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On-Orbit Solar Dynamics Observatory (SDO) Star Tracker Warm Pixel Analysis

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This paper describes the process of identification and analysis of warm pixels in two autonomous star trackers on the Solar Dynamics Observatory (SDO) mission. A brief description of the mission orbit and attitude regimes is discussed and pertinent star tracker specifications are given. Warm pixels are defined and several indicators of anomalous behavior, including the characteristic "inverted-U" pattern in the Quality Index parameter, indicative of warm pixels are introduced. A description of the algorithm used to identify warm pixel candidates is given. Finally, an analysis of dumps of on-orbit star tracker charge coupled device (CCD) images is presented and an operational plan going forward is discussed. This particular star tracker model has been flown on various spacecraft, including NASA and ESA missions, and is planned to be used in the future. This analysis of on-orbit SDO data has been critical to understanding the effects of warm pixels on this particular unit. Additionally, this approach should be useful on all CCD star trackers, in general.

I. Introduction

A. SDO Mission Overview

THE Solar Dynamics Observatory, launched on February 11, 2010 from Cape Canaveral, is NASA's first mission in the Living With a Star (LWS) program. SDO was placed into a geosynchronous transfer orbit aboard its Atlas V launch vehicle. After a series of orbit-raising maneuvers, SDO was positioned in a geosynchronous orbit, with 28.5° inclination, above its dedicated antenna in White Sands, New Mexico. Constant contact with the dedicated ground station facilitates the downlink of nearly continuous, high data rate Sun observations, provided by three science instruments: the Helioseismic and Magnetic Imager (HMI), the Atmospheric Imaging Assembly (AIA), and the Extreme Ultraviolet Variability Experiment (EUVE). The spacecraft was designed and integrated at the Goddard Space Flight Center (GSFC) in Greenbelt, Maryland.

The nominal mission attitude points the spacecraft X-axis at the Sun, with the spacecraft Z-axis roughly aligned with the Solar North Pole. In attitude, SDO rotates at approximately 0.04° per hour, mostly about the spacecraft Z-axis. Attitude knowledge is provided by an onboard Extended Kalman Filter (EKF) which processes measurements from an inertial reference unit (IRU), two star trackers (STs), and a digital sun sensor (DSS). SDO's attitude knowledge requirements are specified as [35,70,70] arcseconds, 3σ, along the spacecraft body X, Y, and Z axes, respectively. Because the most stringent attitude pointing requirement is imposed by the AIA instrument, one of the four guide telescopes (GTs) that accompany AIA is used by the onboard attitude control system (ACS) in the Science Mode control algorithm. The so-called controlling guide telescope (CGT) measurements are used to align the spacecraft X-axis at the approximate Sun center as measured by the AIA instrument. The GTs provide

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arcsecond-level precision pointing. To maintain the roll of the spacecraft body about the Sun vector, the EKF attitude solution is used.

B. Mission Operations

The SDO Mission Operations Center (MOC) is located at GSFC. Co-located with the MOC is the Mission Analysis Room (MAR). All Flight Dynamics and ACS activities are monitored and planned by on-console engineers and analysts from the MAR.

To support attitude operations, the ground-based Multimission Three-Axis Stabilized Spacecraft (MTASS) Attitude Ground Support System (AGSS) is utilized. The MTASS AGSS, referred to simply as "MTASS," has a 20 year history of analysis and operational support of various missions. For SDO, MTASS provides (1) independent attitude determination and validation, (2) attitude sensor calibration, and (3) high gain antenna (HGA) calibration. In addition to MTASS, a special tool called Slew Planning and Momentum Management (SPAMM) was developed to support SDO. SPAMM provides utilities to support (1) attitude menuver planning, (2) long-term system momentum predictions, and (3) momentum manegement. After launch, a Warm Pixel Identification utility, described in this paper, was added to SPAMM to support warm pixel analysis.

C. SDO Star Trackers

The two STs aboard SDO are A-STR autonomous star trackers provided by Galileo Avionica. They are positioned so that their boresights are 52° apart and approximately parallel to the YZ plane. Each unit has a 16.4° x 16.4° field of view (FOV) with charge coupled device (CCD) detectors consisting of 512 pixels x 512 pixels. The trackers autonomously identify the star patterns and provide an attitude estimate in the form of an attitude quaternion. Each unit is able to track up to 9 stars simultaneously.

Star images are purposely defocused prior to appearing on the CCD. The intensities of the illuminated pixels are combined and, through a proprietary algorithm, the centroid of the star image is determined. The defocusing and centroiding allows the star tracker to obtain higher star position accuracy than ½ pixel. Two defocused star images are shown in Fig. 1. Note that all diagrams depicting star images (Fig.1 and Figs. 5-8) are notional examples and do not portray varying pixel intensities.

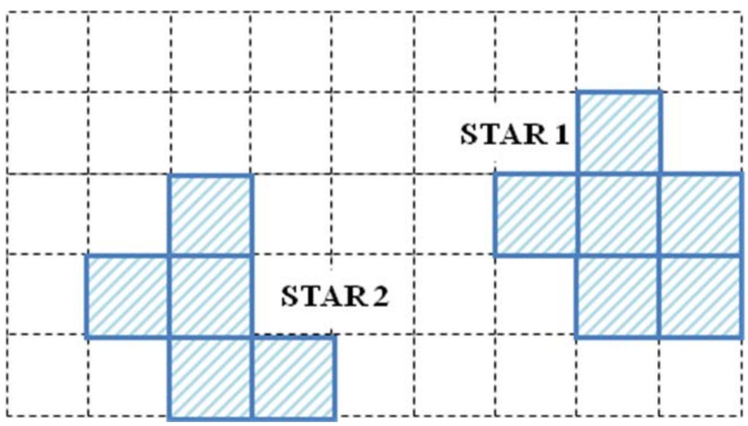


Figure 1. De-focused star images in the CCD.

