Controlling the *Swift* XRT CCD Temperature via Passive Cooling

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ABSTRACT

The *Swift* X-ray Telescope (XRT) is a CCD based X-ray telescope designed for localization, spectroscopy and long term light curve monitoring of Gamma-Ray Bursts and their X-ray afterglows. Shortly after launch there was a failure of the thermo-electric cooler on the XRT CCD. Due to this the *Swift* XRT Team had the unexpected challenge of ensuring that the CCD temperature stayed below -50C utilizing only passive cooling through a radiator mounted on the side of the *Swift*. Here we show that the temperature of the XRT CCD is correlated with the average elevation of the Earth above the XRT radiator, which is in turn related to the targets that *Swift* observes in an orbit. In order to maximize passive cooling of the XRT CCD, the XRT team devised several novel methods for ensuring that the XRT radiator's exposure to the Earth was minimized to ensure efficient cooling. These methods include: picking targets on the sky for *Swift* to point at which are known to put the spacecraft into a good orientation for maximizing XRT cooling; biasing the spacecraft roll angle to point the XRT radiator away from the Earth as much as possible; utilizing time in the SAA, in which all of the instruments on-board *Swift* are non-operational, to point at "cold targets"; and restricting observing time on "warm" targets to only the periods at which the spacecraft is in a favorable orientation for cooling. By doing this at the observation planning stage we have been able to minimize the heating of the CCD and maintain the XRT as a fully operational scientific instrument, without compromising the science goals of the *Swift* mission.

Keywords: *Swift*, XRT, Thermal, Passive Cooling.

1. INTRODUCTION

The *Swift* Gamma-Ray Burst Explorer[1] is a NASA MIDEX satellite designed with the purpose of detection and rapid follow up of Gamma Ray Bursts (GRB). *Swift* was launched from Cape Canaveral Air Force Station on November 20th, 2005 and has been since then has undergone instrument activation, calibration and performance verification phases. On April 5th, 2005 *Swift* entered the operational phase of the mission, in which data became publically available.

Swift consists of 3 main instruments: The Burst Alert Telescope (BAT), a wide field of view Gamma-Ray/Hard X-ray telescope utilizing coded mask optics[2]; The X-ray Telescope[3] (XRT), a Wolter type 1 grazing incidence X-ray telescope with a CCD detector sensitive in the 0.2-10.0 keV range and the Ultraviolet/Optical Telescope (UVOT), a Richie-Critein optical telescope with a micro-channel plate based photon counting detector with lenticular filters in optical and UV wavelength as well as Optical and UV Grisms for spectroscopy[4]. The three detectors on *Swift* combine to make an excellent multi-wavelength observatory, however the major capability of the *Swift* spacecraft is its ability to perform very fast accurate slews in response to detections of GRB by the BAT. This fast response means that follow up observations of the GRB afterglow in X-ray and optical can often be performed often in less than 100 seconds after the burst is detected, and in some cases the X-ray telescope has been able to image the burst as it was still ongoing[5].

The *Swift* XRT is a sensitive (135 cm^2 effective area), moderate field of view (~24 x 24 arcmin) X-ray telescope utilizing a 3.5 meter focal length grazing incidence Wolter type I telescope to focus X-rays onto an EPIC MOS CCD as used in the ESA XMM-Newton X-ray telescope[6]. The XRT prime science objective is to perform rapid localization of GRB afterglows with an uncertainty of ~5 arcseconds, in order to improve the initial position found by the BAT which has an uncertainty of 3 arcminutes. XRT also has spectroscopic capabilities in order to characterize non-thermal emission and possible line spectra from GRBs. The high sensitivity of XRT allows for GRB afterglow follow-up for analysis of long term GRB afterglow light-curves often for weeks after the initial GRB detection.

The XRT CCD was designed to operate at low temperatures (-100C) in order to reduce the effect of CCD dark current and minimize the number of hot pixels. This low temperature is achieved using passive cooling via an thermal radiator mounted on the anti-solar (-Z axis) side of the spacecraft, as well as active cooling using a Peltier cooling device referred to as the Thermo-Electric Cooler (TEC).

Unfortunately during the activation phase of the mission, the TEC power supply failed leaving the XRT cooled purely by the radiator, leading to operating temperatures 30-60C higher than the planned -100C temperature. Although the temperature is much higher than expected, the XRT is still operational and producing excellent data when the CCD temperature stays below -50C. Here we describe the work undertaken to first understand the long period temperature variations seen and also the work performed to keep the *Swift* XRT at a low temperature in order to maintain the XRT as a scientifically useful instrument.

