The BIRD Satellite Mission as a Milestone Toward GPS-based Autonomous Navigation

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ABSTRACT: *This paper describes the onboard navigation system (ONS) for the German BIRD (Bi-spectral InfraRed Detection) microsatellite. BIRD is a technology satellite used for autonomous detection and identification of hot spots such as forest fires or volcanic activities. The ONS computes the instantaneous nadir and flight direction for camera pointing, as well as precise positions for real-time geocoding of image data. Using a GPS Embedded Module (GEM)-S five-channel coarse/acquisition (C/A)-code receiver and an extended Kalman filter, the system performs dynamic orbit determination and provides smooth trajectory data with a nominal accuracy of 5 m during continuous GPS data takes. A 100 m accuracy is achieved in prediction arcs of up to 30 min. In parallel, the ONS performs a real-time estimation of SGP4 mean elements, which allows an onboard forecast of ground station contacts or eclipse times, as well as the downlink of North American Aerospace Defense Command (NORAD)-compatible two-line element sets for autonomous ground station operation.*

THE BIRD MISSION AND SPACECRAFT

The BIRD (Bi-spectral InfraRed Detection) mission is a small satellite project being carried out by the German Aerospace Center (DLR) under the leadership of the Institute of Space Sensor Technology and Planetary Exploration. Its primary scientific objectives comprise testing of a new generation of infrared array sensors, as well as detection and scientific investigation of hot spots (forest fires, volcanic activities, burning oil wells, or coal seams). Furthermore, the mission supports thematic onboard data processing using a neural network classificator and real-time discrimination between smoke and clouds [1].

BIRD will be launched on an Indian polar satellite launch vehicle (PSLV) and injected into a near-circular, sun-synchronous orbit of 560 km altitude. The spacecraft weighs a total of 85 kg (including 26 kg payload) and consists of a cubic structure measuring $50 \times 50 \times 50$ cm^3 (see Figure 1). This structure is divided into a payload platform (optical camera and infrared sensors), an electronics segment, and a service element (batteries, wheels, gyros, etc.). Two self-deployable and one body-fixed solar arrays provide an average power of 60 W throughout a day, which is buffered with batteries to support a peak power consumption of 210 W.

BIRD carries a total of three imaging sensors operating at visible and infrared wavelengths. Among these, the medium-wave infrared sensor (MWIR, 3.4–4.2 μm) and the long-wave infrared sensor (LWIR, 8.5–9.3 μm) provide frame images with a ground resolution of 360 m. The wide-angle optoelectronic stereo scanner (WAOSS), in contrast, is a three-line charge-coupled-device (CCD) stereo camera, which maps the earth at a pixel size of 180 m from a 560 km altitude.

The attitude control system (ACS) comprises two star sensors and a three-axis gyro system for fine pointing, as well as sun sensors and a magnetometer for coarse attitude determination. Control torques can be generated by four reaction wheels and three magnetic torquers. Auxiliary orbit information is provided by the onboard navigation system (ONS), which makes use of a coarse/acquisition (C/A)-code GPS receiver that is connected to a GPS antenna mounted on the −Y-axis of the spacecraft. Aside from safe-mode functions, the ACS supports a sun-pointing and an earth-pointing mode. During most of the day, the spacecraft will be

