Stuck Bit Error Identification for the TerraSAR-X and TanDEM-X Onboard Memory

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Abstract

Errors in memory storage devices in the form of erroneous bits induced by radiation are a common issue for every spacecraft in orbit. Therefore, well established techniques detect and directly correct these errors in the storage hardware. Sporadically single memory cells can temporarily get “stuck” at a false bit in which case they cannot be corrected. Those stuck bits can persist up to several months generating the same errors during every memory scrubbing cycle. In order to assess the current memory status a method to distinguish between regular and stuck-bit errors is needed. This paper therefore presents a classification approach based on the DBSCAN method where stuck bits are identified as outliers and clustered accordingly. The approach first is verified with simulated data that resembles the error structure of memory errors on TerraSAR-X and TanDEM-X. Subsequently, the method is validated with the memory errors recorded by both satellites throughout their lifetime.

1 Introduction

Memory storage devices onboard spacecrafts are generally prone to bit errors induced by radiation. High energy particles are able to penetrate the spacecraft and can alter the charge of single memory cells leading to falsified bits i.e. bit errors [1]. TerraSAR-X (TSX) and TanDEM-X (TDX), two almost identical remote sensing SAR satellites which are operated since 2007 and 2010 [2], experience hundreds of these single bit errors on a daily basis.

In order to counteract data corruption, well established techniques to detect and directly correct these errors are applied [3]. For this purpose, the Reed-Solomon Code [4] used onboard TSX and TDX generates codewords with which erroneous bits are detected in the recorded data and overwritten with the correct information.

Sporadically it can happen that the high energy particles not only alter the charge of single memory cells but also cause temporal damage within the memory cells resulting from total dose effects [5][6]. In these cases, the bit gets “stuck” at its current state. The stored information can then still be read but not changed anymore leading to a persisting bit error. In other words, the cell temporarily changes its function from RAM to ROM. The effect can last from a few minutes to several month in which the information in that bit remains unchanged until it spontaneously “heals” and the error disappears [5]. Until then, the scrubbing function which executes the error detection and correction (EDAC) code in periodic intervals increases its error counter every time it scrubs over the respective memory cell. In the error statistics it is then impossible to distinguished anymore between nominal radiation errors and stuck-bit errors.

As stuck bits are an indicator for weak memory cells and their occurrence increases the electrical degradation of week cells [5], it is important to analyse the occurrence of stuck bits separately. This can be achieved by applying machine learning based classification methods that are able to cluster variable error types.

A solution is provided by the Density Based Spatial Clustering of Applications with Noise (DBSCAN) approach [7]. DBSCAN is an unsupervised classifier that cluster similar datapoints and determines the number of clusters according to the dataset and its parameters. If no cluster can be assigned to a datapoint it is registered as noise which we then define as a stuck bit.

The DBSCAN method and the according setup presented in this paper is derived and validated by simulated bit errors over time. The sampling and distribution of the errors are derived from real data of TSX and TDX. In the end the chosen setup is validated with the memory errors of TSX and TDX experienced throughout their mission lifetime.

2 Solid-State Mass Memory

The Solid-State Mass Memory (SSMM) is used to store SAR raw data captured during datatakes and ancillary data until these data can be dumped to the next ground station. In order to achieve high data rates, the SSMM consists of 6 Ultra-Fast Memory modules (UFM) which allow the concurrent access to multiples of internal data elements. The UFMs are further subdivided into 2 partitions, each organized in 8 wordgroups resulting in a total number of 96 wordgroups. The SSMM structure is depicted in Figure 1. With a capacity of 4 Gbit per wordgroup on TSX and 8 Gbit on TDX the total storage capacity adds up to 384 Gbits on TSX and 768 Gbits on TDX at beginning of life.

In order to prevent data corruption a Reed-Solomon Code [4] generated codeword in form of a parity byte is added to 8-byte sized blocks of data. A scrubbing function then continuously checks the recorded data trying to regenerate the parity bytes for every codeword. In this way false bytes, i.e. false symbols, are identified and single symbol errors (SSE) are corrected. This also avoids the accumulation of bit errors. The scrubbing rate is adjustable and can be changed between fixed intervals. Throughout most of the TSX/TDX mission time the scrubbing remained at a constant rate of 14.7 s per wordgroup for TSX and 37.8 s per wordgroup for TDX resulting in a total time per scrubbing cycle for all 96 wordgroups of 23.52 and 60.48 minutes respectively. During the scrubbing cycles an SSE counter samples the accumulated errors for the single wordgroups and the entire SSMM. The counter is sampled every two minutes and provides the basis for the further analysis.

