FIRST IN-ORBIT EXPERIENCE OF TERRASAR-X FLIGHT DYNAMICS OPERATIONS

R. Kahle, B. Kazeminejad, M. Kirschner, Y. Yoon, R. Kiehling, S. D'Amico

German Space Operations Center (DLR/GSOC)
82234 Wessling, Germany
E-Mail: ralph.kahle@dlr.de

ABSTRACT

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 the Astrium GmbH. TerraSAR-X was launched at June 15, 2007 on top of a Russian DNEPR-1 rocket into a 514 km sun-synchronous dusk-dawn orbit with an 11-day repeat cycle and will be operated for a period of at least 5 years during which it will provide high resolution SAR-data in the X-band.

Due to the objectives of the interferometric campaigns the satellite has to comply to tight orbit control requirements, which are formulated in the form of a 250 m toroidal tube around a pre-flight determined reference trajectory (see [1] for details). The acquisition of the reference orbit was one of the main and key activities during the Launch and Early Orbit Phase (LEOP) and had to compensate for both injection errors and spacecraft safe mode attitude control thruster activities.

The paper summarizes the activities of GSOC flight dynamics team during both LEOP and early Commissioning Phase, where the main tasks have been 1) the first-acquisition support via angle-tracking and GPS-based orbit determination, 2) maneuver planning for target orbit acquisition and maintenance, and 3) precise orbit and attitude determination for SAR processing support. Furthermore, a presentation on the achieved results and encountered problems will be addressed.

INTRODUCTION

On June 15, 2007 the Russian/Ukrainian Dnepr-1 launched the German TerraSAR-X satellite from Baikonour, Ukraine into a sun-synchronous dusk-dawn orbit (inclination 97°, altitude 514 km) with an 11-days repeat cycle. TerraSAR-X will be operated for a minimum 5-years period during which it will provide high resolution SAR-data in the X-Band.

In order to support the S/C AOCS and to enable high-precision orbit reconstruction the satellite bus is equipped with a single frequency GPS receiver and the secondary payload features a dual frequency GPS receiver. During the satellites operation in its Acquisition and Safe Mode (ASM) attitude rate damping and coarse Earth and Sun pointing are performed using the mono-propellant (Hydrazine) 4 x 1 N propulsion system, where the thrusters are slightly tilted in pitch and yaw directions to provide angular acceleration capability in all axes. After stabilization magnetorquers are used as primary actuators for ASM. Upon ground telecommand a transition into the Normal Mode (NOM) occurs, where the spacecrafts attitude is controlled to have a pointing accuracy smaller than 60 arcsec in each axis, which is realized by use of star trackers, reaction wheels and magnetorquers for momentum unloading. The correction of launch vehicle dispersion errors and orbit maintenance is performed in the Orbit Control Mode (OCM), which uses the afore-mentioned Hydrazine system. For a nominal Earth-orientation the thrusters primarily point in anti-flight direction. Thus the satellite has to perform a yaw-slew first to support out-of-plane or orbit lowering maneuvers.

SEPARATION AND FIRST ACQUISITION

The Russian/Ukrainian Dnepr-1 launch vehicle was released from its launch pad in Baikonour, Ukraine on June 15 2007 at 02:14:01.23 UTC. Within the subsequent 925 seconds the burn and separation of first and second stages, the payload fairing jettison and the burn of the upper stage nominally took place followed by the separation of the TerraSAR-X spacecraft from the upper stage within the visibility of Malindi ground-station (the location is depicted in Figure 1). The separation automatically triggered spacecraft activation and OBC boot sequence during which the S-Band transmitter was switched on and started to transmit idle frames. Following a three minutes boot-up sequence the transmission of house-keeping telemetry started. The ESOC Malindi ground-station was able to track the satellite, and received and forwarded the very first housekeeping telemetry to the German Space Operations Center (GSOC) in Oberpfaffenhofen. Based on the telemetry an initial health check could be performed implying green status of all sub-systems, a successful completion of the rate damping process and transition to Earth acquisition attitude mode.

The injection performance is summarized in Table 1. The nominal values for the osculating elements have been propagated based on the Dnepr-1 specification taking into account the slight variations observed for actual platform release time (i.e. 1.23 seconds) and separation time (i.e. -0.21 seconds). The achieved values were reported from the launch provider and are derived from upper-stage measurements. Clearly, all performance requirements (right column) were precisely met.

Table 1. Summary of injection performance

Element (osculating)	**nominal**	**achieved**	**difference (i.e. achieved minus nominal)**	**required accuracy (3-sigma)**
Semi-major axis [km]	6892.742	6892.841	0.099	±2
Eccentricity [-]	0.000029	0.000018	-0.000011	<0.001
Inclination [deg]	97.443	97.440	-0.002	±0.04
Right Ascension of Ascending Node (RAAN) [deg]	173.001	173.003	0.002	±0.05
Argument of Latitude [deg]	179.772	179.776	0.004	n/a

Because of the accurate injection the first acquisition over Malindi could successfully be performed based on the nominal orbit information provided by GSOC before launch. The re-acquisition during the next contacts took place without major problems and without the need for updated orbit information. The time-offset values reported by the stations during the first orbital revolutions were below a few seconds. However frequent updates of the station support products became necessary when the ASM attitude control thruster firings slowly raised the orbit (cf. Figure 2) inducing significant delays in the predicted ground-station events.

