HERA CUBESATS OPERATIONS
C-FDSOC

CUBESATS MISSION PLANNING CONOPS & MISSION ANALYSIS

Pâmini ANNAT, Jean JAUBERT, Sébastien GOULET
On behalf of CNES Mission Planning and Flight Dynamics Teams

Hera SOWG & Workshop @ESAC – 19/11/2024

Cubesats Flight Dynamics & Science Operation Center (C-FDSOC)

- Mission Planning ConOps
- Juventas Mission Analysis
- Milani Mission Analysis
- C-FDSOC Status

Cubesats Mission Planning ConOps for Proximity Operations

CRUISE

PROX-OPS

PLTP
- Pre-Long Term Planning
- Objectives: Define science objectives for each payload per phase

C-FDSOC · CMCC · PayLoads Teams

LTP
- Long Term Planning
- Objectives: Refine the science objectives in science slots

C-FDSOC · CMCC · PayLoads Teams

STP
- Short Term Planning
- Objectives: Produce Science Request

C-FDSOC support for GRASS/VISTA/ASPECT/RSE + NavCams · JuRa Team

VSTP
- Very Short Term Planning
- Objectives: Update Science Request with fresh OD* / Produce MPR & CRF

C-FDSOC

*C-FDSOC: Cubesats Flight Dynamics and Science Operation Center
*CMCC: Cubesats Mission Control Center
*OD: Orbit Determination
*MPR & CRF : commands for Cubesats TC

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Pre Long Term Planning Technical Note – HERA-CNES-CFDSOC-TN-0061 1.0

C R U I S E

P R O X - O P S

Issue 1.0 for C-FDSOC Detailed Design Review (DDR)

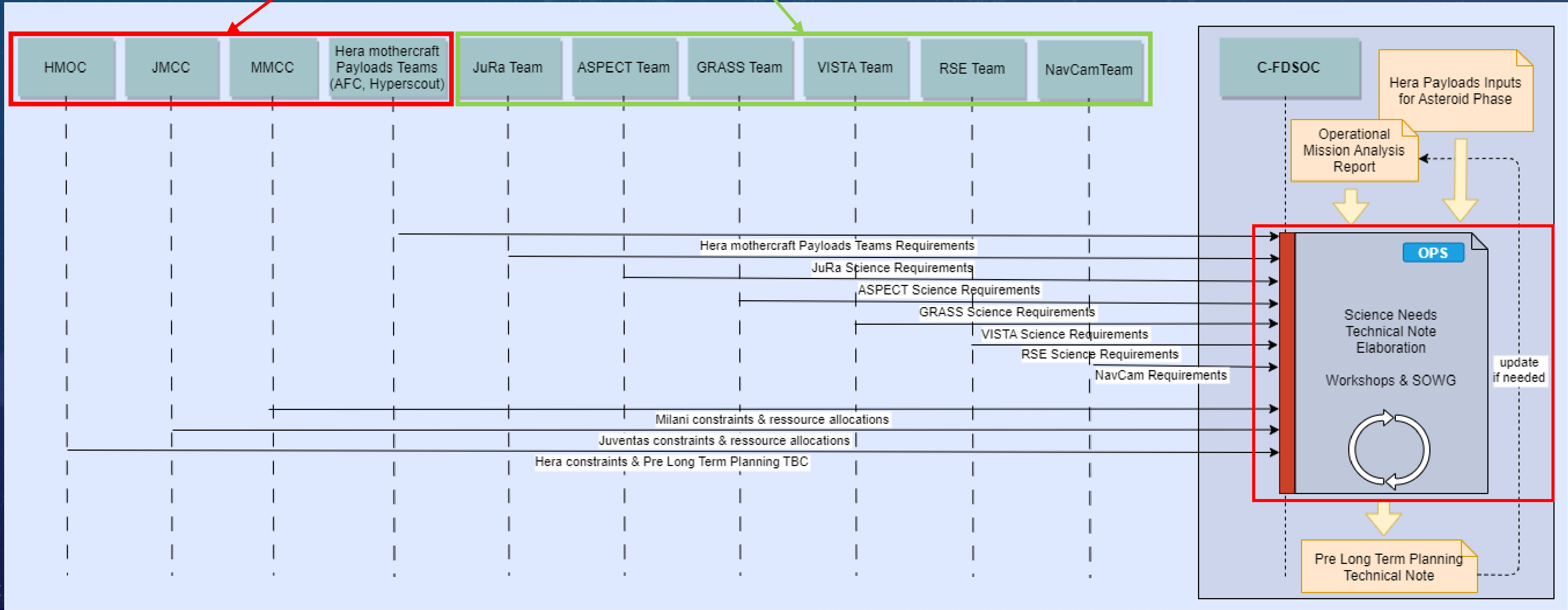
✓A **first version** has been **issued** and **signed by CNES & Payloads Teams**

✓This version contains **up-to-date science requirements and activities** for both cubesats and all payloads (including NavCams and RSE experiment) and for all asteroid phases (including landing).

Open points for future release

- Resource budget (data budget, power consumption) and cubesats constraints
- Cubesats Constraints slots (JMCC & MMCC)
- Baseline ISL slots inputs from HMOC

➔ dedicated splinters / workshops / meetings to be scheduled with ESOC (ISL) + Tyvak & GomSpace (Cubesats Constraints)



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PLTP Technical Note – ASPECT example for FRP

C R U I S E

P R O X - O P S

Activity	Objective	Conditions (incl. geometrical, deployments, simultaneous activations, etc.)	Obs Mode/Attitude	Data (Mbytes)	Freq of Obs	Energy (Wh)
ASPECT dark datacube	TBW	ASPECT shall point outside of the Didymos system ASPECT Sun exclusion angle 45°		about the same as a classical acquisition datacube TBC	At least every two weeks	
Didymos coverage	Imaging Didymos (goal 90% of the illuminated surface)	Resolution <= 2m/pix Phase angle between 5° and 25°. The phase angles for these acquisitions are verified for the center of the asteroid (some surface points may be acquired with a phase angle about 3 deg (semi-NIR field of view) out of this range. Maximum relative velocity 2m/s No Didymos eclipse nor occultation Didymos pointing ASPECT Sun exclusion angle 45°	Configuration: number of acquisitions per acquisition sequence TBD, processing mode TBD, compression ratio TBD	5x TBD	Minimum 5 acquisition sequences and scheduled over spread longitudes to obtain the full coverage *(some images can be common with Didymos phase curve measurement)*	TBD
Dimorphos coverage	Imaging Dimorphos (goal 90% of the illuminated surface)	Resolution <= 2m/pix Phase angle between 5° and 25°. The phase angles for these acquisitions are verified for the center of the asteroid (some surface points may be acquired with a phase angle about 3 deg (semi-NIR field of view) out of this range. Maximum relative velocity 2m/s No Dimorphos eclipse nor occultation Dimorphos pointing (or Didymos pointing if Dimorphos is also in the Fov TBC) ASPECT Sun exclusion angle 45°	Configuration: number of acquisitions per acquisition sequence TBD, processing mode TBD, compression ratio TBD	5x TBD	Minimum 5 acquisition sequences and scheduled over spread longitudes to obtain the full coverage *(some images can be common with Dimorphos phase curve measurement)*	TBD
Phase curve measurement of Didymos	Surface microstructure of Didymos	Phase angle spread between 0° and 60°: The images shall be acquired with different phase angles, distributed as	Configuration: number of acquisitions per acquisition sequence TBD, processing mode	5x TBD	Minimum 5 acquisition sequences	TBD

Example of information / Consolidation expected from Payload teams and Cubesat Teams

PLTP Technical Note – RSE example for Juventas SSTO 3.3km & 2 km

CRUISE

Activity	Objective	Conditions (incl. geometrical, deployments, simultaneous activations, etc.)	Obs Mode/Attitude	Data (Mbytes)	Freq of Obs	Power (W)
RSE nominal	Measurements for gravity fields fine reconstruction for both asteroids through orbit determination	Stabilized cubesat pointing (avoid slews during RSE arcs) Stabilized Hera pointing No propulsion on cubesat and Hera No JuRa observation	No specific pointing Attitude shall be known with a sampling rate of 1 Hz (needed to correct antenna phase during whole RSE arc)	N/A	1 ISL range data per second Each RSE measurement session shall have a minimum duration of 5 minutes For each RSE arc, the total (cumulative) duration of the RSE measurements shall correspond to at least a 40% of the RSE arc duration The RSE measurements should be evenly spaced in orbital position and regularly along the observation phase During RSE arcs, CubeSat NavCam images shall be provided with a sampling rate of 3 h	TBD

PROX-OPS

Activity	Objective	Conditions (incl. geometrical, deployments, simultaneous activations, etc.)	Obs Mode/Attitude	Data (Mbytes)	Freq of Obs	Power (W)
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Example of information / Consolidation expected from Payload teams and Cubesat Teams

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C R U I S E

P R O X - O P S

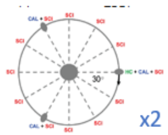
Next step : Elaboration of the Long Term Planning Schedule (LTP Schedule)

- ✓ **LTP Schedule** corresponds to the global **timeline** with all activities from the PLTP TN
- ✓ Depends on the **Cubesats Mission Analysis** and **definition of trajectories** :
  - Trajectories definition **not fully stabilized** (safety distance HERA / MILANI, orbit prediction accuracy for JUVENTAS)
- ✓ Depends on the definition and expression of the **applicable constraints** at payload and cubesats levels :
  - Energy, thermics, commanding, co-existence rules, geometry, orbital events, data volumes and download, …
  - Work in progress with payload teams, cubesats manufacturers and HERA team
  - Impact the definition of trajectories and strategy of acquisition for payloads (ASPECT, JuRa)
- ✓ LTP Schedule also requires the positionning of **dedicated time slots** (CMCC, FDS, ISL) :
  - Work in progress with cubesats manufacturers and HERA team (ISL)

LTP Schedule – Juventas example

work in progress, discussed during Juventas Workshop @ESEC September 2024

From PLTP TN, planning of all payloads activations put all together (columns) in order to check the exclusivity rules between payloads and wrt platform operations (ISL, pre-heating & thrust, PF maintenance …) according to coexistence matrix and constraints defined.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
1	Hera Phas	Juventas Phase	Planning cycl	Date (UTC)	Duration (days	Sub phase	Slot type	Begin date (UTC)	End date (UTC)	OCM / WOL slot	ISL communication slot	CMCC activities	RSE	JURA	GRASS	landing IMU	ADCS & GNC sensors (except NavCam)	NavCam	MPR activity	Energy budget	Data budget
110	OCP	SSTO2	20	Wed 2027-03-24T00:00:00	3	SSTO2 arc 8	MPS						TBD								
111	OCP	SSTO2	20	Wed 2027-03-24T00:00:00	3	SSTO2 arc 8	MPS							TBD							
112	OCP	SSTO2 - Landing	21	Sat 2027-03-27T00:00:00	4	SSTO2 arc 9 - Landing	MPS								Calibration (before landing maneuver)				GRASS_calibration <date, params TBD>		
113	OCP	SSTO2 - Landing	21	Sat 2027-03-27T00:00:00	4	SSTO2 arc 9 - Landing	FDS			L-INSP 2027-03-29T06:30:00 DV: TBD Pre-heating starts at TBD +WOL TBC									PROP_xxx <params TBD>		
114	OCP	SSTO2 - Landing	21	Sat 2027-03-27T00:00:00	4	SSTO2 arc 9 - Landing	CMCC					TBD									
115	OCP	SSTO2 - Landing	21	Sat 2027-03-27T00:00:00	4	SSTO2 arc 9 - Landing	MPS							TBD					Jura_acquisition <date, params TBD>		
116	OCP	SSTO2 - Landing	21	Sat 2027-03-27T00:00:00	4	SSTO2 arc 9 - Landing	MPS								Calibration				GRASS_calibration <date, params TBD>		
117	OCP	SSTO2 - Landing	21	Sat 2027-03-27T00:00:00	4	SSTO2 arc 9 - Landing	MPS								Opportunity science measurement conditions TBD				GRASS_SCI <date, params TBD>		
118	OCP	SSTO2 - Landing	21	Sat 2027-03-27T00:00:00	4	SSTO2 arc 9 - Landing	MPS						TBD								
119	OCP	SSTO2 - Landing	21	Sat 2027-03-27T00:00:00	4	SSTO2 arc 9 - Landing	MPS							TBD							
120	OCP						CMCC					TBD							-		
121	OCP						MPS														
122	OCP						MPS								Calibration (before breaking maneuver)				GRASS_calibration <date, params TBD>		
123	OCP						FDS			Breaking maneuver params TBD									PROP_xxx <params TBD>		
124	OCP						MPS							Antennas retraction					Landing_procedure <date, params		
125	OCP						MPS								Science as free-fall calibration						
126	OCP						MPS				TBD		TBD		Passive measurements outside calibrations		Context data acquisition rates TBD detailed per sensor	NavCam images TBD			
127	OCP					Touch-down and bouncing	MPS									High-rate landing IMU					
128	OCP					Surface operations	MPS				TBD		TBD		Over 2 Dimorphos orbits: 24 SCI Measurements + 3 calibrations per orbit + measurements (ON) in-between  x2	TBD	Context data acquisition rates TBD detailed per sensor	NavCam images TBD			

