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PRECISE ORBIT DETERMINATION FOR THE TERRASAR-X MISSION

O. Montenbruck, Y. Yoon, E. Gill, M.Garcia-Fernandez

Deutsches Zentrum für Luft- und Raumfahrt (DLR),
German Space Operations Center (GSOC), D-82234 Wessling, Germany
(E-mail : oliver.montenbruck@dlr.de)

Abstract

The TerraSAR-X synthetic aperture radar mission relies exclusively on GPS tracking for a precise post-facto orbit reconstruction. Besides a redundant MosaicGNSS single-frequency receiver, the satellite carries the Integrated GPS Occultation Receiver (IGOR), which provides low noise code- and carrier phase measurements on both the L1 and L2 frequencies.

As part of the TerraSAR-X ground segment an automated precise orbit determination system has been built up at the German Space Operations Center (DLR/GSOC). The employed reduced-dynamic batch least-squares filter is designed to work with both ionosphere-free L1/L2 carrier phase data and the ionosphere-free L1 code/carrier combination. Depending on the available GPS receiver and measurement types, a 3D rms position accuracy between 1 m (MosaicGNSS single-frequency data) and 5-10 cm (IGOR dual-frequency data) has been demonstrated in pre-mission tests.

Following a description of the TerraSAR-X mission and spacecraft, the paper describes the adopted orbit determination algorithms and processing methodology. The theoretical background is complemented with practical results from the CHAMP and GRACE missions as well as GPS signal simulator tests.

1. Introduction

TerraSAR-X is an advanced synthetic aperture radar satellite system for scientific and commercial applications that is realized in a public-private partnership between the German Aerospace Center (DLR) and Astrium GmbH. TerraSAR-X is a new generation, high resolution satellite operating in the X-band at 9.65 GHz. The launch of the 1-ton satellite into a 514 km sun-synchronous dusk-dawn orbit with an 11 day repeat period is planned on top of a Russian Dnepr-1 rocket for mid 2006. TerraSAR-X is to be operated for a period of at least 5 years and will thus provide SAR-data on a long-term, operational basis.

For the routine generation of image data products, the control center has to provide reconstructed orbits with an accuracy of better than 2 m within 24 hours. This timeline is driven by the fact that only two ground station contacts are available each day for data dumps. In addition to the “Type-2” orbits, a “Type-3” product with 10-20 cm accuracy must be delivered within at most 3 weeks after data collection. To meet the required accuracies, TerraSAR-X is equipped with a set of single- and dual-frequency GPS receivers (Fig. 1).

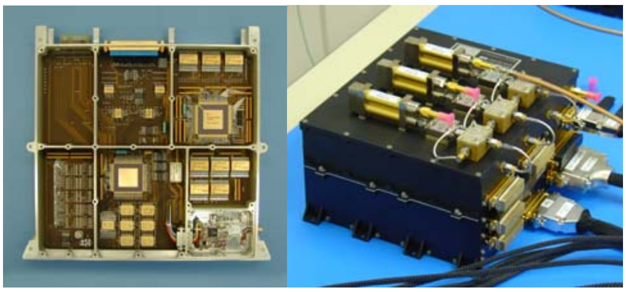

Fig. 1 MosaicGNSS (*left*; © EADS Astrium) and IGOR GPS receiver (*right*) for the TerraSAR-X mission

The IGOR receiver provided by the GeoForschungszentrum (GFZ), Postdam, serves as the primary sensor for high precision orbit reconstruction. It is a successor of JPL’s well-known BlackJack receiver, which has extensive flight heritage on science missions such as CHAMP, GRACE and JA-

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SON-1. The IGOR receiver is only available in a single unit on TerraSAR-X and is therefore complemented by a fully redundant pair of MosaicGNSS receivers built by EADS Astrium. The latter provide real-time navigation and timing data for onboard applications and serve as a backup for ground based orbit reconstruction in case of IGOR failures.

Both receivers have undergone extensive pre-flight testing in a signal-simulator environment to demonstrate their proper functionality and compatibility with the mission requirements ([1],[2]). For elevations above 20°, the IGOR receiver provides C/A- and P1/P2-code measurements with a noise level of less than 20 cm as well as carrier phase measurements with a noise level of less than 1 mm. For the MosaicGNSS representative accuracies of 4-5 m (C/A-code) and 2-3 mm (L1 phase) have been determined in accordance with results given in [3].