The ground track of the spacecraft is shown in Figure 1. The depicted LEOP S-Band TT&C ground station network was chosen in order to respond to the need of extended spacecraft visibility, i.e. on average one contact per orbit should be available in order to safely complete the planned LEOP operations and allow sufficient margin for contingency resolution and fallback plans. The individual stations are:

- Weilheim, Germany as the primary station for uplink, real-time telemetry and house-keeping memory dump downlink. Weilheim is the only remainder of the network when entering the routine operations phase;
- the polar SSC station in Kiruna, Sweden;
- the CSA stations in St. Hubert and Saskatoon, Canada, and
- the aforementioned ESA station in Malindi, Kenya.

Besides, Neustrelitz, Germany serves as the primary SAR-data downlink station in X-Band.

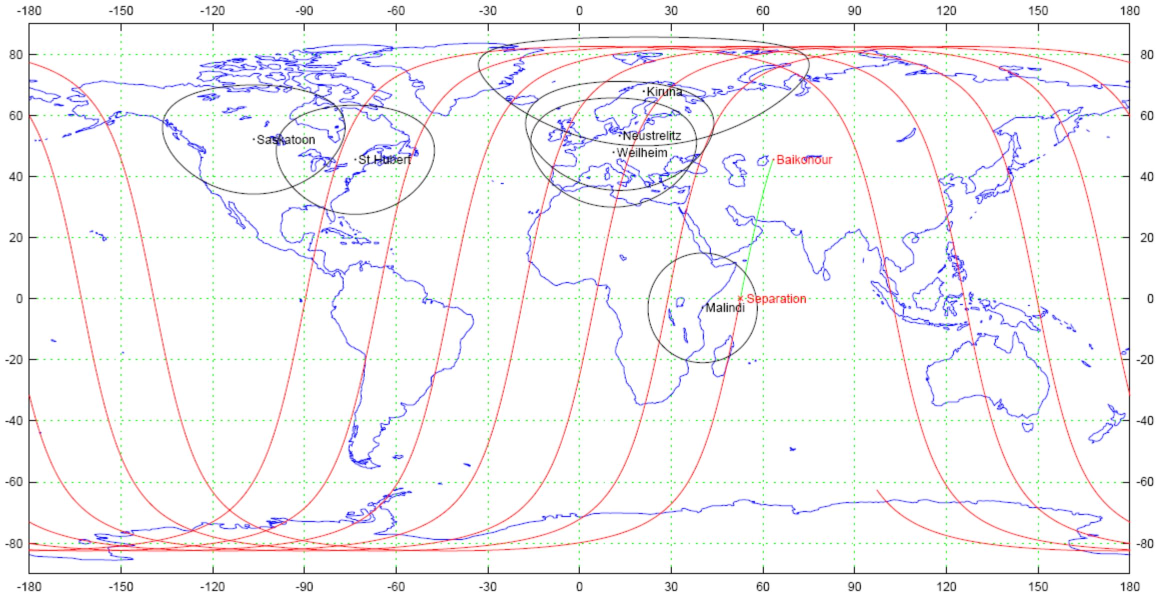

Figure 1. Launcher trajectory (green) and ground track of first 7 orbits (red). Ground station visibility circles are calculated for an elevation of 5 deg.

TARGET ORBIT ACQUISITION

Although the satellite achieved a stable attitude within its Acquisition and Safe Mode (ASM) quite early, the transition in the thruster-free Normal Mode (NOM) had to be repeated several times during the first three days of the mission. Here, diverse settings of monitoring parameters for on-board FDIR functionality had to be adjusted until a robust stay within the NOM mode was achieved. In the meantime safe mode attitude thruster firings mainly lead to orbit raising and significantly increased the orbital deviations compared to the injection performance. The evolution of the semi-major axis up to the moment of stable nominal mode (i.e. MET = 3 days) is depicted in Figure 2. The plot also indicates the locations of the first orbit correction maneuvers as summarized in Table 2.

After reaching a stable NOM mode, the first planned thruster activity aimed on the check-out of the maneuver flight procedure, i.e. the commanding of mode and sub-mode switches and the evaluation of AOCS performance. In order to reduce the complexity an in-flight maneuver was performed instead of anti-flight, which would have been preferred from acquisition planning side of view but requires a 180 deg yaw-slew of the satellite. However, the burn duration was chosen to a minimum of 1 second (maneuver #0, see Table 2) to worsen the orbit as little as possible. The real-time execution took successfully place in the visibility of St. Hubert ground-station. One orbit after a time-tagged anti-flight maneuver (#1) was performed aiming primarily on the calibration of the total active thruster branch and further the check-out of anti-flight AOCS procedure together with a slight correction of orbit altitude (cf. Figure 2). The burn and the back-slew towards nominal orientation were planned within the visibility of Saskatoon in order to have a possibility to abort the burn or to command the satellite in a safe attitude mode. Fortunately none of this was needed.