2. XRT TEMPERATURE VARIATIONS WITHOUT THE TEC

2.1. On Orbit Temperature Variations

Without the TEC actively cooling the XRT CCD, the CCD temperature is subject to orbital thermal variations. These temperature variations appear as both a periodic orbital variation caused by the exposure of *Swift* to sunlight (see Figure 1). These orbital variations typically have vary around +/- 2-4C around the mean temperature level, with an sinusoidal shape with a period of approximately 96 minutes.

However over longer periods of many orbits longer timescale temperature variations have been seen. Figure 2 shows the these temperature variations, in that figure the numbers shown are averaged over a orbit, so as to remove the effect of the smaller scale orbital variations. These longer timescale variations can typically be in the range of -75C to -40C. As can be seen in Figure 2 these temperature changes can occur quite rapidly, with changes in temperature of 10 degrees possible over timescales of ~3 orbits (~5 hours). It is this longer timescale variation that causes the most problems with operation of the XRT CCD, which was designed to operate at a constant temperature level.

It was observed that the temperature of the XRT CCD remained relatively constant when the spacecraft was in a “safe pointing” mode, in which the spacecraft cycles between observing 3 of 6 “safe” points on the sky. Temperature variations seen in Figure 3 were not seen until Swift began observing calibration targets. At this point it was decided that the longer period temperature variations were due to the targets that the spacecraft was observing during its orbit.

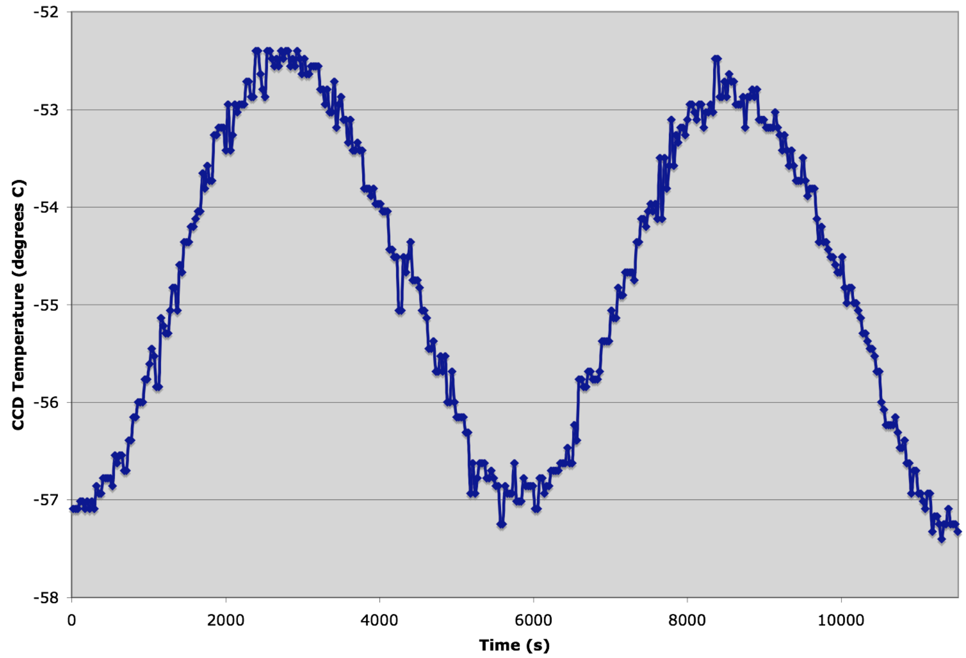

Figure 1. An example of a typical orbital variation of XRT CCD temperature. Two complete *Swift* orbits are shown. The temperature range varies sinusoidally with the ~96 minute orbital period by a factor of approximately +/- 2-4 C around the mean temperature. Note that this plot does show a slight gradient in the mean temperature of the two orbits.