2. Reduced Dynamic Orbit Determination

2.1 Overview

In the context of the TerraSAR-X mission, DLR has developed a dedicated software package for GPS-based precise orbit determination (POD). The GPS High-precision Orbit Determination Software Tools (GHOST) are capable of processing both single- and dual-frequency GPS measurements to support a wide range of spaceborne GPS receivers. If only single-frequency measurements are available, the ionosphere-free linear combination of code and carrier phase measurements ("GRAPHIC" data) is employed. All measurements are processed in an undifferenced manner, thus avoiding the need for a world-wide set of ground based reference stations in the data processing. On the other hand, accurate GPS clock products at suitably high data rates are required for best results. These are presently provided by analysis centers of the International GNSS Service (IGS) with delays of one to two days.

GHOST follows a reduced dynamics approach, in which a vector of empirical accelerations is estimated at intervals of typically ten minutes. This technique enables accurate orbit fits even in case of rapidly varying atmospheric conditions. Other estimation parameters include epoch-wise receiver clock offsets, the initial state vector, drag and radiation pressure coefficients, continuous-thrust orbit maneuvers and pass-by-pass carrier phase or GRAPHIC biases. For a one day data arc and a 30s measurement sampling rate a total of typically 4000 parameters has to be adjusted. Making use of adequate factorizations and parameter elimination techniques, the normal equations can effectively be reduced to a dimension of one thousand, which even allows multiple iterations to be performed in due time. Representative processing times amount to less than 5 min for a one day arc using a modern desktop PC.

2.2 Dynamical Model

The GHOST software suite employs a high-fidelity trajectory model for satellites in low Earth orbit (LEO), which builds-up on core algorithms described in [4]. The dominating gravitational acceleration of the Earth is modelled using a spherical harmonics expansion of the gravitational potential (e.g. GGM01S [5]) with a representative degree and order of 100 x 100. The static gravity field model is complemented by models for the solid Earth tide, pole tides and ocean tides ([6],[7]). The modelling of atmospheric drag is based on a Jacchia71 density model ([8],[4]) which provides an adequate accuracy at a moderate computational workload. Finally, the solar radiation pressure is accounted for by a canon-ball model with an adjustable solar-radiation pressure coefficient. Unlike other precise orbit determination software packages, GHOST does not employ sophisticated finite-element models for the non-gravitational surface forces but relies on the geometric strength of the GPS measurements to adjust a tuneable set of empirical accelerations in the radial (R), along-track (T) and cross-track (N) directions.

The equations of motion are formulated in an inertial reference system which is related to the Earth-fixed system through well established transformations of precession, nutation, Earth rotation and polar motion ([9], [4]). While the Earth-fixed reference system is implicitly defined by the employed GPS ephemeris products (typically IGb00), the specified set of transformations realizes an inertial system that is aligned with the equator and equinox of J2000 (EME2000). Differences with respect to the International Celestial Reference Frame (ITRF, [6]) can safely be neglected since the inertial frame is only used internally and all GHOST orbit products are generated in an Earth-fixed frame.

2.3 Measurement Model

The GHOST software processes undifferenced code and carrier phase measurements of a single GPS receiver. Subject to the availability of dual-frequency data, a ionosphere-free combination

$$\rho_{\mathrm{L12}} = 2.546\rho_{\mathrm{L1}} - 1.546\rho_{\mathrm{L2}} \qquad (1)$$

of L1 and L2 carrier phase measurements with a typical noise level of several millimeters is employed. If only single-frequency measurements are available, the GRAPHIC (GRoup and PHase Ionosphere Correction, [10]) combination is used as a substitute. It is formed as the average

$$\rho_{\mathrm{C1L1}} = \frac{1}{2}(\rho_{\mathrm{C1}} + \rho_{\mathrm{L1}}) \qquad (2)$$

of the C/A code and L1 phase measurements and is likewise free of ionospheric path delays. However, the noise level is substantially higher than that of the dual-frequency carrier phase combination and amounts to one half of C/A-code noise (i.e. approx. 2 m for the MosaicGNSS receiver or 10 cm for the IGOR receiver).

