The Design of the Formation Flying Navigation for Proba-3

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Abstract: *PROBA-3 will perform formation flying in a highly elliptical orbit, and perform Solar coronagraphy and formation maneuvering demonstrations in a six-hour region around apogee. This paper describes the Formation Flying Navigation System developed and prototyped during phase B of the project.*
The formation Flying Navigation System design addresses, as main challenges, the synchronization and processing of measurements from a high number of sources, with different levels of accuracy, misalignment, bias and latencies, and whose availability varies with flight phase; the processing of these measurements concurrently in two spacecraft that communicate through an Inter-Satellite Link which introduces significant latency; and their filtering in a local reference frame, through a model of natural and forced relative dynamics in a highly elliptical orbit.
The paper introduces the design drivers, solution and test results.

Keywords: *Formation Flying, Navigation,PROBA-3*

1. Introduction

PROBA-3 is the first ESA Formation Flying mission. It will demonstrate autonomous formation flying techniques along with on-board autonomy for two spacecraft in a highly elliptical orbit around the Earth. The mission will perform coronagraph observation during the formation flying phases.
A coronagraph spacecraft (CSC) is equipped with fine ranging and line-of-sight sensors and high thrust actuators while an occulter spacecraft (OSC) contains the fine actuators. The Formation Flying Navigation System (FF N), whose design is presented in this paper, is used to estimate the relative state and posture between spacecraft and thus the first in the Formation Flying Autonomous Guidance Navigation and Control (FF GNC) chain. The relative metrology has different operating ranges, and accuracies, latencies with respect to the on-board clocks. Absolute attitude and orbital determination is also available. A relative GPS filter solution is available during pass around perigee.
The Formation Flying Navigation system is part of the Formation Flying Software which commands the formation. It collects data from the sensors and actuation commands, synchronizes them to a common correction time, and processes them in an Extended Kalman Filter which makes use of a model of the dynamics of relative motion in elliptical orbits. The Preliminary Design of the system has been completed in 2012. The algorithms have been designed, prototyped and tested in a functional engineering simulator.
Section 2 of this paper addresses the mission architecture and introduces the challenges posed to the relative navigation function design. Section 3 provides a summary of the solution to these challenges and Section 4 describes, in high level, the developed solutions that constitute the preliminary design of the Formation Flying

Navigation System presented at its Preliminary Design Review, Section 5 shows test results for its nominal operations and Section 6 provides the conclusions.

2. Design Drivers

Proba-3 mission consists of two spacecraft, the coronagraph spacecraft (CSC), carrying higher thrust (1 N) monopropellant thrusters for large impulsive manoeuvres and the occulter spacecraft (OSC) which carries Cold Gas Propulsion thrusters (mN), flying in a high elliptical orbit around the Earth (600x60530 km).
The orbital routine, presented in Fig. 2.1 consists in 6-hour Formation Flying experiments around apogee, followed by a perigee pass based on a two point transfer, and a formation acquisition before next apogee.

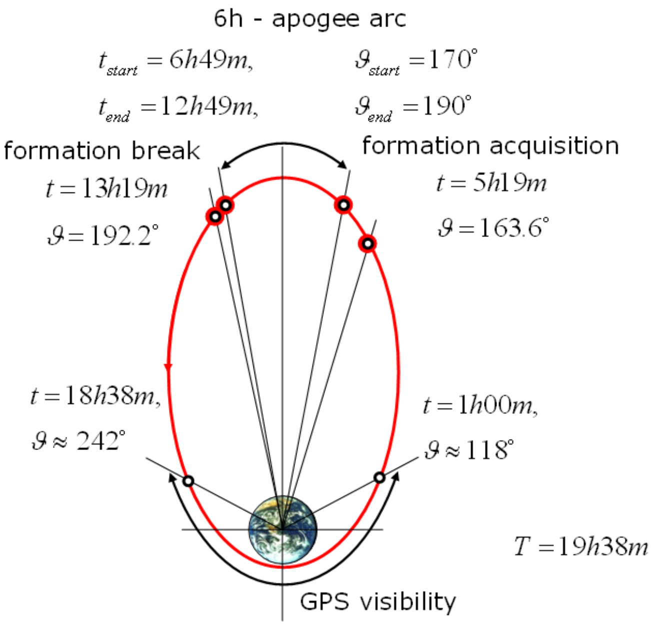

Figure 2.1 Orbital Routine

The Formation Flying Navigation function (FF NAV) is part of the Formation Flying Guidance Navigation and Control (FF GNC)[1]. It processes the measurements and SC-GNC data (the GNC system for absolute attitude and position), directly or via the Inter-Satellite Link (ISL), for the determination of the relative position and attitude (Navigation), computes the adapted trajectories to follow the requests of the Formation Flying Manager (Guidance), and determines the actions required for acquiring these trajectories (Control).

The Formation Flying main tasks are to:

- Acquire sensors data from the SCs; and acquire absolute position and velocity, as well as attitude solution, from the SC-GNC. Commanded thrust, mass and COM location and Sun direction estimates obtained from SC-GNC are also processed.

