The Formation Flying Software of PROBA3

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4. SC-GNC and ACT-MNG
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PROBA3 MISSION (1)

- 2 Spacecraft: OSC and CSC launched in stack configuration and afterwards separated
- ISD of 150m during apogee
- High elliptical orbit around Earth

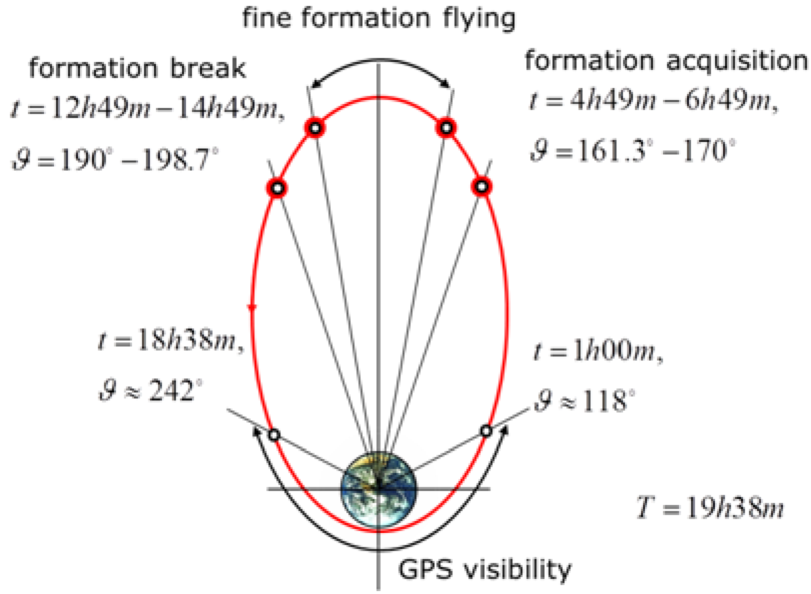
Parameter	Value
Perigee height	600 km
Apogee height	60530 km
Semi-major axis	36943 km
Eccentricity	0.8111 -
Inclination	59°
RAAN	84°
Argument of Perigee	188°
Orbital period	19h38m
Launch date	2016

- Objectives:
  - Demonstration of Formation Flying technologies (Station Keeping, Rigid/Loose Resizing/Retargeting, RV, ...)
  - Sun corona observation
  - Autonomy
- Sensors:
  - STR, Sun sensors, Gyros (both SC)
  - Absolute + Relative GPS (only available around perigee)
  - Coarse Lateral Sensor (CSC, only available around apogee)
  - Fine Lateral and Longitudinal Sensor (CSC, only available around apogee)
  - Inter-Satellite Link (both SC)
  - Visual Based System (OSC, for Rendez Vous Experiment)

PROBA3 MISSION (2)

- Actuators:
  - 1N thrusters on CSC (HPGP)
  - 10mN thrusters on OSC (CGT)
  - Reaction wheels

- Nominal routine:
  - 6h of Formation Flying experiments around apogee
  - Formation break
  - Perigee Pass without manoeuvres
  - Formation reacquisition

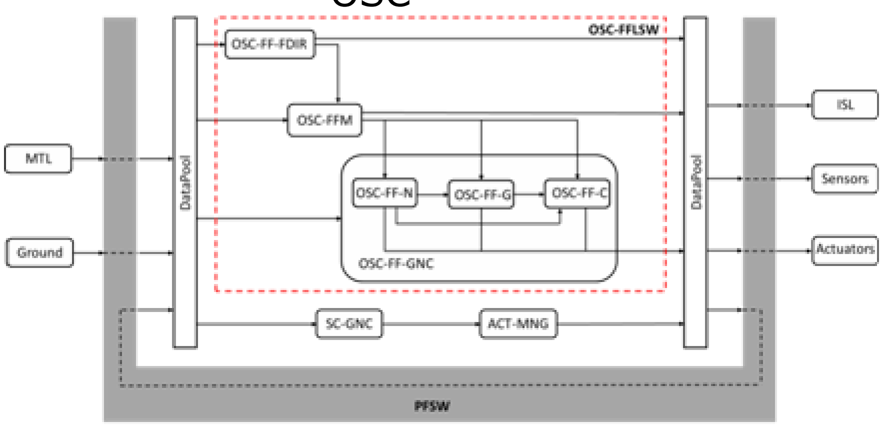


- Expected performances:
  - Relative Displacement Error: RDEx = 1,5mm and RDEyz = 0,73mm
  - Absolute Attitude Error: AAEyz < 2,8arcsec
  - Absolute Attitude Measurement Error: AAMEyz < 1,25arcsec