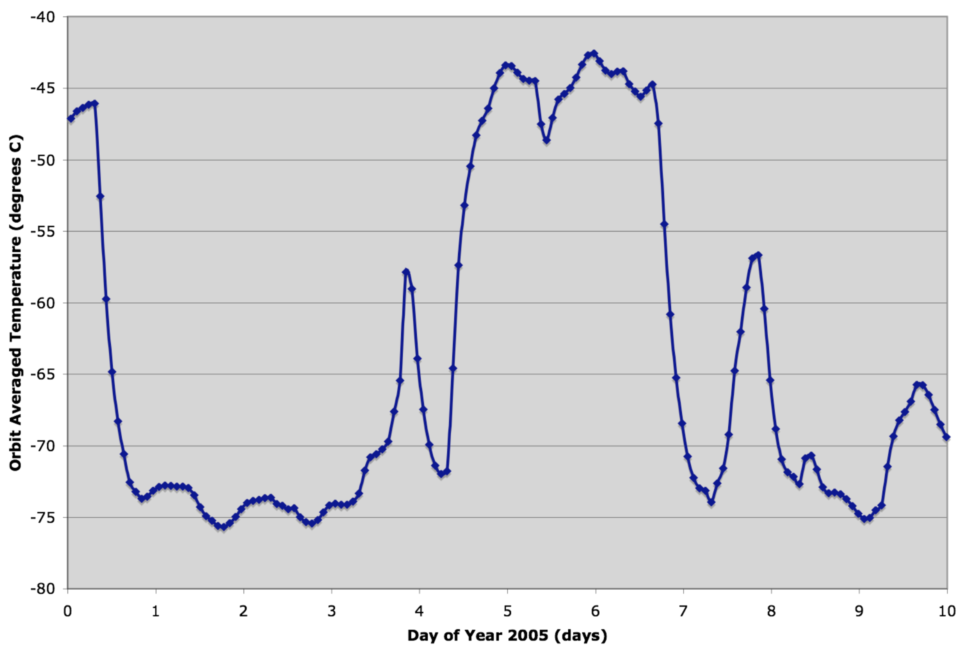

Figure 2. Orbit averaged value of of XRT CCD Temperature over a 10 day period starting midnight Jan 1st 2005. The large variations in average temperatures are clear from this graph, ranging from -75C (unusually low) to greater than -45C, at which point the XRT becomes mainly unusable.

3. PROBLEMS OPERATING XRT AT HIGH TEMPERATURES

3.1. XRT Operating Modes

The XRT CCD employs multiple CCD readout modes in order to collect data in order to minimize the effect of pile up. The most common operating modes are:

Photon Counting (PC) mode: A high sensitivity imaging mode with moderate timing resolution (2.5s). Due to the low time resolution this mode is highly susceptible to pile up, and as such is only suitable for faint sources. However the imaging capability make background subtraction easy making it ideal for long term follow-up of faint afterglows, and the large field of view in this mode however makes it excellent for serendipitous science.

Window Timing (WT) mode: This mode has a higher time resolution (2.2ms), and a smaller region of the detector (200 Pixels wide) is sampled. In WT mode only a single spatial dimension on the detector is retained, which causes the background to higher than PC mode, because of this high background WT is unsuitable for observing faint (>1 c/s) sources.

Photodiode (PD) Mode: In this mode no spatial information is recorded, and the entire detector is read out with 0.14ms timing resolution. This mode is ideal for extremely bright sources that would be piled up in WT mode. For this mode background cannot be determined from the data, so LRPD mode frames are taken during slews between targets for background subtraction. This mode is actually 2 separate modes: Low-Rate Photodiode (LRPD) and Piled-Up Photodiode (PUPD) modes. The only difference between the LRPD and PUPD modes are that in PUPD mode the bias level is not subtracted from the data.

The normal observing state of the XRT is known as "Auto State". In this state the XRT chooses the best mode in which to observe a GRB afterglow based on the brightness of the source in the field. As the source location is not known by the XRT this source brightness is actually the number of counts either on the whole detector or in a window on the detector. This count rate is used to select which XRT mode to use by the Mode Sequence Table (MST) which defines the count rates at which the XRT will switch between mode.

A full description of XRT readout modes and autonomous observing is given by Hill et al (2004)[7].

3.2. Undesirable Effects of High XRT CCD Temperature

3.2.1. Temperature Driven Count Rate

Several temperature dependant effects can cause the count rate in the detector to rise. These are:

Dark Current: At -100C the dark current of the CCD is minimal, however at higher temperatures the dark current rises as a function of CCD temperature and creates a high background in the detector. This higher background can cause the bias level of the CCD to change as a function of temperature. This bias level is calculated during the slew to a new target, and is subtracted off the CCD image before event recognition is performed. If rapid changes in the bias level occur due to dark current, this can be both problematic for spectral calibration, and for event recognition. At temperatures above -45C the dark current rises rapidly causing the background level to rise. When this background level becomes larger than a value known as the "Lower-Level Discriminator", we see a rapid rise in X-ray count rate, as the XRT event recognition mistakes the high background for X-ray photons.

