TDX-TSX - On-board autonomy and FDIR of whispering brothers

A. Schwab[1], Ch. Giese [2] and D. Ulrich[3]
EADS Astrium GmbH, 88039 Friedrichshafen, Germany

TerraSAR-X and TanDEM-X (TerraSAR-X add-on for Digital Elevation Measurement) are German interferometry SAR missions realized as public private partnership programs with Astrium GmbH, as prime contractor for the space segment comprising spacecraft including the SAR instrument, and DLR, as mission lead and operations provider for scientific as well as for commercial. The TanDEM-X satellite represents an almost identical rebuild of the TerraSAR-X satellite. The two satellites orbit in a closely controlled formation and form a single pass SAR interferometer with adjustable baselines (typically below 250 meters) in across- and in along-track. The satellites operate individually for TerraSAR-X mission product generation as well as jointly for Digital Elevation Model product generation, thus forming an integrated system of systems. The paper presents the overall FDIR of the constellation, which is decomposed into ground rules and constraints for planning and on-board FDIR. Special focus is put on the on-board FDIR and autonomy features of the individual satellites as well as on the integrated overall FDIR of the space segment w.r.t. constellation and satellite interactions. The individual satellite on-board FDIR is based on a distributed, hierarchical, multiple level concept, in which each level performs its dedicated failure detection, and (if possible) failure isolation, and (if possible and desired) failure recovery. If a failure cannot be recovered on the respective level, a corresponding event reporting will be performed and the next higher level will take care of the predefined actions. On application SW level the concept is mainly realized by standardized configurable services supported by FDIR preprocessing within on-board algorithms. A special characteristic of each individual satellite is the extremely high power consumption and dissipation of the SAR Instrument during operation (i.e. Data Take). For economic reasons a design to cost and budget approach had to be chosen, with the consequence that e.g. the energy resources and the thermal control system of the satellite are not sized to support a continuous operation of the SAR Instrument. Consequently an improper operation of the instrument, violating the given resource limits, can endanger the satellite. Therefore onboard FDIR must not only cover hardware failures as identified in the FMECA, but also functional operational errors and transient failures e.g. caused by SEU-induced bit-flips in memories or EMI-induced corruption of data during transmission, because all these cases could lead to an exceeding of resource limits. The special characteristic of the TanDEM-x mission is the close formation flying constellation of TanDEM-X and TerraSAR-X satellites. The paper addresses the integrated FDIR of the overall system taking utmost benefit of the distributed hierarchical FDIR and autonomy system design, while utilizing only minimum interaction between the two satellites.

I. Introduction

The TerraSAR-X and TanDEM-X satellites (TSX and TDX) were launched in June 2007 and June 2010, respectively. They represent key elements of the German national radar Earth observation mission and were developed in the frame of a Public Private Partnership between the German Aerospace Centre (DLR) and Astrium Satellites. TSX and TDX are both versatile Synthetic Aperture Radar (SAR) satellites with active phased array antenna technology operating in X-Band. They allow Earth observation independent of time of day or cloud cover. Operating together in close formation, TSX and TDX allow 3-dimensional observation, i.e. derivation of a Digital

[1] MPC Manager Operation & FDIR, AET2, 88039 Friedrichshafen, Germany
[2] TDX Operation & FDIR Architect, ACE72, 88039 Friedrichshafen, Germany
[3] TSX-2 Project Manager, AED7, 88039 Friedrichshafen, Germany

Elevation Model (DEM). Combined operation for 3 years allows data collection for a complete and consistent DEM of the Earth surface with a height resolution of about 2 m [1)]. The TanDEM-X mission became a vision during the development of TSX. Therefore, only the absolutely necessary design extensions have been implemented on TSX to support future synchronized operation of both radars. The bus design of TDX has been extended with respect to TSX to allow formation flight of both satellites. The software changes relevant for the TanDEM-X mission have been verified during the TDX on-ground tests and then also uplinked to TSX in preparation of the formation flight.

II. Key Satellite Design Characteristics

The 5m long and 2.4m wide satellite structure has a hexagonal cross-section which fits the rocket fairing efficiently. One side carries the SAR antenna which is 80 cm in elevation and points to the Earth on the right side of the sub-satellite ground track. The SAR instrument, operation at X-Band (9.65 GHz) allows for weather-independent earth imaging day or night. The design is based on an active antenna using an array of Transmit-Receive Modules which provides rapid electronic beam steering and programmable antenna patterns. Each module feeds a sub-array comprising two slotted-waveguides, one for each of vertical and horizontal polarization. Rapid switching of polarizations and other radar parameters, even pulse-to-pulse, results in a very flexible SAR design which provides a large variety of experimental modes in addition to the modes required for standard product generation. StripMap is the standard mode of bistatic operation of the TanDEM-X mission. It provides a resolution on-ground of 3 meters and a measurement swath width of 30 km. While originally an average SAR operation time of 170 s per orbit had been specified which corresponds to a measurement swath width of about 1200 km, the system in orbit has demonstrated that extended operation profile of an average SAR transmit time of 210 s per orbit and additional 130 s operation time in receive only mode can nominally be operated. Tests have proven that up to 600 s operation time is possible under favorable conditions. In Spotlight mode, azimuth (along track) scanning of the radar beam allows to improve the resolution to 1 meter for measurement scene 'patches' of about 10km x 10km. The active antenna design ensures a small long track separation of the patches. In a special instrument configuration, called Dual Receive Antenna (DRA) the nominal and redundant instrument of one satellite can be operated in parallel basically as two individual instruments including data recording on the SSMM each controlling one half of the antenna.

