Operational Experience of Close Formation Flight at 500 km Altitude during Severe Geomagnetic Storms

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***Abstract* – The TerraSAR-X (TSX) and TanDEM-X (TDX) satellites have operated as a bistatic SAR formation since 2010, providing more than 15 years of close formation-flying experience. High solar activity and strong to extreme geomagnetic storms between 2023 and 2025, especially the 10–11 May 2024 event, significantly challenged atmospheric drag modelling and orbit prediction in low Earth orbit. This paper summarizes the operational experience and lessons learned from these events, including a systematic assessment of space weather prediction data and atmospheric density model combinations for the TSX / TDX mission. The resulting upgrade of the operational orbit determination, prediction, monitoring and control chain in March 2025 reduced along-track prediction errors and restored robust compliance with the formation-flying requirements, as demonstrated during subsequent space weather events including the severe geomagnetic storm in November 2025.**

I. INTRODUCTION

The German Synthetic Aperture Radar (SAR) satellites TerraSAR-X (TSX) and TanDEM-X (TDX) have been in orbit since 2007 and 2010, respectively [1]. Since 2010, both satellites have been operated in close formation with a typical separation of 250 m in a 505 km mean-altitude sun-synchronous orbit, forming a bistatic SAR mission, with the primary mission goal to deliver a global Digital Elevation Model (DEM) [2]. Based on data acquired between 2010 and 2014 the TanDEM-X global DEM featuring outstanding height accuracy became available in 2016 [3]. The on-going TanDEM-X 4D phase started in 2022, aiming on the repeated acquisition of areas with major changes, such as ice-covered or permafrost regions as well as forests or rural areas [4].

Both satellites (see Table 1 for the flight dynamics relevant satellite properties) have exceeded their nominal lifetimes by far, and various challenges have been faced. Although more than 15 years of formation-flying experience are now available, important operational lessons are still being learned.

The space weather conditions during the period from 2023 to 2025, characterised by high solar activity combined with moderate to severe geomagnetic storms, posed significant challenges for satellite operations in low Earth orbit and proved extremely demanding for precise formation flying at these altitudes. Atmospheric drag modelling, and consequently the formation's orbit and relative motion prediction, were often jeopardized by space weather prediction data of insufficient accuracy. The most severe impact on formation flying occurred during the strongest geomagnetic storm of the last 20 years, in the night from 10 to 11 May 2024.

This paper analyses how severe geomagnetic storms affected the operational TSX / TDX formation-flying chain, with particular focus on along-track prediction errors. Based on severe space weather events, several combinations of atmospheric density models and space weather prediction data are evaluated. The resulting operational change and its performance during subsequent storms are presented as lessons learned for long-duration close formation flight in low Earth orbit.

Table 1. TSX and TDX satellite characteristics (flight dynamics relevant parameters only).

<table>
<tr><th></th><th>TerraSAR-X</th><th>TanDEM-X</th></tr>
<tr><td>Launch date</td><td>2007-06-15</td><td>2010-06-21</td></tr>
<tr><td>Drag area</td><td colspan="2">3.2 m²</td></tr>
<tr><td>Mass, Launch</td><td>1346 kg</td><td>1348 kg</td></tr>
<tr><td>Mass, 2024-05</td><td>1293 kg</td><td>1256 kg</td></tr>
<tr><td rowspan="2">Propulsion system</td><td colspan="2">4 x 1N thrusters in anti-flight direction – 78 kg Hydrazine</td></tr>
<tr><td></td><td>2 x 40mN thrusters in flight and anti-flight direction – 36 kg Cold-Gas (Nitrogen)</td></tr>
</table>

A. Orbit and Formation Control

The TSX satellite is operated in a sun-synchronous dusk-dawn orbit (97.44 deg inclination, 505 km mean altitude, frozen eccentricity) with a 167 orbits / 11-day repeat cycle. The TSX osculating orbit is maintained within a maximum absolute cross-track distance of 250 m from a target Earth-fixed reference trajectory, which comprises exactly matching states at the beginning and end of the 11-day cycle enabling highly repeatable data-take conditions. Orbit manoeuvres to counteract luni-solar perturbations and to compensate atmospheric drag are performed 3 to 5 times per year (out-of-plane, up to 30 cm/s Δv) and up to 6 times per week (in-plane, 1 to 6 cm/s Δv), respectively. The implemented guidance and control concept is described in [5] and is foreseen for the entire TSX lifetime including the period of formation flying with TDX.

