TanDEM-X Close Formation Flight
AOCS Safety Measures and Operations

J. Herman[1], D. Schulze[1], S. Löw[1]
[1]*DLR, 82234 Wessling, Germany*

Abstract

The TanDEM-X project is implemented by a "Public-Private Partnership" between the German Aerospace Centre (DLR) and Astrium GmbH.

The primary goal of the TanDEM-X (**T**erraSAR-X **a**dd-o**n** for **D**igital **E**levation **M**easurement) mission is to generate a global digital elevation model. To achieve this, two satellites – TerraSAR-X (TSX) and TanDEM-X (TDX), satellites of almost identical construction in orbit since June 2007 and June 2010 respectively – form the first configurable SAR (Synthetic Aperture Radar) interferometer in space with a separation of only a few hundred metres. A powerful ground segment, which is interlaced with that of TSX, completes the TanDEM-X system. The satellites fly in close formation since December 2010 and will be operated in parallel for three years to cover the entire surface of the Earth.

DLR is responsible for the scientific exploitation of the TSX/TDX data, as well as for planning and implementing the mission, for controlling the two satellites and for generating the digital elevation model. Astrium has built the satellites and shares in the costs of development and exploitation. The responsibility for marketing the data lies in the hands of Infoterra GmbH, a subsidiary of Astrium GmbH.

AOCS operations for two spacecraft flying at low altitude with such unprecedented small separations pose several challenges and required creative solutions, mostly stipulated by the fact that the original mission was not designed for formation flight. Several on-ground safety measures were installed, but due to the short reaction times emphasis lies with the on-board handling of problems. This is achieved by implementation of a data link (one-way) between the satellites, by the regular interchange of a "health" signal (two-way), by the design of a new AOCS safe mode that has no effect on the orbit, by the complete re-work of the FDIR concept (Fault Detection, Isolation and Recovery on-board) and by autonomous formation control.

Emphasis in this paper is on the implemented safety measures, specifically the FDIR concept which will be presented in Section 1.5.2. and on the routine AOCS operations during close formation flight (Section 2). No major contingencies have occurred in the formation so far – something we don't want to change in the future either – but some minor operational issues did occur, which will be presented in Section 3. Section 4 finally gives some conclusions and an outlook on the way forward.

1. Introduction

1.1. Launch and reference orbit

TerraSar-X was launched from Baikonur on June 15, 2007 in a Sun-synchronous dusk-dawn orbit at an altitude of about 515km. Ground coverage is repeated in an eleven day cycle, which is achieved by controlling the spacecraft in a ±250m tube around a prescribed Earth-fixed reference orbit [7].

The second satellite was also launched from Baikonur almost exactly three years after the first, namely on June 21, 2010. The initial distance of 16000km was soon reduced, a first formation at <2km was reached mid of October and the TanDEM mission proper started in December 2010 with an inter-satellite distance of ~300m (see [8] for formation acquisition).

TDX hard- and software are a rebuild of TSX, but some significant changes were made to enable close formation flight. The major changes in the AOCS comprise:

- Cold gas system with 2x4 0.04N thrusters for formation-keeping manoeuvres; the thrusters are located on the spacecraft's length axis at the front- and back-sides.
- S-band receiver / decoder for TSX telemetry via inter-satellite link (ISL); 35 words with about 120 of the most important health parameters are relayed.
- Algorithms for autonomous formation flight; GPS measurements are used for orbit determination, prediction and planning of cold gas manoeuvres.

1.2 Instrument Operations

SAR data takes are normally made under a 33.8° looking angle towards the dark side of the Earth ("right-looking" or NOM-RL), but it is also possible to roll the spacecraft over 67.6° to make a so-called "Sun-side-looking", or "left-looking" data take (also NOM-SSL; see Fig. 1 for an example). Images can be made in several instrument modes and spacecraft formations with ground resolution ranging from ~0.5m to 16m and an area covered from ~50km^2 to 104km^2. A more detailed description of the several options can be found in [6] and [11].

