HIGH-PRECISION ONBOARD ORBIT DETERMINATION FOR SMALL SATELLITES – THE GPS-BASED XNS ON X-SAT

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ABSTRACT

X-SAT is a mini-satellite developed by the Satellite Engineering Centre of the Nanyang Technological University at Singapore. The focus of the technology-driven mission is the high-resolution remote sensing of the Southeast Asian region for environmental monitoring. To achieve the ambitious mission objectives, the GPS-based X-SAT Navigation System (XNS) will provide high-precision onboard orbit determination solutions as well as orbit forecasts. With a targeted real-time position accuracy of about 1–2 m 3D r.m.s., the XNS provides an unprecedented accuracy performance and thus enables the support of any satellite mission which requires precise onboard position knowledge.

1. THE X-SAT MISSION

X-SAT is a technology demonstration mission undertaken as collaboration between the Nanyang Technological University (NTU) and the Defense Science Organisation (DSO) of Singapore.

1.1 X-SAT Orbit and Mission Operations

X-SAT is scheduled for a piggyback launch on a Polar Satellite Launch Vehicle (PSLV) from Shriharikota, South India, in 2006. The X-SAT target orbit is a near-circular, sun-synchronous orbit of 685 km altitude and 98.13º inclination [1].

The mission operations will be conducted at NTU's Satellite Engineering Centre (SEC). The ground segment comprises a 6 m S-Band antenna for TM/TC operations as well as a 13 m X-Band reflector for the downlink of payload data, both located in Singapore. While the S-Band communication link supports 4 kbps for the uplink and 1 Mbps for the downlink [2], the X-Band transmitter provides a data rate of up to 100 Mbps.

1.2 Spacecraft Description and Payload System

X-SAT is a platform with a total mass of 120 kg and a size of about 60x60x80 cm^3 (WxDxH) which is made of a honeycomb panel structure (Fig. 1). Two self-deployable solar arrays with a total area of about 0.9 m^2 provide an average total power of 140 W [3] at end of life.

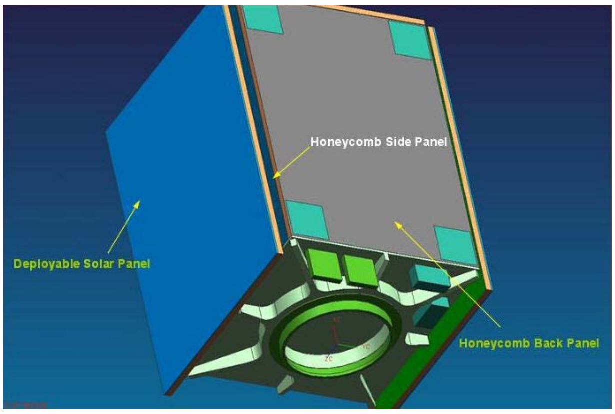

Fig. 1 X-SAT launch configuration with folded solar panels. The two GPS antennas close to the launch adapter face the -*z*-axis (zenith during earth-pointing mode).

The core of the onboard data handling system (OBDH) is the onboard computer (OBC) - a space-proven radiation-hardened 32-bit SPARC embedded processor of Atmel (TSC695F, implementing the ERC32 architecture) performing up to 20 MIPs at a clock speed of 25 MHz [4]. Communications between the OBC and the bus sub-systems as well as the payload is realized by two separate and redundant controller area networks (CAN).

The satellite carries three major payloads: the IRIS multispectral push-broom scanner, the Advanced Data Acquisition and Messaging (ADAM) instrument for communication with remote mobile terminals, and the Parallel Processing Unit (PPU) with multiple applications, e.g. for onboard image processing. Flying at a nominal altitude of 685 km, the IRIS main payload will provide images with 10 m spatial resolution in the green, red, and near-infrared band at a swath width of 50 km in the nadir-looking mode.

1.3 Attitude Determination and Control System

The requirements on the Attitude Determination and Control System (ADCS) are most demanding for the roll and pitch angles with a pointing accuracy of 0.33º and an attitude knowledge of 0.06º [5].

To achieve this goal, one star sensor and three rate sensors are applied together with GPS-derived position and velocity data for an accurate attitude determination during imaging and during large slew maneuvers. Furthermore, the ADCS comprises two three-axes magnetometers and three sun sensors for initial and contingency operations. Spacecraft attitude maneuvers are executed based on a set of three (+1 backup) reaction wheels and three magnetic torquers.