Hot Pixels: Hot Pixels are highly temperature dependent, with the number of hot pixels rising as a function of temperature. The XRT has the ability to mask out individual hot pixels and hot columns so the effect of these hot pixels can be managed this way. However once the CCD temperature rises above -50C we have observed that the number of hot pixels becomes too large to manage with the onboard hot pixel table. This not only reduces the quality of the final data, but also causes a rapid increase in the count rate as a function of temperature.

The effect of the increase in count rate caused by these two effects is that the point at which the XRT mode will change becomes a function of XRT CCD temperature as well as the brightness of the source in the field. Changing modes is highly undesirable when not caused by a change in source brightness. As *Swift* is devoted to the detection and follow-up of GRB afterglows, it is usually observing object that can vary in brightness on very short timescales and in an unpredictable manner. It is therefore extremely important for the XRT to be able to autonomously select the best mode for the current brightness of the X-ray source in order to maximize the observational efficiency and scientific return.

3.2.2. Mode Switching

In some cases the WT count rate will be lower than the PC mode count rate due to differences in window size and how X-ray event recognition and therefore count rate are calculated for these modes. This difference in PC and WT count rate for a single field can cause a state referred to as "mode switching". In this state the high background causes the XRT to swift from PC to WT mode, however as the calculated WT mode count rate is much lower than the PC mode count rate, the XRT switches back into PC mode after only 1 frame. This mode change repeats with the XRT alternating between PC and WT frames continuously. This mode switching is a highly inefficient mode of observation as the overhead of switch modes is roughly comparable to the exposure time of a single frame. Typically in this state less than 50% of the time looking at the source is actually recorded, and often the source in the field is too faint to be detected in the WT mode.

3.2.3. Run Away Photodiode mode

At higher temperatures the high background count rate in the XRT CCD can cause the XRT to switch up into LRPD or PUPD mode. The fast readout of the CCD in this mode causes the CCD to heat up often by several degrees in minutes. This effect can cause a run-away situation in which the higher temperature of the CCD causes a high count rate which causes the XRT to effectively get stuck in LRPD mode, causing further heat input into the detector. At this point passive cooling is insufficient and the XRT CCD temperature will continue to rise. When this run-away situation occurs often the only course of action is to switch the XRT out of LRPD manually and letting the CCD cool down. As this requires manual commanding of the instrument this is a highly undesirable state for the XRT to get into.

4. UNDERSTANDING THE LONG PERIOD TEMPERATURE VARIATIONS

4.1. Earth Albedo effects

Without the TEC power supply the XRT CCD is cooled purely passively by a radiator that is mounted on the –Z axis of the spacecraft. *Swift*'s pointing direction at any point of the orbit is constrained so that this radiator must be pointing away from the sun, so there is never any direct input of sunlight onto the XRT radiator. When the spacecraft is in sunlight, the XRT radiator generally points towards the Earth. It is this albedo flux from the Earth that causes the periodic heating seen around the orbit.

The amount of albedo flux that will be absorbed by the XRT radiator will be strongly dependant on the angle that the XRT radiator makes to the Earth. We refer to this angle as the Earth Elevation Angle (EEA), which we define as the Elevation of a line pointing from *Swift* to the center of the Earth above the plane of the XRT radiator. For simplicity we define the case of the Earth being directly above the XRT radiator (i.e. in the –Z direction) as an EEA of 90 degrees, and if the Earth is on the opposite side of the spacecraft (i.e. in the +Z direction), EEA = -90 degrees.

Early in the mission it was noticed that the mean temperature of the XRT CCD can vary quite quickly and often the temperature profile for one day can differ greatly to the next day. Given that temperature variations caused by the precession of the orbit would be expected to take many days, the only variable that changed on a daily basis were the objects that *Swift* was looking at. It was therefore hypothesized that the long period temperature variations seen were directly related to the amount of exposure the XRT radiator has to the Earth in any one orbit.

We hypothesized that the long period temperature variations of the XRT CCD were caused the amount of albedo flux absorbed by the XRT radiator per orbit. This was parameterized as the orbit average value of the EEA, i.e. the average angle that the XRT radiator makes to the Earth. In this model the larger the orbit averaged EEA is, the more the Earth albedo flux the XRT radiator would absorb. Also if the EEA is low, then the radiator would spend more time pointing away from the Earth into space, and therefore be more able to efficient radiate away heat into space.

In order to test this hypothesis we utilized *Swift* housekeeping data from the first 40 days of XRT operations. We were able to calculate the EEA at any point during the orbit, utilizing the X,Y,Z position of *Swift* with respect to the Earth, which is recorded at 60 second intervals, and the RA, Dec and roll of the spacecraft pointing. These values of EEA were then averaged over the orbit.

