TerraSAR-X and TanDEM-X After 13 Years of Joint SAR and DEM Mission

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ABSTRACT

The German SAR satellites TerraSAR-X and TanDEM-X are in orbit since 2007 and 2010, respectively. This paper gives an overview about the challenges faced by such long-enduring missions, recent measures taken to preserve the satellites and to continue the mission, and major lessons learned for future SAR missions.

***Index Terms*—** TerraSAR-X, TanDEM-X, long enduring mission, battery, fuel consumption

1. INTRODUCTION

The first German radar satellite TerraSAR-X (TSX) was launched June 15, 2007 [1]. It is capable to acquire SAR images in various modes, such as Spotlight, Stripmap or ScanSAR. Due to its flexible commandability, the mode and product portfolio was extended throughout the mission by further high-resolution and wide coverage modes.

The TanDEM-X mission is the first bistatic SAR mission with two satellites [2]. It was realized by placing a second satellite (TDX) in close formation with TerraSAR-X. The primary mission goal was to deliver a global Digital Elevation Model (DEM) at a 12 m posting with a relative vertical accuracy of 2 m/4 m for terrain slopes less/steeper than 20% [3]. Based on data acquired between 2010 and 2014 the TanDEM-X global DEM featuring outstanding height accuracy became available in 2016 [4].

The planned mission duration for the TerraSAR-X satellite was 5.5 years. Joint tandem operations with TanDEM-X was foreseen for 2.5 years. This has already been exceeded by far, as TerraSAR-X has been in orbit for 16 years and TanDEM-X for 13 years. However, this also implies various challenges as discussed in the following chapters covering the instrument preservation, the mission evolution and the lessons learned.

2. SATELLITE AND INSTRUMENT STATUS AND PRESERVATION

The long duration of both missions results in a significant aging of the satellite components. However, both satellites work stable within their performance specifications and are still remarkably well calibrated since the start of the operational phase [5], [6].

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2.1 Instrument Outages

During mission life time, the satellites experienced several contingencies. Like other advanced SAR satellites, TSX and TDX are equipped with a high degree of redundancy. So even if system components of the satellites or the SAR instruments fail, it is possible to switch over to the redundant ones or to implement smart workarounds.

An example was the outage of a component in the so-called transmitter and up-converter stage (TUS). Here, an amplifier on TDX suffered from a malfunction in 2019 [7]. The switch over to the redundant transmit chain was conducted. After readjustment, calibration verification and reestablishment of the formation, the high quality of the SAR and DEM products was similar as before [8]. Since the beginning of the mission, the relative radiometric performance is thus well within specifications [6].

Another recent example was the failure of the Ultra-Stable Oscillator (USO) on TSX in late 2022. Due to problems with the internal temperature stabilization, the USO frequency showed unacceptable high variations. A workaround using external heaters and the synchronization link between TSX and TDX was implemented which successfully stabilized the USO frequency generation. For safety reason in close formation, problem solving on one satellite usually also requires a separation of the satellite twins, to allow continuation of the mission on the other satellite.

2.2 Battery Preservation

The most lifetime limiting on-board components currently are the batteries. Being actively transmitting radar systems, SAR satellites generally have a high demand of instantaneous power. Therefore, they rely on, e.g., lithium-ion batteries for operation of platform and instrument. Such batteries degrade nominally over time, as known from mobile phones. For TSX and TDX this degradation is visible in Fig. 1 when comparing the battery voltage of two acquisitions from 2011 and 2022 respectively. It is though well within the expected range and far better than the predictions.

However, 16 and 13 years is a very long time for lithium-ion batteries flown in space. After about ten years in orbit, an additional effect, the so-called diffusion rate limitation, in the battery unexpectedly appeared. Due to this effect, the ability of ions to travel in the electrolyte slowly decreases over the years. This leads to larger voltage gradients in long data takes after tens of seconds of high-power operation. Operating in the region where the diffusion rate is reduced is undesirable since doing so is assumed to degrade the battery further. As a consequence, the length of SAR acquisitions needs to be restricted.