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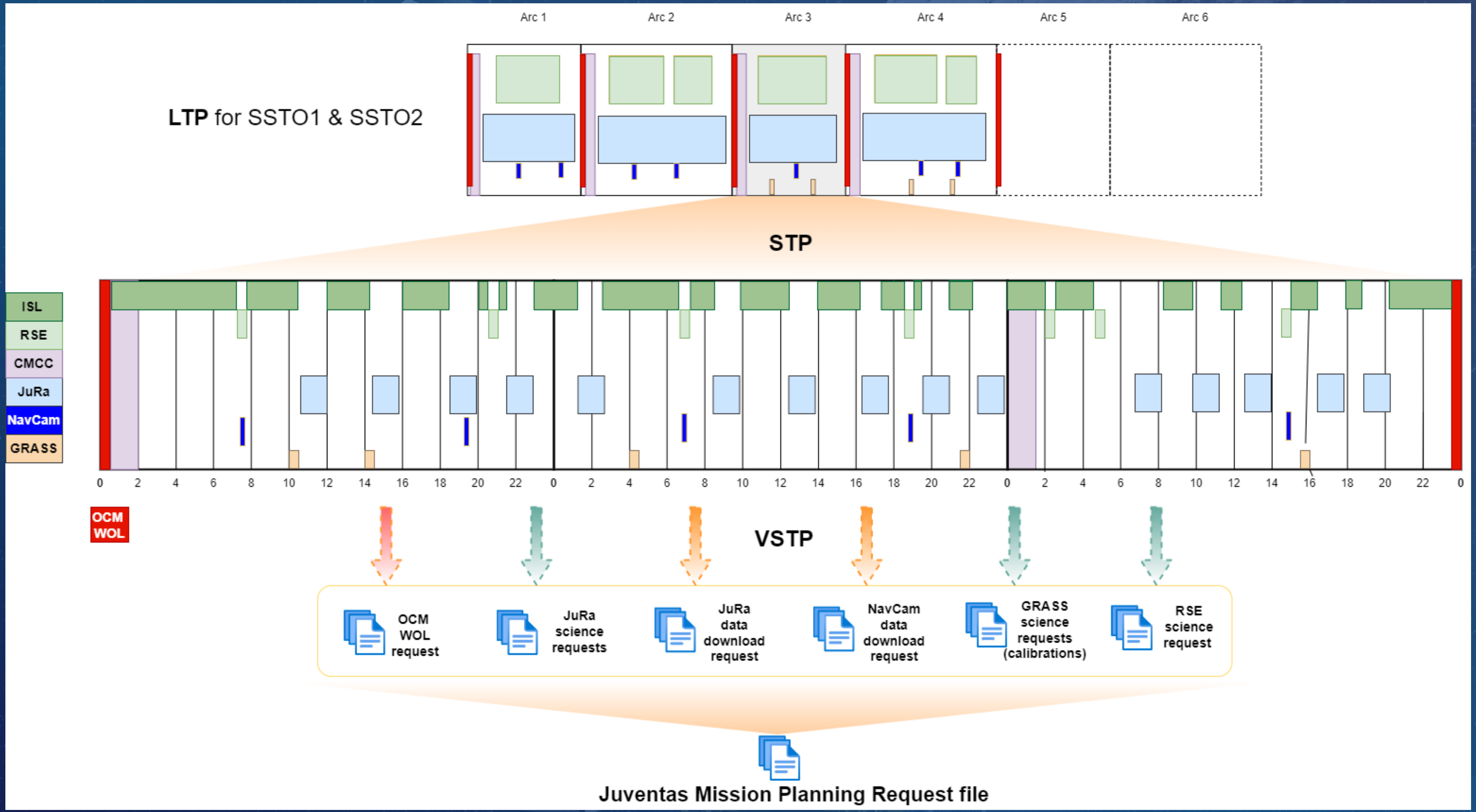
From LTP Schedule to STP and VTSP – Juventas example



LTP Schedule

Preliminary science planning
+ other activities (predefined patterns)

- OCM & WOL slot
- ISL communication slots
- CMCC slots
- JURA slots
- RSE slots
- Additional NavCam acquisition slots

STP & VSTP

Scheduling (or adjustment) of detailed activities considering up-to-date trajectories, events and resources status with checking of all applicable constraints (power, data, thermal):

→ **Draft MPR for STP phase**
→ **Final MPR for VSTP phase**

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- Milani Mission Analysis
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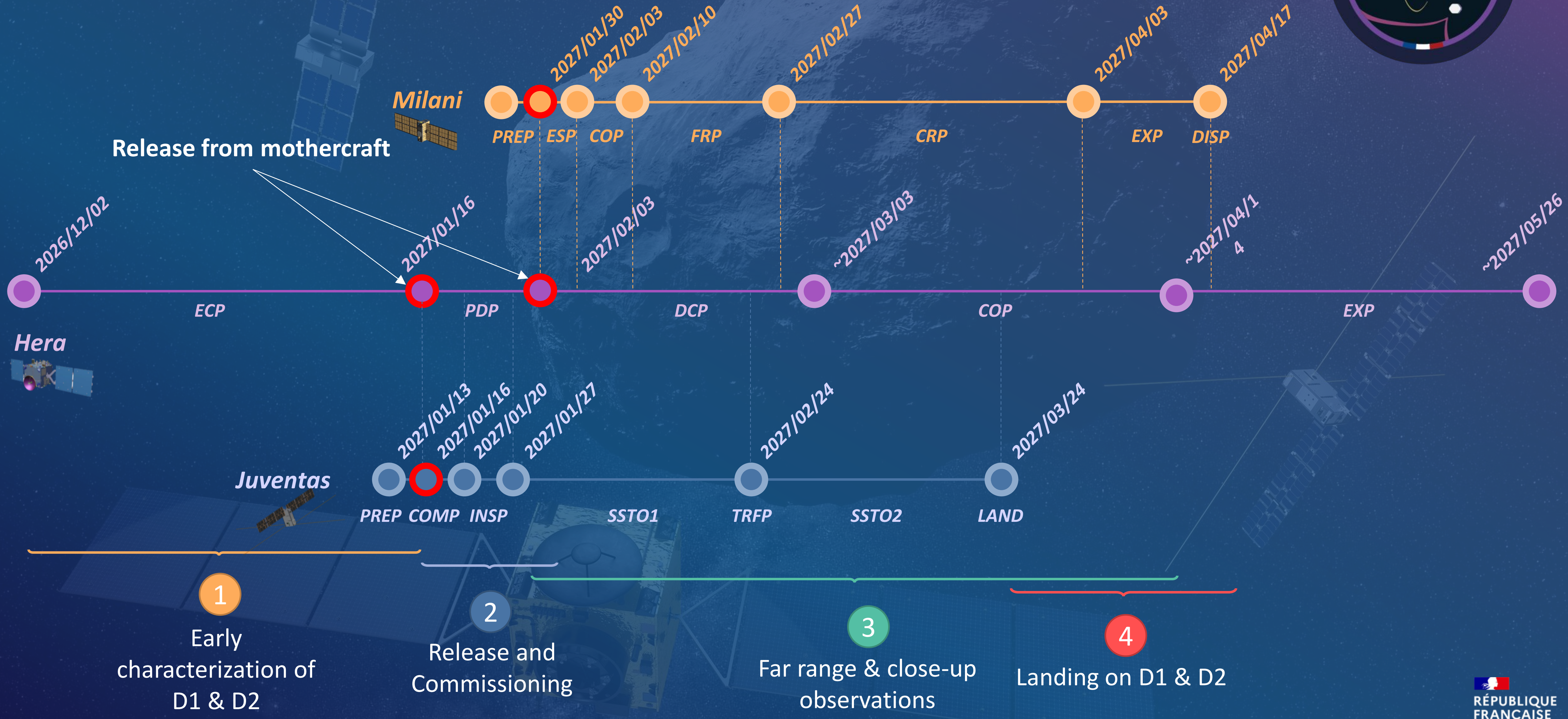
Hera & cubesats mission timeline overview –
Operational Mission Analysis Report 1.0 & reference trajetories



Science Orbits – SSTO 3.3km & SSTO 2km

adapted from GMV baseline

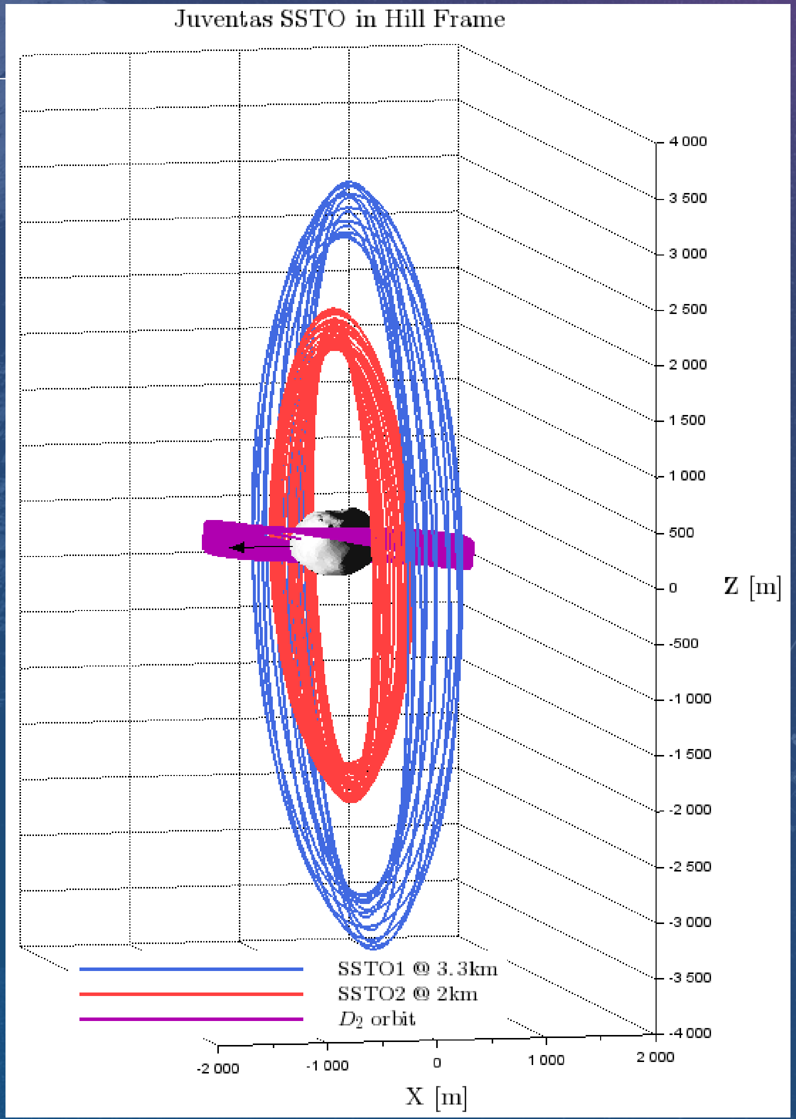
Objective

- Radar sounding acquisitions for tomography
- Diversity of orbital configurations

