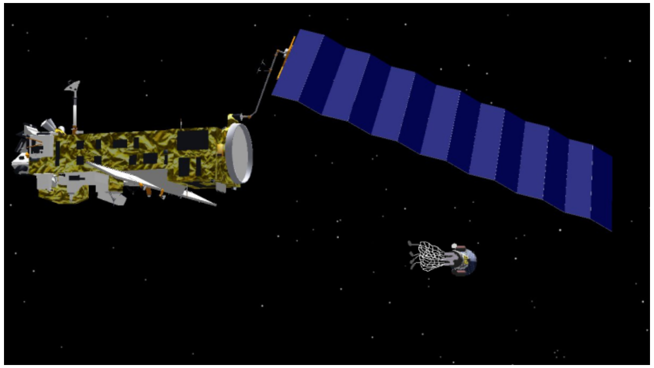
AVUM Proximity Module
GNC/ACS/sensors bay ➔
for Proximity RDV

AVUM PRE
Propulsion
Runtime ➔
Extension

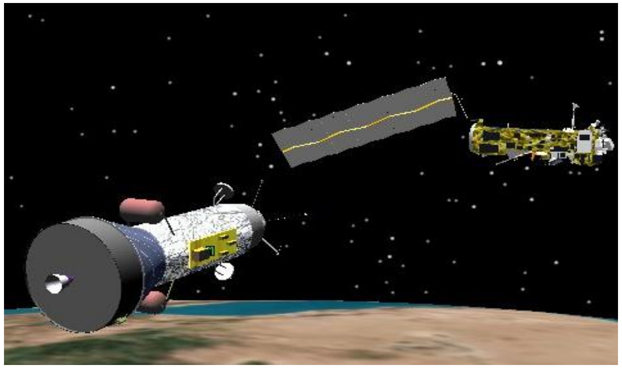
Standard AVUM ➔



AVUM SM + Net layout



AVUM SM + Tentacles layout



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System Modes

System	S/S	Phase: Launch	Parking	Far Range RDV	Close Range RDV	Grabbing	De-orbiting	CAM
Avum Std								
	OBC	1	1	1	0	0	1	1
	GNC	1	1	1	0	0	1	1
	TT&C	1	1	1	1	1	1	1
	Attitude Det.	1	1	1	1	1	1	1
	Thermal	0	1	1	1	1	1	1
	RACS	1	1	1	0	0	1	1
	LPS	1	1	1	0	0	1	0
PRE								
	Thermal	0	1	1	1	1	1	1
	LPS	0	0	1	0	0	1	0
	Power	0	1	1	1	1	1	1
PM								
	GNC	0	0	0	1	1	0	0
	Sensors	0	0	0	1	1	0	0
	OBC	0	0	0	1	1	0	0
	ACS	0	0	0	1	1	0	0
	Thermal	0	0	0	1	1	0	0
GD								
	Tentacles	0	0	0	0	1	1	0
	Clamping	0	0	0	0	1	1	0
	Grabbing Sensors	0	0	0	0	1	1	0
	Net	0	0	0	0	1	1	0
	Theter	0	0	0	0	1	1	0
	Tension Sensors	0	0	0	0	0	1	0

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Modules main features

- Avum Std software/avionics updates
  - Patchable MD to manage more efficiently the Far RDV Phase
  - Hybrid Navigation (GNSS)
  - Attitude determination (star-tracker, GPS...)
  - Power and Data distribution among modules
  - Avionics and RACS Thermal control
  - Coms: TLM (ground based/TDRSS), Commands
- Propulsion Runtime Extension (PRE) slip-on device
  - Extends the AVUM deliverable DV (Propellant and Pressurant tanks)
  - Hosts the Power S/S: Solar Array, battery pack
  - LPS thermal control
  - Tether arms attachment support
- Proximity Device module
  - Hosts GNC, Avionics, Sensors and ACS for Close RDV and Grabbing
- Grabbing Device

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Mission Analysis outcomes 1/2

Loaded software for nominal mission (right day, right time)

- Only 1 trajectory submission for each window (simpler MA)
- Low RAAN compensation capability (no dogleg for plane change)
- Less launch opportunities but faster missioning approach

Ascent Phase to parking orbit as standard Vega flight

- Hybrid navigation with GPS active from lift-off

Parking orbit used for phasing and uploading MD if window missed

After reaching the orbit close to the target control passes to PM

- Vega FPS in idle mode
- PM OBC takes the control
- PM in charge of Closing and Grabbing phase

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Mission Analysis outcomes 2/2

Grabbing Phase

- **Rigid connection → RACS for fast Debris de-spinning**
- **Flexible connection → RACS required for tether pre-tensioning**

De-orbiting

- Control returns to AVUM OBC
- Command from ground if needed to change preloaded sequence
- RACS ignites to dump MEA transients for flexible connection
- Stack separation after de-orbiting boost and AVUM CAM