Figure 1 TerraSAR-X and TanDEM-X satellites

The sun-synchronous dusk-dawn orbit allows the use of a fixed Solar Array which is fixed on the left side of the satellite. The energy is stored in a Li-Ion battery system providing a capacity of more than 100 Ah. The battery design is based on the utilization of lowest capacity cells which are integrated in a high number of parallel strings. Since any open failure in one cell, i.e. in one string, will only lead to the loss of a small amount of capacity without degradation of the overall battery voltage, there is no need for a by-pass. The battery is designed to provide the peak load during operation of the radar instrument in eclipse, while keeping the minimum voltage at the battery terminals higher than the cut off voltage of the input converter of the instrument power distribution unit (IPDU). The worst case variation of the voltage drops due to radar operation from BOL to EOL conditions expected during the design phase are shown in Figure 2. Evidently it has been a key challenge of the power system design to trim the FDIR and particularly the HW protection elements of the power system to fit for any of these conditions. While it is anyhow difficult to determine the state of charge (SOC) of a Li-Ion battery system analysis have shown that the voltage drop

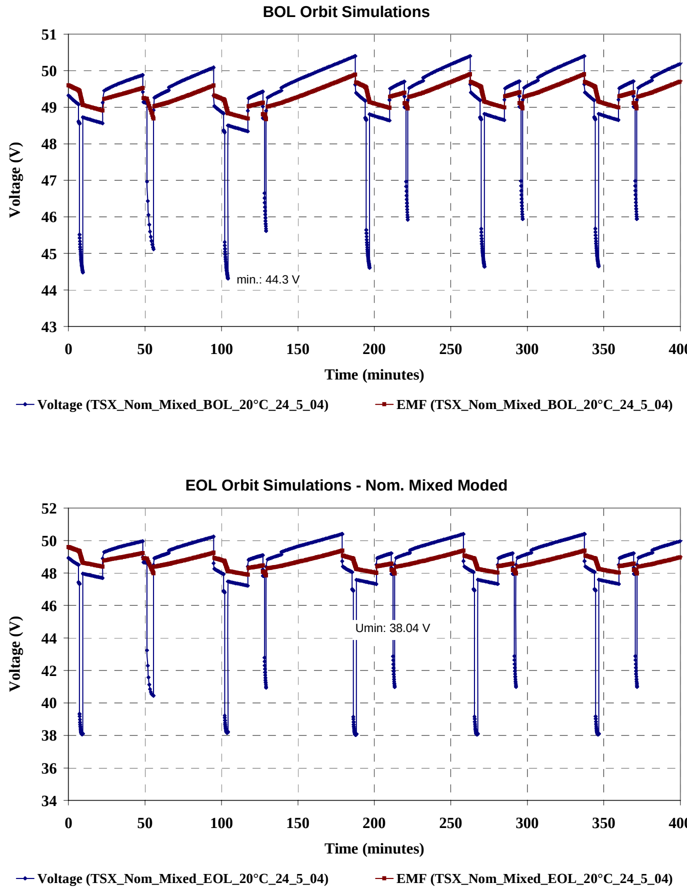

Figure 2 Worst case primary voltage behavior at BOL and EOL for a nominal reference operation scenario (design phase)

at peak load currents is much more dependent on the actual battery impedance than it is on the actual SOC of the battery. As neither the SOC nor the actual battery impedance can be accurately enough known on-board the spacecraft an alternate ground based method for power system surveillance has been introduced. As direct monitor for battery health during ground contacts the on-board system reports the power characteristic during peak load conditions depending on selectable worst case monitor by a consistent set of power system data (several temperature, voltage, current) since last reset of the reference conditions. This minimum battery condition monitor supports simple ground monitoring of the power system health.

Both TSX and TDX carry an IGOR dual frequency GPS receiver connected to zenith POD as well as aft and forward looking occultation antennas and a laser retro reflector to support the Tracking, Occultation and Ranging (TOR) mission of the Geosciences Research Centre (GFZ) in Potsdam. Ground processing of the IGOR POD data verified by high precision laser ranging measurements from both satellites allows accurate and reliable determination of the interferometry baseline (i.e. the effective SAR antenna separation) required to ensure the DEM height accuracy. Besides this synergetic contribution to the SAR mission the TOR mission allows determination of atmospheric pressure, temperature, water vapor content and electron density which can be used for weather prediction or research on climate change from radio occultation measurements of signals through the atmosphere from settling and rising GPS satellites at Earth's horizon [2)].

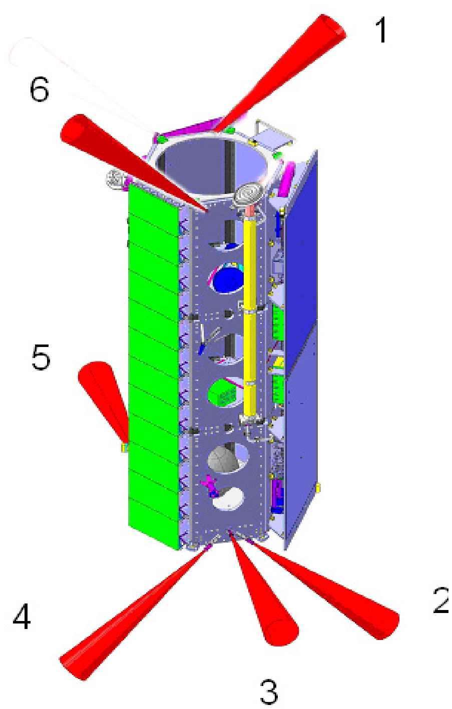

Figure 3 Sync Horn Accommodation

SAR measurement data are transmitted to Ground Stations in the same frequency band as used by the radar. To avoid mutual disturbance, the X-Band Downlink Horn Antenna is mounted at the tip of a 3.3 m long boom. This boom is deployed towards nadir by a reliable passive spring mechanism soon after launch.

