GNC description and result synthesis

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Summary

- **Nominal mission**
  - **Algorithms**
  - **Results synthesis**

- **Extended mission**
  - **Algorithms**
  - **Results synthesis**

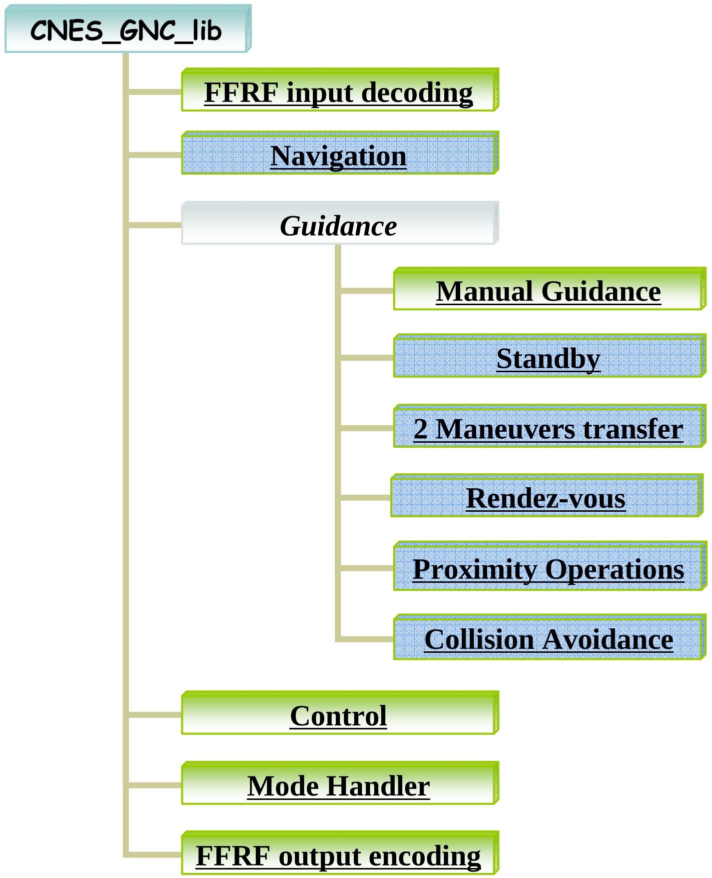
- **GNC results summary**

Nominal Mission GNC Software : GNC functions
OVERVIEW

- **11 functions integrated within CNES_GNC_lib**

- **6 guidance functions, each one dedicated to a Formation Flying experimental phase**

- **Distribution oriented towards:**
  - **Experimental objectives**
  - **Easy validation and development of each function**



Nominal mission: GNC tests

GNC Activity	Number of occurrences	Duration
RF Navigation	Continuously	12 days CL 40 days OL
Standby	4 nominal SBY	2.5 days
	1 with autonomous transfer in case of anomaly	
Proximity operations	7 sessions	2 days
Rendezvous	6 nominal RDV with distances up to 9 km	4 days
	1 reverse RDV	
N* 2 manoeuvres transfer	11 simple 2MT	1 day
	2 multi-orbits 2MT	
Collision avoidance	2 double boosts (“Soft” CA)	2 days
	4 single boost (”Drift” CA)	

12 closed loop days
5.72 m/s delta-V consumption
3 à 4 switch modes / day

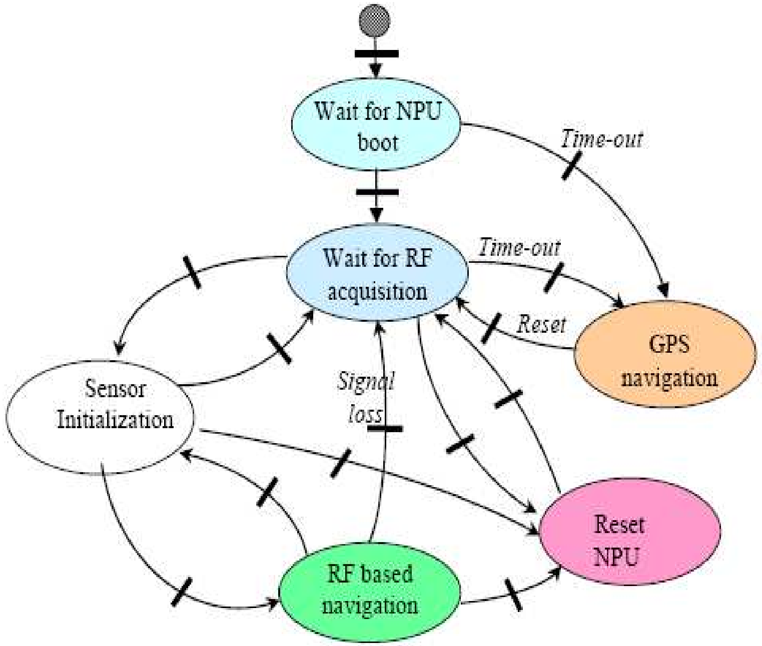
GPS post-processed data by POD-DLR (Precise Orbit Determination) used as reference to performance evaluation

Nominal Mission : GNC functions
Navigation Function

3 main functional blocks / 6 different sub-modes of operation :

- **Estimation of MANGO relative state (in TANGO Local Orbital Frame):**
  - **Extended Kalman Filter to estimate 8 state : 3 for the position, 3 for the velocity and 2 for Light of Sight FFRF bias**

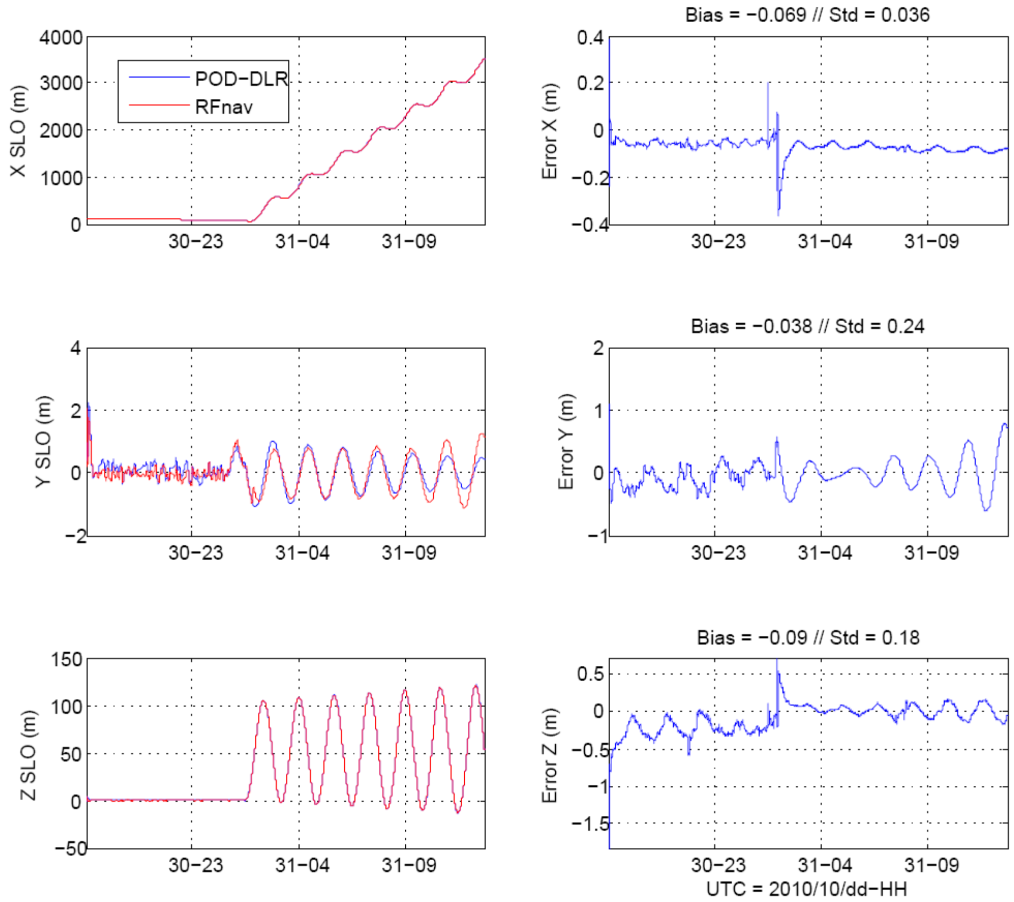
- **Calculation of the Local Orbital Frame (attached to the TARGET):**
  - **propagating the Tango S/C state taking into account external forces (J2, drag and solar pressure). Absolute state updated by the ground on a regular basis.**