- Pre-process and synchronize incoming data, compensating for ISL lags, differences in OSC and CSC clocks and sensor lags. Process measurements and absolute navigation data in adequate relative reference frame.
- Process and incorporate measurements, filter them through dynamic models and compute the navigation solution.
- Process and incorporate estimated thrust (from actuator manager) and predicted CSC impulsive manoeuvres (from FF Guidance) in order to improve navigation solution:
- Propagate solution to the required time (On Board Time OBT)
- Provide navigation solution at the required frequency (1 Hz)
- Provide validity flags and flags/estimated times-to-go to events

The navigation filter runs at 1 Hz but must provide relative position, velocity and attitude estimates and predictions at different instants, depending on the function that requires them as inputs.

The location of sensors and thrusters between the two spacecraft drives the allocation of functionalities between the CSC and the OSC for the different phases of the mission (or orbital routine). Fine actuation can be only performed by the OSC, while fine metrology is only available without significant latency in the CSC, where the sensors are located. High thrust level actuation are available at the CSC only.
The architecture and functionality of the FF-GNC is similar for both spacecraft. In nominal operations the OSC will act as master, ultimately commanding the formation by actuating the OSC Cold Gas thrusters or issuing impulsive commands to be realized in the CSC.

The inputs to be processed in the FF NAV are

- Absolute Spacecraft GNC (SC GNC) orbital and attitude determination
- Metrology (measurements made available in the CSC)
    - Coarse Lateral Sensor (CLS) – provides azimuth and elevation – first step in the metrology chain, its Field of View (FOV) of approximately ±5 deg, allows the FF GNC enough pointing precision to acquire the Fine Longitudinal and Lateral Sensor
    - Fine Longitudinal and Lateral Sensor (FLLS) – provides relative longitudinal and lateral position – its FOV of <10 arcsec is stringent, although much wider for providing longitudinal measurements only (<50 arcsec).
    - Relative GPS filter – provides an estimate of relative position and velocity around perigee (~1 hour around perigee TBC).
- Actuation
    - High-thrust actuation is located in the CSC. They are used for impulsive retargeting manoeuvres. From 4.5 hours before to 4.5 hours after apogee, low-thrust actuation is used for fine formation control. It is located in the OSC.
    - The estimated force inertial frame from one FF NAV step to the next is provided to the FF NAV by the actuation managers with an error of ~10%.

- Because high-thrust guidance commands are sent in advance, at OSC, predicted actuation of the retargeting manoeuvres is possible before the arrival of actuation management data from the CSC through ISL.

In addition to the main data, ancillary data is provided – covariances, FOM, time stamps and validity flags of measurements, attitude / attitude rate / orbital estimation. Attitude and orbital determination (from SC GNC) data, from the host spacecraft is available at the current time (the time at which the FF NAV solution is required). SC NAV from the companion spacecraft is available through the ISL, with a lag of 3 seconds plus desynchronization between SC clocks (thus, 3 to 4 seconds).
Relative metrology is available to the FF NAV of the CSC with negligible lag plus one cycle lag of 1 second, but it is available to the OSC with a lag of 4 seconds plus clock desynchronization between SC clocks.
Estimated actuation is available locally with negligible lag, but information from actuation in the companion spacecraft is provided through the ISL, having a 3 second lag plus desynchronization between SC clocks (thus, 3 to 4 seconds).
RGPS relative position and velocity data is available to the OSC FF NAV with a lag of approximately 6 seconds and to the CSC FF NAV with a lag of 3 seconds with respect to their OBT.
There is a correlation offset between OSC and CSC clocks. The FF NAV shall receive a value for this offset coming from two simultaneous tags. It shall verify its validity, reject jitter, output its value, slope and warning flags in case of time abnormality. It shall furthermore apply this offset to the data coming tagged through the companion spacecraft clock in order to work with coherent time scales.

In summary the issues that defined the FF NAV design choice were:

- Relative metrology doesn't always allow building a relative state through geometric processing. If FLLS is not available, FF NAV only has access to lateral measurements.
- To process measurements and actuation, it is necessary to know the absolute attitude of both vehicles (to determine position and orientation of the sensor and corner cubes)
- The metrology is affected by an error that is assumed to be uncorrelated noise. The bias and misalignments are assumed to have been calibrated to its observable level.
- The dynamic environment is well known (relative motion in elliptical orbits around a spherical central body, plus corrections for SRP).
- The necessary data to process a measurement at OSC FF NAV lags approximately 4 seconds behind the time at which the solution is requested.
- RGPS solution provided to the FF NAV is the result of a filtering and processing of RGPS data using orbital dynamics. It is not a raw measurement subject to uncorrelated noise.

3. Design Choice

The design choice was thus to have a Kalman filter the core of the system, where states are relative position and velocity in the LVLH reference frame.

- The propagation-correction cycle runs up to a cycle correction time, which is an adjusted measurement timetag (virtual if no measurement is available).

- The correction step uses all the available relative measurements that it has to improve the solution – that is – if only CLS is available, it uses CLS measurements. If also longitudinal measurements from FLLS are available, it uses them also. If FLLS lateral measurements are available, they are used instead of the CLS.