II. Warm Pixels

Each pixel in the ST CCD measures the intensity of light incident on that pixel. Ideally, pixels pointed at deep space would register zero intensity. However, due to various effects, even pixels pointed at deep space register some level of background noise intensity or "dark current." A warm pixel is defined as having a measurement *consistently* and *significantly* higher than the mean background intensity level. Additionally, a warm pixel will not move across the ST field of view as the attitude changes (as a star image would).

Warm pixels (sometimes referred to as "hot" pixels) are a well documented issue in all CCDs; this is not an issue specific to this particular star tracker or even to star trackers in general. Within space applications, warm pixels have been written about, although not extensively. Warm pixel detection in the Chandra X-Ray Observatory camera[2] and hot pixels in the James Webb Space Telescope camera[1] have been documented. Most similar to the analysis presented in this paper, however, is the warm pixel anomaly detected in the Herchel star trackers[3].

III. Initial Indicators of Possible Anomaly

A. Star Tracker Alignment Calibration

During on-orbit alignment calibration of the star trackers relative to each other and relative to the Guide Telescopes, an anomaly was found. This anomaly was traced to unusually large ST2 residuals during one data period on day-of-year (DOY) 68 of 2010 (March 9, 2010). These large residuals were characterized through the use of an EKF/Smoother using IRU, star tracker, and guide telescope data as input in the MTASS ground attitude software. The guide telescope residuals were less than 1 arcseconds and ST1 residuals were less than 20 arcseconds. ST2, however, showed a large increase in the residual magnitude starting at about 12:00 UTC. These are shown in Fig. 2 in which 300 second boxcar averaging has been applied to reduce the high frequency noise.

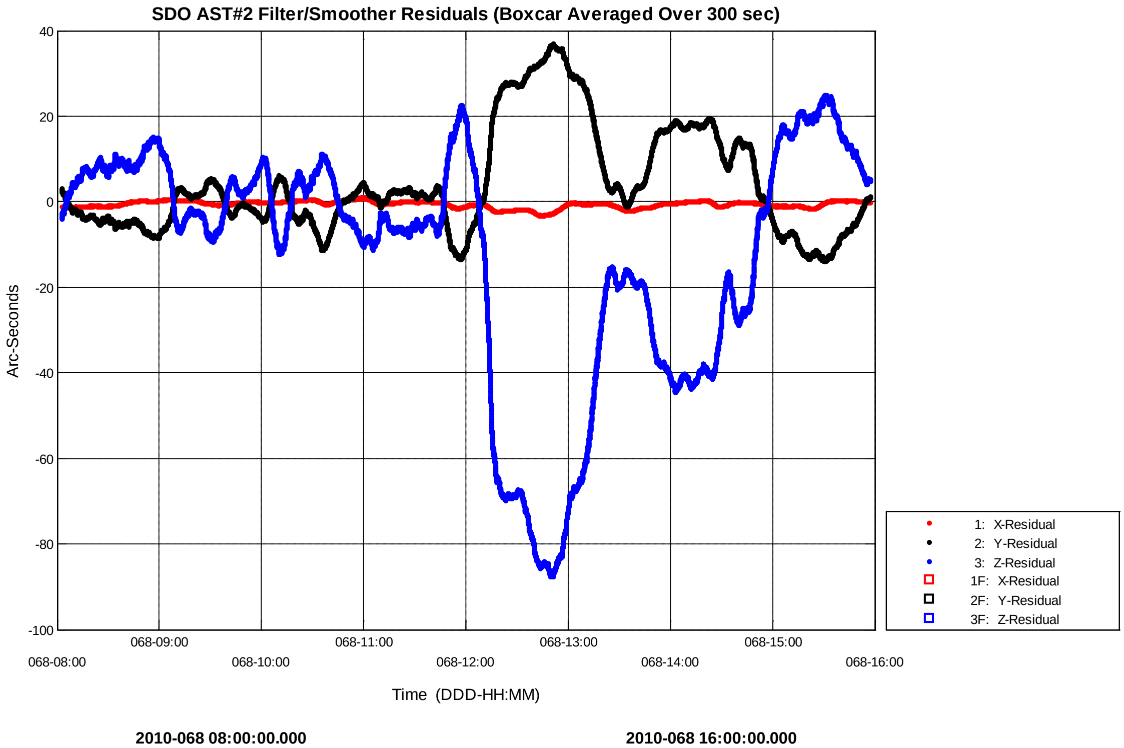


Figure 2. ST2 EKF/Smoother Residuals (Boxcar Averaged Over 300 Seconds)

The abnormally large ST2 residuals found during the relative alignment calibration were the first indication of the warm pixel anomaly, which was then studied further. The ST2 Quality Index, described in the next section, was found to have had the characteristic "inverted-U" pattern at the same time. Additionally, the inverted-U pattern will be qualitatively described by a potential warm pixel corruption.

B. Quality Index

The Galileo Avionica star trackers used on SDO provide a convenient measure of the quality of attitude solution output by the unit called the Quality Index. This scalar value, ranging from 0 to 1, is computed and telemetered with each attitude quaternion. When the Quality Index is equal to or close to 1, the attitude quaternion provided by the tracker is expected to be of high accuracy. A lower Quality Index indicates a lower accuracy attitude quaternion. The exact algorithm for computing the Quality Index is proprietary to the manufacturer; however, it is known that a drop in Quality Index can be brought on by an error in the observed position of a star in the FOV.

Following the abnormally large ST2 residuals found during relative alignment calibration, the Quality Indices of both star trackers were examined. It was found that at least twice, ST2 reported a low Quality Index for periods of hours at a time. Additionally, the Quality Index had a very distinct inverted-U shape, as shown in Figs. 3 and 4.

