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

Oliver Montenbruck, *Deutsches Zentrum für Luft- und Raumfahrt (DLR), German Space Operations Center, 82234 Wessling, Germany, oliver.montenbruck@dlr.de*
Eberhard Gill, *DLR, German Space Operations Center, 82234 Wessling, Germany*
Hakan Kayal, *DLR, Institute of Space Sensor Technology and Planetary Exploration, Rutherfordstrasse 2, 12489 Berlin*

BBIOGRAPHY

Oliver Montenbruck is head of the GPS Technology and Navigation Group at DLR's German Space Operations Center (GSOC). He received his Ph.D. from Munich's University of Technology in 1991. Since 1987 he's working at DLR/GSOC as a flight dynamics engineer, where he specialized in satellite orbit determination and stationkeeping of geostationary satellites. His current field of work comprises the development of on-board navigation systems and spaceborne GPS applications. He's written various text books on computational astronomy and satellite orbits.

Eberhard Gill is a member of the scientific staff at the German Space Operations Center of DLR. He received his Ph.D. in Physics at the University of Tübingen, Germany, in 1989. At DLR, he has been working in the field of satellite orbit determination and consider covariance analysis with emphasis on force and measurement modeling. Starting in 1996, he has been working in the field of GPS and GNSS with focus on GPS-based orbit determination as well as project studies for GNSS2. Since 1999, he is in charge of autonomous navigation within GSOC's Spaceflight Technology section. His main task is the development of the Onboard Navigation System ONS for the German BIRD satellite. He is author of various papers on spaceflight dynamics and co-author of a text book an satellite orbits.

Hakan Kayal is a member of the Institute of Space Sensor Technology and Planetary Exploration at DLR Berlin since December 1996. He received his diploma degree in aerospace engineering at the Technical University of Berlin and is currently performing a Ph.D. study on an experimental ground station for the BIRD satellite. Within the BIRD project, Hakan Kayal is responsible for the development of the telemetry and telecommand system as well as operational procedures.

ABSTRACT

The paper describes the design and implementation of an on-board navigation system for the German BIRD microsatellite. BIRD is a technology and science satellite aiming at the autonomous detection and identification of hot spots like forest fires or volcanic activities. The Onboard Navigation System (ONS) will provide the instantaneous nadir and along-track direction for Earth-fixed camera pointing as well as precise position values for real-time geocoding of the optical and infrared images and derived data. It employs a GEM-S 5 channel C/A code receiver which provides GPS position fixes with a typical accuracy of 100 m (Selective Availability on). Using an extended Kalman filter and a fidelity force model, a dynamical orbit determination and prediction is performed to provide smooth trajectory data with a nominal accuracy of 30 m during continuous GPS data takes and an accuracy of better than 100 m for prediction arcs of up to 30 mins. The ONS is, furthermore, supplemented by a prototype software for the real-time estimation of SGP4 mean elements, which allows an on-board forecast of ground station contacts or eclipse times. In addition, NORAD compatible twoline element sets can be created and downlinked to a ground terminal for autonomous station operation.

1. THE BIRD MISSION AND SPACECRAFT

The BIRD (Bi-spectral InfraRed Detection) mission is a small satellite project carried out by its German Aerospace Center (DLR) under leadership of the Institute of Space Sensor Technology and Planetary Exploration. Its primary scientific objectives comprise the test of a new generation of infrared array sensors as well as the detection and scientific investigation of hots 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 [BRI99].