A pre-processing block verifies (cross checks), synchronizes (propagates/back-propagates) all the buffered SC GNC and actuation data to the cycle correction time, so that the Kalman filter can run. The solution of the Kalman filter is input to an outer propagation function. This function makes use of the buffered knowledge of Cold Gas and HPGP actuation from SC actuation manager and also of predicted estimation of HPGP actuation from FF Guidance. The output of the relative position and velocity determination is the output of this subfunction plus ancillary data.
This outer propagation shall provide estimates of the relative position and velocity to the timetags at which they are to be used: time of measurements, time of reception of FFLSW commands, and time of computation of actuations.
A reset flag will reset the filter covariances and states with the FLLS (if available) or RGPS (if available) or SC GNC data. This is how the filter is initialized and/or reset.

- If RGPS is available, its solution replaces the current state. This is because RGPS is already a filtered data assumed better than the Kalman filter data at perigee (because relative metrology is not expected to have been available for more than 5 hours)
- Every process issues a validity flags based on their conditions. The pre-processing block does cross-checking of input data. The validity flags of the subsequent blocks depend on a combination of the flags of their inputs.
- Relative attitude is computed by manipulating the synchronized (in the pre processing function) absolute attitudes.
- The architecture, apart from adjustments regarding timing of available measurements, is shared between OSC and CSC FF NAV

4. Formation Flying Navigation System Design

The relative position and velocity estimation the relative navigation is implemented as a Kalman Filter, preceded by a synchronization of the OSC absolute navigation data with the CSC absolute navigation data and the sensor measurements arriving through the ISL. The Kalman filter propagates and corrects its states (position and velocity in the unactuated-spacecraft-centred Local Vertical Local Horizontal (LVLH) relative reference frame[2] at the measurement time-tag, and is followed by propagation to the OSC OBT.
This Kalman filter is at the core of the system. The dynamic modelling of relative motion in elliptical orbit is based on the Yamanaka-Ankersen[2] formulation. Relative state is processed in the LVLH frame. During most of the operation, it is centred in the CSC because, except during impulsive actuation, the CSC is the unactuated spacecraft. From a relative motion perspective the orbital elements of the unactuated spacecraft define the dynamics of the system.

Fig. 4.1 shows a high level overview of the functions of the OSC FF NAV, where the main functions are identified:

- The relative attitude computation function uses the (pre-processed) absolute attitude to provide the quaternion of relative attitude at OSC OBT.
- The flag computation function issues validity and mode flags.