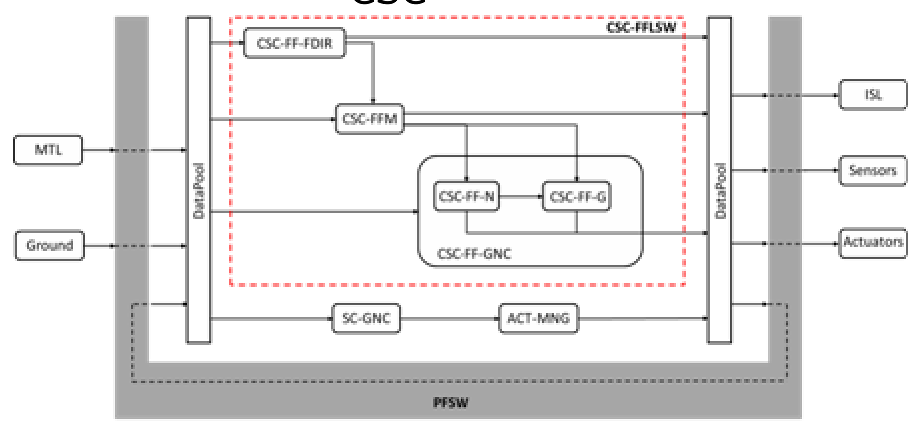
PROBA3 ARCHITECTURE

- Main elements of the Formation Flying Software:
  - FFM: plans, coordinates, manages FF activities autonomously
  - FF-FDIR: coordinates detection and flags processing coming from FFM, FF-GNC and FF-related metrologies
  - FF-GNC: determines the relative position and attitude (Navigation), computes the adapted trajectories to follow FFM requests (Guidance), and determines the actions for acquiring these trajectories (Control)
  - SC-GNC: controls the SC absolute states
  - ACT-MNG: receives and coordinates forces and torques
- Share of functionalities
  - OSC FFM is the master and CSC slave during nominal operations
  - Fine actuations performed by OSC, large actuations by CSC
  - All functionalities run OSC, only some of them in CSC during nominal operations

OSC



CSC



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FFLSW (1): FF-FDIR

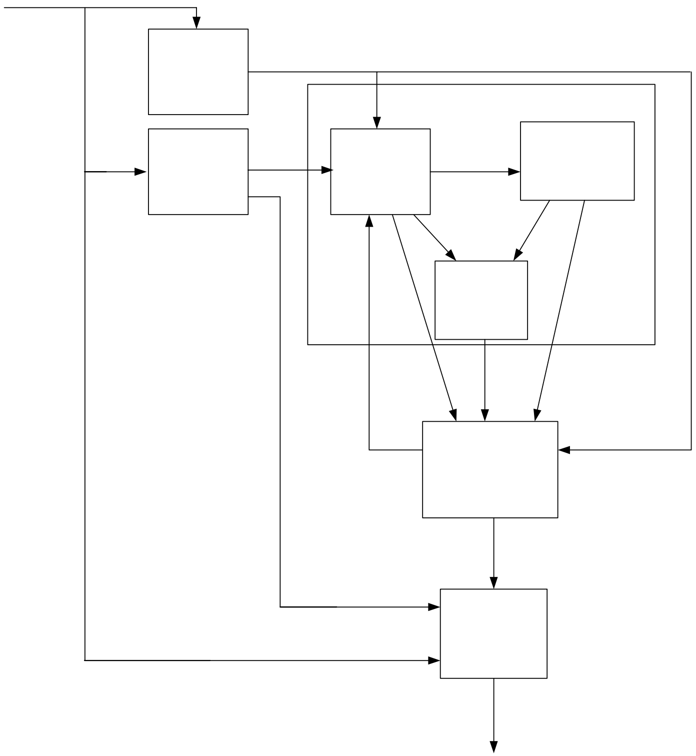
- Formation Flying Level Software, composed by:
  - FF-FDIR
  - FFM
  - FF-Navigation
  - FF-Guidance
  - FF-Control

FF-FDIR:

- Failure Detection Isolation and Recovery for Formation Flying
- Responsible for ensuring the formation safety during the mission:
  - Check formation status
  - Perform actions to prevent loss of the mission
  - Check status of FFS system in charge of the position control on the SC
- Works in complement with SC-FDIR that manages the failures at Attitude Determination and control System level
- FF-FDIR scheduled to be fully validated by the following phase C and fully integrated in FFS afterwards