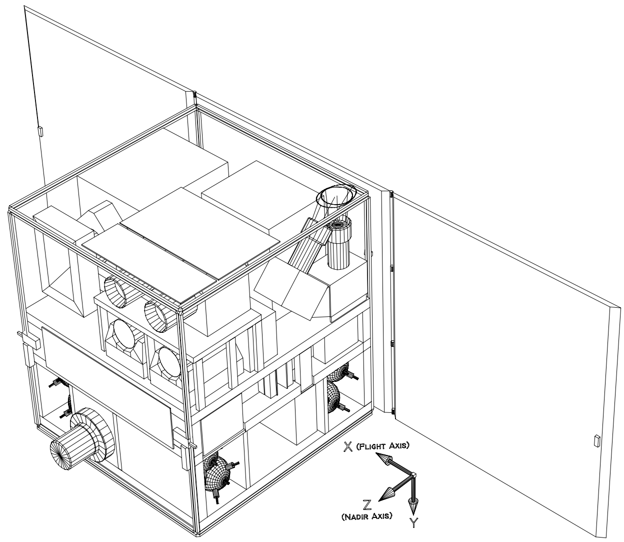

Fig. 1 The BIRD spacecraft in flight configuration

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 x 50 x 50 cm^3. This is devided into a payload platform (optical camera & infrared sensors), an electronics segment and a service element (batteries, wheels, gyros, etc.). Two self-deployable and one body-fixed solar array provide an average power of 60 W throughout a day, which is buffered in 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. WOASS (Wide Angle Optoelectrocic Stereo Scanner), in contrast, is a 3-line 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 3-axis gyro system for fine pointing as well as Sun sensors and a magnetometer for coarse attitude determination. Control torques can be generated by 4 reaction wheels and 3 magnetic torquers. Auxiliary orbit information is provided by the Onboard Navigation System (ONS), which makes use of a C/A code GPS receiver. Aside from safe-mode functions, the ACS supports a Sun-pointing mode and an Earth-pointing mode. During most of the day, the spacecraft will be Sun-pointing to charge the battery between subsequent camera data takes. For imaging sessions that last for typically 10-15 mins, the spacecraft is temporarily oriented into a nadir-pointing attitude (with optional biases) and reoriented thereafter. As a consequence of the limited on-board power resources and antenna placement restrictions, the GPS receiver will only be operated before or between image data takes. Therefore, the Onboard Navigation System must be able to bridge GPS outages of up to half an hour and still provide a half pixel (ca. 90 m) position accuracy.

2. THE GEM-S GPS RECEIVER

The Onboard Navigation System of the BIRD satellite makes use of a Rockwell-Collins GEM-S (GPS Embedded Module, [ROC97]) receiver to obtain GPS position measurements for real-time orbit determination. It is a five channel C/A- and P-code receiver that is restricted to work on the L1 frequency. The GEM-S receiver has earlier been flown on Space Shuttle missions [CAR99].

The primary power input to GEM-S is provided through ±5 V DC and approximately 6.4 W are 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 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.

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

Besides the GEM-S position fixes, that are used for onboard orbit determination, a One-Pulse-Per-Second (1PPS) signal is issued by the receiver, that is used for synchronization of the BIRD onboard time.

Table 1 Key characteristics of the Rockwell Collins GEM-S receiver

Channels	5
Supported frequencies	L1
Code Tracking	C/A, P
Position accuracy (rms)	6-100 m
Controller Interfaces	DPRAM, RS-422
RS-422 Baud Rate	T 76800, R 19200 or T/R 9600
Dimensions W x L x H	14.5 cm x 15.0 cm x 1.5 cm
Mass	0.4 kg
Power supply	± 5 V DC
Power consumption	6.5 W
Temperature range	[-54, +85] ºC

Operations of the GPS receiver is complicated, since the receiver applies a variety of data formats as input and output messages that have to be supported by the ONS. Furthermore, the serial interface of GEM-S does not fully support the initialization for space operations. This necessitates the commanding of a series of memory change commands, that directly access the receivers internal memory.

The GEM-S receiver does not provide access to raw GPS measurements (pseudo-range and phase) via the serial interface in normal operations. As such, position fixes and, optionally, velocity fixes from line-of-sight Doppler measurements, provide the sole means of navigation information for a dynamical onboard orbit determination. While this is of no concern, if at least 4 satellites are in view of the GPS antenna and locked by the receiver, it implies a notable restriction to the availability of measurement data in 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 Sun-pointing mode. Therefore, measurement gaps are expected for at least certain fractions of each orbit.

3. ONS DESIGN AND IMPLEMENTATION

The design of the BIRD Onboard Navigation System (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), and
- the ONS shall provide orbit information at the specified accuracy and data rate for prediction intervals of up to 30 mins in the absence of GPS measurements.

To achieve these goals, a fidelity trajectory model is applied, which 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 ten, while perturbation due to drag, solar radiation pressure, as well as 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 [MOG00b]. 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 high-frequency geocoding of the payload images. Step sizes depend on the measurement times and may vary between 30 and 65 s.