The acquisition of the TanDEM-X DEM requires the coordinated operation of two satellites flying in close formation. The chosen formation geometry implies maximum out-of-plane orbit separation near the equator crossings and maximum radial separation at the poles. This is realized by small ascending node differences and by slightly different eccentricity vectors, respectively. This concept of relative eccentricity / inclination vector (e/i) separation results in a helix-like relative motion of the satellites along the orbit and provides a maximum level of passive safety in the plane perpendicular to flight direction in case of vanishing along-track separation. The relative navigation and control concept is described in [6] and flight results are summarized in [7].

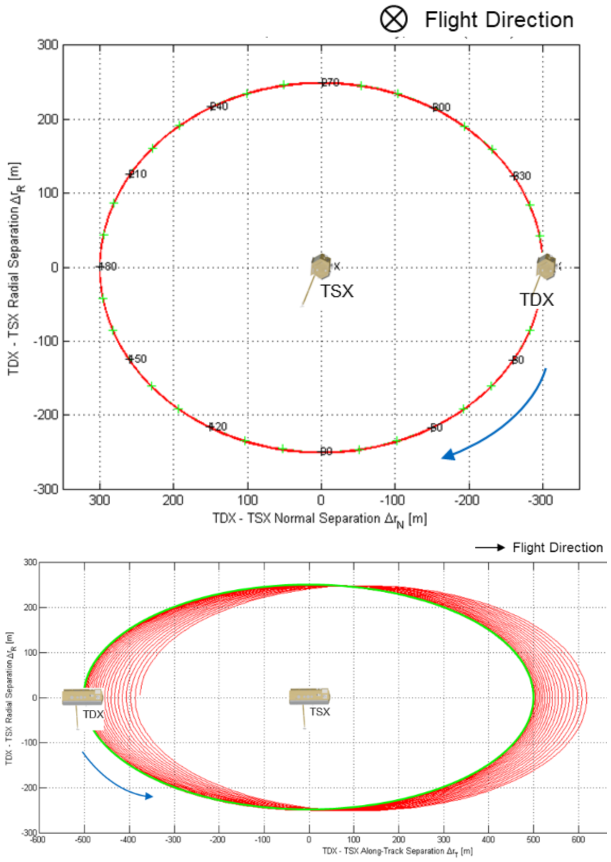

Fig. 1. Simulated TDX-TSX relative motion in Hill frame (Note: the satellite illustrations are oversized). Once per orbital revolution (~95 minutes), TDX moves in an elliptical path around TSX. Initial (green) and perturbed evolution within 36 h or 23 relative orbits (red) for the formation geometry of May 2024. Change of Radial / Normal separation induced by Earth's oblateness perturbation (top), and Along-track drift caused by moderate differential drag (bottom).

In addition to the TSX orbit control manoeuvres, TDX performs cold-gas and hydrazine manoeuvres to maintain the TDX-TSX relative motion. This results in a higher ΔV budget for TDX, which also depends on the formation geometry and demands of formation changes implied by the TanDEM-X acquisition plan.

Because of Earth oblateness, the relative eccentricity vector rotates about the origin of the relative eccentricity vector plane with a period of roughly 100 days. The resulting rotation and deformation of the relative motion ellipse can be deduced from Fig. 1 (top) over a 36-hour simulation. This drift needs to be compensated by suitable in-plane formation keeping manoeuvres to maintain a stable configuration. In-plane manoeuvres also affect the relative semi-major axis, and any residual relative semi-major axis offset results in a secular along-track drift of the formation. For example, a 250 m vertical separation demands every day two burns with ~4 mm/s Δv each and separated by typically half a revolution. These manoeuvres are additionally used to adjust the along-track separation and to compensate (previous) manoeuvre execution inaccuracies and differential drag effects. Fig. 1 (bottom) depicts the uncorrected drift in along-track direction resulting from moderate differential drag.