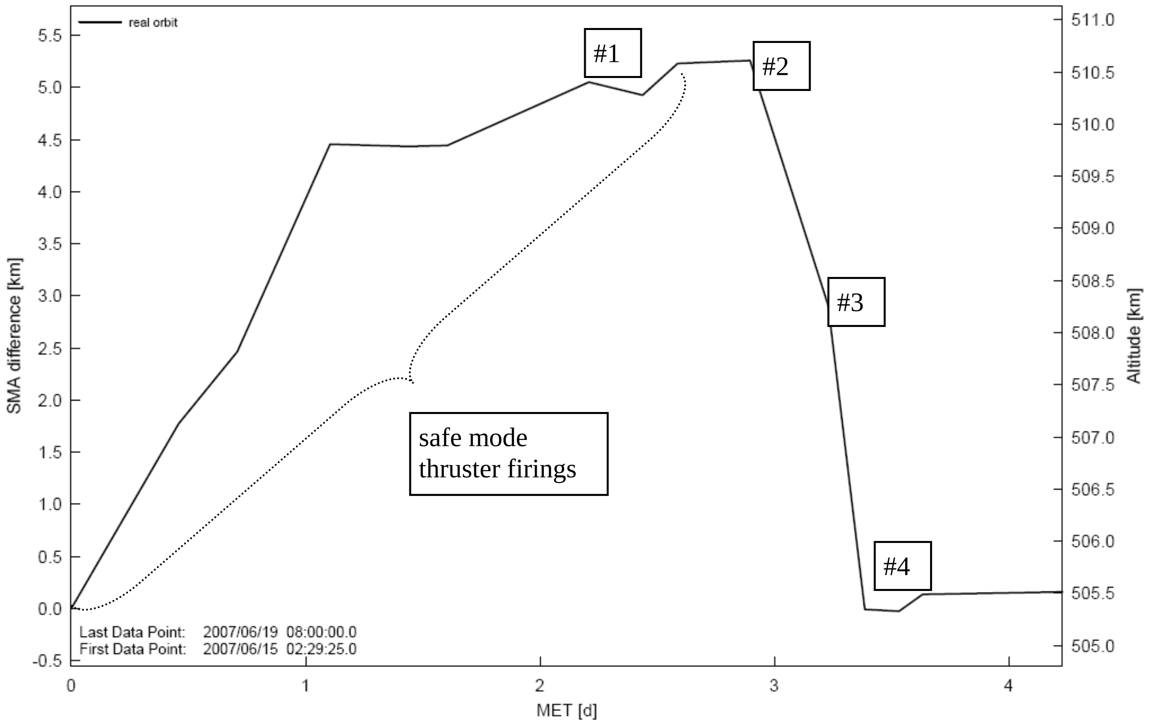

Figure 2. Evolution of relative mean semi-major axis ($\Delta a = a_{TSX} - a_{REF}$) during the first 4 days.

Table 2. Summary of orbit correction maneuvers until moment of target orbit acquisition.

#	Epoch	MET [d]	Δv [m/s]	Direction	Burn duration [s]	Maneuver type
0	2007/06/17	2	0.003	Tangential	1	Procedure test
1	2007/06/17	2	-0.053	Tangential	20	Calibration
2	2007/06/18	3	-1.327	Tangential	500	Drift reduction
3	2007/06/18	3	-1.549	Tangential	600	Drift stop
4	2007/06/18	3	-0.811	Normal	322	Coarse inclination correction
5	2007/06/19	4	-1.426	Tangential	586	Back-drift start and Δe-reduction
6	2007/06/25	10	1.187	Tangential	501	Back-drift reduction
7	2007/06/25	10	1.507	Tangential	650	Back-drift stop and coarse adjustment of e (1/2)
8	2007/06/25	10	-1.326	Tangential	581	Coarse adjustment of e (2/2)
9	2007/06/26	11	0.253	Normal	112	RAAN and inclination adjustment
10	2007/06/26	11	0.064	Tangential	28	Fine adjustment of e (1/2)
11	2007/06/26	11	-0.081	Tangential	35	Fine adjustment of e (2/2)

Having confidence in the OCM, larger maneuvers were planned to align the satellite with its desired target orbit. As depicted in Figure 2 the safe mode firings raised the orbit altitude by 5 km introducing a significant along-track drift. Anti-flight direction maneuvers #2 and #3 were planned to reduce and finally stop that drift respectively by adjusting the altitude with the reference altitude. Further, an out-of-plane maneuver (#4) was performed over Malindi in order to roughly correct the inclination and further to reduce the combined (Δa, Δi) effect on the RAAN rate drift. Because of a small attitude miss-alignment a thrust component in flight direction caused a slight increase of the semi-major axis (cf. Figure 2).