Self-Stabilized Terminator Orbit

- Equilibrium between asteroid attraction and solar radiation pressure
- Quasi periodic stable orbit
- Orbit contained in a plane normal to the Sun direction
- Plan offset from the barycenter of the system by ten to hundred meters along this direction

$$DV(SSTO_{total}) = 0.154\ m/s$$

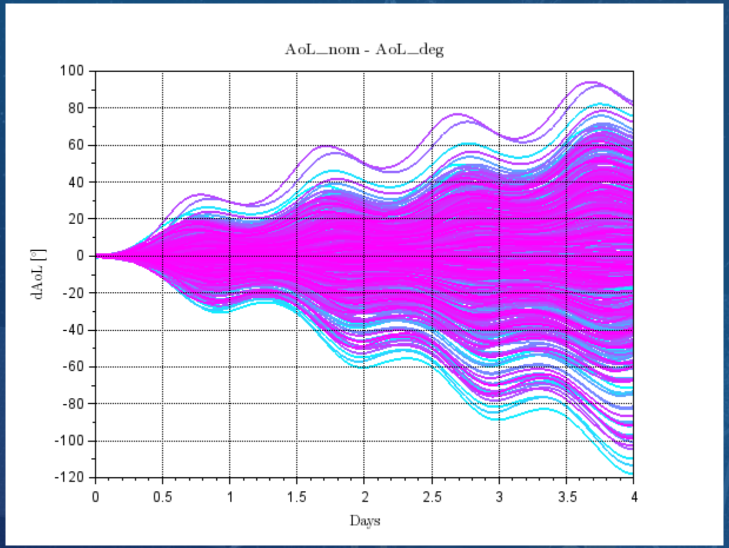


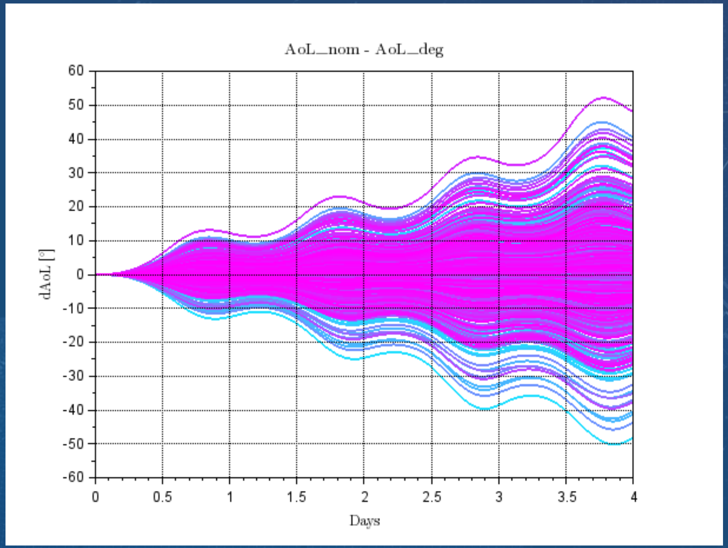
Note: alternatives SSTO phases durations for coverage optimization under study

Dispersion and Juventas manoeuvre strategy

Dispersion analysis outcomes:

- High dispersions are observed with regards to the angular position of Juventas on its SSTO (« AoL »), even on a short-term horizon.
- JuRa programming based on a reference trajectory is not realistic (especially a long-term predicted trajectory).
- Current baseline is that JuRa programming should be adjusted on the short-term predicted trajectory or should be built with regular acquisitions (regardless of the trajectory).

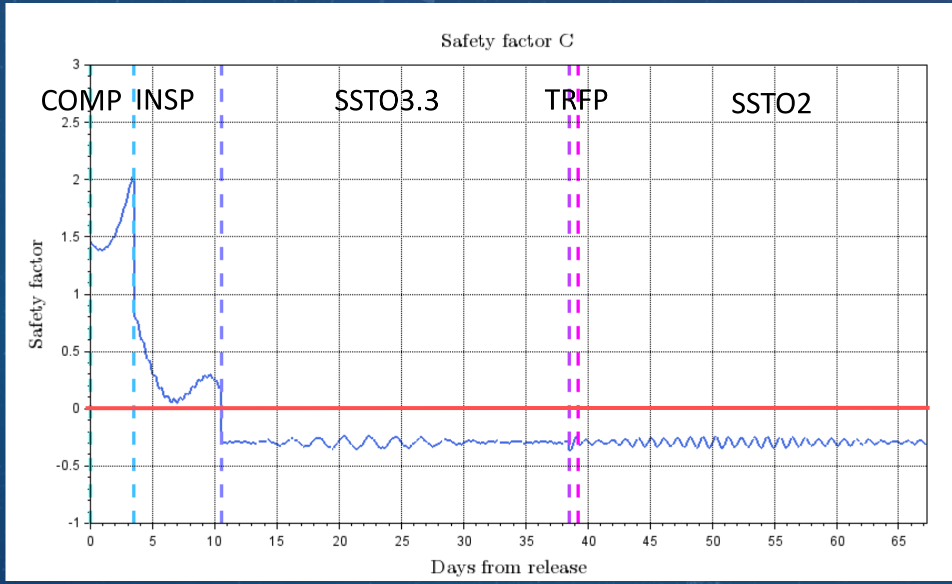




Evolution of delta in « AoL » between the reference and the real trajectory
Conservative scenario (right), optimistic scenario (left)

Juventas trajectory vs operational constraints

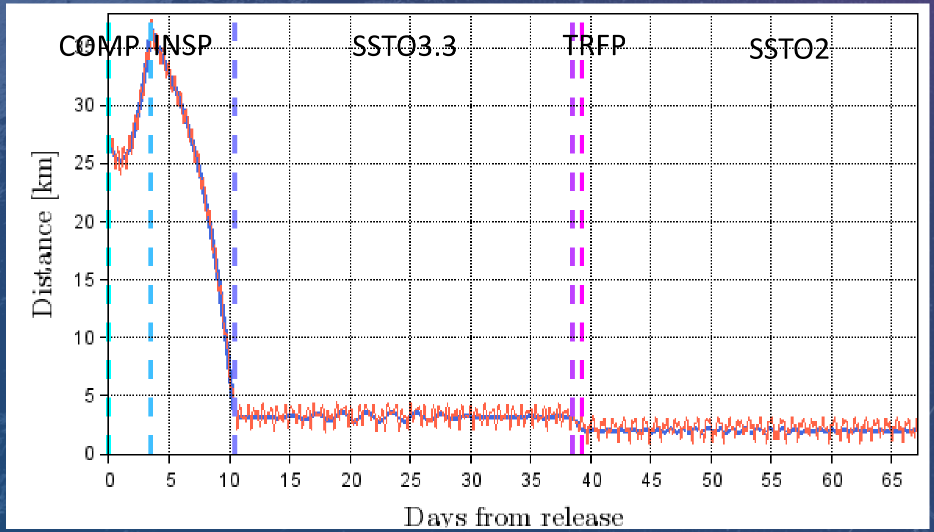
Safety factor *



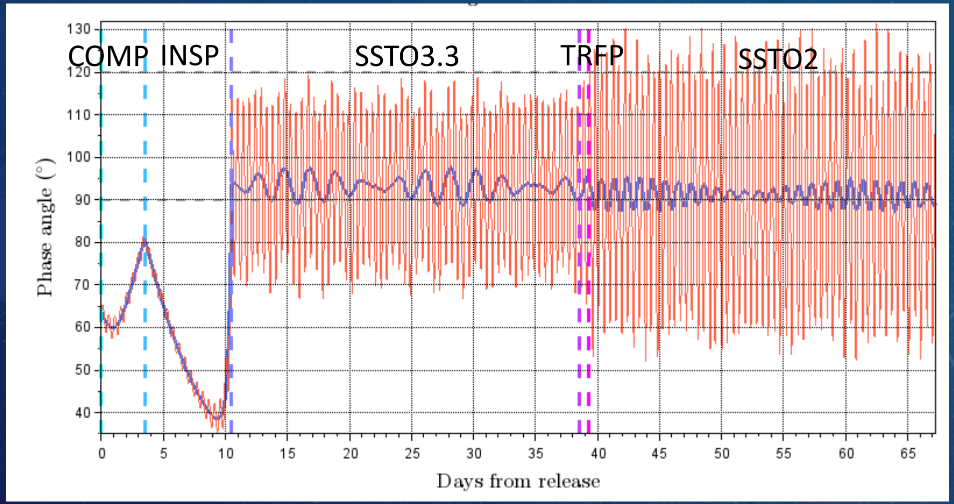
** excess instantaneous velocity compared to a parabolic trajectory (in a Keplerian environment)*

> 0 during manoeuvre for escape in case of missed manoeuvre

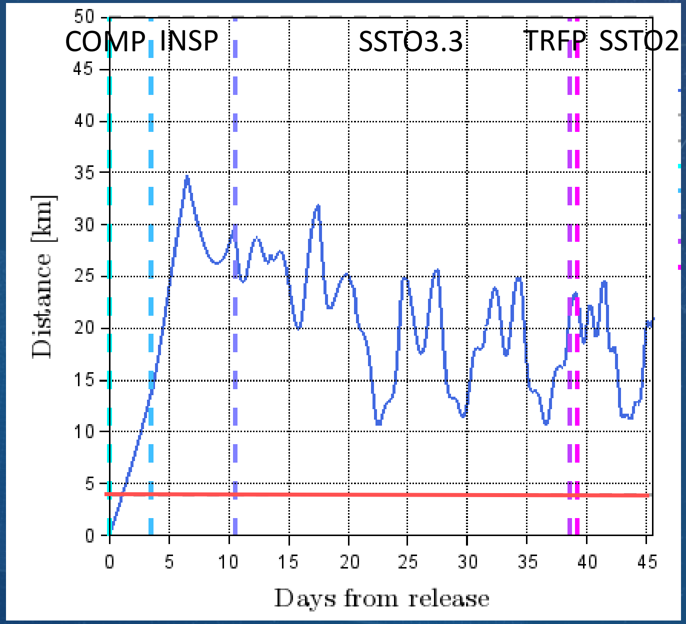
Distance to Asteroids



Phase angle (optical navigation)



Distance to Hera (safety & ISL link)

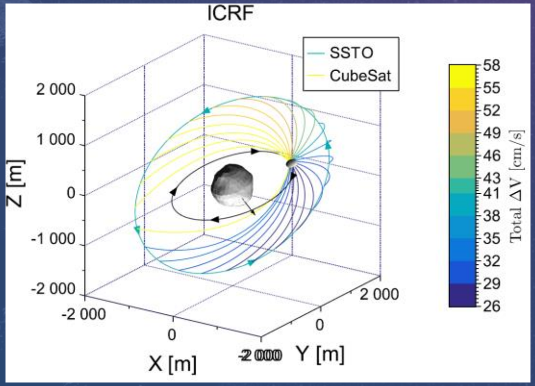


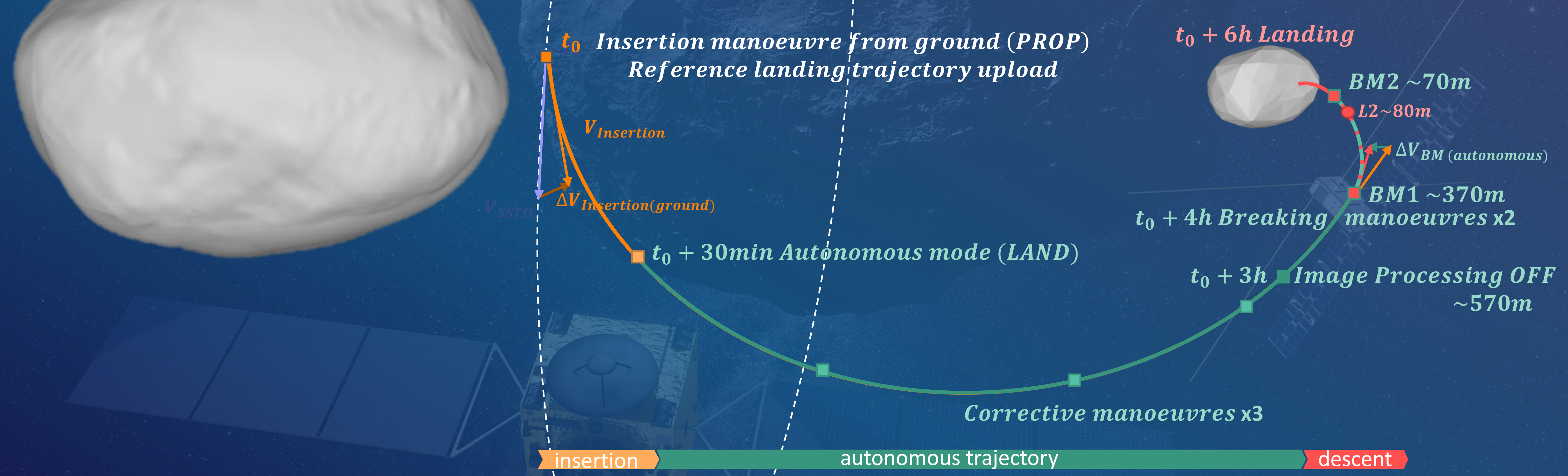
$$* \; C = V\sqrt{\frac{r}{2\mu}} - 1$$

Juventas landing sequence through L2

work in progress, discussed during Landing Workshop @CNES June 2024

On going phasing studies for direct landing with braking maneuver and shooting method developement for trajectory optimization (DV, time of flight, impact speed, impact angle)