In both cases, the ionosphere-free measurements can be modelled as a biased pseudorange

$$\rho = |\boldsymbol{r} - \boldsymbol{r}_{\mathrm{GPS}}| + c\delta t - c\delta t_{\mathrm{GPS}} + B \qquad (3)$$

which differs from the geometric distance of the receiver and GPS satellite by the respective clock-offsets and a bias, which is constant over a continuous arc of uninterrupted carrier tracking. In the above measurement model, the receiver position $\boldsymbol{r}$ and clock-offset $c\delta t$ as well as the bias B constitute unknowns that need to be determined as part of the orbit determination process. The GPS satellite position $\boldsymbol{r}_{\mathrm{GPS}}$ and clock-offset $c\delta t_{\mathrm{GPS}}$, in contrast are considered known quantities. They are independently derived from a world-wide net of GPS receivers operated by the International GNSS Service (IGS, [11]) and provided to the scientific community with latencies of 3 hours (ultra-rapid products) to 13 days (final products). While the accuracy of the GPS ephemerides increases with the time-to-availability, even the ultra-rapid products enable a 10cm-level orbit determination [12]. For best results, IGS products with a 30s step size are recommended for the GHOST software to minimize the impact of GPS clock interpolation errors.

2.4 Least-Squares Filtering

The GHOST suite supports both an extended Kalman filter/smoother and a batch least-squares filter for reduced dynamic orbit determination of LEO satellites using GPS measurements. Even though the batch filtering is more demanding in terms of computational resources, it has been found to be more stable and accurate than the Kalman-filter [13] and has therefore been adopted for the TerraSAR-X mission.

The estimated parameters comprise

- a vector of epochwise receiver clock offsets,
- a dynamical parameter vector made up of the epoch state, the drag and radiation pressure coefficients as well as piecewise accelerations in RTN direction (empirical accelerations or orbit maneuvers), and
- a vector of pass-by-pass carrier phase or GRAPHIC biases.

Code-based a-priori constraints for the bias parameters and the clock-offsets are incorporated into the normal equations to avoid singularities in a purely carrier phase based processing.

Within a 24-hour orbit arc processed at 30s step size, GHOST manages a total of approximately 3000 clock offset parameters and 500 bias parameters. In addition, about 400 unknowns need to be adjusted when estimating a set of empirical accelerations per 10 min interval.

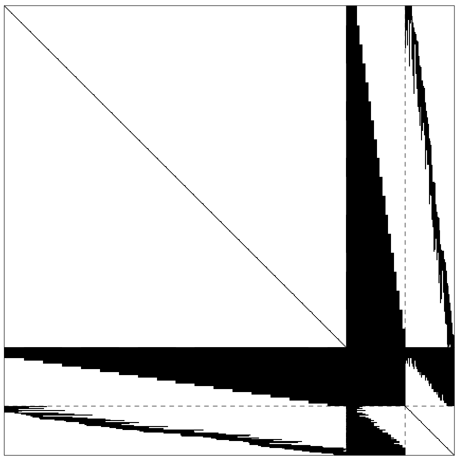

Fig. 2 Structure of normal equations for the adjustment of the clock-offset vector ***T***, the dynamical parameter vector ***Y*** and the bias vector ***B*** ([13]).

Evidently, the large number of estimation parameters represents a major drawback of the least-squares filtering approach. However, the normal equations matrix is not fully populated (Fig. 2) and can readily be handled using a block-elimination technique. As described in full detail in [13], the clock-offset parameters are first eliminated yielding an equivalent, but much smaller, set of normal equations for the dynamical parameter vector and the bias vector. After solving this system, the clock offsets are then determined by a simple back-substitution.

2.5 Data Editing

Due to the large number of adjustable parameters the processing scheme described above is particularly sensitive to erroneous measurements. Also, individual outliers may degrade the solution over extended time intervals due to the coupling of consecutive epochs via common biasees. A careful and robust data screening is therefore mandatory to exploit the full strength of the GPS measurements.

Besides simple checks for elevation cut-off angle and signal-to-noise ratio, faulty measurements are identified and eliminated in the GHOST software through dedicated consistency checks in comparison with a preliminary reference orbit [13]. This trajectory is first constructed by a dynamical filtering of pseudo-range based single-point positions. It exhibits an absolute accuracy of 0.5 m (dual-frequency) to 2 m (single-frequency) and a much higher relative accuracy. Cycle slips or outliers can thus be identified in a reliable manner prior to the actual reduced-dynamic orbit determination.

3. Performance Assessment

In preparation for the TerraSAR-X mission, numerous tests have been conducted to assess the precise orbit determination (POD) performance and the compatibility with the ground system requirements. Aside from the quality of the POD software and its internal modeling, the achievable accuracy depends on

- the type of GPS measurements (single- or dual-frequency),
- the measurements noise and systematic errors,
- and the accuracy of the available GPS orbit and clock products.

