

Mitigation of GPS Signal Interference for TanDEM-X

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Abstract

The satellites TerraSAR-X and TanDEM-X are operated in close formation since 2010 to acquire synthetic aperture radar (SAR) images for scientific and commercial applications as well as for global high precision digital elevation models (DEMs). Since 2020, and even more since 2022, the GPS receivers of the satellites have been affected by signal interference, that is limited to certain geographic regions, but very persistent. This paper describes the GPS receivers, how they are affected and which measures have been taken recently to mitigate the impact on the running satellite missions.

1 Introduction

The two German SAR satellites – TerraSAR-X (TSX) and TanDEM-X (TDX) – have been in orbit for more than 18 years and 15 years respectively and continue to deliver reliable, high quality SAR products. Each satellite is equipped with a high-resolution X-band active phased array antenna that is capable of acquiring data in several acquisition modes [1].

When operated stand-alone, each of them serves the TerraSAR-X mission (TSM) by providing high quality monostatic SAR images. When operated together, they serve the TanDEM-X mission (TDM) by forming the first satellite-based SAR interferometer that delivers cross-track single-pass interferometric products [2].

Although both satellites have by far exceeded their design lifetime of 5.5 years, the quality of the SAR products is well within their specification. After the extended TanDEM-X mission objectives of acquiring bistatic SAR data for a global Digital Elevation Model (DEM) product, and later on for a global DEM Update, the so-called TanDEM-X DEM 2020, have been reached [3], the mission entered into its next, so-called TanDEM-X 4D phase. The new phase allows to provide further DEM updates by reacquiring regions of the Earth where dynamic processes are expected.

Nonetheless, both satellites have now reached an age in which it is mandatory not only to monitor but also to manage the satellites' limited resources. Special attention is given to the propellant levels (Hydrazine) and to the batteries. Among the measures to preserve battery states are a tight monitoring and a considerable reduction in the allowed maximum duration of data takes. The latter has an impact on the systematic process of TanDEM-X acquisition planning, which considers this constraint in an adapted DEM acquisition strategy, placing a larger number of shorter acquisitions [4][5][6] in the acquisition timeline, compared to previous mission years.

In addition to these age-induced mission challenges there have been other ones that are caused by external factors. This paper describes GPS signal interference issues observed in recent years and presents the efforts that have

been undertaken in order to understand and mitigate the impact especially on the TanDEM-X mission.

2 The MosaicGNSS GPS receivers

For navigation, time-keeping and orbit determination both satellites are equipped with a redundant pair of GPS receivers. The used MosaicGNSS receiver was originally developed by Airbus Defence and Space (ADS) in the late 90ies. They are single-channel GPS receivers with a nominal (3D RMS) accuracy of 10 m that can track up to eight of the visible GPS satellites [7]. They use only the GPS L1 C/A public signal, and are realized as software-based GPS correlators using a digital signal processor (DSP) [8].

These receivers were not only chosen for the satellites TSX and TDX, but for several other Low-Earth-Orbit (LEO) satellite missions, among them the Spanish PAZ satellite [9].

It shall be noted that both satellites carry additional GPS receivers as part of the secondary payload TOR/IGOR. These are two-channel GPS receivers. The data of these receivers is used for precise orbit & baseline determination for TanDEM-X interferometric processing and is also augmenting the SAR processing for monostatic TerraSAR-X acquisitions. They are not used for on-board timeline execution and time synchronization. These GPS receivers are not discussed here, as they are not affected by the described degradations in the same way.

3 GPS signal interference

A statistically significant degradation has been observed on both satellites regarding the overall number of tracked and used GPS satellites, starting in 2020. The instabilities were regionally correlated to the Middle East region. Multiple satellites flying the MosaicGNSS receiver including TSX and TDX reported issues with the number of used satellites dropping below three over that region.

A detailed signal level analysis indicated that this might be caused by the “flex-power” feature of newer GPS satellites. This means, that the signal levels in the military P(Y) code

were found to be increased, whereas the civilian C/A code showed locally decreased signal levels. The signal level increases in P(Y) caused the TOR/IGOR receivers to perform software reboots, whereas the reduced C/A signal levels led to the number of used GPS satellites to drop temporarily below two for the MosaicGNSS receivers.