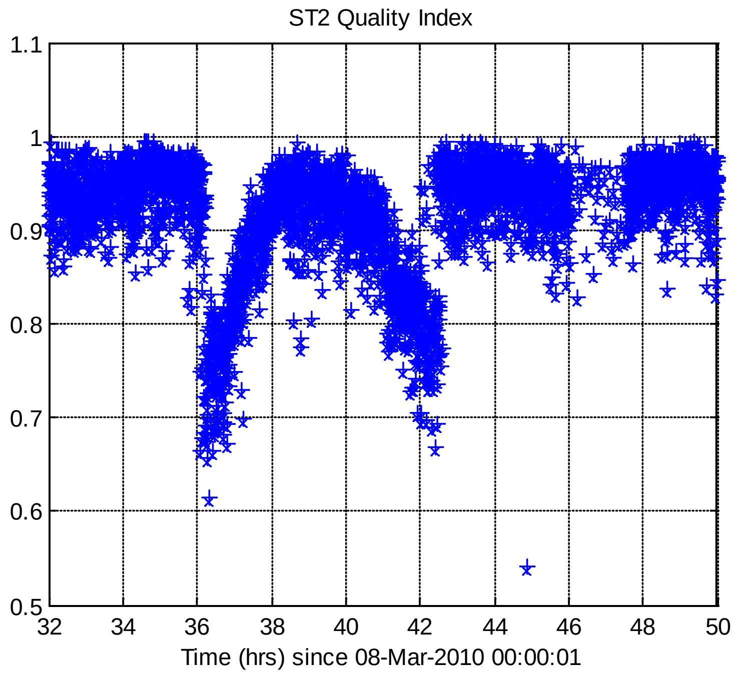


Figure 3. ST2 Quality Index from March 9 (DOY 68), 2010 08:00 to March 10 (DOY 69), 2010 02:00 (UTC)

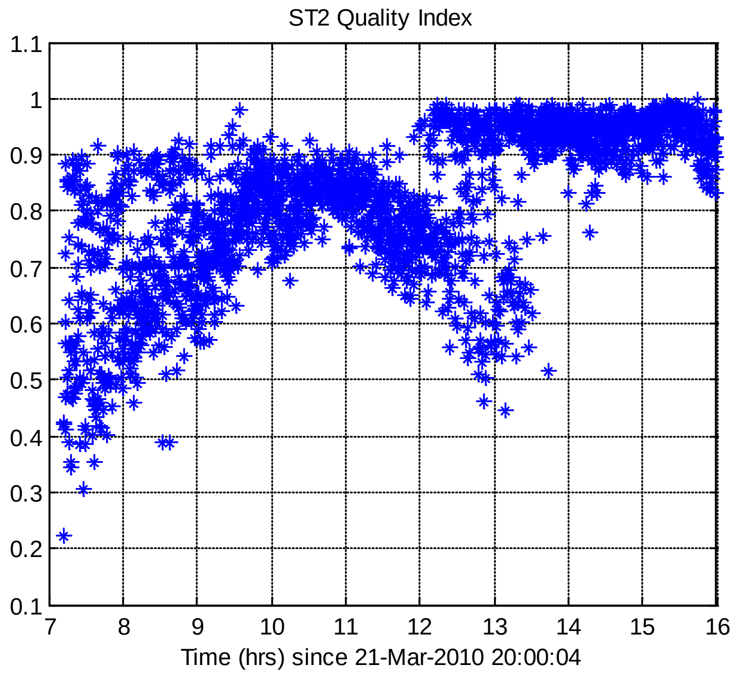


Figure 4. ST2 Quality Index from March 22 (DOY 81), 2010 03:00 to March 22 (DOY 82), 2010 12:00 (UTC)

The finding of two separate incidents of the inverted-U pattern alerted the analysts involved in SDO mission operations to a potential anomaly, and this characteristic inverted-U pattern was investigated further. As a result, the inverted-U behavior of the Quality Index was tentatively explained by a possible warm pixel in the star tracker CCD.

Figure 5 illustrates a defocused star image in the ST CCD, shown as blue shaded pixels. This particular star image is in the vicinity of a warm pixel, shown as a red shaded pixel; however, the warm pixel is far enough from the star image that the star centroiding algorithm does not consider the warm pixel to be part of the star image. In this case, the de-focused star image is *un*corrupted and the star tracker correctly calculates the centroid, shown as the encircled "X".

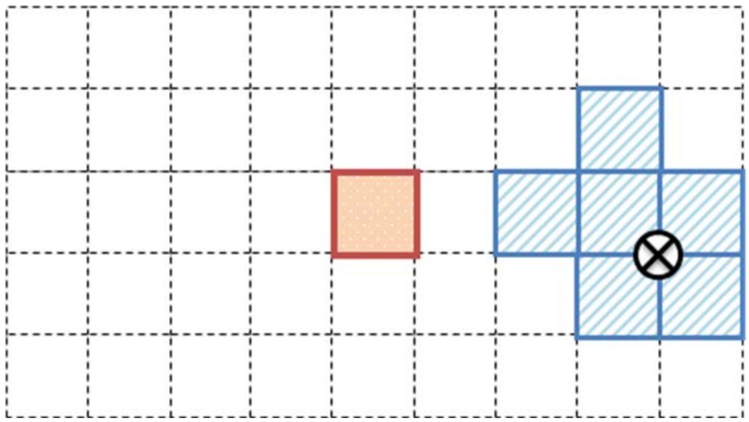


Figure 5. CCD star image in vicinity of warm pixel

As the attitude of the spacecraft changes, the stars in the ST FOV move. In Fig. 6, the attitude has changed such that the star image has shifted to be adjacent to the warm pixel. With the warm pixel adjacent to the star image, the centroiding algorithm can not distinguish the warm pixel from the star image itself. The warm pixel is now included in the centroid calculation and corrupts the calculation of the centroid by artificially shifting it towards the warm pixel. Figure 7 shows this corruption.