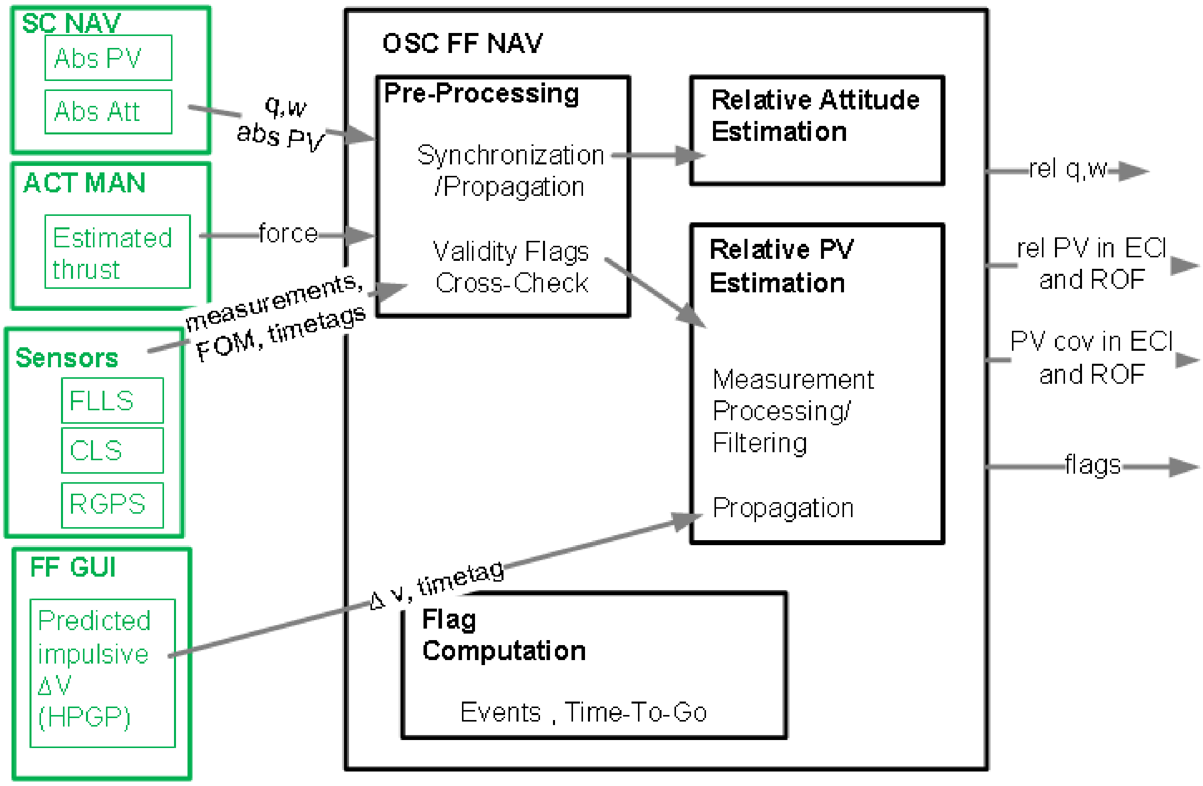

Figure 4.1 OSC FF NAV Architecture overview

- The pre-processing function receives data from the host spacecraft (OSC), and the companion (CSC). The data, including actuation, absolute attitude and position and velocity determination from SC-GNC, is used to allow reference frame conversions and aiding dynamic propagation. Because of desynchronization between SC clocks, ISL lag, sensor lag, this data does not refer to the same time instant. The pre-processing block is responsible to synchronize current and buffered data to compute absolute position, velocity, attitude, and thrust at the time of interest - the time of the measurement timetags.
- The core of the position and velocity computation function is a Kalman filter, where states are relative position and velocity in LVLH. The propagation-correction loop runs to the timetag of the measurements (CLS or FLLS). The propagation is performed in a local reference frame centred on the CSC using Yamanaka-Ankersen formulation and the expected thrust from actuation management (after pre-processing). Solar Radiation Pressure is also taken into account. Input matrices for CLS and/or FLLS measurement processing are built using the pre-processed absolute navigation data, synchronized to the measurement timetag. The available measurements are weighted through the Kalman gain (computed using these input matrices) to improve the solution. CLS, located in the CSC, provides azimuth, elevation to a corner cube (in the OSC) in its reference frame. FLLS, with a narrower field of view than the CLS, and also located in the CSC, provides longitudinal (LOS direction) and (in a narrower field of view than for longitudinal) lateral (perpendicular to LOS) measurements to a corner cube located in the OSC, in its reference frame.

Finally an RGPS solution, if available, will reset the Kalman filter with its estimated relative position, velocity and covariance.
The Kalman filter propagates and correct the state up to the measurement timetag and is thus followed by propagation to the OSC OBT. The propagation makes use of buffered Cold Gas thrust information available at OSC FF NAV through actuation management, as well as high thrust information from CSC actuation management, available at OSC FF NAV through ISL.

Fig. 4.2 below illustrates the issue of synchronization between data from OSC and CSC. The red connections refer to data sent through the ISL from CSC to OSC, blue are time-instants of the CSC cycle, and green refers to data available at current time from OSC GNC, actuation management and FF Guidance:

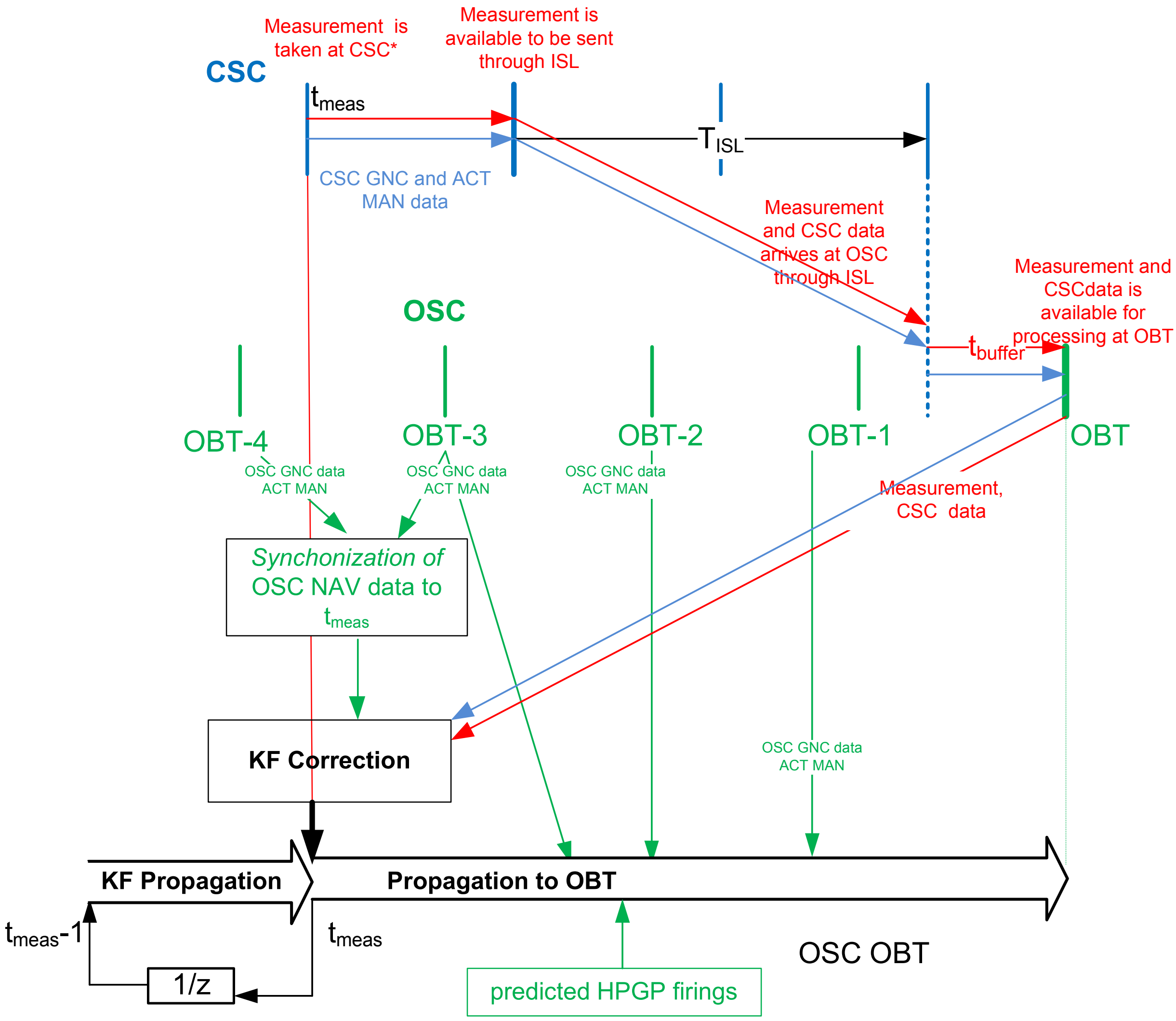

Figure 4.2 OSC FF NAV design (Focus on Synchronization)

