CCDs in space:

the effects of radiation on *Hubble's* Advanced Camera for Surveys (ACS)

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Photo: Astronauts John Grunsfeld and Drew Feustel during *Hubble* Servicing Mission 4 in May 2009

Introduction: The Advanced Camera for Surveys (ACS) has been continuously exposed to the space radiation environment since being installed during Hubble Servicing Mission 3B in March 2002. We have been monitoring the effects of radiation damage in the CCDs during this 7-year period. Radiation damage on-orbit leads to a continuous growth of permanent hot pixels (defined to be > 0.08 e-/s), and an increase of the mean dark current per pixel, and loss of charge transfer efficiency (CTE). We have also experimented *raising* the operating temperature a few degrees, and also cutting our anneal time in half, from 12 down to 6 hours at +20 C . In July 2006, coincident with the switch to the redundant side 2 electronics, the operating temperature of the CCDs was lowered from -77 C to -81 C, which caused the dark current rate and the hot pixel contamination to be reduced by more than 50% (see Figure 1). The CTE tails are also fainter, and along with the lower hot pixel contamination, this reduced the image noise. Following the ACS failure in January 2007, the camera experienced a relatively warm 28-month period at -10 C. We summarize the more recent radiation damage history of the CCDs, with results following the on-orbit installation of the new controller electronics box (CEB-R) during Hubble Servicing Mission 4 in May 2009, and the resumption of science observations at the nominal operating temperature of -81 C. Since the ACS High Resolution Channel (HRC) was not recovered during SM4, we discuss only the two Wide Field Channel (WFC) CCDs. A report by Gilliland (2008, internal) summarized the characteristics of ACS at the time of the failure in January 2007, with extrapolations into the future as criterion for the success of the repair effort. We compare those predictions to initial post-SM4 results, and discuss what the complex thermal history of the ACS CCDs has revealed.

Mean dark current: At launch in 2002, operating at -77 C with monthly 12-hour anneals the mean dark current was 7.8 e-/hour and 7.5 e-/pix/hr (for WFC1 and WFC2 respectively), and increasing at a rate of 2.1 and 1.6 e-/pix/hr/yr. When ACS failed in January 2007 we were operating at -81 C with dark current 10.7 e-/pix/hr, and at this temperature we have seen a rate of 3.1 and 3.6 e-/pix/hr/yr. Our recent post-SM4 measurement of 22.0 e-/pix/hr/yr is higher than the prediction of 15 e-/pix/hr/yr, but is not problematic. See Figure 1. Experimenting with 6-hour anneals at -77 C yielded rates of 3.8 and 3.1 e-/pix/hour/year, respectively, and after reducing the operating temperature to -81 C in July 2006, these 6-hour anneals yielded rates of 3.0 and 3.2 e-/pix/hour/year. Although on a monthly basis the anneal does not seem to have any effect on the mean dark current, reducing the length of the anneal from 12 to 6 hours clearly has a detrimental effect on the growth of dark current, so we have reverted to the longer anneals. The 28-month "annealing" at -10 C did not have a significant effect: the dark current has grown as expected based on the trend from the few months of operation at -81C in 2006-2007.

Hot pixels: Operating at -77C from launch in 2002 until July 2006, we measured a permanent hot pixel growth rate of rate of ~71 pixels/chip/day with 12-hour monthly anneals. Experimenting with 6-hour anneals produced a rate of ~105 pixels/chip/day – 40% faster! A direct comparison with the growth rate at -77 C is no longer possible because a different pixel population is involved. Operating at -81 C after July 2006 this rate decreased to ~34 pixels/chip/day until in January 2007, the fraction of the WFC covered by permanent hot pixels (those not removed in monthly anneals) was 0.68%. The fraction anticipated for May 2009 (after the first anneal) is 1.1%, and the early count is very close to prediction at 1.15%. It is too early to reliably measure the post-SM4 rate of permanent hot pixel growth. In addition to hot pixels, other evolving dark structure is evident in the comparison of dark images spanning the on-orbit life of ACS (Figure 3). The dark features visible in 2002 have faded into the rising dark current and noise. Even when we last saw ACS in 2007, the cumulative effect of the CTE tails of hot pixels was evident as a brightening towards the chip gaps (farthest from the readout amplifiers). This effect, plus a new horizontal striping feature (caused by the new electronics, not radiation damage) is evident in the 2009 post-SM4 dark.

