Changes to CCDs in Space

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In order to prepare for changes which might occur to the SNAP detectors after launch, I have gathered information on the performance of several existing space cameras.

- HST WFPC2
- HST ACS
- MOST

Let us compare their properties briefly:

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                  WFPC2                 ACS                  MOST
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Maker              Loral                 SITE              Marconi 47-
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Form               thick               thinned              thinned
                front-illum         back-illum           back-illum

Pixels             800x800             2048x4096            1024x1024
                15 microns          15 microns           13 microns

Full-well (e-)     90,000              85,000               100,000

Oper Temp (C)      -88                 -76                  -37

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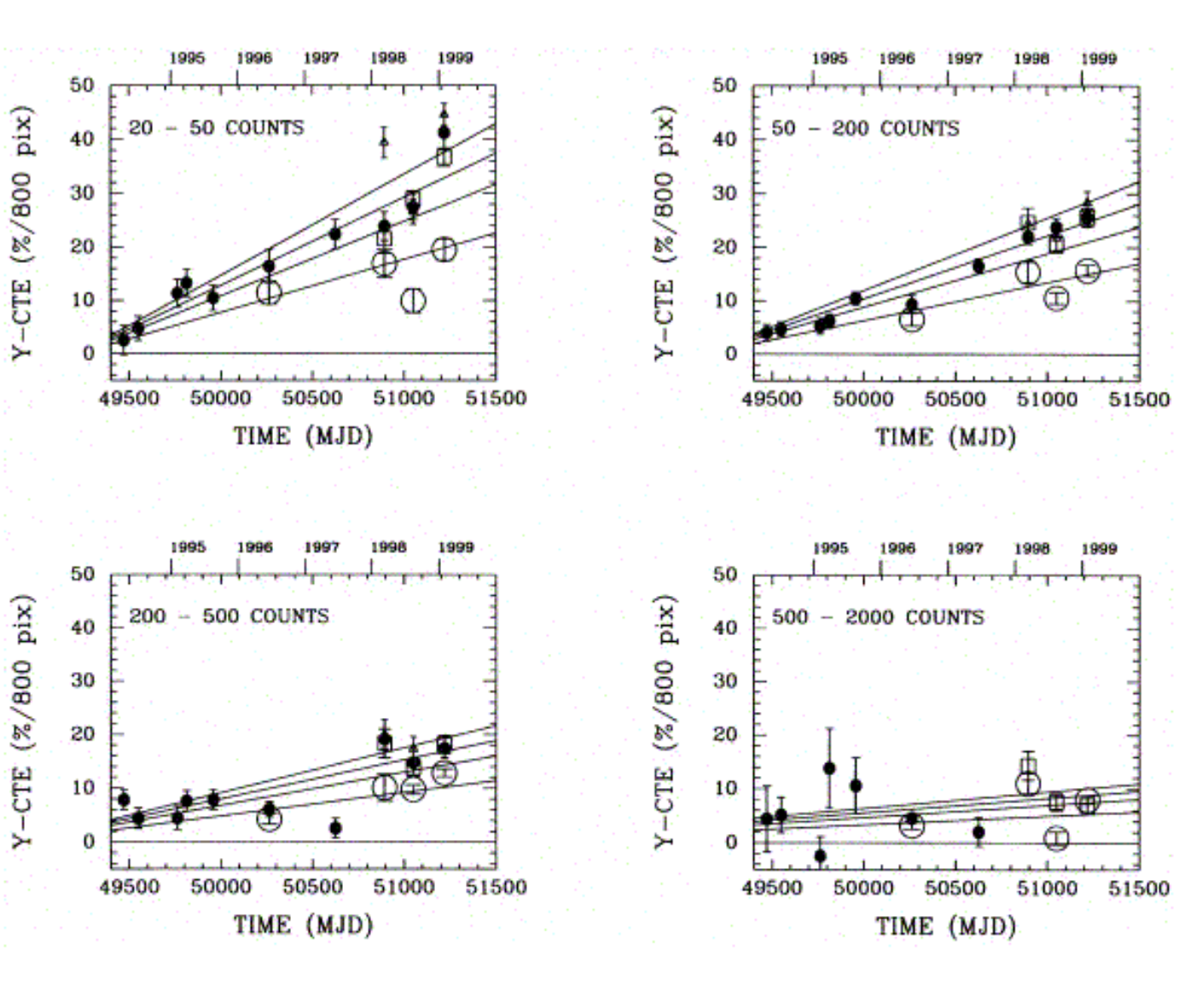
HST WFPC2

Over the years since it was launched, WFPC2 has suffered from a gradual loss in overall sensitivity. Much, perhaps all, of the loss is due to degradation of the Charge Transfer Efficiency (CTE). The effect is largest in the "Y-direction" on the chip.

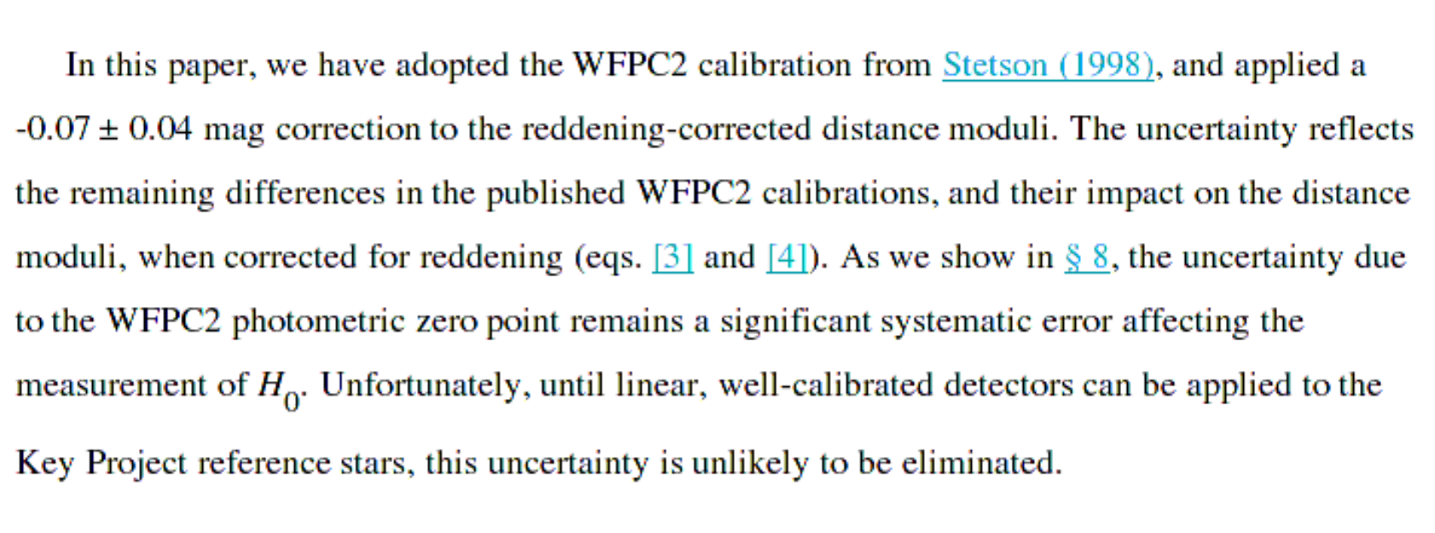


Correcting for this failure to move charge packets from pixel-to-pixel across the chip is complicated by the variation in CTE as a function of

- stellar brightness -- faint stars suffer greater losses
- background value -- objects surrounded by low signal suffer greater losses

Note that SNAP's primary mission of studying distant SNe Ia falls into a danger zone: we will be looking at very faint sources which are often immersed in a galaxy's light (though the galaxies will often have very low surface brightness, it's true), and comparing them to a group of faint comparison stars which presumably will be located in blank sky.

