GPS-BASED AUTONOMOUS NAVIGATION FOR THE BIRD SATELLITE

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***ABSTRACT** - The German micro-satellite BIRD will be equipped with an autonomous navigation system that provides real-time onboard orbit determination capabilities based on GPS position fixes. The navigation system design is presented together with a description of the algorithms required to achieve a position and velocity accuracy better than the performance of the GPS position fixes. The BIRD navigation system enhances the spacecraft autonomy as it provides onboard position predictions and enables for the first time a geocoding of satellite images on-the-flight. Accordingly, the post-processing and ground operations workload is reduced, that renders the system especially attractive for future highly autonomous satellite missions.*

1 INTRODUCTION

Satellite autonomy implies, in general, the shift of functions from the satellite control centers to onboard computers. In the field of space flight dynamics, spaceborne GPS sensors offer precise instantaneous position fixes onboard the satellite and are thus ideal sensors for autonomous navigation systems. Such systems may support the attitude control system, improve the management of onboard resources, allow a geocoding of payload data, or even autonomously control the spacecraft's orbit within certain limits.

Among the increasing number of missions with an autonomous navigation system like SPOT and PROBA, the German satellite BIRD applies a GPS-based Onboard Navigation System (ONS). Following a description of the BIRD mission, this paper presents the requirements of the ONS, the applied force and measurement models, as well as the software design of the system. Particular emphasis is given to a realistic simulation scenario, that allows the ONS system verification. In this framework, the results from a hardware-in-the-loop simulation are presented and the consequences from the stop of the SA degradation of the GPS signals are addressed.

2 THE BIRD MISSION

BIRD is a small satellite mission funded by German Aerospace Center (DLR). A support of the BIRD development comes from the cooperation partners of the German National Research Center for Information Technology and the DaimlerChrysler Aerospace corporation.

2.1 Mission Objectives

The satellite mission BIRD (Bi-spectral Infrared Detection) is dedicated to hot spot detection and investigation from space by means of a new generation of infrared array sensors. A bi-spectral cooled infrared sensor system (MIR/TIR) is applied to detect hot spot events, such as forest and vegetation fires, volcanic activity or burning oil wells and coal seams. In addition, the Wide-Angle Optoelectronic Stereo Sensor (WAOSS) is applied for vegetation analysis and fire classification. Based on a neural network classification in orbit, a thematic onboard data processing is performed.

2.2 Spacecraft Bus

The 3-axis stabilized spacecraft bus (Fig. 1) is a new development of DLR. It is based on a cubic shape structure of 50 cm length in each axis with two deployable solar arrays. The total spacecraft mass, including payload and launch adapter, is less than 100 kg. The payload instruments are oriented in the +*z*-direction, as well as the S-band antenna for communications with the ground stations.

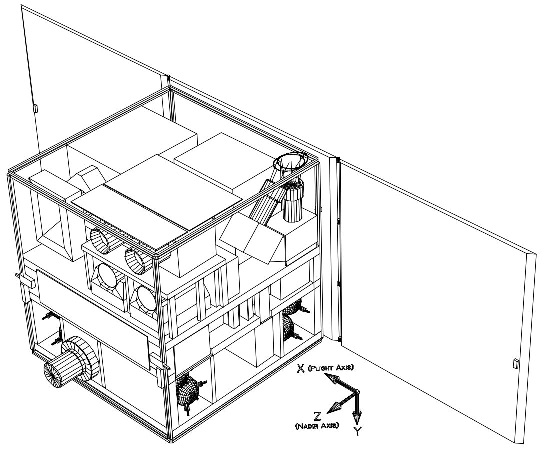

Fig. 1 BIRD spacecraft in flight configuration

2.3 BIRD Orbit and Mission Timeline

A key requirement of the mission is to implement the payload on a micro satellite suitable for a piggyback launch. The BIRD mission is now in the Phase C/D and is expected to be launched by the Indian PSLV-C3 in the beginning of the year 2001.

The BIRD satellite will be injected into a sun-synchronous circular low-Earth orbit. The orbital altitude is 572 km with an inclination of 98.7° and a local equatorial crossing time of 10:30. During its one-year mission lifetime the spacecraft operations will be conducted at DLR's German Space Operations Center.

2.4 Attitude Control System

The Attitude Control System (ACS) supports two major modes:

1. the Sun-Pointing Mode
2. the Earth Pointing Mode.

During most of its time in orbit, the spacecraft is oriented in an inertially-fixed orientation with its solar arrays pointing towards the Sun. For the imaging sessions, the spacecraft rotates to the Earth Pointing Mode, where the antennas and the payload point into nadir direction. Each Earth Pointing Mode is maintained for a typical duration of 20 minutes.