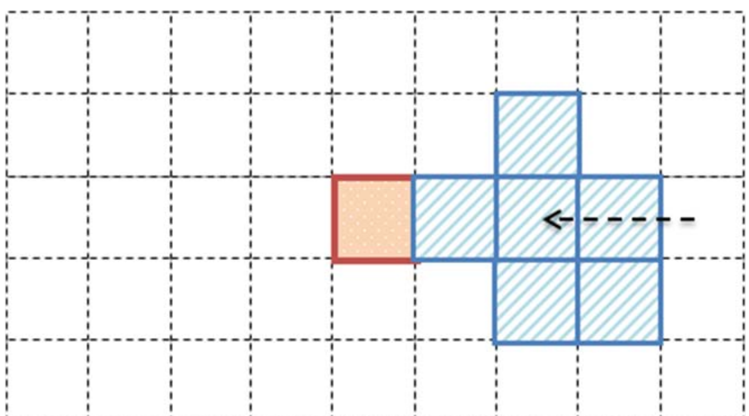


Figure 6. CCD star image under influence of warm pixel

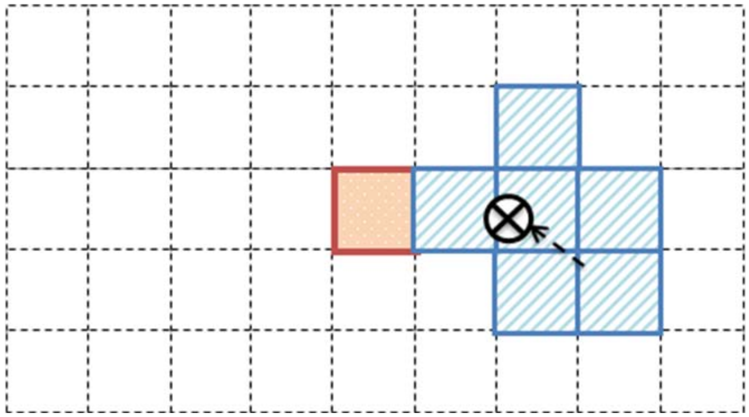
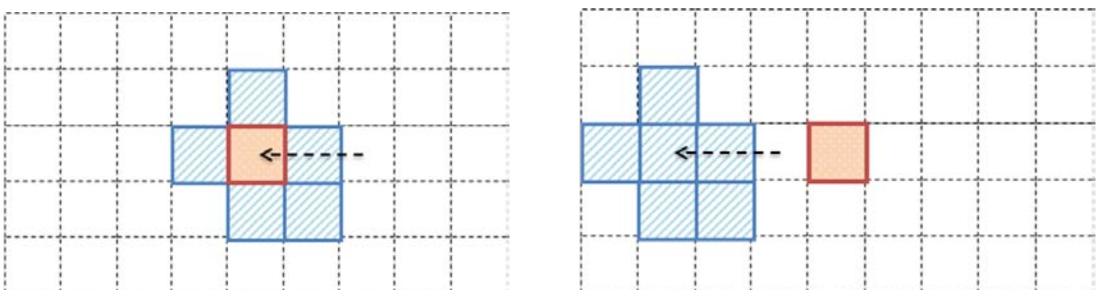


Figure 7. Corrupted star centroid under influence of warm pixel

As the attitude continues to change, the star image eventually moves away from the warm pixel until the warm pixel is, again, outside of the region that the star tracker considers in its centroid calculation. Figure 8 illustrates this motion.



a) b)

Figure 8. Star image moving (a) over and (b) past a warm pixel.

The attitude of SDO rotates approximately 0.04° per hour, mostly about the spacecraft Z-axis. The star trackers are mounted at about 26° from the spacecraft Z-axis, so the ST fields of view are moving at approximately 0.036° per hour. The duration of the degraded Quality Index, as seen in Figs. 3 and 4 above, is about 6 hours in both cases. In 6 hours, at a rate of 0.036° per hour, a star centroid position would move 0.216° or approximately 6-7 pixels. This is consistent with the size of an average defocused star image used by the tracker in an attitude solution. In other words, a star image which is 6-7 pixels in width takes approximately 6 hours to traverse a warm pixel, and this matches well with the duration of the degraded Quality Index.

Furthermore, as a star image traverses a warm pixel, the greatest effect on the star position centroid occurs when the warm pixel is at the edge of the defocused image. At this point, the distortion is the largest and the expected Quality Index would be at its lowest. As the star image moves and the center of the star gets closer to the warm pixel, the effect on the centroid is lessened. At the center, the Quality Index would show almost no degradation. Finally, as the image continues to move, the warm pixel "exits" the star image at the other end. Again, at this point, the Quality Index would drop to a low value. This is why an inverted-U shape is expected in the Quality Index during a warm pixel event. In brief, the Quality Index drops when the warm pixel is on the leading edge of the star image. It then rises as the image and the warm pixel merge. It again drops as the star moves to put the warm pixel near the trailing edge of the image.

IV. Initial ST2 CCD Analysis

Having seen reports of the anomaly in the Herschel star trackers, an attempt was made to identify any anomalously active pixels in the SDO star trackers. Shortly following the first inverted-U Quality Index event, three snapshots of raw CCD measurements from ST2 were telemetered over the course of several days. The three CCD images of the ST2 CCD were telemetered on DOYs 73, 81, and 82; each CCD "dump" took about 90 minutes to complete and each time an inertially fixed attitude was held to reduce the spacecraft motion throughout the dump (although pointing and knowledge errors resulted in some movement of the spacecraft). SDO analysts developed an algorithm that, given raw CCD measurements, identified warm pixel candidates in the FOV at the time the CCD measurements were telemetered.

A. Results From Initial Three ST2 CCD Dumps

1. Warm Pixel Identification

For this analysis, pixel intensities in the three ST2 CCD dumps were examined. The object of this analysis was to identify pixels that were *consistently* and *significantly* above the background noise level but did not represent the images of stars. To do this, the following procedure was used:

1. Find the mean and standard deviation (σ) of pixel intensity in all three CCD dumps combined.
2. Consider as pixels with only background noise those that have intensities less than the mean plus 3σ.
3. Find the mean and standard deviation of only the background noise pixels (mean = 835.32 counts, σ = 2.65 counts).
4. Find all pixels that have values more than the mean plus 6σ in all three CCD dumps.