For TanDEM-X DEM data collection, formation flight is necessary with separations between the two satellites down to 150 m and a synchronized operation of the SAR instruments of TSX and TDX is necessary. For the latter the SAR design was extended to allow exchange of so-called Sync Pulses to support coherent operation of both SARs during bistatic operation. Six Sync Horns on each satellite provide a quasi-omnidirectional coverage. These are fed by Transmit-Receive Modules which were already present as intermediate amplifiers with spare input/output ports. In order to support the close formation flying constellation TDX is equipped with an additional propulsion system based on high-pressure Nitrogen gas. This Cold Gas System (CGS) provides smaller impulse bits than the primary Hydrazine system which is used for major orbit maintenance on both satellites. Last but not least an Inter-Satellite Link Receiver & Decoder is accommodated as additional hardware on TDX, which allows TDX to 'listen' to the TSX low rate S-Band telemetry. The S-band telemetry contains all housekeeping data from the satellite. This one-way inter-satellite link works the nominal formation flying separation range. Since the S-band antennas are mounted in nadir and zenith direction and the ground station contacts are nominally performed in high rate there are contact gaps depending on the relative formation geometry [2)].

III. Individual Satellite FDIR

The functional operational architecture of the TSX had been consequently defined to provide an utmost modular and flexible design to support easy integration and update of key functions as well as adaptation and sub-sequent increase of on-board autonomy without endangering the spacecraft health. While the basic system configuration focused on a preservation of the S/C health, several autonomous on-board recovery procedures are implemented, which have been subsequently enabled thus ensuring a higher operational state. In addition the S/C resources provide potential for further increase of the on-board autonomy and supported a relatively easy upgrade from TSX to TDX with substantial additional functionality. The system modularity is achieved by a functional breakdown of the overall system in application processes providing individually its dedicated functions, which are embedded in a common set of operational services for standard functions. This basic set of operational services provide full commandability and observability for the individual applications as well as the application specific FDIR. The communication in-between the applications including the flight operation system on ground is based on an application and service concept following the ECSS E-70-11 standard. The hierarchical relation of the applications as shown in Figure 4 ensures that an efficient and transparent routing of command and telemetry packets and an efficient handling of failures on the lowest possible level and earliest in time. In case a failure could not be resolved at lower levels a more stringent reaction on a higher level is defined. As top level on-board application the system control is responsible for command distribution from and telemetry routing to the mission operation segment (MOS) on-ground as well as for the overall system FDIR. The BusControl and AOCS application provide all services and functions required for operating the platform and supporting the overall satellite system. The Payload Manager application provides the S/C support functions including related FDIR for the payload compartment of the satellite, which is composed of further applications distributed on several different HW units, which are responsible for operation of the SAR instrument in standard cold redundant SAR as well as hot parallel dual receive antenna configuration (ICU1 & ICU2), payload data recording on a solid state mass memory (SSMM), as well as data transmission via laser communication terminal (LCT). All applications are supporting a common service set ensuring command acknowledgment, observability, function management as well as local FDIR. Higher level applications are only responsible to resolve problems, which can be identified in failure signatures visible in directly acquired