The requirement on the attitude determination accuracy is 0.2 arcmin, while the attitude control requirement on the pointing accuracy per axis is 7 arcmin (3σ). To meet these requirements, the ACS comprises the following components:

- low-cost star sensors for micro satellites (new development)
- a 3-axis laser gyroscope (furnished item)
- a set of Sun detectors for safe mode (furnished item)
- a 3-axis magnetometer (furnished item, for the contingency case)
- reaction wheels for micro satellites (new development)
- magnetic coils (new development)

- a GPS receiver (furnished item)
- the Onboard Navigation System ONS (software, new development)
- a Satellite Board Computer (SBC).

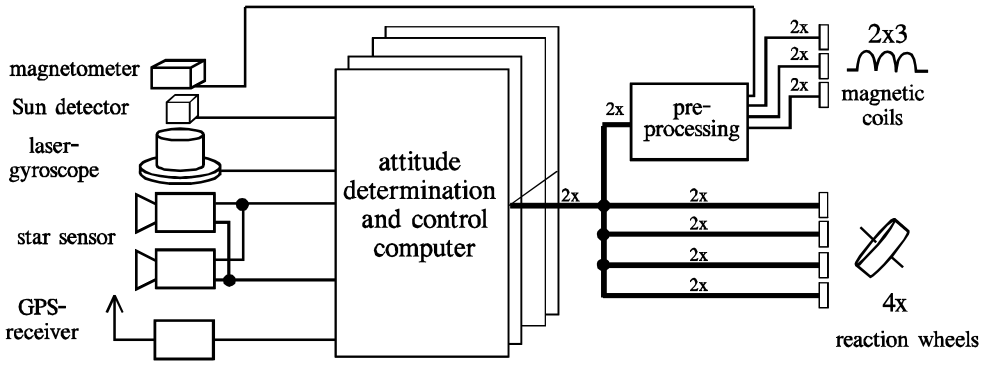

Fig. 2 Block scheme of the ACS system

3 THE ONBOARD NAVIGATION SYSTEM

3.1 Functional Requirements

As the BIRD inertial attitude is based on star camera data, position information is required for the nadir pointing of the payload sensors. To this end, the ONS provides quaternions to the ACS, that describe the orientation of the local-horizontal local-vertical system (LHLV) with respect to the inertial true-of-date system. The accuracy of the quaternions shall be 0.5 arcmin, equivalent to an inertial position error of about 1 km. As the GPS receiver is switched off during the payload data takes for power budget reasons, the ONS has to provide quaternions for a prediction interval of up to 30 minutes.

A second requirement stems from the payload data handling (PDH) system, that calls for a geocoding of the image data with an accuracy of half a pixel, or 90 m at 570 km altitude. As is the case for the ACS, the PDH accuracy requirement shall be met for GPS-free arcs of a maximum length of 30 minutes. Finally, a robust backup concept shall be implemented, that guarantees an ACS and PDH support, in case of a failure of the GPS receiver or the orbit determination task.

Tab. 1 Requirements for the Onboard Navigation System

Origin	Data Type	Accuracy	Frame	Provision	Timing Characteristics
ACS	LHLV Quaternion	0.5 arc mins	True-of-date	real-time	30 min prediction time
PDH	Position	90 m	WGS84	real-time	30 min prediction time

3.2 The GPS Receiver

The ONS applies a GPS Embedded Module III (GEM-S) by Rockwell Collins (1997). GEM-S is a five channel SPS C/A- and P-code receiver, that operates at the L1 frequency. With physical dimensions similar to a CD-ROM drive, and a mass of 0.4 kg, it consumes approximately 6.5 W during nominal operations. For BIRD, the RS422 bi-directional, asynchronous, and serial data interface will be applied with a data rate of 9600 baud.

The GEM-S provides position fixes for the onboard orbit determination, as well as a One-Pulse-Per-Second (1PPS) signal, that serves for the synchronization of the BIRD onboard time.

3.3 Force Model and Reference Systems

The ONS force model has been selected as to satisfy the 90 m position accuracy within prediction intervals of up to 30 minutes past the last GPS position fix. For an altitude of 570 km, these requirements can be met considering an Earth gravity field, that is complete to order and degree of 10, while drag, solar radiation pressure, as well as the third body forces from the Sun and the Moon need not to be modeled (Gill et al. 2000).