An extended Kalman filter is employed to update the computed trajectory based on GPS position fixes that are treated as statistically independent pseudo-measurements. Individual navigation solutions are typically accurate to 100 m in the presence of Selective Availability (S/A), which allows an overall position accuracy of roughly 35 m after the filtering. Given the inferior relative accuracy of the velocity estimates provided by the GEMS receiver ($\sigma_v \approx 1$-2 m/s), these data are only used for a 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, 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 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), which are treated in three consecutive scalar updates to avoid the inversion of a 3x3 matrix.

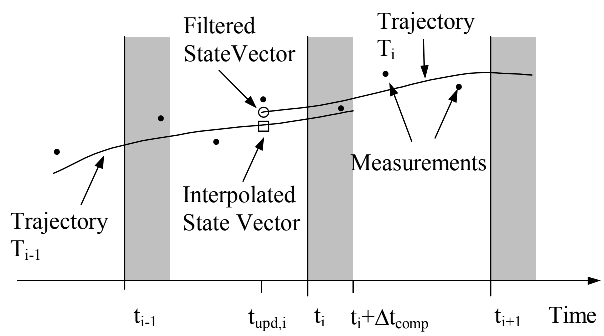

Fig. 2 Timeline of the BIRD real-time navigation process. Shaded bars indicate computational activity.

The filter update and orbit prediction is invoked at discrete intervals (t_i) as illustrated in Fig. 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 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 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 between a minimum of $h+\Delta t_{comp}$ and $2h+\Delta t_{comp}$, 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 as well as 8 serial and 1 parallel port for external communication. The real-time operating system BIRT developed by GMD/First separates the kernel run-time system and a hardware dependant layer, which allows an emulation on standard Linux workstations as well as an easy adaptation to different processors. BIRT is a preemptive 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 computation intensive tasks with long duty cycles.

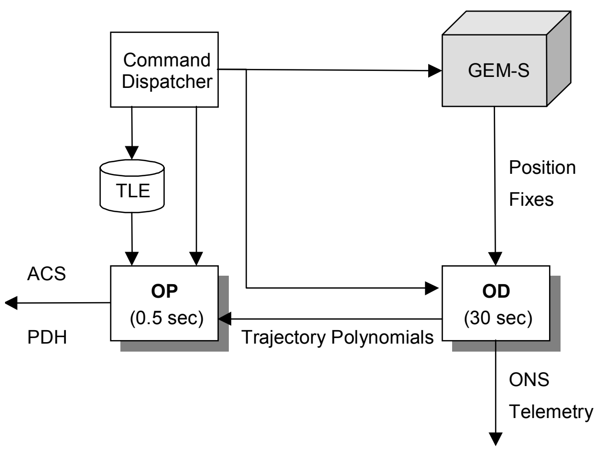

Fig. 3 Schematic view of the ONS architecture. Software threads are indicated by shaded boxes.

For execution under the BIRT operating system, the ONS software has been implemented in C++, building up on component libraries and the RTOD demonstration program provided in [MOG00a]. A simplified view of the overall s/w structure is shown in Fig. 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 which 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 Thread* (OD) accepts measurements from the GEM-S GPS receiver, performs the filter update, propagates the trajectory and generates the interpolating polynomial. It is invoked every 30 s by the operating system and requires a total CPU time of roughly 500 ms.
- The *Orbit Prediction Thread* (OP) evaluates the trajectory polynomials to obtain the Earth-fixed s/c position and the inertial orientation of the local-horizontal-local-vertical frame that are passed to the payload data handling system (PDH) and the Attitude Control System (ACS). To safeguard against potential failures of the GPS based navigation, these data can alternatively be computed from ground-commanded NORAD twoline elements (TLE) with a corresponding loss of precision. The OP thread is executed every 0.5 s in accord with the cycle duration of the Attitude Control System.

4. ONS PERFORMANCE VALUATION

For a pre-flight software validation and filter tuning a series of hardware-in-the-loop tests have been conducted using the GEM-S engineering model, a Global Simulation Systems STR2760 GPS signal simulator and a laboratory prototype of the BIRD onboard processor board (Fig. 4). The simulator generates C/A code signals on the L1 frequency for 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 suffers from signal blockage by the Earth during certain parts of each orbit. This results in a temporary unavailability of 4-satellite tracking and associated losses of GPS position fixes. In accord with the US president's recent decision to disable the intentional degradation of the GPS navigation accuracy for civil users, no SA effects have been considered in the final tests.