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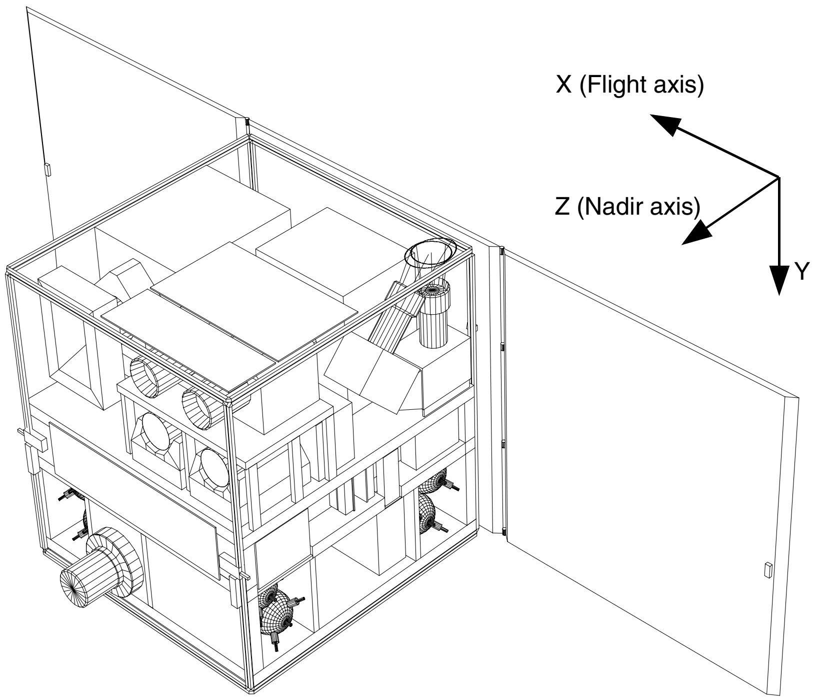

Fig. 1 – The BIRD Spacecraft in Flight Configuration

sun-pointing to charge the battery between camera data takes. For imaging sessions that typically last 10–15 min, the spacecraft is temporarily oriented into a nadir-pointing attitude (with optional biases) and reoriented thereafter. As a consequence of the limited onboard power resources and antenna placement restrictions, the GPS receiver will be operated only before or between image data takes. Therefore, the ONS must be able to bridge GPS outages of up to .5 h and still provide a .5 pixel (~90 m) position accuracy.

THE GEM-S GPS RECEIVER

The ONS makes use of a Rockwell-Collins GPS Embedded Module (GEM)-S [2] receiver to obtain GPS position measurements for real-time orbit determination; key characteristics of the receiver are presented in Table 1. It is a five-channel C/A- and precision (P)-code receiver that is restricted to work on the L1 frequency. The GEM-S receiver has previously been flown on space shuttle missions [3].

The primary power input to GEM-S is provided through ±5 V DC, and approximately 6.4 W is required for nominal operations. In addition, a battery-backed power supply will always be connected to maintain the low-power time source (LPTS) and hold up the critical nonvolatile memory (CNVM) in the random access memory (RAM). When shut down, the receiver is in idle mode, where it holds the space configuration and the ballistic propagation mode valid and maintains the GPS almanac. The power consumption in idle mode is less than 0.5 mW.

Table 1 — Key Characteristics of the Rockwell Collins GEM-S Receiver

Parameter	Value
Channels	5
Supported frequencies	L1
Code tracking	C/A, P
Position accuracy (root mean square)	6–100 m
Controller interfaces	DPRAM, RS422
RS422 baud rate	T 76800, R 19200, or T/R 9600
Dimensions W × L × H	14.5 × 15.0 × 1.5 cm
Mass	0.4 kg
Power supply	±5 V DC
Power consumption	6.5 W
Temperature range	−54 to +85 °C

GEM-S supports a military standard (MIL-STD) dual-port RAM interface (DPRAM), as well as an RS422 serial interface for user communication. Although DPRAM is considered the primary interface for GEM-S operations in embedded systems, it will not be applied for BIRD because of its complexity. Instead, the operations will rely entirely on the RS422 interface, which is operated at a data rate of 9,600 baud in both directions.

In addition to the GEM-S position fixes that are used for onboard orbit determination, a one-pulse-per-second (1PPS) signal is issued by the receiver. This signal is used for synchronization of the BIRD onboard time.

Operation of the GPS receiver is complex, since the receiver applies a variety of data formats as input and output messages that must be supported by the ONS. Furthermore, the serial interface of GEM-S does not fully support initialization for space operations. Thus a series of memory change commands that directly access the receiver's internal memory is necessary.