The orbit averaged CCD Temperature was also calculated for the same period. Given that the warming and cooling of the XRT CCD can often take several hours to come to equilibrium, only data points where the temperature gradient was low were used in order to compare the equilibrium XRT CCD temperature with the orbit averaged EEA. The results are plotted in Figure 3.

This plot clearly shows a strong correlation between the XRT CCD temperature and the orbit averaged EEA. Utilizing this empirical model it is possible to predict the temperature of the XRT CCD given the EEA, which gives us a powerful tool in understanding how to passively cool the instrument.

4.2. Beta Angle Dependence

The Beta angle is defined as the angle between the orbit plane and the ecliptic plane. *Swift*'s orbit has a 21 degree inclination and the precession of the orbit causes this Beta angle to change on timescales of roughly 40 days, varying from 0 to +/-42 degrees. The amount of Earth albedo flux is highly dependant on the beta angle: with the albedo flux being highest when Beta=0 degrees, and lowest when |B| = 42 degrees. This extra albedo flux causes the XRT CCD temperature to experience higher than expected temperatures during periods of low Beta angle.

Using the model fit above to data taken over the first 6 months of the mission, we were able to find the amount of the excess temperature as a function of Beta angle, and therefore creating a 2^{nd} order correction to the temperature prediction model. This correction is show in Figure 4.

4.3. The Temperature Prediction Model

The final model used to predict the XRT CCD temperature has the following form:

$$T_{CCD} = -54.5421 + 0.7304\,\overline{EEA} - 0.0909\beta \qquad {}^{o}\mathrm{C} \qquad (1)$$

Figure 5 shows typical results using Equation 1 to predict the temperature of the XRT CCD. Although the model does not predict how the temperature of the XRT CCD rises and falls, it is able to accurately predict the temperature at equilibrium for any given EEA. This equation is therefore a powerful tool for understanding the XRT Temperature for a given set of observations.

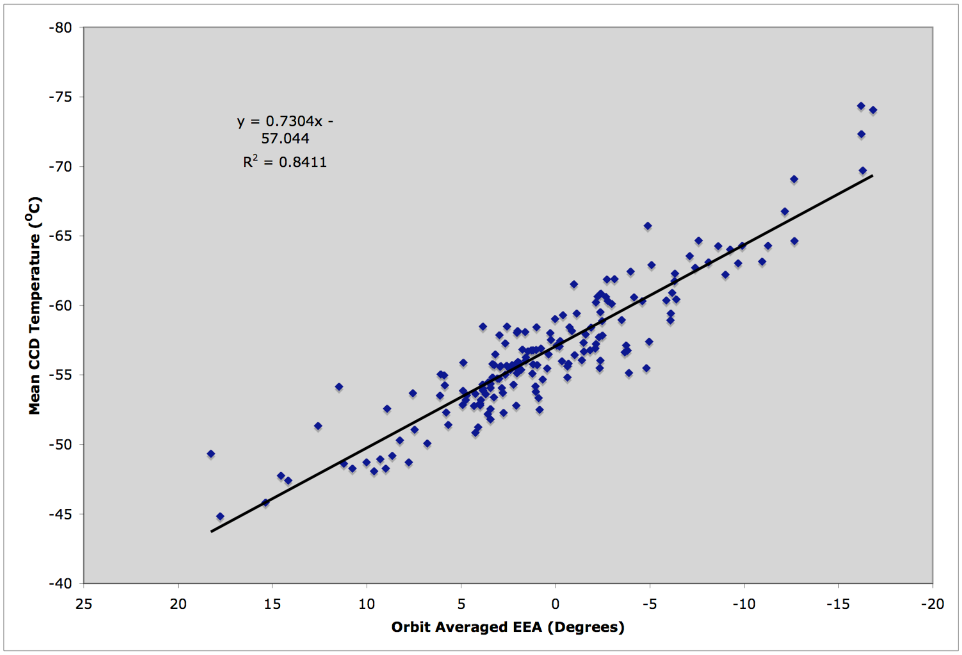

Figure 3. The empirical relationship between Orbit Averaged Earth Elevation Angle and the XRT CCD temperature.