The attitude in the standard operational modes is controlled within 0.3mrad (3σ) using Astro 10 star trackers from Jena-Optronik GmbH and four reaction wheels from Rockwell Collins Deutschland GmbH with a torque capability of 0.2Nm. Continuous wheel unloading is performed with the magnetic torque rods that are mounted parallel to the spacecraft's axes. A Mosaic GPS receiver from Astrium GmbH is used for position and velocity determination, as well as for the time synchronisation on-board (see [2] for a detailed description of all sensors and actuators).

1.3 Orbit correction manoeuvres and formation-keeping

TSX was during the first three years and still is controlled on its reference orbit (Section 1.1). Orbit correction manoeuvres are made with a hydrazine propulsion system, which is pressurised by helium and operated in blow-down mode. The thrusters are arranged in two branches with four 1N thrusters each that are all located at the rear of the satellite (not visible in Fig. 1, which is a front view). Inclination manoeuvres, or manoeuvres in anti-flight direction thus require a ±90° or 180° yaw slew. All hydrazine manoeuvres on TSX are mirrored on TDX as long as they are in close formation.

TDX has an almost identical orbit, but it describes a helix around the first satellite's trajectory. The relative helical orbit is achieved by so-called ***e***-,***i***-vector separation (relative eccentricity / relative inclination, whereby maximum cross-track separation occurs at the equator and maximum radial separation at the poles [5,8,9,10]). Both spacecraft carry out the standard hydrazine manoeuvres with the same Δv (velocity increment), which due to their different ages and hence remaining hydrazine pressure are realised with distinct thruster on-times. In addition, formation keeping- or reconfiguration- manoeuvres are made by TDX alone with the cold gas system, which comprises two 0.04N thrusters on front and back each (see Section 2.3. for the practical implementation).

1.4. Communication between the two spacecraft

1.4.1. Inter-satellite link

The existing S-band downlink system on TSX is used to relay important health data to a dedicated receiver/decoder added on TDX. Note that the traffic is one-way, because a corresponding receiver is not available on TSX. A full description of the ISL can be found in [1] and some of the limitations are listed in [6].

1.4.2. Sync pulses

Bi-static operations, where the SAR signals of the one spacecraft are also detected by the other, require synchronous processing of both data takes. The synchronous start of data takes is achieved by exchanging "sync pulses" based upon the GPS sync signal at a rate of ~5 Hz (configurable). Sync pulses are transmitted and received by six horns, which are mounted in such a way that *4π steradians* coverage is achieved. Best signal-to-noise ratio is obtained by selecting the appropriate pair.