- **Management of FFRF sensor:**
  - **Computing aiding data,**
  - **Monitoring FDIR (NPU reset) mechanism**

Nominal Mission: RF Navigation

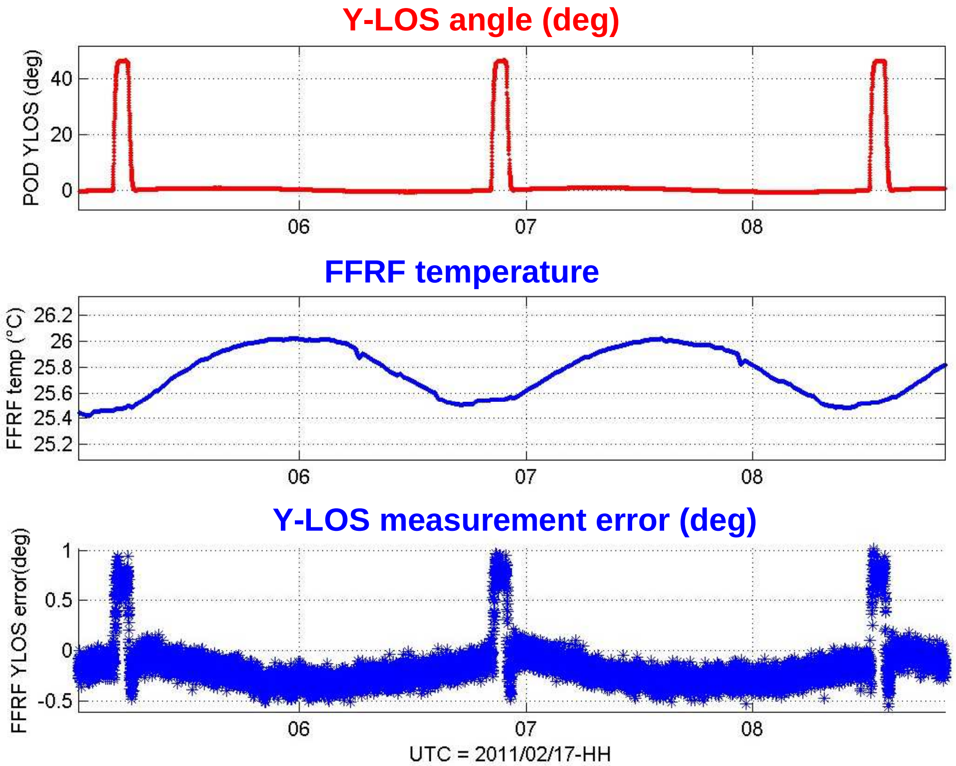
- Provides aid during Initialization (IAR)
- Typical convergence time = 3000s for LOS bias estimation
- Performance depends on relative range and manœuvre frequency
  - Best performance achieved during PROX activities: a few cm error
  - Range impact is particulary visible during RDV and separation after CAM : a few m error in cross track



Nominal Mission: RF Navigation

- **Most important error source is LOS bias variation :**
  1. **Multipath during attitude manoeuvres**
  2. **FFRF temperature evolution**

- **1st effect mitigated by covariance adaptation during large manœuvres**
- **2nd effect mitigated by a specific attitude programming**

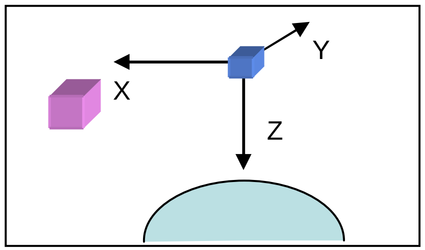


Nominal Mission: Navigation RF

Mode	Inter satellite Distance (ISD)	Error in position estimation in SLO (cm) frame	Error in bias LOS estimation (deg)
RDV	4000 – 200 m	Bias [5.7 24 0.9] Std [1.7 350 7.4]	Bias [0.0016 0.0039] Std [0.009 0.091]
CA	60 – 4200 m	Bias [8 -1.3 2.1] Std [3.5 27 10]	Bias [0.002 -3e-4] Std [0.037 0.037]
SBY	60 - 140 m	Bias [-31 2.3 1.0] Std [3.0 13.0 5.5]	Bias [-0.0022 0.0023] Std [0.038 0.093]
PROX	20 m	Bias [-2.8 1 5.7] Std [0.6 1.4 1.7]	Bias [0.16 0.028] Std [0.050 0.039]

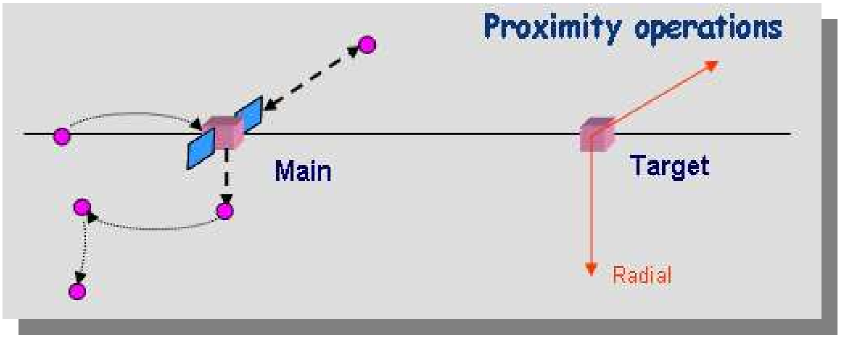
Reduced crosstrack accuracy

centimetric accuracy



Nominal Mission : GNC functions
Proximity operations functions

Maintain MANGO on a hold point and / or forced translation (following the 3 axis) :



«Guidance» component :