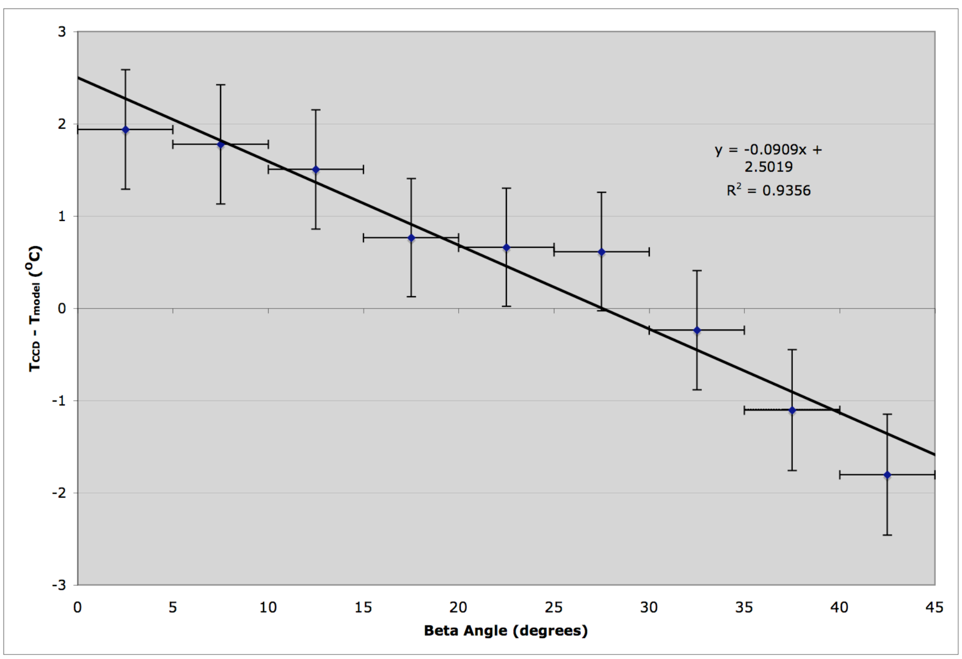

Figure 4. The Beta angle correction factor for the empirical model shown in Figure 3 above. By applying this model to the temperature prediction we are able to remove any effects of the beta angle to the temperature model.

5. CONTROLLING THE XRT CCD TEMPERATURE

Although software changes have been made in order to reduce the effects of these temperature dependant issues, for the optimal operation of the *Swift* XRT it is highly desirable to keep the CCD at as low temperature as possible. We have found that operating the XRT CCD gives good quality data if the temperature is below -50C, above this temperature the data quality becomes significantly degraded due to the effects discussed in Section 3. We have established that the XRT CCD Temperature is a directly related to the EEA. As EEA is a function of the position of the spacecraft, the pointing direction of the spacecraft and the roll, it is possible to minimize the EEA low by picking appropriate targets on the sky that minimize the value of EEA, and therefore the CCD temperature. In general given the orbital variation of XRT CCD temperature, to ensure good data an orbit averaged temperature of around -55C is the aim.

5.1. The Pre-Planned Science Timeline

The observation plan for *Swift* is prepared on a daily basis by the "Science Planner" utilizing the TAKO mission planning software package. The observation plan that is produced is referred to as the "Pre-Planned Science Timeline" (PPST), which is uploaded to *Swift* daily and covers either 24 hours of *Swift* operation, or on weekends 72 hours. On a typical day a PPST will contain observations of between 3 and 6 targets. As *Swift* is in a low Earth orbit these targets are generally observed once per orbit, interleaved with one another. Due to the constraint that *Swift* cannot point within 45 degrees of the Earth's limb, targets will only be visible during certain times in the orbit.

The EEA varies sinusoidally with the orbit, with the EEA highest when *Swift* is on the sunlit side of the Earth, and lowest when *Swift* is in eclipse. The magnitude of the EEA variation is strongly dependant on the region of sky that one is looking at, and therefore in order to minimize the orbit averaged EEA it is desirable to pick targets that have the lowest average EEA during their visibility periods. To illustrate this Figure 6 shows the mean EEA values for the whole sky. This figure shows that there are some regions of the sky that are more preferable to look at than others. Picking "cold targets" that are closer to the blue regions on this plot will cause the orbit averaged EEA to be lower. Observations of targets in the red "hot" regions in this plot are considered undesirable from an XRT temperature point of view. Note that the regions of the sky that are considered "good" are strongly dependant on both the Beta angle and the position of the Sun.

After creating a PPST the science planner utilizes a tool to plot the predicted XRT temperature for the planned day. Based on this plot the planner can decide if the XRT temperature will be acceptable, or whether changes need to be made to the PPST.