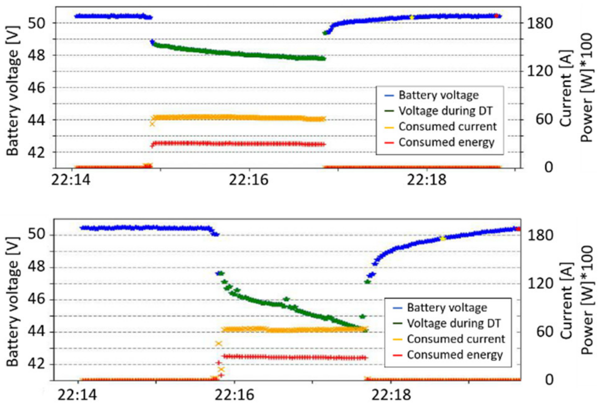

Figure 1: Degradation of the TDX battery in terms of voltage drop during DTs in 2011 (upper) and in 2022 (lower).

As a countermeasure, the maximum duration of data takes has been stepwise restricted from 170 sec / 360 sec (TSX/ TDX) in 2019 to 140 sec / 200 sec in 2021 down to 60 sec / 90 sec in 2023. From a planning perspective this means, that acquisitions have to be chopped into smaller pieces, which slightly increases the overhead due to prologue and epilogue at the beginning and the end of each data take. In addition, pauses after each long data take as long as the acquisition itself are introduced where possible in order to allow the battery to recover completely.

Furthermore, analyses are currently conducted to assess if a reduced transmit duty cycle could be beneficial without significantly deteriorating the performance of the SAR and DEM products.

2.3. Propellant

Such a long mission faces challenges in terms of on-board consumables. Both satellites host a propulsion system with a large amount of hydrazine. As margins for orbit injection were not expended, there is still propellant on board both satellites. Initially, around 75 kg of hydrazine was stored in the tanks of TSX and TDX each. This amount was estimated to be a worst-case necessary in case of a large initial orbit injection errors and in case of safe-mode events employing thrusters during the nominal life time of 5.5 years. Due to proper injection and improved attitude safe mode procedures, even 13 and 16 years after launch, more than 20 kg hydrazine are still available on each satellite. About 7 kg of fuel are reserved for end of life orbit lowering. Main drivers in terms of fuel consumption are formation change and formation keeping maneuvers, which were mainly performed by the TDX satellite in the first years of the mission. Here, a dedicated additional cold-gas propulsion system was implemented on TDX comprising 36 kg of Nitrogen, sufficient for in-plane formation maintenance throughout a 3-years nominal formation flying period. The cold-gas lifetime was significantly stretched by implementing the mixed formation control concept, where the daily negative DV component of the in-plane formation maintenance was executed by the cold-gas thrusters (mounted in flight- and anti-flight-direction) and the positive component by the Hydrazine thrusters (only in anti-flight direction). Besides saving of cold-gas, the maneuver sequence previously including long attitude slew and back-slew phases could be shortened. Finally, when the TDX cold-gas was almost depleted by end of 2015, the more sophisticated distributed formation control concept was introduced by flight dynamics, basically assigning half of the daily formation maintenance effort to the TSX satellite [9], [1].

The formation itself is mainly defined by the vertical baseline between the satellites in radial orbit direction (typically maximal at the poles) and the horizontal baseline resulting from the orbital plane differences (maximum separation at equator crossings).

To further reduce the fuel consumption, the formation changes required to realize appropriate baselines for DEM acquisitions were optimized. This is shown in Fig. 3. In former times, the horizontal baseline (blue) was changed instantaneously at the end of different mission phases or even in between. In the Science Phase 2020-2022 (compare Chapter 3), a total delta-v corresponding to about 0.5 kg hydrazine was required for horizontal formation changes. For the current 4D Phase, a horizontal drift is realized by establishing a small difference in the inclination of the satellites. The orbital plane of the TDX satellite is slightly tilted against the TSX orbital plane by an out-of-plane maneuver at the start of the phase. Consequently, a differential node drift is forced and the horizontal separation with 0.7 m per day and increases the horizontal baseline from 200 m to 330 m over 6 months. The cost of the required maneuvers corresponds to a velocity change (delta-v) with less than 0.05 kg hydrazine per year. The generally smaller horizontal baselines in this phase in consequence mean, that acquisitions demanding large effective baselines need to be acquired with steeper incidence angles, but with the benefit to allow for about one extra year in close formation flight.

In terms of the vertical separation (orange in Fig. 3) a 250 m minimum distance is required for formation safety, i.e. to avoid a collision between the two spacecraft. Therefore, the eccentricity vector has to be maintained at the desired distance and the rotation of the eccentricity plane has to be compensated. This is achieved by small daily in-plane maneuvers performed with the distributed formation control concept described above.

