FLIGHT RESULTS FROM THE BIRD ONBOARD NAVIGATION SYSTEM

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ABSTRACT

The German small satellite BIRD carries an elaborate GPS-based Onboard Navigation System (ONS) which provides precise real-time orbit determination as well as orbit and event prediction capabilities. The ONS supports the BIRD Attitude Control System to allow for a nadir pointing of the spacecraft during payload image sessions and enables a geocoding of BIRD sensor images on-the-flight. The analysis of the BIRD ONS flight data indicates an orbit determination accuracy of 5 m for position and 0.006 m/s for velocity. In the absence of GPS data for a two hour period, the ONS predicts the BIRD position with an accuracy of better than 110 m. In addition to the ONS, a Real-time Twoline Generator is operated which estimates Twoline elements from GPS data onboard the spacecraft. This enables orbit forecasts over one week with timing errors of less than 5 s.

1. INTRODUCTION

BIRD (Bi-spectral Infra-Red Detection) is a small satellite (cf. Fig. 1), developed by the German Aerospace Center (DLR). An Indian PSLV rocket, launched on October 22 2001, injected the satellite into a near-circular sun-synchronous orbit at 568 km altitude with a local equator crossing time of 10:30.

The BIRD major mission objectives comprise the test of a new generation of infrared array sensors as well as the detection and scientific investigation of hot spots, like forest fires, or volcanic activities [1].

To that end, BIRD carries a total of four imaging sensors operating at visible and infrared wavelengths. Among these, the Medium Wave Infrared Sensor (MWIR, 3.5-4.3 μm) and the Long Wave Infrared Sensor (LWIR, 8.5-9.3 μm) provide frame images with a ground sample distance of 185 m at a swath width of 190 km. WAOSS (Wide Angle Optoelectronic Stereo Scanner) is a 3-line CCD stereo camera, which maps the Earth at a pixel size of 185 m and a swath width of 533 km. In addition, the panchromatic array camera HORUS has been added to the payload segment to provide a 6 m ground pixel size at a ground footprint size of 4.5 km.

As a technology and scientific satellite, BIRD is furthermore equipped with a GPS-based autonomous Onboard Navigation System (ONS) for precise real-time orbit determination and prediction.

In addition to the ONS functionality, NORAD Twoline elements are autonomously generated onboard from GPS data for long-term orbit prediction purposes. The Twoline elements may be provided via telemetry to re-locatable ground terminals for antenna pointing and pass scheduling which enables an autonomous terminal operation.

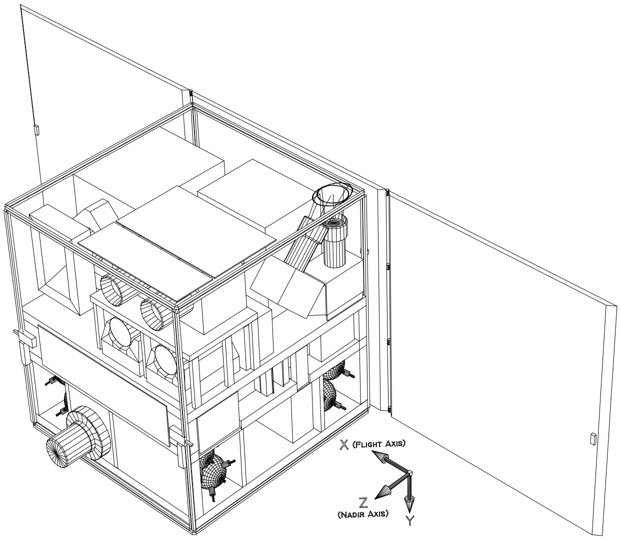

Fig. 1 BIRD (180x60x60cm) in flight configuration

2. THE ONBOARD NAVIGATION SYSTEM

From a functional point of view, the ONS is part of the BIRD Attitude Control System (ACS), since it acts as a complex sensor to the ACS, enabling the nadir pointing of the payload sensors and of the S-band high-gain antenna. However, due to its inherent complexity the ONS is treated as a separate system onboard BIRD.

2.1 System Objectives and Conception

The ONS objectives arise both from requirements to support the ACS as well as from its role as a technology demonstrator and comprise the

- Provision of the ACS with orbit information, that is required for the Earth-pointing of the spacecraft
- Provision of Earth-fixed position information for the geocoding of the BIRD image data
- Support of the spacecraft clock synchronization using the GPS One-Pulse-Per-Second.

