5TH INTERNATIONAL CONFERENCE ON SPACECRAFT FORMATION FLYING MISSIONS AND TECHNOLOGIES

RELATIVE MISSION ANALYSIS FOR PROBA 3: SAFE ORBITS AND CAM

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T. V. Peters
D. Escorial
Presented by J. Branco

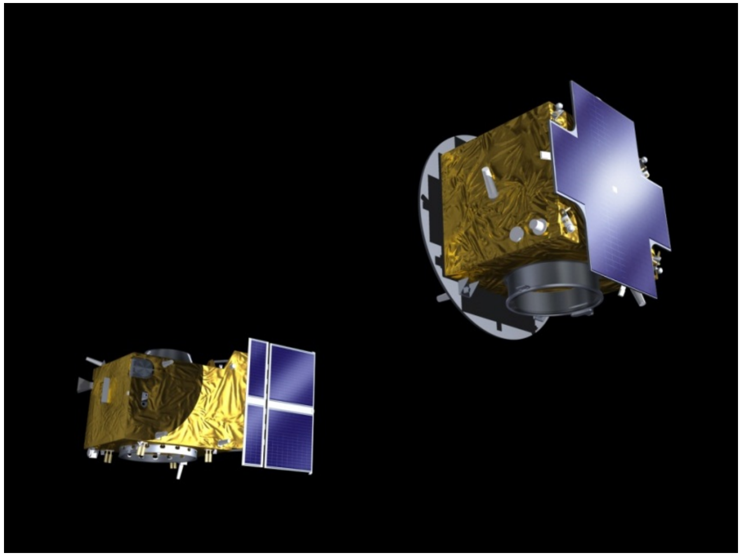
INNOVATING SOLUTIONS

INTRODUCTION

- Safe Orbit
  - Overview
  - Stability
  - Sizing
  - Entry
  - Resizing
  - Return to nominal
- CAM
  - Algorithm
  - Short term behavior
  - Return to mission
  - Long term behaviour
- Conclusion

INTRODUCTION: PROBA3

- Formation flying in highly eccentric orbit
  - Solar coronagraphy
  - Demonstration of resizing & retargeting maneuvers
- Propulsion
  - 1 N HPGP on OSC
  - 10 mN Cold gas on CSC
  - Accuracy 1° in direction, 5% in magnitude



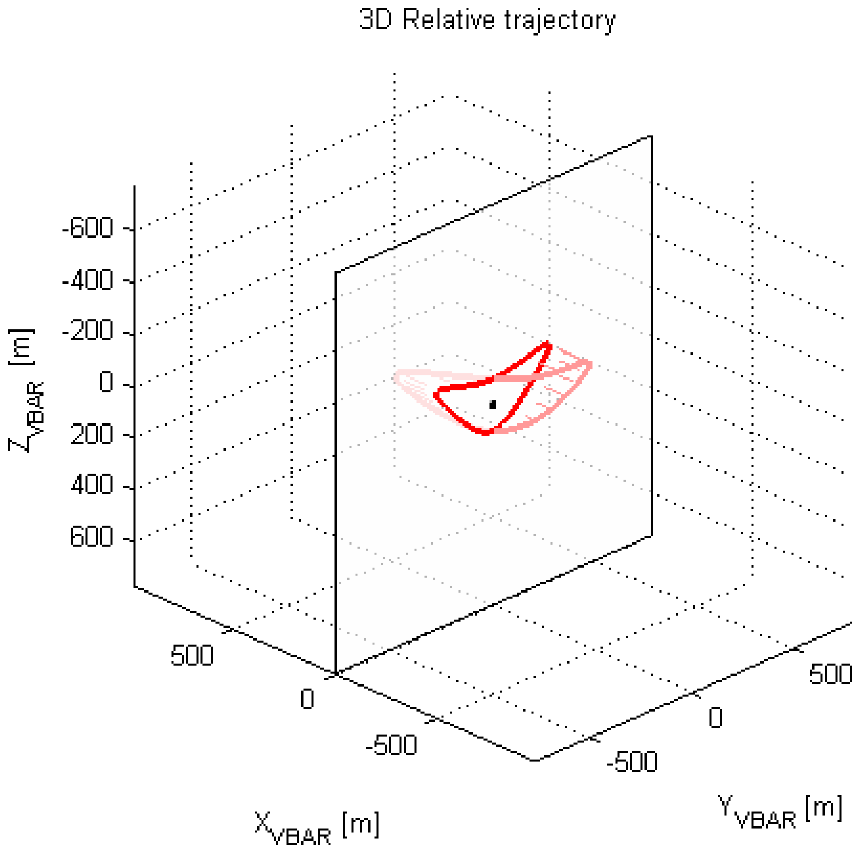
Parameter	OSC	CSC
Area [m2]	1.77	3.34
Wet mass [kg]	211	339
Dry mass [kg]	190	327
SRP coefficient [-]	1.9 (1.5)	1.29
Thrust per thruster [mN]	10	1000
Number of thrusters in direction of minimum thrust [-]	1.43	2.1
Fraction of thrust allocated for control	0.2	-