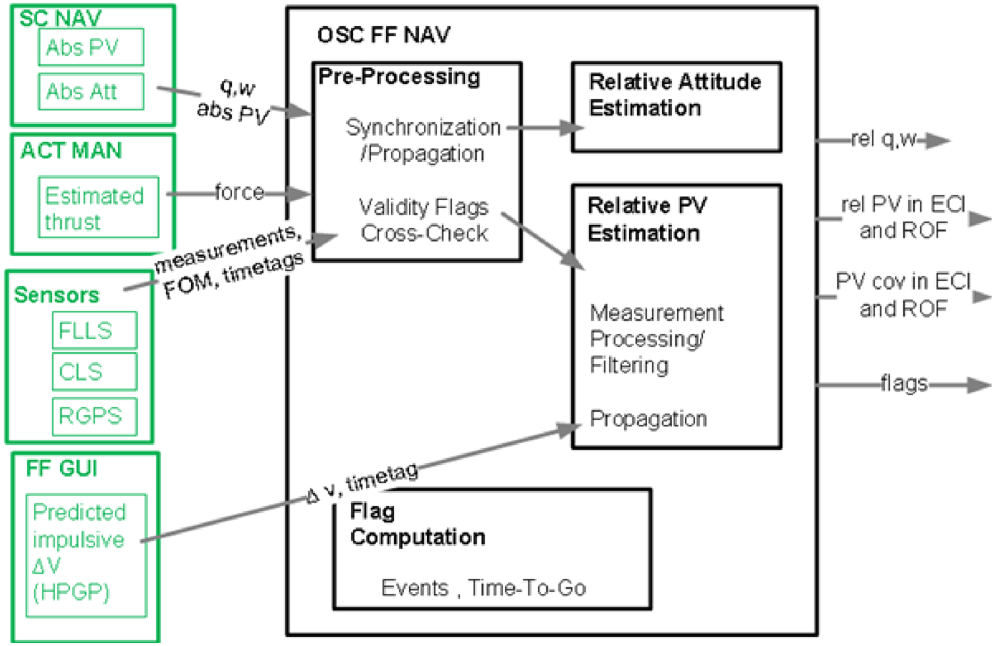
FFLSW (2): FFM

- Commands and monitors actions to acquire maintain and change the different formation configurations.
- Keystone for the autonomy (Ground commands for one week)
- Two levels of commands and Ground intervention:
  - High level: Modes management through high level commands from Ground (high level timeline, valid for one week)
  - Low level: Modes execution and monitoring at low level (event list execution), allowing to take control of the satellites
- Functional design:
  - Inputs Manager: reorganizes inputs
  - TC Manager: interface through which Ground sends timelines and commands
  - Mode Management (Select Mode, Compute Reset Flag, Load New Mode):checks the FF-GNC mode transition and selects the new FF-GNC mode that has to be used
  - Mode Execution: manages the loaded event list related to the FF-GNC mode, by performing the checks and commands needed
  - Output Manager: prepares outputs for the rest of the FFSW



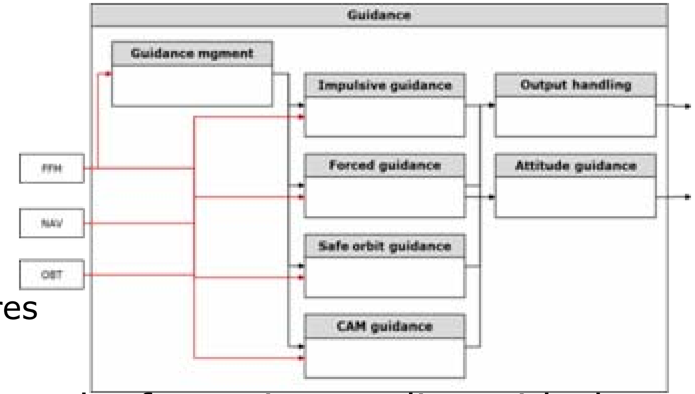
FFLSW (3): FF-NAVIGATION

- Processes absolute position and attitude coming from SC-GNC, along with relative sensors measurements
- Challenges:
  - Synchronisation
  - Diversity of measurements (SC-GNC determination, CLS, FLLS, RGPS, actuations computed by OSC)
  - Different levels of accuracy
  - Misalignments, biases, latencies
  - Presence of the ISL
  - Management of the actuations
- Based on Extended Kalman Filter
- Propagation using relative dynamics (Yamanaka-Ankersen formulation) in the Local Vertical Local Horizontal frame