Changes in WFPC2's performance over its lifetime remain one of the largest sources of systematic error in the HST Key Project for measuring the Hubble Constant, as these two extracts from a recent paper (Freedman et al. 2001) show:



In this paper, we have adopted the WFPC2 calibration from Stetson (1998), and applied a -0.07 ± 0.04 mag correction to the reddening-corrected distance moduli. The uncertainty reflects the remaining differences in the published WFPC2 calibrations, and their impact on the distance moduli, when corrected for reddening (eqs. [3] and [4]). As we show in § 8, the uncertainty due to the WFPC2 photometric zero point remains a significant systematic error affecting the measurement of H_0. Unfortunately, until linear, well-calibrated detectors can be applied to the Key Project reference stars, this uncertainty is unlikely to be eliminated.

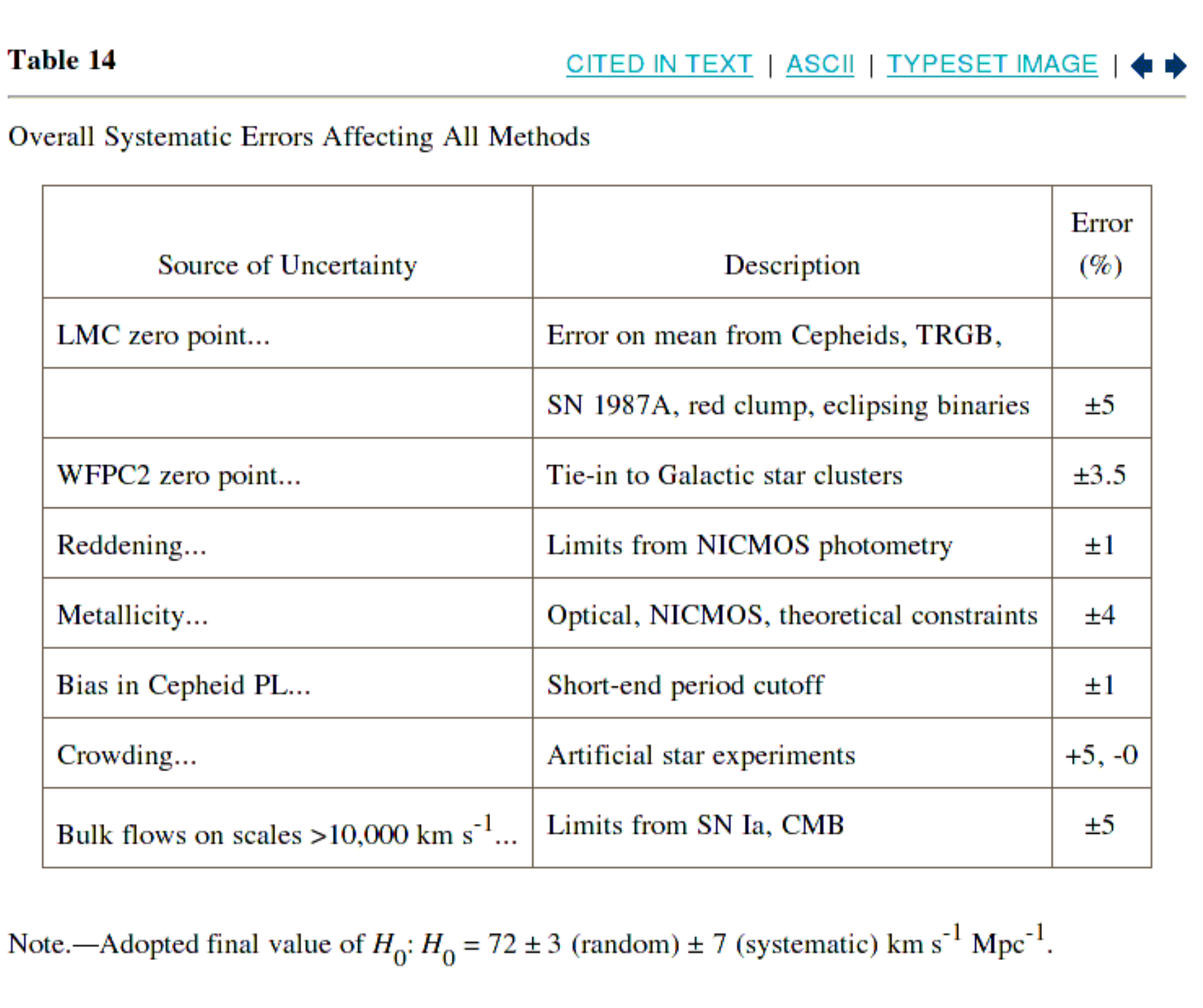


Table 14 CITED IN TEXT | ASCII | TYPESET IMAGE |

Overall Systematic Errors Affecting All Methods

Source of Uncertainty	Description	Error (%)
LMC zero point...	Error on mean from Cepheids, TRGB,	
	SN 1987A, red clump, eclipsing binaries	±5
WFPC2 zero point...	Tie-in to Galactic star clusters	±3.5
Reddening...	Limits from NICMOS photometry	±1
Metallicity...	Optical, NICMOS, theoretical constraints	±4
Bias in Cepheid PL...	Short-end period cutoff	±1
Crowding...	Artificial star experiments	+5, -0
Bulk flows on scales >10,000 km s^{-1}...	Limits from SN Ia, CMB	±5

Note.—Adopted final value of H_0: $H_0 = 72 \pm 3$ (random) ± 7 (systematic) km s^{-1} Mpc^{-1}.

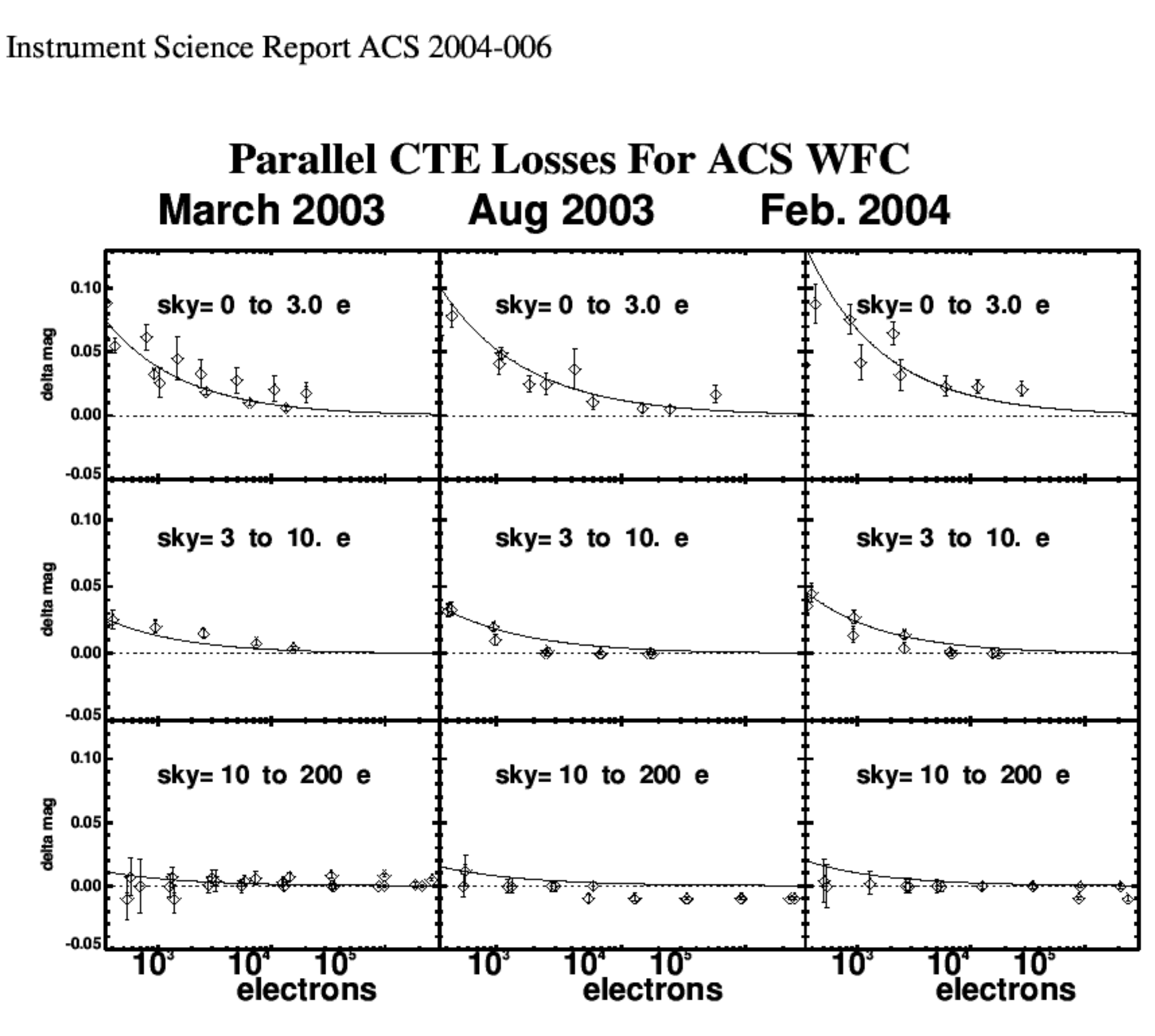
The phrase

> *... until linear, well-calibrated detectors can be applied to the Key Project reference stars, this uncertainty is unlikely to be eliminated.*

gives some support to the idea that a rocket-borne detector be used to calibrate stars properly.