The GEM-S receiver does not provide access to raw GPS measurements (pseudorange and phase) via the serial interface in normal operations. Consequently, position fixes and, optionally, velocity fixes from line-of-sight Doppler measurements provide the sole means of navigation information for dynamic onboard orbit determination. While this limitation is of no concern if at least four satellites are in view of the GPS antenna and locked by the receiver, it represents a notable restriction on the availability of measurement data in the case of visibility limitations. For the BIRD satellite, a zenith-looking attitude (as assumed by the GEM-S satellite selection and channel allocation algorithm) cannot be maintained during both sun-pointing mode and imaging sessions. Therefore, measurement gaps are expected for at least certain fractions of each orbit in addition to data gaps during the imaging sessions.

ONBOARD NAVIGATION SYSTEM DESIGN AND IMPLEMENTATION

The design of the ONS is driven by three key requirements:

- The ONS shall provide smooth position information with an absolute accuracy of better than 90 m (for WAOSS image reconstruction and geocoding).
- The ONS shall provide orbit information at a 2 Hz data rate (for earth-pointing attitude control and geocoding).
- The ONS shall provide orbit information at the specified accuracy and data rate for prediction intervals of up to 30 min in the absence of GPS measurements.

To meet these requirements, a dynamic trajectory model is applied that involves a numerical integration of the equation of motion and accounts for relevant perturbations. At an altitude of 560 km, the specified orbit prediction accuracy can be met by considering harmonic coefficients of the earth's gravity field up to degree and order 10, while perturbation due to drag, solar radiation pressure, and third-body forces from the sun and the moon can be neglected. The ONS employs an advanced numerical integration scheme (RK4R) that extends the common Runge-Kutta 4th-order algorithm by Richardson extrapolation and a 5th-order Hermite interpolation [4]. The algorithm comprises two elementary RK4 step sizes of length h and can be shown to be effectively of 5th order with 6 function calls/h. The Hermite interpolation of the spacecraft position allows for an efficient provision of dense position output, which is required for high-frequency geocoding of the payload images. Step sizes depend on the measurement times and may vary from 30 to 65 s.

An extended Kalman filter is used to update the computed trajectory based on GPS position fixes that are treated as statistically independent pseudomeasurements. Individual navigation solutions are typically accurate to 10 m in the absence of Selective Availability (S/A), which allows an overall position accuracy of roughly 5 m after the filtering. Given the inferior relative accuracy of the velocity estimates provided by the GEM-S receiver ($\sigma_v \approx 1$–2 m/s), these data are used only for self-initialization of the orbit determination process, but not incorporated as independent measurements. The Kalman filter comprises the time update phase with a propagation of the previous estimate to the time of the latest measurement, as well as the computation of the state transition matrix and the state covariance matrix. In view of moderate step sizes, a Keplerian approximation of the state transition matrix is employed, which allows an analytical computation. To account for 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), which are treated in three consecutive scalar updates to avoid the inversion of a 3×3 matrix.

The filter update and orbit prediction are invoked at discrete intervals (t_i) as illustrated in Figure 2. Assuming that a continuous representation of the trajectory is available from the past cycle, the predicted state vector at the time of the latest measurement ($t_{upd,i}$) is found by interpolation. In addition, the state transition matrix covering the time between the previous and the current update is

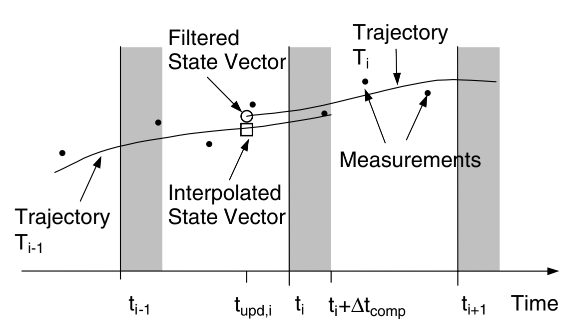

Fig. 2 – Timeline of BIRD Real-Time Navigation Process (Shadowed bars indicate computational activity.)