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The handling of the synchronization illustrated in the figure is as follows:

- A relative-position measurement from CLS and/or FLLS is taken at CSC at time t_{meas}.
- The measurement is quasi-synchronous with a CSC cycle t^*_{meas}. This lag (datation) error is smaller than a given threshold (otherwise the pre-

processing block will consider it invalid). It is propagated through simple linear extrapolation.

- The measurement, together with CSC estimates of absolute position, velocity, attitude, thrust, is forwarded to the OSC through ISL in the next CSC cycle. It arrives at OSC approximately 3 seconds later (1 cycle time plus ISL time of 2 seconds).
- Because the clocks in CSC and OSC are not synchronized, the measurement will only be made available in the next OSC cycle. The measurements and information from CSC will thus only be available for FF NAV 3 to 4 seconds after they are taken
- A Kalman filter with the typical Propagation-Correction is running, it will propagate from its last buffered estimate to the measurement time, where it will perform a correction based on the available measurements.
- To perform a correction, the input matrices for measurements need to be computed. To do this, OSC and CSC absolute navigation data are necessary at measurement time instant.
- CSC SC-GNC and actuation data that refers to the measurement time instant, is available in a buffer. It is the data from one cycle before the sending of the data package that contains the measurement through the ISL. .
- OSC SC-GNC data does not refer to this time instant. Because of desyncronization, buffered OSC data from the instants before and after t^*_{meas}. need to be propagated to form a pseudo - OSC SC-GNC set at t^*_{meas}.
- With the synchronized SC-GNC data, the Kalman filter can improve its solution using any available measurements. It uses the estimated acceleration from previous to current Kalman filter step in the propagation and it will use attitude and orbital data at t^*_{meas}. for correction.
- A filtered solution for the state (relative position and velocity in LVLH) at time t^*_{meas}. is thus available as a result of the Kalman filter step.

- A solution for estimated state is necessary at OSC OBT. An outer propagation is thus performed from t^*_{meas} to OSC OBT. Notice that a history of attitude and OSC thrust is available from t^*_{meas} to OSC OBT so acceleration can be taken into account (from Actuation Manager)
- Predicted monopropellant impulsive actuations from t^*_{meas} to OSC OBT, available from translational guidance, are also taken into account.

The main functions in the FF N design are the *pre-processing* and the *Kalman filtering.*

4.1 Pre-Processing

The input-data-pre-processing function is decomposed in the following tasks:

- Time-correlation computation - Compute the time-correlation from data tagged in the CSC and coming through ISL. Compute slope, reject jitters and update all the timetags from CSC. These are outputs of the FF NAV function.
- Build the cycle correction time t^*_{meas} , a timetag that shall be synchronous with a 1-cycle-buffered CSC GNC attitude determination timetag, if it is available and valid. If it is not, then it will be equal to the previous t^*_{meas} plus one second.

- Cross-checking and validation of input data – more specifically, verify if time tags of input data correspond to the assumptions. Reject inputs that don't fit in the assumptions and reset their validity flags.
- Synchronize the attitude and orbital element (absolute navigation)data from OSC GNC CSC GNC, as well as sensor data to the same instant, t^*_{meas}. This includes propagation of the orbital elements to the time instants necessary for propagation.

4.2 Position and Velocity Estimation Filtering

The relative position and velocity estimation filter receives as inputs:

- Buffered pre-processed measurements, associated figure of merit, timetags and validity flags
- Pre-processed absolute navigation estimates:
- Absolute Attitude and attitude rate and associated covariance in the form of a quaternion, vector, and covariance matrices respectively.
- Absolute Position and Velocity estimates and associated covariances.

Its main outputs are relative position and velocity estimates.

Its design is based on an Extended Kalman filter, whose states are relative position and velocity in LVLH (CSC to OSC centres of mass vector) running its loop to process observables (from relative measurement sensors) at their timetag, followed by propagation to the current OSC OBT.