Considering the IGOR dual-frequency receiver, GPS measurements from the CHAMP and GRACE spacecraft can serve as a suitable reference for the performance assessment of TerraSAR-X. Making use of GPS data from the CHAMP satellite as well as the GPS orbit and high-rate clock products from the Center of Orbit Determination in Europe (CODE), a 10 cm 3D rms orbit determination accuracy has earlier been demonstrated in comparison with GFZ rapid science orbits [14]. As for GRACE, an even higher accuracy of 5 cm has been achieved in comparison with JPL reference solutions [13] and satellite laser ranging measurements (Z. Kang, priv. comm.). Performance differences between both data sets are attributed to the lower altitude (with increased force model uncertainties) of the CHAMP satellites and a degradation of the measurements caused by cross-talk in the receiver front-end (cf. [15]). In any case, the results clearly demonstrate the feasibility of achieving the Type-3 orbit determination accuracy (10-20 cm) with the available IGOR receiver and the available data processing system. Sample results for a 24h CHAMP data arc are shown in Fig. 3 (top).

To meet the timeliness requirements for Type-2 processing, IGS ultra-rapid orbit and clock data have to be employed instead of the more accurate CODE products. This results in a small degradation of the achievable accuracy when processing dual-frequency data (CHAMP 10-15 cm 3D rms, GRACE 10 cm 3D rms) but is still well within the specified 2 m accuracy.

On the other hand, provision of the Type-2 orbit products for SAR mage reconstruction is mandatory even in the case of an IGOR failure. In the absence of actual flight data from the MosaicGNSS receiver, a long-term signal simulator test has therefore been conducted [2]. The resulting C/A-code and L1 carrier phase measurements were subsequently processed in the GHOST software and the resulting orbit was compared against the simulated truth trajectory. The ionosphere-free GRAPHIC combination formed from the MosaicGNSS raw measurements has a typical noise level of 2 m and the final orbit product was found to exhibit a 3D rms error of about 1 m (cf. Fig. 3, bottom). Despite the much lower performance of the MosaicGNSS receiver, the Type-2 product generation can thus be ensured even without IGOR dual-frequency measurements.