The GPS measurements are obtained in the Earth-fixed WGS84 system, while the orbit determination results are provided to the ACS in the true-of-date (TOD) system. The required transformation from the WGS84 to the TOD system considers, for sake of simplicity, robustness, and computational efficiency, only the sidereal rotation matrix, assuming UT1=UTC (Montenbruck et al. 2000). On the other hand, the ACS attitude is based on the star camera that provides quaternions in the International Celestial Reference Frame (ICRF). The transformation from the ICRF to the TOD system of the ACS accounts for precession only, while neglecting nutation.

3.4 Numerical Integration and Transition Matrix Computation

The ONS applies a numerical integration of the equations of satellite motion making use of an advanced numerical integration scheme, that extends the common Runge-Kutta 4^{th} order algorithm by a Richardson extrapolation and a Newton interpolation. The algorithm comprises two elementary RK4 step sizes of length h, and can be shown to be effectively of 5^{th} order with 5.5 function calls per h. The Newton interpolation of the spacecraft position allows for an efficient provision of dense position output, that is required for high-frequency geocoding of the payload images. Step sizes depend on the measurement times and may vary between 30 and 65 s. The state transition matrix is computed based on a Keplerian approximation, according to the algorithm of Goodyear (1965) and Shepperd (1985).

3.5 Measurement Model and Estimation Concept

The orbit determination software processes GPS position fixes as statistically independent pseudo-measurements. The estimation concept is based on an extended Kalman filter to cope with the non-linearity of the orbit determination problem. It comprises the time update phase with the propagation of the previous estimate, the computation of the state transition matrix and the state covariance matrix. To account for an imperfect modeling of the satellite dynamics, the covariance matrix is increased in each step by a constant and diagonal state noise matrix. The measurement update assumes uncorrelated position coordinates (x, y, z). The position coordinates are treated strictly sequentially, where the Kalman gain matrix collapses to a six-dimensional vector.

3.6 Processor Hardware and Operating System

The BIRD onboard processor is built by the Institute for Computer Architecture and Software Technology of the German National Research Center for Information Technology (GMD/First). It features a Motorola Power PC 823 processor, operated at a 48 MHz clock rate (without floating point support), 8 MB of RAM memory, as well as various ports for external communication. The real-time operating system (OS), developed by GMD/First, is a multitasking operating system, well suited for real-time and onboard applications. Processes are executed as separate threads, which are controlled by a central scheduler, based on pre-assigned priorities and timers. In this way, short and high-priority activities (e.g. commanding, attitude control) can well be separated from slow, computation intensive tasks like onboard orbit determination. The OS, as well as the application software, is written in C++.

3.7 ONS Software Architecture

A schematic view of the ONS architecture is given in Fig. 3. A dedicated command dispatcher distributes ONS-related commands both to the GEM-S receiver and the individual software threads.

After a lock on four GPS satellites, the GEM-S delivers position fixes to the orbit determination (OD) thread, that is executed every 30 s. Here, a measurement update is performed using the latest GPS measurement available. A numerical integration of the state vector is then performed and the trajectory polynomials, valid for a 35-65 s interpolation interval following the measurement time tag, are provided to the orbit prediction thread (OP). The OP thread is executed every 0.5 s, and efficiently evaluates the current position based on the OD trajectory polynomials. The split-up of the ONS into the OD and OP threads allows to de-couple the computationally intensive OD thread from the OP thread, that is executed every 500 ms, but requires a much less computational load.

For backup purposes, the spacecraft position is computed from a set of NORAD two-line elements (TLE), that are uploaded once per week, in case that the OD position variance exceeds a configurable threshold. The NORAD two-line elements thus guarantee the availability of orbit positions even for complete failures of the GPS receiver or the orbit determination process.

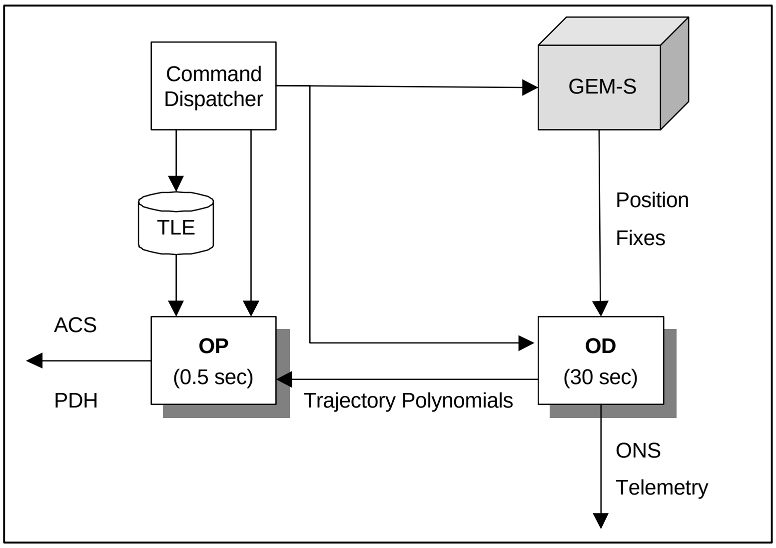

Fig. 3 Schematic view of the ONS architecture. Software threads are indicated by shaded boxes.