FFLSW (4): FF-GUIDANCE

- Computes both impulsive manoeuvres and forced motion profiles
- Functional architecture:
  - Guidance Management: switches between the different modules
  - Impulsive Guidance:
    - In nominal orbit, DTM1, cold gas correction, DTM2, all computed as a two points transfer
    - Transfer Manoeuvres to Parking, computed as a two points transfer
    - Parking Maintenance manoeuvres, computed as a two points transfer between true anomaly of 90º and 180º
    - Transfer from Parking to Nominal, computed as a single impulsive manoeuvre at 180º to acquire the Sun aligned state vector
  - Forced Guidance :
    - In nominal orbit, desired state for both Formation Acquisition and Station Keeping and acceleration needed to compensate perturbations
    - In FF-Experiments, profile of the reconfiguration manoeuvre (Rigid/Loose Resizing/Retargeting) and acceleration needed for both compensating the perturbations and following the profile
  - Safe Orbit Guidance :
    - Computation of the Safe Orbit that suits the state knowledge accuracy
    - Transfer to Safe Orbit, computed as a two points transfer
  - CAM Guidance :
    - Impulsive ΔV to stop the motion
    - Impulsive ΔV to escape
  - Outputs Handling: prepares outputs
  - Attitude Guidance: Attitude needed for reconfiguration manoeuvres



- The Parking orbit is a controlled non-drifting orbit that allows the formation to align with the Sun at apogee and requires less ΔV to maintain than the nominal orbit
- The safe orbit is a trajectory that remains collision-free for 30 days

FFLSW (5): FF-CONTROL

- 3 controllers designed with different methods and for different purpose:
  - Coarse Acquisition Control:
    - acquires the formation after perigee pass: Initial error of 5m, FLLS in the loop, fuel consumption optimization, Final error lower than 1cm
    - Inputs: ideal position from FF-G
    - PD feedback controller aided with feed-forward term for gravity gradient
    - Presence of non-linear elements (saturation, dead-band, low-pass filter)
  - High Performance Control:
    - Conditions: Dynamics around apogee with CSC in free-flying and OSC actively controlled with CGT. High precision position and attitude estimation available. Gravity gradient and solar pressure
    - Controller based on $H\infty$ formulation
    - Position and attitude controller designed separately, with different bandwidth to avoid interactions
    - Feed forward term needed when actuations.
    - Integral action needed to counteract perturbation efefcts
  - Impulse Manoeuvre Control:
    - To perform significant impulses with milli-newton thrusters: loose reconfiguration manoeuvres, orbit corrections, CAM
    - Receives ΔV from FF-G and accumulates them in a buffer (that can be emptied)

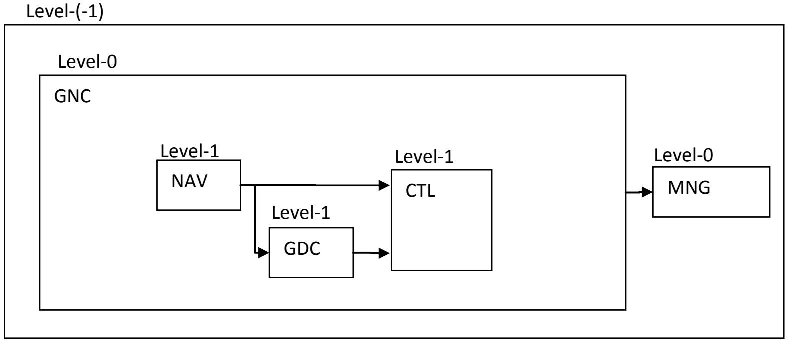
SC-GNC AND ACT-MNG (1)

- SC-GNC performs the tasks:
  - absolute attitude control
  - angular momentum management
  - delta-V realisation in a dedicated mode
  - absolute orbit navigation

- SC-GNC modes:
  - Stand-By Mode (SBM): Idle mode
  - Sun Acquisition Mode (SAM and SAM_STACK): orients the SC to maximises the solar panel illumination
  - Inertial Attitude Mode (IAM and IAM_STACK) : orients the SC in a specific attitude defined in the inertial frame
  - Orbit Control Mode (OCM): keeps the SC oriented along a specific attitude while realising the required ΔV
  - Target Pointing Mode (TPM): orients the SC towards the other SC
  - Thruster Based Inertial Mode (TBIM): Mail-Box mode where control torque and force come from formation flight or rendezvous experiences modules