Parameter	Value
Perigee height	600 km
Apogee height	60530 km
Semi-major axis	36943 km
Eccentricity	0.8111 -
Inclination	59°
RAAN	84°
AoP	188°
Orbital period	19h38m

SAFE ORBIT

SAFE ORBIT: OVERVIEW

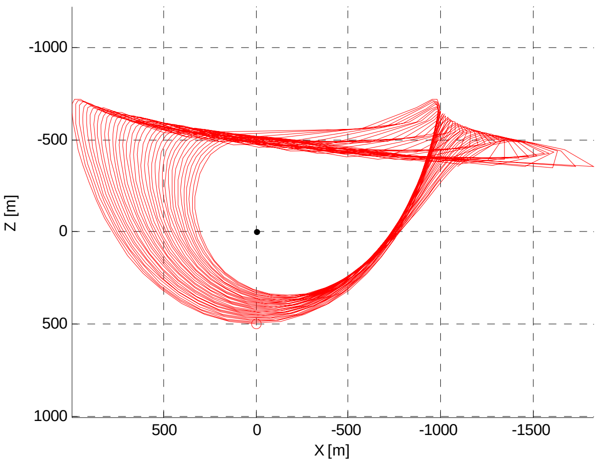
- Generalization of the eccentricity / inclination vector separation strategy
  - Coronagraph above or below occulter at apogee and perigee
- Four configurations possible
  - Sign of in-plane motion
  - Sign of out-of-plane motion



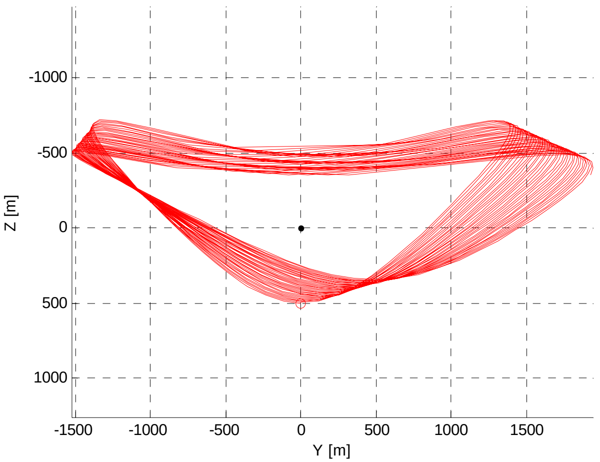
SAFE ORBIT: STABILITY

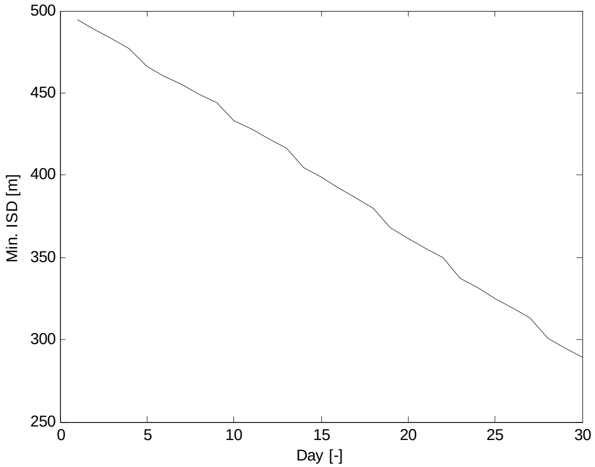
- Stability analyzed for various dates w. simulator including perturbations
  - Separated absolute propagation
  - Propagation for 30 days
  - J_2 + SRP have biggest impact on trajectory evolution
- Along-track drift may be present when safe orbit is initialized
  - Navigation and actuation errors during safe orbit entry
  - Unmodelled J2 effect
  - Up to a total of 26 km in 30 days

