Acta Astronautica 91 (2013) 341–355

Contents lists available at SciVerse ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

GPS-based relative navigation for the Proba-3 formation flying mission ☆

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ARTICLE INFO

Article history:
Received 22 February 2013
Received in revised form
29 April 2013
Accepted 19 June 2013
Available online 26 June 2013

Keywords:
Formation flying
Highly elliptical orbit
GPS navigation

ABSTRACT

The primary objective of the Proba-3 mission is to build a solar coronagraph composed of two satellites flying in close formation on a high elliptical orbit and tightly controlled at apogee. Both spacecraft will embark a low-cost GPS receiver, originally designed for low-Earth orbits, to support the mission operations and planning during the perigee passage, when the GPS constellation is visible. The paper demonstrates the possibility of extending the utilization range of the GPS-based navigation system to serve as sensor for formation acquisition and coarse formation keeping. The results presented in the paper aim at achieving an unprecedented degree of realism using a high-fidelity simulation environment with hardware-in-the-loop capabilities. A modified version of the flight-proven PRISMA navigation system, composed of two single-frequency Phoenix GPS receivers and an advanced real-time onboard navigation filter, has been retained for this analysis. For several-day long simulations, the GPS receivers are replaced by software emulation to accelerate the simulation process. Special attention has been paid to the receiver link budget and to the selection of a proper attitude profile. Overall the paper demonstrates that, despite a limited GPS tracking time, the onboard navigation filter gets enough measurements to perform a relative orbit determination accurate at the centimeter level at perigee. Afterwards, the orbit prediction performance depends mainly on the quality of the onboard modeling of the differential solar radiation pressure acting on the satellites. When not taken into account, this perturbation is responsible for relative navigation errors at apogee up to 50 m. The errors can be reduced to only 10 m if the navigation filter is able to model this disturbance with 70% fidelity.

1. Introduction

Proba-3 is the third mission in ESA's Project for Onboard Autonomy. The Proba spacecraft provide a platform for the joint validation of new space technology and conduction of scientific experiments. Proba-3 will demonstrate precision formation flying using optical metrology and pave the way for future astronomical formation flying missions based on virtual telescopes or distributed apertures. Proba-3 itself will enable observation of the solar corona with one spacecraft acting as occulter and one spacecraft carrying the instrumentation. The relative position and attitude of the two spacecraft will be tightly controlled to form a virtual telescope with a length of 150 m.

The two spacecraft will be launched into a highly elliptical orbit with a period of about 20 h and a 59° inclination. Along this orbit, the altitude varies from 800 km to more than 60,000 km. The high apogee altitude enables long arcs of fine formation keeping and coronagraph operations due to the very low level of orbital perturbations. In total, science operations will be performed

☆ 'This paper was presented during the 63rd IAC in Naples'.

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http://dx.doi.org/10.1016/j.actaastro.2013.06.025

throughout a six-hour-arc centered on apogee during which the formation is controlled by high-accuracy metrology and micro-thrusters. After the apogee the formation is broken up and later reassembled in a sequence of mid-course and fine correction maneuvers [1]. Both the Occulter spacecraft (OSC) and Coronagraph spacecraft (CSC) will be equipped with a cold-redundant pair of GPS receivers. Due to limitations in GPS visibility at high altitudes, the receivers will primarily be operated in the vicinity of the perigee passages. Despite a limited orbital coverage, the GPS measurements will enable the determination and prediction of the spacecraft orbit with adequate accuracy for mission planning and operations (e.g., antenna pointing, scheduling, etc.). More importantly, relative navigation information from the GPS tracking on both spacecraft will be used to assist the planning of the mid-course maneuvers and the reacquisition of the formation after the perigee passage.

In view of tight financial and engineering budgets, the use of commercial-off-the-shelf (COTS) GPS technology is considered as a baseline for the Proba-3 mission. Other than receivers specially designed for use in highly elliptical orbit or geostationary orbit (see [2]), such receivers will primarily be able to track GPS signals and provide a navigation fix in the vicinity of the pericenter arc. Navigation information at other points of the orbit will instead need to be generated through orbit prediction after adequate filtering of the GPS-measurements collected during the perigee passage.