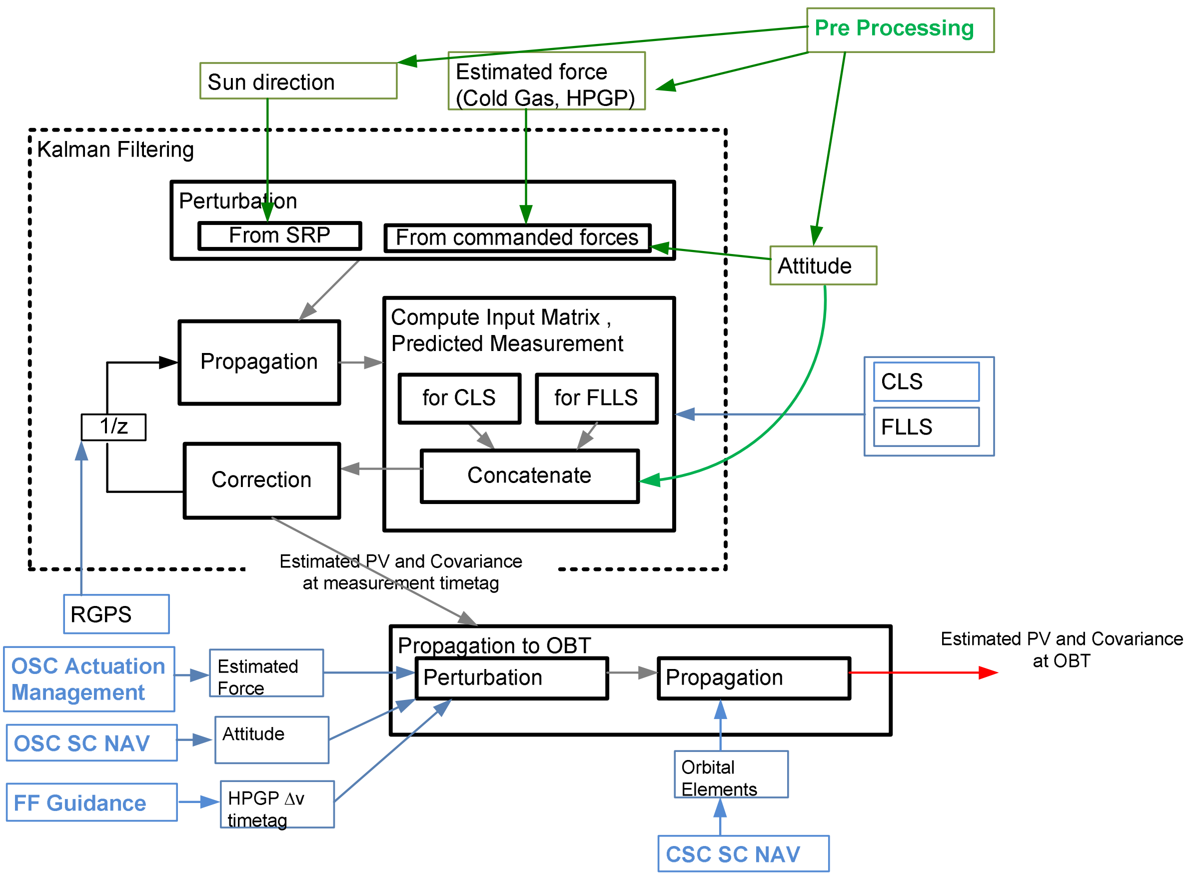

Figure 4.3 Position and velocity estimation filter architecture

Fig. 4.3 illustrates the data exchanges, sub-functions and auxiliary functions in the position and velocity estimation filter:

- The estimated actuation from t^*_{meas-1} to t^*_{meas} for both spacecraft is obtained from pre-processing actuation management data. Solar radiation pressure is obtained using sun direction from pre-processing SC GNC data, and pre-set parameters. These are used to compute the perturbation to free relative motion in elliptical orbits, motion induced by these forces, together with the additional process noise introduced by them. To do so the forces are first converted from spacecraft's body-fixed frame to inertial reference frame using the pre-processed estimate of attitude from t^*_{meas-1} to t_{*meas}. and then converted to LVLH using the Yamanaka-Ankersen state transition matrix built around passive spacecraft's orbital elements synchronized to t_{*meas}
- Propagation (a-priori estimation) is performed from last buffered state (at $t_{*meas-1}$) for relative position, velocity and associated covariances to the measurement cycle correction timetag (t^*_{meas}) using Kalman Filter formulation and Yamanaka-Ankersen equations to account for central gravity. and forced motion. Forced motion terms are used to account for thrusting and solar radiation pressure. Given the short propagation times, the contribution of the forces to the motion in LVLH is accounted for through a first order approximation. The contribution of uncertainties in solar radiation force, thrust and other perturbations are accounted for as process noise.
- In case a relative measurement is available from relative position sensor, CLS or FLLS measurement, the predicted measurement and input matrices needed for the Kalman gain computation are computed, using pre-processed attitude and CSC NAV absolute orbital information. If both CLS and longitudinal-only FLLS are available, the input matrices and measurement residuals are concatenated to form a unique input matrix and set of measurements, to be processed in a batch. If FLLS longitudinal and lateral measurements are available, then CLS measurements are not used and the input matrix is computed for the FLLS measurements. The measurement noise covariance matrices associated with the measurements are built based on FOM information from the sensors.
- A correction to the a-priori estimation is performed based on Kalman gain computed from the input matrix and the computed residuals. The a-posteriori covariance matrices and relative state is computed and made available.
- The Kalman filter outputs the state and covariance to be propagated from t_{meas} to OSC OBT. To propagate to OSC OBT, the 2 last instances of estimated force in the OSC Cold Gas Thrusters from the actuation management pre-processed are used. Also used is the predicted Δv and timetag of HPGP manoeuvres from FF Guidance.
- The CSC NAV absolute navigation orbital elements are propagated from time t_{meas} to OSC OBT assuming Keplerian motion, to obtain the ECI to LVLH conversion matrix. This is converted to a quaternion that is one of the outputs of the FF NAV. The matrix is also used to convert the output of the propagation block to the final outputs of the FF NAV Position and Velocity function: relative position and velocity vectors and covariances in LVLH and ECI frames.