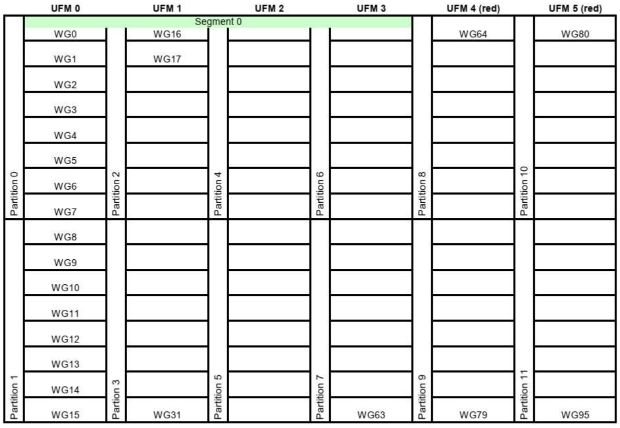

Figure 1: TSX/TDX SSMM structure

3 Single Symbol Errors (Memory Errors Sources)

3.1 Radiation Errors

One of the reasons for memory errors in Earth orbiting spacecrafts is radiation in form of high energy particles such as protons and heavy ions. These charged particles are able to penetrate the spacecraft and interact with the single memory cells. During the interaction the charge of the memory cell can change which alters the stored information and which is then registered as an error by the onboard EDAC process.

In general, origins of radiation in space are solar particle events induced by flares or Coronal Mass Ejections, the South-Atlantic Anomaly and Galactic Cosmic Rays e.g. from Supernovae [8]. Since the satellites fly an orbit that passes the South-Atlantic Anomaly only in two to three of the 167 orbits in one repeat cycle and the frequency of solar particle events is much higher towards Galactic Cosmic Rays, solar radiation constitutes the dominant source of radiation for the TSX/TDX satellites.

The influence of solar radiation on memory errors becomes particularly visible in the eclipse season between April and August [9]. During this period the satellites enter the shadow of the Earth for a fraction of the orbit on the southern hemisphere shielding the satellites from the sun. As a consequence, the SSEs on both satellites significantly decrease as can be seen as yearly bow-shaped trends in Figure 2.

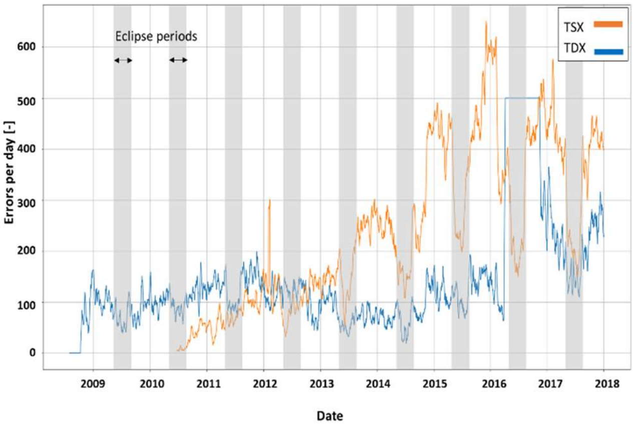

Figure 2: TSX (blue) and TDX (orange) detected SSEs over mission time

3.2 Stuck Bits

In some cases, high energy particles, besides altering the state of a memory cell, can also cause a temporal damage to it. If the charge of the particle is high enough it can lead to so called total dose effects and damage the gate-oxide in the transistor. As a consequence, the leakage current of the transistor is higher than its charging current and therefore the state of the memory cell, i.e. the bit, remains unchanged. In other words, the bit gets stuck at its current state. Reading the stored information is still possible but the information cannot be altered anymore for the time the bit is stuck. Due to annealing processes this condition is not permanent. Over time the bit is released and again available for information storage. The time until the effect anneals is not predictable and can take between several minutes up to several months [6].

During that time the scrubbing function therefore detects and counts the same error with every scrubbing cycle. In the error statistics by means of recorded SSE per day and total SSE, the source of the errors cannot be determined anymore.