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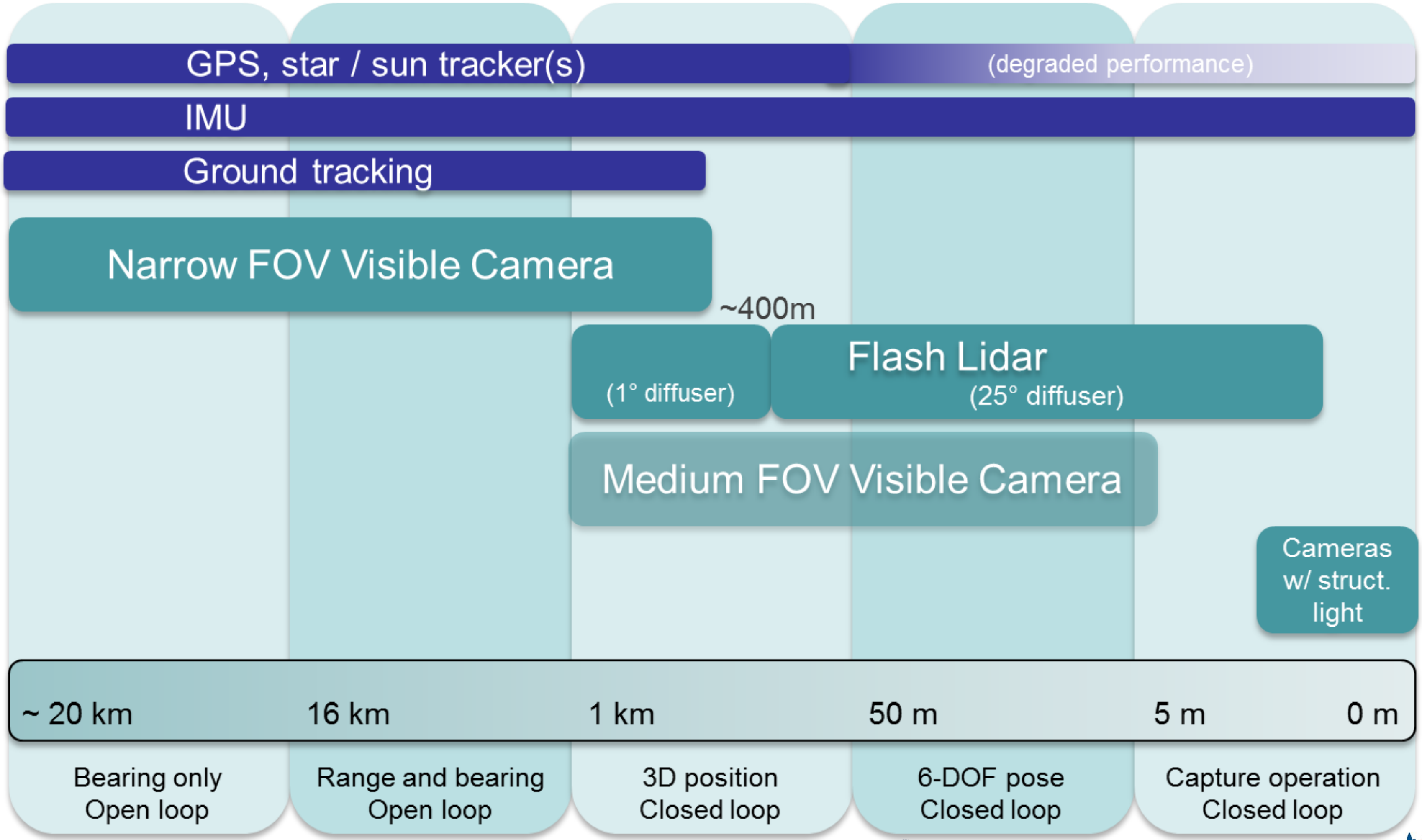
CRDV/Grabbing Sensor Selection