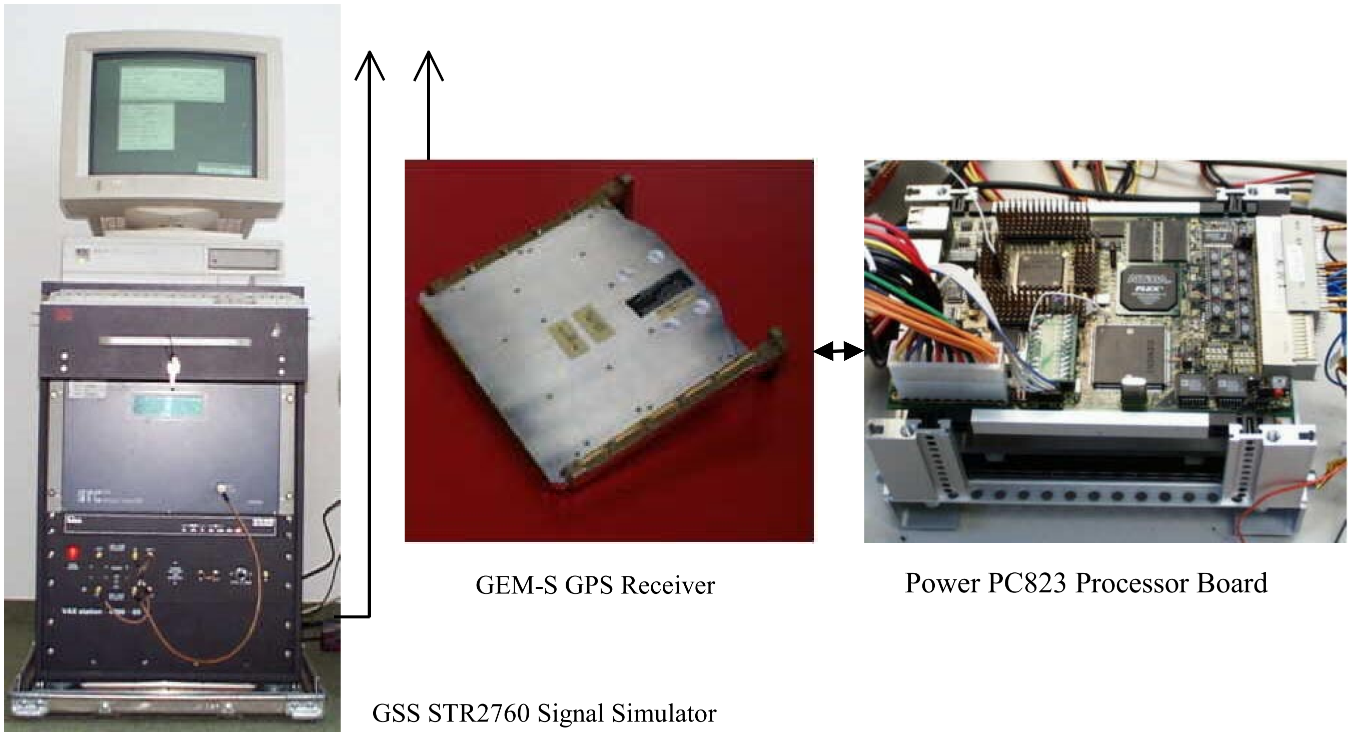

Fig 4 Hardware-in-the-Loop simulation setup for ONS software validation and testing