2D VBAR Relative trajectory, XZ-plane, for 30 days after 27 September 2017



2D VBAR Relative trajectory, YZ-plane, for 30 days after 27 September 2017





SAFE ORBIT: SIZING

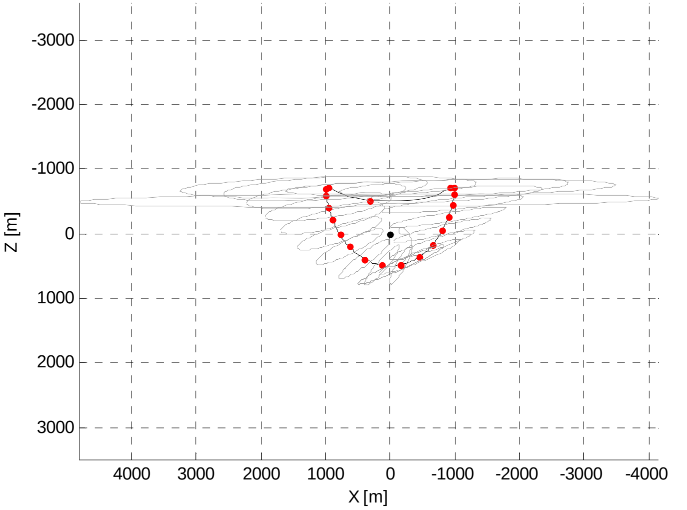
- Sizing of safe orbit takes into account
  - Stay time in the safe orbit
  - Insertion accuracy
  - Minimum approach distance
- Characteristic dimension large enough to cope with
  - Insertion uncertainties
  - Influence of perturbations, mainly J2 and SRP.
- Minimum characteristic dimension is sum of three contributions
  - Maximum expected trajectory uncertainties at closest approach
  - Maximum expected impact of the perturbations
  - Minimum ISD.

Duration (days)	Perturb. margin (m)	insertion accuracy margin (m)	minimum ISD (m)	characteristic dimension (m)	min entry ΔV (mm/s)	max entry ΔV (mm/s)	resize ΔV 150m safe (mm/s)
10	70	90	80	240	36	70	18
15	100	100	80	280	44	78	26
20	140	130	80	350	56	93	40
25	180	160	80	420	69	108	54
30	220	200	80	500	80	125	70

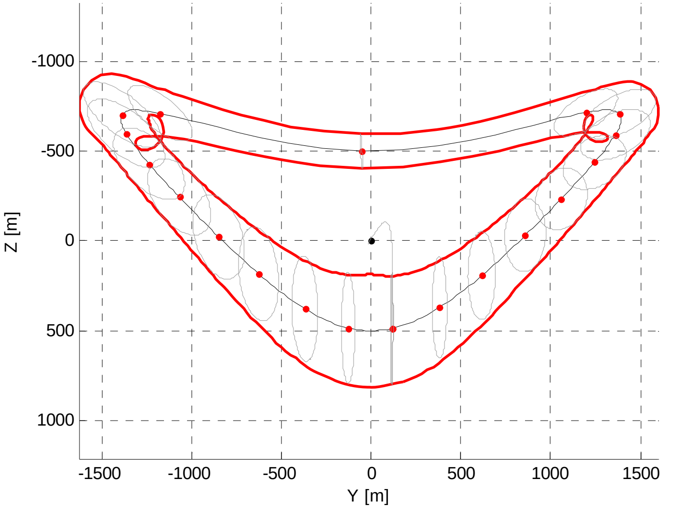
SAFE ORBIT: ENTRY

- Transfer to safe orbit needs to be available for
  - For any orbit during the mission life
  - For any point along the orbit
- Transfers have been investigated systematically with extensive simulations
- Maximum 3σ trajectory bounds due to insertion errors that can reasonably be expected are 200 m
- ΔV required to enter safe orbit from nominal orbit routine lies between 80 and 125 mm/s