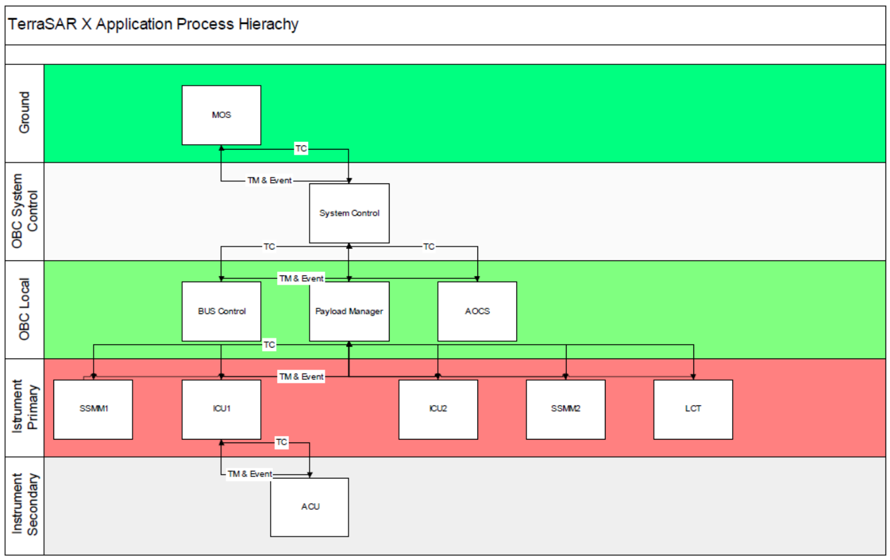

Figure 4 Application Process Hierarchy

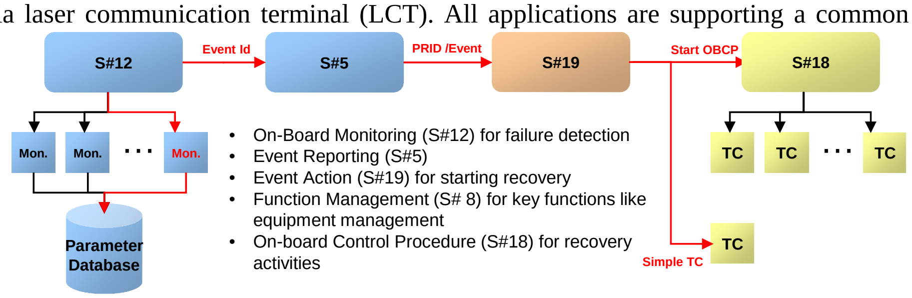

Figure 5. PUS Service Application Process Hierarchy

telemetry information or which are reported via event reports, which cannot be resolved on individual application level. The FDIR within each application is constituted by a configurable set of services based on the ECSS-E-70-41A Packet Utilization Standard (PUS) as depicted in Figure 5. This distributed hierarchical on-board FDIR system on SW level is accompanied by HW embedded FDIR functions. As an example the power system FDIR is constituted by several primary bus voltage monitors on SW level, so called SW DNEL monitors on platform and satellite level. In addition to the primary bus voltage SW surveillances of the bus control application, several levels of power shedding functions for non-essential equipment, essential equipment and ultimate battery health protections as well as a consistent recovery levels for startup from absolutely depleted energy resources as soon as a minimum solar input is available. This FDIR is extensively verified during system level tests as depicted in Figure 6, which includes the famous Astrium "Munchhausen" low power contingency recovery test. The name of this test is freely chosen along the literature 'The Adventures of Baron Munchausen', being able to recover with minimum external support basically fully on own resources. At (1) sun simulator is switched off. The fully charged battery is discharged, if necessary by an external load. Subsequently the installed SW and HW primary power bus monitors trip. At each level correct occurrence of the related FDIR is checked. At (3) all non-essential loads are disconnected, which results in a small increase of the primary bus voltage. Due to power consumption of the remaining essential units and heaters which are still ON at some time the LCL UVP voltage is reached (4), causing the PCDU converters and all remaining loads including heaters to switched off. Without external load the battery voltage raises slightly. After some time the sun simulator is switched ON with a faint stimuli (300 W/m²) (5). Due to the charge current the battery voltage raises immediately, as soon as the switch-on level of essential loads are reached the PCDU and essential equipments (OBC 1 & 2, RX1,RX2, TX1) are switched on, system reconfiguration sequence in the OBC is triggered and the system initialisation sequence of the CSW is started, recovering the system into its satellite safe mode (7). Finally the sun simulator stimuli is switched to simulating full illumination. In this condition the satellite has its nominal position w.r.t. the sun. The battery is charged up and reaches full state of charge. The satellite is fully recovered.

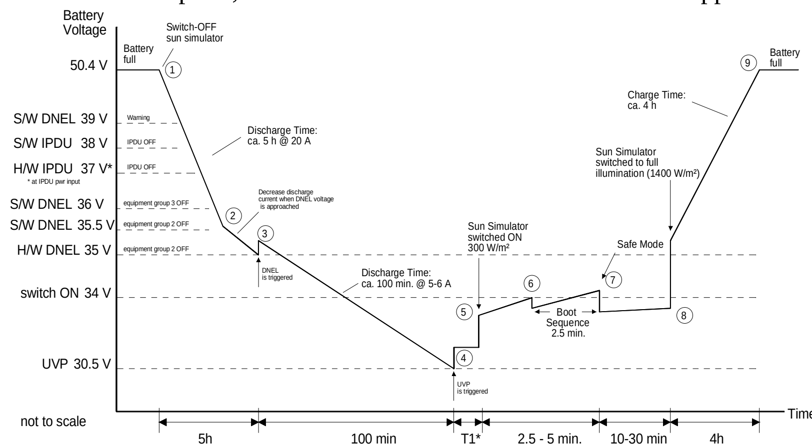

Figure 6. Voltage profile during low power FDIR test

As a final resort of the hierarchical system surveillance the mission operations center performs regular monitoring of long term system behavior. This FDIR design ensures an utmost robust system even for multiple failure cases.

IV. TanDEM-X Mission FDIR

For DEM data collection, formation flight is necessary with separations between the two satellites down to about 150 m. The close formation flying constellation is primary safeguarded by introducing a special orbit control approach ensuring a helix formation under all circumstances (Figure 7). By combining an out-of-plane (horizontal) orbital displacement via different ascending nodes with a radial (vertical) separation via different eccentricities and arguments of perigee, an elliptic relative motion is achieved between the satellites. Since the orbits never cross, autonomous control is not necessary for safe satellite operation. In other words, the helix orbit provides passive safety. Nevertheless, the very close formation infers risk of collision of the satellites and risk of mutual illumination by the main beams of the radar antennas.

A number of new functions and extension of TSX original FDIR have been introduced in the satellite design to safe-guard against these risks. The major changes with respect to the original TSX implementation are:

- The additional magnetic torquer safe mode (ASM-MTQ)
- Thruster safe mode (ASM-RCS) as fallback safe mode in case of dynamic or power/thermal problems during ASM-MTQ
- Surveillance of close formation flight by exclusion zones, InterSatellite Link (ISL) and sync warning data takes

- System Level reactions, comprising safety measures in several sub-systems in parallel
- FDIR for automated on-board relative navigation via the TAFF algorithm

The mechanisms are realized by a combination of new hard coded software functions and additional monitoring, event action and OBCP definitions, which are installed via configuration data update of the individual services in the affected applications.