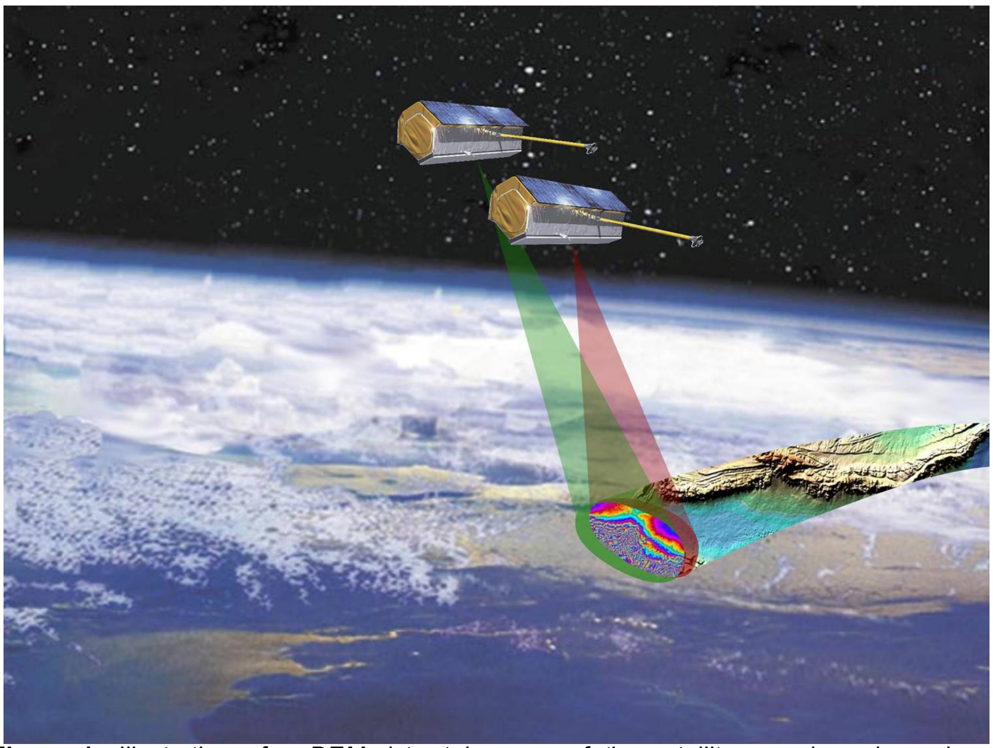

Figure 1. Illustration of a DEM data take; one of the satellites sends radar pulses illuminating a swath, or a hot spot on the Earth's surface. The back-scatter is detected by both SAR antennae enabling the construction of a digital elevation model. The orientation of the satellites indicates that in this case a "left-looking" data take is made. Note that pulses can only be sent if the second spacecraft is not in the beam. In a special application pulses are sent alternating from each spacecraft and received by both. No other configurations will be routinely used, apart from the stand-alone mode [11].

1.4.3. Sync warning data takes

Sync warning data takes are normal, albeit very short, data takes where the signal is sent out by one satellite and detected by the second. Again a selected pair of sync horns is used for this operation and not the SAR instrument. A positive result will allow SAR data takes on the receiving side for the next 50 minutes.

The aim of regular sync warning data takes is to detect any problem – e.g. a drop to AOCS safe mode – on the sending satellite in which case instrument operations on the receiving spacecraft will immediately be suspended.

1.5 Safety Measures

The two major risks for spacecraft flying at a separation of the order of a few hundred meters only are:

- Instrument damage by radiation; a direct hit of the SAR signal, which delivers pulses of kW strength, in the instrument of the second satellite would be up to nine orders of magnitude stronger than the normally detected back-scatter from the Earth's surface, which is of the order of µW.
- Collision; uncontrolled changes of the orbit can lead to a considerable increase of the collision risk.

Both points are primarily guarded against by avoiding uncontrolled orbital changes. This is achieved by an AOCS safe mode that doesn't use the thrusters accompanied by an elaborate FDIR scheme. Frequent contacts and permanent on-call support by key personnel will in every "nominal" contingency case suffice to prevent any thruster activity at all. Radiation damage is furthermore prevented by implementation of so-called exclusion zones, orbital regions where the sending of radar pulses is forbidden to one of the satellites and by inhibiting signals to be sent out in case of problems.

1.5.1. Magnetorquer safe mode (ASM-MTQ)

A second safe mode branch was implemented on both satellites with the magnetic torque rods as the sole actuators [2]. It still uses CESS, magnetometer and IMU as sensors, just like the original thruster-based safe mode (ASM-RCS). The torque rods and magnetometers are operated in alternation to allow disturbance free measurements of the Earth's magnetic field.

The concept has been extensively tested in flight on both spacecraft under quite harsh circumstances. One satellite was for example sent into ASM-MTQ at maximum yaw slew velocity of 0.5°/s near the South-Pole, where control of the yaw-axis with magnetorquers is impossible. Still, the mode proved to be robust and full stabilisation was obtained within two orbits. ASM-MTQ thus presents the possibility to avoid orbital changes completely in case of an AOCS safe mode entry.

1.5.2 FDIR concept

The FDIR concept for close formation flight is shown in Fig. 2. The major changes with respect to the original TSX implementation are:

- The magnetorquer safe mode (ASM-MTQ).
- Limited thruster on-time at first thruster-based safe mode (ASM-RCS) entry.
- Surveillance of the ISL, TAFF (on-board algorithms for autonomous formation flight), sync pulses and sync warning data takes.
- System-level reactions, comprising safety measures in several sub-systems in parallel. The reactions also extend to the second satellite, where e.g. data takes will be inhibited in case of a safe mode on the first.
- Additional power/thermal monitoring functions.