2D VBAR Rel. traj., XZ-plane, on 21 February 2017, ini. θ = 12 ° (180 ° after DTM1)

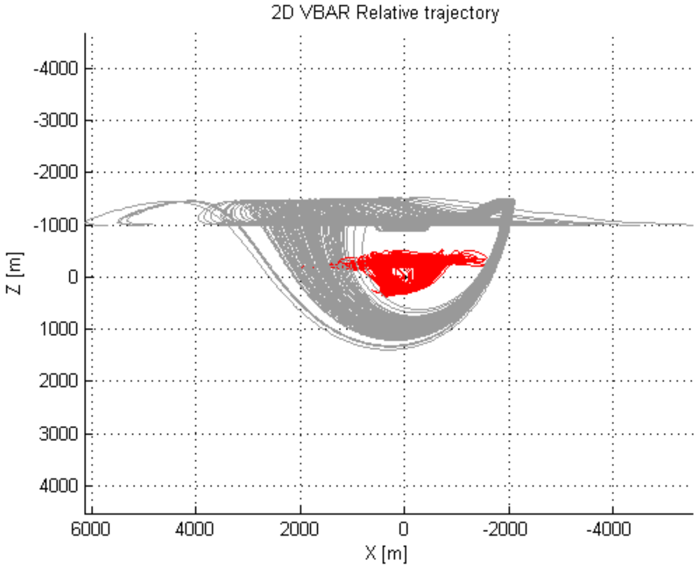


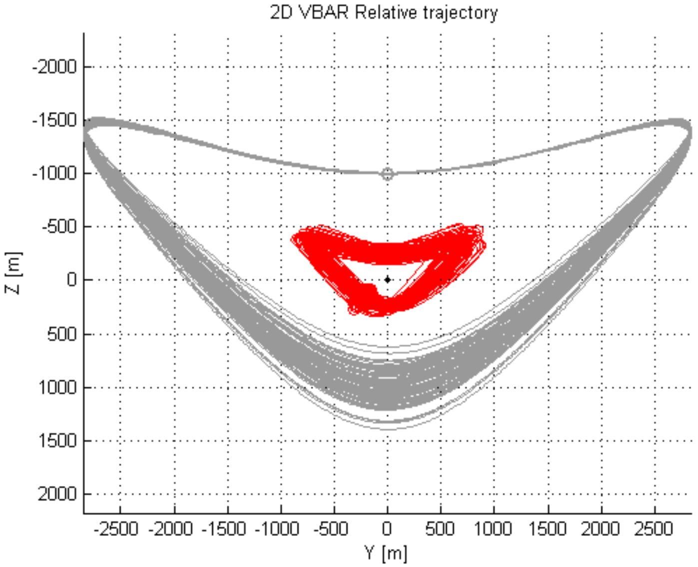
2D VBAR Rel. traj., YZ-plane, on 21 February 2017, ini. θ = 336 ° (144 ° after DTM1)



SAFE ORBIT: RESIZING

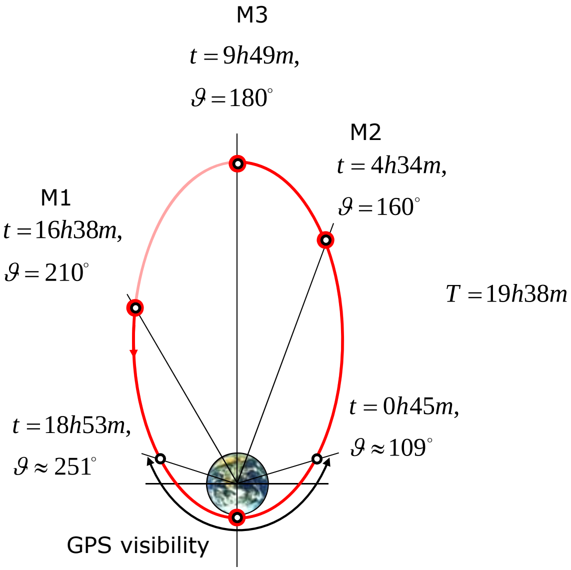
- Need to resize
  - Larger safe orbit needed for longer stay time
  - Smaller safe orbit needed for transfer back to nominal conditions
- Characteristic dimensions used
  - 150 m, used for transferring back to nominal
  - 500 m, safe orbit dimension for 30 day mission interruptions
  - 1000 m, during deployment and CAM recovery – shrinking in two steps
- Shrinking of safe orbit needs to take into account actuation errors
- ΔV required for shrinking safe orbit (1000m to 250m) is 145.31 mm/s, with a 3σ uncertainty of 13.75 mm/s