4 ONS SYSTEM VALIDATION

4.1 Hardware-in-the-Loop Simulation

A rigorous validation of the ONS system has been carried out using real GPS data from the GEM-S receiver hardware and executing the software on the BIRD processor PPC823, as indicated in Fig. 4. In this framework, a realistic BIRD orbit scenario has been setup and implemented on a GPS signal simulator (GSS) of Global Simulation Systems (model STR2760). The GSS generated C/A-code on the L1 frequency for 10 channels, covering a total simulation time of four hours. Care has been taken to appropriately model the inertial spacecraft attitude during the simulation and to account for the effects of Selective Availability (SA) of the GPS system.

Based on the collected GEM-S position data, the ONS software was then loaded from a host PC to the BIRD computer board and executed on the PPC823 processor, to achieve a proper validation of the overall ONS system. Due to the restrictions of the dynamical model of the GSS, a reference trajectory was furthermore generated using a precise orbit determination software with the same GPS data set.

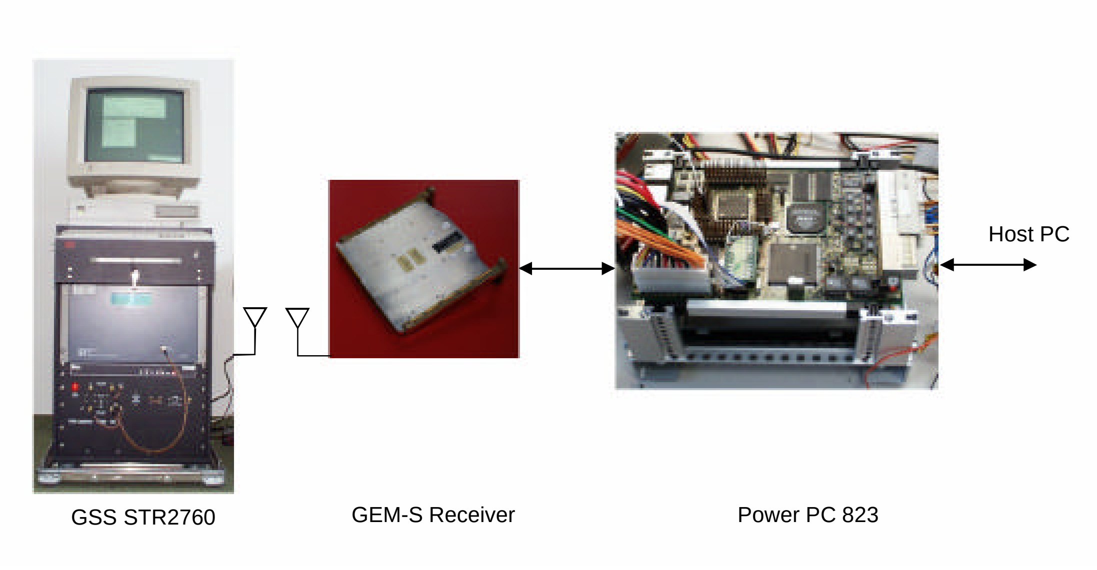

Fig. 4 Hardware-in-the-Loop simulation scenario for verification of the ONS software.

4.2 Results and Discussion

As result of the ONS task, the BIRD ephemeris, the associated position variance, as well as the position residuals were recorded during the entire data arc. The position differences of the ONS and the reference solution are displayed in Fig. 5, along with the position variance and the GPS position residuals.

