ASSESSING THE SUSCEPTIBILITY OF EUROPA CLIPPER ONBOARD THERMAL ANOMALY DETECTION TO RADIATION.
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Introduction: The Europa Clipper mission [1] will conduct over 40 flybys of Jupiter's moon Europa to study its habitability. Europa Clipper's suite of nine instruments includes the Europa Thermal Emission Imaging System (E-THEMIS), which will be used to study the temperature and thermal properties of the surface, and search for thermal anomalies [2]. Such an anomalously warm region could indicate an interaction between the surface ice and subsurface ocean of the moon, including new plume deposits and areas of active or recent resurfacing. Such regions would be areas of high scientific interest to target with follow-up observations using other instruments during subsequent flybys.

Given the relatively short two-week flyby cadence planned for Europa Clipper, any knowledge of thermal anomalies obtained during one flyby must be downlinked to Earth as soon as possible to provide maximal utility for planning subsequent flybys. The limited downlink bandwidth available to Europa Clipper at Jupiter means that it could take nearly the full two-week inter-flyby period for all of the data from one flyby to be completely transmitted to Earth. Therefore, we have investigated approaches to analyze data *onboard* Europa Clipper to autonomously identify high-value processes (e.g., surface thermal anomalies) within observations, allowing reprioritization of those data for preferential downlink [3].

One risk of analyzing data onboard Europa Clipper to identify thermal anomalies is that "single-event upsets" (SEUs), which are flipped bits in memory caused by radiation, can confuse detection algorithms and lead to false positive or negative detections. Radiation tolerance is a concern for all spacecraft, but is particularly important to consider in Jupiter's harsh radiation environment. While specialized "radiation-hardened" electronics can be used in conjunction with a "vault" to provide additional shielding, SEUs can still be expected to occur during the mission. Therefore, software, not just hardware, should be made robust to radiation. Accordingly, this study is designed to assess the tolerance of thermal anomaly detection algorithms for use onboard Europa Clipper to observation data corruption by radiation.

Simulating E-THEMIS Data: E-THEMIS will observe Europa in three infrared bands: Band 1 (7–14 μm), Band 2 (14–28 μm), and Band 3 (28–70 μm). The cross-track field-of view is approximately 5.7 deg, split across approximately 360 pixels in Bands 1 and 2, and 240 pixels in Band 3 (dependent on pixel binning). To evaluate thermal anomaly detection algorithms, we have produced synthetic data for E-THEMIS by simulating observations.[1] The simulation uses a version of the KRC thermal model [4] adapted for Europa to compute expected background surface temperatures as a function of latitude, longitude, local solar time, and surface thermal properties. A random anomaly with radius between 1 m and 25 km and temperature between 75 K and 275 K is then introduced on the surface. Each observation of Europa with an injected thermal anomaly is generated by selecting a random flyby, then a random spacecraft location within 50,000 km of closest approach. The resulting dataset of 100,000 observations provides coverage of a range of anomaly sizes, temperatures, and viewing geometries as described above [5]. The temperature-derived radiance values observed according to the simulation are converted into corresponding digital numbers (DNs) for each band, as shown in Figure 1.

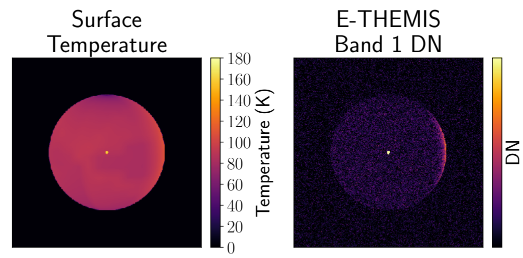

Figure 1: An example simulated E-THEMIS observation showing the instrument field-of-view in both temperature and derived DN values for Band 1 (7–14 μm).

The anomaly detection algorithm analyzed in prior work [5] uses a simple threshold-based approach to flag potential anomalous pixels in each observation. In each band, a DN threshold corresponding to 140 K is selected, since that temperature is $3\,\sigma$ higher than any modeled background temperature. This ensures that according to the simulation, any pixel flagged as an anomaly is in fact anomalous (i.e., there are no false positives).