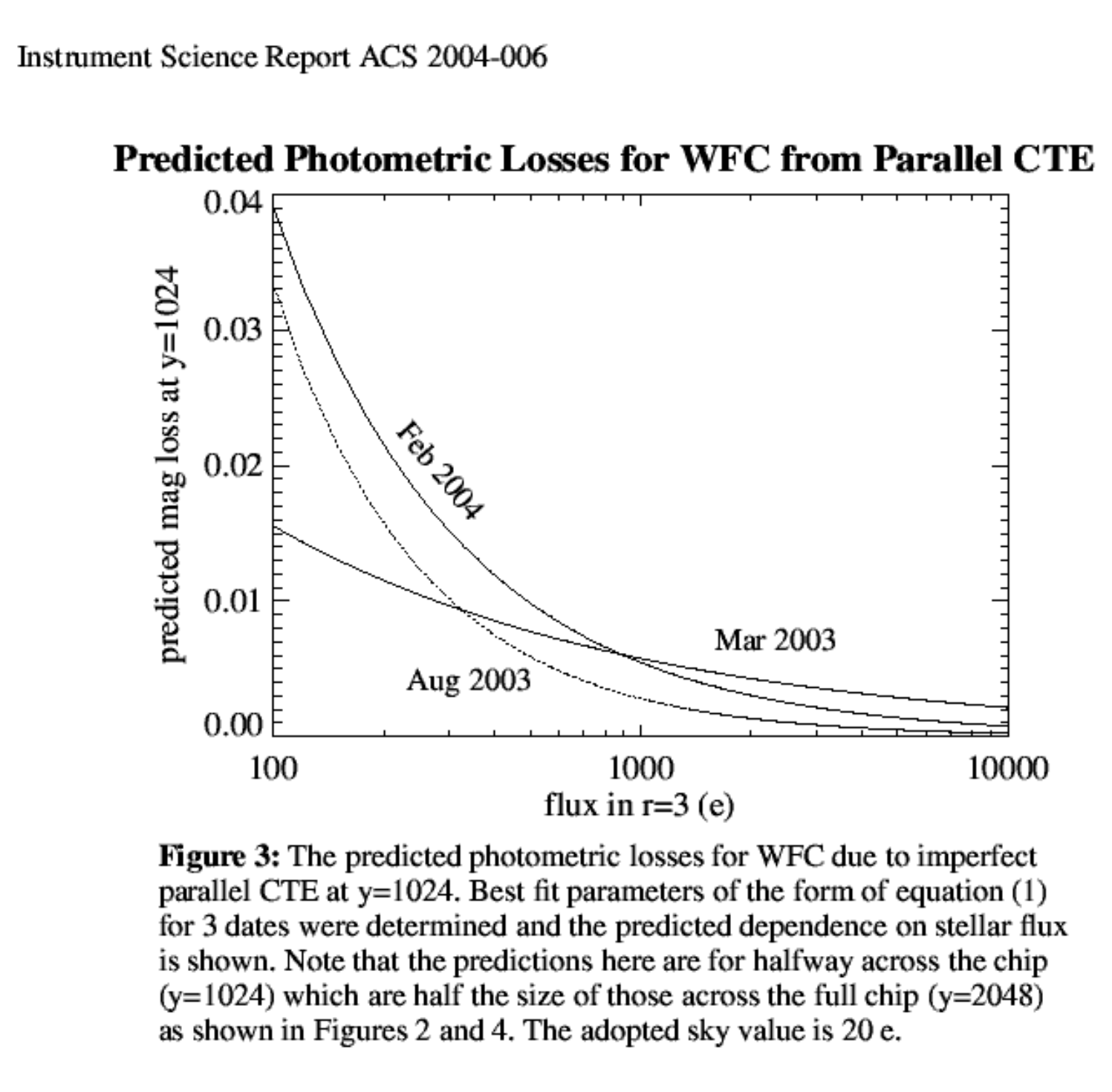
HST ACS

The Advanced Camera for Surveys on HST has been in service for only a few years, but it, too, shows a gradual loss in CTE. Like WFPC2, the effect is largest for faint stars, as one can see from actual measurements:



Instrument Science Report ACS 2004-006

... and in a model fitted to the data:



Instrument Science Report ACS 2004-006

Figure 3: The predicted photometric losses for WFC due to imperfect parallel CTE at y=1024. Best fit parameters of the form of equation (1) for 3 dates were determined and the predicted dependence on stellar flux is shown. Note that the predictions here are for halfway across the chip (y=1024) which are half the size of those across the full chip (y=2048) as shown in Figures 2 and 4. The adopted sky value is 20 e.

Note again that the size of the CTE loss in sensitivity varies depending on both the brightness of the target, and the brightness of the background.