In accordance with the warm pixel definition presented earlier in this paper, "significantly above the background noise" was defined as 6σ above the mean and "consistently" was defined as warm pixels present in all three CCD dumps. There are 45 candidate warm pixels found in the three CCD dumps. These are presented in Table 1. The fact that the intensities change by only a few counts in most of these pixels from one CCD dump to another suggests that the elevated signal levels are inherent in the pixels.

The CCD dumps from DOY 81 and DOY 82 were sent to Galileo Avianoca for further independent analysis. Their report agreed very well with the findings presented in this paper. In fact, the 19 warm pixels found in the Galileo analysis were a subset of the 45 warm pixels found by SDO analysts.

2. Attempt to Correlate Warm Pixels to Observed Stars

In addition to the three CCD dumps described in the previous section, star observations from ST2 were telemetered on DOY 82 during a time when the Quality Index was low. The star observation data contains observed star positions (centroids) and magnitudes for the stars used by the tracker in the attitude solution at that time. The CCD was dumped along with star observations. During the CCD dump, the Quality Index is invalid in telemetry and therefore it is unclear whether the characteristic inverted-U shape was exhibited at the time of the gathered star observations.

The proximities of the 45 warm pixels, identified from the CCD dumps, to the observed stars on DOY 82 were analyzed. It was found that none of the 45 warm pixels appeared close enough to any of the observed stars to corrupt their centroid. The closest warm pixel was about 1° away from the nearest star used by the tracker. This indicates that there may be other causes for low Quality Indices than warm pixel effects.

3. Distribution of Pixel Intensities in CCDs

Another interesting result of this analysis was the determination of the distribution of background levels in all of the pixels (not containing stars) in all three CCD dumps. This distribution appears to be approximately Gaussian but with a non-Gaussian tail at high levels. It is possible that a characteristic of the CCD material is that high background levels are more common than would be expected from a "normal" distribution. These distributions are shown in Figs. 9 and 10, where Fig. 10 shows an expanded section of Fig. 9.

4. Conclusions From Initial Analysis

Although 45 warm pixels were found to be present in three CCD dumps on DOYs 73, 81, and 82, the locations of the warm pixels did not correlate to observed star positions during a time when the Quality Index was low. Furthermore, not knowing the algorithm used to determine the Quality Index prevented a definitive evaluation of the relation between the increase in pixel intensity and the decrease in Quality Index.

Table 1. Warm Pixel Candidates Found in Three ST2 CCD Dumps

Row	Column	Intensity on DOY 73 [counts]	Intensity on DOY 81 [counts]	Intensity on DOY 82 [counts]	Δ(73,81) [counts]	Δ(73,82) [counts]	Δ(81,82) [counts]
10	13	860	854	855	6	5	-1
22	493	859	876	870	-17	-11	6
36	505	856	853	852	3	4	1
47	430	854	859	857	-5	-3	2
64	447	856	863	859	-7	-3	4
69	341	854	868	870	-14	-16	-2
70	393	869	906	905	-37	-36	1
71	496	858	856	856	2	2	0
93	213	865	857	862	8	3	-5
115	342	861	856	863	5	-2	-7
137	365	860	863	863	-3	-3	0
148	202	917	900	900	17	17	0
176	463	858	864	864	-6	-6	0
187	347	854	853	852	1	2	1
208	306	856	855	857	1	-1	-2
216	133	864	863	860	1	4	3
217	493	881	853	854	28	27	-1
220	362	869	862	870	7	-1	-8
222	396	860	853	852	7	8	1
225	323	857	855	854	2	3	1
227	17	861	863	856	-2	5	7
227	443	853	857	859	-4	-6	-2
232	377	862	856	859	6	3	-3
250	276	863	864	860	-1	3	4
255	379	854	860	853	-6	1	7
259	505	864	866	865	-2	-1	1
271	173	858	863	867	-5	-9	-4
330	148	856	865	861	-9	-5	4
345	240	858	858	861	0	-3	-3
346	466	854	860	853	-6	1	7
363	350	861	857	858	4	3	-1
396	187	867	870	866	-3	1	4
406	220	870	872	864	-2	6	8
413	423	877	868	869	9	8	-1
418	122	857	856	857	1	0	-1
428	146	862	864	864	-2	-2	0
429	145	866	854	859	12	7	-5
448	190	853	859	862	-6	-9	-3
450	490	858	860	860	-2	-2	0
473	58	869	872	866	-3	3	6
491	284	858	854	852	4	6	2
491	368	860	858	858	2	2	0
498	293	852	852	854	0	-2	-2
498	501	860	861	863	-1	-3	-2
507	270	855	853	853	2	2	0