2. THE X-SAT NAVIGATION SYSTEM

The X-SAT Navigation System (XNS) comprises GPS receiver hardware as well as GPS tracking and navigation software. Since both the tracking and navigation software reside on the same receiver platform, an integrated navigation system is obtained which is especially well-suited for accommodation on small satellites.

2.1 XNS Objectives

The XNS objectives [6] arise both from mission support requirements of NTU, such as the

- Provision of GPS single point position and velocity solutions with an accuracy of 15 m (3D r.m.s.) and 1.5 cm/s (3D r.m.s.) for the X-SAT ADCS
- Provision of GPS navigation solutions and GPS raw data for use within the PPU navigation applications
- Provision of a GPS-based Pulse-per-Second signal with an accuracy of 1 ms for onboard clock synchronization,

as well as from its role as a technology demonstrator with the following requirements:

- Demonstration of real-time navigation based on ionosphere-free single-frequency GPS raw code and phase data
- Delivery of continuous and filtered position and velocity information with an accuracy of 2 m (3D r.m.s.) and 0.2 cm/s (3D r.m.s.) in Earth-pointing mode
- Delivery of continuous and filtered/predicted position information with an accuracy of 100 m (3D r.m.s.) in Sun-pointing mode.

2.2 GPS Hardware and Tracking Software

Core of the XNS is the Phoenix low-cost GPS receiver, a development by DLR/GSOC [7] based on a Zarlink GP4020 chip. It provides L1 C/A code and carrier tracking in twelve channels making use of a 32 bit ARM7TDMI microprocessor. The GPS tracking software has been designed for fast acquisition of GPS signals in LEO with a typical time-to-first-fix (TTFF) of about 30 s based on the availability of Two-Line Elements (TLE), a standard orbit format of NORAD. In addition to the provision of navigation solutions for the X-SAT ADCS, the receiver provides a Pulse-per-Second (PPS) for steering of the X-SAT onboard clock.

The GPS receiver board (Fig. 2), which hosts the GP4020 chip and several peripheral functions such as the real-time clock and two UARTS, provides a 512 kByte flash EPROM for storing the receiver software. Since the standard receiver functionality is significantly enhanced by the XNS orbit determination and prediction capability, the standard 256 kByte RAM memory for run-time code and data has been replaced by a 512 kByte RAM. New receiver software can be uploaded to the XNS “on-the-fly”.

The Phoenix receiver has successfully undergone total ionizing dose (TID) tests of up to 15 krad [8]. The small form factor of 70 x 47 x 11 mm^3 of the GPS board, a total mass of the XNS of less than 250 g (including interface board and housing), as well as a power consumption below 1 W render this system of particular interest for use on small satellites.

The XNS hardware is complemented by a passive single frequency GPS antenna (S67-1575-62) by Sensor Systems Inc. and a separate preamplifier.

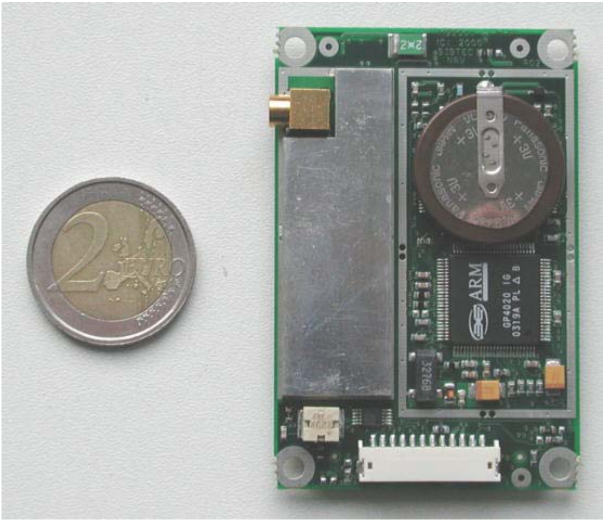

Fig. 2 Phoenix receiver board

The Phoenix receiver provides raw pseudorange, carrier phase, and Doppler measurements with noise levels of 0.3 m, 0.5 mm, and 0.06 m/s, respectively, at a carrier-to-noise ratio of 45 db-Hz [9]. In addition, carrier phase smoothed pseudoranges are provided with a noise level of 6 cm. All measurements are synchronized to integer GPS seconds with a representative accuracy of 0.2 µs.