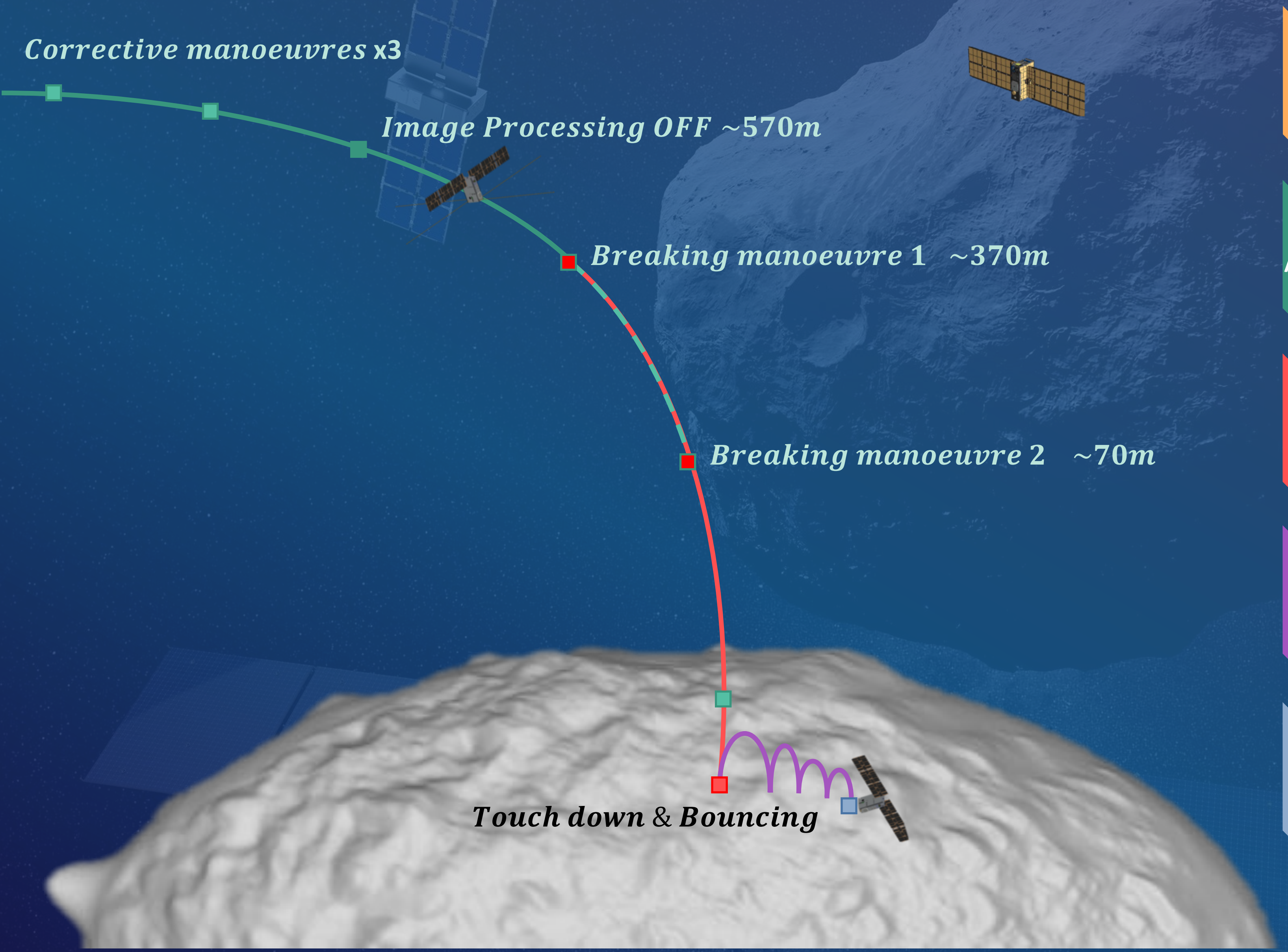


D2 shape after impact - Raducan et. al

Based on current GNC design, courtesy of GMV (JUV-GS-GNC-RP-0003)

Payloads acquisitions during Juventas descent, landing, surface phases

work in progress, discussed during Landing Workshop @CNES June 2024



Insertion trajectory
- JuRa
- GRASS
- NavCam
- RSE

Autonomous trajectory
- JuRa *(antenna retractation?)*
- GRASS
- NavCam
- RSE

Descent

GRASS, Landing IMU, ADCS
JuRa
NavCam
RSE

Bouncing

Landing IMU, ADCS
NavCam
ContextCam
RSE

Surface ops
- GRASS, Landing IMU, ADCS
- NavCam
- ContextCam
- RSE
- … JuRa ?

ASPECT
NavCam

cnes

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Milani FRP – Far Range Phase

adapted from PoliMi baseline

Objective

- Trajectory designed for global and microstructure mapping
- Resolution of 2m/pix

ASPECT constraints for D1 global mapping

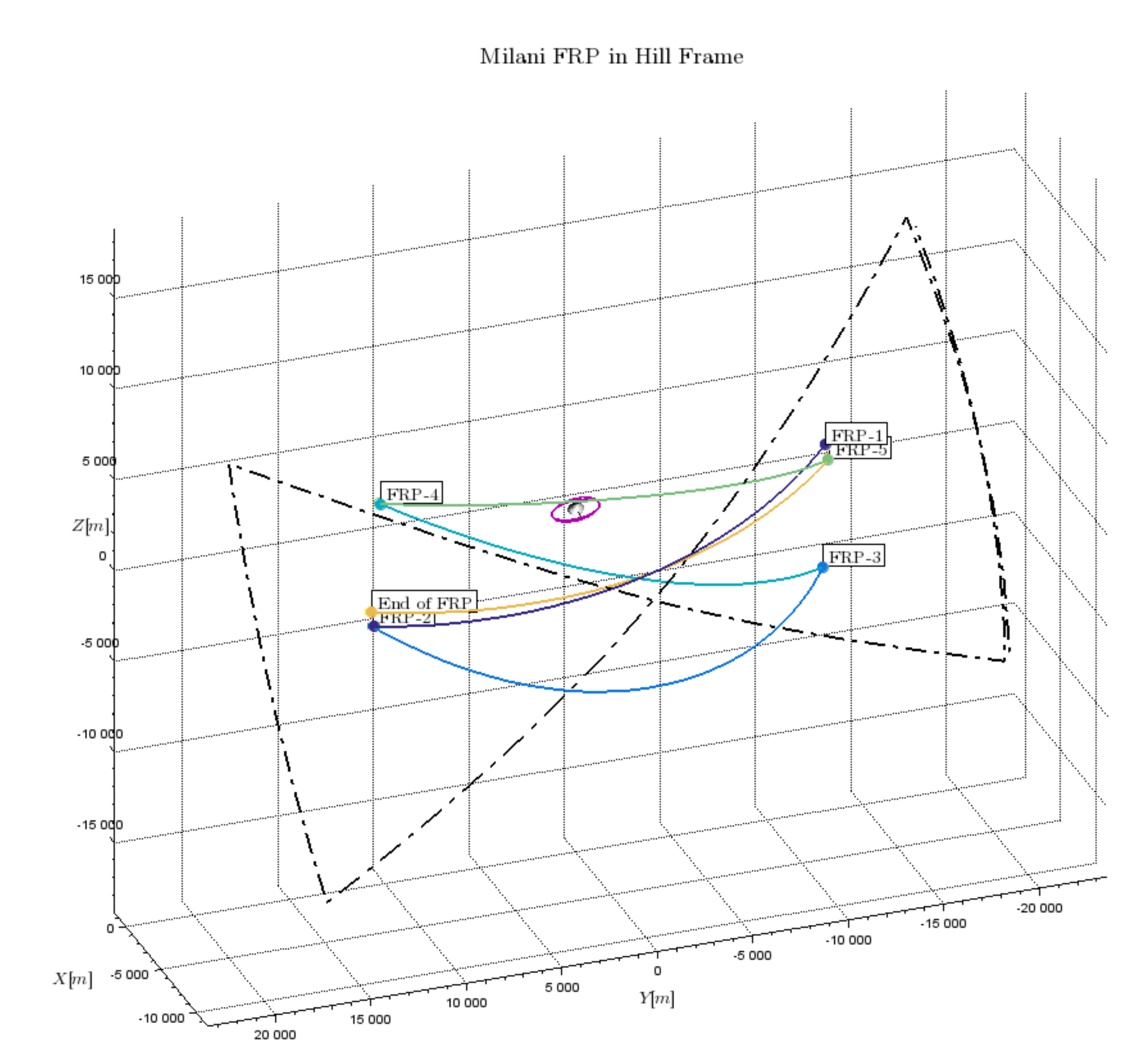
- Distance to D1 < 11,25 km
- Phase angle within $[5, 25]°$

Operational constraints

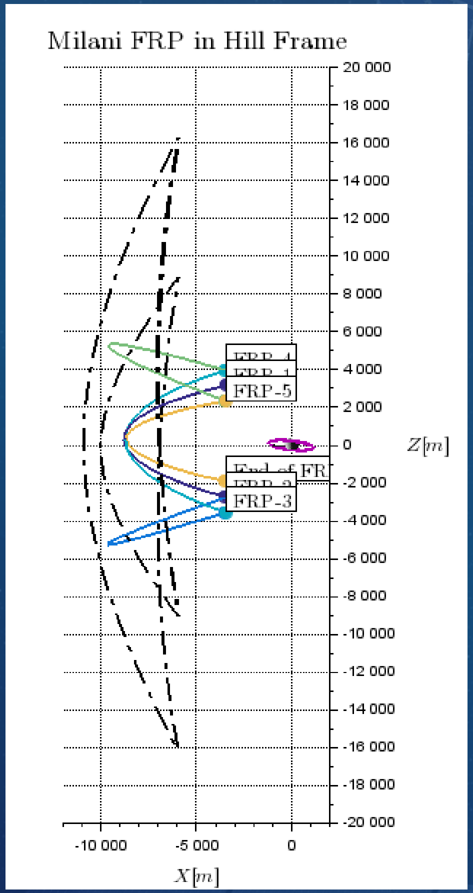
- Arcs respecting the 3-4 days Hera maneuvre pattern
- Increase of minimum distance to Hera for safety (>4 km, previously 1.5km)
- Hyperbolic arcs (for asteroid mapping)
- Day-side of Didymos