MDA analysis



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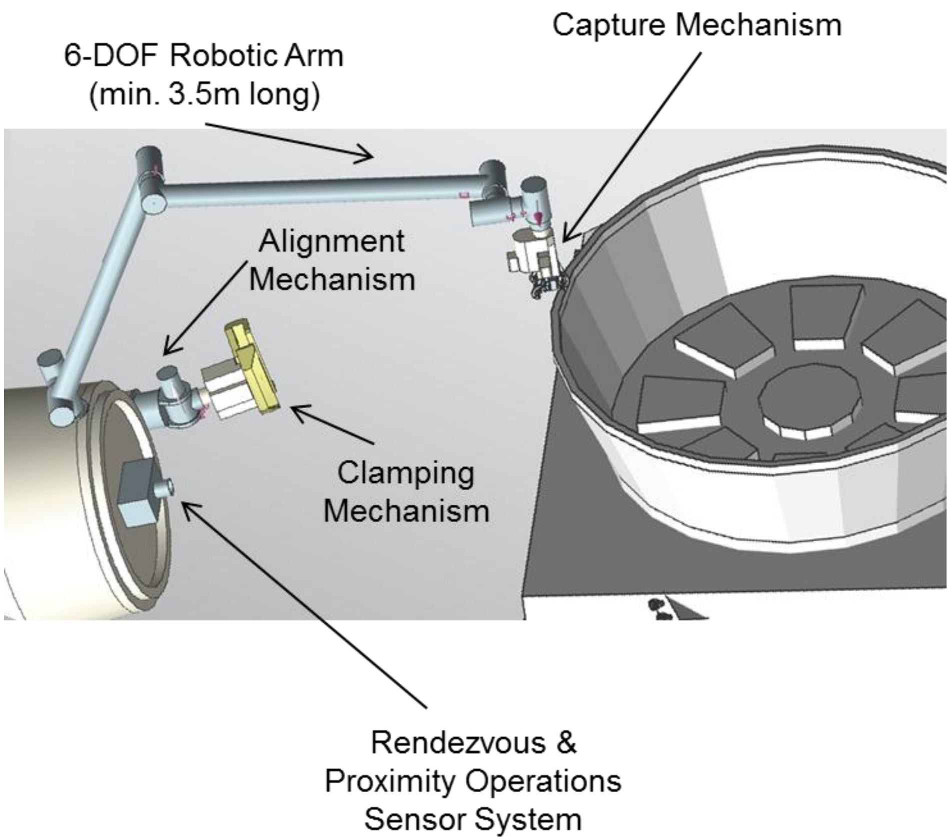
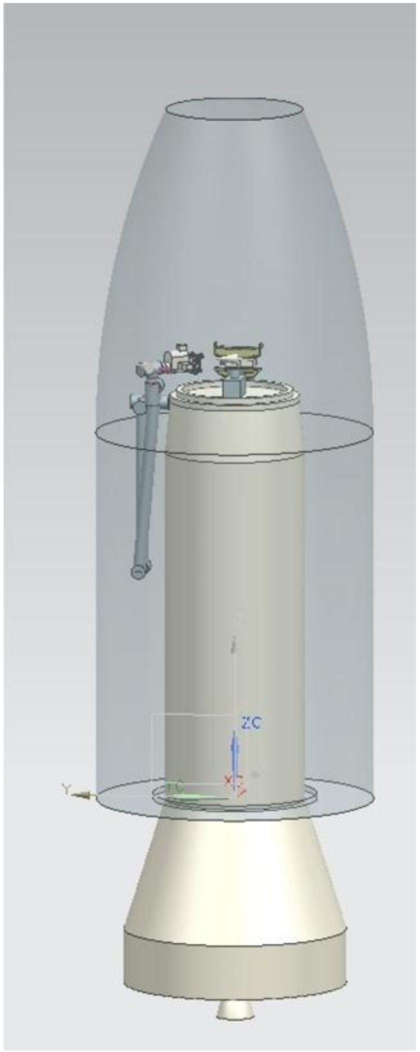
Grabbing devices overview - Robotic