2.3 XNS Navigation Software

The XNS navigation software employs algorithms for a dynamic orbit determination and prediction. A dynamic treatment is mandatory, since kinematic GPS position fixes may exhibit outages or degradations in accuracy depending on the orientation of the GPS antenna with respect to the GPS space segment. Moreover, an orbit determination from raw GPS measurements provides not only continuous ephemerides but offers an increased accuracy in position and velocity. The latter is of particular importance for orbit prediction purposes, where no GPS data are available. Finally, a dynamic orbit determination allows the elimination of ionospheric path delays in real-time applications.

Navigation Software Architecture

Adding navigation-related software to the GPS core receiver software significantly enhances the amount and complexity of the software running on the ARM7TDMI microprocessor. To keep a clear separation between the core receiver software and the navigation software, the latter is treated as an additional task running on the processor with a minimum of interfaces between the two parts (Fig. 3). Besides XNS-specific commands and messages, the core receiver software does not depend on any function or result related to the navigation software. The navigation software, on the other hand, benefits from an easy access e.g. to the GPS raw data through a data pool provided by the core receiver software.

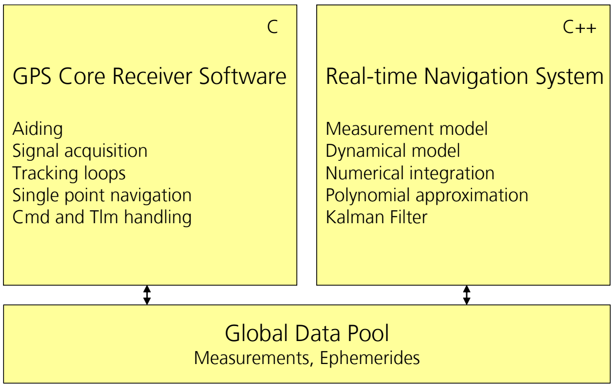

Fig. 3 XNS basic software architecture

A language mixing has been adopted with most parts of the core receiver software implemented in ANSI C, while the navigation software is completely based on C++. Key parts of the navigation software comprise the GPS measurement model, the dynamic model of the spacecraft motion, the numerical integration with the polynomial approximation, as well as the estimation concept, which are described in the sequel.

GPS Measurement Model

While previous onboard navigation systems have largely been based on the dynamic filtering of kinematic position fixes [10], a more advanced and complex approach applies raw GPS measurements.

In the framework of the XNS, the basic measurement type is a linear combination of GPS L1 C/A code and carrier phase. Since both data types are affected by systematic ionospheric errors with the same magnitude but opposite signs, their arithmetic mean is free of ionospheric errors. This approach, as proposed by Yunck in 1996 [11], removes the dominant systematic error source for raw GPS data, which may amount to 10-20 m [12] at low elevations. As a matter of fact, the resulting so-called GRAPHIC data (Group and Phase Ionospheric Calibration) provide a low-noise biased range with an accuracy of half the C/A code noise. For the Phoenix receiver in particular, which delivers pseudo-range measurements with an accuracy of about 0.4 m, the GRAPHIC data accuracy is as low as 0.2 m.

A drawback of using the GRAPHIC data type originates from the employed carrier phase data which introduce range biases for each of the twelve receiver channels. As consequence, twelve range biases have to be adjusted as part of the estimation process which significantly complicates the XNS algorithms. Finally, it has to be noted, that GPS broadcast ephemeris errors with a mean standard deviation of about 4 m (3D position) and 1 m (User Equivalent Range Error, UERE) [13] are still present in real-time applications, if no counter measures, such as the upload of precise ephemerides, are taken.

Dynamic Model

A dynamic model of the spacecraft motion essentially adds a priori knowledge from the equations of the orbital motion to the kinematic position knowledge as obtained from the raw GPS measurements.

In case of the XNS, the dynamic model incorporates the complex Earth gravity field (GGM01S [14]) truncated to order and degree 15. Furthermore, the third body forces from the sun and the moon are accounted for based on analytical theories of the solar and lunar motion. Non-gravitational forces are considered through solar radiation pressure and atmospheric drag making use of a simple Harris-Priester atmospheric density model.

In addition to deterministic accelerations, as described above, and to cope with any unmodeled accelerations acting on the spacecraft, a set of three empirical acceleration components in the orbital reference frame (a_R, a_T, a_N) is considered as well. The corresponding numerical values are determined in each measurement update of the filter as part of the estimated state vector.