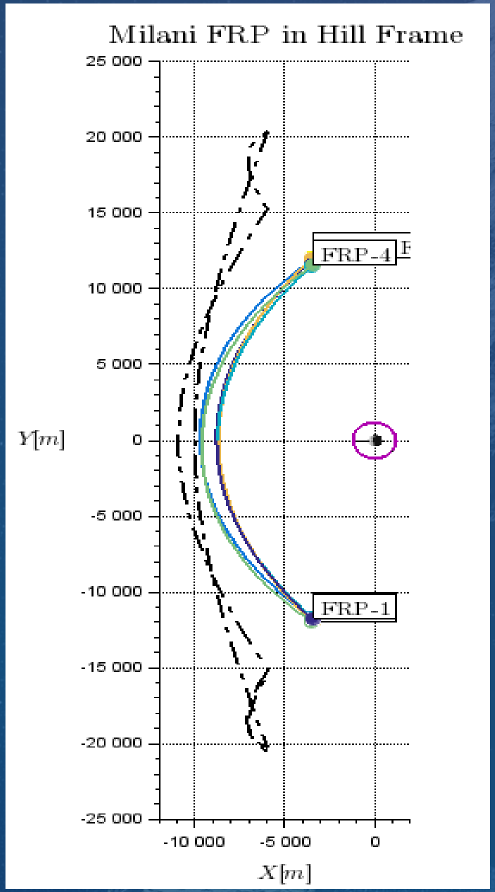
Method

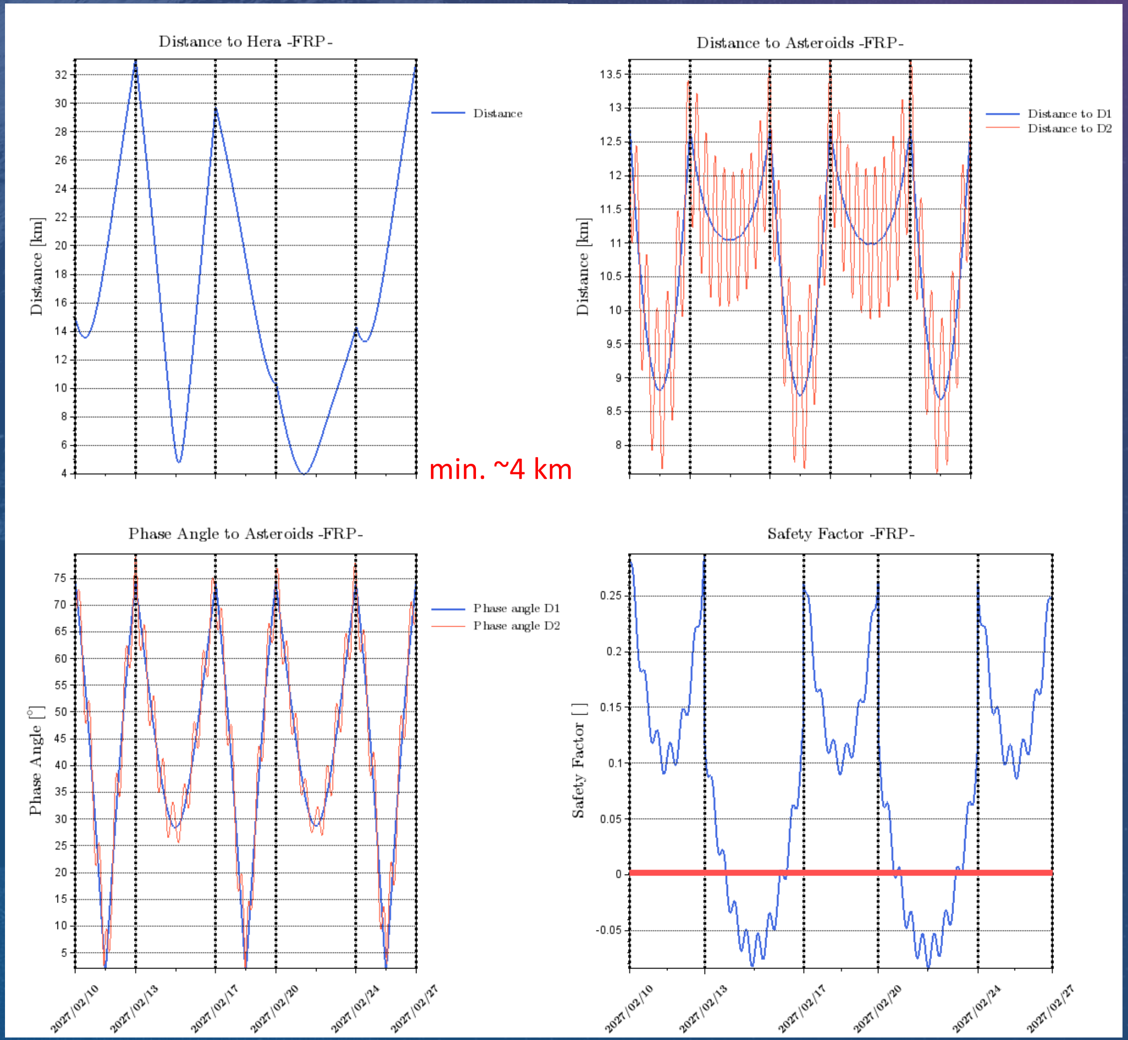
- Definition of ***waypoints*** with above constraints (shooting method)



Milani FRP – Far Range Phase







Dispersion analyses suggest the need for a new design to increase even more the minimum distance with Hera

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Milani CRP – Close Range Phase

Objective

- Trajectory designed for close D2 impact zone imaging
- Resolution of 0.5m/pix

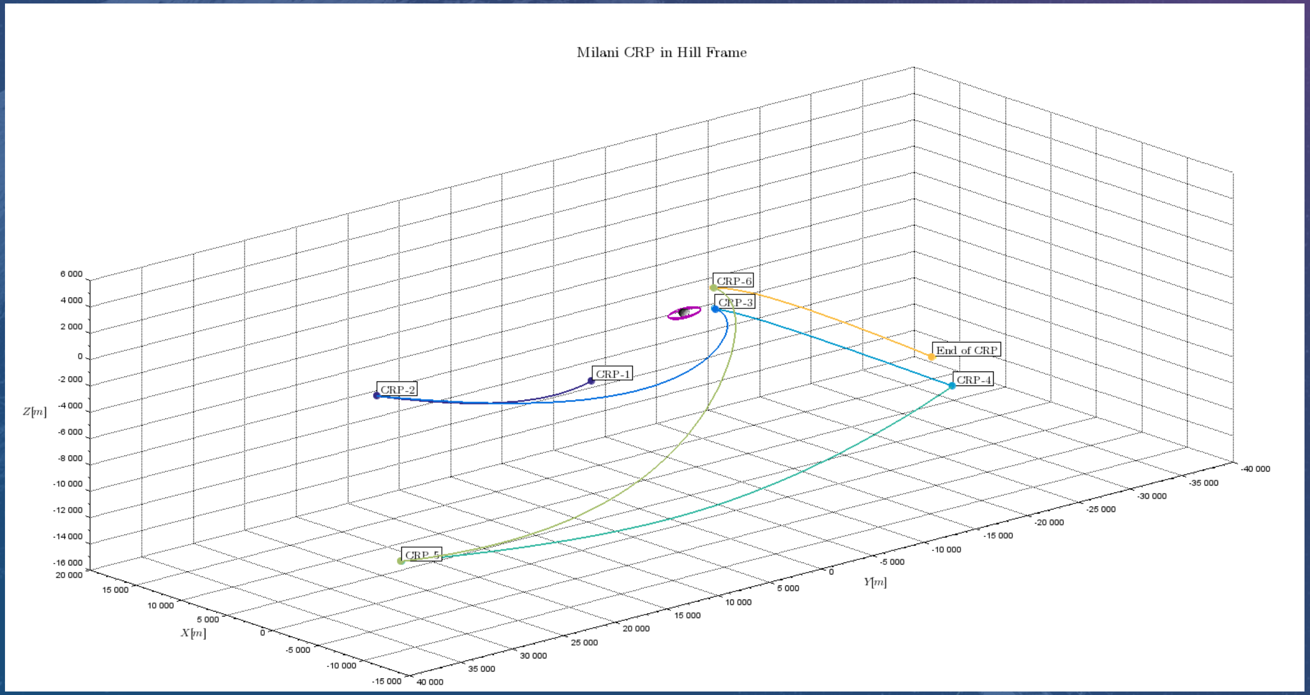
ASPECT images constraints

- Distance < 2,78 km
- Phase angle $\in [0,10]° \; and \; [30,60]°$

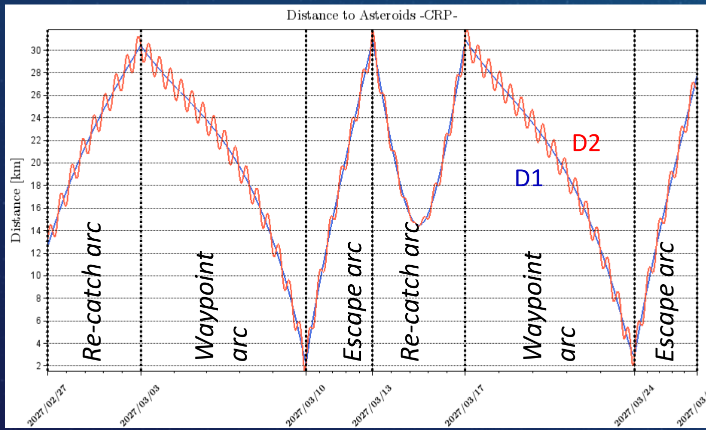
Method

- Sucession of ***waypoints***, escape and re-catch arcs
- Alternating between 3-4 days and 7 days

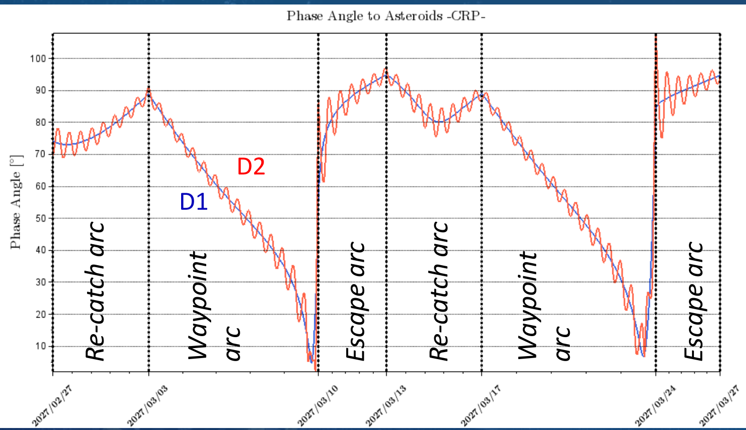
Expensive maneuvers due to close proximity to the system



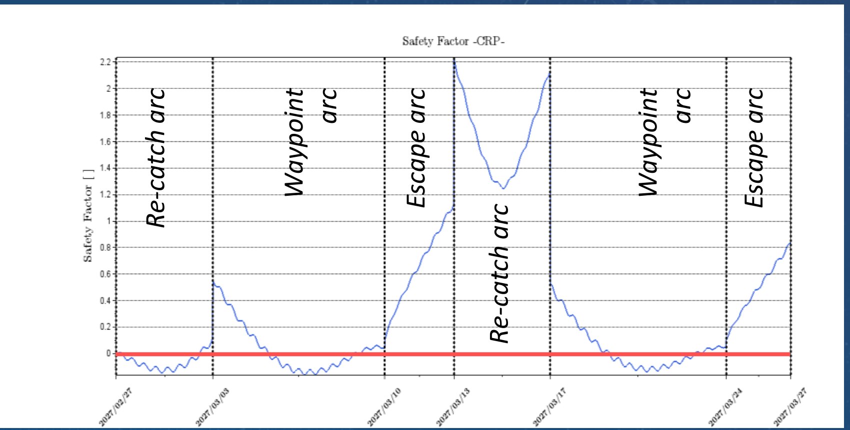
Distance to asteroids



Phase angle



Safety factor



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Milani CRP – Focus on waypoint arc

Objective

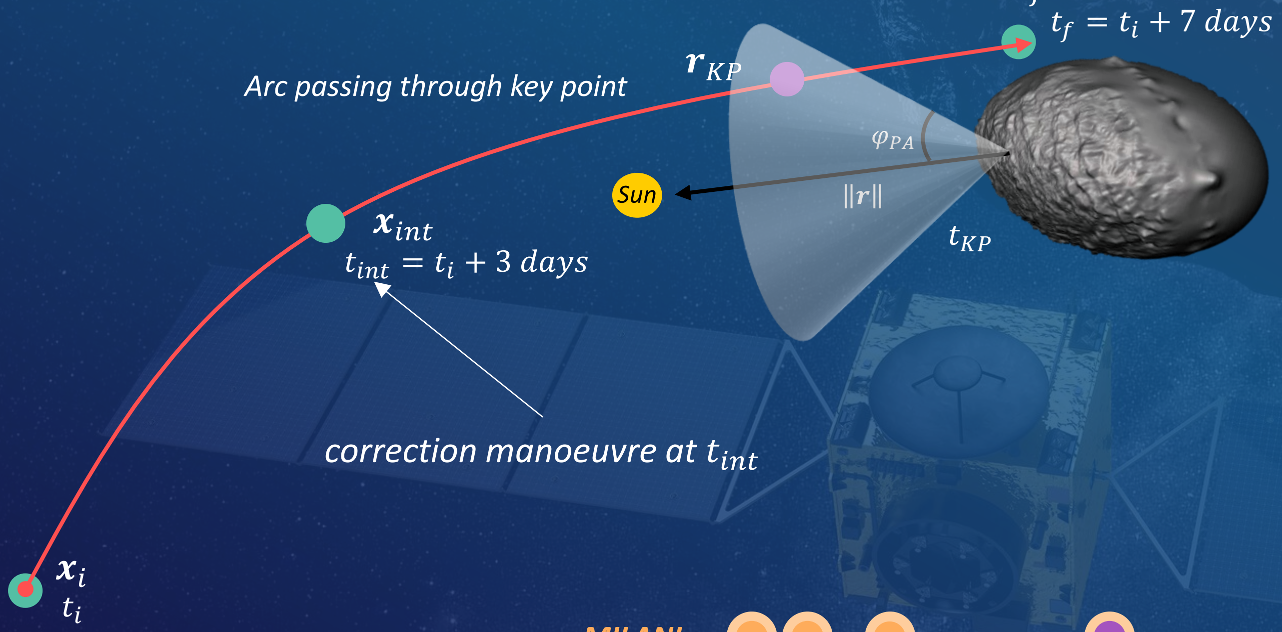
- D2 impact zone imaging 0.5m/pix

Challenge

- Very close proximity to the asteroids, leading to significant safety risk

Method for risk mitigation

- Add a **correction manoeuvre** at t_{int} to correct manoeuvre execution errors at t_i and trajectory prediction errors , or even abort the approach



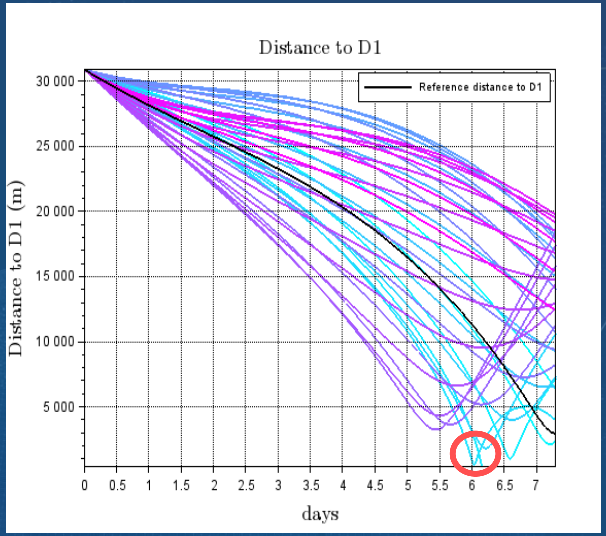
Robustness against manoeuvre execution errors