While the locations of the first maneuvers were pre-determined by the need for ground-station visibility, the next maneuvers were placed in order to correct the eccentricity vector towards a frozen eccentricity, i.e. an orbit where the perigee is always located above the North Pole and the geodetic altitude is more or less constant for given latitude. Introducing the argument of perigee ω the eccentricity (e) vector in general is defined as (cf. [2])

$$(e_x, e_y) = (e*\cos\omega, e*\sin\omega), \tag{2}$$

the frozen eccentricity vector as

$$(e_{xf}, e_{yf}) = (0, e_f), \tag{3}$$

and the relative eccentricity vector as

$$(\Delta e_x, \Delta e_y) = (e_x - e_{xf}, e_y - e_{yf}) = (e_x, e*\sin\omega - e_f). \tag{4}$$

The installation process during the LEOP is depicted in Figure 3, where the product of relative eccentricity vector and mean semi-major axis is presented in meters.

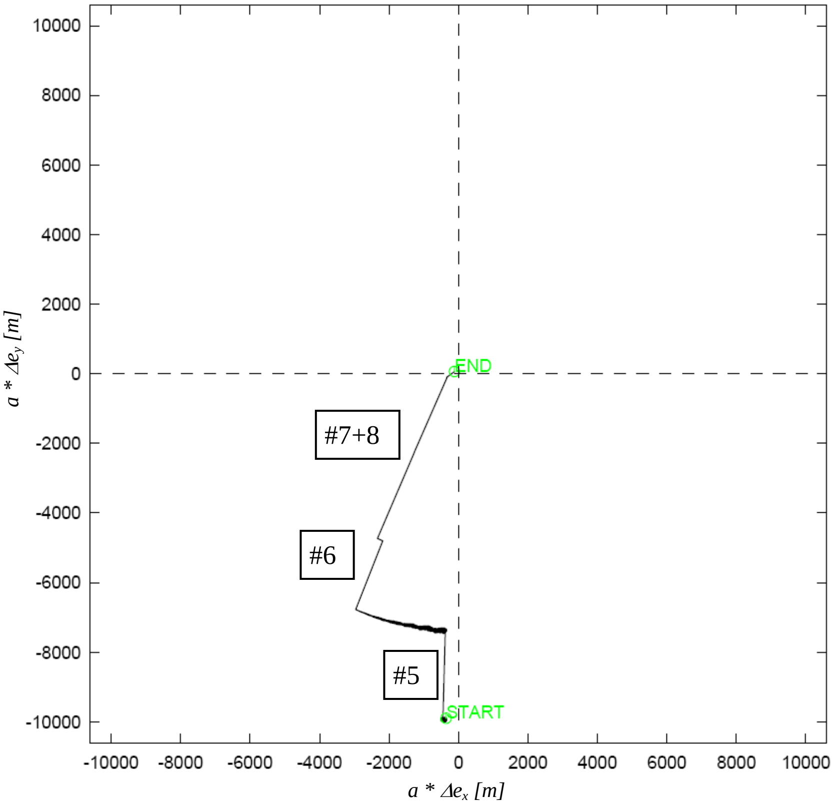

Figure 3. Evolution of product of relative eccentricity vector and mean semi-major axis during MET 4 (Start) and MET 12 days (End).

After the coarse orbit adjustments (maneuvers #1 to #4) an offset of about $1.5*10^{-3}$ in Δe remained (see Figure 3). The locations of the next orbit correction maneuvers were determined in order to have a maximum side-effect on the relative eccentricity.

The anti-flight maneuver #5 decreased the orbital height by 2.5 km (cf. Figure 4) inducing both a reduction of the relative phase (i.e. $a*\Delta u = a*(u_{TSX} - u_{REF})$, where u is the argument of latitude), which was off by more than 2000 km (cf. Figure 5), and a reduction of the relative eccentricity by about $3*10^{-4}$ (equivalent to $a*\Delta e$ of 2 km, cf. Figure 3). The size of the maneuver (cf. Table 2) was driven by the back-drift rate required to achieve the reference orbit within the first 11-days cycle of the mission preceding the SAR instrument commissioning phase. After five days the drift became reduced by maneuver #6, which again aimed on a reduction of the Δe difference.