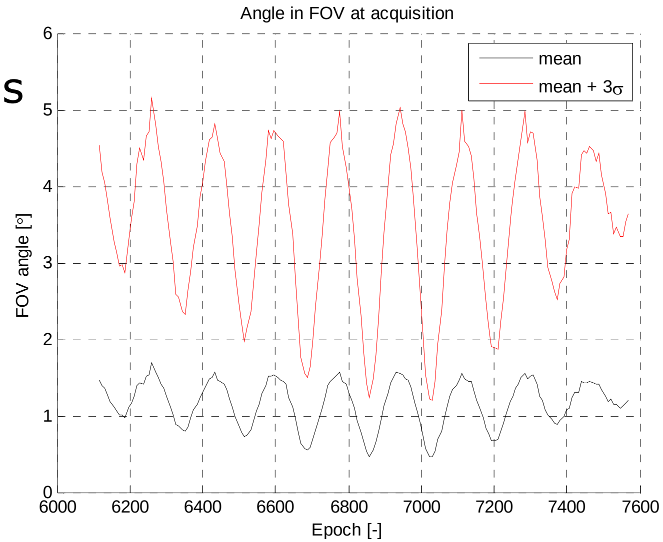




SAFE ORBIT: RETURN TO NOMINAL

- Return to nominal performed by ground
- OSC needs to be in field of view (= 5°) of CLS at end of transfer to nominal orbit
  - No scanning for target
  - Condition needs to be fulfilled for succesful handover of control
  - Simulations show condition is met
- Transfer
  - Initiated as two point transfer between 210° true anomaly to apogee of next orbit
  - GPS measurements taken when formation passes through perigee
  - Correction maneuver computed and uploaded before formation reaches 160° true anomaly
  - Correction maneuver is two-point transfer between 160° true anomaly of and apogee
  - mean ΔV 35 mm/s, mean + 3σ ΔV 45 mm/s