5. Tests and Performance

The Formation Flying Navigation system described in the previous section was developed and prototyped in the Proba3 Functional Engineering Simulator based on GNCDE.
Tuning and preliminary performance assessment was performed taking in account nominal performances of sensors, actuation and SC GNC NAV performances.

Fig. 5.1 and 5.2 present an overview of the test results for a nominal orbital routine, from sensor acquisition 3 hours before apogee to perigee (where relative GPS estimates are acquired). In the velocity plot it is visible the process of acquisition of fine metrology, including first the CLS and then FLLS for range / CLS for lateral measurements. At ~11 000 seconds the retargeting manoeuvre is executed for perigee pass and fine metrology is lost and consequently estimation performance degrades. At t=33000 the RGPS measurements are used to reset the navigation solution.

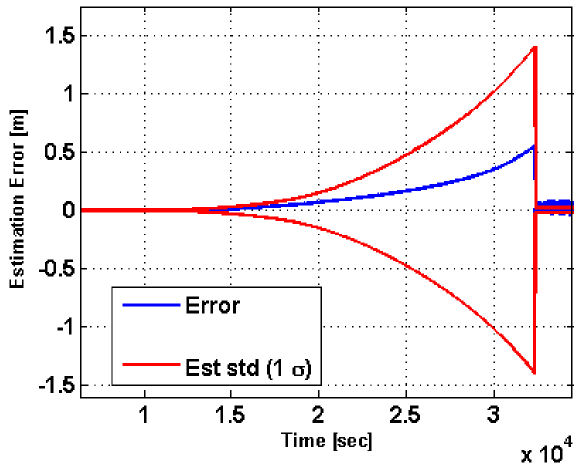

Figure 5.1 Relative position estimation error and covariance from formation acquisition to next perigee

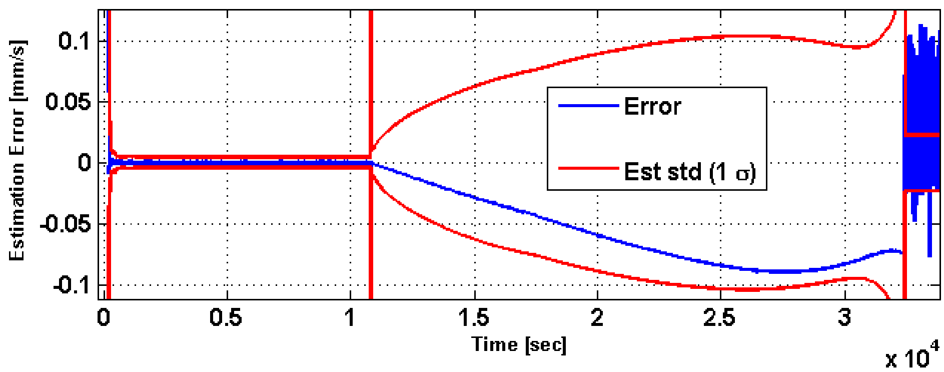

Figure 5.2 Relative velocity estimation error and covariance from formation acquisition to next perigee

Fig. 5.3 and 5.4, show, respectively, the convergence of the estimate error and covariance estimate upon acquisition CLS after a reset in navigation (resets use SC GNC absolute navigation delta to determine relative position and velocity).
The CLS measurements become available, immediately improving the solution in the lateral (normal to formation LOS) direction. After 6 seconds the FLLS is acquired.

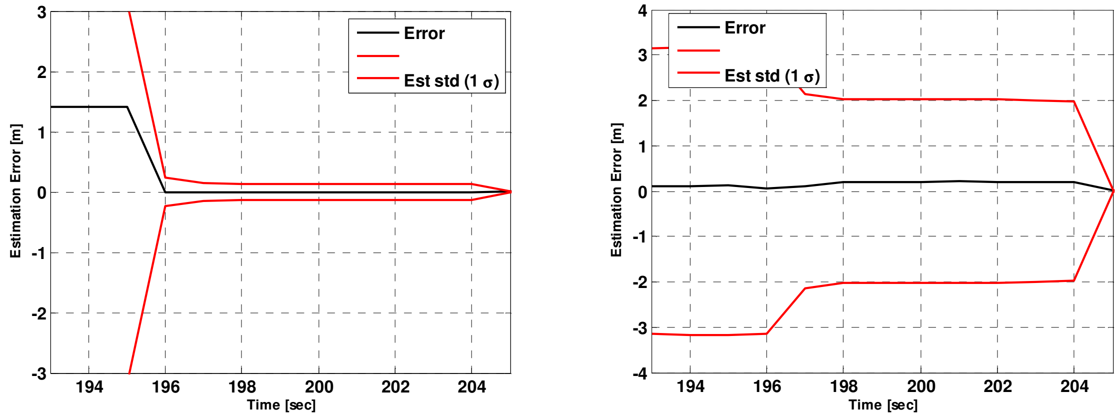

Figure 5.3 Estimation error – position (left lateral, right longitudinal)