To realize these objectives and to satisfy the accuracy requirement of 90 m over a one hour orbit prediction arc, the ONS key functionality consists of a precise orbit determination using GPS data. The GPS position fixes are treated by the ONS as statistically independent pseudo-measurements which are processed within an extended Kalman filter. The a priori state vector is based on GPS position and velocity measurements, while the GPS velocity measurements are not applied as measurements within the filter due to their inferior accuracy. The time update phase comprises 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), that are treated sequentially, in which case the Kalman gain matrix collapses to a six-dimensional vector and a matrix inversion is avoided.

The ONS employs an advanced numerical integration scheme (RK4R), that extends the common Runge-Kutta 4th order algorithm (RK4) by a Richardson extrapolation and a Hermite interpolation [2]. 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 per h. The Hermite interpolation of the spacecraft position allows for an efficient provision of dense position output, that is required for the high-frequency geocoding of the payload images. Integrator step sizes depend on the measurement times and may vary between 30 and 65 s [3]. In view of the moderate step sizes, the state transition matrix is computed based on a Keplerian approximation.

The ONS force model applies the JGM-3 coefficients to model the Earth’s gravity field, that is completely taken into account up to order and degree of 10. Considering measurement update periods of 30 s and prediction periods of 30 minutes, accelerations due to drag, solar radiation pressure, as well as gravitational perturbations from the sun and the moon may safely be neglected.

2.2 GPS Receiver and Flight Computer

The BIRD Onboard Navigation System makes use of a GPS Embedded Module III (GEM-S) by Rockwell Collins [4] to obtain GPS position fixes for real-time orbit determination. GEM-S is a five channel L1 SPS C/A- and P-code receiver, that has earlier been flown on several Space Shuttle missions. On BIRD, the GEM-S operations entirely rely on the RS422 interface due to its simplicity. Extensive use is made of high-level macro commands to facilitate the complex GEM-S initialization for space and to limit the telecommand load. In addition to the GPS data interface, a One-Pulse-Per-Second signal is issued by the receiver, that is used for synchronization of the BIRD onboard clock.

The ONS executes on the BIRD flight computer, which features an industrial Power PC 823e processor operated at 48 MHz clock rate (without floating point support) with a performance of 66 MIPS. A total of 8 MB of DRAM memory is available as well as 8 MB of shadow mirror memory and 128 kB of ROM to save critical run-time parameters. The DRAM is parity protected and duplicated which allows for error detection and correction. The real-time preemptive and multitasking operating system BOSS separates the kernel run-time system and a hardware dependant layer, which allows emulation on standard Linux workstations as well as an easy adaptation to different processors. 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) can well be separated from computation intensive tasks with long duty cycles (e.g. orbit determination). The operating system itself, as well as the different applications implemented on the flight computer, were developed in C++.

2.3 ONS Flight Results

The space initialization of the GEM-S receiver applies high-level macro commands with initialization date and time as sole parameters, while the ONS derives onboard the associated position and velocity from Twoline elements. All GEM-S initializations conducted so far were successful and required Time-To-First-Fixes of 45-290 s, in accordance with typical values found in the Hardware-in-the-Loop (HWIL) tests.

The availability of GPS data is slightly degraded by a spontaneous loss of track of the receiver. However, in about 95% of such losses, a reacquisition occurs within 30 minutes without any ground intervention.

To assess the quality of the GEM-S navigation solutions, a reference orbit has been established based on a dynamical smoothing of GEM-S position data using a precision orbit determination software. When eliminating obvious outliers, a position accuracy of 10 m (3D rms) has been determined together with a velocity accuracy of 0.4 m/s (3D rms). This is in agreement to the HWIL results of 7 m (3D rms) for position and 0.6 m/s (3D rms) for velocity. The quality of the GEM-S position fixes is comparable to other GPS receivers, e.g. JPL’s Blackjack receiver on the Champ satellite.

The position residuals exhibit pronounced spikes which occur about ten times per day and reach up to 300 m. Similar spikes were already detected during HWIL simulations and are obviously related to the rise or set of GPS satellites in the local horizon of the GPS antenna. In part, those errors arise from an improper treatment of ionospheric errors for space applications within the GEM-S. Another contribution to the observed spikes is the degraded radial position accuracy, resulting from a poor observation geometry when GPS satellites are close to the GPS antenna’s local horizon. This problem is related to the low number of tracking channels provided by GEM-S.

The quality of the ONS orbit determination solution has been assessed using ONS results as well as GEM-S position fixes transmitted via telemetry. To that end, GSOC's precise orbit determination tool has been applied to determine a reference trajectory using a GEM-S position fix arc which precedes and extends the ONS monitoring arc by one orbital period.