Numerical Integration

The XNS employs an advanced numerical integration scheme (RK4R), which extends the common Runge-Kutta 4th order algorithm (RK4) by a Richardson extrapolation and a Hermite interpolation [15]. The algorithm comprises two elementary RK4 step sizes of length h and can be shown to be effectively of 5th order with six function calls per h with h=40 s. The Hermite interpolation of the spacecraft position allows for an efficient provision of dense position output which is required by the OBC at a rate of 1 Hz [16].

In view of the available processing power of the ARM7TDMI, the state transition matrix and the sensitivity matrix are computed from a numerical integration of the variational equations. In this context, a simplified dynamic model is applied which accounts, in addition to the Earth's mass, for the C_{20} contribution of the Earth's gravity field.

In contrast to the common approach of a numerical integration in an inertial reference frame, the XNS integrates the equations of motion and the variational equations in the rotating Earth-fixed frame. Although this adds some complexity, especially due to the Coriolis and centrifugal acceleration in the dynamic model, no reference system transformations are required in the main program since input (initial position and velocity), as well as the XNS output are consistently referring to the Earth-fixed frame. In this way, reference system transformations may completely be encapsulated in the dynamic model. Moreover, some dynamic algorithms, which compute e.g. the accelerations due to the Earth's gravity field and the atmospheric drag, may be formulated simpler in an Earth-fixed than in an inertial frame. Finally, since input and output data refer to the same system, there is no need to consider UT1-UTC time differences or polar motion.

Estimation Concept

The XNS applies an extended Kalman filter (EKF) to estimate the state vector which comprises 22 components:

- orbit position (3)
- orbit velocity (3)
- receiver clock bias (1)
- empirical accelerations (3)
- range bias values (12).

The time update phase of the EKF includes the propagation of the previous estimate, the computation of the state transition matrix and the state covariance matrix. The subsequent measurement update adjusts the state vector components to best fit the GRAPHIC data.

A particular advantage of the complex orbit determination scheme is a dynamically filtered orbit solution based on ionosphere-free GPS data, which provides smooth and precise trajectory data with a position accuracy of 1–2 m.

Timing Concept and Characteristic Tasking Times

The filter update is invoked at discrete intervals (t_i) as illustrated in Fig. 4 where the state vector is obtained from an interpolation of the previous cycle. Following the measurement update, an improved (filtered) state vector at t_i is available. This state is then integrated to t_i+h which is beyond the time t_{i+1} of the next processing step. The total processing time Δt_{comp} of the XNS task is indicated in Fig. 4 by the shaded areas and may amount, with some safety margin, up to 50% of a task cycle period. As part of the numerical integration process, a continuous polynomial representation of the trajectory between t_i and $t_{i+1}+h$ 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 epoch with GPS raw measurements is processed per cycle.

The XNS timing is based on raw GPS measurements which are generated every 0.1 s within the Phoenix receiver while the tracking loops are invoked with a period of 1 ms. Based on the raw GPS measurements, kinematic GPS positions are provided every 1 s while the XNS navigation task is invoked only every 30 s with a fixed integrator stepsize of 40 s. Since the navigation task is augmented with a suitable interpolation scheme, an efficient and dense output of dynamically filtered position information, e.g. at a 1 Hz rate, is still available without sacrificing the computational margins of the employed microprocessor.

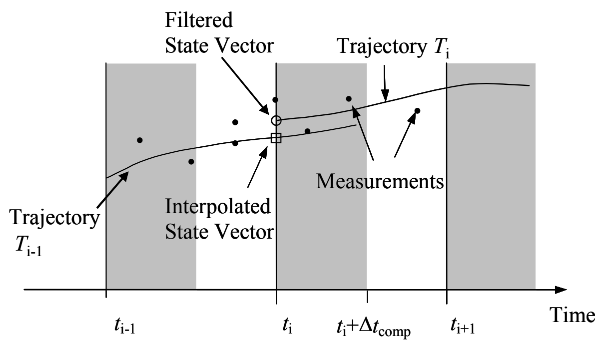

Fig. 4 Timeline of the XNS process

2.4 Concept Validation

A XNS concept validation was undertaken by several hardware-in-the-loop tests. All tests were based on a representative LEO satellite scenario making use of a Spirent STR4760 12 channel signal simulator and the DLR/GSOC Phoenix GPS receiver.