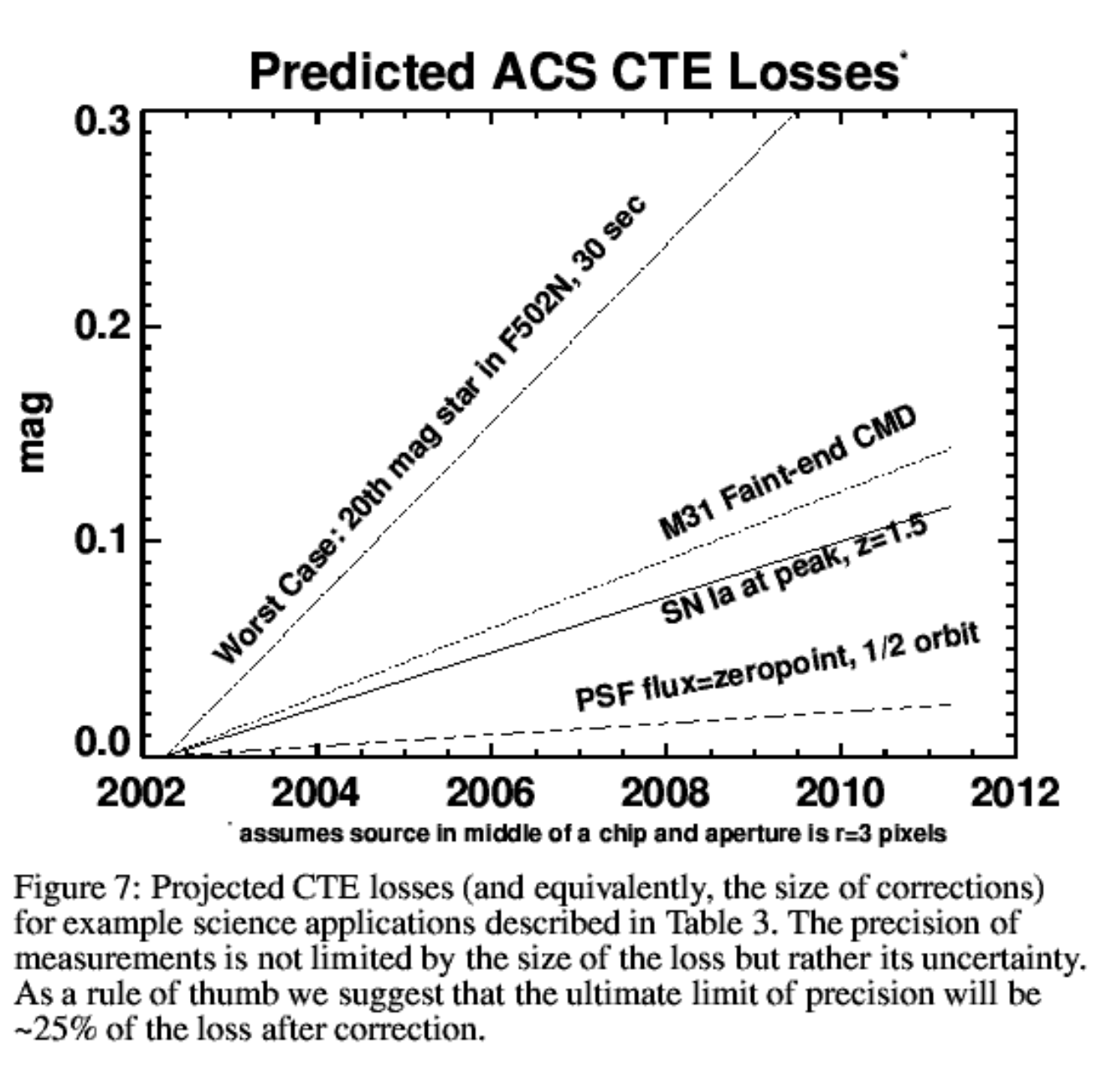
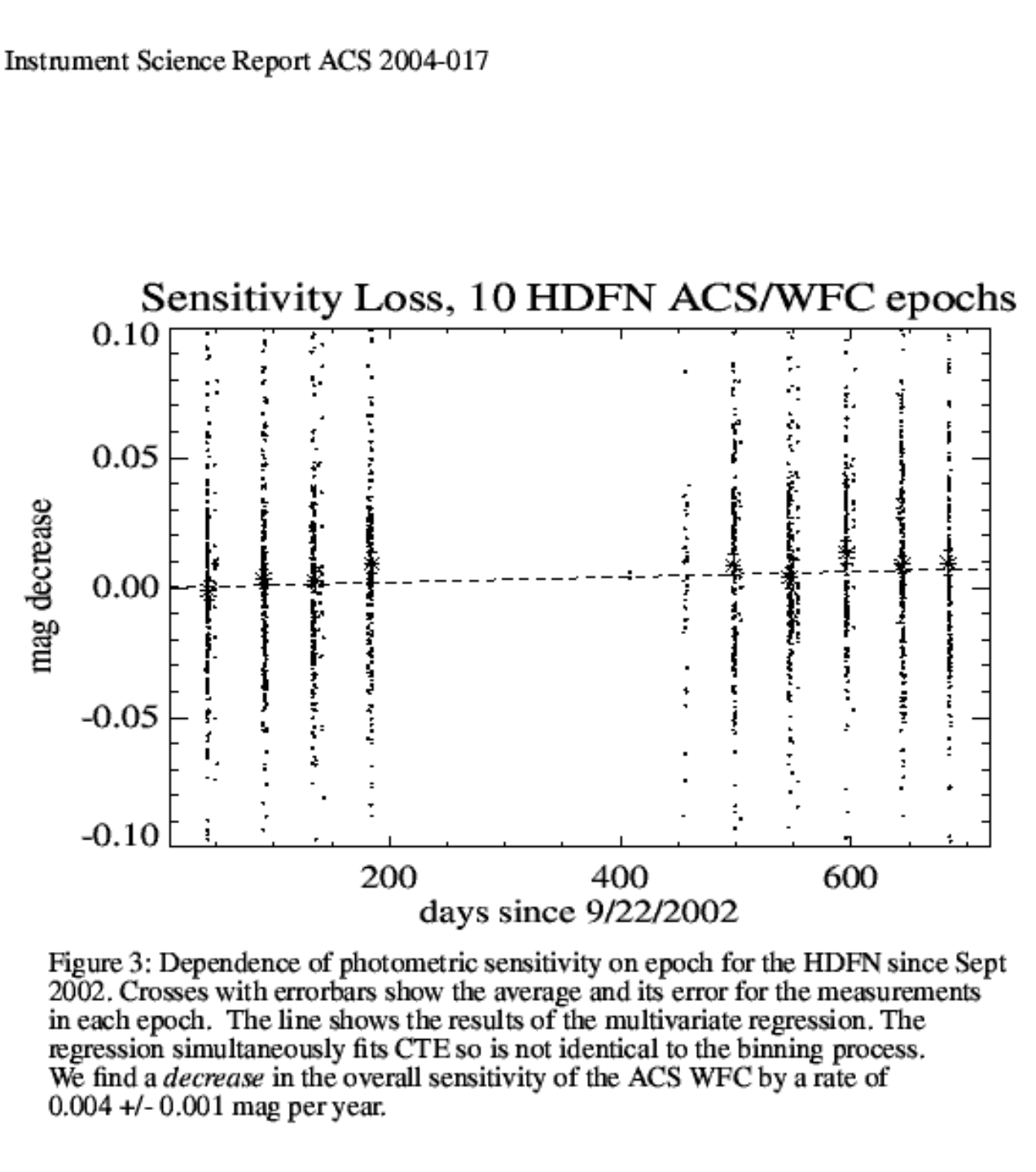


Figure 7: Projected CTE losses (and equivalently, the size of corrections) for example science applications described in Table 3. The precision of measurements is not limited by the size of the loss but rather its uncertainty. As a rule of thumb we suggest that the ultimate limit of precision will be ~25% of the loss after correction.

The overall sensitivity of ACS has been decreasing at a rate of about 0.004 mag per year. Ralph Bohlin tells me that this figure is **separate from** the CTE losses, and shared by ACS, STIS, and other HST instrument. It may be due to contaminants accumulating on the optics.



Instrument Science Report ACS 2004-017

Figure 3: Dependence of photometric sensitivity on epoch for the HDFN since Sept 2002. Crosses with errorbars show the average and its error for the measurements in each epoch. The line shows the results of the multivariate regression. The regression simultaneously fits CTE so is not identical to the binning process. We find a *decrease* in the overall sensitivity of the ACS WFC by a rate of 0.004 +/- 0.001 mag per year.

The most recent document I could find on this topic (Riess et al. 2004) states that it is not yet known if the loss in sensitivity depends on the filter.

MOST satellite

The Microvariability and Oscillations of STars (MOST) satellite contains a small telescope which stares at a few selected stars for weeks on end, looking for pulsations which reveal the internal structure of the atmosphere. It has an unusual camera: two CCDs, one of which is devoted to tracking, the other to science. The science CCD is partially covered by a microlens array, which images the pupil of the telescope onto the focal plane.