Unfortunately the need to do real science with *Swift* often means that we cannot pick our targets based purely on how cool they will keep the XRT CCD temperature. In this case we have developed several techniques that can aide the science planner in producing a PPST, which are described in the following subsections.

5.1.1. Cold Fill in targets

Swift's primary science goal of following up GRB afterglows will often not completely fill the time available during an orbit. On average a target in the sky can be observed for approximately 1/3 of the 96 minute orbit. In the case that we are following up only one GRB, this leaves the other 2/3 of free to observe other targets of interest. Due to this *Swift* has a database of scientifically interesting "Fill-in" targets that are observed during times at which no GRBs are visible. These fill in targets are not time critical observations, so can be used whenever they are convenient.

We have developed a software tool that, for a given gap in the PPST, will pick from a database of potential fill-in targets the best target for keeping the XRT cool. As the temperature depends on the orbit averaged EEA, this means that the effect of a "hot" GRB target on CCD temperature can be offset by scheduling a "cold" fill-in target in a different part of the orbit.

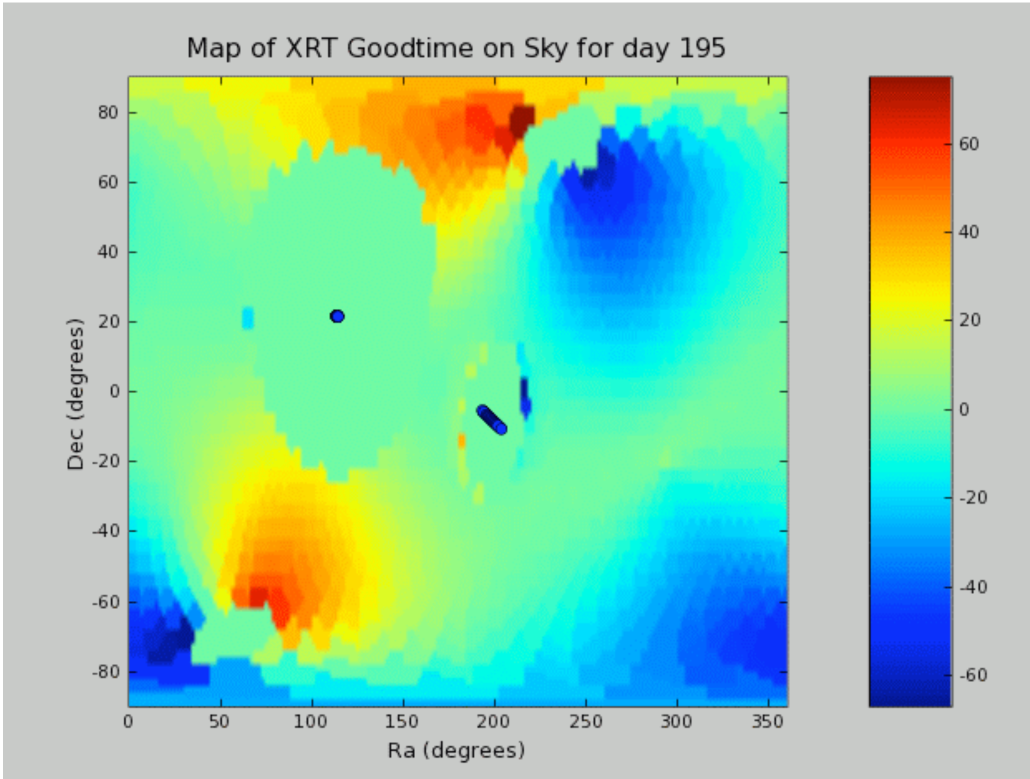

Figure 6. Example of map used to determine which areas of the sky are good in terms of keeping the XRT CCD cool. The key on the right side of this plot represents the average value of EEA for any point on the sky. The two points in this graph represent the Sun (the single point) and the Moon (the elongated point showing its motion during the day). The blank regions around these positions show the areas where *Swift* is unable to look due to observing constraints.

5.1.2. Roll angle biasing

The roll angle for any particular pointing is constrained by the need to keep the angle between the Sun and the normal of the *Swift* Solar Panels to +/-10 degrees. This means that the roll is generally constrained to be within +/-10 degrees of a nominal value, although this variation can be larger depending on the Sun Angle.

Using this small amount flexibility in the roll we are able to pick a roll within the constraint for any observation that preferentially points the radiator on average away from the Earth. Although the roll angle variation is small, it has been shown that by biasing the roll angle it is possible to lower the average temperature of the XRT CCD by up to 4C.