As a permanent workaround the allowed internal MosaicGNSS propagation time was increased from 5 min to 8 min on March 27th 2020. With the increased propagation capability, the receiver is able to bridge longer periods without a navigation solution for Position/Velocity/Time (PVT), i.e. times, when not enough GPS satellite signals can be used for computation of PVT.

While the internal propagation of the MosaicGNSS receiver provides a fairly good performance and typically is accurate in the order of few microseconds after several minutes of propagation, it cannot guarantee a stable solution for an unlimited time. Therefore, when the configured propagation time limit is reached, the PVT solution is declared invalid. The generation of the GPS 1-pulse-per-second (1-PPS) signal is handed over to the satellite's On-Board Computer (OBC) and is then based on its internal clock that is rather inaccurate, compared to MosaicGNSS.

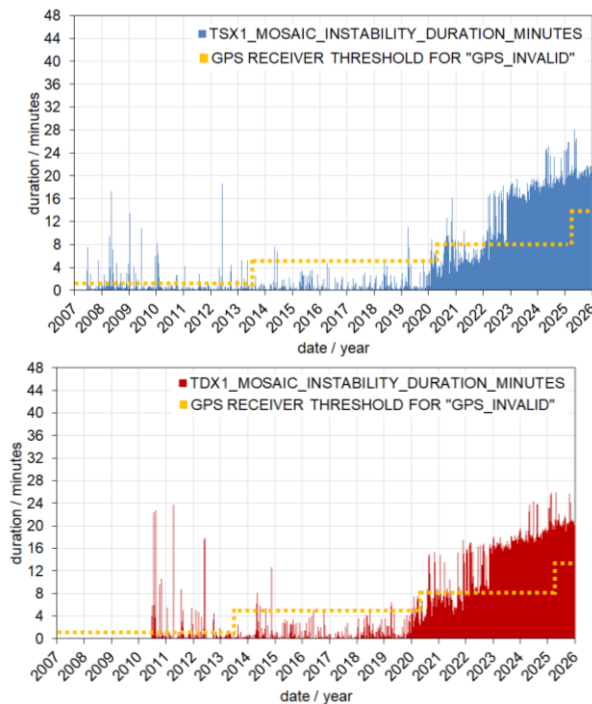


Figure 1 Evolution of GPS instabilities over mission time in comparison to the configured threshold for MosaicGNSS-internal propagation (top: TSX, bottom: TDX).

Figure 1 shows the duration of GPS instabilities for the MosaicGNSS receivers of TSX and TDX for the whole mission time. The duration of a GPS instability is defined as the time period during which the GPS receiver can only use the signal of less than two GPS satellites. The first increase in 2020 is clearly visible for both satellites.

Another significant increase in PVT losses, that is visible in the plots, has been observed starting from the beginning of 2022. Peak values for the duration of GPS outages often

reached 16 minutes. At the end of the year the effect became permanent, affecting each orbit repeat cycle without exception. A trend towards longer outages followed, so that, at the end of 2025, GPS outages regularly exceeded 20 minutes.

It shall be noted that, other than the plots in Figure 1 might suggest, not every satellite orbit is affected. The phenomenon is spatially limited to certain geographic regions (see **Figure 2**). It affects both satellites with their respective GPS receivers in the same way and was building up mainly in the course of 2022 and 2023, as described above. Hence it was concluded that the source of the disturbances is ground-based signal jamming. It is reasonable to assume that the political situation is playing a role for the observed GNSS signal levels, that persist until today, as the instabilities typically started over the Scandinavian area for descending orbits, and over the Middle East for ascending orbits.

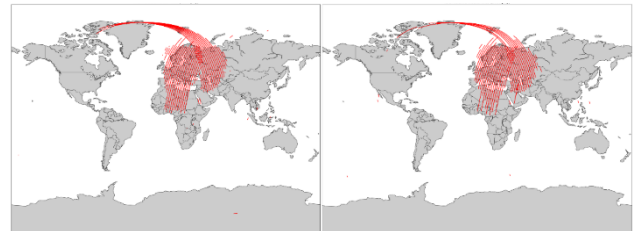


Figure 2 Satellite orbit tracks affected by GPS interference (July 2023, TSX left, TDX right). Plot provided by TDM Mission Operations group of the German Space Operations Center (GSOC).