For the Proba-3 mission, an investigation has been carried out into the possibility of using GPS based relative navigation to aid in formation re-acquisition after perigee transits, or possibly even of employing GPS as the primary navigation sensor for formation re-acquisition. In this case, the navigation and control performance of the GPS-based formation acquisition system shall allow the transition to optical metrology at apogee, i.e. the achieved relative position at apogee shall be compliant with the maximal utilization range of the optical metrology system (250 m) [3].

For the needs of this study, a highly realistic assessment of the GPS-based relative navigation performance has been performed. To that end, special care has been paid to the adoption of realistic assumptions regarding the spacecraft characteristics, formation configuration and attitude profile. In addition, some efforts have been put to select two simulation epochs representing the best and worst conditions in terms of GPS visibility. The resulting simulation scenario is presented in the second section. The simulations have been conducted using a version of the PRISMA GPS-navigation system tailored for high-elliptic orbits and running in a highly realistic simulation environment with hardware-in-the-loop capabilities. This simulation environment is described together with the GPS navigation system in the third section. The simulation results are finally presented and discussed in the last section.

2. Scenario definition

2.1. Formation and spacecraft parameters

Following the preliminary results of the Proba-3 mission design activities [3], a 60,254 × 800 km orbit with 59° inclination and argument of perigee of 188° has been retained for this analysis.

The orbit of the CSC is defined with respect to the orbit of the OSC by the introduction of the relative state (CSC-OSC) in the Hill co-moving frame.

The Hill frame, also named Rotating Orbit Frame (ROF) in the sequel, is defined as depicted in Fig. 1 as follows: the *z*-axis is pointing toward the Earth (nadir), the *y*-axis is aligned with the normal to the orbit plane, pointing towards negative orbit angular momentum, and the *x*-axis completes the triad.

The formation is designed to exhibit initially an inter-satellite distance of 500 m at apogee and 4000 m at perigee in the *x*-direction only. The corresponding relative velocities are solved when initializing the simulation using a solver based on the Yamanaka–Ankersen (YA) equations of motion [4]. This leads to the definition of the initial relative state at apogee in the Hill frame (Table 1). These initial conditions are intended to simulate the error affecting the formation after the separation of the two spacecraft from the launcher at the beginning of the mission.

At the beginning of the simulation, the inertial state vector of the CSC is defined by adding the relative state of the formation to the inertial state vector of the OSC. Both state vectors of the OSC and CSC are then propagated numerically and independently.

The spacecraft characteristics adopted in the simulation are summarized in Table 2. The solar radiation pressure coefficient of the CSC has been set to 3.27 in order to introduce a nominal differential acceleration of 6.6×10^{-8} m/s² given by relative solar radiation pressure, which is compliant with the order of magnitude of 10^{-8} m/s² commonly adopted in the Proba-3 mission analyses [5].

As a baseline, the GPS system embarked by both spacecraft is assumed to be composed of a single frequency Phoenix GPS receiver and two antennas located at opposite sides of the spacecraft. As depicted in Fig. 2, the

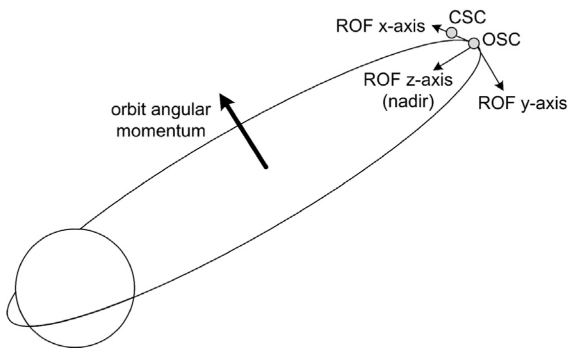

Fig. 1. Graphical representation of the Hill frame (at apogee).

Table 1
Relative state in the Hill frame at apogee.

Initial relative state	Value
Relative position [m]	[500 0 0]
Relative velocity [m/s]	[0 0 0.028621]