- **Calculation of references linear trajectories between two hold points.**

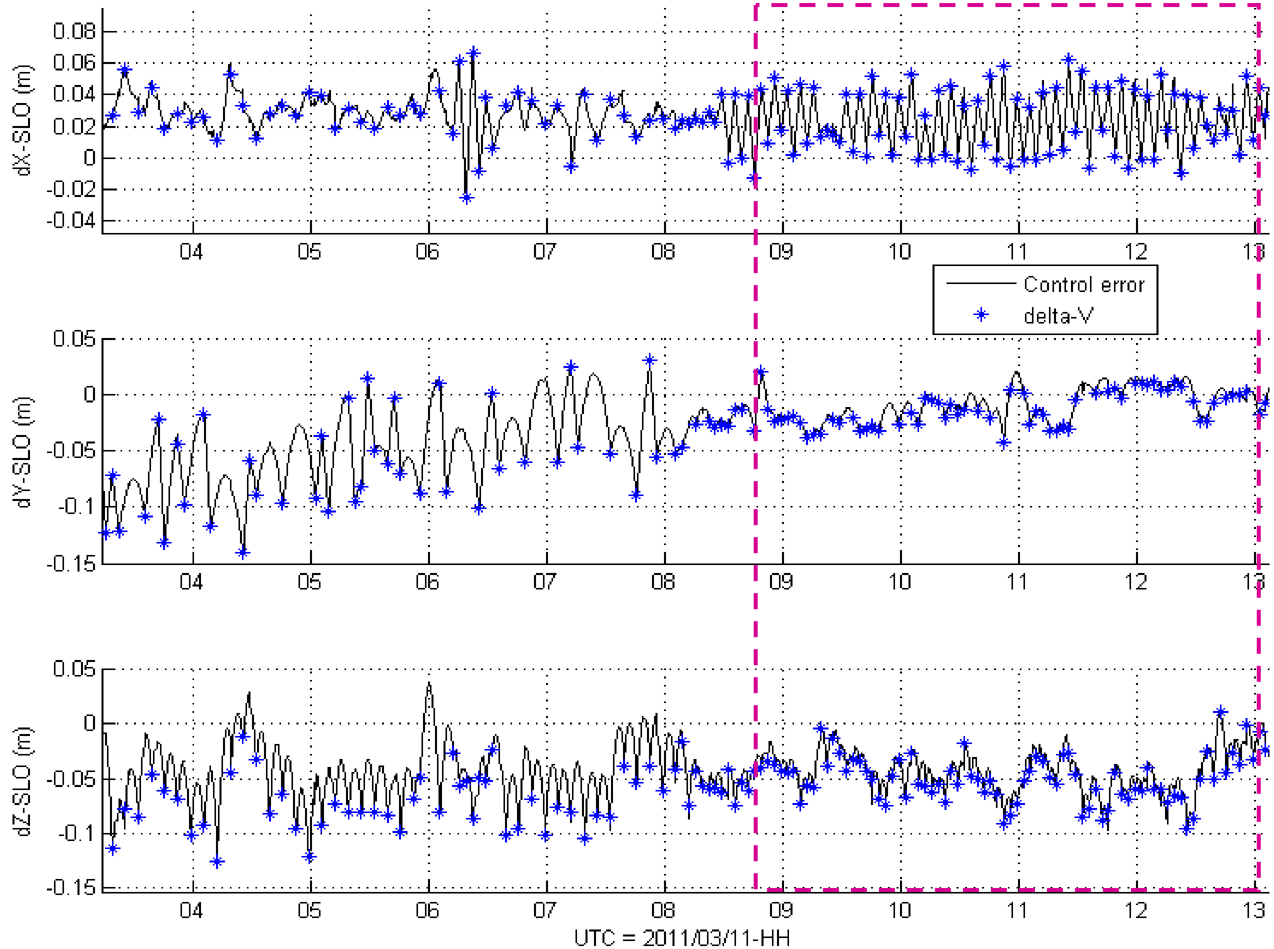
«Control» component :

- **Periodic dV computation to follow the reference trajectory,**
- **Linear Quadratic Regulator (LQR) control,**
- **Control gains pre-computed on ground (Clohessy-Wiltshire model),**
- **«Feed forward» *M* gains to take into account some perturbations : drag and solar pressure**
- **Control period : [100s , 400s]**

Nominal Mission: Proximity operations

- **Impact of the thrusters frequency (MIB = 0.4 mm/s)**
- **Improving accuracy**
- **dV consumption :**
  3 cm/s/orbit
  ↓
  5 cm/s/orbit

Control error following the 3 axis, at ISD = 20 m



Thrusters operating in a differential way

cnes

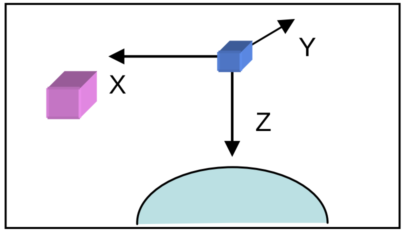
Nominal Mission: Proximity operations

Error due to control part only

Closed-loop global error

Activity	Navigation error (cm) POD as Ref	Control accuracy (cm) RF nav as Ref	Control accuracy (cm) POD as Ref
80m SK no sub-pulse	Bias = [-3.7 -11 5] Std = [0.5 4.7 5.4	Bias = [0.1 0.6 1.6] Std = [1.8 2.5 3.2]	Bias = [3.8 12 -3.4] Std = [1.8 5.7 6.7]
80m SK with sub-pulse	Bias = [-3.5 -15 14] Std = [0.5 3.4 3.3]	Bias = [-0.1 -0.1 0.9] Std = [0.9 1.8 1.6]	Bias = [3.4 14 -13] Std = [0.9 4.1 3.5]
20m SK no sub-pulse	Bias = [-2.7 6.2 5.4] Std = [0.6 2.2 1.8]	Bias = [0.2 1.3 1.1] Std = [1.1 2.3 2]	Bias = [2.9 -4.7 -4.3] Std = [1.1 3.6 2.7]
20m SK with sub-pulse	Bias = [-2.8 1 5.7] Std = [0.6 1.4 1.7]	Bias = [-0.4 -0.1 1.4] **Std = [1.1 0.7 0.8]**	Bias = [2.4 -1.1 -4.3] **Std = [1.3 1.5 1.9]**

Contributor : intrinsic POD error (on Xslo) whose standard deviation amplitude is around 6 mm (comparison with the FFRF distance whose noise is much lower than that)

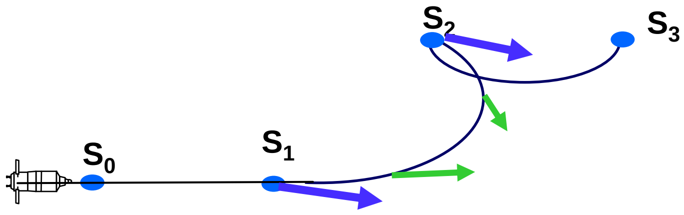


FFIORD

Prisma Satellites

Nominal Mission : GNC functions
2 Maneuvers transfer function

- **Description : Transfer between 2 MANGO relative positions via 2 impulsive maneuvers (Similar than Far RdV ATV)**



- **Relative dynamic modelisation:**
  - **Tschauner-Hempel equations=> Yamanaka-Ankersen STM (take into account eccentricity) + curvilinear correction of relative positions and velocities**

- **Two impulsive maneuvers : {t0, ΔV} et {tf, ΔW}**
  - **Linear system inversion (on board) : 6 equations , 6 unknowns**
  - **Addition of trim maneuvers and way-point target**

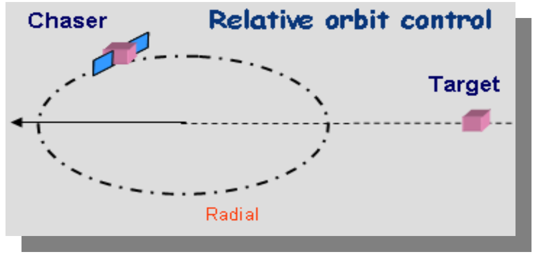
Nominal Mission: 2MT

Theoretical Conditions: Initial Position Final Targeted Position (m)	Transfer Duration (orbits)	Delta-V consumption (cm/s)	Number of manoeuvres	Transfer accuracy (m and mm/s) POD as Ref
330 m ➔ 600 m	0.75	3.6	4	3.72 m / 25.0 mm/s
500 m ➔ 100 m	0.75	12.3	4	1.08 m / 18.58 mm/s
500 m ➔ 260 m	1.75	14.2	5	1.75 m / 3.41 mm/s
-100 m ➔ -30 m	0.70	2.7	4	1.0 m / 4.94 mm/s

Nominal Mission : GNC functions
Stand-by function (relative orbit keeping)