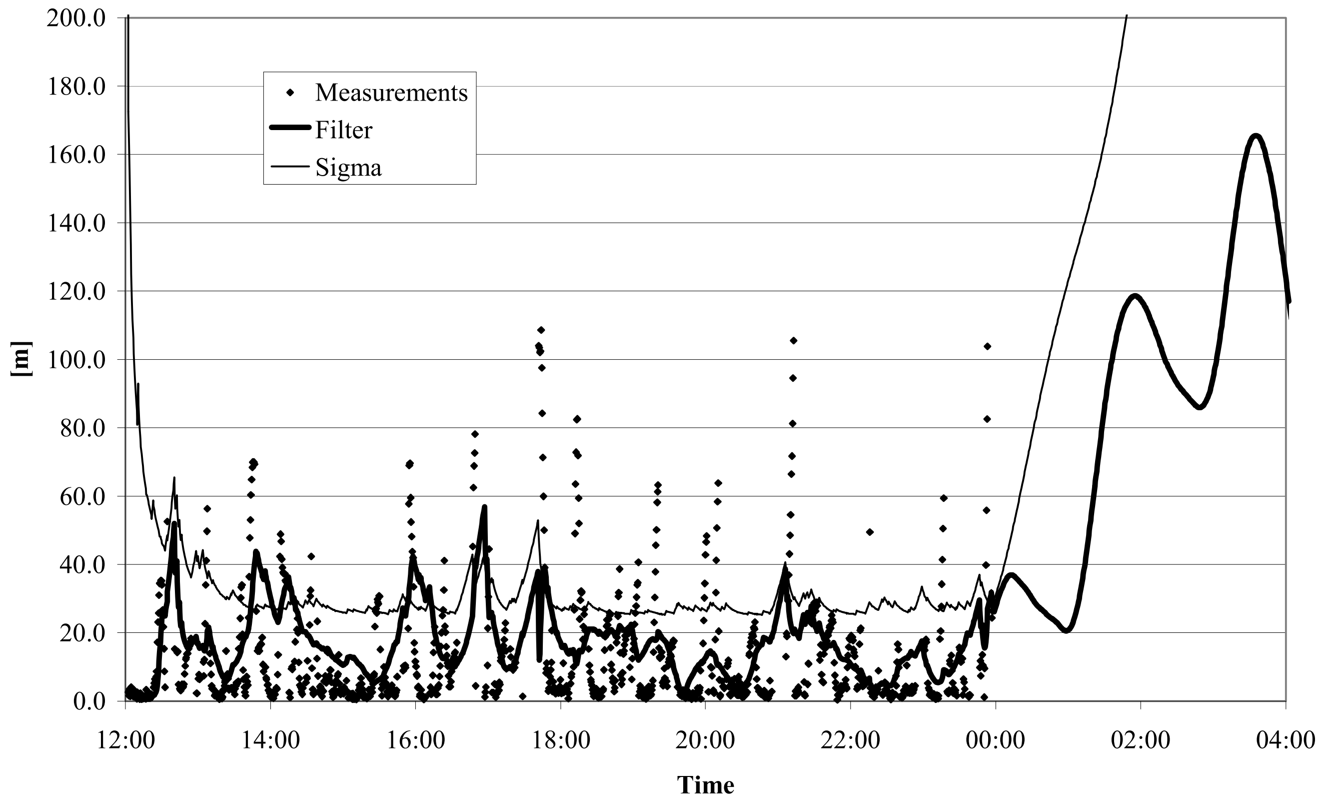

Fig 5 ONS results of a 12h hardware-in-the loop simulation in the absence of Selective Availability effects

The simulations covered a time frame of up to 12 hours, during which the GPS positions 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 a about 75% of a 12 hours tracking arc. This value is in good agreement with the results of an independent GPS visibility analysis [GMT00] requiring at least five satellites in the field of view of the BIRD GPS antenna. The bulk (62%) of the available position measurements exhibits an accuracy of better than 10 m. About 7% of the measurements are off by more than 40 m, with peak errors reaching a value of 150 m. As illustrated in Fig. 5, the error distribution is far from random, however. Instead, pronounced systematic errors are clearly discernible before and after periods of lacking navigation. These errors directly affect the achieved performance of the Onboard Navigation System, which exhibits peak errors of up to 50 m. The cause of the observed GEM-S tracking errors and suitable strategies for an adaptive editing of erroneous measurements inside the ONS are currently under investigation. For completeness the reader is referred to [GMB00], which provides results of the hardware-in-the-loop simulations carried out in an S/A-affected scenario. Here, typical accuracies of 40 m are achieved by the ONS while measurements are available.

Throughout the simulation, the actual ONS errors stay well within the 1σ bounds of the computed standard deviation, which converges to a steady-state value of slightly less than 30 m within 2 hours (one revolution). In parallel, the velocity standard deviation reduces from its apriori 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 remains well within the specified limit of 90 m over much more than 30 mins.