Under nominal conditions, the established formation-control strategy maintains the required geometry with high accuracy. During enhanced solar activity, however, increased and poorly predicted atmospheric drag directly affects the relative semi-major axis and therefore the along-track separation, which is the most critical quantity for the operational constraints discussed below.

B. *Operational Constraints*

The TSX / TDX formation implies two major risks: collision of the spacecraft and exposure of the partner satellite to the transmitted radar beam. Multiple safety features have been implemented within the ground and the space segment to prevent occurrence of such events [8].

While the e/i-vector separation implies very high passive collision safety, the mutual illumination risk has to be actively mitigated. For this purpose, the synchronization (sync) pulses exchanged between the two satellites for oscillator synchronization before bistatic instrument operations are also used as a safety measure: SAR transmissions are inhibited if the received signal strength falls below a threshold. The correct selection of the TSX-TDX sync horn pairs within the mission planning process requires a relative position knowledge in along-track direction of < 200 m over 36 hours. This is the main constraint for the relative orbit propagation accuracy. Violating the 200 m requirement typically results in sync failures, resulting in the loss of SAR acquisitions, which then leads to delays or even outages in the mission timeline.

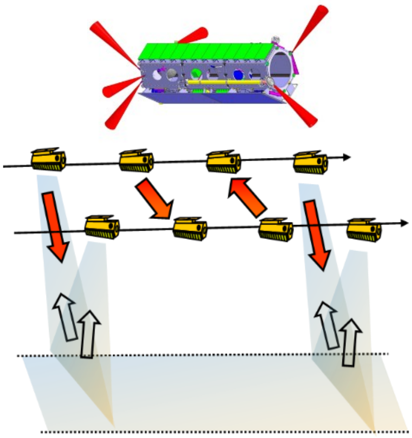

Fig. 2. *TDX synchronisation horn beams (top) and synchronization scheme (bottom) [20].*

C. *Influence of Differential Drag*

The TDX-TSX relative along-track acceleration is driven by the differences in their ballistic coefficients

$$\varepsilon = (b_{TDX} - b_{TSX})/b_{TSX}, \qquad (1)$$

with ballistic coefficient $b = C_D(A/m)$, where A is the satellite's cross-section area, m is the satellite mass, and C_D is the aerodynamic drag coefficient. C_D is equal for both satellites and can be assumed to be 2.3. Area and mass are summarized in Table 1. This causes an accumulated along-track offset [9]

$$\Delta r_T = 3/4\ \varepsilon\ b_{TSX}\ \rho\ v^2\ \Delta t^2 \qquad (2)$$

over a time interval Δt. In (2) ρ is the atmospheric density and v the velocity, which is about 7,600 m/s for TSX. Thus, for a fixed prediction horizon, the along-track error scales directly with atmospheric density and with the relative ballistic-coefficient difference. Both effects became more critical during the 2023–2025 high solar-activity period.

At the beginning of the TanDEM-X mission, when TDX entered the close formation flight with TSX in October 2010, the impact of differential drag was minimal because of almost identical ballistic coefficients (ε < 1%). Over the 15 years of formation flight, the unequal fuel expenditure led to an imbalance in the individual satellite masses (cf. Table 1), accumulating to a relative ballistic coefficient of 3% during the high solar activity phase in 2023-2025.

Fig. 1 and 3 depict the formation geometry flown in May 2024, comprising of 250 m radial ($a \cdot \Delta e$) and 300 m normal separation ($a \cdot \Delta i$). The TDX-TSX relative motion is simulated beginning with ideal conditions (green curve) and propagated over 36 hours, i.e. 23 orbits. Fig. 1 (bottom) shows the impact of moderate solar activity with an average atmospheric density of ~1 g/km³ at 505 km altitude.