computed. Following the measurement update, an improved state vector at $t_{upd,i}$ is available, which is integrated to $t_i + h + \Delta t_{comp}$ that is beyond the time $t_{i+1} = t_i + h$ of the next processing step. Here, the margin Δt_{comp} accounts for the processing time required to complete all computations. As part of the numerical integration process, a continuous polynomial representation of the trajectory between $t_{upd,i}$ and $t_{i+1} + \Delta t_{comp}$ is made available, which serves as a starting point for the next Kalman update and orbit prediction step. The processing scheme implies that at most one GPS position measurement is processed per cycle of duration h and that the length of an integration step may vary from $h + \Delta t_{comp}$ to $2h + \Delta t_{comp}$, depending on the actual time of the respective measurement inside the interval $[t_i - h, t_i]$. For BIRD, a cycle duration of 30 s has been selected, which results in integration step sizes of 30 to 65 s. These values provide a near-optimum working point for the applied RK4R integrator and a reasonable number of processed GPS measurements per orbit.

The ONS software executes on the BIRD onboard processor, which is built by the Institute for Computer Architecture and Software Technology of the German National Research Center for Information Technology (GMD/First). It features an industrial Power PC 823 processor operated at a 48 MHz clock rate (without floating-point support), 8 MB of RAM memory, and eight serial and one parallel ports for external communication. The real-time operating system, BIRT, developed by GMD/First, separates the kernel run-time system and a hardware-dependent layer, which allows emulation on standard Linux workstations, as well as an easy adaptation to different processors. BIRT is a preemptive multitasking operating system well suited to real-time and onboard applications. Processes are executed as separate threads, which are controlled by a central scheduler based on preassigned priorities and timers. In this way, short and high-priority activities (e.g., commanding, attitude control) can be separated from computation-intensive tasks with long duty cycles.

For execution under the BIRT operating system, the ONS software has been implemented in C++ based on component libraries and the real-time orbit determination (RTOD) demonstration program provided in [5]. A simplified view of the overall software structure is shown in Figure 3, which illustrates the ONS core components:

- The *command dispatcher* receives ONS-related commands from the onboard processor and executes them to control the operation of the orbit prediction and determination threads, as well as the GPS receiver. To facilitate receiver operations and reduce the ground command load, the command dispatcher supports the interpretation of macro commands that autogenerate predefined sequences of native GEM-S command messages. Likewise, it stores GPS almanac information between successive GEM-S operations to speed up receiver initialization and signal acquisition.
- The *orbit determination* (*OD*) *thread* accepts measurements from the GEM-S GPS receiver, performs the filter update, propagates the trajectory, and generates the interpolating Hermite polynomial. It is invoked every 30 s by the operating system and requires a total central processing unit (CPU) time of roughly 500 ms.
- The *orbit prediction* (*OP*) *thread* evaluates the trajectory polynomials to obtain the earth-fixed spacecraft position and the inertial orientation of the local-horizontal-local-vertical frame, which are passed to the payload data handling system (PDH) and the ACS. To safeguard against potential failures of the GPS-based navigation, these data can alternatively be computed from ground-commanded North American Aerospace Defense Command (NORAD) two-line elements (TLEs) with a corresponding loss of precision. The OP thread is executed every 0.5 s in accordance with the cycle duration of the ACS.