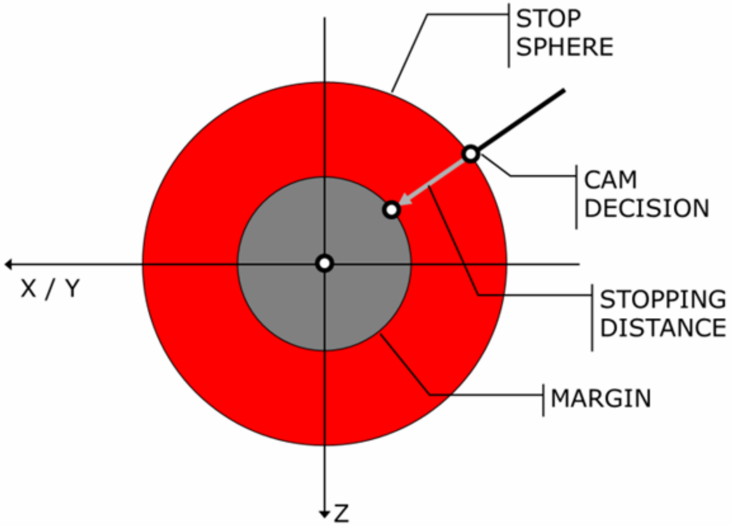


RELATIVE MISSION ANALYSIS FOR PROBA 3: SAFE ORBITS AND CAM

CAM

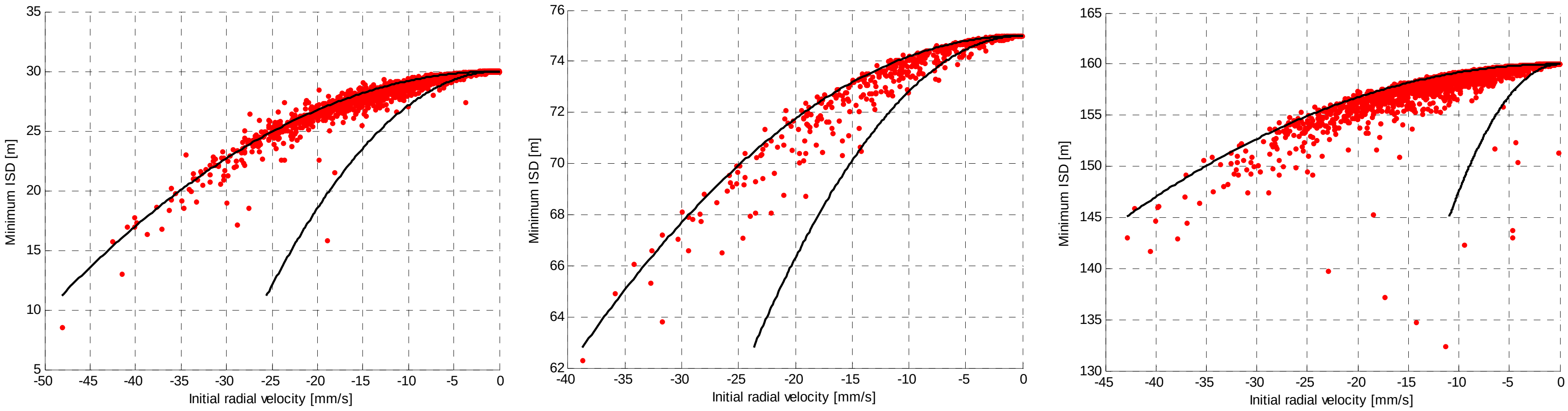
CAM: ALGORITHM

- CAM ΔV composed of
  - ΔV to stop the motion
  - ΔV to induce specified drift per orbit
- Safety sphere sizing
  - Assume velocity directed towards origin
  - Safety sphere radius = Stop distance + Margin
  - Stop distance proportional to square of velocity
  - Maximum relative velocity in nominal orbit 20 mm/s => OSC stop distance of 7 m

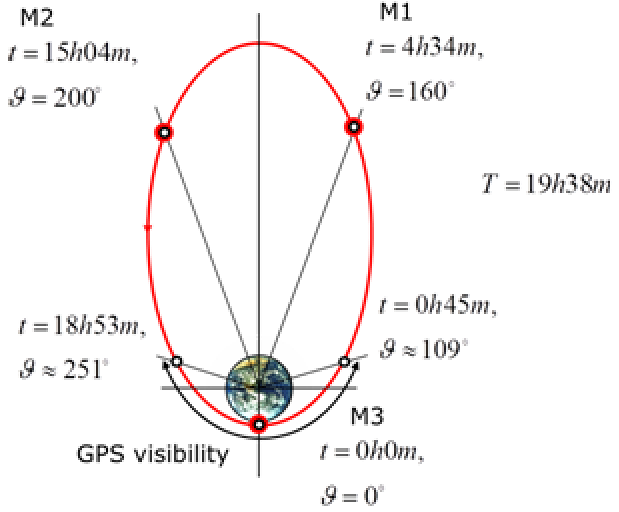


CAM: SHORT-TERM BEHAVIOR

- Monte Carlo simulation of CAM algorithm
  - Started at specific distance (short range 30m, medium range 75m, long range 160m)
  - Initial velocity 20 mm/s in random direction
  - CAM ΔV applied with 5% error in magnitude (1σ) and 1° in direction (1σ)
- Minimum approach distance approximated well by stop distance estimate