Robotic Arm/Clamp MDA concept





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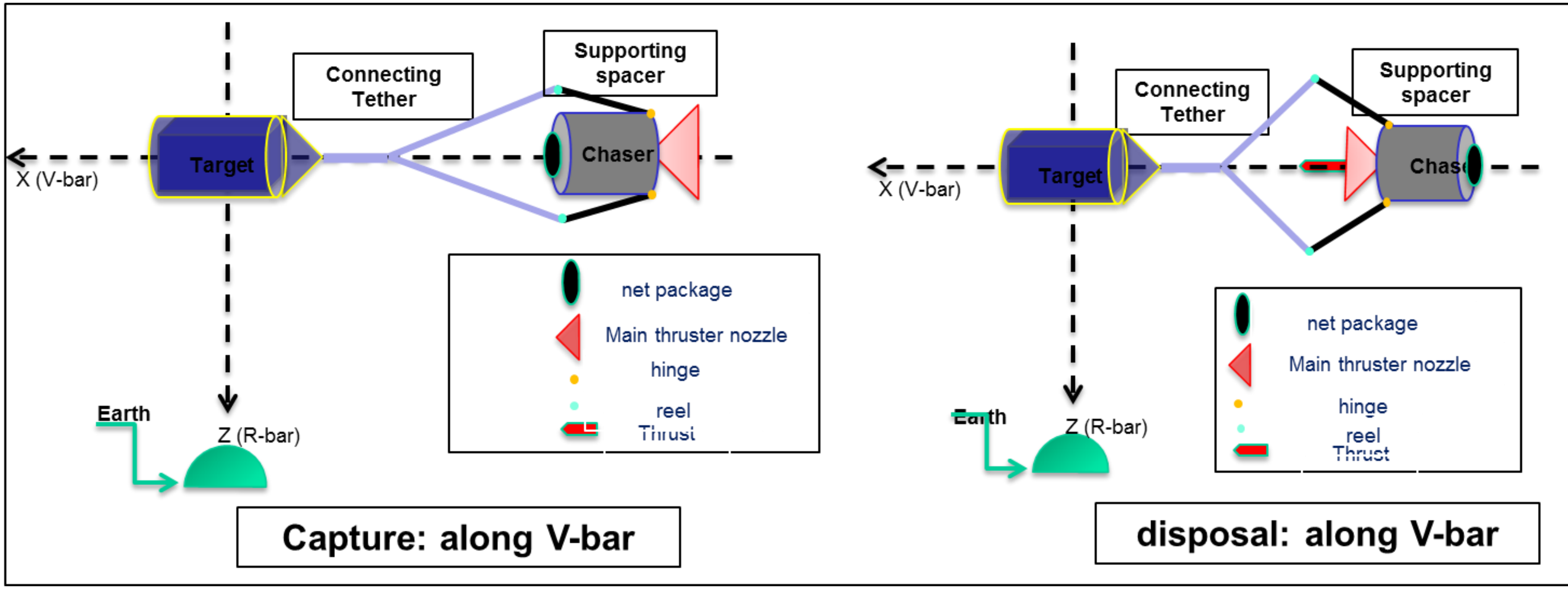
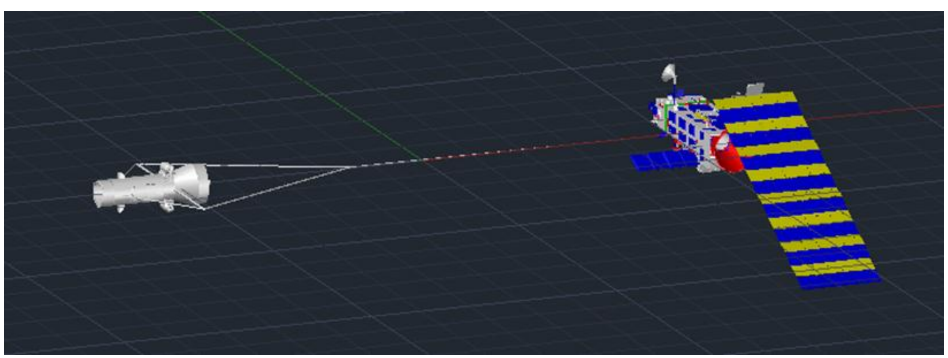
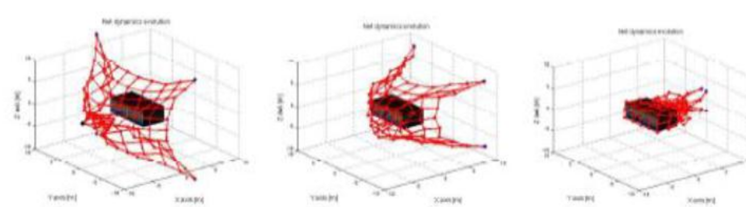
Grabbing devices overview - Net

Net/Tether PoliMi Concept





Pulling by tether simulation



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Models and Simulators

The analyses led to a set of sizing values

- Tether and tentacles **length**, **damping** and **stiffness**.

- Tentacle and tether support structure **position** on Avum.

- **Grabbing point** on Target Debris, in tentacle case definition.

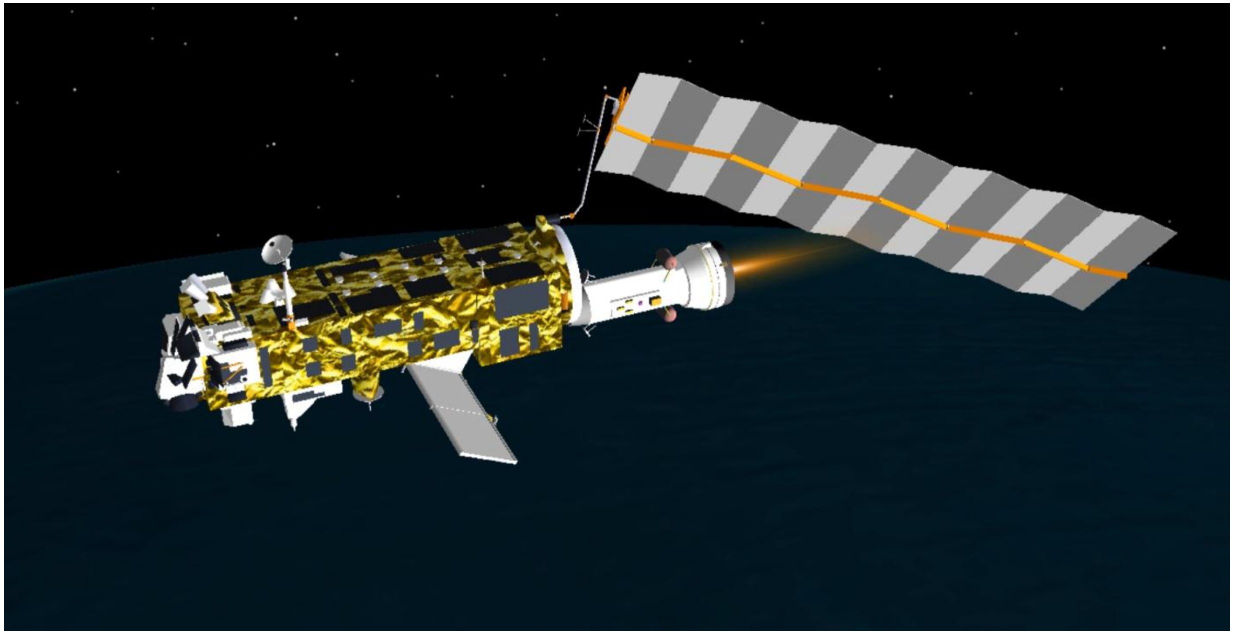
Two class of models used to demonstrate the de-orbiting