To help the science planner a tool was developed that for a given position on the sky, will calculate the optimum roll angle for keeping the XRT CCD cool.

5.1.3. SAA cold pointing

Swift spends approximately 20% of the day passing through the South Atlantic Anomoly (SAA). During these SAA passages all instrumentation is either turned off or not collecting data due to the high level of events from trapped high-energy particles. As this time is unutilized it was decided that this time would be best used pointing *Swift* at a “cold” target. To help the science planner achieve this a tool was developed that calculates the best position on the sky to point during the passage through the SAA.

This so called “SAA cold pointing” can have dramatic effects on the XRT CCD temperature during parts of the day where *Swift* is spending a great deal of time in the SAA, lowering the temperature by 10-15C. One caveat with this method however is that *Swift* does not pass through the SAA each orbit, and on average only approximately 50% of all orbits include an SAA passage, meaning that this method is only effective for parts of the day in which *Swift* is making SAA passages.

5.1.4. Modification of planning software

To aide in keeping the XRT CCD cool, the TAKO planning software was modified to provide a running average of EEA during the process of scheduling observations. This gives the Science Planner an idea of how well the targets he/she has selected and scheduled will affect the XRT temperature. This has lead to planners being able to create a good PPST much quicker than previously possible when only post-planning analysis software was available to give a temperature prediction.

Utilizing the methods above it is possible for the science planner to plan a set of *Swift* observations that will ensure that the XRT CCD temperature stays below -50C. Software tools developed to aide this purpose have made the planning process for *Swift* change from one that could often take 10-16 hours of work to ensure both a good scientific program of observations and a cool XRT CCD, to a more reasonable 1-5 hours on average currently.

5.2. Caveats

There are problems with this approach to keeping the XRT CCD cool. Firstly in the situation were we are following up 3-4 GRB afterglows, these follow up observations may fill up the PPST. In this case it is not possible to pick targets based on how well they cool the XRT. In this case the Science Planner must either drop or reduce the amount of observing time on some targets in order to put in “cold” targets. SAA cold pointing helps a lot in this example, but usually only for about 50% of the day. Usually cases like this involve sacrificing exposure time on objects, and therefore science return.

Another problem is that of Automated Targets (AT). When the BAT detects a GRB *Swift* observe this burst and override the current planned observations of the PPST. A new unplanned target will affect the EEA profile for the day, and therefore affect the XRT CCD temperature. It has been seen often that a new AT can cause both increases in CCD temperature, as well as decreases.

As the location of a new AT is unpredictable there is little that can be done about possible temperature rises caused by an AT. However using a software tool developed for this purpose, it is possible to predict the effects of a new AT on the current predicted temperature profile. If it is shown that the XRT CCD temperature will be adversely affected by the new AT, then the only method of keep the XRT scientifically operational is to cancel these observations. Luckily as the rise in temperature is generally over a period of several hours, it is usually possible to still get good data on the few few hours of the burst before the necessity to cancel arises.

It is clear that the approach we have taken to control the XRT temperature, although effective, often means that decisions about which targets to observe now often need to be made for reasons other than the scientific merit of a particular target.

6. CONCLUSION

Shortly after launch the *Swift* XRT suffered a failure of the TEC power supply, removing the active cooling for the XRT CCD. Since then the XRT CCD has been cooled purely passively by the XRT radiator. Although the XRT CCD was designed to operate at approximately -100C, it has been found that good quality science data can be obtained if the temperature remains below -50C. However it has been found that above that temperature the quality of the data dramatically drops above that temperature.

We have found a correlation between the average temperature of the XRT CCD and the average amount of time the XRT radiator spends pointing towards the Earth in a single orbit (the orbit averaged EEA). Utilizing this model to predict the CCD Temperature, we are able to lower the average temperature of the XRT CCD by lowering the orbit averaged EEA by picking targets on the sky that lower the orbit averaged EEA, and therefore the temperature.

To further improve the temperature we additionally bias the roll angle of the spacecraft in order to point the radiator away from the Earth as much as possible and utilize time during the SAA (in which no instruments are normally operating) to further bias the EEA to lower values. These minor tweaks to the observing schedule can dramatically improve the overall temperature of the XRT CCD.

Although due to the Automated nature of *Swift*, it has not always been possible to keep the XRT CCD temperature as cool as would be desirable. Utilizing the model for XRT CCD temperature and these planning method, we have been able to make the *Swift* XRT a good quality scientific instrument with a very high degree of observational efficiency.

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