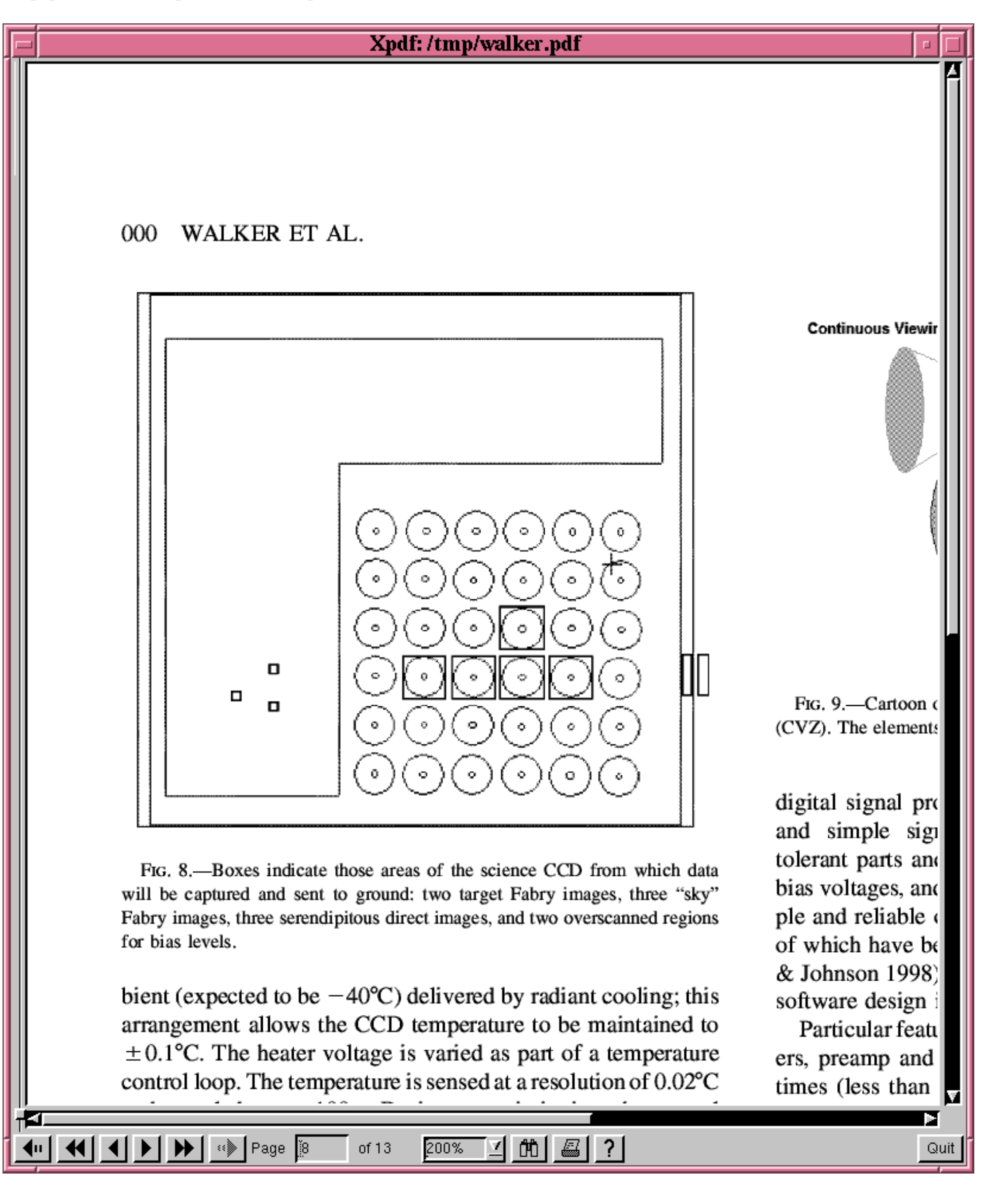


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Fig. 8.—Boxes indicate those areas of the science CCD from which data will be captured and sent to ground: two target Fabry images, three "sky" Fabry images, three serendipitous direct images, and two overscanned regions for bias levels.

bient (expected to be −40°C) delivered by radiant cooling; this arrangement allows the CCD temperature to be maintained to ±0.1°C. The heater voltage is varied as part of a temperature control loop. The temperature is sensed at a resolution of 0.02°C