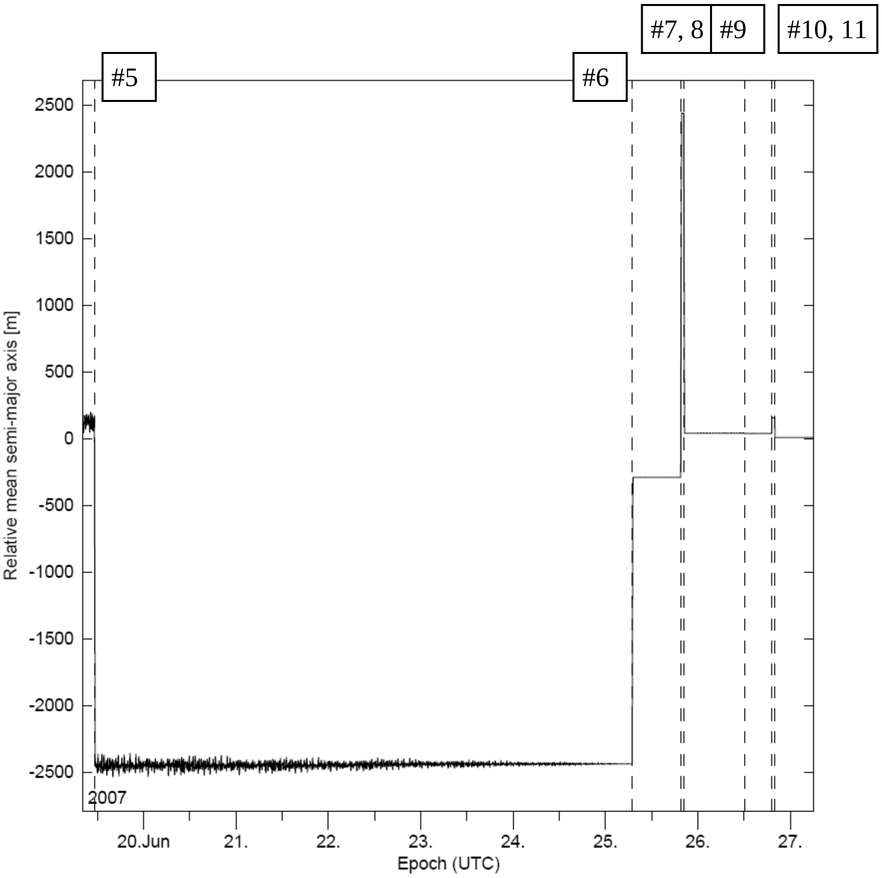

Figure 4. Evolution of relative mean semi-major axis $\Delta a = a_{TSX} - a_{REF}$.

The remaining adjustment of relative eccentricity could not be afforded by other orbit correction maneuvers. Therefore a double maneuver (#7 and #8) comprising of in- and anti-flight maneuvers at opposite orbit positions was performed. This time, the relative phase drift was almost stopped at -7 km distance from the reference position (cf. Figure 5), corresponding to less than -1 sec of flight time.

Finally, the maneuver pair #10 and #11 fine adjusted the relative eccentricity vector. However, both maneuvers were so small (below 10 cm/s each, cf. Table 2) that their effect can hardly be seen in Figure 3. For completeness, the out-of-plane maneuver #9 fine-adjusted both RAAN and inclination.