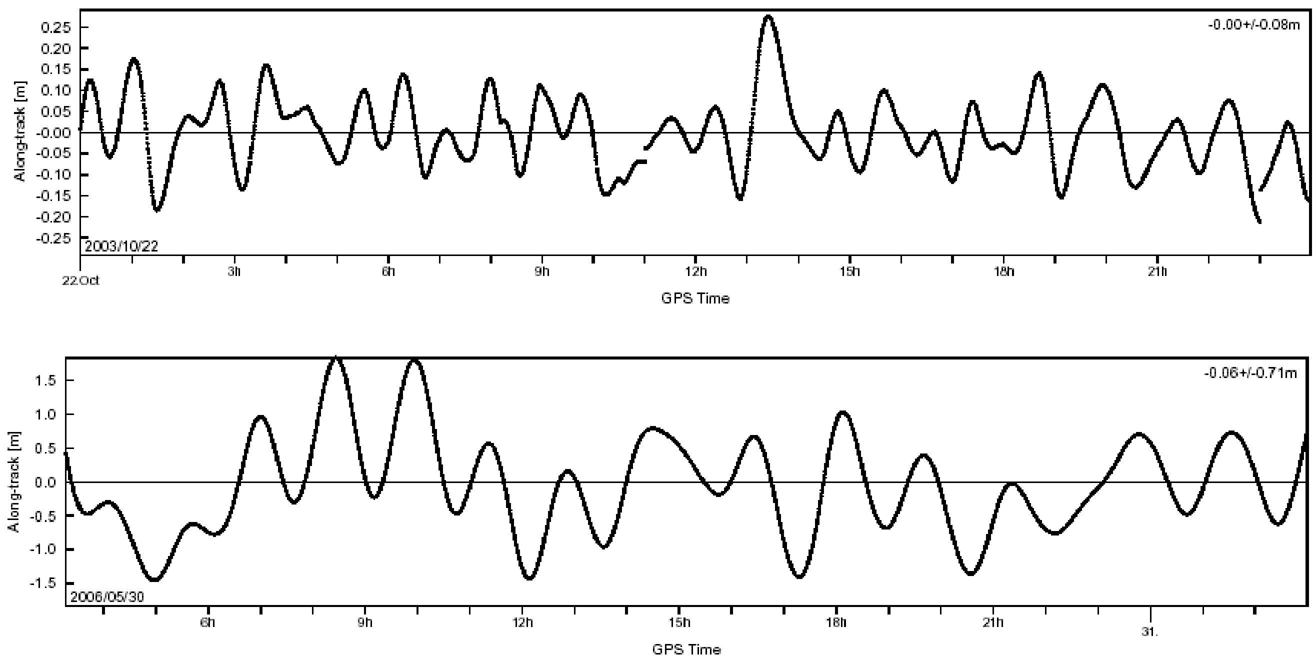

Fig. 3 Errors of CHAMP orbit determination relative to GFZ Rapid Science Orbit (*top*) and error of MosaicGNSS based single-frequency orbit determination relative to signal simulator truth orbit (*bottom*). Only the along-track component is shown in both cases. Note the different scales.

3. Automation and Scheduling

The precise orbit determination system for TerraSAR-X is implemented on a fully redundant Linux cluster and will be operated in a highly automated manner with minimum user intervention. Core processes include

- the retrieval of auxiliary data (GPS orbit and clock products, Earth orientation parameters, solar flux and geomagnetic activity data) from public internet sources
- the telemetry extraction and preprocessing of IGOR and MosaicGNSS raw measurements (RINEX conversion and generation of circular 72h files)
- the telemetry extraction and preprocessing of TerraSAR-X attitude information
- the reduced dynamic orbit determination (including the reference orbit generation for data editing)
- quality and consistency checks (residuals statistics, overlap comparions, etc.)
- the merging of the orbit, attitude and maneuver information in XML format for provision to the TerraSAR-X data archive.

These processes are realized by Perl or shell scripts and executed via cron jobs at regular time intervals.

As an example, the timeline for Type-2 processing is illustrated in Fig. 4. Here, orbit solutions are generated twice per day for the [0h,12h] and [12h,24h] time intervals. The actual data arc is extended by 3 hours at the beginning and end to allow for overlap comparisons. At a total duration of 18 hours, telemetry data from both a morning pass and an afternoon pass need to be received. Likewise, a matching set of (reconstructed) IGS utrarapid GPS ephemerides must be available before starting the respective orbit determination. Processing of the [-3h,15h] data arc can thus commence at 21h UTC, when the latest full set of IGS ultra-rapid data becomes available.

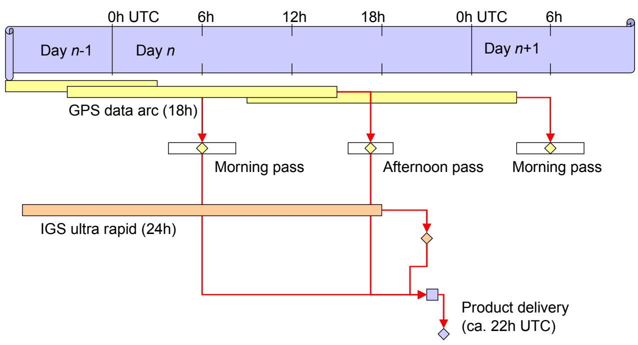

Fig. 4 TerraSAR-X processing scheme for Type-2 orbit determination products

Summary and Conclusions

To satisfy the needs for high-precision trajectory information in the TerraSAR-X mission, an automated reduced dynamic orbit determination system based on GPS measurements has been built-up at DLR/GSOC. Extensive tests conducted with dual-frequency GPS measurements from the CHAMP and GRACE mission demonstrate that the 10 cm 3D rms position accuracy requirement can essentially be met in the Type-2 processing of the IGOR GPS data which makes use of IGS ultra-rapid orbit products. If only the single-frequency measurements from the MosaicGNSS receiver are available, a 1 m 3D rms orbit accuracy can still be achieved which ensures the proper generation of the SAR images (but is inadequate for interferometric applications). The latency for the delivery of precise TerraSAR-X orbit products is presently limited by half-daily data dumps, a three hour latency of the IGS ultrarapid ephemerides and fixed the 12h+6h processing arcs. Alternatively, JPL's real-time GPS ephemeredes can be used to reduced the latency to roughly 15 min after a data dump without sacrificing the 10 cm accuracy limit.

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