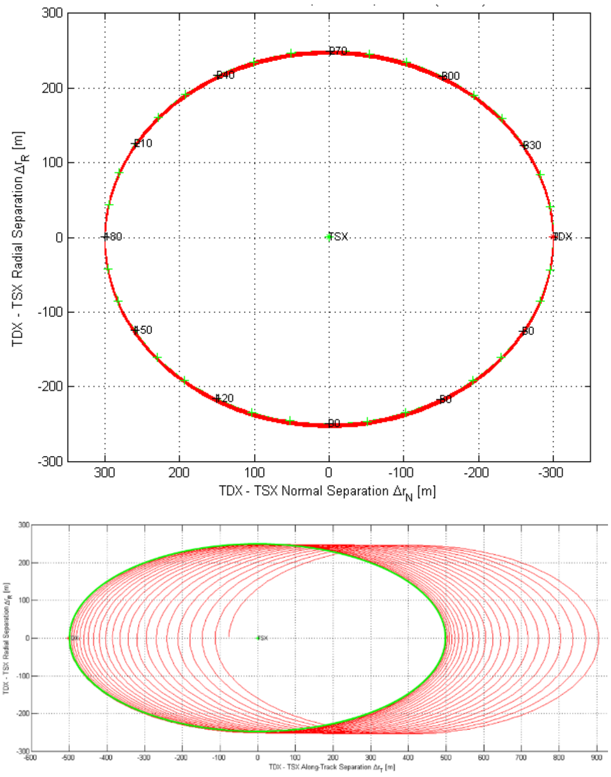

Fig. 3. Simulated TDX-TSX relative motion exposed to strong differential drag as experienced during G5 storm in May 2024. The along-track separation exceeds the operational ±200 m prediction requirement within approximately 24 h.

Even after 36 hours of uncontrolled relative motion, the relative along-track position is well within the required ±200 m w.r.t. nominal position.

The peak density experienced during the G5 storm of May 2024 was five times higher. In Fig. 3 we applied an average density of 3.4 g/km³ to demonstrate the strong impact on the relative along-track motion. Here, the 200 m requirement is violated within 24 hours or 15 orbits. Contrary to the simulation, in operations the starting point often differs from the ideal formation geometry. Navigation inaccuracies and manoeuvre execution errors contribute to relative semi-major axis offsets, which, in the worst case, amplifies the relative along-track drift. Furthermore, a positive offset in the relative along-track distance shortens the period until constraint violation further.

As a consequence, sync pulses failed quite often during severe and extreme geomagnetic storms. The correlation is summarized in Table 2. Due to the nature of the e/i-vector separation, the formation was always passively safe during all events. For example, in Fig. 3 (top) there is almost no impact of the high differential drag on the relative motion in the plane perpendicular to flight direction.

Table 2. Correlation of sync pulse failures with strong (G3), severe (G4), and extreme (G5) geomagnetic storms.

Space Weather Event	**TanDEM-X Mission Impact**
Before March 2025	
G3 2023/02/27	Formation ok, no sync failures
G4 2023/03/24	Formation ok, no sync failures
G4 2023/04/23-24	Formation ok, no sync failures
G3 2023/11/05-06	Formation ok, no sync failures
G3 2023/11/13	Formation ok, no sync failures
G4 2024/03/24	Formation affected (along-track), sync failures
G5 2024/05/10-12	Formation ok, sync failures
G4 2024/08/12	Formation ok, no sync failures
G5 2024/10/10-11	Formation affected (along-track), sync failures
G4 2025/01/01	Formation affected (along-track), sync failures
*After March 2025** *(TSX / TDX FD system change)*	
G4 2025/04/16	Formation ok, no sync failures
G4 2025/06/01-03	Formation ok, no sync failures
G4 2025/11/12-13	Formation ok, no sync failures
G4 2026/01/19-21	Formation ok, no sync failures
G3 2026/03/22	Formation ok, no sync failures

* The operational processing chain was upgraded on 30 March 2025 from the previous Jacchia-Gill based setup to MSIS-00 with USAF forecast data.

II. ATMOSPHERIC DENSITY MODELS AND SPACE WEATHER FORECAST TRADE-OFF

Following the May 2024 G5 storm, the operational objective was to identify a density-model and space weather data combination that reduced along-track prediction errors during disturbed conditions while remaining robust and computationally suitable for daily flight dynamics operations.