- Magnitude: +/- 5%
- Direction: 5° cone
- ⇒ 36 tested trajectories

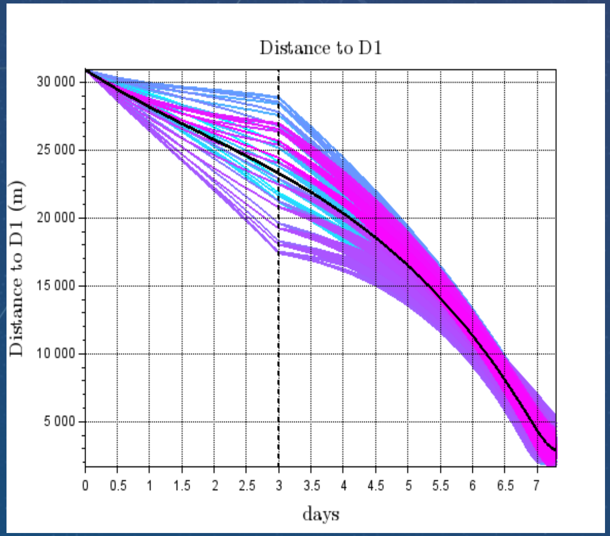
Results

- Collision case detected without correction manoeuvre
- No collision detected with correction manoeuvre, but very close proximity which suggests collision risk considering all dispersions (measures, models…)

Without correction manoeuvre at t_{int}



With correction manoeuvre at t_{int}



MILANI
ESP COP FRP CRP EXP DISP

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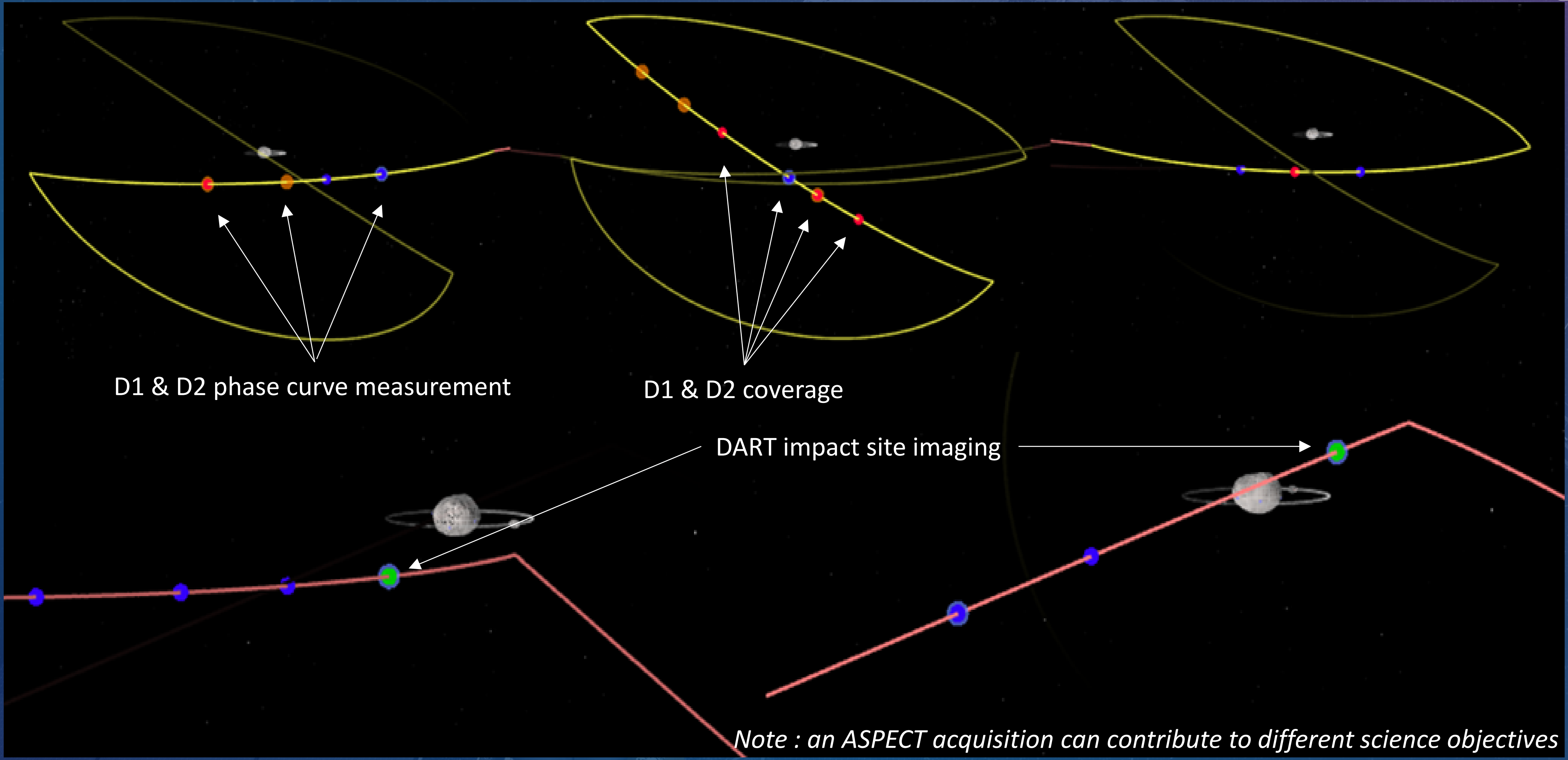
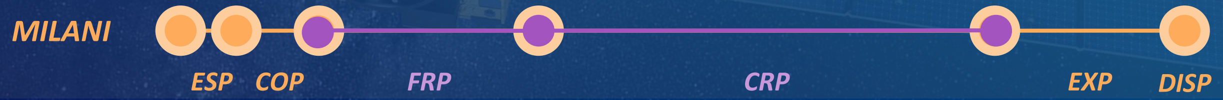
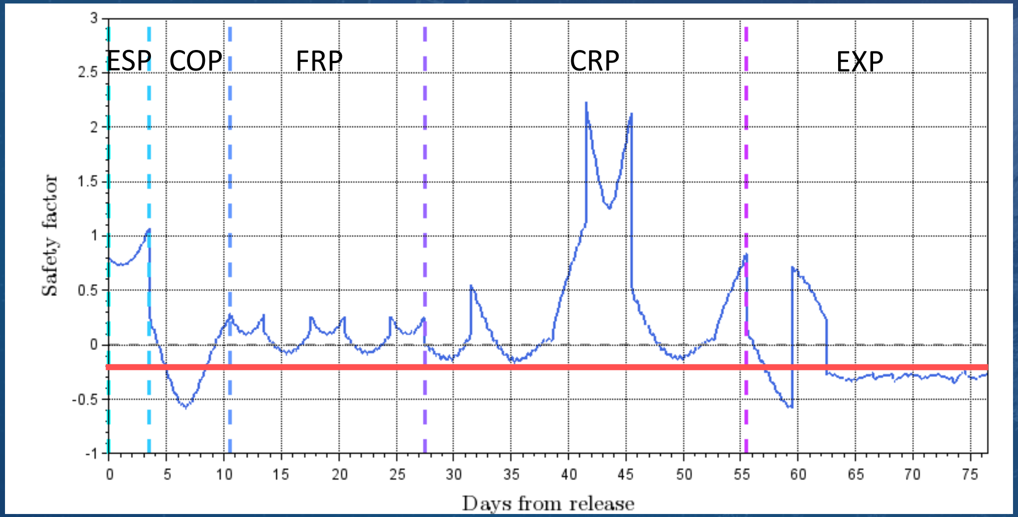
Milani ASPECT acquisitions in FRP & CRP





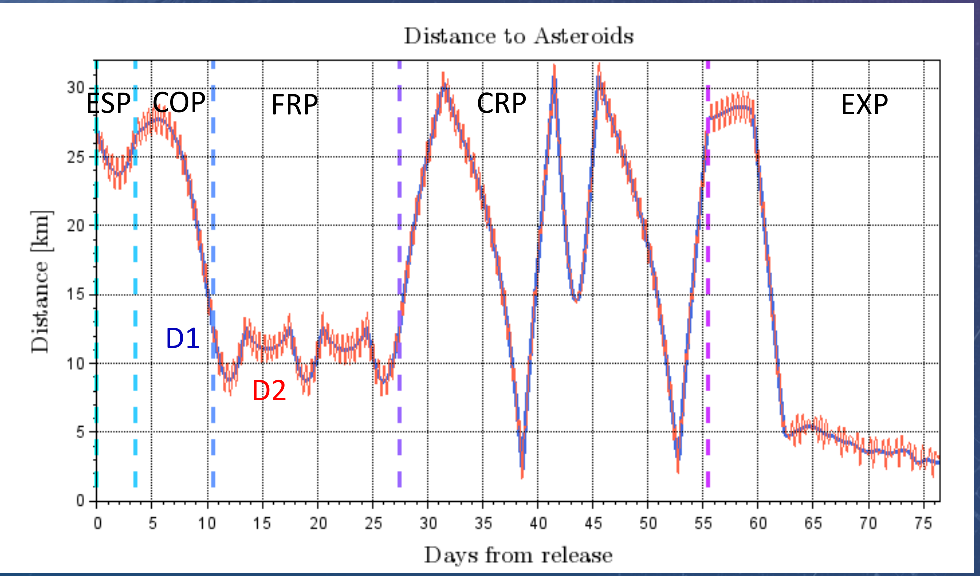
Milani trajectory vs operational constraints

Safety factor *

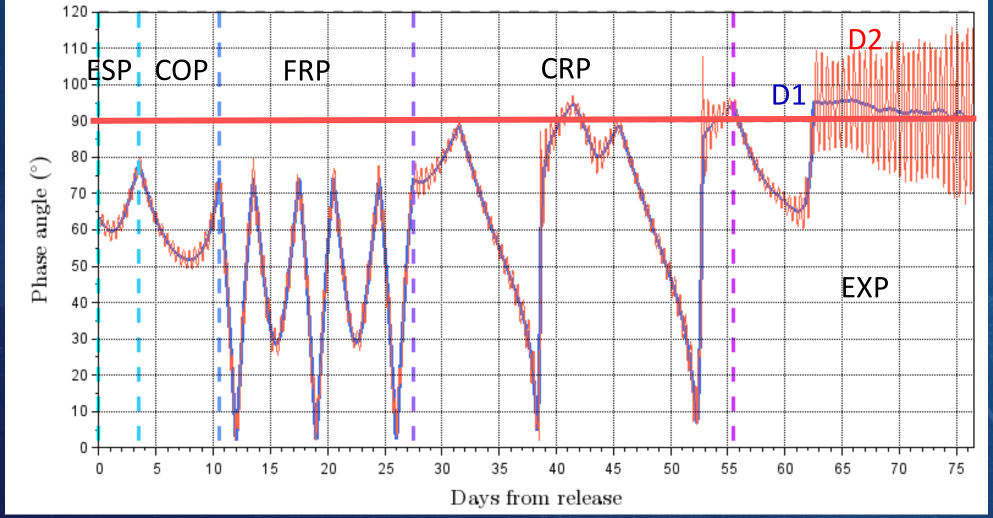


** excess instantaneous velocity compared to a parabolic trajectory (in a Keplerian environment)*
> 0 during manoeuvre for escape in case of missed manoeuvre

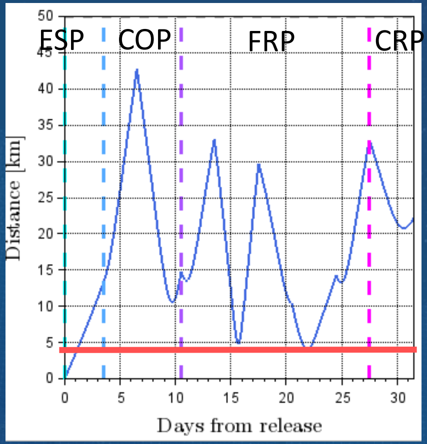
Distance to Asteroids



Phase angle (optical navigation)



Distance to Hera (safety & ISL link)