4 Stuck Bit Classification

4.1 Data Preparation and DBSCAN Approach

In order to assess the status of the memory storage unit it is important to analyse the occurrence of stuck bit independently from nominal radiation errors. Therefore, nominal and stuck bit errors need to be separated in the error statistics.

A solution for this issue is provided by the DBSCAN method. The method operates on a density-bases approach which clusters similar datapoints based on a distance measure and determines the number of clusters according to the structure in the dataset. In contrast to other classification techniques this has the advantage that the number of clusters do not have to be specified beforehand. The algorithm determines the number of clusters itself. Another advantage is that DBSCAN is able to characterize outliers in the data and classify them as noise. Considering the fact that stuck bit errors only occur sporadically and produce much higher numbers of errors than nominal radiation errors, they are consequently identified as outliers and labelled accordingly. The remaining found clusters then represent all errors induced by radiation which could be corrected immediately. Hence, by separating the clusters from the noise, the stuck bit errors can be separated for further analysis.

As the SSE data on TSX and TDX is sampled in the time domain and DBSCAN uses a distance measure to determine clusters, the data has to be restructured. In order to achieve a spatial representation of the time-sampled data, the data is divided into equal segments by applying a sliding window. The length of the window is then used to define the number of spatial dimensions. In other words, every sliding window represents one point in a k-dimensional space with k being the length of the window. By computing the distance matrix for all single windows based on the dimensions, similar errors can then be grouped accordingly by the DBSCAN algorithm. Introducing an overlap of the sliding windows furthermore stabilizes the clustering results [10]. A schematic overview of the segmentation can be seen in Figure 3**.**

For TSX and TDX the windowed segmentation is performed for the SSEs in every single wordgroup. Based on the distance measures of the resulting segments of every wordgroup, the clustering parameters, i.e. the clustering radius ε and the minimum number of samples to define a cluster n, for the DBSCAN are derived. Those then serve as input to the error clustering of every wordgroup. This avoids an overfitting of the model and a more general classification of the different error types. In the following chapter the determination of the input parameters will be explained in detail.

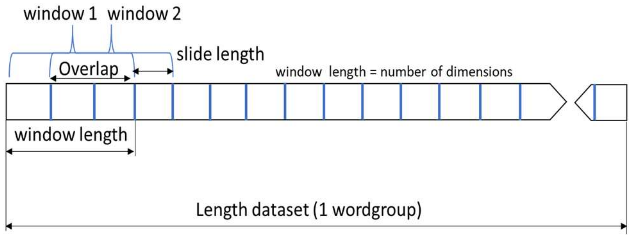

Figure 3: Illustration of data segmentation by applying a sliding window with overlap. The spatial representation is achieved by considering the number of samples in a window as number of spatial dimensions.

4.2 Simulated Errors

For the evaluation of the DBSCAN clustering, simulated stuck bit errors are used which resemble the error structure of real TSX/TDX data. This means the timeframe as well as the time sampling in two minutes steps is equal and also errors can only occur after one full scrubbing cycle. Furthermore, if a stuck bit occurs in the simulated data, a random function decides if it produces an error after scrubbing or not. In this way the possibility of new information being written to the respective bit and matching the stuck bit information, is considered. This can be seen in Figure 4.

In order to segment the data and derive the input parameters for the DBSCAN algorithm the following assumptions are made:

- The clustering radius ε to define a cluster is dependent on the standard deviation of the maximum window distance of all wordgroups. In this way it is ensured that the classified stuck bits significantly differ from others errors.
- The minimum number of samples to define a cluster n is based on the number of segments hence the total length of the dataset. This ensures the correct clustering of smaller datasets e.g. when analysing only a section of the mission time.
- The window length as well as the slide length have to be small enough to identify stuck bits with short annealing periods and at the same time big enough to avoid classification of correctable errors as stuck bits
- The overlap has to be big enough to ensure independence from the variance of single dimensions and to support a stable clustering.

In an iterative evaluation process, varying the above described parameters, the number of introduced stuck bits as well as the time they persist, the input parameters are then refined and further validated with the simulated SSEs. The goal is that independent from the number of stuck bits and the time they need to anneal, all of them are correctly classified. In Figure 4 the result for clustering simulated data for seven stuck bits (red colored errors) with increasing annealing times from 2 to 20 days are shown. The classification was performed with ε= 4.4, n = 500, a window length of 4,000 samples and an overlap of 500 samples. These parameters have proven to produce the most robust classification. As can be seen all stuck bits are identified correctly and the remaining errors are classified as no errors.