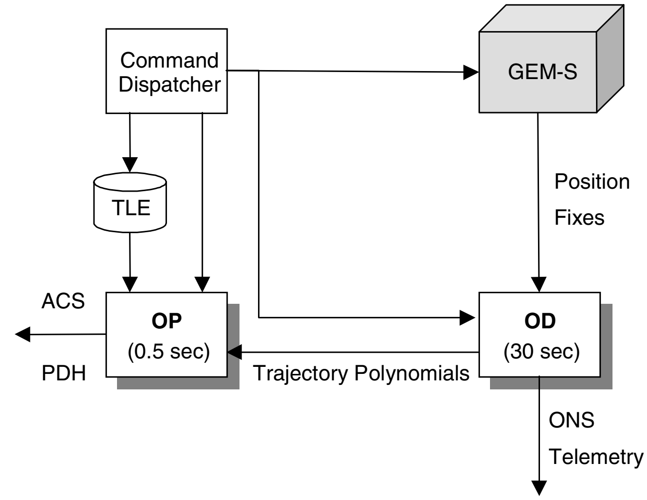

Fig. 3 – Schematic View of ONS Architecture (Software threads are indicated by shadowed boxes.)

ONBOARD NAVIGATION SYSTEM PERFORMANCE VALUATION

For preflight software validation and filter tuning, a series of hardware-in-the-loop tests was conducted using the GEM-S flight model, a Global Simulation Systems STR2760 GPS signal simulator, and a laboratory prototype of the BIRD onboard processor board (see Figure 4). The simulator generated C/A-code signals on the L1 frequency for

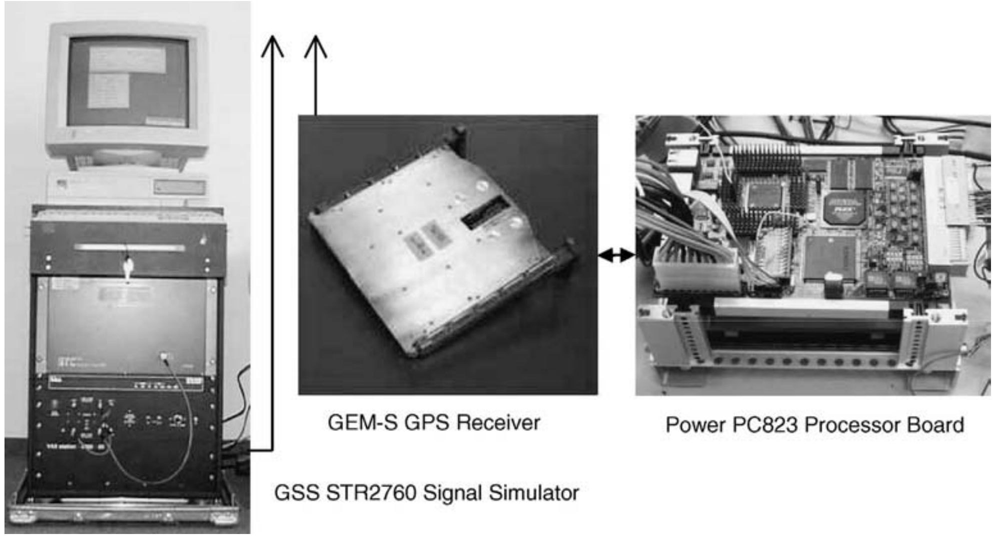

Fig. 4 – Hardware-in-the-Loop Simulation Setup for ONS Software Validation and Testing

up to 10 visible GPS satellites and a predefined user spacecraft orbit and attitude. For all simulations, the BIRD satellite was assumed to be in an inertially fixed sun-pointing attitude, with the GPS antenna boresight perpendicular to the sun and north-south direction. For the given sun-synchronous orbit with a 10 h equator crossing time, the GPS antenna suffered from signal blockage by the earth during certain parts of each orbit. The result was a temporary unavailability of four-satellite tracking and associated losses of GPS position fixes. In accordance with the U.S. decision to disable the intentional degradation of GPS navigation accuracy for civil users, no S/A effects were considered in the tests.