Entry point in case of problems in one of the operational modes will always be ASM-MTQ-RD (rate damping in magnetorquer safe mode). This will first of all suspend all payload operations on both satellites (the second one via ISL or missing sync warnings). A board-autonomous sequence will bring the spacecraft in Earth/Sun acquisition mode (ASM-MTQ-AQ) once the rotation rates are below a certain threshold that is currently set at 0.14°/s. If the rates are not below the specified limit after ~3 orbits, an on-board computer (OBC) warm boot is triggered after which the spacecraft returns to ASM-MTQ. Only after a 5th OBC reboot the thruster-based safe mode with un-limited *Δv* will be invoked.

A second board-autonomous transition into the operational modes occurs when full stabilisation could be achieved in ASM-MTQ-AQ (Earth- and Sun-pointing ≤10° and ≤15° respectively, and rates ≤0.074°/s).

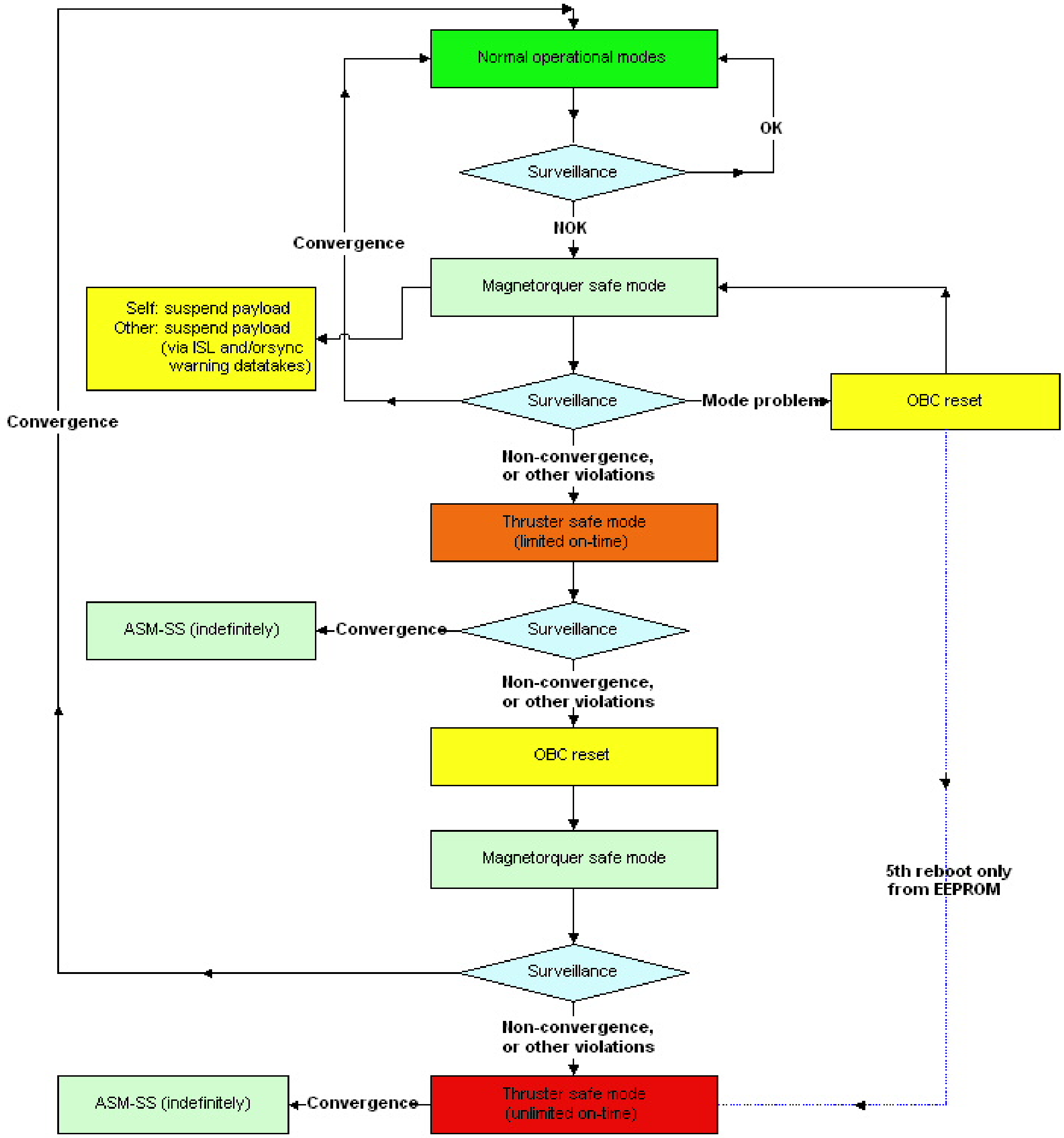

Figure 2. FDIR scheme used for formation flight on both satellites. The nominal operational mode is on top of the diagram (see also [2], their figure 8.2-7)

Some unlikely circumstances could necessitate leaving ASM-MTQ for ASM-RCS (at first with limited on-time). The cases are a) rotation rates >2°/s that can't be handled by the torquers, b) non-convergence after three orbits and c) violations of critical power or thermal constraints (see also [6]). Then the thruster-based safe mode is invoked, but with a total Δv limited to an amount that can not threaten the formation.

The spacecraft is put into ASM-SS (steady state in ASM-RCS, which uses – almost – solely the torquers) indefinitely if full convergence is reached with the limited amount of Δv. If this was not yet the case when the Δv limit is reached, an OBC warm boot is made after which another try in magnetorquer safe mode begins (this time with somewhat wider power/thermal limits).