A. Atmospheric Density Models

The operational default model at DLR/GSOC had been a modified version of Jacchia71, referred to as Jacchia-Gill (JG) [10]. Instead of numerical integration, it uses a bi-polynomial fit of the density values. This leads to a significant improvement of the computational speed (factor of 9). The geomagnetic Ap and Kp indices, and the F10.7 flux serve as an input (also referred to as proxies). To work within daily operations, the density model has to fulfil certain requirements:

- An altitude coverage of the region of interest, 100 – 1000+ km.
- Availability of its proxies, including historical and prediction data.
- Total mass density as output, which is essential to compute the atmospheric drag.
- Fast computation time within orbit determination and prediction.

After the severe geomagnetic storms in 2024, several models were analysed, including empirical (NRLMSIS-00 [11] and NRLMSIS 2.0 [12], Jacchia-Bowman [13]) and semi-empirical (Drag-Temperature-Model [14]) models. Due to their robustness and the availability of their input proxies, the standard NRLMSIS-00 (referred to as MSIS-00) model and its 2.0 version (MSIS-2.0) were selected for implementation. Both were added to the DLR Flight Dynamics Services (FDS) atmospheric model library to assess different combinations of space-weather data sources and atmospheric density models.

During initial simulations, almost identical results for MSIS-00 and MSIS-2.0 were obtained. Because of the significantly larger CPU-time for MSIS-2.0, MSIS-00 was preferred over MSIS-2.0, and is hereafter referred to as MSIS.

B. Space Weather Data

The geomagnetic indices (Ap and Kp) and the F10.7 flux are the critical input parameters needed for JG and MSIS, to compute the atmospheric density for a certain point in time. Their availability is crucial for accurate orbit determination and propagation. To ensure redundancy, multiple data sources were utilized. The default setup used for JG has been the following:

- The observational (history) data is provided by NOAA [15], while the flux and geomagnetic index forecast comes from ESA/ESOC. They provide a 27-day short-term and 20-year long-term forecast which is based on a software developed by the British Geological Survey under ESA contract.

In addition, the following public products were included in the process to ensure a variety of stable and available proxies:

- F10.7 and Ap 45-day forecast provided by NOAA (formerly provided by United States Air Force, USAF) [15].
- 3-day real-time Kp forecast provided by GFZ (GFZ Helmholtz Centre for Geosciences, Potsdam, Germany) [16].

In order of appearance, the sources are in the following referred to as ESOC, USAF and GFZ. Different combinations have been used as input for JG and MSIS as stated in the next section. The data is fetched on a daily basis and stored in a PostgreSQL database cluster. The 3-hourly geomagnetic index is updated 8 times/day. Archiving of all sources is in place since 09/2024. This allows re-computation and analysis of certain events of interest.

C. Orbit Determination and Prediction

At GSOC, two independent orbit determination and prediction programs have been implemented, maintained and operationally used. The ODEM software is a general orbit determination and propagation program for Earth-orbiting satellites. Through the use of elaborate force models and the capability to process a variety of tracking measurement types as well as GNSS navigation data, the program is well suited for operational applications ranging from LEO to GEO missions, including the calibration of orbit-control manoeuvres. Its strength lies in the various modelling and estimation features that have been used over many years for various spacecraft missions.

For satellite missions requiring higher orbit-determination accuracy, FDS also uses the GNSS High Performance Software Tools (GHOST) for precise orbit determination (POD) [17]. The GHOST software suite processes GNSS code and carrier-phase observations in combination with GNSS ephemeris and clock products, allowing orbit determination accuracies at the centimetre level. Since empirical accelerations are estimated in this process, the resulting POD solutions are less sensitive to atmospheric-density modelling errors during disturbed space weather conditions.

The routine TSX / TDX formation-monitoring and control process is based on a time-synchronous orbit determination of TSX / TDX. ODEM is more robust and independent of auxiliary data as compared to POD, making ODEM well suited for these routine operations. Under nominal space-weather conditions, the relative navigation used in the formation-control process is accurate to about 0.5 m RMS in the across-track plane and about 1 m in along-track direction [18].