However, regular acceleration maneuvers to lift the orbit are required anyway to fight the atmospheric drag. Due to the currently increased solar activity and approaching a solar maximum, these acceleration maneuvers are co-used to keep the vertical baseline. Hence, keeping the vertical separation currently does not consume extra propellant.

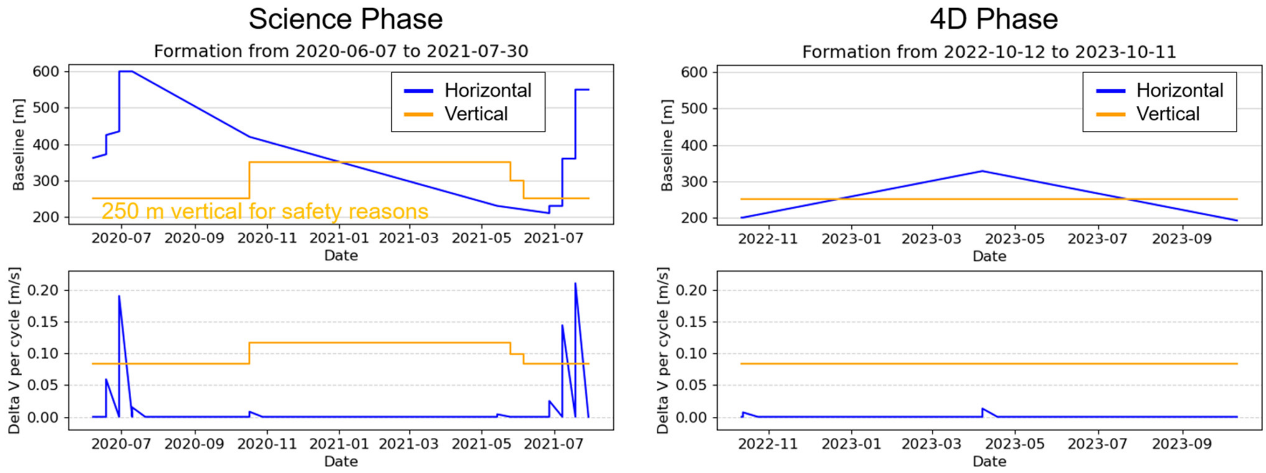

Figure 3: Formation changes and correlated theoretical fuel consumption for the science phase in 2020/2021 (left) and the optimized formation during the 4D phase in 2022/2023 (right)

All these measures help to maximize the mission life time. Current predictions show that the TSX satellite will run out of fuel in 2032. The hydrazine on the TDX satellite will last approximately until 2029, as TDX currently has less hydrazine due to the formation change and keeping maneuvers in earlier years.

3. DEM MISSION EVOLUTION

The primary goal of the TanDEM-X mission, the global DEM, was achieved with acquisitions until 2014. Beyond that, TanDEM-X offers great scientific potential for both interferometry and new radar imaging techniques and applications, which was addressed by the Science Phase 2014-2016 [10].

Between 2017 and 2020 the so-called TanDEM-X DEM 2020, indicating the changes compared to the first global DEM, was acquired [11]. This coverage is currently in processing. Both, a new global DEM [12] as well as dedicated DEM change maps [13] will be generated and made available to the scientific community.

3.1. Science Phase 2020-2022

From 2020 to 2022 an additional Science Phase was conducted to monitor forests, ice and urban areas. Forests and glaciers are rapidly changing environments. Both are main drivers for the climate change on Earth and need to be understood by climate scientists [14]. In urban areas, the generation of 3D city models is one main application of TanDEM-X time series [15].

3.2. TanDEM-X 4D Phase

Currently, the mission is in its 4D Phase with a focus on continuous monitoring of changes in the Earth's topography. With the knowledge of the changing regions of the Earth from former coverages, the acquisitions are concentrated on these dynamic areas.

The 4D Phase is planned to continue until the end of the TanDEM-X mission, i.e. the end of the close formation flight. Until then, monitoring temporal changes in the height will be the main goal in this phase. Acquisitions of forests and glacial areas from the Science Phase 2020-2022 (solid green in Figure 4) will be alternated with areas with large changes (shown in orange). The crosshatched green areas will be interspersed during the forest/glacier phases.