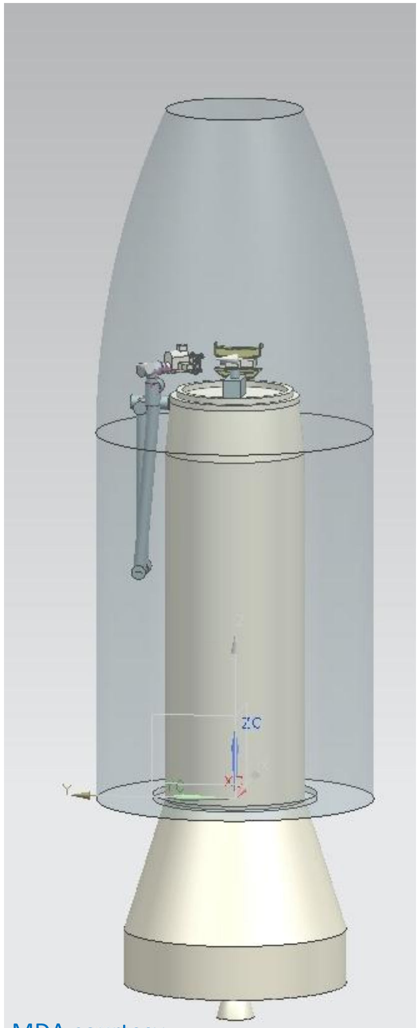
- **Planar linear models:** a simplified dynamic system is developed in orbital plan in order to highlights the main aspect of de-orbiting manoeuvre (Stability, Controllability, etc..)

- **6DOF model:** a complex model is used to simulate the entire dynamic system.

Rigid connection

Consolidated configuration for the Grabbing from MDA:

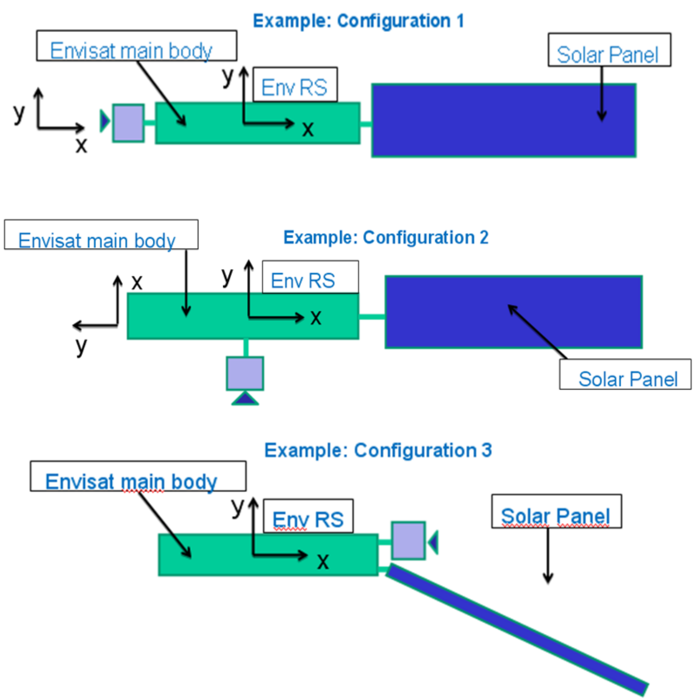




MDA courtesy

Robotics: Results

	Controllability	Stability
Configuration I	Yes	Yes
Configuration II	No (capability very Low)	Yes / Low
Configuration III	Limited	Yes



Configuration 1 is the best for Controllability and Stability, but it presents drawbacks for the grabbing opportunities.