Figure 2 shows, as an example, the satellite ground tracks of TSX and TDX where GPS signal reception is degraded, i.e. the number of usable GPS satellite signals is insufficient (< 2). The plots show a full orbit repeat cycle (11 days) in 2023.

4 Impact on mission TerraSAR-X

A degraded on-board time due to internal time propagation of the GPS receiver can result in an azimuth shift of the commanded monostatic data take. This is because the start of the recording is set based on the GPS time. Subsequent data take execution itself and the recording of echo lines is not affected, because the instrument's Ultra-Stable Oscillator (USO) is used for timing of pulses and echo windows. While, in general, this small azimuth shift is tolerable and does not pose a big problem, it can be an issue when acquisitions are repeated for building up image stacks.

Another aspect is that the time stamps in the SAR raw data (rangeline headers) is based on the on-board (GPS) time, and any inaccuracy of the on-board time will affect this annotated time information. These time stamp inaccuracies can directly translate into geocoding errors during screening and SAR processing of the data, resulting e.g. in shifted boundary polygons of the imaged scene.

In addition to the presence of inaccuracies of the on-board time in the form of time shifts building up over time, there is also a certain risk of discontinuities. They are observed

particularly at the end of a GPS instability, when the GPS receiver output gets valid again, and an on-board time synchronization event is triggered over the subsystems of the satellite. These discontinuities can lead to complex errors in the execution of sequences of (time-tagged) commands. A typical occurrence is the abortion of a running data take recording. In such cases, that are observed at irregular intervals, the respective data take is lost. If the respective data take happens to be part of a bistatic, cooperative TDM acquisition, then the whole TDM acquisition has to be considered as lost.

5 Impact on mission TanDEM-X

TanDEM-X acquisitions require synchronized operation of two independent SAR instruments. Inaccuracies in the satellites' on-board time are much more critical for these acquisitions than for monostatic acquisitions. Precise timing is crucial for both the timely transmission and reception of radar echoes on both satellites and the timely exchange of complete, untruncated synchronization pulses. Therefore, a relative time shift between the two satellites that considerably exceeds a value of $10\ \mu\text{s}$ will lead to an unprocessable data take pair. This limit is, in most cases, not exceeded by TanDEM-X acquisitions within shorter GPS instabilities of up to 8 minutes, that are handled by the MosaicGNSS receiver. These acquisitions can be processed with good quality, because small relative time shifts between the two concurrent datatakes are covered by temporal margins that are operationally foreseen by the TanDEM-X Request-To-Command Converter (R2CC).

The situation is different for longer GPS instabilities beyond 8 minutes, where the OBC starts propagating the on-board time. Instantly after the switch-over the errors of the on-board time will exceed the tolerable level for TDM acquisitions.

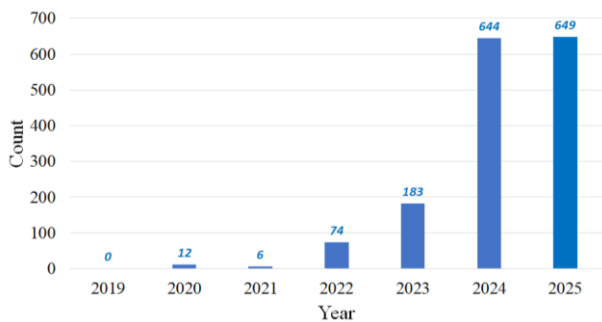


Figure 3 Yearly number of TanDEM-X acquisitions that cannot be processed due to the effects of GPS instabilities.

Figure 3 shows the overall number of lost TanDEM-X acquisitions over the past years. Since 2022, the number is significant and increased each year, as the affected geographic regions were growing in size. From 2024 onwards, the number reached its current, high level.

As long as the external GPS interference situation is as permanent as it is currently in 2025, the reacquisition of a failed bistatic datatake at a certain orbit position does not

help, because the repeated acquisition will likely fail in the same way.