A. Safe Mode Aspects

In the sense of a robust a simple system approach the original Safe Mode of TSX and TDX had been based on the propulsion system a prime actuation system which is supported by Magnet Torques to minimize fuel consumption. Analyses have shown that the usage of thrusters in Safe Mode leads to an unacceptable risk of collision for certain satellite formation geometries. During close formation flight, i.e. vertical separations < 300 m, the collision risk was evaluated to be 1:500 in case one spacecraft experiences a safe mode drop. Usage of Magnetic torque actuation only avoids change in altitude in case of a drop to the AOCS Acquisition and Safe Mode. Thus on both satellites in the AOCS application an AOCS Acquisition and Safe Mode (ASM) Sub-mode was introduced which is solely based on use of the Magnet Torquers. These actuators are powerful enough to regain attitude and pointing stability for moderate rotation rates of the satellite, however under the constraint of a significantly longer convergence time. Due to this constraint the original more powerful Safe Mode based on the use of Hydrazine thrusters is maintained as a safety net to handle residual risks of significant low power conditions, as well as unfavorable thermal conditions of particularly exposed critical spacecraft elements. In order to maintain simple orbit injection in LEOP for the TDX satellite RCS based ASM has also been used fast initial acquisition. Due to the longer convergence times to a power and thermal safe attitude during the MTQ controlled safe mode and the transitions between MTQ and RCS controlled ASM impacts on power and thermal system required an extension of related FDIR settings on platform and system level.

Figure 7. Helix Formation

The logic for the handling of safe mode recoveries focused on the AOCS mode and sub-mode impacts is shown in Figure 8. Entry point in case of problems in one of the operational modes is always the rate damping in magnet torquer safe mode (ASM-MTQ-RD). An on-board autonomous sequence brings the spacecraft in earth and sun oriented acquisition mode (ASM-MTQ-AQ) once the rotation rates are below a certain threshold. If the rates are not below the specified limit within few hours, an on-board computer (OBC) warm boot is triggered to recover potential sensor, actuator or software problems. Thereafter the spacecraft starts again in ASM-MTQ-RD. Exception to this scenario occurs in case of severe thermal or power problems in which case the transition into ASM (RCS) occurs immediately. The total amount of thruster activities upon first entry of ASM (RCS) is limited, such that

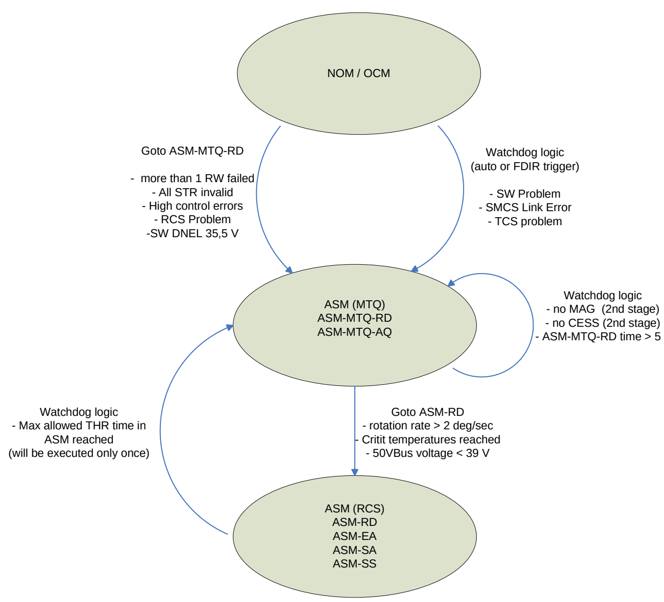

Figure 8. Safe Mode Transition Logic

the maximum orbit change does not lead to a substantially increased collision risk. The actual limits depend upon inter-satellite distance and current tank pressure.

After transition to ASM (RCS) thruster on time is monitored to realize limited thruster operation. Depending on formation and tank pressure the limit will be adapted from ground. If the maximum thruster limits are reached an OBC reboot will be performed and the ASM-MTQ is reactivated again. If the limited thruster activities cannot recover the previous problem the ASM (RCS) is triggered a second time with unlimited thruster activities.

B. Exclusion Zone FDIR

In order to handle the mutual illumination risk by the radar main beams in the close formation flying constellation a so-called Exclusion Zone logic is introduced on both satellites (Figure 9). Bistatic operation of the radars is used for DEM data collection where only one SAR instrument transmits but both radars receive. Radar transmission is allocated to that satellite having no risk to illuminate the partner satellite by the main beam of its radar antenna for a part of the orbit. Radar transmission by the other satellite is prevented within this part of the orbit by an on-board logic – being its 'Exclusion Zone'. The on-board 'Exclusion Zone' logic is implemented by a new Payload Manager (PLM) application software function and updates of onboard FDIR settings (monitoring, event/action, OBCP execution) in the OBC Central SW and ICU application SW, which are interacting according to the following scheme:

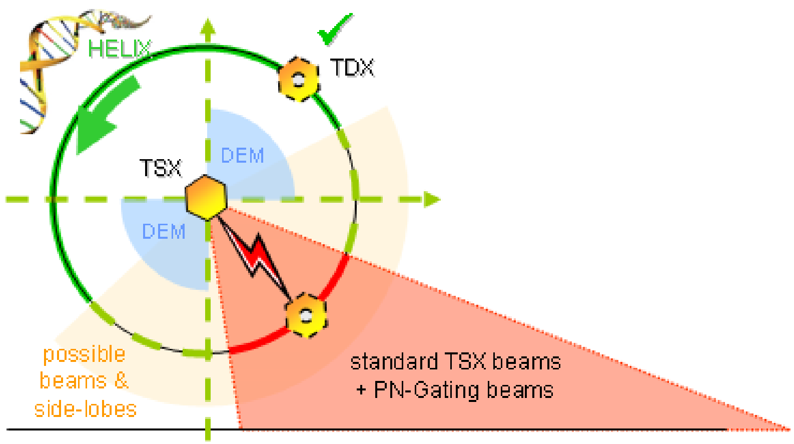

Figure 9 Relative Orbit geometry and Exclusion Zone

- The Payload manager application generates nominal events which are indicating the start and the end of exclusion zone and triggers a PLM OBCP.
- Within the instrument SAR transmission is prevented for data takes which are started inside the exclusion zone. For on-going SAR data takes active transmission is aborted at the beginning of the exclusion zone