This sequence is tried only once. When there is still no convergence, or the power / thermal problem persists a transition to ASM-RCS with unlimited thruster on-time is made as a last resort. The extremely unlikely cases in which the unlimited thruster safe mode could be reached are listed in [6] (one example would be *both* magnetometers defunct).

1.5.3. Station coverage

The FDIR concept dictates the desired interval between contacts. The current implementation normally guarantees at least 2x3 orbits, or roughly ten hours in total during which no, or at most limited, orbital changes will occur when the satellite drops to safe mode. Contacts are therefore separated by six hours at the most allowing timely discovery and recovery to be made (see [4] and [6] for more details).

1.5.4. On-call strategy and automatic data surveillance

An extended on-call service is provided for the TanDEM mission. A complete description can be found in [4]. Data surveillance will be discussed in Section 2.1.

1.5.5. Exclusion zones

Radiation damage is also avoided by prohibiting data takes when the second satellite is passing through the beam of the first. Both "right-looking" and "left-looking" must of course be accounted for. The duration for crossing the exclusion zone depends upon inter-satellite distance and along-track separation. The extent is roughly ±30° and it is directed either to the dark, or to the illuminated side of the Earth depending upon whether a normal, or a left-looking data take is planned. A considerable safety margin is comprised within the 60°. The exclusion zones are made even larger (e.g. ±45°) after orbit manoeuvres. An illustration is given in Fig. 3, where the formation is seen along the flight trajectory. Checks are performed not only on ground when planning the data takes, but also on-board before they will actually be executed.