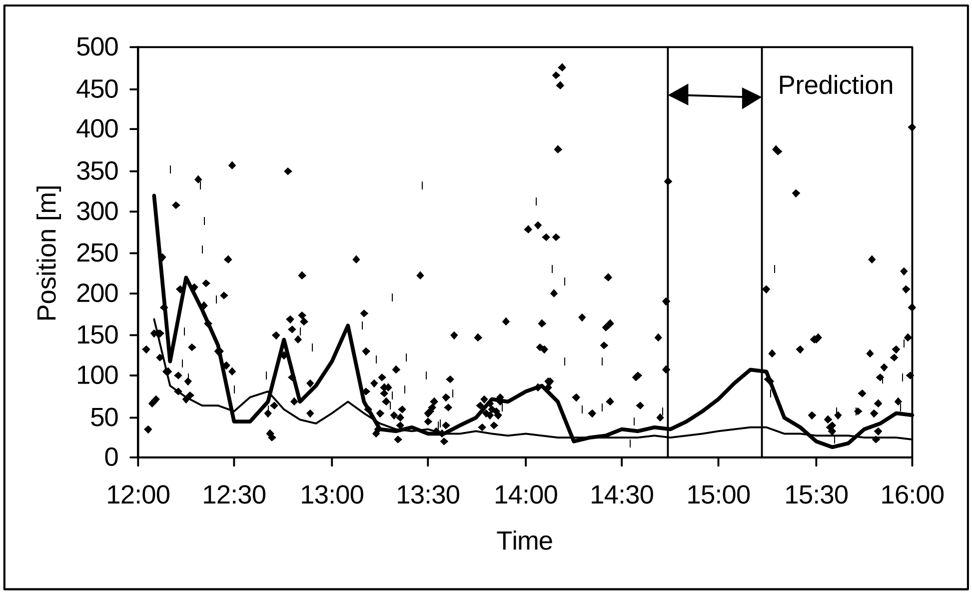

Fig. 5 ONS performance from hardware-in-the-loop simulations with a four hour GEM-S data set. The bold line indicates the difference of the ONS filter results and a precise reference trajectory. The thin line indicates the position variance of the filter, while the measurement residuals are marked as diamonds.

The filter convergence is achieved after about two hours, when the standard deviation approaches a level of roughly 30 m. Nevertheless, the filter is still sensitive to GPS position data with degraded accuracy, as can be seen from the increasing position errors at 14:00 UTC.

Following a 2-3 hour GPS operations phase, the receiver is turned off for power budget reasons prior to the payload data take. At that time, the spacecraft is rotated from the Sun-pointing mode to the Earth Pointing Mode, following a data take of about 10 min, and a re-orientation to the Sun-pointing mode. This phase may last for 30 minutes at maximum. It is emphasized again, that ONS position data are in particular required during the data takes, where the GPS receiver cannot be operated. Due to the absence of GPS data during this phase, the ONS predicts the satellite state vector and its variance. In Fig. 5, the position error increase from 40 m to 100 m can be seen in the time frame 14:45-15:15 UTC, which is mainly due to the truncated Earth gravity field employed by the ONS. Within the prediction phase, the statistical variance therefore significantly underestimates the total position error.

5 SUMMARY

The Onboard Navigation System has been developed to provide real-time position information to the Attitude Control System and the Payload Data Handling of the BIRD satellite mission. This enables a nadir pointing of the spacecraft during imaging sequences of the optical and infrared cameras. In addition, a geocoding of the image data is achieved onboard the satellite, that has so-far only be performed during post-processing on-ground. To this end, the ONS applies the GEM-S position fixes, that are treated as measurements using an extended Kalman filter and a complex force model. An advanced numerical integration scheme is implemented to allow a dense output of the trajectory at a minimum computational load.

A GPS signal simulator with an appropriate orbit scenario has been employed to derive realistic GEM-S position data, that were then applied for the verification of the ONS software. The software was executed on a prototype of the BIRD Satellite Computer which features a PPC823 processor. The hardware-in-the-loop simulations allowed a verification of the ONS system and demonstrated, that an accuracy level of 30-40 m is achievable during GPS data arcs. Even in the absence of GPS data, the position may be predicted at a level of 100 m over a time interval of 30 min.

As a result of the U.S. President announcement to stop the GPS system degradation (SA) from May, 1^s 2000 onwards (The White House; 2000), the accuracy of GPS position fixes from low-cost single frequency C/A-code receivers improves from about 100 m by one magnitude to 10 m. This improvement does also affect spaceborne GPS receivers like GEM-S on the BIRD spacecraft. As a result, the accuracy of the position solutions, and hence of the orbit determination result, is expected to improve to a level of 10 m or better. In contrast, the position errors within the orbit prediction arcs, being largely governed by the dynamical force models, are expected to improve only little in the absence of SA. Although the current ONS concept satisfies the accuracy requirements of the BIRD mission, the absence of SA offers the chance to significantly improve the achievable onboard orbit determination, and, with a more elaborate force model, also the orbit prediction accuracy. This, in turn, renders autonomous onboard navigation systems an attractive field of work for many upcoming satellite missions.

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