Fig. 9.—Cartoon c
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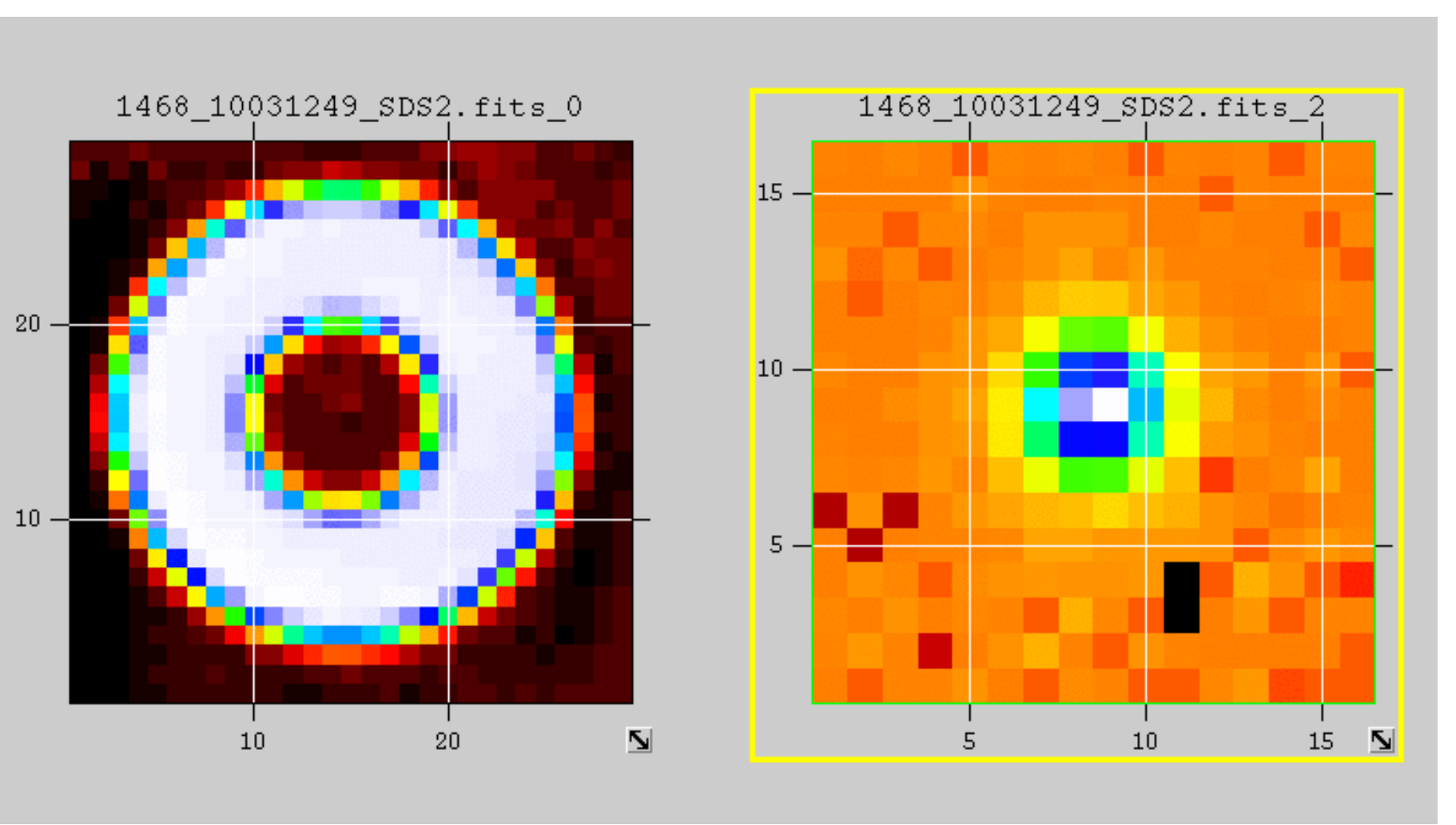
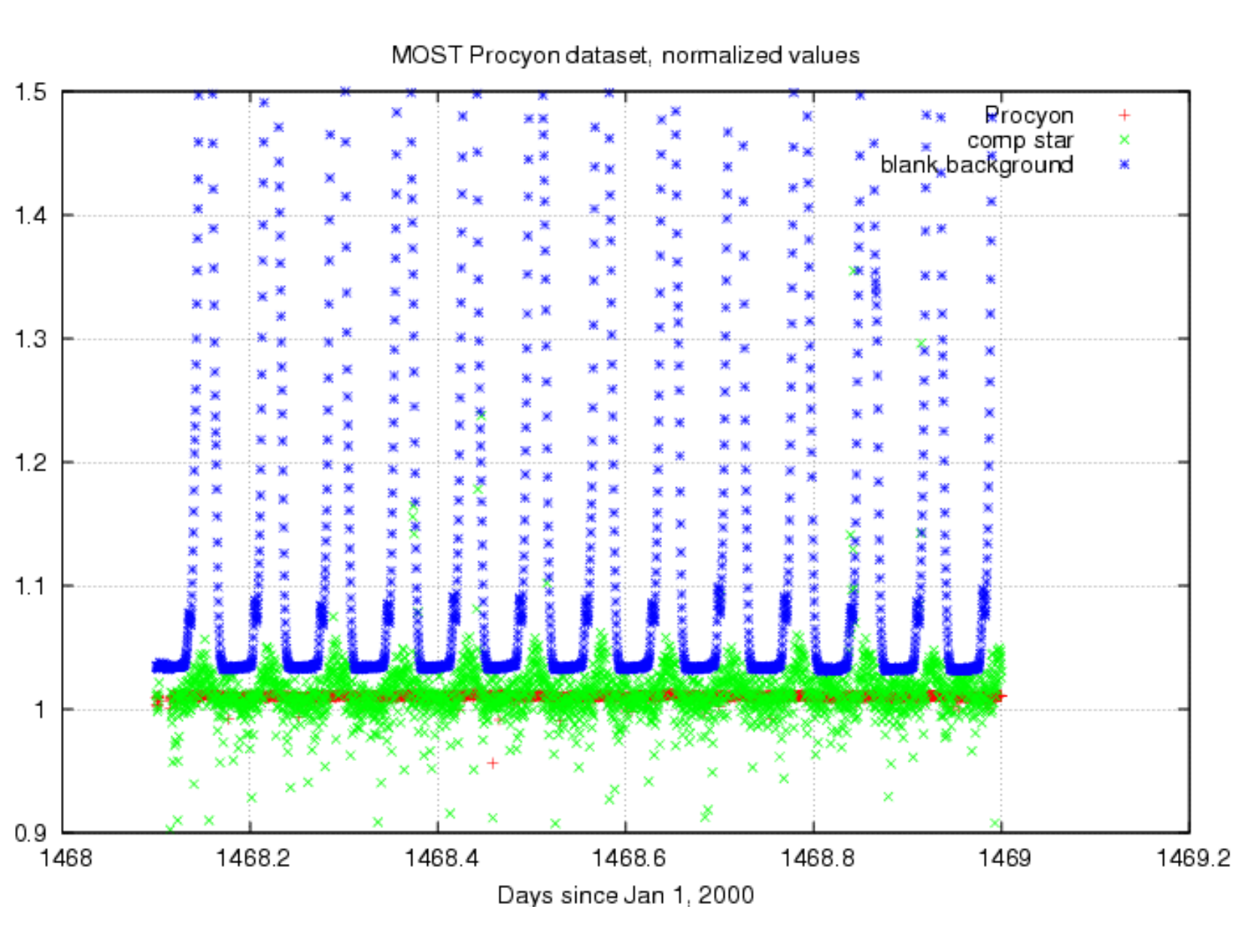
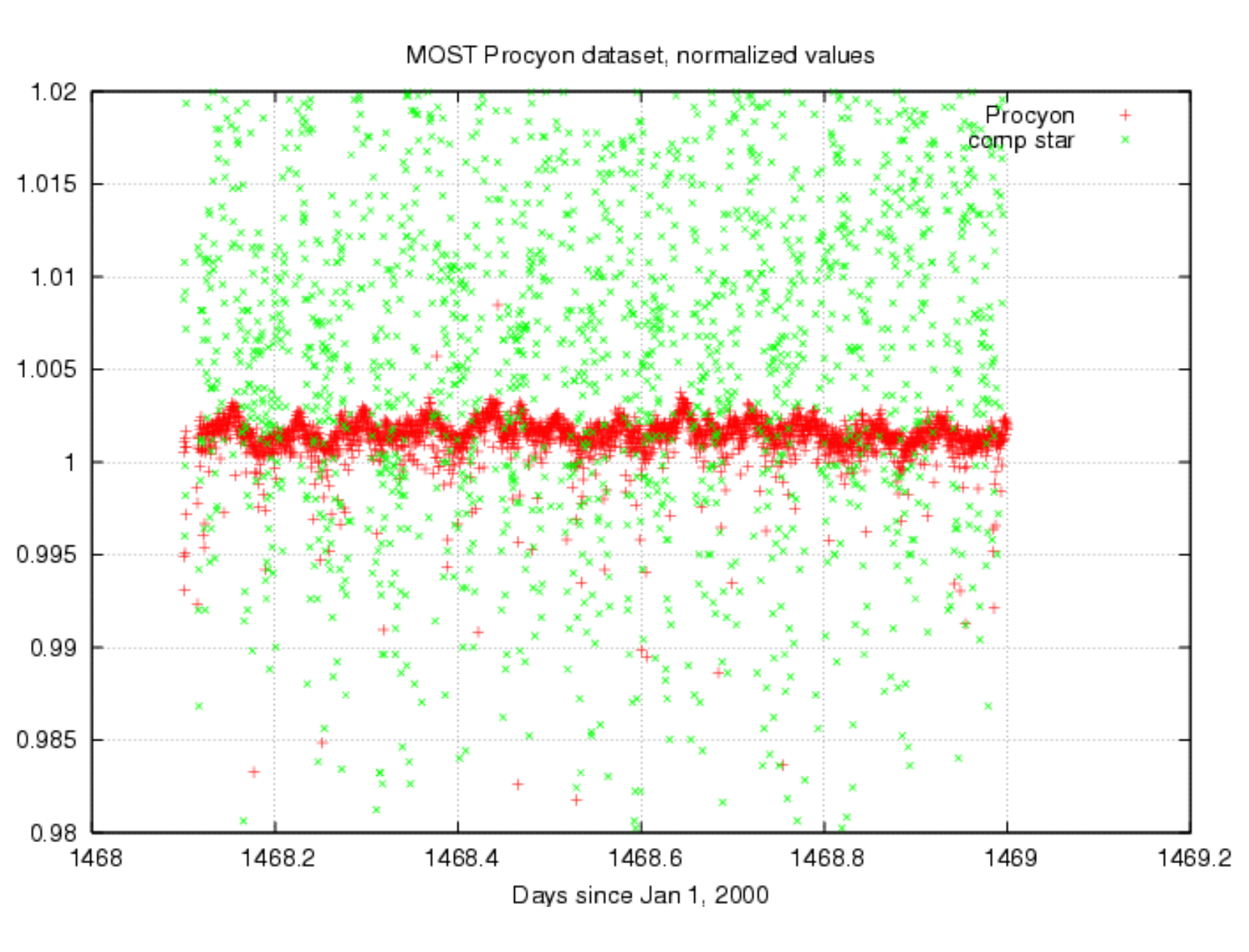
Typically, a single primary science target falls onto one of the microlenses, and cutouts around several fainter stars from the "ordinary" portions of the CCD are also monitored.