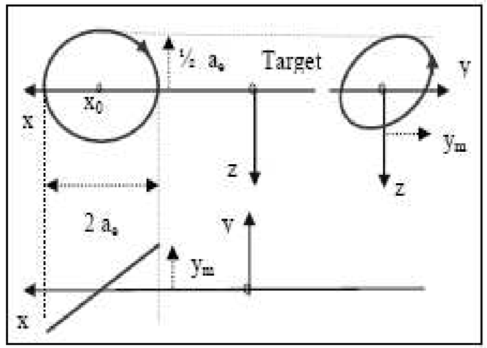
■ **Description:**

- **Maintain MANGO on a stable relative orbit during "stand-by" phases (nominal mode), with minimizing dV consumption,**
- **After an anomaly, retreat to a stable relative orbit whatever MANGO initial states (retreat mode), with minimizing dV consumption**



■ **Relative dynamic modelisation:**

- **Tschauner-Hempel equations => Yamanaka-Ankersen STM (take into account eccentricity) + curvilinear correction of relative positions and velocities relatives**
- **MANGO maintained on a stable « football » orbit**



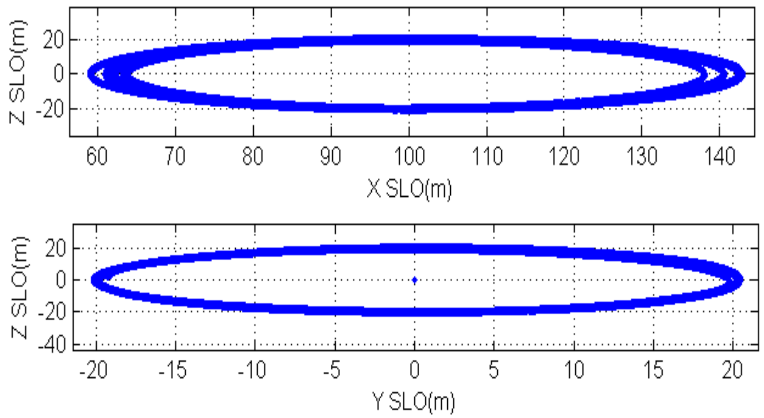
■ **Maneuvers control :**

- **Periodic control using 2-maneuver transfer**
- **Decoupled in-plane and out-of-plan motion => decoupled control**
- **Optimization of "retreat" maneuver (destination in case of "soft" anomaly)**

Nominal Mission: Stand-by

- 3 slots in normal mode – few orbits
- 1 slot in recovery mode for in-flight anomaly recovery scheme qualification
- 1 slot in normal mode -1.5 day - to asses long term performance and the link between orbital position and orbit maintenance cost

➔40 orbits for an overall cost of 6.86 cm/s ie 1.7 mm/s/orbit



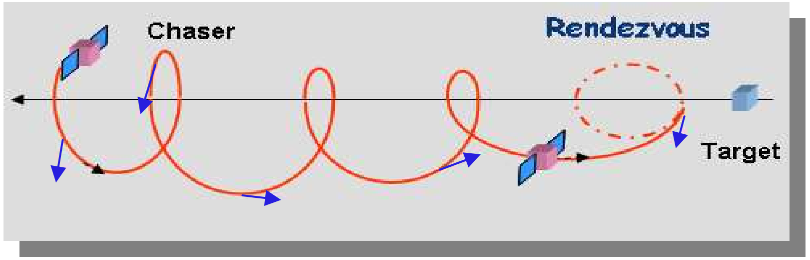
	Mean control error (1 sigma)	
	x0 (m)	ym (m) ym_ref = 20m
x0ref = 300m, ~3 orbits	1.36 (2.16)	0.61 (0.24)
x0ref = 300m, ~5 orbits	5.27 (2.91)	0.56
x0ref = -200m, ~3 orbits	-5.18 (1.64)	- (0.13)
x0ref = 102m, ~7 orbits (recovery)	-0.56 (1.57)	0.16 (0.14)
x0ref = 300m, ~20 orbits	-3.04 (2.2)	-0.34 (0.27)

Mean bias = 3 m
Mean sigma = 2m

Mean bias = 0.3 m
Mean sigma = 0.2 m

Nominal Mission : GNC functions
Rendezvous function

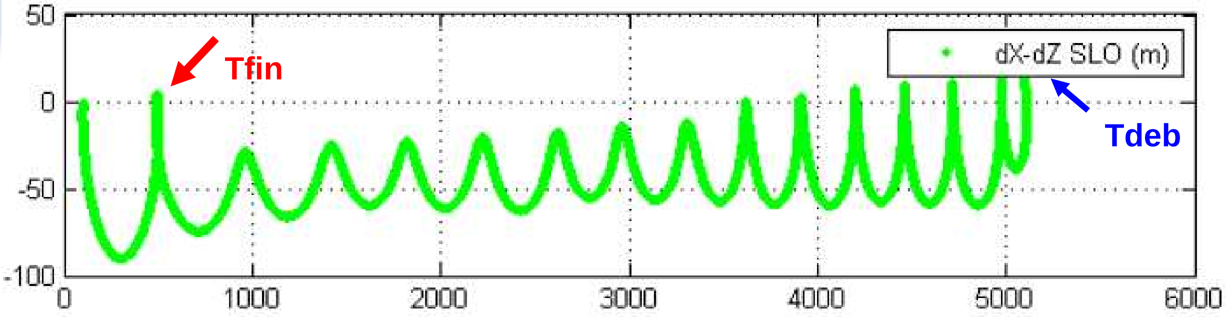
- **Description: Rendezvous (or deployment) between MANGO current position and the vicinity of a target point:**



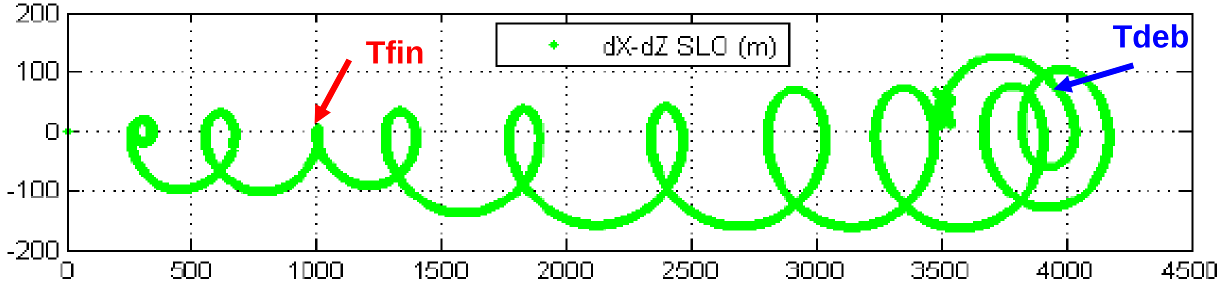
- **Relative dynamic modelisation:**
  - **Tschauner-Hempel equations => Yamanaka-Ankersen STM (take into account eccentricity) + curvilinear correction of relative positions and velocities relatives**
  - **Linear time variant (LTV) state-space model**

- **ΔV optimization:**
  - **Maneuver plan : impulsive ΔV_k (k≤10) with fixed realization dates**
  - **Quadratic programming problem with linear equality constraints + feedback scheme based in MPC (Model Predictive Control) framework to update (on board) the maneuver plan,**
  - **Guidance Q_n matrices : pre-calculated on ground and then uploaded by TC**