Simulating Radiation Effects: To simulate the effects of radiation on the E-THEMIS thermal anomaly detection algorithm, we use the previously-developed BITFLIPS tool [6] to inject SEUs into the program as it is running. BITFLIPS enables introducing single- and multi-bit errors in specific memory regions at a user-specified rate (in SEU per kilobyte-instruction). Faults are introduced uniformly at random throughout the specified region with events following a Poisson distribution with the given rate parameter. By choosing a processor speed in instructions-per-second corresponding to the

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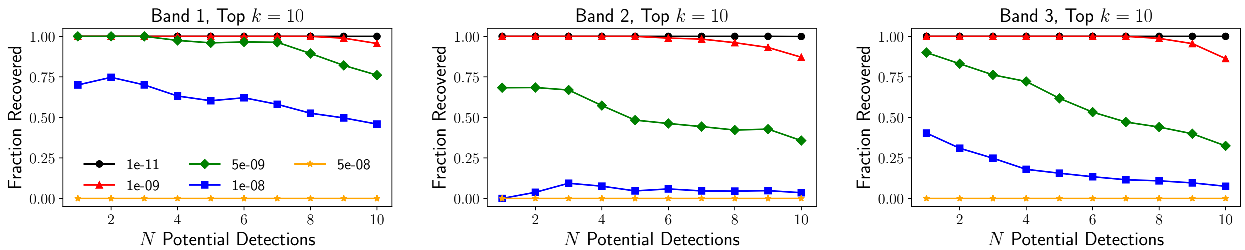

Figure 2: Results showing the average fraction of top k detection that are still recoverable as SEUs are introduced at various rates.

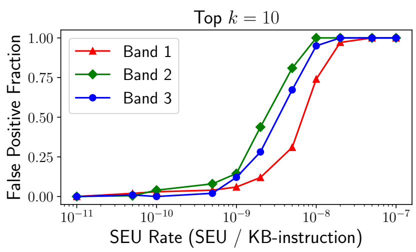

Figure 3: The fraction of false positives within the top k detections for each band as a function of SEU rate.

target processor, it is possible to interpret the BITFLIPS fault rate in more physically relevant units of SEU per kilobyte-second.

Europa Clipper is required to be designed with memory tolerating at most 10^{-10} SEU/(bit$\times$day) [7], which translates to approximately 10^{-11} SEU/(KB$\times$sec). The RAD750 processor used by Europa Clipper will be capable of executing on the order of 100 million instructions per second (MIPS), which translates to an SEU rate of 10^{-19} SEU/(KB$\times$instruction). We found that the E-THEMIS thermal anomaly detection algorithm can handle many orders of magnitude more SEUs before any noticeable effects are observed. We assume that the long-term, non-volatile bulk data storage system is more robust against data corruption by SEUs. Therefore, the data is most susceptible to corruption while it is in volatile memory during the detection algorithm's execution. Accordingly, we only model the effect of SEUs during execution.

Radiation Sensitivity Analysis: We performed our analysis on the 100,000 simulated observation with 10 randomly seeded trials for each observation and fault rates ranging from 1×10^{-11} to 1×10^{-7} SEU/(KB$\times$instruction). To simulate a limited downlink budget for transmitting detections to Earth, we limit analysis to the top $k = 10$ detections within each band exceeding the 140 K threshold. Compared to the algorithm's output in the absence of any SEUs, yielding a certain number of detected "hot" pixels (along the x axis), Figure 2 shows the fraction of the top k detections that are "recoverable" in the downlink. That is, if there is potentially 1 hot pixel to be downlinked, and 3 false positive detections are introduced, then that one hot pixel is still recoverable within the top 10 that are downlinked. It is also possible but much less likely that an anomalous pixel is affect by a bit flip and no longer appears in the list of top anomalous pixels (i.e., a false negative). We see that towards the right-hand side of the figures when the entire downlink budget is already full of true positive detections, the effect of noise is higher because each false positive pushes a true positive out of the downlink. Although the Band 3 data footprint is smaller and therefore has less chance of being affected by SEUs, the DN values in this band tend to be smaller, so each SEU has a larger change of introducing a false positive.

In Figure 3, we show the fraction of false positives occurring within the top $k = 10$ downlink slots for each band. There is similar behavior across the three bands, although as mentioned earlier, Bands 2 and 3 tend to have smaller DN values at relevant temperatures, so there is a greater chance that a bit flip in one of the significant bits of the DN values will increase the apparent temperature and produce a false positive.

Conclusion: Our analysis shows that the E-THEMIS thermal anomaly detection algorithm is tolerant to SEUs up to rates of 10^{-11} SEU/(KB$\times$instruction), which is well above the expected rate of 10^{-19} SEU/(KB$\times$instruction). If more robustness to SEUs were required, the algorithm could incorporate error correcting codes or other sanity checks (e.g., excluding DNs corresponding to temperatures above physically plausible values like 273 K at which the surface would be sublimating). Next, we will focus on analyzing the effects of radiation on the E-THEMIS detector itself, which could introduce false pixel values before the observation is even stored in memory.

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