The simulations covered a time frame of up to 15 h, during which the GPS position and velocity measurements, the estimated state vectors, and their variances were recorded. Using the simulated BIRD trajectory as a reference, both the GPS measurement errors and the errors of the resulting ONS trajectory estimates could be determined. For the assumed spacecraft orbit and attitude, the GEM-S receiver generated valid navigation solutions for about 75 percent of a 9 h tracking arc.

The available position measurements exhibit a standard deviation of 6.5 m, where the bulk (84 percent) of the measurements is accurate to better than 10 m. About 10 percent of the measurements are off by more than 20 m, with peak errors reaching a value of 50 m. As illustrated in Figure 5, the measurement error distribution is far from random, however. Instead, pronounced systematic errors are clearly discernible, which originate from incompatible treatment of ionospheric effects by the GPS signal simulator (no ionospheric corrections applied) and the GEM-S receiver (terrestrial ionospheric correction algorithm). The achieved filter

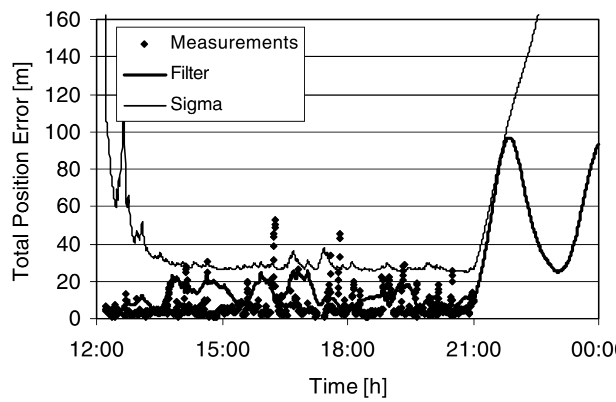

Fig. 5 – ONS Results for 9 h Hardware-in-the-Loop Simulation

performance of the ONS exhibits peak errors of up to 25 m and a filter standard deviation of 5.6 m. At first glance, the filter results appear to be unexpectedly high and thus in conflict with the observed GPS measurement accuracy. This is, however, not the case, since this particular filter performance can be attributed to the inconsistency of the ONS dynamical model, which applies harmonic coefficients of the earth's gravity field of up to degree and order 10, and the GPS signal simulator model, which is limited to a gravity field of up to degree and order 8. This observation is demonstrated by adjusting the ONS gravity model to the model applied by the GPS signal simulator, which results in typical ONS filter errors of less than 5 m with a standard deviation of 2.3 m. For completeness, the reader is referred to [6], which provides results of hardware-in-the-loop simulations carried out in an S/A-affected scenario. Here, typical accuracies of 40 m were achieved by the ONS while measurements were available.

Throughout the simulation, the actual ONS errors remain well within the 1 σ bounds of the computed standard deviation, which converges to a steady-state value of slightly less than 30 m within 90 min (one revolution). In parallel, the velocity standard deviation decreases from its a priori value of 17 m/s to a steady-state value of 3 cm/s. The resulting orbit prediction after the end of the GPS measurement arc leads to position errors of 70 m within a 30 min period; these errors remain well within the specified limit of 90 m, and stay below 100 m over much more than 30 min.

GPS-BASED REAL-TIME ESTIMATION OF TWO-LINE ELEMENTS

Though adapted to the particular requirements of the BIRD mission, the ONS makes use of established real-time estimation concepts. The state vectors that are provided by a Kalman filter at the measurement times can be used directly for real-time applications such as geocoding of images and three-axis attitude control. On the other hand, the derived orbital parameters are not appropriate for onboard orbit forecasts over several orbits ahead of time, since reliable orbit predictions from osculating orbital elements or state vectors require complex numerical propagation models that often exceed the available onboard computer resources. Therefore, onboard scheduling functions that require the prediction of spacecraft-related events such as shadows, ground station contacts, and image target hits remain difficult to implement despite the availability of onboard orbit information.