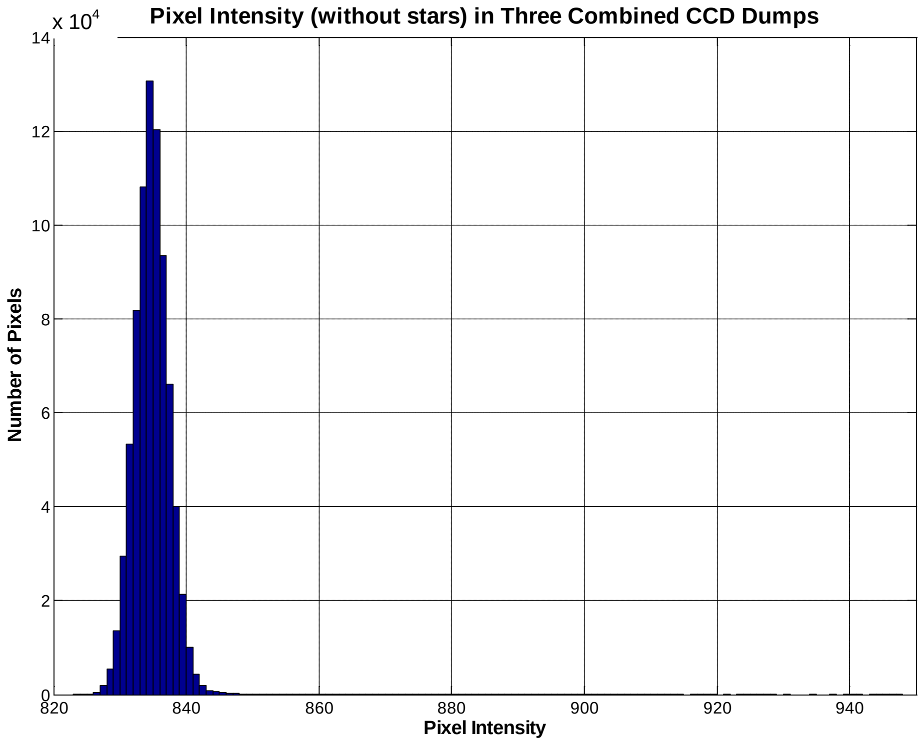


Figure 9. Distribution of Pixel Intensity in ST2 CCD Dumps

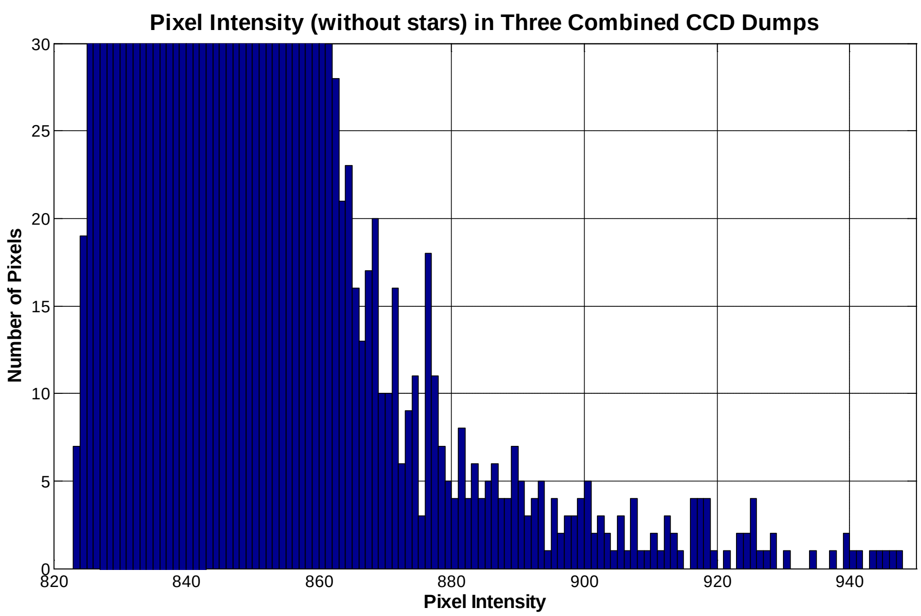


Figure 10. Tail of Distribution of Pixel Intensity in ST2 CCD Dumps

V. Operational Warm Pixel Identification Software

A. Warm Pixel Identification Software

The warm pixel detection software was designed to find pixels that did not contain star images and that had intensities that were consistently above background levels. For each CCD image, lower and upper thresholds were established. The lower threshold was that below which a pixel's intensity was considered background and the upper threshold was that above which a pixel's intensity was considered to represent a portion of a star image. The values of these thresholds were estimated from the first few CCD dumps.

Each CCD dump was processed through the following algorithm:

1. Pixels below the lower threshold or above the higher were eliminated from consideration.
2. The location of the remaining pixels was saved for use by the software in processing subsequent CCD dumps.
3. The location of these remaining pixels was compared to locations from the previous dump.
4. Any pixels that were active in the previous and the current dump were considered possible warm pixels.
5. All possible warm pixels detected for a CCD dump were used to amend a table of statistics on previous possible warm pixels.
6. A report was written that summarized the results of analysis of this CCD dump as well as a cumulative summary of the previous dumps.

The algorithm in the operational software is slightly different from the algorithm used to detect warm pixels during the initial analysis of the three ST2 CCD dumps. During analysis, warm pixels were identified using the statistics of the background pixels. A threshold of 6σ above the mean intensity in all background pixels was used. For the operational software, a constant threshold (the "lower" threshold described in the algorithm above) was used to identify warm pixels. It was decided that it would be easier to re-configure this threshold in the future as more CCD dumps are analyzed because the threshold is independent of the statistics of each individual CCD image.

The algorithm above was implemented in the Warm Pixel Identification Utility and installed in the SDO MAR as part of the SPAMM software.

VI. Monthly Results and Trends

A. Current Results and Trends

Since the first observed data Quality Index disturbance on ST 2 in March 2010, the SDO flight operations team has been performing dumps of the star tracker CCDs roughly once per month per tracker in order to characterize and trend the location of both previously known and newly developing suspected warm pixels. As of April 2011, a total of 12 dumps have been performed of the ST1 CCD and 14 of the ST2 CCD. A general summary of the dump results for ST1 and ST2 is given in Tables 2 and 3, respectively. It is worth noting that the algorithm used by the warm pixel detection software to analyze CCD dumps will not flag any pixels as warm in the first dump analyzed for a given tracker, as no baseline for comparison exists.

Table 2. Summary of ST1 CCD Dump Analysis Results

Dump Number	Warm Pixels Flagged	New Warm Pixels Flagged	Cumulative Distinct Warm Pixels Flagged
1	0	0	0
2	0	0	0
3	4	4	4
4	2	0	4
5	3	1	5
6	4	2	7
7	3	0	7
8	3	1	8
9	4	1	9
10	4	0	9
11	4	1	10
12	5	1	11

Table 3. Summary of ST2 CCD Dump Analysis Results

Dump Number	Warm Pixels Flagged	New Warm Pixels Flagged	Cumulative Distinct Warm Pixels Flagged
1	0	0	0
2	11	11	11
3	20	10	21
4	9	0	21
5	14	9	30
6	14	3	33
7	10	3	36
8	14	5	41
9	14	3	44
10	11	0	44
11	12	2	46
12	11	3	49
13	19	5	54
14	15	0	54

Although the high number of pixels flagged as warm pixel candidates on ST2 relative to ST1 was initially disconcerting, this concern has been somewhat alleviated by the fact that the detection software has shown itself to be more sensitive when flagging pixels with regards to ST2. Many of the pixels flagged by the software as warm pixel candidates on ST2 have only been labeled as such in one or two of the dump analyses, with only a small fraction being consistently present. A similar pattern was seen in the ST1 results, though not to the exaggerated degree seen with ST2. A distribution of the pixels that have been flagged as warm pixel candidates based on the number of times they have been flagged as such by the detection software is shown, for each tracker, in Figs. 11 and 12.

