COMBINED SPACE-GROUND AUTONOMY FOR THE BIRD SMALL SATELLITE MISSION

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ABSTRACT

As part of the BIRD satellite mission, a GPS-based onboard navigation system (ONS) has been developed which supports the attitude control system, the geocoding of payload data as well the onboard time synchronization. In addition to the ONS functions, the GPS position data are applied to estimate the mean orbital elements and the ballistic coefficient of the SGP4 analytical orbit model using a Kalman filter. Based on the estimated mean elements, onboard eclipse predictions and station contact forecasts are performed and NORAD-compatible Twoline elements are generated. A combined space-ground autonomy is achieved, since the Twoline elements are transmitted from the BIRD satellite to an experimental ground station and thus allow an autonomous operation of the station without the need for a dedicated ground-based orbit interface.

1. INTRODUCTION

Small satellites are especially suited to demonstrate low-cost approaches to contemporary spacecraft operations. This is in particular achieved through the autonomous navigation of the satellites, as well as the automation of ground control facilities. In the framework of the BIRD (Bispectral InfraRed Detection) mission, a novel concept for a GPS-based combined space-ground autonomy is demonstrated.

Here, the GPS position fixes from the spaceborne GEM-S receiver [1] are applied to estimate the mean epoch elements of the SGP4 analytical orbit model using an epoch state Kalman filter. This is accomplished by the Realtime Twoline Generator (RTG), which, in addition, generates onboard Twoline elements and computes the shadow transits and station contact times. By adjusting the ballistic coefficient along with the mean epoch elements, orbit predictions with moderate accuracy are possible in the range of days to weeks.

As the generated Twoline elements are transmitted from BIRD to an experimental ground station (EGS), a combined space-ground autonomy is achieved (Fig. 1). At the EGS, the satellite contact times are computed based on a commercial off-the-shelf (COTS) software, thus avoiding any further external orbit interfaces. The described autonomy concept is extended even further, since a dedicated interface to the user of spaceborne images allows an easy and direct access to preprocessed, tailored, and thematically classified image data.

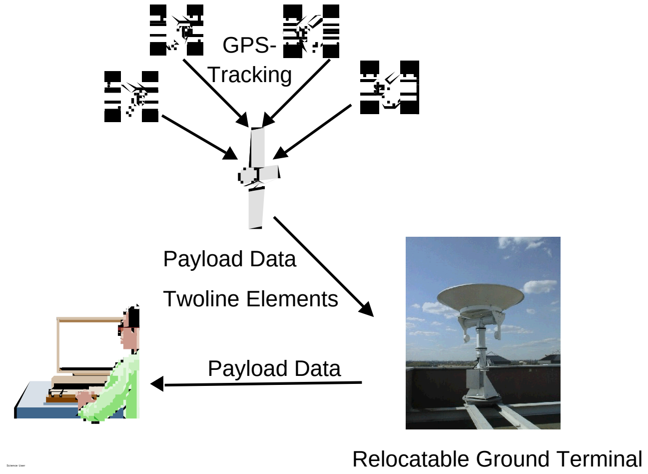

Fig. 1 Satellite operations for a combined autonomous space and ground segment

2. REALTIME TWOLINE GENERATION

2.1 Requirements

The design of the BIRD Realtime Twoline Generator (RTG) is driven by four requirements:

- the RTG shall generate sets of NORAD-compatible Twoline elements
- the RTG shall allow long-term orbit propagation in the range of several days
- the RTG shall be initialized autonomously without a priori orbit data from ground
- the RTG shall support a configurable station location and Kalman filter parameter set.

2.2 Concept

To achieve these goals, a real-time orbit determination algorithm for the direct estimation of mean SGP4 orbital parameters has been developed [2]. The choice of SGP4, which forms the basis for NORAD's Twoline element sets, is based on its widespread application for near-circular, low-altitude satellites and its high communality with existing ground equipment and COTS software products.

The RTG algorithm is based on the position fixes, provided by the low-cost five channel L1 and C/A-code GPS receiver GEM-S of Rockwell Collins, that are treated as pseudo-measurements within the orbit determination process. 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.

Furthermore, the SGP4 model is able to account for the atmospheric drag via a ballistic coefficient B, which allows prediction intervals of more than a week with a single parameter set. Thus, given RTG's 7-dimensional state vector $(\bar{x}_0, \bar{y}_0, \bar{z}_0, \dot{\bar{x}}_0, \dot{\bar{y}}_0, \dot{\bar{z}}_0, B)$ 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 an 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 [3].