Configuration 2 is discarded considering the low controllability margins

Configuration 3 is good as well considering that additional degree of freedom is guarantee with the clamping system.

The simulation 6dof confirms the planar model results with a successful de-orbiting.

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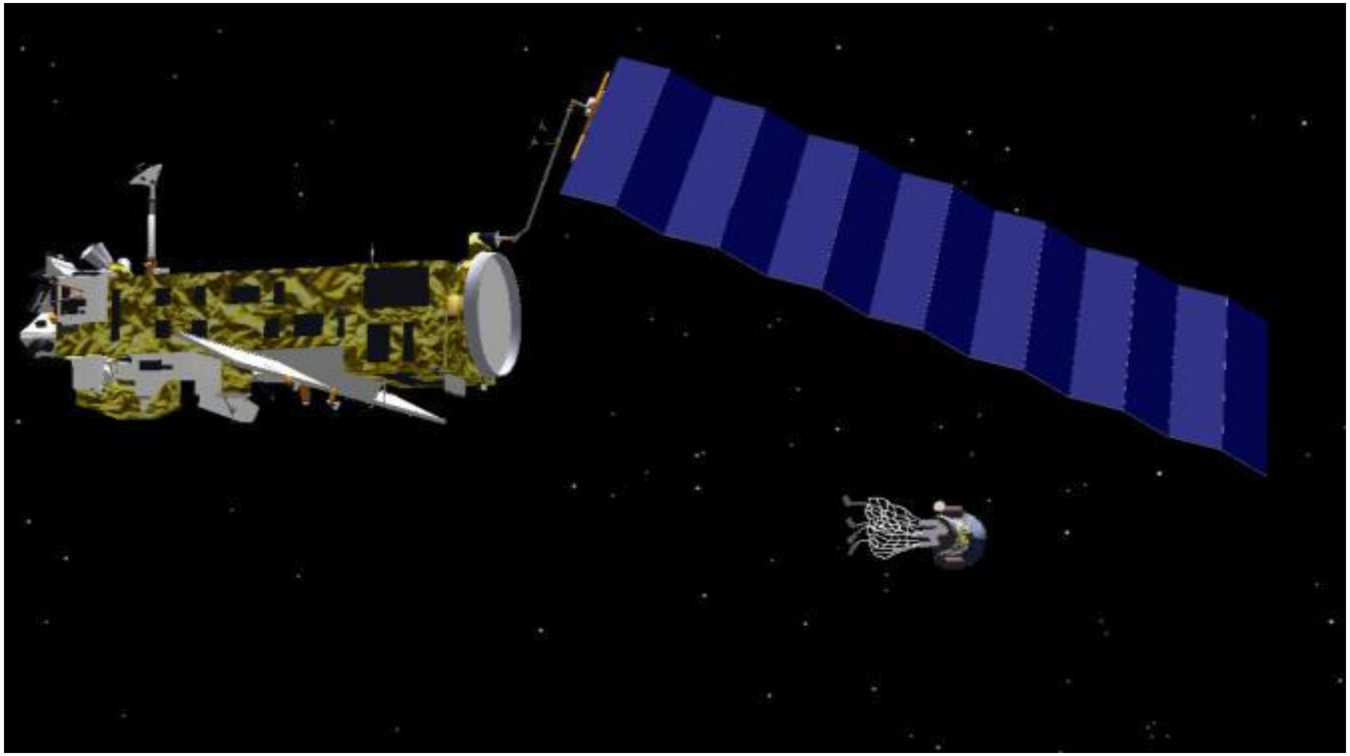
Flexible connection