Charge transfer efficiency (CTE): The CTE as measured by Extended Pixel Edge Response (EPER) at a signal level of 1620e in January 2007 was 0.999949, with an extrapolation for May 2009 of 0.999921. The actual EPER results measured were slightly lower than this prediction, but still above the level considered problematic (see Figure 2). The rate of CTE degradation has remained predictable, with no effects due to temperature changes, although the shape and brightness of the CTE tails is now shorter and brighter .

Conclusions: The two WFC CCDs are from the same silicon wafer and they went through a similar processing, and they show a very similar CTE and hot pixel contamination -- but clearly the dark current grows at a different rate in the two chips. The first dark after the 28 month "anneal" had no temporary hot pixels, only the most damaging traps (those that do not anneal at +20 C), which have accumulated at a rate similar to the one measured at -81 C with monthly anneals, so the chip degradation has continued as we would expect if ACS had been operating during this down time.

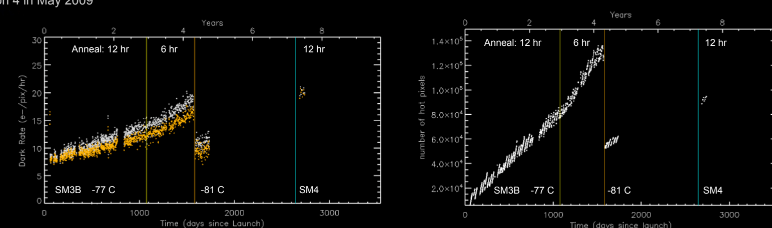


Figure 1: At left, th e mean dark current (e-/pix/hr/yr) over time, illustrating the effect of reducing the operating temperature from -77 C to -81 C, and the rate following the 28-month period between ACS failure and repair. At right, the same trends for the growth of hot pixels.

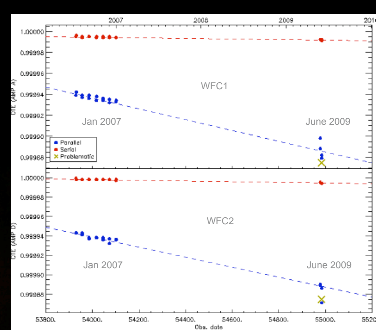


Figure 2: Parallel (blue) and serial (red) CTE as measured by the EPER test at one signal level (1620e), showing post-SM4 results to be near extrapolations from January 2007

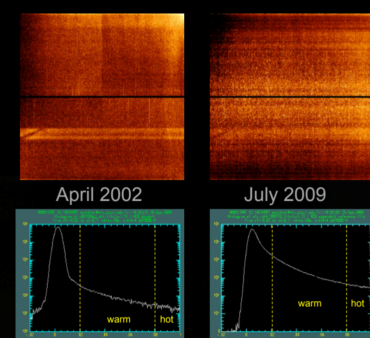
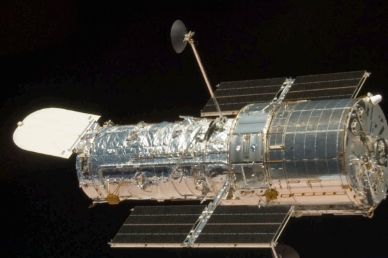


Figure 3: A comparison of dark images (above) obtained shortly after ACS installation in 2002, and following the repair in 2009. The brightening near the chip gap reflects the cumulative effects of hot pixel CTE tails far from the readout amps, and a horizontal striping feature from the new electronics (not a dark feature) is evident. Corresponding histograms (bottom) indicate the growing population of warm and hot pixels over this period.



For more, see the ACS website:
http://www.stsci.edu/hst/acs/