The map plot in **Figure 4** shows the right-looking imaging ground regions of TSX and TDX for July 2023, where TDM acquisitions are disturbed. The plot covers the same mission time and therefore corresponds directly with Figure 2, but takes into account that the GPS-receiver can initially propagate orbit and time sufficiently accurate when entering a GPS instability zone. The problematic regions are therefore shorter in flight direction by the aforementioned 8 minutes, which translates to an along-track distance of about 3600 km.

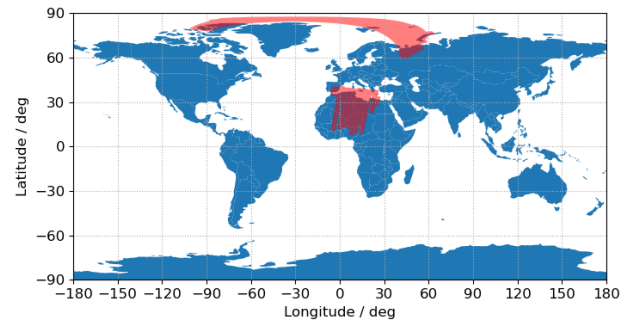


Figure 4 Right-Looking imaging regions affected by GPS instabilities (July 2023, both satellites).

GPS instabilities have one further impact on the TanDEM-X mission. As a part of the safety concept in close satellite formation, so-called Sync-Warning data takes are frequently executed, at least once per orbit. By exchange of synchronization pulses it is checked that both satellites are at their expected orbit position and attitude. As described in the previous chapter, GPS instabilities can cause the interruption of the on-board execution of a data take. An aborted Sync-Warning data take, if not followed up in time by a successful one, will automatically lead to the passivation of the SAR instruments on both satellites. The consequence of this is that multiple data takes of both missions TerraSAR-X and TanDEM-X are lost, until the situation is cleared and the satellites are switched back to active transmission.

This problem has been solved operationally by implementation of “Sync-Warning free” time windows. The mission planning system will not place Sync-Warning data takes at these positions where there is a certain risk that they could fail. In case the GPS interference situation is dynamic and changes over time, these windows have to be readjusted.

6 GPS receiver software patch

A software patch has been developed and tested by ADS in the course of the year 2024. It was a combined effort for the TerraSAR-X, TanDEM-X and PAZ missions. The software patch was provided to DLR in the end of 2024, and activated on both satellites in January 2025.

While the patch cannot solve the core problem of GPS signal interference, it improves the situation with a refinement of the MosaicGNSS-internal clock modeling. By that, the receiver can propagate its solution over a longer period of

time, and further delay the critical switchover to the less accurate OBC time propagation.

The underlying idea for an improved MosaicGNSS-internal clock modeling is to store in memory, for one or even multiple orbits, the history of internal clock bias and drift values, that the receiver is monitoring continuously. This is an improvement compared to the previous, simpler strategy for compensation of clock drifts in propagation mode based on a static value.

How far the propagation time could finally be extended with this new algorithm depended on in-orbit tests and analyses, but the potential for extension of the MosaicGNSS propagation time from 480 s to at least 800 s was estimated at the time of software patch development, based on tests with realistic orbit profiles.

7 Performance analysis

Figure 5 shows the relative shift for TanDEM-X data take pairs from the year 2023, which were taken in poor GPS reception conditions over the previously shown problematic geographical regions. The longer the poor reception situation had already lasted at the beginning of the respective recording, the further to the right the corresponding data take appears. The limit of 480 s, until which the Mosaic receiver itself was configured to propagate, is clearly recognizable by the strong increase in observed relative time shifts.

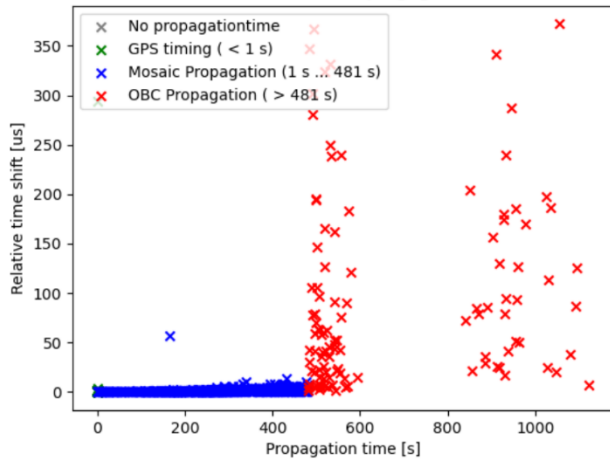


Figure 5 Relative time shift of TDM data take pairs affected by GPS instabilities in 2023.