SC-GNC AND ACT-MNG (2)

- SC-GNC is divided into 4 sub-modules:
  - SC Navigation:
    - Determines the current dynamical state of the SC
    - Computes ephemerides
    - Manages OBT
  - SC Guidance:
    - Computes the desired dynamical absolute state of the SC
    - computes the difference between the desired dynamical state and the current dynamical state
  - SC Control:
    - Determines and executes the necessary control commands to bring the current dynamical state of the SC to the desired state in a stable and accurate way
  - Actuator Manager:
    - post-processes both FF-GNC and SC-GNC commands to allow the actuators to execute them



- Requirements on the SC-GNC:

CSC			X-Axis Around LOS	Y-axis	Z-axis
HPAP	CTL	AAE	300 arcsec (TBC) (1σ)	2.8 arcsec (TBC) (1σ)	2.8 arcsec (TBC) (1σ)
		AAS	30 arcsec over 10 seconds (TBC) (1σ)	0.88 arcsec over 10 seconds (TBC) (1σ)	0.88 arcsec over 10 seconds (TBC) (1σ)
	NAV	AAME	30 arcsec (TBC) (1σ)	1.25 arcsec (TBC) (1σ)	1.25 arcsec (TBC) (1σ)
		AAMS	0.75 (TBC) arcsec (1σ), over 4hr	0.75 (TBC) arcsec (1σ), over 4 hr	0.75 (TBC) arcsec (1σ), over 4hr

OSC			X-Axis Around LOS	Y-axis	Z-axis
HPAP	CTL	AAE	900 arcsec (TBC) (1σ)	30 arcsec (TBC) (1σ)	30 arcsec (TBC) (1σ)
		AAS	N/A	N/A	N/A
	NAV	AAME	300 arcsec (TBC) (1σ)	5 arcsec (TBC) (1σ)	5 arcsec (TBC) (1σ)
		AAMS	TBC arcsec (1σ)	TBC arcsec (1σ)	TBC arcsec (1σ)

INTEGRATION PROCESS

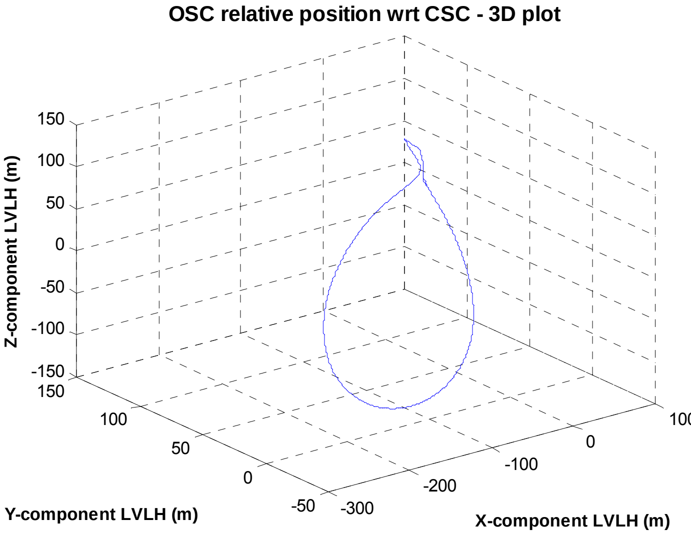
- Software developed in GNCDE framework:
  - Easy management of parameters initialization and outputs
  - Possibility to use the integrated library
  - Integrated tools for performing analysis on the prototype
- Simplified FES have been created to develop the FFLSW and the SC-GNC
- A complete FES has been developed in GNCDE, containing:
  - Real World: ephemeris, sensors, actuators, power system and DKE for each SC
  - Ground Segment: simulating orders to the SC
  - CSC_OBC and OSC_OBC: on-board computer of the CSC and the OSC, it contains the CSC and OSC Formation Flying software, along with platform software emulator
- Inside OBC, FFLSW runs at 1Hz, while SC-GNC run at 4Hz due to strong requirements on the attitude
- Application of coding rules permits using autocoding techniques for both the FFSW and the Real World:
  - Real world autocoded into SMP2 and integrated in the real time SBTB (Software Based Test Bench)
  - The FFSW is autocoded into C then encapsulated in a behavioural code of the platform software and inserted inside the SBTB
- Tests in SBTB are performed for any version of the code validated in the FES, even without the final version of the platform software, in order to detect and correct possible problems at the earliest moment