The disadvantage of numerical orbit prediction may be overcome by the use of analytical orbit models, which can be evaluated at arbitrary times and do not require a step-wise integration of the trajectory. Use of these models allows off-line predictions over mid- and long-term time scales (multiple revolutions to multiple days) at the expense of a decreased short-term (< 1 revolution) accuracy. Analytical models cannot, however, be used with osculating orbit information, but require a dedicated set of mean orbital elements. Furthermore, no explicit conversion from osculating to mean elements exists. Any erroneous use of mean elements in a numerical model or osculating elements in an analytical model would result in semimajor axis offsets of 1–10 km, with associated along-track errors of up to 100 km per orbit.

To cope with this problem, a real-time orbit determination algorithm for the direct estimation of mean SGP4 orbital parameters is developed in [7]. The choice of SGP4, which forms the basis for NORAD's TLE sets [8], is based on its widespread application for near-circular, low-altitude satellites and its high compatibility with existing ground equipment and commercial off-the-shelf (COTS) software products. Furthermore, the SGP4 model is able to account for atmospheric drag via a ballistic coefficient, which allows prediction intervals of more than a week with a single parameter set.

Since the argument of perigee is undefined for circular orbits, the concept of the estimation of SGP4 mean Keplerian elements is abandoned for the near-circular BIRD orbit. It is replaced by the estimation of an associated SGP4 mean state vector that is obtained from the traditional conversion between Keplerian elements and state vectors. Differences between the mean and osculating state vectors at the same time stem from the periodic perturbations induced by the earth's oblateness. Given the mean state vector and the associated ballistic coefficient at some epoch t_0, the spacecraft position and velocity at the time t of a GPS measurement can be computed from the SGP4 model. Likewise, partial derivatives of the s/c position with respect to the SGP4 mean state vector and the ballistic coefficient are obtained from a numerical difference quotient approximation. This computation allows the formulation of a recursive estimator (or epoch state Kalman filter), which updates the value of the mean epoch state vector from the difference between the GPS position measurement and the predicted SGP4 position. Details of the respective mathematical formulation are given in [7].

Compared with classical Kalman filters using numerical orbit models, this new approach can cope with small measurement rates and data gaps of up to several days. Its built-in capability to adjust a free drag parameter, as well as the analytical formulation of the orbit model, facilitates mid-term forecasts and allows the implementation of onboard algorithms for the prediction of station contacts or eclipse times. While the use of continuous measurements adds to the stability and accuracy of the adjusted parameters, the process is robust enough to work with a data coverage of even less than one orbit per day. This makes the process particularly useful for microsatellites with limited onboard resources and tight constraints on the permissible time of GPS receiver operations.

As part of a space-ground autonomy experiment, the real-time estimation of SGP4 orbit parameters and the onboard generation of NORAD-type TLEs are implemented on the BIRD satellite. The software is designed to operate essentially independently of the ONS and the ACS. No direct interaction with the spacecraft bus is foreseen, which nevertheless allows the (open-loop) study of new autonomy concepts.

The TLEs generated from GPS measurements onboard the BIRD satellite will be used for the computation of station contact times (governing the transmitter activation) as a generic example of onboard scheduling functions. In addition, the TLEs will be incorporated into the telemetry data stream for extraction by an experimental ground station. The orbital elements will in turn provide the necessary information for antenna pointing during upcoming satellite passes.

SUMMARY AND CONCLUSIONS

An onboard navigation system (ONS) for the BIRD microsatellite has been developed that provides real-time orbit information for attitude control and onboard geocoding of payload images. A GEM-S receiver is used to obtain GPS position fixes, which are processed in an extended Kalman filter with a reliable force model. This approach allows an overall accuracy of better than the 90 m .5 pixel width to be achieved even in GPS-free prediction arcs of up to 30 min. Complementary to the ONS, experimental software for the GPS-based generation of two-line orbital elements will be flown on BIRD to support the development of new onboard and onground autonomy concepts.

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