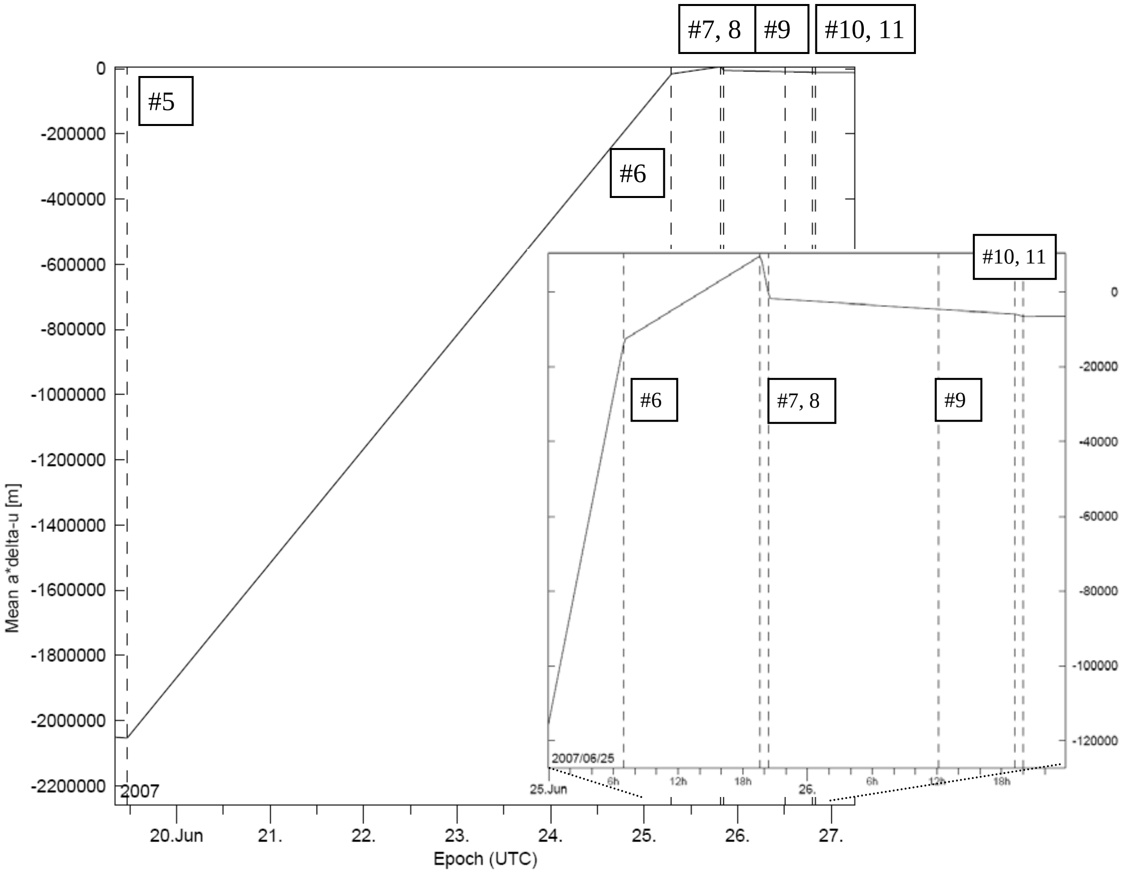

Figure 5. Evolution of relative phase $a^*(u_{TSX} - u_{REF})$.

TARGET ORBIT MAINTENANCE

The achieved cross-track deviation of TerraSAR-X from the reference orbit and its evolution are depicted in Figure 6 and Figure 7. Due to atmospheric drag as well as Sun and Moon perturbations the radial and normal separations vary and would violate the 250 m 1-sigma control requirement. Hence orbit maintenance maneuvers are necessary to keep the satellite within the required limits. To minimize both the interruption of SAR data takes and the total amount of thruster firings, which is limited by acceptance test level that was applied to another mission using the same propulsion system, the maintenance of semi-major axis and eccentricity is simultaneously achieved by a single maneuver at an optimized location (cf. [2]).

After the executions of maneuvers #10 and #11 a maximum normal deviation of -400 m at the ascending node (and +400 m at descending node) was achieved (see Figure 6). However, at this time the radial difference was negative implying a forward motion of the relative phase (i.e. from about -7 km as depicted in Figure 5 towards 0). A change in relative phase is equivalent to a change in relative flight time, which corresponds to a normal displacement at the equator crossing w.r.t. reference orbit. For example, a change in $a\Delta u$ by 7.6 km corresponds to a change in relative flight time of 1 sec which is equivalent to 500 m normal displacement. This interrelation can be seen in Figure 6 where the red-plotted normal displacement at the ascending node evolves from -400 m towards +250 m.

When reaching the upper control limit the in-plane maneuver #12 ($\Delta v = 0.01$ m/s) was triggered to change the semi-major axis by about 20 m achieving a positive radial error and hence a back-drift of both relative phase and normal displacement. The orbital decay of TerraSAR-X naturally stops that back-drift (i.e. when reaching $\Delta a = 0$ (close to July 11 in Figure 6)) and initiates a forward-drift. The resulting parabola-shaped evolution of the normal error in Figure 6 is characteristic for a maneuver cycle.

Care has to be taken when controlling the relative eccentricity vector. Due to the required maximum difference of ±250 m cross-track w.r.t. the reference orbit a deviation from the frozen orbit mainly affects the cross-track error in radial direction. To stay inside the tube the maximum permitted error for the eccentricity is about $3.6*10^{-5}$ according to

$$r_{peri} = a*(1-e) \tag{1}$$

where r_{peri} is the radius at the perigee. The main contribution to the radial error comes from the orbital decay by atmospheric drag. In order to maximize the time between two orbit maintenance (i.e. orbit raising) maneuvers the difference to the frozen eccentricity vector should be kept as small as possible. Because of the low solar activity the current duration of a maneuver cycle is on the order of 2 to 3 weeks.

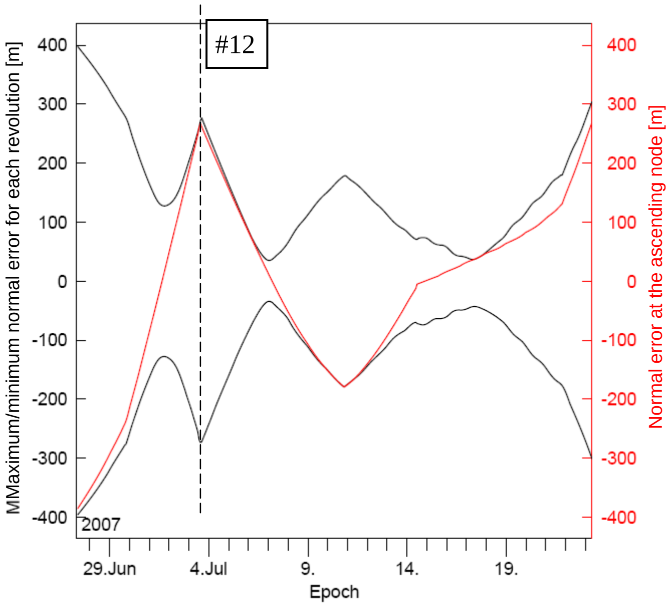

Figure 6. Evolution of normal error during orbit maintenance phase.