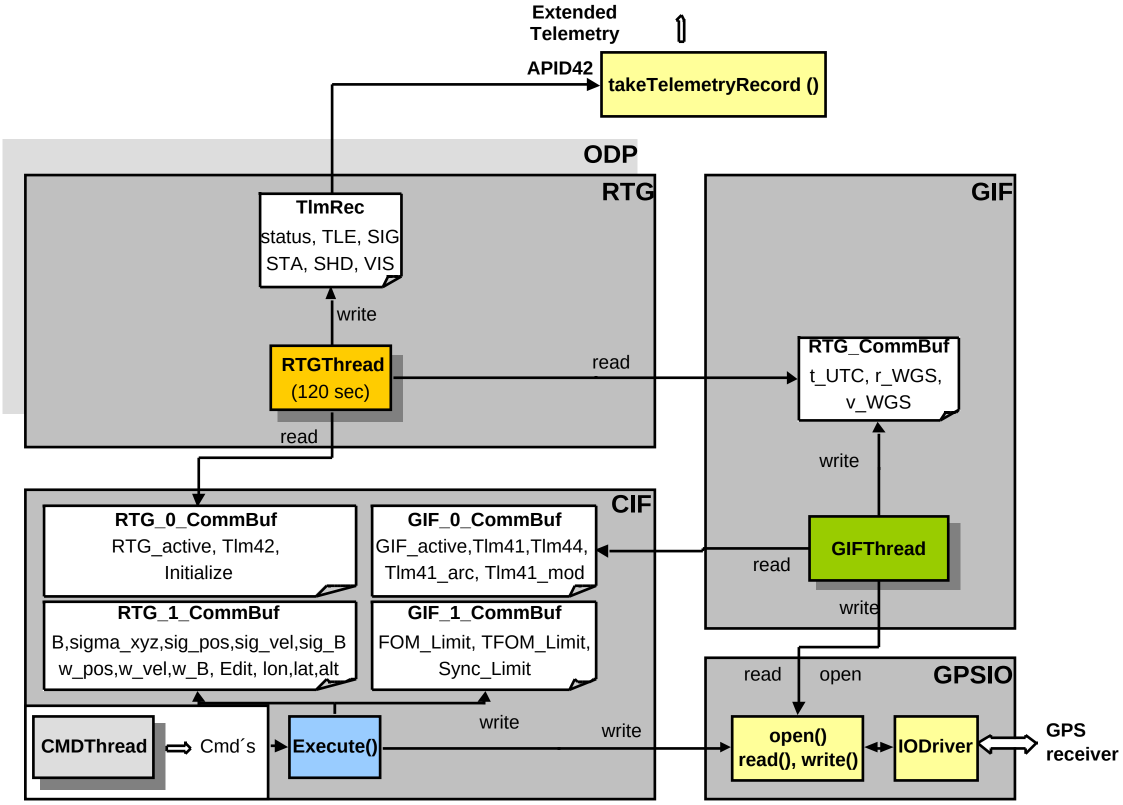

Fig. 2 Software Architecture of the BIRD Realtime Twoline Generator (RTG)

2.3 Implementation

The RTG software architecture is depicted in Fig. 2. Based on telecommands from the control center, that are routed through the ONS command interface (CIF), the GPS interface (GIF) and the RTG are controlled. Upon operations of the GPS receiver, GIF delivers GPS position and velocity data at UTC times t_i to the RTG thread, that is executed every 120 s. While the GPS data are used primarily as measurements for RTG, they are also applied for the orbit initialization of the RTG, thus enabling the autonomous RTG operations. On the other hand, orbit determination parameters, like the measurement standard deviation, the a priori standard deviations and the process noise of the estimation parameters may be explicitly set by ground commands, thus enabling flexible operations of the RTG.

2.4 Orbit Events Computation

Both analytical and numerical orbit models may be used to compute the shadow transit and station contact times based on a step-by-step evaluation of the shadow and visibility criteria throughout a certain orbit prediction interval. However, this method proves to be rather inefficient, since within a one-day prediction arc the resolution of shadow and visibility events with, e.g., 10 s requires about 9000 evaluations of the SGP4 algorithm.

An adequate approach is given, however, when the Earth shadow and station contact times in each orbit are computed in closed form, based on the Keplerian approximation. To compute the shadow entry and exit times for a spherical Earth, a fourth-degree equation in the cosine of the true anomaly is established, which may be solved in closed form by quartic radicals [4]. As concerns the station contacts, the rise-and-set times of the satellite from a specific ground station may be obtained from a closed-form solution of a single transcendental equation in the eccentric anomalies [4], which correspond to the rise-and-set times for that pass.

2.5 RTG Operations

The RTG is a technology demonstration for increased onboard and combined space-ground autonomy. In the present implementation, no direct interaction with the spacecraft bus (such as the transmitter activation for station contacts) is foreseen, which nevertheless allows the (open loop) study of new autonomy concepts.

Within the RTG, the shadow transit and station contact times are evaluated every 12 hours for a 24 hour prediction arc. Thus, within a 24 hour RTG operations phase, only $2 \cdot 14$ evaluations of the SGP4 algorithm are required for the computation of the shadow transits and the station contacts, that renders the implementation very efficient.

The RTG initialization is done autonomously onboard, while the RTG operations may, as an option, be configured in a flexible way for various orbit determination parameters or ground station locations. The approach proves robust enough to handle large data gaps in case of limited onboard resources for GPS operations.

3. REFERENCES

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4. Escobal P. R.; *Methods of Orbit Determination*; John Wiley&Sons, Inc., New York (1965). Reprint: Krieger Publishing Company, Malabar, Florida (1976).