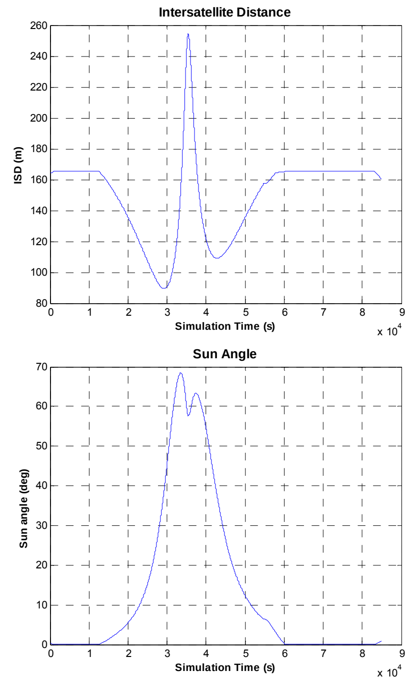
TEST RESULTS (1): NOMINAL ORBIT

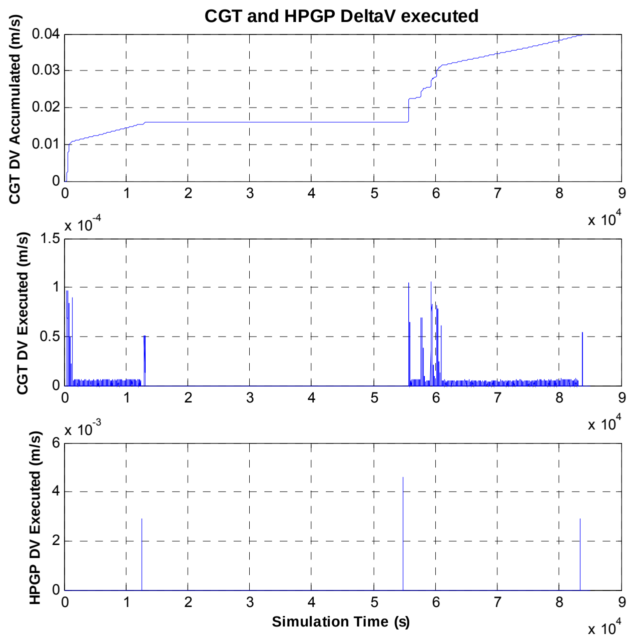
- For demonstrating that the FFSW fulfils the requirements for representative scenarios:

Test	Title	Description
Test 1	Multiple Nominal Orbit	Covers 3 nominal orbits. Demonstrates the integration of the software, the stability of the modules.
Test 2	Parking Orbit	Several orbits. Covers Parking Acquisition, Maintenance and Return to Nominal. Demonstrates each of these manoeuvres.
Test 3	CAM	Demonstrates the CAM computation and application.
Test 4	Deployment	Demonstrates the dynamics of the two satellites after deployment through to Commissioning Orbit acquisition and its safety.
Test 5	Nominal Orbit fully instrumented	One orbit. Evaluates the performances of the system in a nominal orbit.
Test 6	Safe Orbit	Demonstrate the dynamics of the two satellites during the Safe Orbit, and the possibility to reacquire correctly the Nominal Orbit afterwards.

- Nominal Orbit Test:

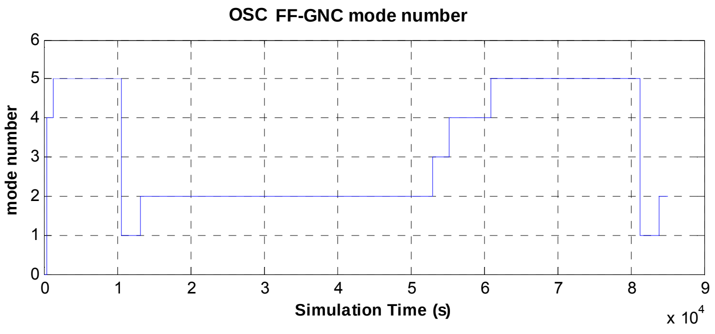




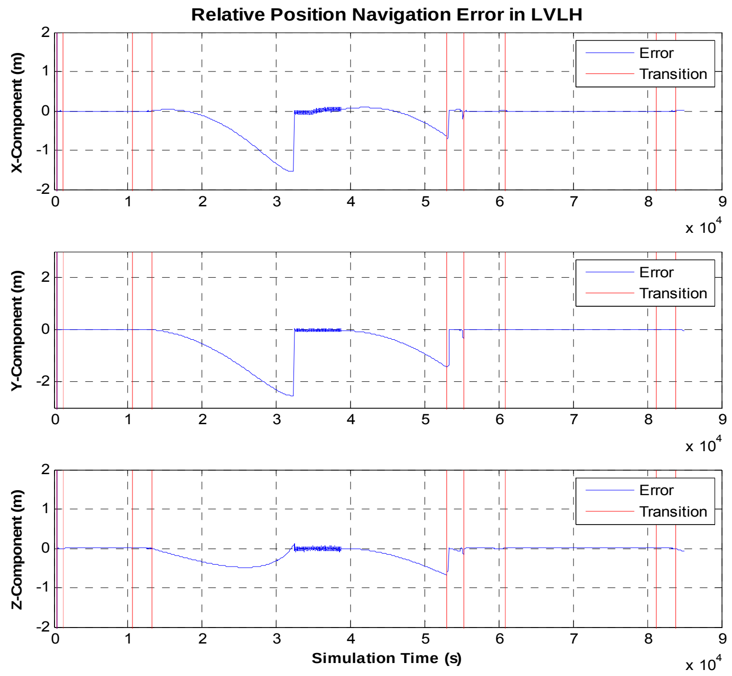


TEST RESULTS (2): NOMINAL ORBIT PERFORMANCES

- Nominal orbit:
  - Apogee with SK
  - Perigee pass with DTM and correction with CGT
  - GPS around perigee
- Performances computed during Apogee station keeping



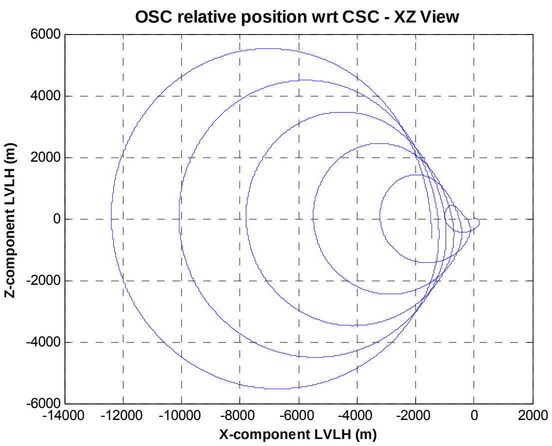
SC	Type	Error	xyz	HPAP Value	HPAP Unit	HPAP Remarks
CSC	CONTROL	AAE	yz	0,08 ± 3,08	arcsec	All ISD
			x	2,08 ± 2,31	arcsec	All ISD
		AAS	yz	0,0004 ± 0,63	arcsec	All ISD, over 10 sec
			x	0,0001 ± 0,42	arcsec	All ISD , over 10 sec
	MEAS.	AAME	yz	0,05 ± 0,57	arcsec	All ISD
			x	2,04 ± 0,48	arcsec	All ISD
		AAMS	xyz	0,03 ± 0,58	arcsec	over 4h in post-pro
OSC	CONTROL	AAE	yz	0,47 ± 8,72	arcsec	All ISD
			x	1,67 ± 8,29	arcsec	All ISD
	MEAS.	AAME	yz	0,02 ± 1,62	arcsec	All ISD
			x	2,02 ± 1,38	arcsec	All ISD
Formation	CONTROL	RDE	yz	1,05 ± 0,14	mm	ISD <160m
			x	0,16 ± 0.20	mm	All ISD
	MEAS.	RDMS	yz	0,039 ± 0,11	mm	over 4h in post-pro
			x	0,006 ± 0,02	-	-