Already on TSX the PLM application can request via on-board data access functions various on-board data to establish a satellite ancillary data service to support individual payloads and instrument operation, as well as embedding of related information in the TSX mission data stream. In case of SAR transmission permitting operational AOCS modes i.e. stable right looking or sun side looking attitude, the 'Exclusion Zone' logic uses the actual orbit position, which determined by the AOCS application on-board from the navigation solution of Astrium Mosaic GPS receiver, to release individual normal progress severity event reports (EZ_TX_OFF and EZ_TX_ON) for indication and triggering of start and end of the exclusion zones. For each satellite and operating mode, i.e. right-looking and left-looking, individual lower and upper limits for the exclusion zone is defined. All exclusion zone limits are configurable and given as argument of latitude values. When the helix orbit is changed the exclusion zone limits have to be updated via flight procedures from ground. Figure 10 shows the 'Exclusion Zone' logic and related FDIR implementation.

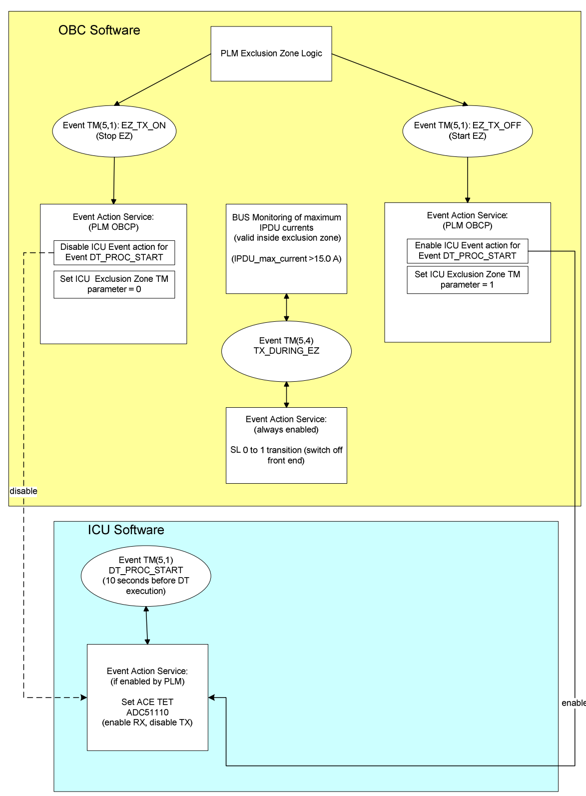

Figure 10. Exclusion Zone FDIR

Detection of EZ_TX_OFF event triggers a PLM OBCP which enables an event/action entry in the ICU and sets an ICU on-board parameter, controlling the exclusion zone behavior of the instrument. Thanks to the efficient operational progress reporting of the instrument data take preparation and execution functions as well as their comfortable configuration capabilities, the enabled event action triggers an appropriate preventive reprogramming step in the antenna control electronic setup upon occurrence of an ICU data take processing start event (DT_PROC_START). This reprogramming step disables the transmission of radar signals for the front end TRMs. As soon as an EZ_TX_ON event is detected a PLM OBCP disables the related ICU FDIR reaction and resets the ICU on-board parameter to indicate unconstraint instrument operation. For data takes which starts outside the exclusion zone and are continuing into the exclusion zone the reprogramming of the ACE is not possible. Therefore an exclusion zone dependent monitoring of the high power instrument supply current is implemented which shut down the SAR front end in case of active RF transmission in forbidden zones.

Passive Bi-static as well as sync warning data takes are not influenced by exclusion zone reaction. The on-board logic provides the online protection for the individual satellites. The primary protection is given by a similar logic, implemented in the Ground Segment to check and prohibit dangerous operation using the planned orbit geometry during mission plan preparation and generation.

C. Sync Warning Mechanism

While the before mentioned exclusion zone FDIR addresses the top level interactivity coordination between the two brothers, we are now looking into the whispering communication exchange between them. The synchronization antenna system comprises six circular polarized X-band horn antennas arranged in such a way, that a spherical coverage is obtained (See Figure 11). Bi-static data takes for DEM generation make use of exchange of RF pulses between the radar instruments of the two satellites via selectable horn antennas as part of a synchronization scheme. This allows monitoring of phase difference and minimization of the interferometric phase error. Besides these nominal exchange of calibration sequences in-between the two brother satellites during synchronous TanDEM-X data take operations on the two satellites this exclusive bi-directional communication channel in-between the two satellites has been identified as an excellent mean for a minimum information exchange in-between the two whenever no operational data take is executed. Like two brothers prowling through a dangerous area without visible connection at predetermined times each one is whispering "I'm okay", while waiting for the same message from the other one.