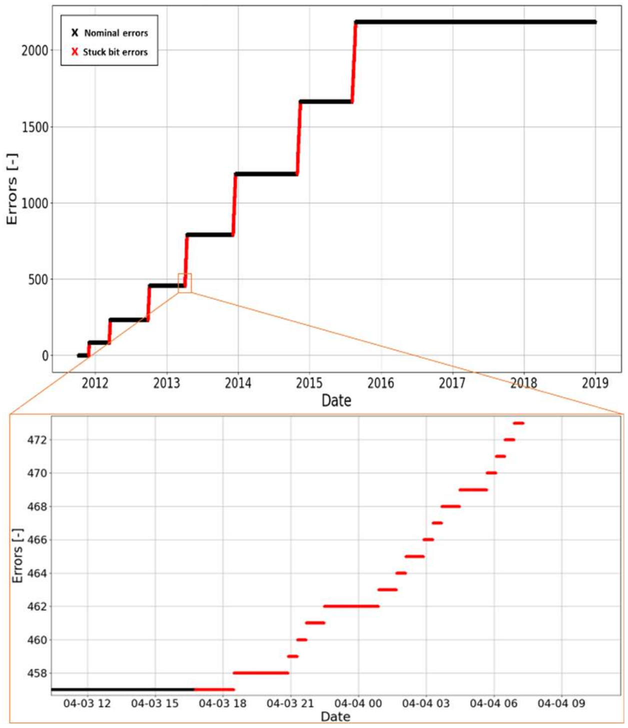

Figure 4: Clustering of simulated SSEs in stuck bits (red) and no errors (black); the zoom on the bottom visualizes the error structure

4.3 TSX/TDX Wordgroup Errors

After verifying the input parameters and the data segmentation by means of simulated SSEs, the model is validated using real TSX/TDX mission data. For this purpose, every wordgroup is analysed individually and compared to the other wordgroups.

One validation criterion is the maximum value of ε which is determined once as a pre-processing step and applied to all wordgroups. Due to ε being computed depending on the standard deviation of the maximum distance between all windows and of all wordgroups, the results are expected to show that some wordgroups do not experience any stuck bits while others show a very high number of stuck bits. An example is displayed for the first 8 wordgroups of the TSX SSMM in Figure 5. Note that since 2012 the sampling rate of the SSMM error counter has changed hence the results are not displayed since the beginning of the mission. The difference in sampling rate between seven days and two minutes is too high to apply the same DBSCAN parameters and achieve the same results.

In the clustering results it can be seen that the wordgroups considerably differ in SSEs over time and therefore also in the classification of stuck bits. Wordgroup 1 e.g. shows a very clear case of stuck bits in the beginning of the timeframe while the result for wordgroup 0 shows no stuck bits at all. This result is a consequence of the determined ε and can be explained by considering the different error levels of the two wordgroups. Looking at the total error numbers it can be seen that on wordgroup 1 more than 30,000 SSEs occurred while wordgroup 0 experienced less than 600 SSEs. This means that on wordgroup 0 no accumulations of errors in a short time were experienced leading to conclusion that no stuck bit errors occurred. In this way the classification results are first evaluated on all wordgroups.

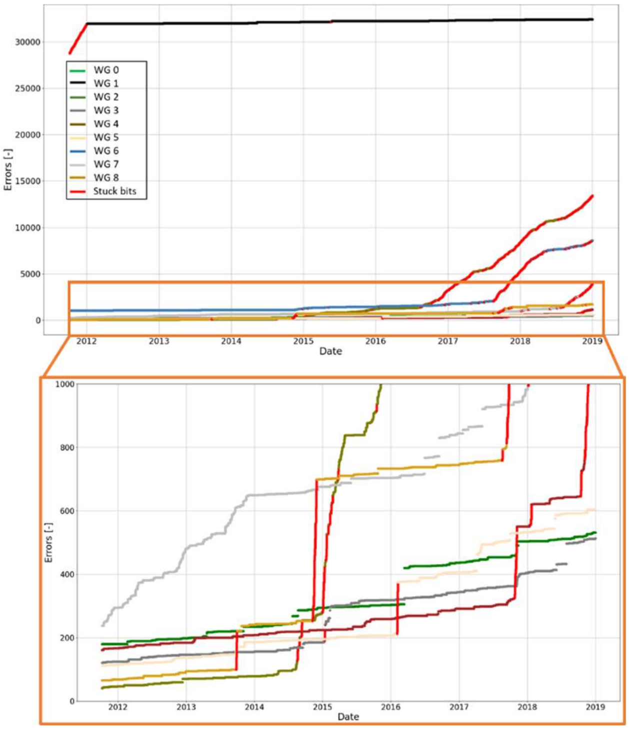

Figure 5: stuck bit errors (red) classification results for wordgroups 0 to 8 on TSX (top) and zoom for better visualization of the wordgroups with low error numbers (bottom).