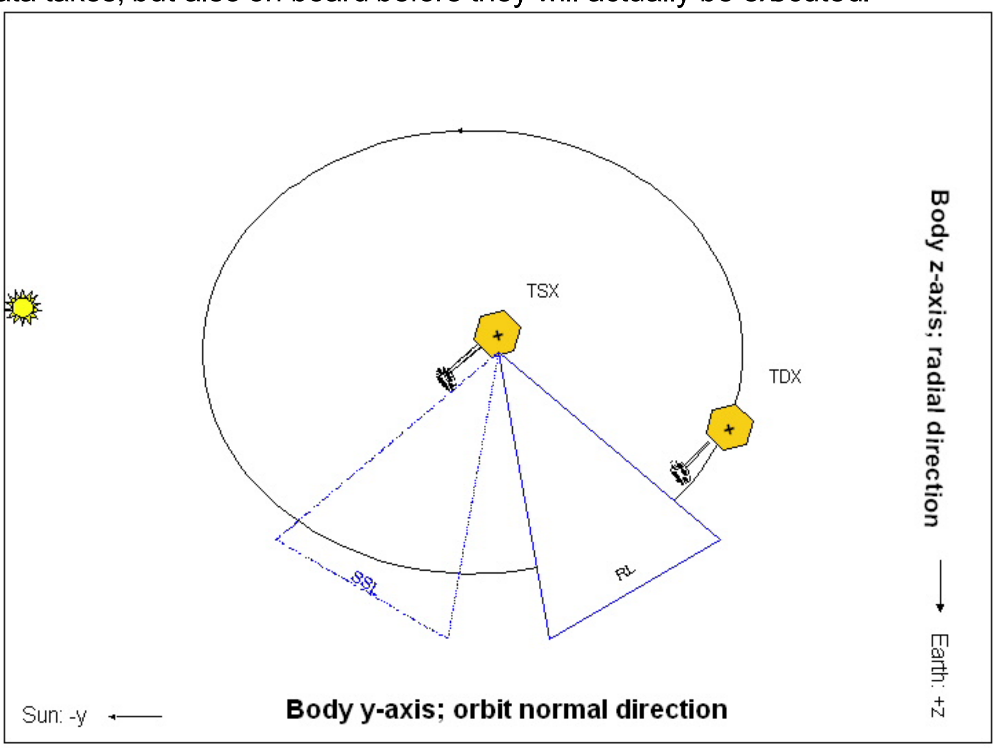

Figure 3. An example is shown of TDX just exiting the exclusion zones of TSX. View is along the flight trajectory with TSX fixed at the centre. The two areas show the exclusion zone for the "right-looking" and "left-looking" modes of TSX, respectively and are ±30° each.

2. Routine operations

2.1. AOCS surveillance

Hundreds of variable parameters, such as attitude errors, actuator commands, sensor performance, etc., are continuously monitored on-board. Limit violations are flagged yellow or red during contacts, depending upon the severity. Dump files covering 100% of the time are screened with the same limit settings and an automatic E-mail notification with detailed information is sent out to responsible personnel in case a violation is detected.
Several hundred AOCS parameters more can be commanded to a desired setting, but will normally remain constant for a longer time. These parameters are dumped at least once per day and compared with a file containing the currently desired settings. The complete AOCS FDIR tables are dumped at least once per week and also compared with the defaults. These routinely made checks safeguard against spontaneous bit-flips on the one and against commanding errors on the other hand.

2.2. Resources, analysis and parameter adjustment

Routine AOCS operations furthermore comprise offline calculation and administration of the expended cold gas and hydrazine fuel as well as the registration of the number of thruster cycles and mode switches. Use of resources is converted into a mission life expectancy (see Fig. 4 for an example). Long-term analyses are made among others of CESS and reaction wheel performance leading e.g. to parameter adjustment or lubrication to reduce friction.