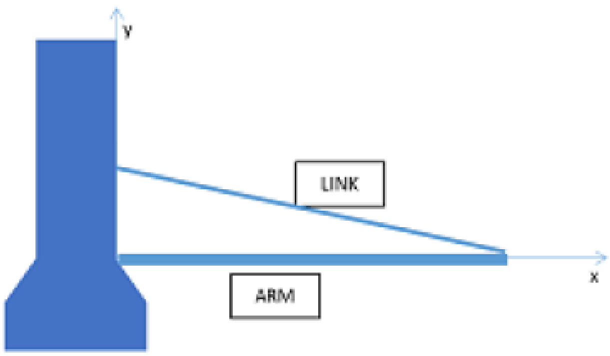


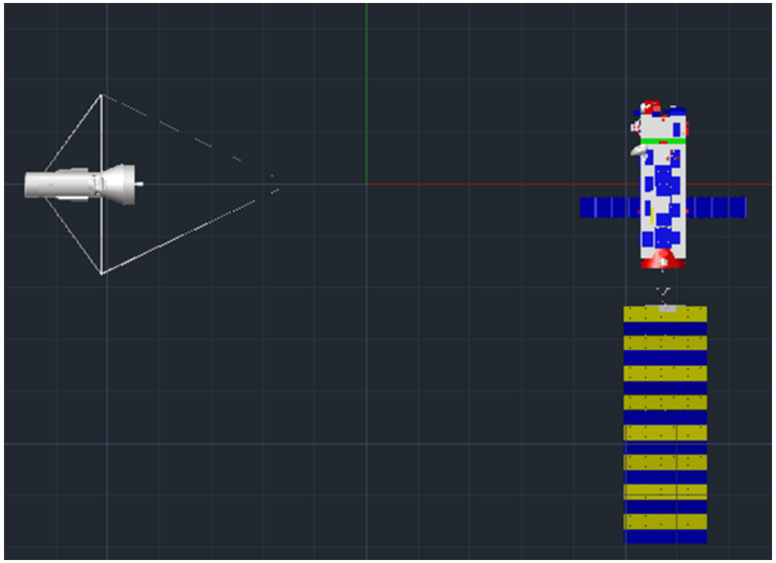
Net: Results

The **Controllability** analyses report that, fixing the AVUM attachment points in a precise region of the AVUM SM, the de-orbiting is assured even considering a possible disturbing torque due to the different tension of the tether (tether support structure at AVUM side)

The **Stability** analyses states that applying an ad-hoc control law the over all system has enough margins and residual oscillation are negligible.

The **simulation 6dof** confirms the planar model results with a successful de-orbiting.