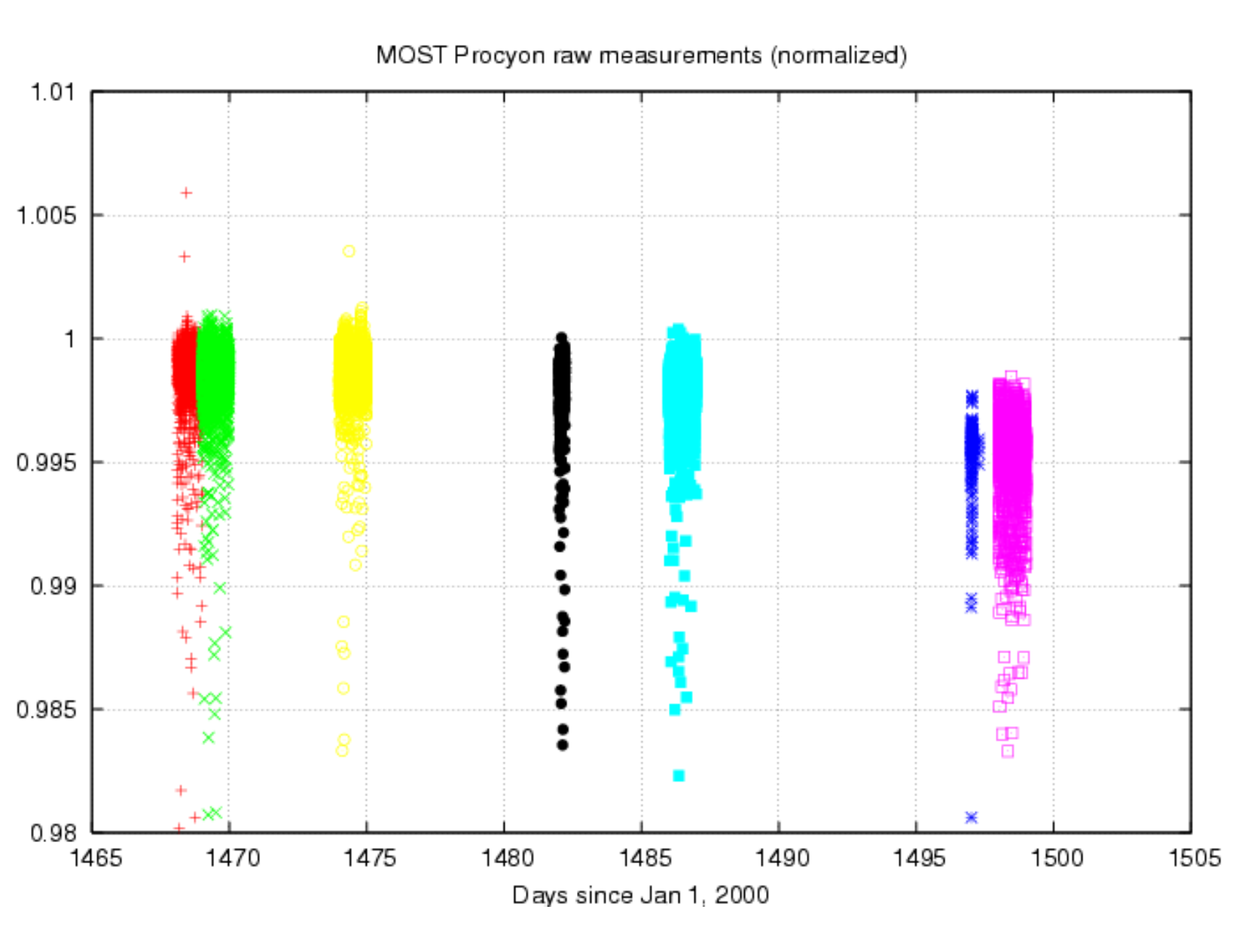
The satellite was launched on June 30, 2003. One of its first targets, and the only one for which data has been released to the public, was the bright star Procyon. It was observed continuously from Jan 8, 2004 to Feb 9, 2004. There were problems with scattered light from the Moon falling into the field of view during certain portions of the orbit, which increased the background levels signficantly:



I grabbed raw FITS images from the MOST Science Archive -- raw images are all that are available. The effect of the varying background is large on faint secondary stars, but very small for the bright primary star Procyon (which provides about 6.7 million photoelectrons per exposure).

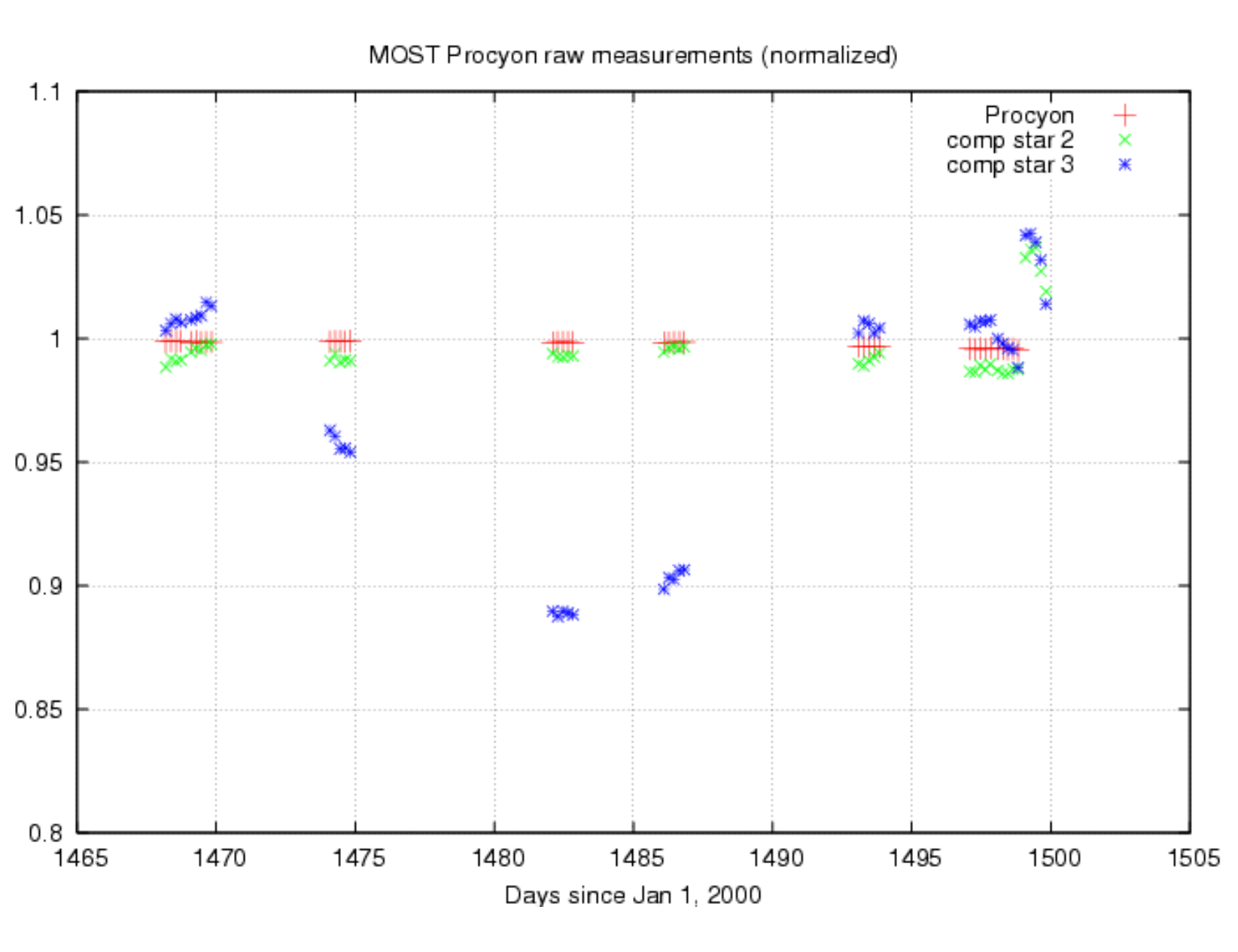


We are interested in the long-term changes (if any) in the sensitivity of the camera. A first glance at the measurements of Procyon over the month-long observing run suggests that there may have been a small loss of sensitivity. Shown below are data from only a few days out of the month; I have not had time to reduce the entire 30-day dataset.