For the present analysis, GHOST POD solutions were used as reference orbits to assess the performance of ODEM-based orbit determination and prediction under disturbed space weather conditions. For each tested atmospheric-density model and space weather data combination, orbit determination and prediction were performed at 3-hourly epochs and compared against the corresponding POD solution, with particular focus on the tangential prediction error. This error component is operationally most relevant, because it directly maps into the relative along-track prediction accuracy.

To study the space weather impact on the TSX / TDX orbit determination and prediction, the following combinations of space-weather prediction data and atmospheric density models were implemented in a test-bed:

- USAF – JG
- ESOC – JG (DLR/GSOC standard)
- USAF – MSIS
- ESOC – MSIS
- ESOC/GFZ – JG
- USAF/GFZ – JG
- ESOC/GFZ – MSIS
- USAF/GFZ – MSIS

III. SIMULATION AND RESULTS

The following figures show the absolute tangential position errors of the predicted TSX orbit with respect to the GHOST POD reference solution. Since the relative ballistic-coefficient difference between TDX and TSX was approximately 3% during the analysed high solar-activity period, the relative along-track prediction errors relevant for formation flying are expected to amount to approximately 3% of the absolute tangential errors. The evaluation therefore focuses on whether the resulting relative prediction error remains compatible with the ±200 m along-track requirement over the 36 hours horizon.

The first relevant extreme event after the investigation was in place occurred in October 2024, when a Kp index of 9 was observed. At this stage, only the USAF and ESOC data sources were available, limiting the analysis to the combinations USAF-MSIS, USAF-JG, ESOC-MSIS and ESOC-JG.

Fig. 4 shows the tangential RMS error of the orbit achieved by ODEM compared to the POD solution at the end of the 24-hour orbit determination arc (first row), and for predictions of 24 hours, 36 hours, and 48 hours (second to fourth row, respectively). The RMS error increases for all space-weather data source–model combinations; however, the two MSIS solutions perform significantly better than the JG solutions. For example, the 36-hour prediction results in approximately 470 m (3% of the observed RMS) relative position error of the formation for the JG cases and therefore violating the threshold, while the errors remained well below the 200 m requirement for MSIS.

Another analysis was performed around the G3/G4 storm in January 2025. By this time, additional space-weather data from ESOC and Kp correction files from GFZ were added to the analysis allowing the comparison of more source – model combinations. The results of the analysis for January 2025 are shown in Fig. 5. All combinations showed increased errors in the morning of 1 January 2025, but again the ESOC-MSIS and USAF-MSIS combinations recovered faster than the JG solutions.

Parker & Linares [19] reported that the Kp forecast models work reasonably well during quiet times, but struggled in forecasting the G5 storm of May 2024. Furthermore, for the 2024-2025 period we observed for all severe and for some strong storms a 1-2 day delay between the occurrence of peak Kp values and maximum prediction errors. This is related to the underpredicted Kp values at the beginning of geomagnetic storms and Kp overpredictions after the storms mostly passed.

The analysis conducted could reproduce the observed behaviour in operations, but also showed how different data source – atmospheric density model combinations perform in high solar activity.