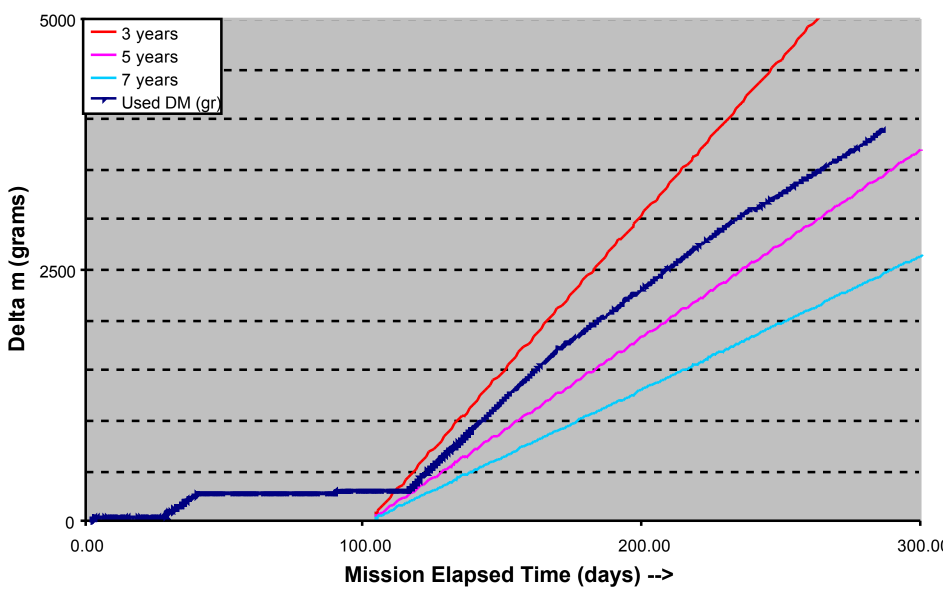

Figure 4. Cold gas expenditure as computed from the tank pressure and temperature is shown as a thick blue line. The onset of the close formation four months after launch is clearly visible. The other lines show the fuel usage expected for several mission durations. It can be seen that the 3 years required to complete the DEM (digital elevation model) of the Earth are easily attained.

Several parameters need regular updates, e.g. because of seasonal or secular variation, because of formation changes, or due to pressure dependency. A good example is the limit for the on-time in ASM-RCS's first entry (see Section 1.5.2.). The allowed amount of Δv (e.g. in cm/s) depends of course on the actual formation and inter-satellite distance. The corresponding FDIR limit on-board is set in seconds of thruster on-time, however. The conversion of velocity increment into seconds depends upon the hydrazine pressure, which is decreasing with time and is also different for TSX and TDX.

2.3. Manoeuvres

The strategy for orbit correction and formation keeping manoeuvres was discussed in Section 1.3. Here the practical implementation is presented.

2.3.1. Simultaneous orbit corrections (hydrazine)

These manoeuvres are calculated by the flight dynamics group, who also send out an E-mail announcing that a simultaneous burn on both satellites is planned. The operators have to confirm the upload of *both* AOCS procedures that actually perform the manoeuvres on-board. The procedures contain two build-in safeties; a heater switch-off command after a fixed time and a timer set to a value just over the desired on-time. Both would interrupt any ongoing manoeuvre and thus guard against commanding errors. An FDIR will close the entire branch if a thruster is stuck open. Another FDIR, finally, which is available on TDX only, checks shortly beforehand via ISL whether the propulsion system on TSX is ready to perform the manoeuvre. If such is not the case, it will inhibit the manoeuvre on TDX also.
Data takes are prohibited in a certain time window (roughly 10 min. without slew) around hydrazine manoeuvres. It is also guaranteed that any underperformance on either satellite (down to no burn at all!) does not enhance collision (planning of location and size) or radiation risk (increase of exclusion zones).

2.3.2. Formation keeping (cold gas)

Execution problems on the cold gas manoeuvres do not have such grave consequences as for the hydrazine system, the thrusters being a factor of 25 weaker. Still, safety measures are in place, that limit the total number of manoeuvres per orbit and also the duration of each individual burn to 300s, which yields a maximum Δv that can not threaten the formation. Passive safety is given by the fact that the formation is stable for at least a week (9.5 days are actually expected) without any manoeuvres at all. This also safeguards against failed, or only partially carried out cold gas manoeuvres.
TDX furthermore carries a software module with algorithms for the on-board determination of its own orbit relative to TSX. The so-called TAFF (for TanDEM autonomous formation flight) uses data from the Mosaic GPS receivers on both spacecraft. It can not only determine and predict the relative helical orbit, but also compute the necessary cold gas manoeuvres to keep the prescribed formation and ultimately carry these out autonomously.
A first successful try of full on-board autonomy was made from 29 until 31 March 2011 with the two spacecraft at a distance of about 250 m (a full description of this in-orbit test is given in [3]). The limits within the TAFF module were taken even tighter than in the FDIR scheme; e.g. the maximum burn time was set to 90s.