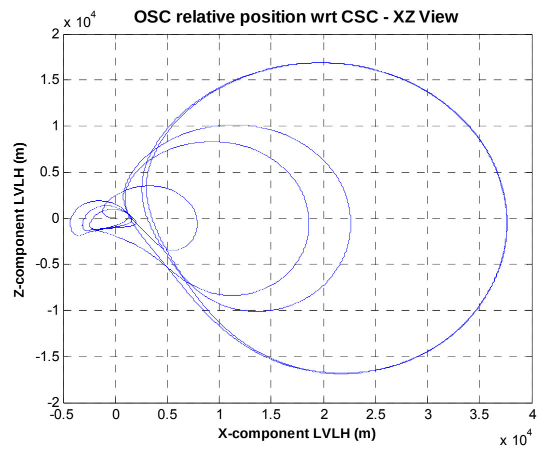


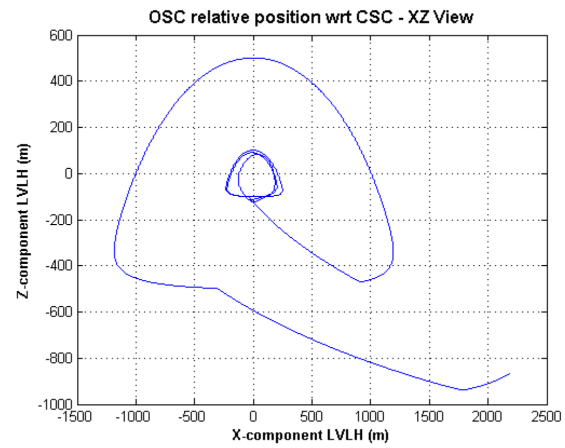
TEST RESULTS (3): OTHER TESTS

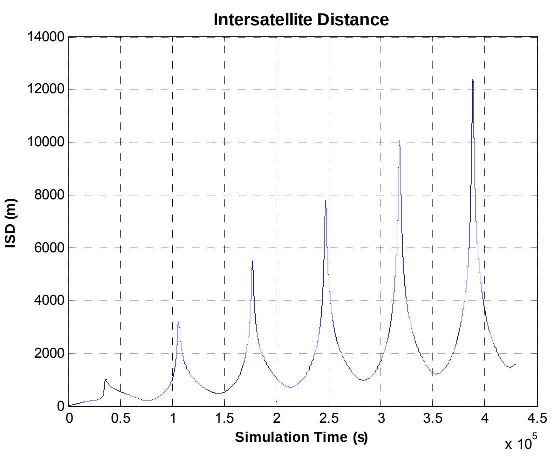
- In plane Relative Position (in LVLH) of the OSC, and Inter-Satellite Distance for the following tests:

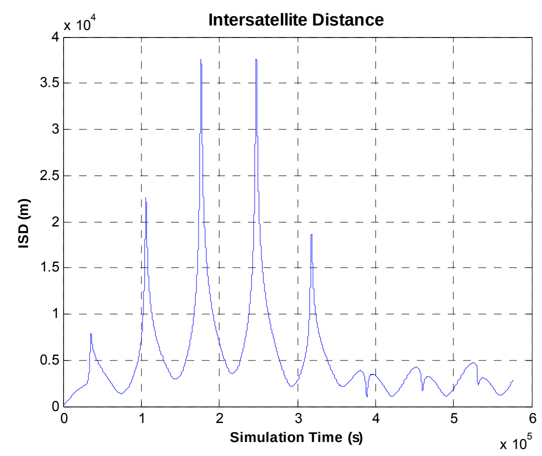
CAM	Deployment	Safe Orbit

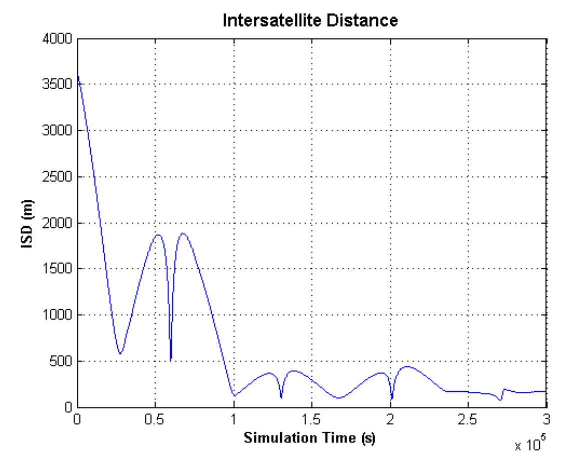












CONCLUSION

- The Phase B2 of the project concluded with a successful Preliminary Design Review in late 2012
- The software has been prototyped and tested in a Functional Engineering Simulator
- Tests have demonstrated the initial formation deployment, nominal orbital routine, return to nominal from safe orbit and Collision Avoidance Manoeuvres
- The software has been autocoded and integrated in the Software Based Test Bench, and the integration tests in the SBTB have been satesfactory
- Phase C is about to start, and will see the complete development of the FFSW for all the needs of the mission

Thank you

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