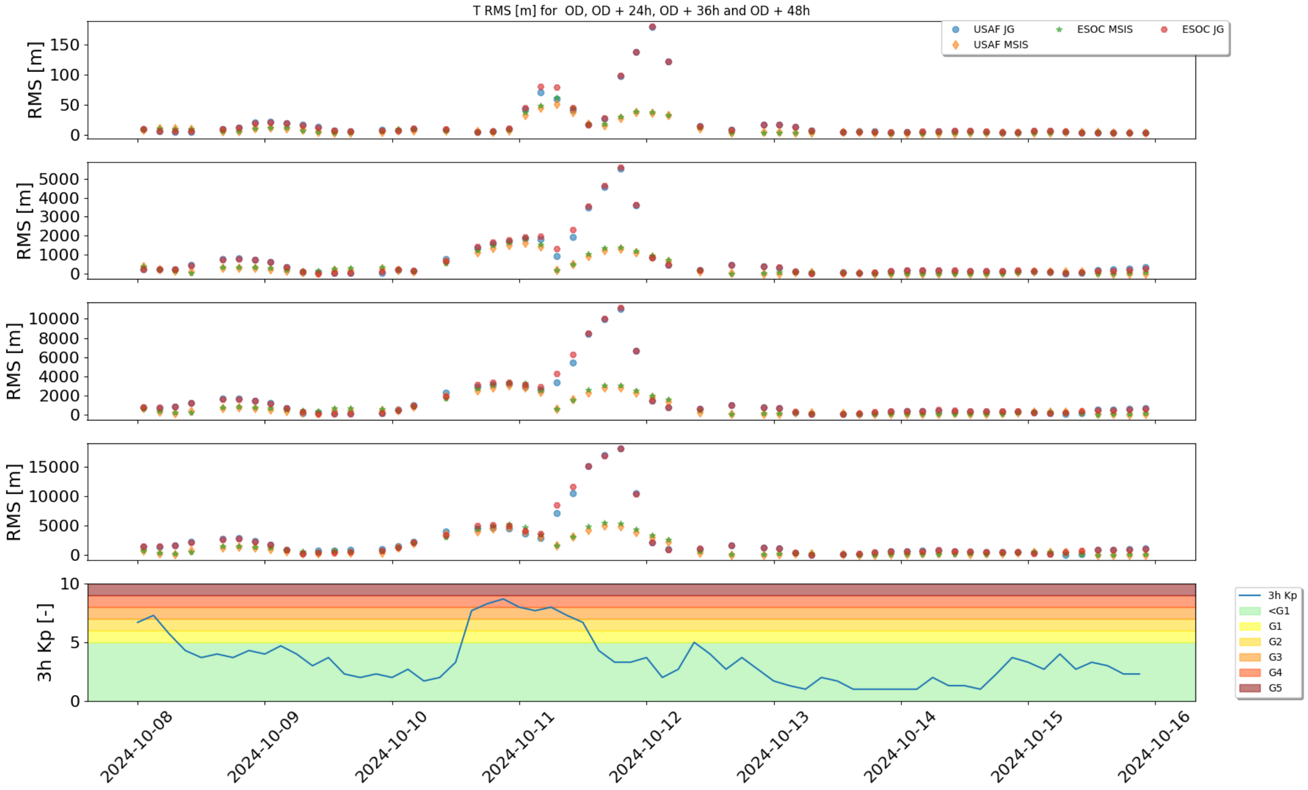

Fig. 4. Tangential RMS error after 24 h orbit determination (top), and orbit prediction over 24, 36 and 48 h, and measured Kp (bottom) around G5 storm in Oct 2024.