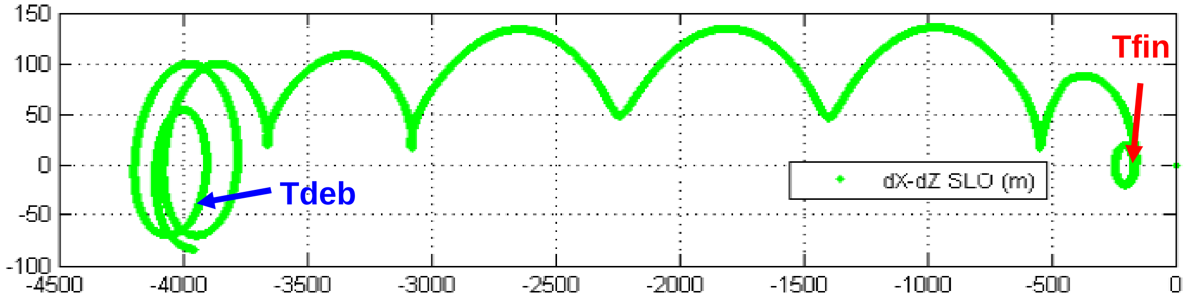
Nominal Mission: rendezvous operations
Some trajectories



GNC1-1-b :
[5000, 0, 0] => [500, 0, 0]
Duration : 23 h 45 min
10 Maneuvers



GNC1-2-b :
[4000, 5, 90] => [1000, 0, 0]
Duration : 13 h
9 Maneuvers



GNC1-3-b :
[-3723, -1.4, -42] => [-160, 20, 0]
Duration: 13 h
8 Maneuvers

Nominal Mission: rendezvous operations

Theoretical Conditions: Initial Position Final Targeted Position (m)	Rendezvous Duration (orbits)	Rendezvous accuracy (m and mm/s) RF nav as Ref	Rendezvous accuracy (m and mm/s) POD as Ref
5000 m ➔500 m	14.25	2.49 m / 1.99 mm/s	1.40 m / 1.74 mm/s
170 m ➔ 100 m	2	0.73 m / 0.68 mm/s	0.53 m / 3.57 mm/s
-3720 m ➔ -160 m	7.8	0.73 m / 0.60 mm/s	0.25 m / 7.48 mm/s
6750 m ➔ 500 m	6.8	2.60 m / 0.51 mm/s	1.72 m / 7.63 mm/s
-7200 ➔ -2000 m	7.8	2.36 m / 1.18 mm/s	3.12 m / 9.78 mm/s

worst case @2 km
Position error : < 3.2 m
Velocity error : < 1 cm/s

RDV Requirements:
Position error : ≤ 50 cm
Velocity error : ≤ 1 cm/s

Nominal Mission: rendezvous operations dV consumption

Theoretical Conditions: Initial Position Final Targeted Position (m)	Monte Carlo simulations (cm/s)	Pre-computed on ground Delta-V (cm/s)	Delta-V on-board consumption (cm/s)
5000 m ➔ 500 m	7.27 / 2.44	2.30	8.6 (x3.7)
4000 m ➔ 1000 m	12.9 / 3.23	13.0	15.3 (x1.2)
170 m ➔ 100 m	2.66 / 0.06	3.6	3.0 (x0.8)
-3720 m ➔ -160 m	12.2 / 2.12	12.53	15.5 (x1.25)
6750 m ➔ 500 m	n.a.	17.3	27.3 (x1.6)
-7200 m ➔ -2000 m	n.a.	19.0	17.7 (x0.9)

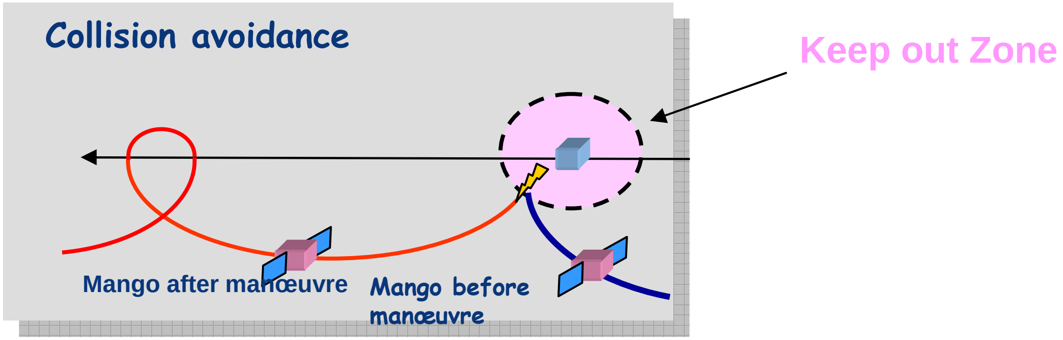
Coherence between simus MC and on flight results

Coherent additional cost with others RDV projects

Nominal Mission : GNC functions
Collision Avoidance function

■ **Description:**

- **If collision risk is detected (ISD < threshold), collision avoidance algorithms shall compute a manoeuvre that sets the main spacecraft onto a relative orbit that remains outside the defined safety sphere, for a long enough period so that ground can hand over :**



■ **ΔV CAM :**

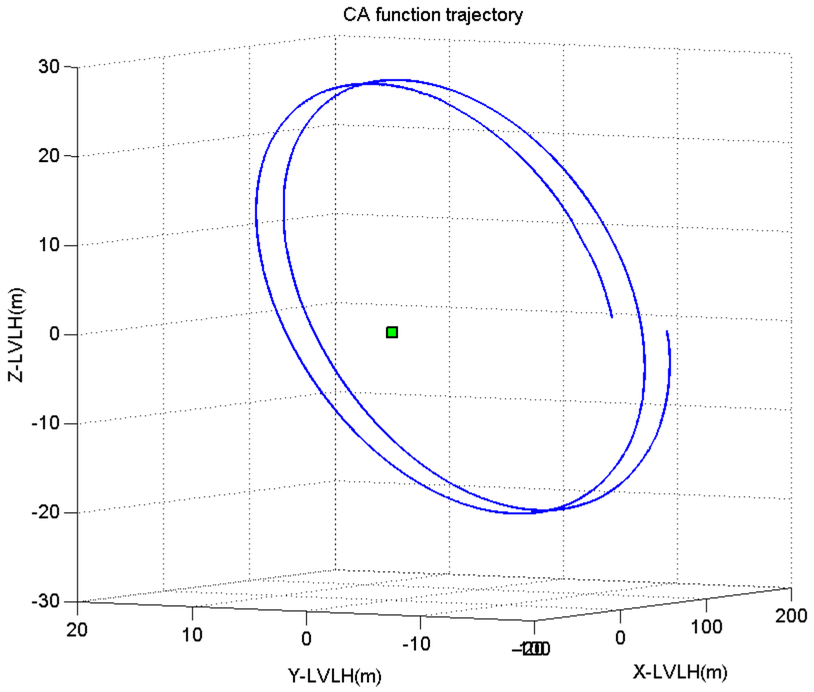
- **Two modes:**
  - **«Drift» CAM: 1 dV (explicit formula) consists in creating a drift between Mango and Tango**
  - **«Soft» CAM : 2 dV (explicit formulas) aims at setting the main spacecraft onto a stable relative orbit around the target (radial and normal separations phased in quadrature)**