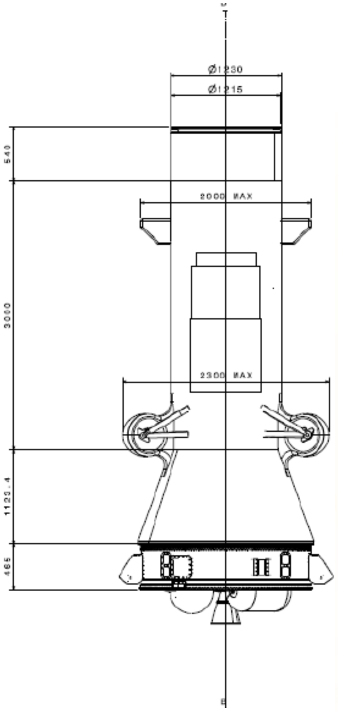


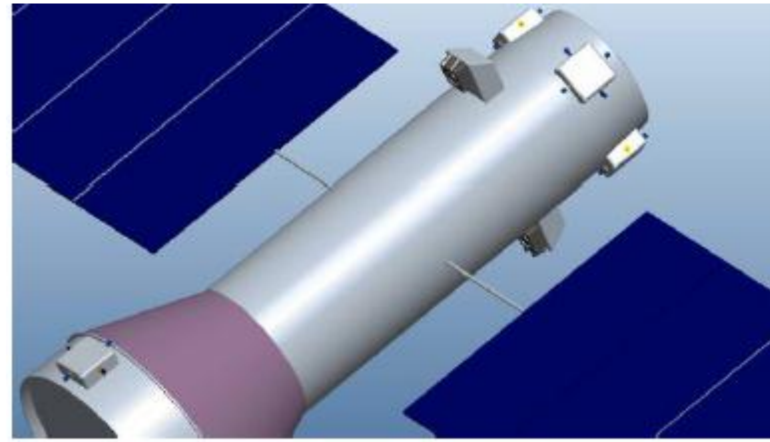
PoliMi picture

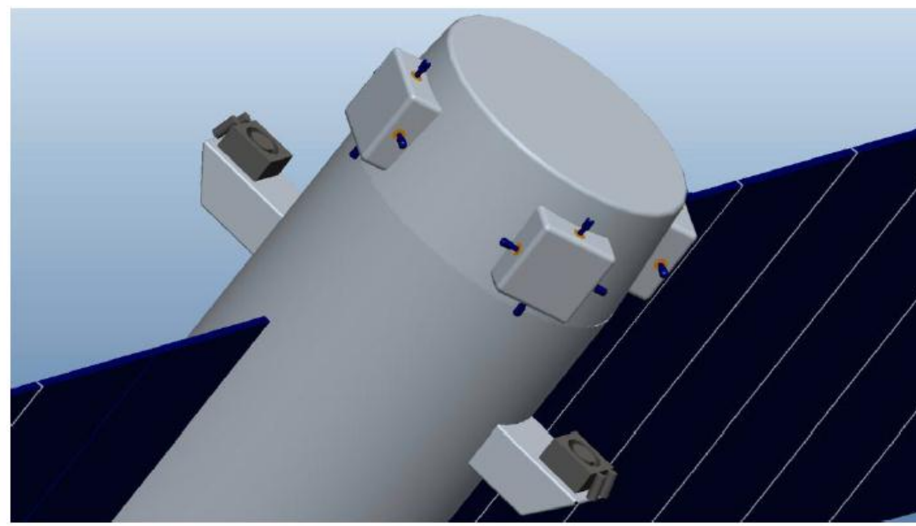
Electric Propulsion Orbit Rising

SA deployed

EPS Concept







Thrusters
HET
2 x PPS-5000
P= 10 kW

SA stowed inside PLF

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In Orbit Demonstration

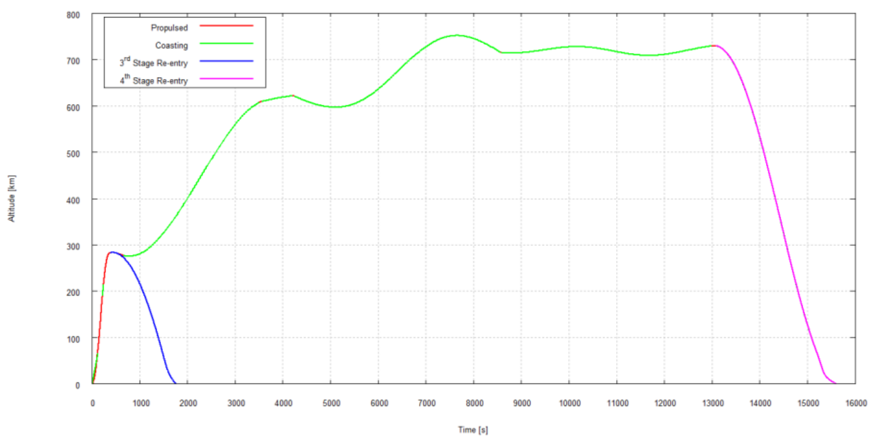
This is basically a quasi-standard Vega mission aimed to test key technologies in flight

Typical mission scenario

- 1st P/L release (350kg) on a 600km quasi-SSO orbit
- After the phasing maneuver the Debris is targeted (within a range of ≈50km)
- 1 orbit is elapsed near it.
- A deorbit boost is performed to place the Avum stage into a straight-to-the-sea re-entry path.
- The instrumentation mass penalty of Avum has been accounted to be about 100kg.

The required phasing and RDV could be obtained by

- properly chosen mission data: this lead to a reduced number of launch opportunities per year, but with no impact on the launcher.
- Improvement of the guidance on board algorithm: this improve the number of the launch opportunities, but need a change in the LV configuration.



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Technology Maturity and risks

All the chosen components have already an high TRL /Flight Proven

In the system development some risks remains

- Low cost approach and Vega performance impose to limit redundancies
    - higher risk for in-flight contingencies
- Short mission could led to an high risk to have long stand by on ground for window missing
- Avum Avionics upgrade (hybrid navigation, radiation hardening, thermal control)
- FPS patchable (orbital phase only)
- MEA Delta Qualification
- RACS Delta Qualification
- Power S/S

- Proximity Module is a New S/C
    - Avionics
    - Sensors
    - GNC
    - Software

- Grabbing Devices
    - New development

System	Subsystem	Items	TRL	Risks
AVUM Enhanced	AVUM Standard	Vega 4th stage	9	-Radiation hardening -Active thermal control -IRS Hybridizing -FPS upgrade
	AVUM PRE	-Additional LPS tanks -Additional Pressurant tank -Additional RACS tank	6	-New LPS feeding system design -MEA Delta Qualification -RACS Delta Qualification
AVUM proximity module	Additional GNC and Avionics	OBC	COTS	Low
		CAM	COTS	Low
		MFU	COTS	Low
		OBB-A	COTS	Low
		LIDAR	COTS	Low
		GPS Antenna (x2)	COTS	Low
		LNA Antenna GPS	COTS	Low
		GPS Receiver	COTS	Low
		IRS	COTS	Low
		Power conditioning	COTS	Low
		Solar arrays	COTS	Body mounted
		Dedicated ACS	COTS	For Close RDV and Grabbing
		Dedicated FPS	2	New development, but simplified wrt LV FPS

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ADR by Vega Status of the activities

The study allowed to

- Assess the feasibility of an ADR by adaption of Vega Upper Stage

- Define the System level conceptual design of the spacecraft
  - including all sub-systems for two capture scenarios
    - Net/Tether grabbing
    - Tentacles/Arm grabbing

- Trade-off several mission profiles

- Demonstrate the feasibility of de-orbit scenario
  - By means of representative models for both options:
    - Flexible: Net/Tether
    - Rigid: Tentacles/Arm

- Assess programmatic, risk and cost aspects of the identified mission options

No major show-stopper arose on the adaption of Vega system for ADR service

AVUM + PRE can offer a flexible platform to carry a PM and its GD close to a Target Debris

And eventually de-orbit the whole stack by its powerful MEA.

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Thank you!

AO-13780
Active Debris Removal
by Vega U/S adaptation

WS, 06/05/2014

ELV System Team

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