The total cross-track error for the time from target orbit acquisition (i.e. June 27th) to completion of first orbit maintenance maneuver cycle (i.e. July 23th) is depicted in Figure 7. Clearly, the 1-sigma 250 m control requirement could be achieved proofing both theory (see [3] for details) and implementation of the complex control algorithm.

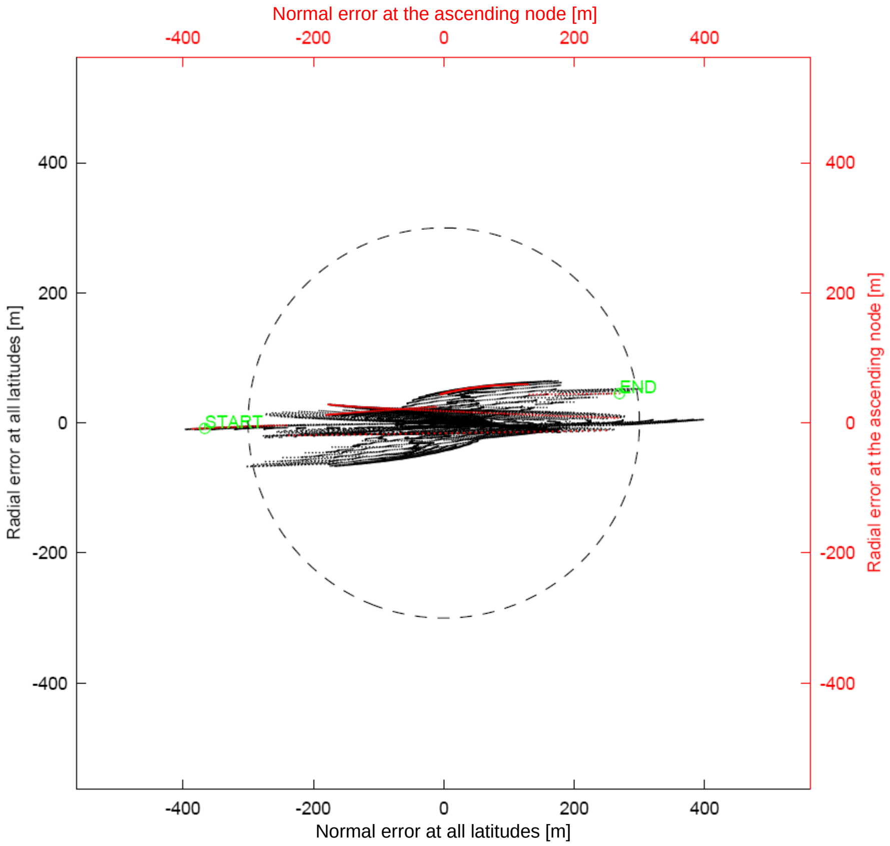

Figure 7. Evolution of normal and radial error during orbit maintenance phase (depicted interval starts at June 27 and stops at July 23).

PRECISE ORBIT AND ATTITUDE DETERMINATION

The maneuver activities described so far were planned by dedicated S/W for target orbit acquisition and 250 m tube control. For both processes it is mandatory to have precise knowledge on the current orbit. Further, for the routine generation of SAR image data products, GSOC has to provide reconstructed orbit and attitude information. The underlying processes of orbit and attitude determination of TerraSAR-X will be addressed in this section.

For the period shortly after the S/C separation, the rapid orbit determination (ROD) was performed based on tracking angle measurements obtained from the LEOP network ground stations. During the first orbits there were mainly Malindi and Kiruna. In order to have more precise and frequent measurements, the on-board GPS receiver was switched-on during the Malindi contact within the 2nd orbital revolution. Thereafter the dumped GPS navigation solution data was exclusively used for orbit determination and prediction.

The ROD performs a least-squares batch adjustment of the following estimation parameters: epoch state vector (position and velocity), drag coefficient, solar radiation coefficient, extended maneuvers, and measurement biases. As a result of ROD and orbit prediction, the following products are made available to the ground-segment:

- Type 0 (Predicted) orbit product with 700 m required accuracy (along-track, 1-sigma);
- Type 1 (Quicklook) orbit product with 10 m required accuracy (3D, 1 Sigma).