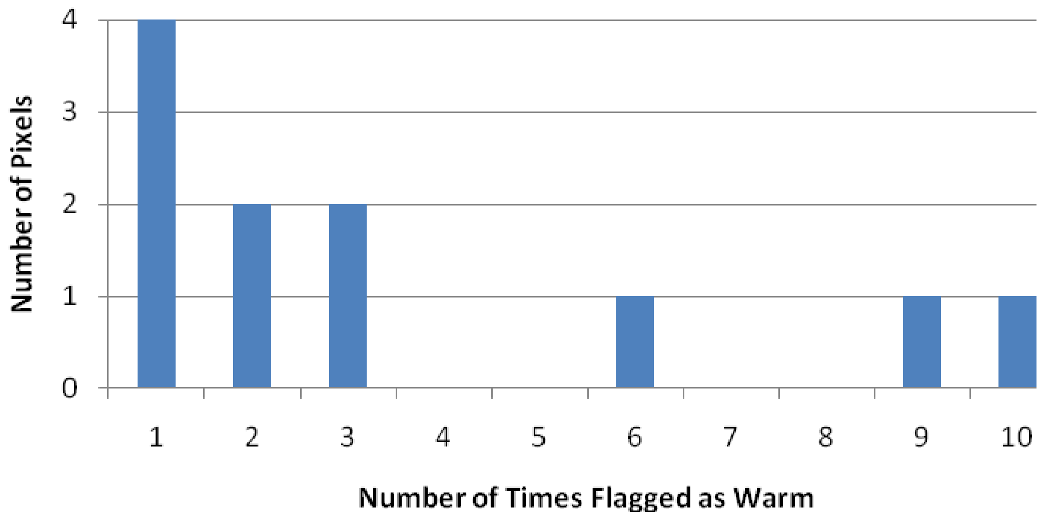


Figure 11. ST1 Warm Pixel Candidate Distribution by Number of Times Flagged as Warm

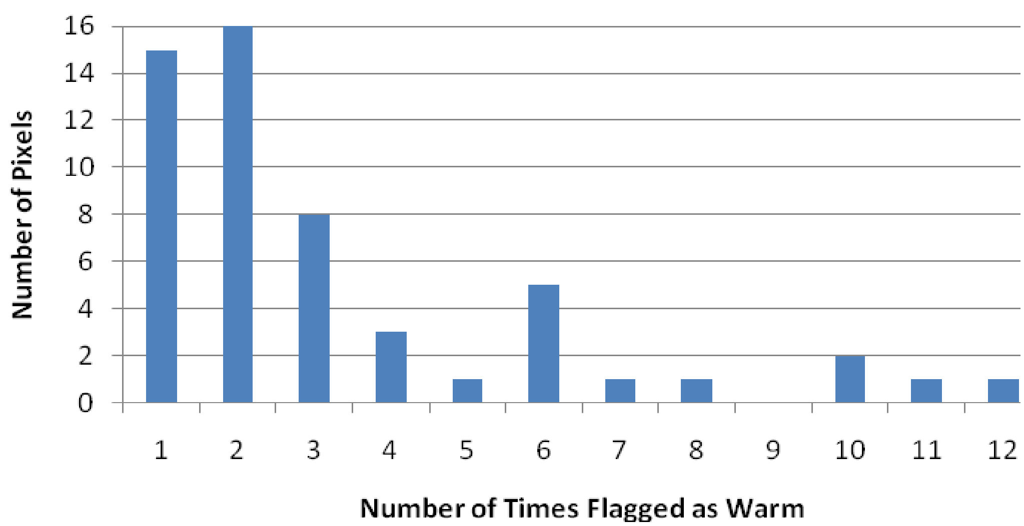


Figure 12. ST2 Warm Pixel Candidate Distribution by Number of Times Flagged as Warm

B. Day of Year 81 Anomaly and Future Analysis

As discussed in previous sections, the initial investigation into the warm pixel phenomenon on SDO was partially prompted by a severe drop in the ST2 data quality on DOY 81 (March 22nd) of 2010 that demonstrated the characteristic inverted-U shape of the data Quality Index associated with warm pixel corruption. Exactly a year later, a nearly identical drop in quality was seen on ST2. As the result of SDO's attitude and orbital geometry, ST2 was observing the same patch of sky on both occasions and a comparison of CCD dumps performed on DOY 81 in 2010 and 2011 confirmed the same stars in the tracker's field of view with nearly identical placement. Analysis of these dumps, along with those performed in the following days of both years, failed to identify any warm pixel candidates in the general vicinity of the stars within the tracker's field of view.

As of April 2011, there have been two other occasions (one per tracker) in which CCD dumps were performed immediately following the observance of an inverted-U shape in the data Quality Index. On both occasions the detection software flagged warm pixel candidates within a few pixels of stars that were currently in the tracker's field of view.

As such, consideration is now being given to the possibility that an unrelated problem could be producing symptoms similar to that of a warm pixel corruption. Particular attention is being given to the presence of the star Vega in ST2's field of view during the time period near DOY 81, as it is by far the brightest of the stars which passes through the tracker's field of view over the course of a year and has demonstrated a widely varying distribution of light intensity across the pixels surrounding it over time. With assistance from Galileo Avionica, the possible existence of a secondary image bright enough to affect the attitude solution is being examined. If this is indeed the case, additional analysis will be necessary to determine both the factors that produce the secondary image and how to distinguish inverted-U shape events caused by this effect from those caused by warm pixel corruptions. It may be worthwhile to attempt to obtain CCD dump data immediately following observances of lesser-magnitude inverted-U shape events throughout the year.