As mentioned in Section 2.2, battery degradation limits the maximal data take length. With an intelligent planning concept, the acquisitions of large areas are now chopped into shorter pieces with longer pauses afterwards to meet this restriction. In addition, the formation flying concept was optimized for fuel-saving formation changes as described in Section 2.3 to facilitate flying in close formation for several more years.

4. LESSONS LEARNED FOR FUTURE SAR MISSIONS

Satellite missions often run much longer than expected, as RADARSAT-1/2 [16][14], Cosmo-Skymed, and Terra-SAR- X/TanDEM-X [3] have impressively shown.

Hence, it is important to carefully manage the consumables even from the beginning. If possible, it is valuable to already foresee consumables for some extra years in orbit or to completely fill the, often standardized, propellant tanks. Also the selection of critical components, like the USOs, have to be performed with care and in view of a long mission duration, maybe with further redundancies.

In addition, all other resources, like the battery shall be handled with care from the beginning. A thorough monitoring of these consumables and critical components needs to be established which ensures the escalation on management level and discussion of information or effects concerning their status throughout the mission life time.

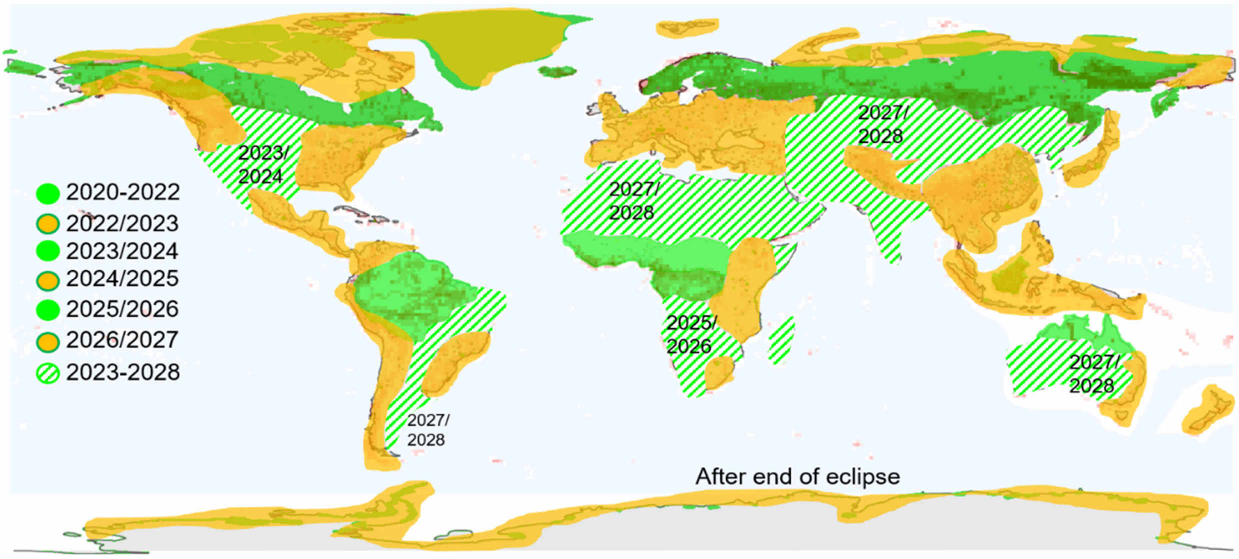

Fig 4: Coverage of the TanDEM-X 4D Phase. The goal of this phase is to acquire multi-temporal coverages in regions with major changes, like forests, glaciers, mountains and some densely populated areas.

It is also important to thoroughly document expert knowledge and all measures undertaken to maintain the systems during mission life time. This has to be ensured by proper quality assurance procedures, which are effective and beneficial for mission operations that often spread over more than a decade and therefore inevitably experience changes in organizations and teams. These needs have to be reflected in the quality management system and in the documentation management system. It is though most important that the mission actively "lives" this concept.

5. CONCLUSION

TanDEM-X is the first bistatic SAR interferometer with two satellites in space. Both satellites still work with remarkable performance, even after 16 and 13 years in orbit. Several contingencies had to be mitigated during recent years, but all have been fixed successfully and with no loss to product quality. Limitations to preserve the battery and reduce the amount of fuel consumption have been established. Finally, the mission continues to provide highly valuable and high-quality SAR and DEM data to support scientists in solving urgent questions of the Earth system.

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