3. Contingencies

The good news is that both satellites are operating so well that there have been no appreciable contingencies while in close formation. The last time a drop to safe mode occurred was 13.08.2010 on TDX with the inter-satellite distance still 20 km, when due to an unexplained blinding all three star cameras did not deliver data for several minutes. This provided an extra in-orbit test of the magnetorquer safe mode and gave

us the opportunity to improve on one of the FDIRs, which performs a mode re-initialisation at the moment one of the three cameras starts delivering data again.
TDX lost one star camera on 11.02.2011 (more likely the LCL and not the camera is defunct), but it still has two other cameras that work perfectly well.
A number of deviations of the order of several hundred meters were seen in the solutions of the GPS receivers, which would be a problem if formation control is done autonomously on-board (Section 2.3.2.). The cause was the inclusion of GPS satellites with large negative elevation in the solutions. By increasing the elevation limit from -20° to -10° the deviations could be reduced by an order of magnitude.

4. Conclusions

TSX and TDX are successfully flying in close formation since half a year now and all safety measures, precautions and stringent surveillance proved to be of theoretical importance only so far. Everybody in the project wants to keep it this way!
Still, the safety measures and concepts developed for the formation flight have proved to be well thought out and worked very well when tested on the spacecraft simulator or in orbit.
The successful in-orbit test of autonomous formation flight in March this year might make the continuous computation and upload of formation keeping manoeuvres by the flight dynamics team obsolete in the near future.
The tracking of available resources shows that, even with the currently increasing solar activity, the mission goal of at least three years formation flight to obtain a full digital elevation model of the Earth can easily be attained.
The commercial and scientific success of the TerraSAR and TanDEM missions are an incentive for several follow-up and similar missions. Currently PAZ, a copy of TSX, is built for Spain, Russia contemplates having two SAR satellites, and the successor to TSX will be TX2. Plans are made of flying with larger appliances or in formations with more than two satellites.

Acknowledgments

The authors wish to thank Marie Licht for her helpful comments and the flight dynamics group for providing their contributions to this conference prior to publication.

References

[1] TanDEM-X; Inter-Satellite Link – Decoder; TDX-AED-DD-0002; Astrium, 2007

[2] TanDEM-X: Design & Interface Document; TDX-AED-DD-0001; Astrium 2008

[3] J.S. Ardaens, S. D'Amico, D. Fischer: Early Flight Results from the TanDEM-X Autonomous Formation Flying System; These proceedings, 2011

[4] A. Codazzi; Extended On-Call Support for TerraSAR-X; SpaceOps conference; Huntsville, USA, 2010

[5] S. D'Amico, O. Montenbruck: Proximity Operations of Formation-Flying Spacecraft using eccentricity/inclination vector separation, Journal of Guidance, Control, and Dynamics, 2005

[6] J. Herman, D. Fischer, D. Schulze, S. Loew, M. Licht; AOCS for TanDEM-X; Formation Flight at 200m Separation in low-Earth Orbit; SpaceOps conference, Huntsville, USA, 2010

[7] R. Kahle; TSX/TDX Formation Collision & Illumination Aspects; TD-MOS-TN-4060; GSOC 2008

[8] R. Kahle, B. Schlepp, F. Meissner, M. Kirschner, R. Kiehling; TerraSAR-X/ TanDEM-X Formation Acquisition – Analysis and Flight Results; 21st AAS/AIAA Space Flight Mechanics meeting; New Orleans, USA, 2011

[9] R. Kahle, B. Schlepp, M. Kirschner; TerraSAR-X/TanDEM-X Formation Control – First Results from Commissioning and Routine Operations; 22nd international symposium on Spaceflight Dynamics; Sao Jose dos Campos, Brazil, 2011

[10] R. Kahle; The TerraSAR-X / TanDEM-X Formation Flight: Challenges to Flight Dynamics and First Results; These proceedings, 2011

[11] G. Krieger, A. Moreira, H. Fiedler, I. Hajnsek, M. Werner, M. Younis, M. Zink; TanDEM-X: A Satellite Formation for high-resolution SAR Interferometry, IEEE Transaction on Geoscience and Remote Sensing, Vol. 45, No. 11, pp. 3317 – 3341, 2010