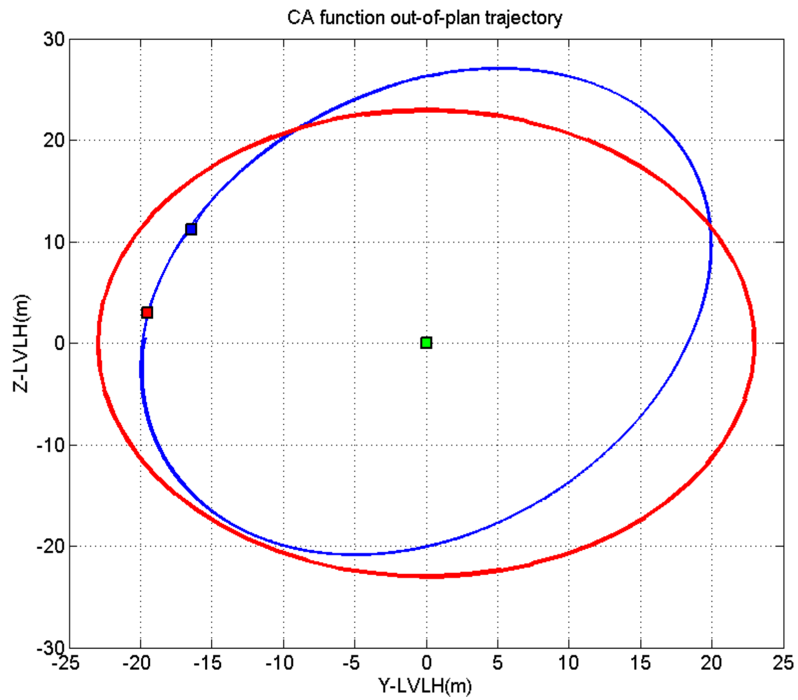
Nominal Mission: CAM operations «Drift» CAM 1 dV

Fictitious or Real Target	Target position (m)	KOZ threshold (m)	Duration free drift (orbits)	Delta-V consumption (cm/s)	KOZ criteria
Fictitious	[90 0 0]	22	6.7	3.9	Ok
Real	[0 0 0]	22	8.3	3.8	Ok
	[0 0 0]	40	7.0	8.0	Ok
	[0 0 0]	45	6	10.5	Ok

- **All «drift» CA successfully executed**
- **Exiting Keep out Zone a few seconds after CA maneuver**

Nominal Mission: CAM operations «Soft» CAM 2 dV





Potential risk of this strategy

- **Weak drift on Xslo**
- **Projection onto the $\{Y,Z\}_{slo}$ plan ≠ circle whose radius = KoZ threshold**

Summary

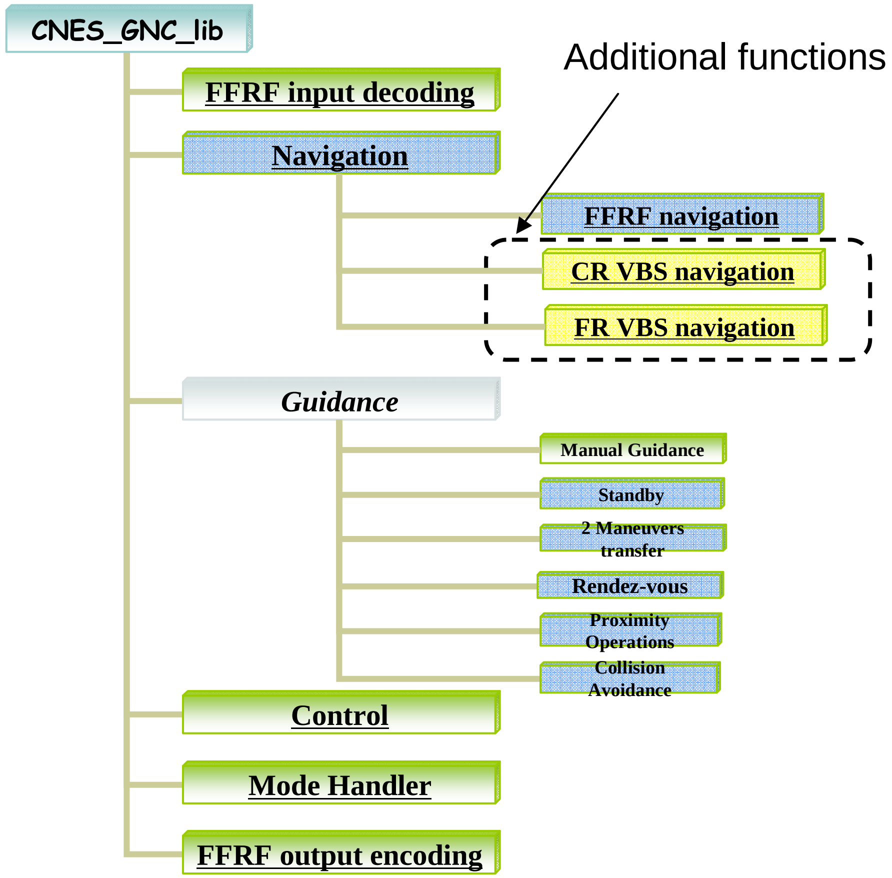
- Nominal mission
  - Algorithms
  - Results synthesis

- **Extended mission**
  - **Algorithms**
  - **Results synthesis**

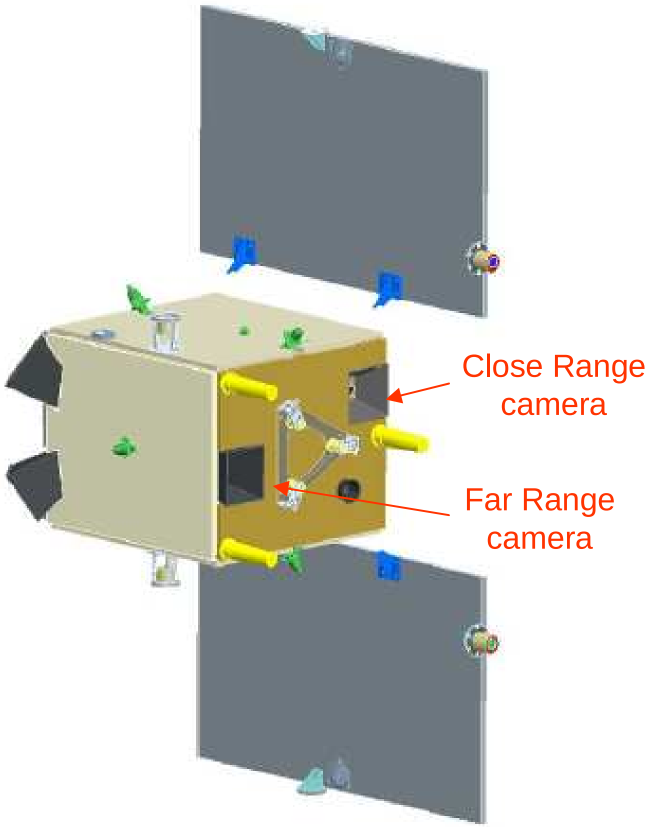
- GNC results summary

Extended mission GNC Software: GNC functions overview

- 2 new navigation functions integrated within CNES_GNC_lib to process VBS measurements
- 1 guidance function (2 MT) programmed differently to allow guidance via waypoints



Extended mission
VBS cameras



Short range camera:

- works in cooperative mode at short range (d < 50 m)
  ➔ relies on IR LEDs activation on Target satellite
- determines @ 1 Hz Target relative position and orientation by comparing the diodes pattern with the model stored in database
- CNES will only use the position measurement

Far range camera:

- Customized star tracker that can detect orbital objects
- Detection of an orbital object is made by comparison with the star catalogue and analysis of the apparent motion (→ brightest object only)
- Tracks the target and delivers its direction angles along with the camera inertial attitude
- *Basic image processing performed at short range ??*

Extended mission GNC tests

GNC Activity	Number of occurrences	Duration
Metrology transition	1 open loop session 3 closed loop sessions	4 days
Vision based rendezvous	1 open loop session 3 closed loop sessions	4 days
Vision based relative orbit keeping	1 session	0,5 days