The achieved accuracies are 70 m for Type 0 and 3 m for Type 1 when using the navigation data from the secondary payload dual-frequency TOR-IGOR GPS receiver. The achievable accuracy for the Type 0 product (i.e. 24h prediction) will change within the 5 years mission life-time and is expected to degrade during periods of moderate and high solar activity (cf. [4]). Based on the ROD results, orbit related products are regularly generated and distributed, e.g. pointing data and two-line elements for S-Band ground station support, input to mission operations sequence of event planning, and orbit parameter messages for laser tracking support.

The precise orbit determination (POD) is performed based on the GPS carrier phase and pseudorange data obtained from the dual-frequency GPS receiver. Auxiliary data such as the GPS orbit and clock products, Earth orientation parameters, and S/C attitude information are acquired prior to the generation of the precise orbits. The latency of the auxiliary data drives the availability of individual POD product types, i.e.:

- Type 2 (Rapid) orbit product with 2 m required accuracy (3-D, 1-sigma);
- Type 3 (Science) orbit product with 20 cm required accuracy (3D, 1 Sigma).

A reduced dynamic orbit determination process generates the Type 2 product using the commercial JPL real-time GPS orbit and clock products. The achieved radial and 3D accuracy are better than 10 cm and 20cm respectively, which even fulfills the Type 3 orbit accuracy requirement of the mission.

The delivery of the Type 3 product is dependent on the latency of the AIUB/CODE rapid GPS products. If this is unavailable, the IGS final orbits and 30s clocks are used as an alternative. For the first case Type 3 products are generally made available within 4 days at the earliest. The achieved absolute accuracy can be quantified from an external verification by means of satellite laser ranging measurements. Here, the average range bias between the laser range measurements and the GPS-based generated orbits is better than 10 cm for both the precise orbit products at high elevation passes. It is important to note that both the Type 2 and 3 orbit accuracies are achieved even for periods with orbit maneuvers. The POD software is capable of handling the orbit maintenance activities by treating them as constant accelerations over the maneuver burn duration. Detailed information on orbit maneuver handling within the POD software can be found in [5].

The three-axis attitude determination and analysis is performed based on dumped AOCS housekeeping data comprising among others of sensor measurements from Coarse Earth & Sun Sensor (CESS) and star trackers. CESS measurements were considered for AOCS analysis before the period of star-tracker check-out. Thereafter precise S/C attitude has been determined based on star-tracker measurements and AOCS status data in order to generate an attitude product with 0.01 deg accuracy (3D, 1-sigma). Aiming on more accurate results, optimal quaternion combination is applied whenever simultaneous measurements from two or three of the differently aligned star-trackers are available.

Because of unavailable reference information an external verification of the attitude product accuracy is not feasible. However, an implicit verification by means of SAR mono-pulse and Doppler measurements will be performed by the instrument calibration team in order to determine the total misalignment of the instrument.

AUTOMATION STATUS

So far, most of the TerraSAR-X GSOC Flight Dynamics functionalities have been automated after successfully passing manual test phases within the LEOP and early Commissioning Phase. While the generation of operations support products, e.g. orbit data messages, and the POD including Type 2 and 3 orbit product generation run at pre-defined times twice a day, other functionalities are embedded in a processing chain that is triggered by the availability of new housekeeping dump data, which is typically provided by the Weilheim ground station having two morning and two evening passes per day on the average. Here, the attitude determination and maneuver screening process runs at first generating attitude input for both POD and ground-segment distribution. The extracted maneuver information is made available to the subsequent rapid orbit determination process. Finally, Type 0 and Type 1 orbit products are generated. The dump-triggered sequence is generally finished within less than 15 minutes.

The automation was complicated by corrupted or missing house-keeping dump data, which occurred quite often especially during the LEOP. At that period the amount of telemetry requested by all sub-system engineers was much higher than during nominal operations leading to the need of additional dumps outside

Weilheim. The transfer and processing of the non-nominal dump often delayed or even perturbed the complete dump pre-processing. Together with other anomalies like data losses during zenith passes (i.e. keyhole problem), wrong time stamps in telemetry packets or server problems a reliable data delivery was not given. Nowadays the problems are solved and the automated scripts are robust enough to compensate for minor data gaps.

Finally, the automation of the maneuver planning process for target orbit maintenance remains as a future activity. Since it is the most critical area, the upcoming weeks will be used to gain more experience in both handling the software and operating the satellite. Thereafter only special activities such as the 30 m tube control for supporting interferometric campaigns will have to be supported manually.

CONCLUSIONS

The TerraSAR-X satellite was successfully launched and injected on June 15, 2007. A total of 11 orbit correction maneuvers were performed in order to compensate for launcher and safe mode induced orbit deviations and to acquire the targeted reference orbit within the first 11-days repeat-orbit cycle. After completing the drift into the 250 m cross-track control tube, the maintenance of the orbit within the tiny control-area could be demonstrated. Currently the processing sequences for orbit and attitude determination and related product generation are both validated and already automated. The automation of the maneuver planning for orbit maintenance remains as a future activity.

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