Technically this is achieved by dedicated sync warning data takes, which are performed synchronously by TSX and TDX using deterministic sync horn pairs. Typically two sync warning data take pairs per orbit are planned from ground based on fully predictable satellite orbit position and attitude. An ICU on-board logic has been added to compare the received signal level (SNR) with an adjustable threshold value. A value below the threshold is interpreted as a potential discrepancy in the planned relative formation geometry and a high severity event is generated by the ICU. The reaction mechanism is realized by the exclusion zone FDIR as described. After a failed sync warning data take event SAR transmission is suppressed to avoid risk of mutual illumination by call of exclusion zone OBCP and the exclusion zone function is disabled afterwards. Recovery from a sync warning failure can be performed either by ground operation or automatically after next successful sync warning data take.

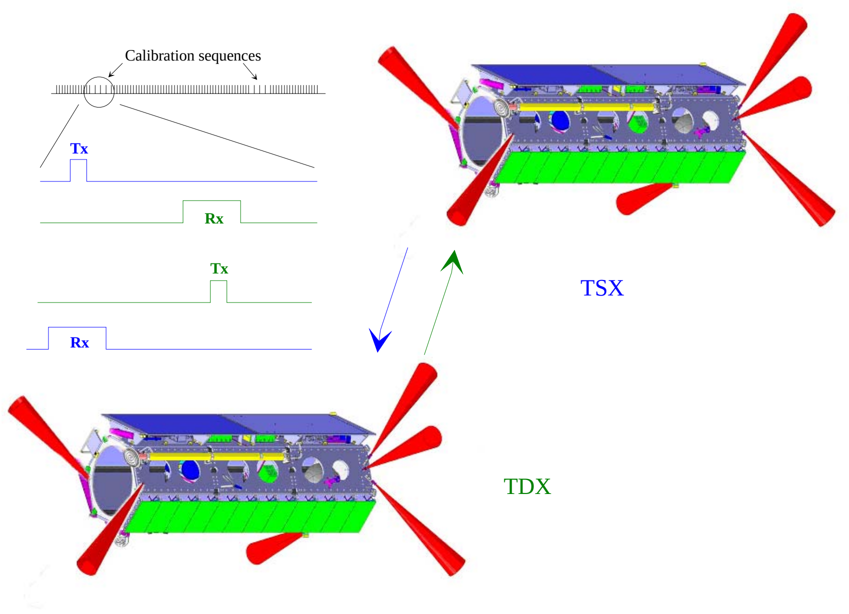

Figure 11. Sync Warning Exchange

D. Constellation Maintenance and Autonomous Orbit Control FDIR

As a second but only unidirectional mean in the whispering communication exchange of the two satellites an additional S-band receiver and decoder have been installed on TDX allowing to 'listen' to TSX S-band telemetry data. Thanks to this information link TDX gains enhanced and real-time knowledge about TSX. Utilizing the configuration capability of the housekeeping and diagnostic report service capability a special diagnostic telemetry packet is defined on TSX which contains GPS navigation and TSX overall satellite status data. This one-way inter-satellite link works for low data rates within the nominal separation distance range of the constellation, but leaves some contact gaps depending on communication system settings as well as on the relative formation geometry. The S-band antennas are mounted in nadir and zenith direction, therefore gaps occur at equator crossing when the two spacecrafts are next to each other. These gaps depend on the foreseen helix orbit and will not exceed 15 min per orbit.

While the nominal formation flying is under ground control, TDX embarks an autonomous formation flying algorithm (TAFF) being able to conduct autonomous on-board constellation maintenance via the additional Cold Gas System on TDX. Data received from TSX TM via the ISL as well as internal TDX AOCS parameters are pre-processed within a specific module of the AOCS software (constellation safety preprocessing) to derive on-board parameters which can be monitored by the related on-board services. Furthermore, the received TSX GPS navigation solution data is used as input for the TanDEM-X Autonomous Formation Flying (TAFF) algorithm running on the onboard computer. The TAFF algorithm was tested in navigation and open-loop mode during the commissioning phase. Meanwhile the TAFF was also successfully operated in closed loop mode.

Obviously this novel approach of autonomous on-board constellation maintenance deserved an extension of the TDX FDIR. Based on before mentioned preprocessed data the configuration tables of the FDIR service suite in the AOCS application have been amended to cope with feared events of the constellation and orbit maintenance operations. As an example the constellation maintenance FDIR terminates and disables all autonomous constellation activities in case the TAFF algorithm indicates a collision risk but also if the time since the last valid data update expires beyond a given threshold. In order to ensure coordinated and synchronous orbit maintenance maneuvers on TSX and TDX the execution of orbit control maneuvers on TDX is prohibited if TSX is not ready to transition to OCM. Last but not least all orbit control or constellation maneuvers are disabled and SAR transmission function is prevented if the received TSX status via ISL indicates an OBC re-boot or a switch to AOCS ASM.

V. Conclusion

The ambitious demands and risks of the close formation flight of TSX and TDX, forming the first configurable synthetic aperture radar interferometer in space, are handled by a variety of failure management mechanisms implemented on-ground, intrinsic in the constellation management as well as on-board. The latter ones building the last resort of satellite health preservation as well as a key for high satellite availability have been outlined within this paper. The considerable challenges of the system upgrade from TSX to TDX could be efficiently implemented thanks to the modular functional architecture and consequently following software design. The very few cases where experience could be gained during nominal operation are already showing the operational benefit of the implemented failure management mechanisms. Fortunately, no safe mode has been occurred since satellites are flying in the close formation. All data takes have been reliable planned with respect to exclusion zone limits and uploaded to the satellites by