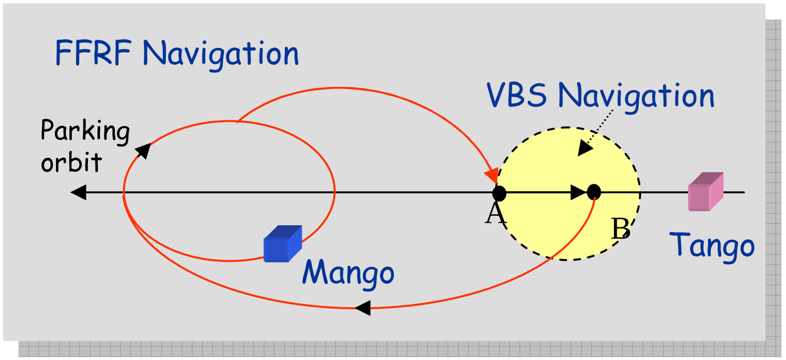
8,5 jours de boucle fermée
4.8 m/s delta-V
3 à 4 changements de mode par jour

POD-DLR (Precise Orbit Determination) are used as reference for performance evaluation

Extended mission add-on GNC functions
Vision based navigation at short range

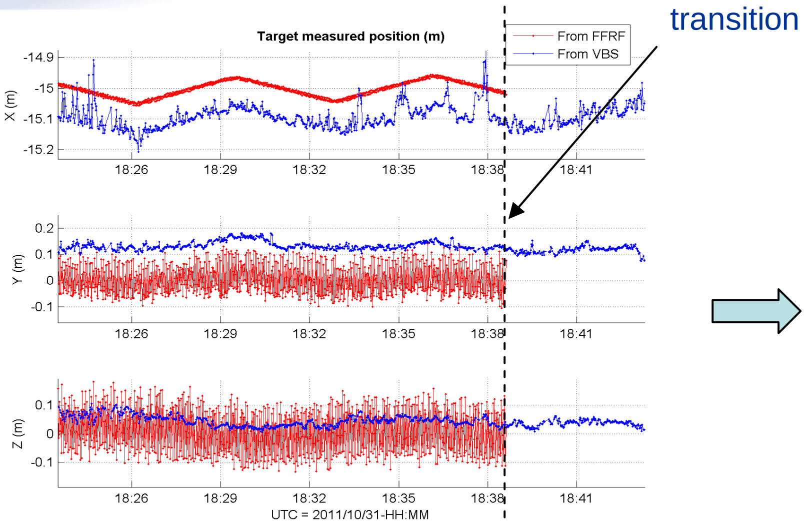
- **Function : Determination of MANGO relative state using CR VBS data**
  - EKF to estimate up to 8 states : 3 for position, 3 for position rate and optionally 2 for the VBS direction biases
  - Adaptation of the FFRF navigation filter for the processing of slightly different measurements (3D position set converted into distance and direction angles)
  - Tango Local orbital frame obtained by propagation (as for FFRF navigation)
  - Developped in C code

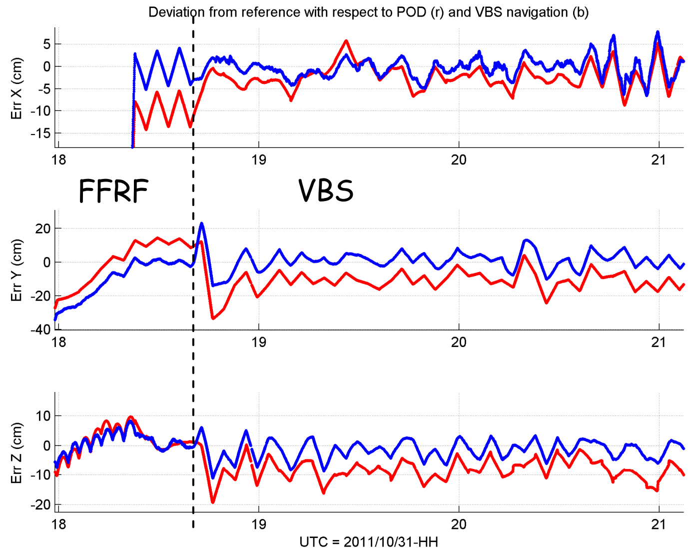
➔ This function allows to exercise metrology transitions: FFRF -> VBS and VBS -> FFRF and test proximity control performance



➔ A similar function is available in PRISMA and can be used in FFIORD loop for performance comparison

Extended mission GNC results
Proximity operations with metrology transition (1)



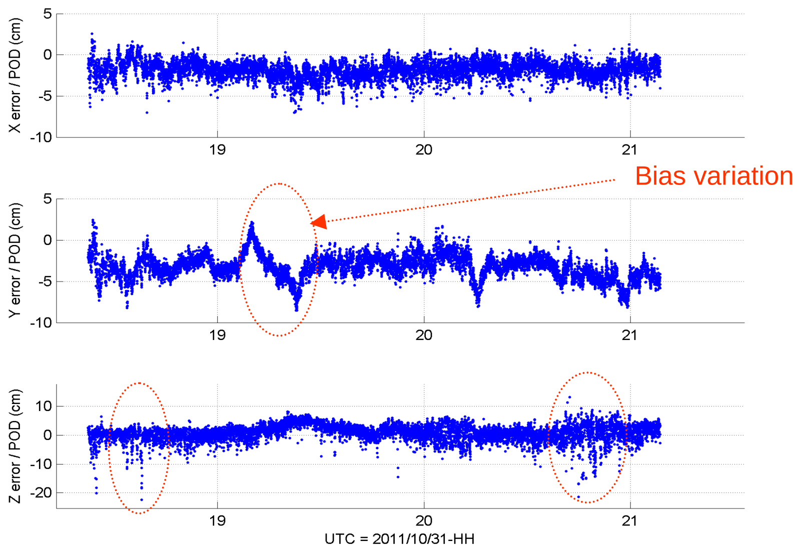


- 4 transition experiments were performed with a satisfactory functional behaviour
- Distance errors affect the navigation performance and control accuracy is not improved w.r.t. FFRFnavigation
- Control strategy is to be tailored to reduce navigation stress (to be relaxed before and during transition phase

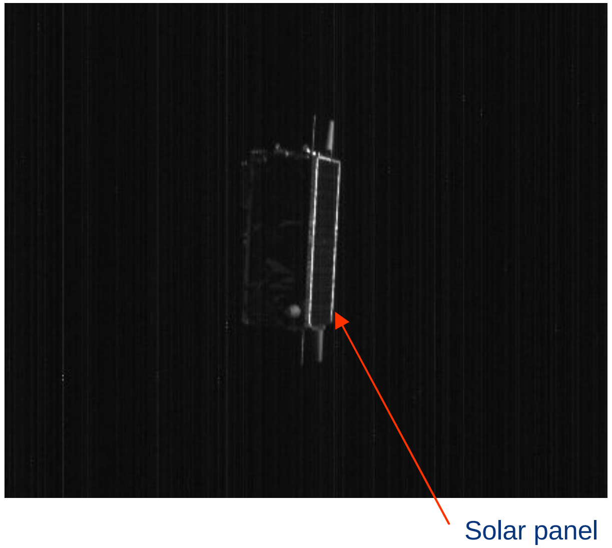
Experiment	Navigation error (cm) POD as ref	Control error (cm) VBS nav as ref	Control error (cm) POD as ref
PROX @ 15 m (OHB nav)	Bias [0.8 2.4 3.1] Std [5.6 1.4 1.2	Bias [2.8 0.1 0.1] Std [14 4.4 5.3]	Bias [4.1 2.4 2.9] Std [14 4.5 5.2]
PROX @ 15 m (CNES nav)	Bias [2.0 12 6.4] Std [1.9 3.8 2.0]	Bias [0.2 1.1 1.6] Std [2.2 5.3 2.9]	Bias [2.2 11 8.2] Std [2.5 6.0 3.3]