~4 km

* $C = V\sqrt{\frac{r}{2\mu}} - 1$

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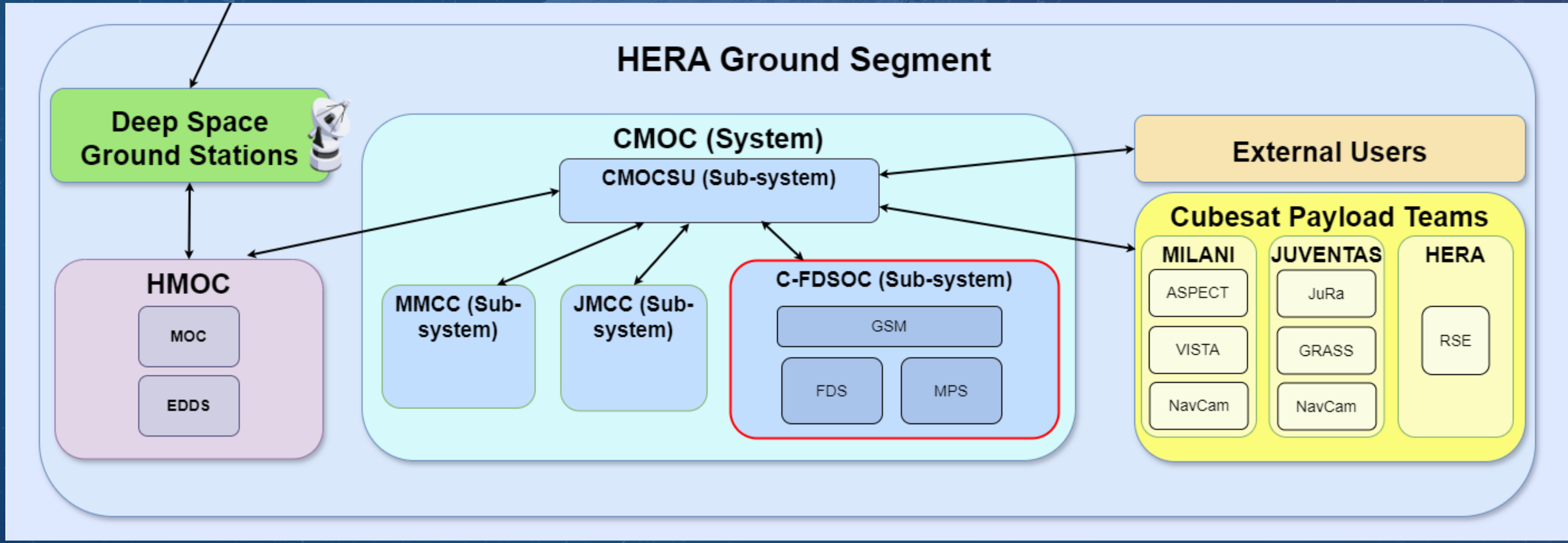
- Milani Mission Analysis
- C-FDSOC Status

CMOC/C-FDSOC defintion & development status

Ongoing Detailed Design Review

- Detailed requirements and sequences for Flight Dynamics and Mission Planning operational softwares



Main open points for Asteroid Phase

- Missing inputs for Flight Dynamics and Mission Planning commanding definition ➔ splinters, workshops (landing in June, Juventas in September, Milani in December), meetings …
- Remaining work for detailed definition of On-Board Control Procedures and associated ground commands for manœuvres & payloads acquisitions
- Cubesats trajectory safety strategy robustness to dispersions envelopes wrt Hera & Asteroids

Mission Planning System development status

✓ MPS is involved into the on-going **Detailed Definition Review (DDR)** of C-FDSOC

✓ Functional and operational **requirements** have been **expressed** in Software Requirements Specifications :

- Science requests elaboration from LTP Schedule
- Elaboration and check of programming plan for each planing cycle
- Generation of Mission Planning Request (MPR) interface to be sent to CMCC
- Retrieval of Science Request execution status
- Payload and resources status management and monitoring from telemetry (TM)

✓ Some points are still **TBD** or **TBC** :

- **Estimation** of available dynamic **resources** for mission planning
- Applicable **constraints** and associated **checks** to be performed to ensure the validity of every MPR produced
- Detailed needs for **payload TM monitoring** at C-FDSOC level

✓ **Start** of incremental development intended at the **beginning of 2025**

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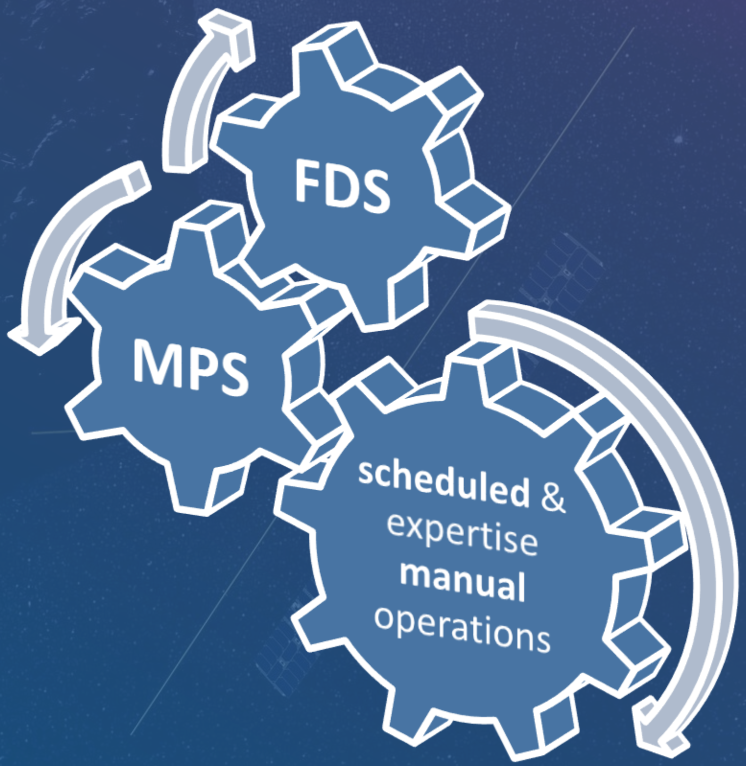
Conclusion

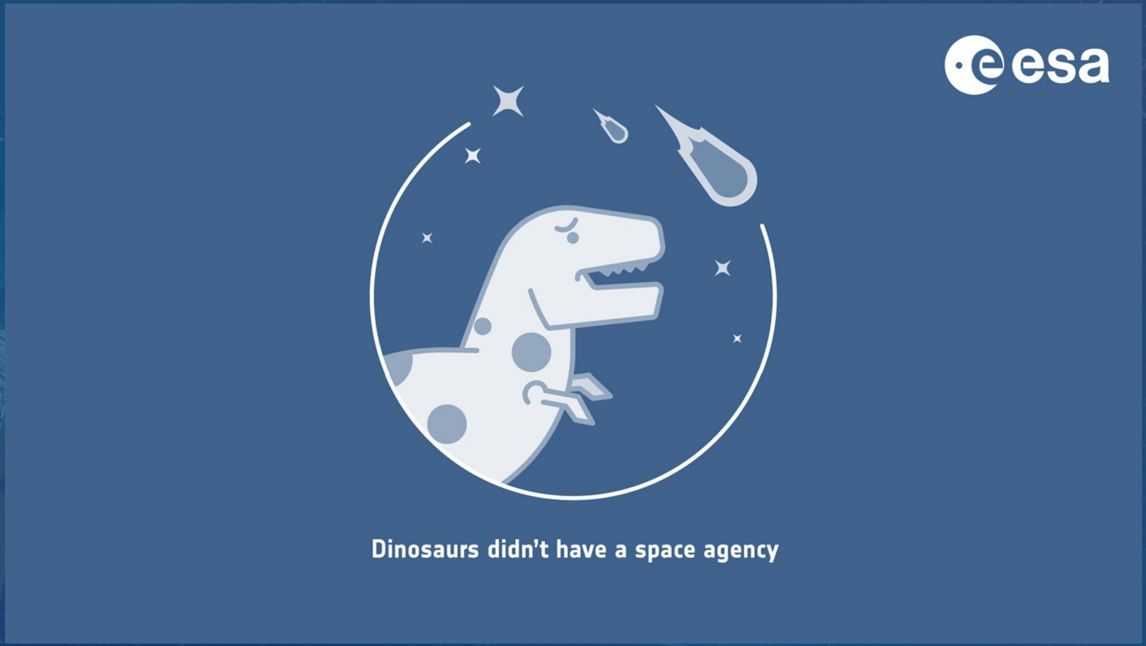
ConOps & trajectory design implies adaptation

- to the **real asteroid system post-impact** (D2 reshaped, orientation/shape/gravity, impact zone … *floating boulders !?)*
- to contingency cases (unpredicted maneuver efficiency, missed maneuver, post-safe mode recovery, collision avoidance…)
- for final EXPerimental Phase
- with landing site selection process (*if possible ith tumbling?)*



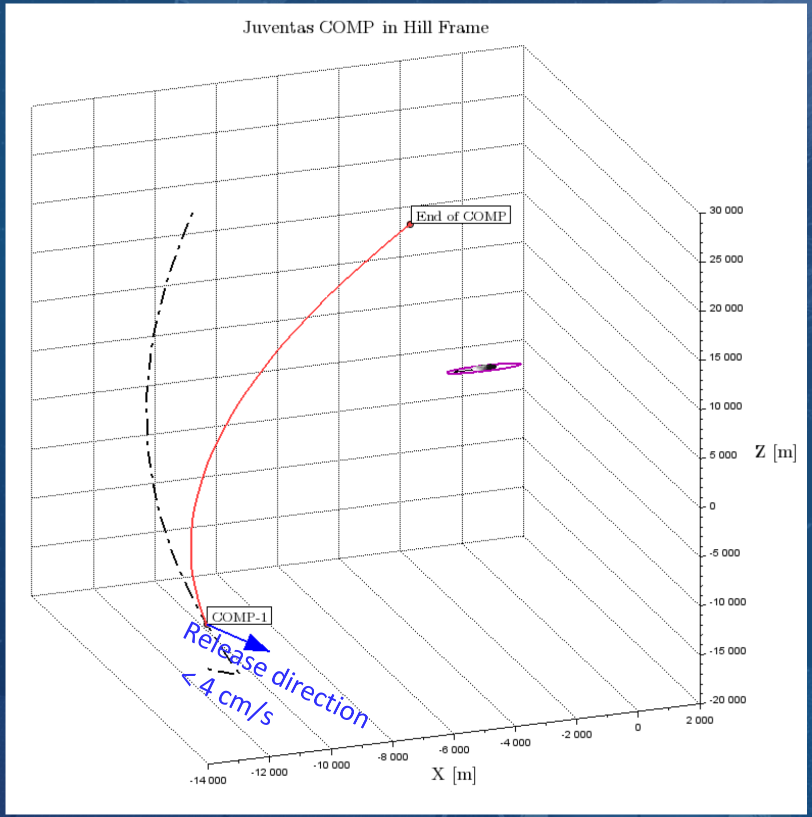
Thank you for your attention.

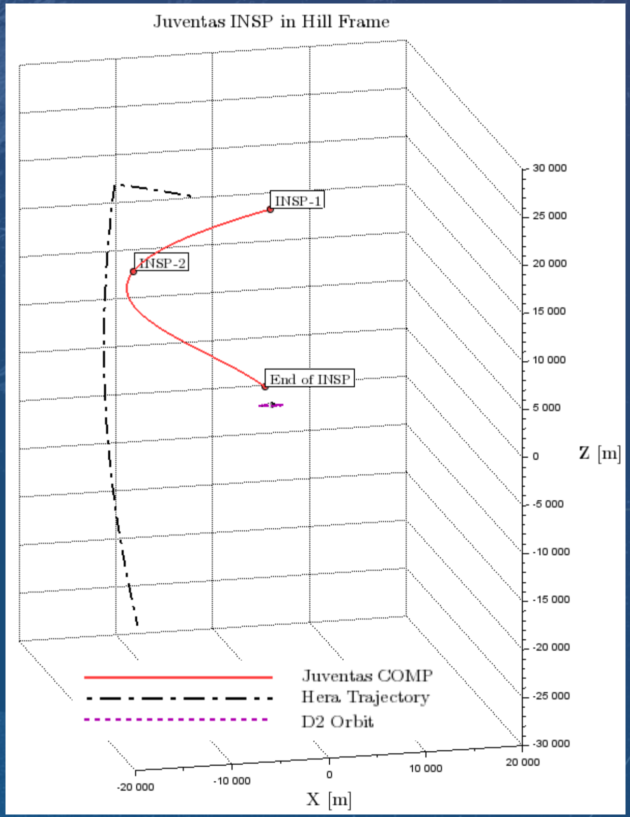
Any questions ?