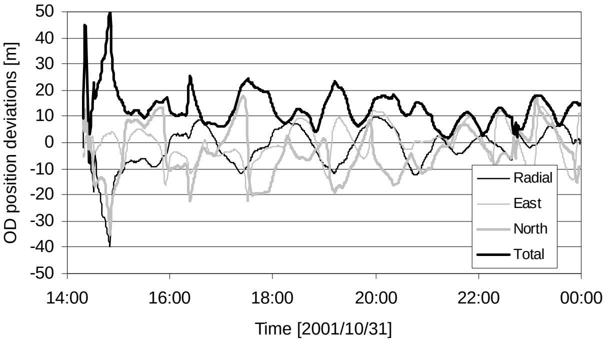

Fig. 2 ONS position residuals after its first initialization

In Fig. 2 the position residuals of the ONS onboard determined solution with respect to the reference trajectory are shown over an arc of more than 6 orbital periods. Following the filter convergence, the position residuals stay basically below 20 m. The position residuals in the north-track component, which are essentially along-track components, depict a slightly higher error than in radial or eastern direction. Furthermore a minor periodic amplitude modulation is visible in the total position error with a half-orbit period. Upon filter convergence, the obtained orbit determination accuracy for the position is 5.3 m (3D rms). Thus the dynamical model applied within the Kalman filtering improves the kinematic GEM-S position accuracy by a factor of about two.

Even of higher importance than the position error is the velocity accuracy, resulting from a dynamical smoothing of kinematic GEM-S position fixes. Following the filter convergence, the velocity residuals stay essentially below 2 cm/s and the achieved accuracy of the ONS orbit determination velocity is 6.3 mm/s (3D rms). The major improvement from a dynamical smoothing of the instantaneous GEM-S solutions is thus gained for the velocity errors which are improved by more than a factor of 50. This is of particular relevance for orbit prediction purposes, where velocity errors significantly effect the accumulated position predictions with time.

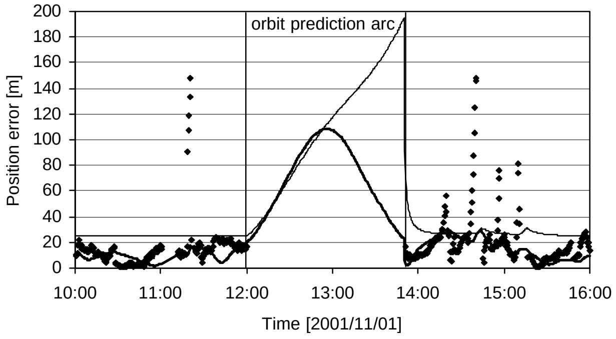

Fig. 3 ONS position errors for orbit determination and prediction. (diamonds: GEM-S residuals, bold line: ONS solution, thin line: standard deviation)

The ONS capability to bridge GPS data gaps and propagate the orbit is depicted in Fig. 3, where the receiver lost track and turned back to its nominal tracking mode without any ground intervention after about 110 min. Thus a continuous orbit prediction arc of more than one orbit revolution was available, which served for the analysis of the ONS orbit prediction performance.

To monitor the GPS measurements as well as ONS filter solution over the entire orbit prediction arc, a reference trajectory has been established as described above. Based on the reference trajectory, the ONS orbit determination and prediction performance was monitored over an arc of four orbital periods (cf. Fig. 3). Within the first 50 min of the prediction phase, an almost linearly increasing position error is observed, which closely matches the computed standard deviation of the ONS position. Having reached a maximum error of 108 m, the position error decreases again to a level of 25 m without any new measurements. Following the receiver's reacquisition, the filter reacquires a stable performance at least within one hour.

The decrease of the ONS predicted position error within the second part of the prediction phase is easily explained by the relative motion of the ONS position versus the reference position as a result of the ONS radial velocity error in the last measurement update [2].

3. THE REAL-TIME TWOLINE GENERATOR

While the ONS is especially suited for navigation applications with short prediction intervals, the use of an analytical orbit model can overcome those limitations. It allows off-line predictions over mid- and long-term periods (multiple revolutions to multiple days) at the expense of a decreased short-term accuracy. The analytical model used by the Real-time Twoline Generator (RTG) is the SGP4 model [5], which is employed by the North American Aerospace Defense Command (NORAD) for the generation of Twoline elements, a widespread standard format for the exchange of orbit information for near-circular, low-altitude satellites.