Extended mission GNC results
Proximity operations with metrology transition (2)

VBS measurement error (POD reference)



Target satellite at 15 m distance



VBS measurements suffer from temporary noise increase (distance) and bias variations that affect control performance (LED detection perturbed by optical artefacts)

➔ Positioning stability could not reach the level obtained with FFRF measurements even through ground replay tests

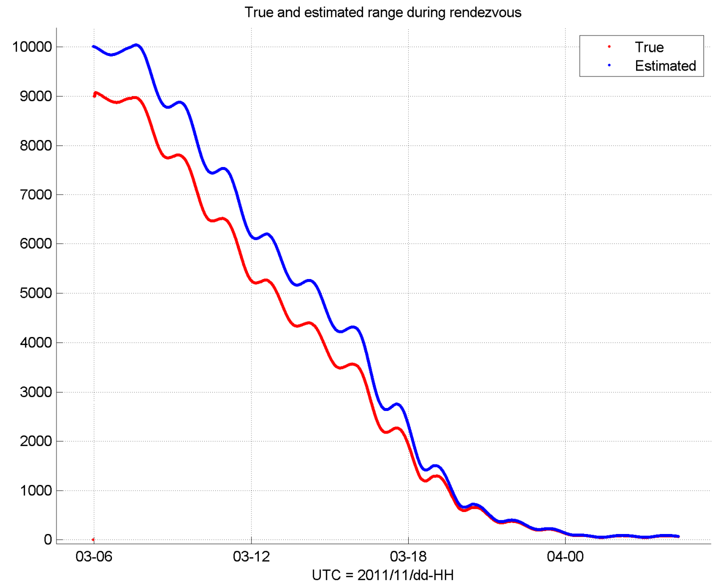
➔ High performance is achievable but requires cleaner optical conditions (robustness of the optical target detection to be improved)

Extended mission add-on functionality
Vision based rendezvous (FR VBS)

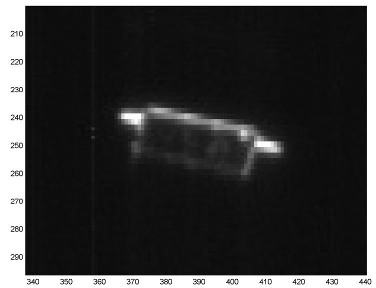
- **Navigation Function : estimation of MANGO relative state using FR VBS data**
  - **Distance is not available but can be observed in presence of manœuvres applied along the rendezvous trajectory**
  - **Based on an Extended Kalman Filter with 6 states : 3 for position, 3 for position rate**
  - **Dynamic model: Yamanaka Ankersen formulation**
  - **Automatic tuning of filter parameters (scheduling depending on relative range)**
- **Navigation Characteristics**
  - **Simulink implementation**
  - **Development by TAS Cannes (R&T) and encapsulated by CNES**
  - **Performance very dependent on guidance strategy (manœuvres direction and amplitude) and relative range initial uncertainty**
- **Guidance function**
  - **Implementation of a waypoint oriented strategy using an already available algorithm (multiple manœuvre transfer) with a different programming method**

Extended mission GNC results
Angles only navigation (1)

Experiment	Duration (hours)	Range accuracy (%)	Expected Delta V (cm/s)	Real Delta V (cm/s)
RdV 4 km to 100 m (OL)	16.2	1.8%	N/A	N/A
RdV 4 km to 100 m (CL)	16.2	2%	54.0	42.6
RdV 10 km to 100 m (CL)	18.5	3 %	98.5	86.8
RdV 10 km to 50 m (CL)	19.5	5.5%	74.0	73.6



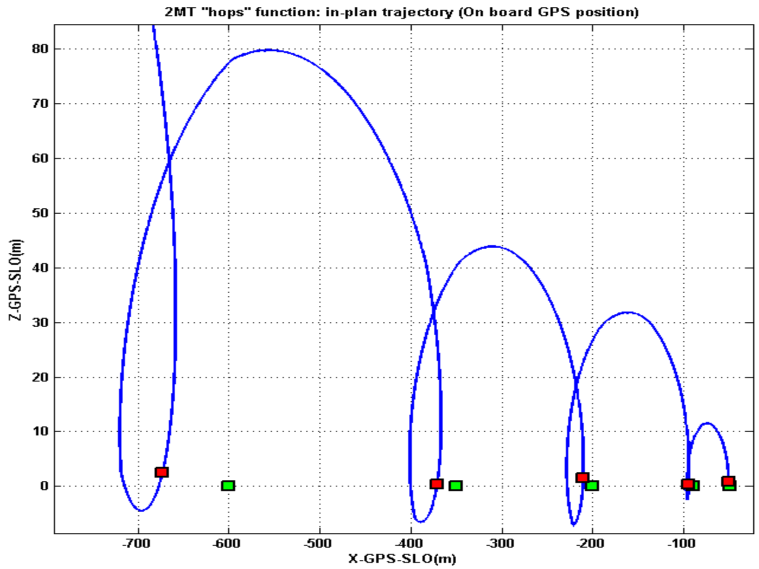
- 4 RDV achieved successfully
- Satisfactory VBS behaviour at long and medium range (target detection and tracking)
- Range uncertainty reduction is not significant above 2 km
- Limited range accuracy at short range due to the target direction uncertainty



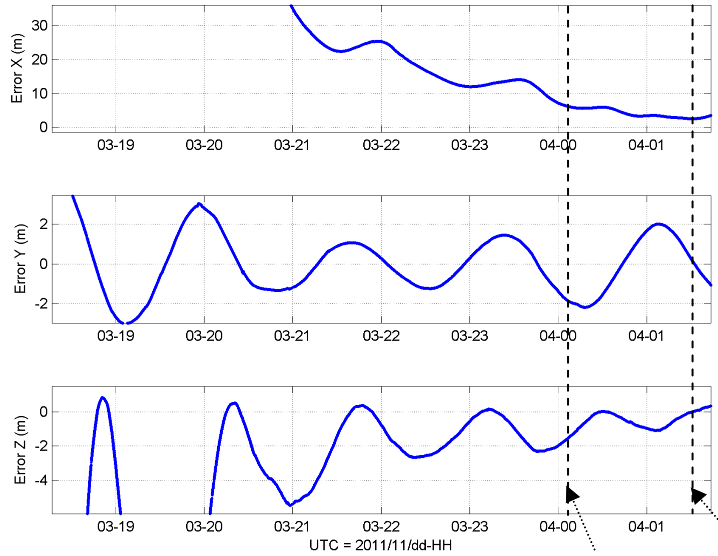
target size > 40 pixels at 50 m

Extended mission GNC results
Angles only navigation (2)

Illustration of waypoint oriented guidance



Performance at short range



• Difficulty to reduce relative range uncertainty at long distance at a reasonable cost

• Performance improvement at short range is achievable with some basic image processing (outside the VBS)

Conclusion

- **FFRF based activities**
  - **All RDV and FF activities were successfully demonstrated**
    - sensor & algorithm integrated behavior showed a great robustness ➔ complex sequences were routinely performed (autonomy) with the expected performance level
  - **Short range positioning was achieved with a high stability (a few cm)**
    - positioning performance exceeds requirements for a first stage metrology

- **VBS based activities**
  - **RDV based on Angles-only navigation was demonstrated several times**
    - VBS showed a satisfactory robustness at all ranges
    - Navigation performance at short range can be improved by image processing implemented in the OBC (not possible on PRISMA)
  - **Metrology transition / VBS based control was exercised several times**
    - Allowed to evaluate the transition issues in terms of navigation and control performance
    - VBS behavior was satisfactory but measurement performance was not sufficient to demonstrate a higher positioning accuracy ➔ high performance requires a better robustness of the target identification process