The total amount of stuck bits per wordgroup over mission time are displayed in Table 1. One can see that these match the observations for the total error numbers, as shown in Figure 5. For example, although the error counter on wordgroup 1 reaches very high values, only two stuck bits are identified. This coincides with a stuck bit which persists for a longer period, visible in Figure 5. Furthermore, it can be seen that wordgroups with a high number of stuck bits experience these in particular towards the end of the timeframe, as observable for wordgroups 2, 6, 7 and 8.

Table 1: stuck bit classification results for wordgroups 0 - 8

# WG	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Stuck bits	0	2	83	1	9	1	44	24	16

Another validation criterion is the expected influence of the memory age. Due to the degradation of the memory elements the SSMM becomes more sensitive towards total dose effects and is expected to show increased stuck bit errors over time. The results show that this is the case for the analysed wordgroups. In Figure 5 it can be seen that a considerable number of wordgroups experiences stuck bits towards the end of the displayed timeframe. This coincides with memory ageing and the increase of weak cells over time.

In conclusion the results provide a reasonable classification of stuck bits and correctable errors. Both errors can be well separated. Figure 6 shows the distribution of stuck bits over the entire TSX SSMM for the given timeframe. A stuck bit in this case is only counted at the first occurrence independent from how long it persists or how many errors it generates. The result correlates to both the sporadic occurrence as well as the increase of stuck bit errors with ageing memory. The SSMM results furthermore show, that some stuck bits can last even for years before they disappear which correlates with possible long annealing periods.

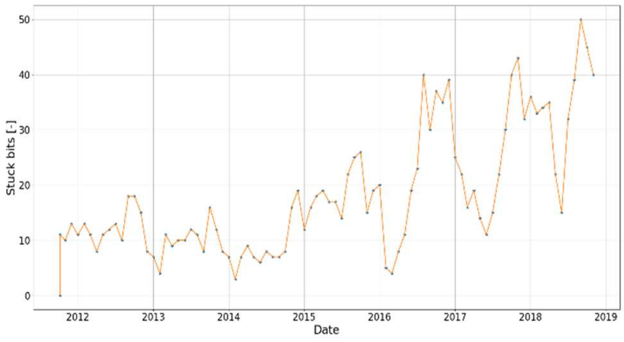

Figure 6: Stuck bit occurrences on TSX SSMM over mission duration

5 Conclusion

Although the SSMMs on both TSX and TDX provide an EDAC system to protect themselves against radiation induces bit errors, not all of the detected errors can also be corrected. Some of the errors can persist as they cause temporal damage to the single memory cells. In these cases, the cells are referred to as stuck bit. In order to separate the stuck bits from correctable errors and assess the status of the SSMMs, a machine learning approach based on the DBSCAN method is used. With this method it is possible to classify the stuck bit errors in the clustering and analyse them individually.

After generating and preparing simulated data to be processed by the DBSCAN, the input parameters are first adjusted in an iterative process and verified. The spatial representation of the time sampled data, is achieved by segmentation. Subsequently, feeding real SSE data from TSX and TDX missions into the verified model, achieves the desired separation of the errors. In this way, the stuck bit errors can be extracted and visualized. The results show that stuck bits sporadically occur all over the mission time but in particular towards the end which coincides with an increased vulnerability due to memory ageing.

As the SSE data on TSX and TDX is only provided per entire wordgroups, an accurate validation of the DBCSAN model can only be performed considering memory ageing effects and distinctive errors. For a more refined differentiation between stuck bits and correctable errors, SSE data needs to be provided in greater detail. Although this leads to higher amount of housekeeping data, it enables a detailed validation of stuck bit occurrences. Ideally the SSEs of the smallest accessible memory blocks would be provided which should be considered in future research.

6 Acknowledgements

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7 Literature

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