3.1 RTG Objective and Conception

The major objective of the RTG is to generate onboard Twoline elements to be transmitted to a relocatable ground station on an experimental basis. Here, the Twoline elements may be applied using Commercial-off-the-Shelf (COTS) software to perform the antenna steering and upcoming pass predictions, which provides an essential prerequisite for autonomous ground station operations.

The RTG applies GPS position measurements within an epoch state Kalman filter, which updates the value of the mean epoch state vector from the difference between GPS position measurements and the predicted SGP4 position [6]. Using a mean epoch state vector for

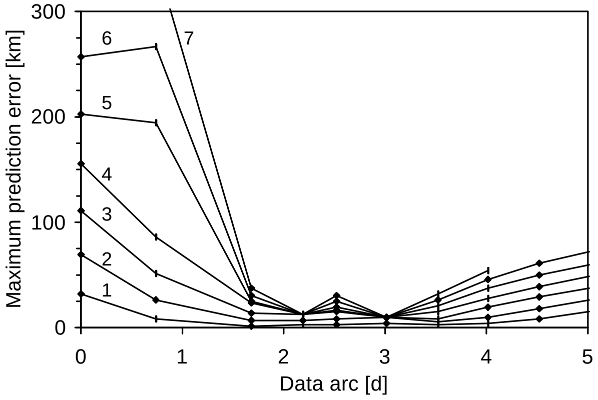

Fig. 4 Maximum RTG position prediction errors. The prediction arc in units of days is displayed as parameter for the different curves.

estimation as opposed to the mean orbital elements avoids the inherent singularity of the orbital elements for near-circular orbits. In addition to the SGP4 mean state vector, the RTG also accounts for the atmospheric drag by estimating a ballistic coefficient, which is part of the SGP4 algorithm.

3.2 RTG Flight Results

The analysis of the RTG results is primarily based on a sequence of transmitted Twoline elements as well as native GEM-S position fixes, which were applied to establish a reference trajectory on ground. A RTG filter convergence has been observed within about two days in accordance with pre-flight tests. Computing the RTG-derived position and velocity residuals with respect to the reference trajectory yields maximum position and velocity errors of 1.8 km and 1.6 m/s, respectively. The associated standard deviations are 0.3 km for position and 0.3 m/s for velocity, similar to residual characteristics resulting from ground-based generation of Twoline elements.

To demonstrate the potential of the RTG for onboard long-term predictions, the maximum RTG prediction errors for various prediction arcs in dependence of the applied data arc are displayed in Fig. 4. It is obvious, that for all prediction intervals the data arc should preferably be longer than 1 day to operate in the converged regime of the Kalman filter. A moderate increase of the prediction error is observed if Towline elements from data arcs of 5 days or longer are applied. This is in particular attributed to the limited complexity of the SGP4 dynamic model, which is not able to optimally fit data arcs longer than 5 to 7 days. A surprising result is the fact, that in an optimum regime of the filter based on about 1.5-3.5 d of tracking data, the maximum position prediction errors are not very sensitive to the prediction period. Even for a 7 day prediction arc, the maximum position errors are less than 38 km, corresponding to a 5 s timing error, which is tolerable for many applications.

CONCLUSIONS

Following a successful launch of the BIRD satellite on October 22, 2001, flight data from the Onboard Navigation System (ONS) and the Realtime Twoline Generator (RTG) have been analyzed. The ONS makes use of a low-cost GPS receiver to demonstrate autonomous navigation technologies onboard a small satellite. Based on a precise dynamical Kalman filter algorithm, the real-time provision of precise position and velocity data for the support of the satellite attitude control system is demonstrated as well as the geocoding of payload imagery on-the-flight.

Analysis of the GEM-S data shows an accuracy level of 10 m (3D rms) for the position and of 0.4 m/s (3D rms) for the velocity. Based on a dynamical filtering of the GEM-S position solutions, the ONS delivers a real-time accuracy of 5 m (3D rms) for position and 0.006 m/s (3D rms) for velocity, that improves the raw measurement performance by a factor of 2 and 50, respectively. Especially the improved velocity knowledge, gained from the ONS, provides a prerequisite for the ONS orbit prediction capabilities, which have been demonstrated to be as good as 110 m for a two hour forecast.

The RTG allows to demonstrate a long-term orbit prediction accuracy of better than 5 s for a 7 day arc, which renders this concept very promising for autonomous onboard functions, such as resource management and payload scheduling. Furthermore, the availability of transmitted Twoline elements at the ground station paves the way for an autonomous ground station operation.

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