CAM: RETURN TO MISSION

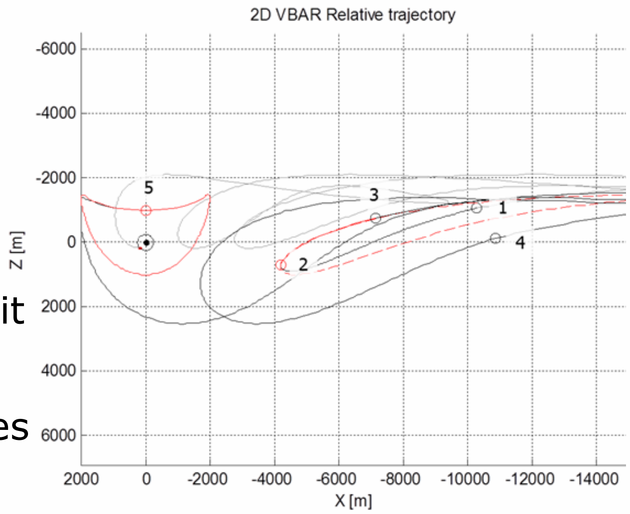


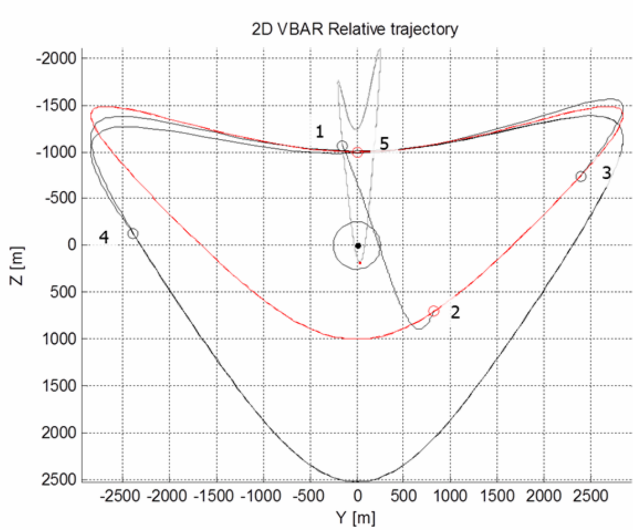
- Recovery under ground control
  - Recovery strategy after CAM is similar to formation deployment
  - Recovery after CAM should be as rapid as possible not to lose operational time
- Recovery strategy:

1. Transfer to safe orbit, ΔV1
2. Transfer to safe orbit, ΔV2
3. 3-burn transfer, ΔV1
4. 3-burn transfer, ΔV2
5. 3-burn transfer, ΔV3

Maneuver 5 establishes safe orbit around origin

Nominal CAM + recovery requires 610 mm/s





CAM: LONG-TERM BEHAVIOR

- Long-term behavior defined as drift for longer than 5 orbits after CAM
- Fast recovery is still required, so:
  - Two-point transfer to recover large distance
  - Followed by recovery strategy described in previous slide for safety
- Parametric analysis carried out taking into account
  - type of CAM performed (short, medium or long range)
  - drifting time (30 or 60 days)
  - recovery time (0.7, 2.7 or 5.7 orbits)
  - ΔV can be of the order of meters per second!

Return in # orbits		**5.7**		**2.7**		**0.7**	
Drifting days		60	30	60	30	60	30
Short range	mean ΔV	0.770	0.449	1.407	0.659	2.428	1.049
	max ΔV	0.295	0.149	0.511	0.257	1.041	0.523
Med. range	mean ΔV	1.459	0.800	2.712	1.287	4.347	2.203
	max ΔV	0.739	0.372	1.279	0.647	2.612	1.308
Long range	mean ΔV	2.382	1.281	3.805	1.932	6.808	3.354
	max ΔV	1.176	0.595	2.044	1.030	4.189	2.093

RELATIVE MISSION ANALYSIS FOR PROBA 3: SAFE ORBITS AND CAM

CONCLUSION

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CONCLUSIONS

- Strategies developed for all maneuvers related to safe orbit and CAM for PROBA-3 are feasible
  - All maneuvers are safe, and can be performed under ground control
  - Control can successfully be handed back to spacecraft after ground commands a transfer from safe orbit to nominal conditions
- ΔV for off-nominal situations
  - Range from 10’s to 100’s of mm/s
    - CAM recovery after 30 to 60 days requires higher ΔV
  - Comparable to ΔV’s required for nominal operations

Thank you

João Branco
Diego Escorial

Thomas Peters
Email: tpeters@gmv.com
www.gmv.com

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