An offline kinematic position solution based on a 2 h set of GRAPHIC data demonstrated an overall 3D

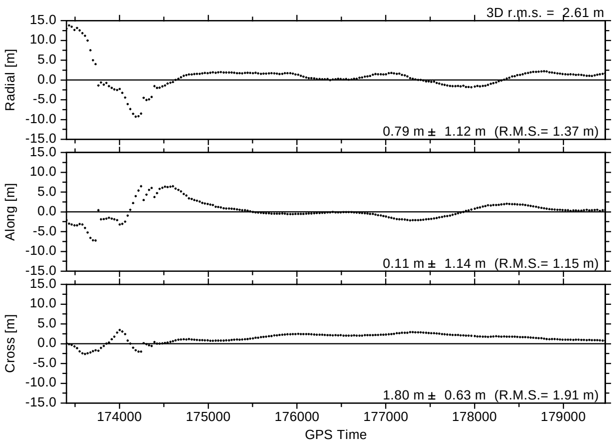

Fig. 5 Absolute position residuals in the radial, tangential, and normal (RTN) frame with respect to the reference trajectory [17].

r.m.s. position of about 0.5 m [9] which is consistent with the accuracy of the Phoenix GRAPHIC measurements.

Furthermore, a real-time reduced-dynamic simulation covering a 2 h arc yielded an overall 3D r.m.s. position error of about 2.6 m (Fig. 5), including the initial convergence phase of the filter [17]. The velocity error was found to be 0.34 cm/s consistent with the corresponding position error. In this simulation, a vertical ionospheric delay of 3.2 m and broadcast ephemeris errors of 2.5 m r.m.s. had been assumed.

The major remaining single error source in the overall position error budget is the ephemeris error of the GPS orbits, which would have to be uploaded for a subsequent removal. Optionally, the demonstration of such a highly-advanced orbit determination approach might be implemented as part of the suite of applications, executed on the X-SAT PPU payload.

2.5 Visibility Conditions and Routine Operations

The XNS GPS antenna is mounted on the *-x* base plate of X-SAT, close to the launch adapter (Fig. 1). An antenna pointing direction in the *-z* direction has been selected which assures a zenith looking direction for optimum visibility of the GPS segment in the Earth-pointing mode. However, as the spacecraft will operate most parts of the orbit in the sun-pointing mode, the visibility of the GPS constellation is restricted during these periods. Under pessimistic assumptions, GPS data gaps of up to 30 minutes may arise which may still be bridged by the XNS with an accuracy of the predicted position of better than 100 m. Although in sun-pointing mode the number of tracked satellites does not necessarily drop below four [15], it nevertheless inevitably degrades the achievable orbit determination accuracy. As consequence, a continuous and optimum visibility of the GPS constellation is enforced in dedicated XNS sessions. Here, X-SAT will maintain the Earth-pointing mode for a 48 hour arc once every month to demonstrate high-precision real-time orbit determination.

XNS routine operations are conducted under the responsibility of NTU making use of the X-SAT ground segment. This comprises the regular upload of X-SAT Two-Line Elements on a weekly basis as well as the download of XNS messages. Upon reception of the X-SAT telemetry data stream, the XNS-specific data are extracted by NTU and provided on an FTP server for access and further analysis by DLR/GSOC. The support of DLR/GSOC with commands and, potentially, software uploads is limited to the early operations phase of the XNS as well as to contingency situations.

3. SUMMARY AND CONCLUSIONS

The XNS provides GPS-based precise and real-time orbit determination and prediction functions for the X-SAT satellite mission. Making use of a combination of pseudorange and carrier phase data for ionospheric error removal as well as an elaborate dynamic model of the spacecraft motion, a position reconstruction accuracy of about 1–2 m 3D r.m.s. is aimed at. Compared to previous flight demonstrations of onboard orbit determination algorithms with a position accuracy of about 5 m (as achieved with ONS on the German BIRD satellite), an unprecedented accuracy level will thus be achieved, paving the way for novel applications in the field of autonomous navigation.

Due to the integrated system design of the XNS as well as its low mass and volume characteristics, the accommodation of the XNS on any small satellite is easily achievable. The low power consumption furthermore enables a continuous GPS receiver operation throughout the orbit which facilitates, together with a fast signal acquisition based on available Twoline elements, the operations of the receiver. The precise performance of the XNS at the meter level together with a Pulse-per-Second signal and a flexible output message structure renders the XNS a powerful navigation system for a wide range of applications on small satellites.

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