Another possible analysis that can be done in the future is to examine the Single Shot Attitude (SSA) data from the star tracker during an inverted-U Quality Index event. The ST SSA data shows the stars that are being used in the attitude solution, their magnitudes, and their calculated position centroids. If a warm pixel is affecting a star measurement, both the observed star magnitude and position will be corrupted. A similar investigation was done by Galileo in their analysis of Herschel ST data. With the Warm Pixel Identification Utility having been run for some number of months, a prediction can be made of when a star will be in the vicinity of a warm pixel. While this would be ideal, dumping CCD images in telemetry is difficult to do and time consuming. More information on the method by which CCD images are downlinked in SDO telemetry can be found in Ref. 4.

VII. Mitigation of Warm Pixel Effects

Mitigation strategies for the effects of warm pixels in the ST CCD fall into three different areas: mitigation by the spacecraft FSW, mitigation by the ST software, and operational mitigation. Strategies for each of these areas are discussed below.

A. Mitigation by the Spacecraft Flight Software (FSW)

The first level of mitigation for the effects of potential warm pixels occurs within the spacecraft flight software (FSW). The ST data processing algorithm monitors the Quality Index reported by the ST and will flag as "low quality" any ST data whose Quality Index is below a database specified level. That limit is currently set to a value of 0.7, but could be changed at any time via table load. The onboard Extended Kalman Filter (EKF) will then reject any ST residuals that have been flagged as "low quality", thus preventing potentially erroneous data from corrupting the onboard estimates of the spacecraft attitude and IRU biases. Additional mitigation is provided by the design of the Science Mode controller. The Science Mode controller only uses the estimated attitude from the EKF for attitude control of the spacecraft roll axis (X-axis). The spacecraft pitch and yaw axes (Y- and Z-axes, respectively) are controlled directly from the controlling guide telescope. Thus, only the roll is subject to control errors arising from warm pixel effects.

B. Mitigation by the Star Tracker Software

In addition to the mitigation by the spacecraft FSW, the ST software also has within it logic to mitigate the effects of bad pixels. The ST health and safety algorithm continuously scans through all 512 by 512 pixels of the ST CCD and monitors the health of the pixels. Pixels that are determined by the ST to be defective are included in a "defective pixel table." Pixels in the defective pixel table are not used in calculating the ST attitude. A pixel is determined to be defective if the energy level of the pixel is persistently more than a database specified value and/or if the ratio between the pixel's energy and the total energy of the surrounding pixels is higher than a database specified limit. Both the persistent energy level and the energy ratio limits are command changeable. In addition, pixels can be manually entered into the defective pixel table via commands to the ST.

Another mitigation available within the ST software is the running of the thermo electric cooler (TEC) when the temperature is above a commandable set point. It is known that if the ST CCD temperature is cooler, some previously noted warm pixels could "recover" and return to near their previous energy levels. The nominal set point for the TEC on SDO is set such that the TEC does not nominally run.

C. Operational Mitigation

Operational mitigation methods and strategies include (1) monitoring both ST CCDs and (2) utilization and/or modification of the available mitigations within the spacecraft and ST software. From a monitoring perspective, the ST Quality Index will be trended in an effort to watch for additional "warm pixel events". In addition, as described in this paper, the CCDs of each ST will be dumped on a monthly basis and the data analyzed by the SDO operations team and sent to Galileo Avionica for potential additional analysis. The CCD dumps will be performed one at a time, at a time when both STs have a clear FOV. The CCD dump procedure takes approximately 2 hours and requires taking the ST out of tracking mode, which thus makes it unavailable for attitude and IRU bias estimation. The SDO knowledge requirements are such that only two out of the three fine attitude sensors (DSS included) are needed at one time, so temporary removal of one tracker will not cause an impact on spacecraft attitude knowledge.

Should the CCD dumps of the STs, over time, reveal an increase in the number of warm pixels in the ST CCD, or if the noted warm pixels start to affect spacecraft pointing, modifications can be made to the spacecraft and/or ST software parameters to better utilize the existing mitigation strategies. The temperatures of the SDO ST CCDs are currently around 0° C, so the TEC does not normally run. A command could be sent to the ST to lower the set point of the TEC to force it to run and cool down the ST CCD. Lowering the CCD temperature could potentially recover some of the existing warm pixels and/or minimize the development of new warm pixels. Another option would be to include some of the existing warm pixels in the defective pixel table. This can be done by changing the parameters that define a defective pixel so that the ST would automatically enter them into the table. Alternatively, warm pixels found using the ground-based warm pixel identification software (or other method) can be manually entered into the defective pixel table via a command uplink. Finally, the spacecraft "low Quality Index" limit could be changed to a higher value to reject more low quality tracker quaternions from entering the EKF algorithm.

VIII. Conclusion

Star tracker alignment calibration and monitoring of the star tracker Quality Index revealed an anomaly in the star trackers that was studied by SDO analysts and by the star tracker manufacturer. Having knowledge of a warm pixel anomaly on the Herschel observatory, a strategy for identifying warm pixels in the SDO star trackers was designed. Initial analysis showed that the star trackers potentially had warm pixels in their CCDs, however the warm pixels found in the CCD could not be correlated to tracked stars during a "low Quality Index" event. Operational software for monitoring and trending warm pixels was developed and instituted as part of SDO operations.

It should be noted that the maximum error introduced in the star tracker attitude solution during suspected warm pixel corruptions is within the specified 3σ attitude knowledge error budget requirement of [35, 70, 70] arcseconds. Thus, the star tracker attitude accuracy remains within the specification for SDO. However, this anomaly did have some effect on the attitude. The analysis presented in this paper has been instrumental in understanding the effect of warm pixels on this particular star tracker. For spacecraft with either tighter requirements on pointing or those that rely more heavily on the star tracker for attitude control, a warm pixel anomaly could cause a spacecraft to lose pointing accuracy. Therefore, understanding the effects of warm pixels could be crucial in resolving CCD star tracker anomalies, in general.

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