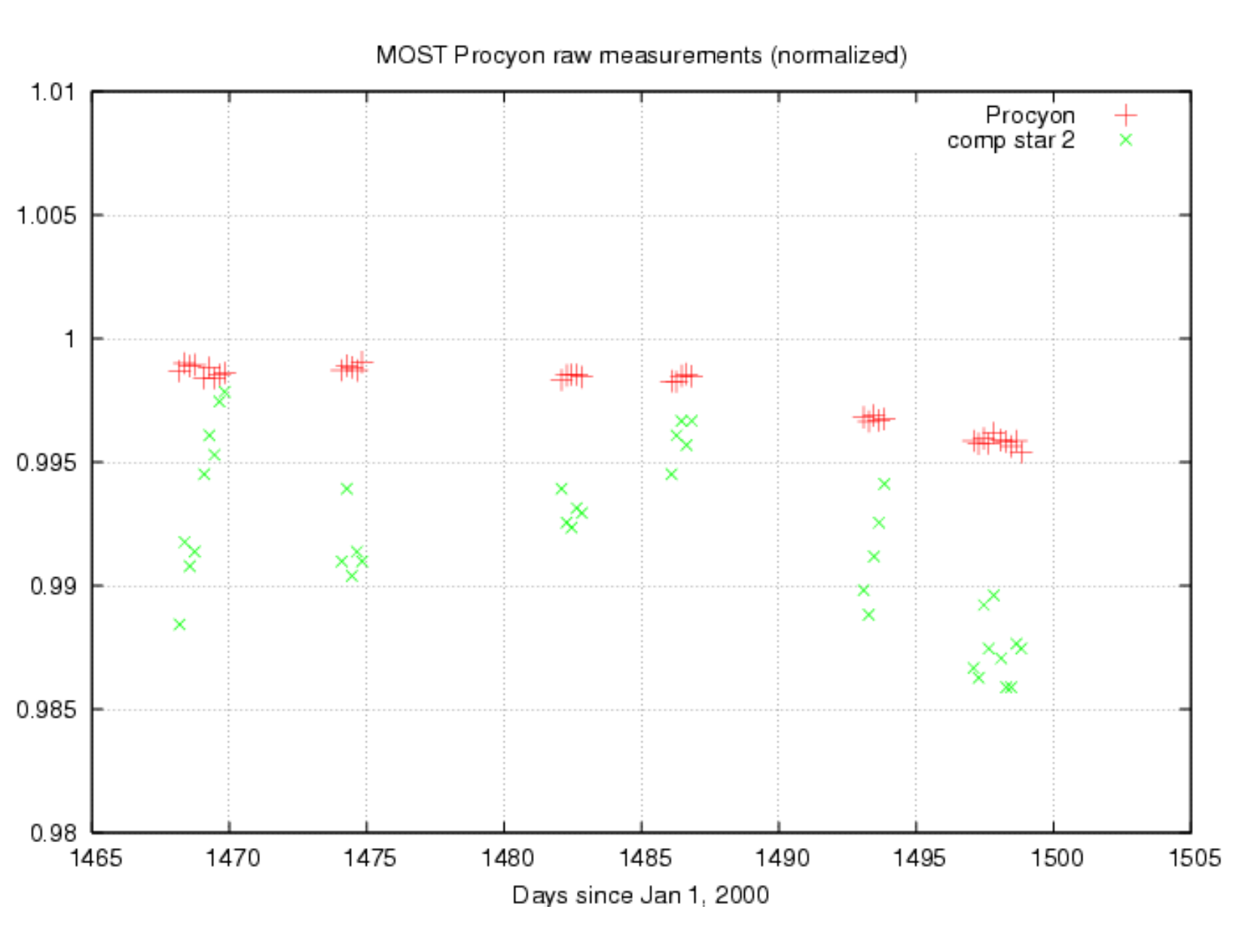


Was this due to the instrument, or due to a change in the intrinsic luminosity of Procyon? There were three secondary stars measured along with Procyon, from the "normal" region of the CCD not covered by microlenses. I looked at the two brightest of these secondaries. In order to decrease the random scatter, rather than show the measurement in each 30-second exposure, I plot below the median of all measurements over 530 exposures (spanning about 3 orbits).

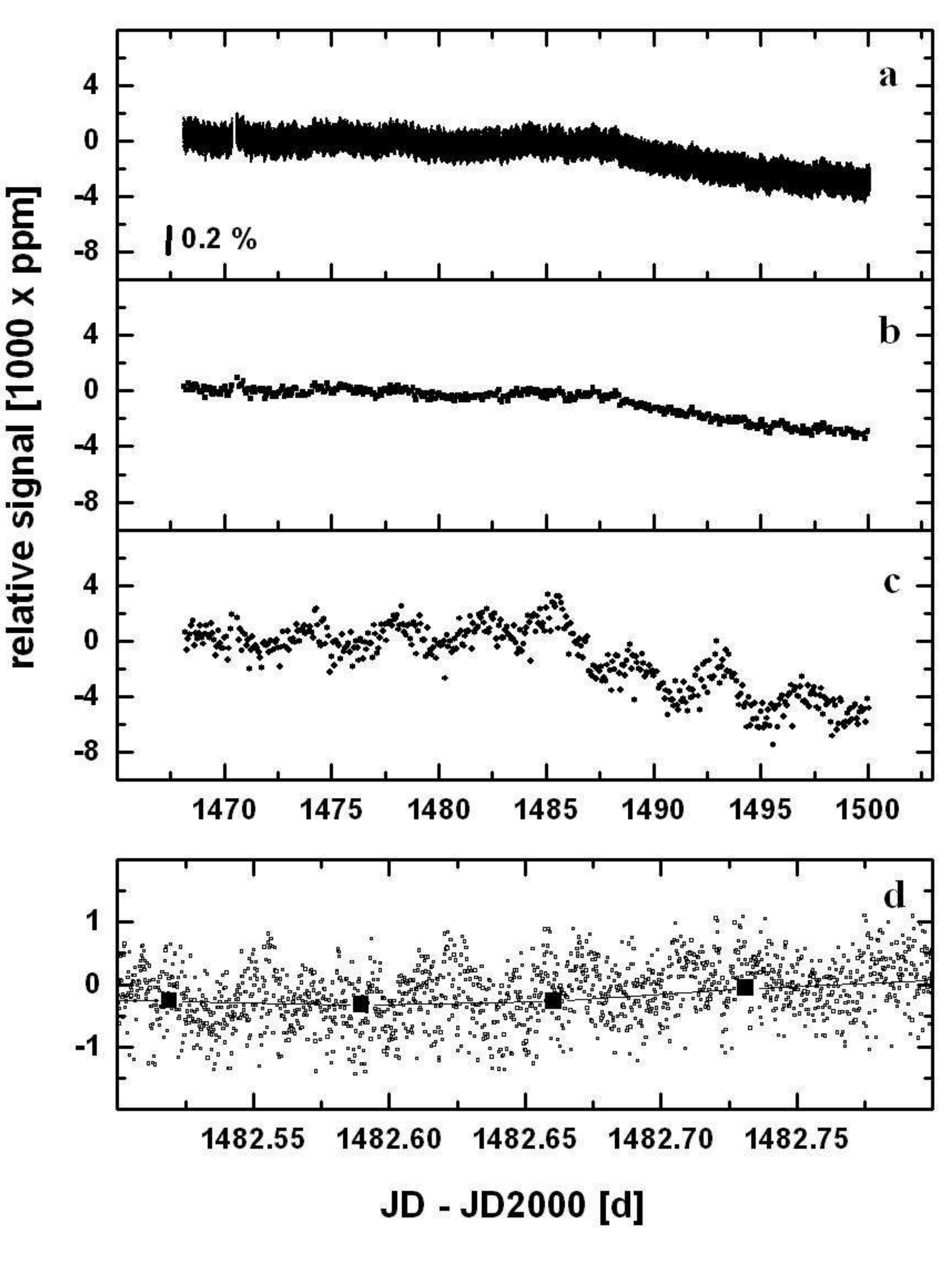
One of the secondary stars is obviously a variable:



But the other star shows a long-term variation in brightness which mirrors that of Procyon.



The values I calculated match reasonably well to those in a figure from the MOST team's own paper on their observations of Procyon. Compare my figure above to the top two panels below.



Matthews et al, Figure 2

I deduce an overall decrease in sensitivity of a factor of about 0.29 percent over a 30-day period. If one were to project this linearly to a full year, it would amount to a decrease of about 3.5 percent.

Conclusion

Two of these three of these CCD cameras have suffered measureable losses in sensitivity over timescales of years, and there are indications that the third will as well.

- **HST:** CTE losses in the worst case (faint stars on low backgrounds) grew from 3% after launch in 1994 to 40% in 1999
- **ACS:** CTE losses which range from 0.3% per year to about 2% per year, depending on the source and background; plus a loss of overall sensitivity of 0.004 mag per year, or approx 0.4% per year;
- **MOST:** a projected loss of approx 3% in a year

Bruce Woodgate reminded me at the end of my presentation that the SNAP project is developing p-channel CCD devices, which will be much less sensitive to CTE losses than the CCDs in WFPC2 and ACS. Good!

References

WFPC2
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MOST
- Matthews et al., Nature 430, 51 (2004) No stellar p-mode oscillations in space-based photometry of Procyon
- Walker et al., PASP 115, 1023 (2003) The MOST Asteroseismology Mission: Ultraprecise Photometry from Space