While the relative shift is below 10 μs for almost all recordings with MosaicGNSS propagation (blue color), it is significantly higher in the area of OBC propagation (red color). Only for a small percentage of these acquisitions the timing is good enough for interferometric processing. Therefore, the intended extension of MosaicGNSS propagation time was very promising.

7.1 Test campaign with forced Mosaic propagation

A dedicated test campaign with forced Mosaic propagation was performed in February 2025, i.e. shortly after the Mosaic receiver software update. The advantage of deliberately forcing the MosaicGNSS receivers into propagation mode is that we were free in locating the artificial GPS outages in geographic areas where nominal TSM and TDM data acquisitions are not disturbed. We were also free in deciding if only the GPS receiver of one satellite shall propagate or both.

Within an artificial GPS interference zone, the number of tracked and used GPS satellites was commanded to zero. The GPS receivers of one or both satellites (TSX/TDX) were commanded into propagation mode. A maximum of 20 minutes propagation time of the GPS receiver was configured, which is above the estimated capability of the software patch, but corresponded to the largest GPS instabilities, that had been observed. Ten short test TDM data takes were ordered within each of these 1200 s GPS-propagation periods, nearly equally spaced.

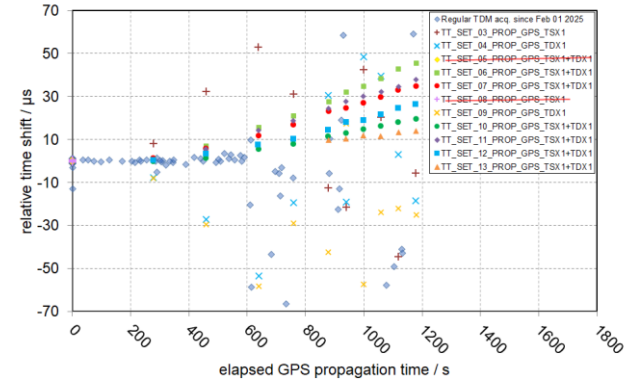


Figure 6 Relative time shift of data take pairs within the artificial GPS outages. Nine sets of TDM test acquisitions could be commanded. For comparison, regular TDM acquisitions affected by real GPS signal interference outside of the artificial GPS-propagation zones are shown, too.

The results of this test campaign are shown in **Figure 6**, and led us to the following conclusion:

- When the GPS receivers of the two satellites both have to propagate the GPS solution at the time of data taking, the relative data take shift typically degrades gracefully. When only one GPS receiver propagates, the shifts are larger and more randomly distributed. For the behavior of the GPS receivers within real GPS instabilities this is only partly relevant, because the instant of time that the GPS receivers on the two satellites enter and leave propagation mode is quite aligned and differs by a few seconds only.

7.2 Nominal TDM acquisitions with up to 840 s MOSAIC propagation

Nominal TDM acquisitions have been monitored and analyzed during the Summer of 2025 and beyond. The threshold for switch-over of PVT propagation from GPS receiver to OBC was set to 840 s, i.e. slightly above the expected

capability of the patched GPS receivers. Focus of the subsequent analysis was on the performance of MosaicGNSS PVT propagation in situations where, at the time of data take execution, the GPS signal interference lasted between 480 and 840 s, i.e. the propagation time interval, that previously was handled by OBC, and now is handled by the GPS receiver. The result of the analysis is shown in **Figure 7**. It led us to the following conclusions:

- The results were much better than the performance of OBC propagation as shown in Figure 5, and therefore it was decided to keep the limit for MosaicGNSS PVT propagation at 14 min (840 s). This means that the objective set during the development of the software patch could be achieved.
- Measured relative start time shifts reached up to 50 μs , which exceeds the target value of 10 μs , but the majority of acquisitions does not exceed the target value of 10 μs .
- Consequently, a certain percentage of violations of the 10 μs limit is expected within this propagation time interval, and shall be tolerated in the ongoing mission. There is still potential for further reduction of the percentage of violations, as described in the following section.
- Furthermore, the analysis helped to identify an issue in the input data handling of the Interferometric TanDEM-X Processor (ITP) that led to the abortion of the processing of acquisitions with a relative time shift, even though the interferometric data quality was sufficient for a good result. Consequently, the issue was solved by the ITP team, and a software update of the processor was performed, increasing the number of successful TDM acquisitions in regions with difficult GPS signal reception conditions.

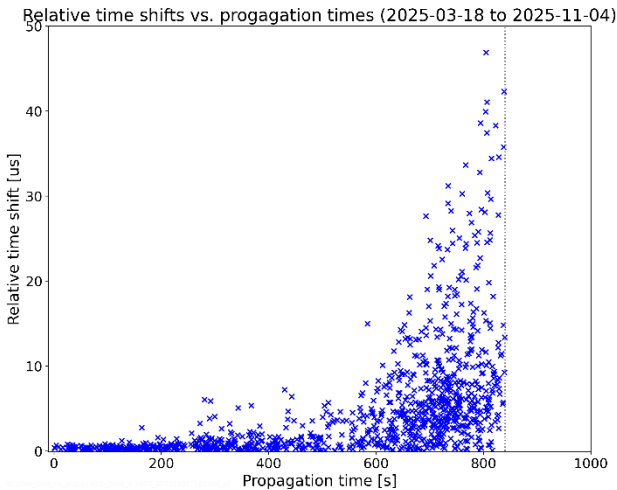


Figure 7 Relative shift of TDM data take pairs acquired since March 2025 with the new MosaicGNSS propagation settings.

8 Further improvements

Further improvements may be feasible and are currently under investigation and test. For example, it might be pos-

sible to implement improvements in the commanding strategy of TDM acquisitions, that allow interferometric processing even in case the relative shift exceeds 10 μs . The idea is to analyze the R2CC timing margins that were mentioned in section 5, and to further extend, as much as possible, the receive echo window for imaging pulses of the passive channel of a bistatic data take pair. The same is investigated for the receiving side of exchanged synchronization pulses. This could compensate for temporal shifts and provide sufficient energy received and recorded for shifted transmit pulses. Last but not least there is also the possibility to test alternative settings of the MosaicGNSS receiver's internal orbit buffer handling, which might yield an additional improvement.

9 Conclusion

The development and deployment of the MosaicGNSS software patch has been a success and the TanDEM-X mission already profits from it. The extended orbit propagation is reliable and stable. The current setting already allows TanDEM-X data collection in areas that were previously blocked, e.g. in Southern Europe, the Mediterranean and North Africa, and the majority of acquisitions there can now be successfully processed. **Figure 8** shows the current situation of the remaining blocked regions, that can be directly compared to the previous situation as shown in Figure 4.

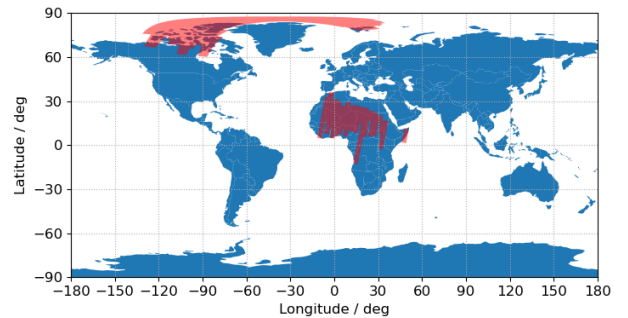


Figure 8 Right-Looking imaging regions affected by GPS instabilities that can not be handled by the GPS receivers (October 2025, both satellites).

Work on this topic will continue in order to extend the PVT propagation capability of the MosaicGNSS receivers as much as possible, so that the sporadic abortion of running TSM, TDM and Sync Warning data takes on-board the satellites can be further reduced.

10 Acknowledgement

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11 Literature

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