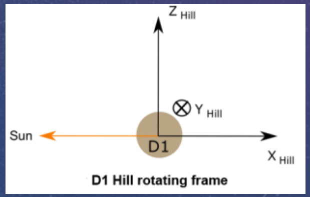


Juventas COMP – Commissioning Phase ➔ INSP – Insertion Phase

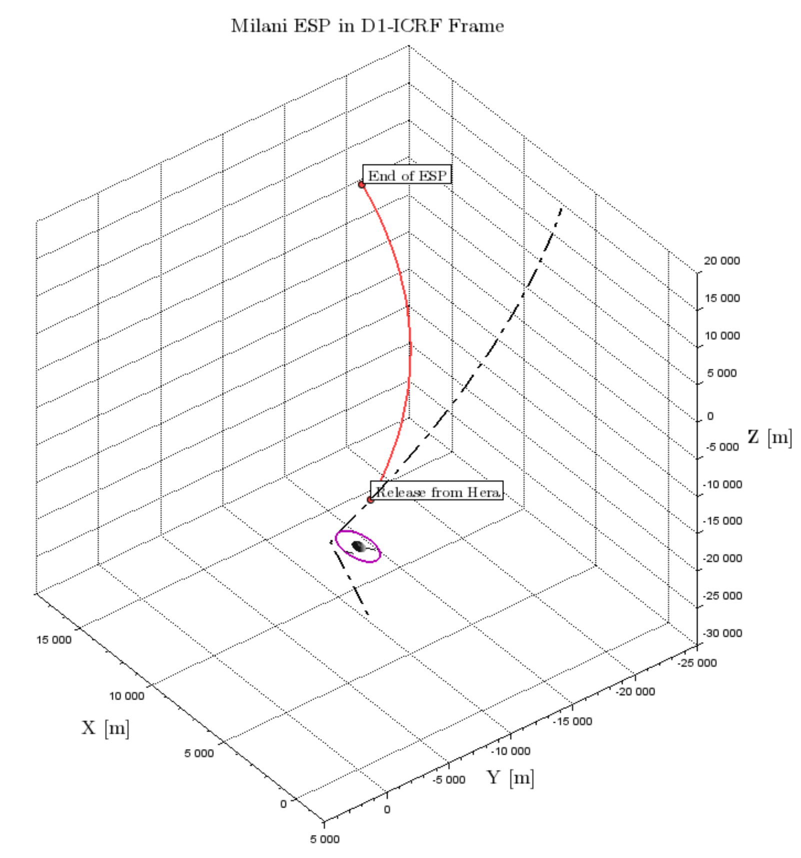
From release to SSTO insertion

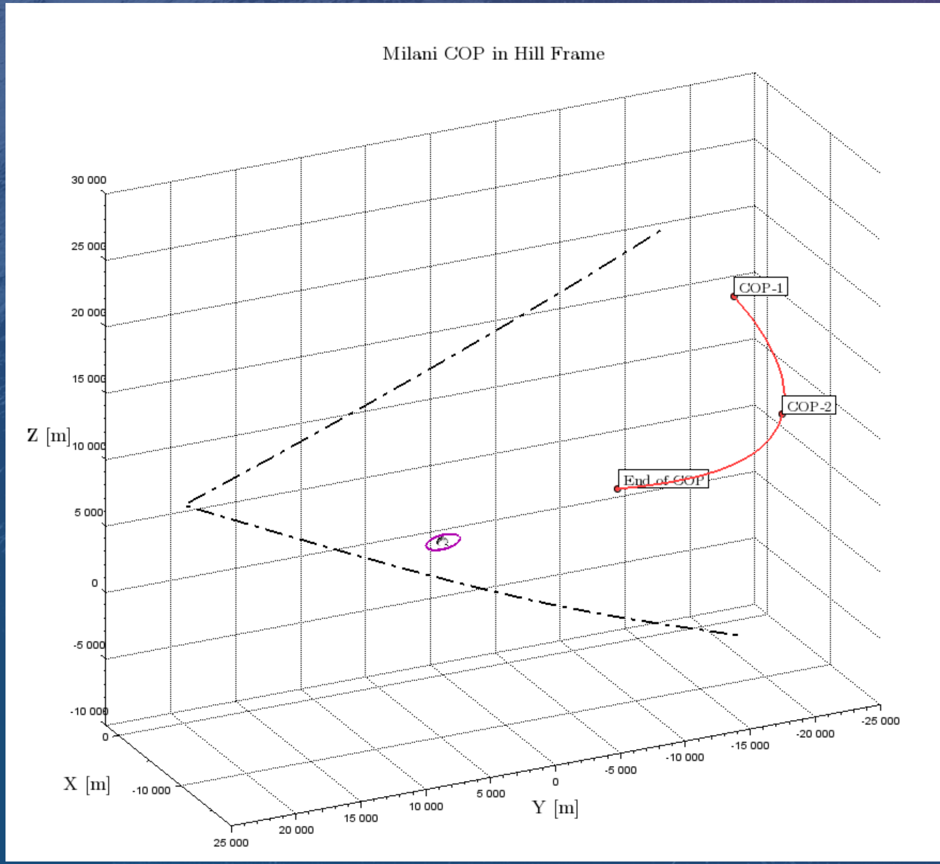






Milani ESP – Ejection and Separation Phase → COP – Commisioning Phase





Release Milani onto a safe ballistic arc, perform instruments and systems checks

Insert the cubesat on its first observation orbit

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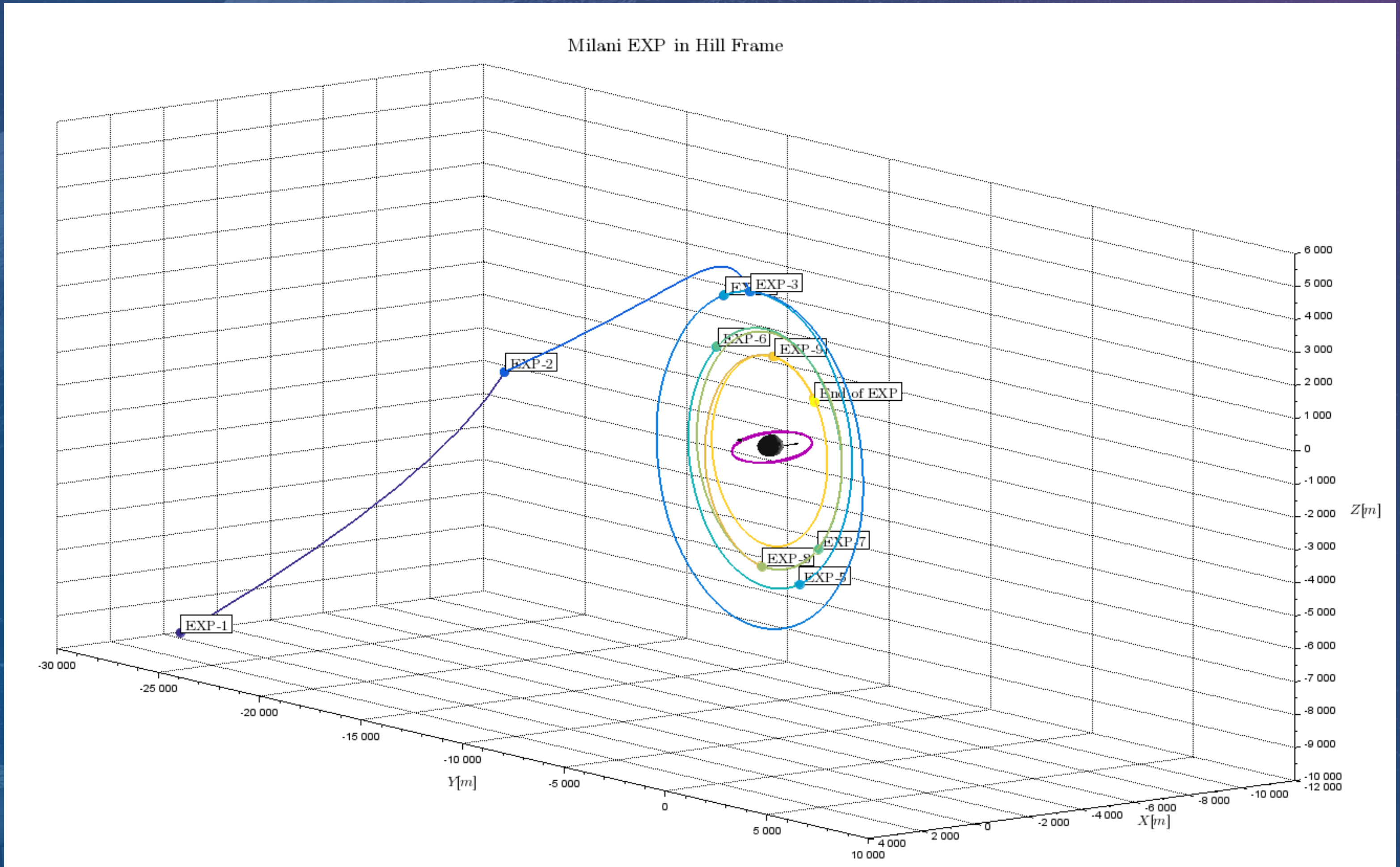
Milani EXP – Experimental Phase



Objective

- Complementary imagery of the whole binary system (poles)
- Observation of Juventas before/after landing (TBD)

Method

- 2 manoeuves to transfer to **6 km** SSTO
- Series of manoeuvres to reduce progressively the distance to D1 up to **3 km** SSTO

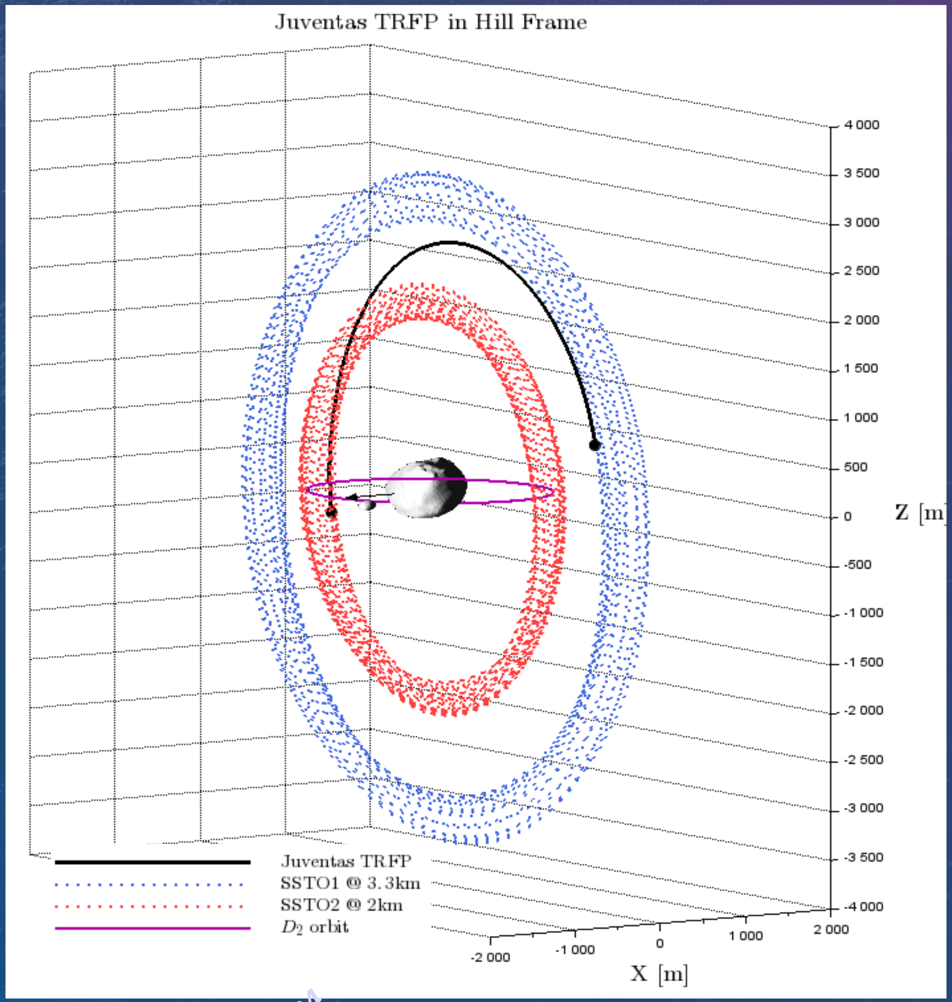
Science Orbits – TRFP – Transfert Phase

Transfer manoeuvres

- SSTO semi-major axis modification induces an out-of-plan oscillation that allows to intersect the plan of another SSTO
- Two maneuvers are 180° apart and initially computed using Keplerian hypothesis for semi-major axis modification
- Tangential correction adjusted to match the final semi-major axis
- Half a transfer orbit period ~17 hours for transfer from SSTO 3.3km to SSTO 2km

$$DV(TRFP_1) = 0.013\ m/s$$

$$DV(TRFP_2) = 0.016\ m/s$$



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