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

Though adapted to the particular requirements of the BIRD mission, the Onboard Navigation System described above makes use of established real-time estimation concepts. The state vectors that are provided by a Kalman filter at the measurements times can directly be used for real-time applications like geocoding of images and 3-axis attitude control. On the other hand, the derived orbital parameters are not appropriate for onboard orbit forecasts over several orbits ahead of time. This is due to the fact that reliable orbit predictions from osculating orbital elements or state vectors require complex numerical propagation models which often exceed the available onboard computer resources. Therefore, onboard scheduling functions that require the prediction of spacecraft-related events like 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, that can be evaluated at arbitrary times and do not require a step-wise integration of the trajectory. This 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 rev) 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 does exist. Any erroneous use of mean elements in a numerical model or osculating elements in an analytical model would result in semi-major 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 has been developed in [MON00]. The choice of SGP4, which forms the basis for NORAD's twoline element sets [HOR80], is based on its widespread application for near-circular, low-altitude satellites and its high communality with existing ground equipment and commercial off-the-shelf software (COTS) 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.

To avoid an inherent singularity for near-circular orbits, the SGP4 mean elements are mapped into an associated mean state vector via the traditional conversion between Keplerian elements and state vectors. Differences between the mean and osculating state vector at the same time stem from the periodic perturbations induced by the Earth's oblatenes. 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 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 [MON00].

Compared to classical Kalman filters using numerical orbit models, this new approach can cope with small measurement rates and data gaps up to several days in size. 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 it particularly useful for micro-satellites 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 on-board generation of NORAD-type twoline elements will be implemented on the BIRD satellite. The software is designed to operate essentially independent of the Onboard Navigation System and the Attitude Control System described above. No direct interaction with the spacecraft bus is foreseen, which nevertheless allows the (open loop) study of new autonomy concepts.

Fig. 6 DLR's experimental ground station will receive GPS based twoline elements from BIRD to allow autonomous pass predictions and antenna pointing

The twoline elements 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 twoline elements will be incorporated into the telemetry data stream for extraction by an experimental ground station. Here 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 which provides real-time orbit information for attitude control and onboard geocoding of payload images. A GEM-S receiver is employed to obtain GPS position fixes which are processed in an extended Kalman filter with a reliable force model. This allows an overall accuracy of better than the 90 m half-pixel width to be achieved even in GPS free prediction arcs of up to 30 mins. Complementary to the ONS, an experimental software for the GPS based generation of twoline orbital elements will be flown on BIRD, which supports new onboard and onground autonomy concepts

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of Kayser-Threde GmbH, Munich, which has kindly provided access to the GSS STR2760 signal simulator used in the hardware-in-the-loop simulations.

REFERENCES

[BRI99] Brieß K., Bärwald W., Gerlich T., Jahn H., Lura F., Studemund H.; *The DLR Small Satellite Mission BIRD*; in: *Small satellites for Earth Observation*, 2nd International Symposium of the IAA, Berlin April 12-16 (1999).

[CAR99] Carpenter R. J., Schiesser E. R.; *The Importance of Semi-Major Axis Knowledge in the Determination of Near-Circular Orbits*; AAS/AIAA Space Flight Dynamics Meeting, AAS 99-190, Breckenridge, Co. (1999).

[GMB00] Gill E., Montenbruck O., Brieß K.; *GPS-Based Autonomous Navigation for the BIRD Satellite*; International Symposium on Spaceflight Dynamics, Biarritz, 26-30 June (2000).

[GMT00] Gill E., Montenbruck O. Terzibaschian Th.; *An Autonomous Navigation System for the German Small Satellite Mission BIRD*; AAS/AIAA Spaceflight Mechanics Meeting; Clearwater, Florida 23-26 January, (2000).

[HOR80] Hoots F. R., Roehrich R. L.; *Models for propagation of NORAD element sets*; Project Spacecraft Report No. 3; Aerospace Defense Command, United States Air Force; Dec. (1980).

[MON00] Montenbruck O.; *An epoch state filter for use with analytical orbit models of low earth satellites*; Aerospace Science and Technology 4, 277-287 (2000).

[MOG00a] Montenbruck O., Gill E.; *Satellite Orbits – Models, Methods, and Applications*; Springer Verlag, Heidelberg (2000).

[MOG00b] Montenbruck O., Gill E.; *State Interpolation for On-board Navigation Systems*; submitted to Aerospace Science and Technology; (2000)

[ROC97] Rockwell Collins; Specification for the Rockwell Collins 60J-3 GPS Embedded Module – Phase III (GEM III) Receiver CPN 822-0453-001 and 822-0453-005 for Use in the User Equipment Segment of the NAVSTAR Global Positioning System; CPN 752-9085-001 Rev. F (1997).