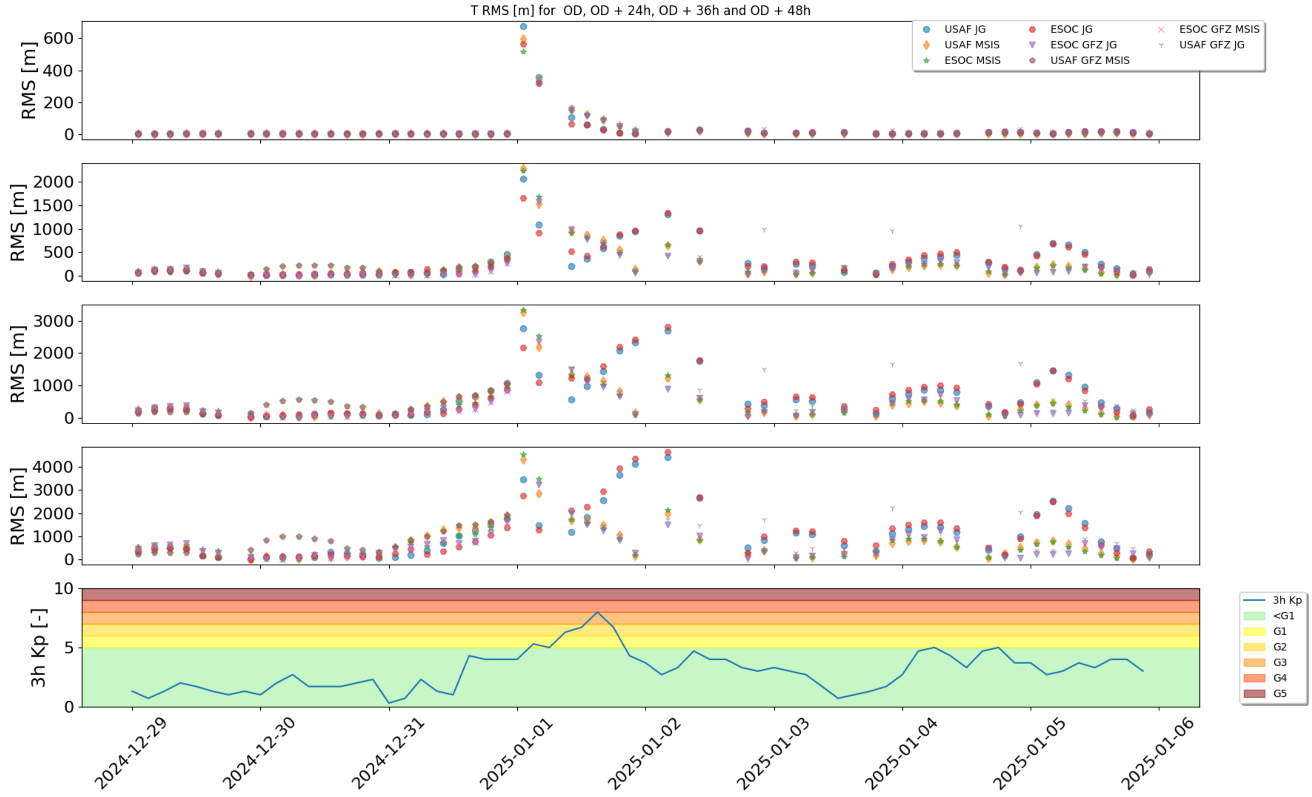

Fig. 5. Tangential RMS error after 24 h orbit determination (top), and orbit prediction over 24, 36 and 48 h, and measured Kp (bottom) around G4 storm in Jan 2025.

Across the analysed disturbed periods, the MSIS-based combinations consistently showed smaller and faster-recovering tangential prediction errors than the Jacchia-Gill based combinations. Among the tested space weather data sources, the USAF 45-day F10.7 and Ap forecast in combination with MSIS-00 provided the most robust and accurate behaviour during high-Kp events. Therefore, the complete TSX / TDX operational processing chain – comprising orbit determination and prediction as well as formation monitoring and control – was upgraded on 30 March 2025 to this combination of atmospheric model and space-weather prediction data. Since then, no along-track formation control problems occurred and no sync pulses failed. In particular the space weather events experienced thereafter, including the severe geomagnetic storms in November 2025 and in January 2026, demonstrated the improved accuracy and robustness of close formation flying at low Earth orbit altitudes.

IV. Conclusion

TanDEM-X is the first bistatic SAR interferometer with two satellites in space. Both satellites still work with remarkable performance, even after 18 and 15 years in orbit. The flight experience gathered during the extreme space weather events in 2023-2025 has been presented, motivating a reassessment of the operational atmospheric model and space-weather prediction data. From a survey of space-weather prediction data in combination with atmospheric density models, and the systematic investigation and numerical simulation of various data / model combinations applied to the TanDEM-X mission, MSIS in combination with USAF forecast data was selected for operational use. The complete operational processing chain - comprising orbit determination and prediction as well as formation monitoring and control - was upgraded in March 2025. Finally, space weather events experienced thereafter demonstrated the improved accuracy and robustness of close formation flying at low Earth orbit altitudes. Both missions continue to provide highly valuable and high-quality SAR and DEM data to support scientists in solving urgent questions of the Earth system.

V. Acknowledgements

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