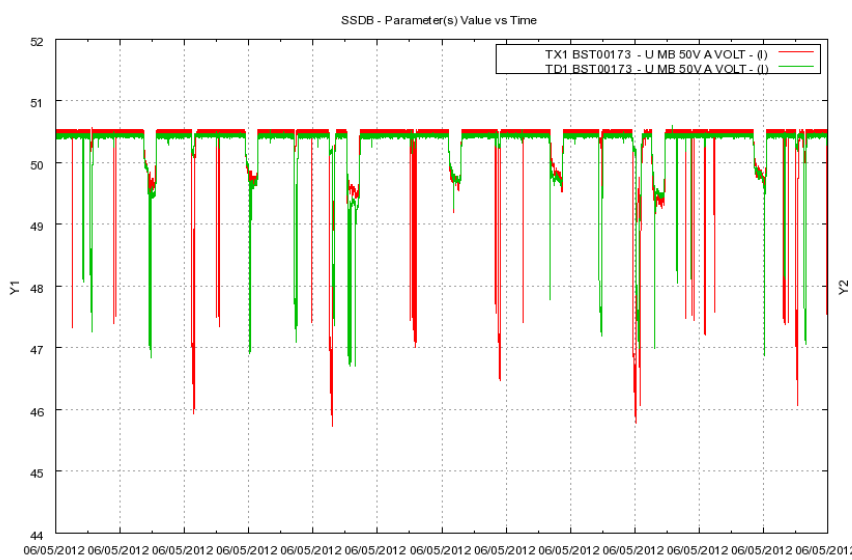

Figure 12. Battery Main Bus Voltage during SAR operation

the mission operations center, hence the on-board exclusion zone mechanism never need to prevent SAR transmission or abort an active data take. The same applies for the energy resource management, being an integrated part of the mission planning system as well as for the orbit control performed by the flight dynamics system of the DLR ground segment, supporting an efficient and safe operation of this ambitious mission [4-8].

More than 16 000 sync warning data takes have been successfully exchanged between the satellites during the last 18 month of mission. Once due to a small difference of sync warning data take start times, a failed sync warning was detected during a short period without full on-board time synchronization to GPST. During the next ground contact immediately after detection of the event the related recovery action has been performed by ground operation. If the installed event action entry, which is installed to further increase the availability of the SAR instrument and reducing ground operation interaction, would have been enabled, after the next successful sync warning a fully autonomous recovery back to full operational state would have performed without ground interaction.

The longterm monitoring of satellite main bus voltages shows excellent margins to the defined SW and HW DNEL levels even for TSX approaching its specified lifetime within this year. Figure 12 shows the TSX and TDX main bus voltages during a typical SAR operation scenario, comprising individual single satellite TerraSAR-X mission data takes as well as combined TanDEM-X mission data takes on both satellites. The chosen period includes periodic discharge phase of the batteries during summer solstice eclipses. The slightly smaller minimum battery voltage of TSX compared to TDX is consistent with the longer in-orbit life of TSX. As reported for other S/C resources the TSX power system characteristic, being far better than the original predictions, will allow a mission extension far beyond the specified as well as original planned mission life time.

Appendix A
Acronym List

ACE	Antenna Control Electronic
AOCS	Attitude and Orbit Control System
ASM	Acquisition and Safe Mode
DEM	Digital Elevation Model
DNEL	Disconnect Non-Essential Load
EMI	Elector Magnetic Interference
EMF	Electro Motoric Force
FDIR	Failure Detection Isolation and Recovery
FMECA	Failure Mechanism Effects Criticality Analysis
GPST	GPS Time Reference
HW	Hardware
ICU	Instrument Control Unit
ISL	Inter Satellite Link
Li	Lithium
MPC	Major Project Component
MTQ	Magnetic Torquer
OBC	Onboard Computer
OBCP	Onboard Command Procedure
OCM	Orbit Control Maneuver
PLM	Payload Manager
POD	Precision Orbit Determination
RCS	Reaction Control System
SAR	Synthetic Aperture Radar
SNR	Signal to Noise Ratio
SOC	State of Charge
SEU	Single Event Upset
SW	Software
TAFF	TanDEM-X Autonomous Formation Flight
TDX	TanDEM-X satellite
TRM	Transmit Receive Module
TSX	TerraSAR-X satellite

Acknowledgments

The TanDEM-X project is financed and implemented as a public private partnership between DLR and Astrium, with partial funding by the German Federal Ministry for Economics and Technology (Förderkennzeichen 50 EE 0601).

References

[1] Zimmermann R., D. Fischer, Giese C., Miller D.: "Safety Mechanisms for Operational Formation Flight of TerraSAR-X and TanDEM-X"; 4th Spacecraft Formation Flying Missions & Technologies Conference, St. Hubert, Canada, 2011

[2]Giese C, Ulrich D.: "The TANDEM-X SPACE SEGMENT", IEEE International Geoscience and Remote Sensing Symposium, Vancouver, Canada, July 2011

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

[4]Ardaens, J.S., D'Amico, S., Fischer, D.: "Early Flight Results from the TanDEM-X Autonomous Formation Flying System"; 4th Spacecraft Formation Flying Missions & Technologies Conference, St.Hubert, Canada, 2011

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

[6]Herman, J., Schulze, D., Loew, S.; "TanDEM-X Close Formation Flight - AOCS Safety Measures and Operations"; SpaceOps Conference, Huntsville, USA, 2010

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

[8]Schättler B., Kahle R., Metzig R., Steinbrecher U., Zink M.; "THE JOINT TERRASAR-X / TANDEM-X GROUND SEGMENT"; IEEE International Geoscience and Remote Sensing Symposium, Vancouver, Canada, July 2011