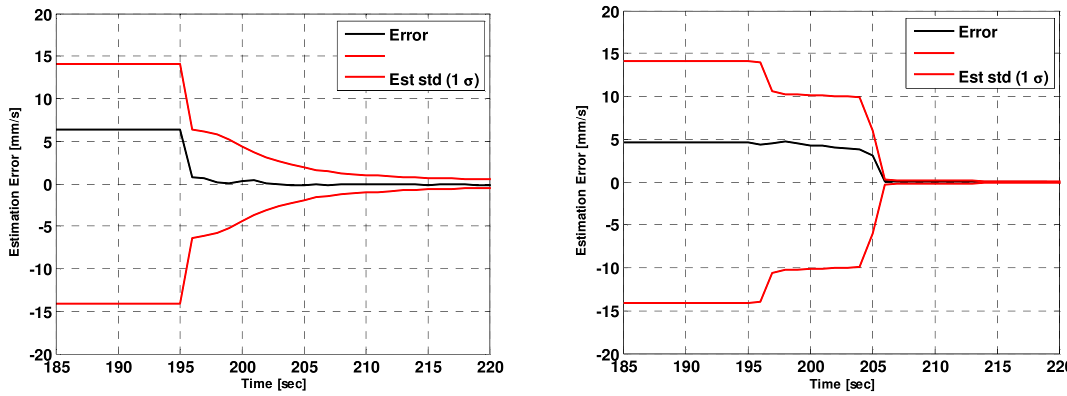

Figure 5.4 Estimation error – velocity (left lateral, right longitudinal)

Fig. 5.5 show the convergence of the position estimate error and covariance upon FLLS acquisition. It is visible that, due to attitude error, the estimate for relative position is much better in the LOS direction.

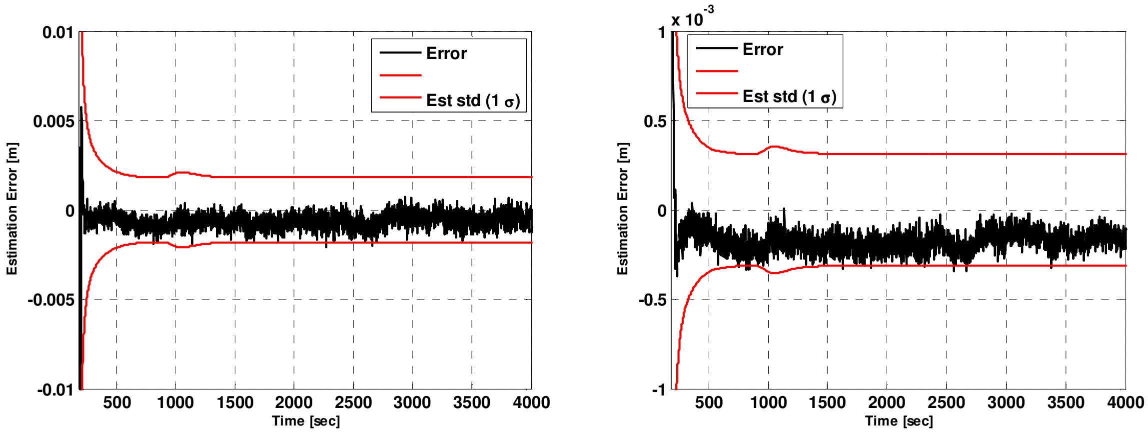

Figure 5.5 Estimation error – position (left lateral, right longitudinal)

Summary of test results

Tab. 5.1 presents the summary from the preliminary tuning for a nominal orbital routine. The sequence of operation allowed testing the Navigation performances in several situations in order to adjust the tuning of assumed Process and

Measurement noises. Whereas the routine doesn't reflect exactly the baseline in terms of acquisition and loss of sensors, it allowed to verify the behaviour of the FF NAV filter in all of its working conditions.

Table 5.1 FF NAV performances

#	Longitudinal Position [mm]	Lateral Position [mm]	Longitudinal Velocity [mm/s]	Lateral velocity [mm/s]
CLS acquisition	200	25	5	0.5
FLLS acquisition	0.3	2.5	0.0015	0.0020
Perigee pass (propagation) before RGPS	1250	510	0.12	0.075
RGPS	100 *		0.1	

* With assumed RGPS performances

6. Conclusions

The developed solution to the complex problem of handling the multiple sources of information and integrating them to provide the relative motion estimate at any time is handled by careful dedicated pre-processing of the data through Keplerian propagation (orbital data), attitude dynamics (attitude estimates), and extrapolations of buffered data in case of actuation. Previous estimates are propagated through equations of relative motion in elliptical orbits to the time tags to which the metrology refers, so the measurements can be coherently processed. The same methods are then used to provide a solution at the times of interest for the Guidance and Control functions that make use of this FF NAV output.

The preliminary design and prototyping was part of Phase B2 of the project, which concluded with a successful Preliminary Design Review in late 2012.

The software has been prototyped and tested in a Functional Engineering Simulator which included models of the aforementioned datation errors and latencies. Tests have demonstrated the relative navigation accuracy meets the requirements.

The software has been autocoded, integrated and exercised in a real time simulator called Software Based Test Bench incorporating a target processor emulator.

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