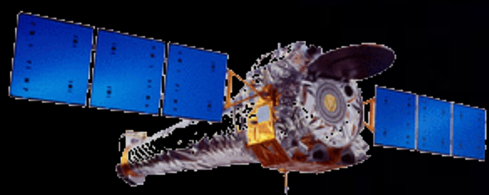
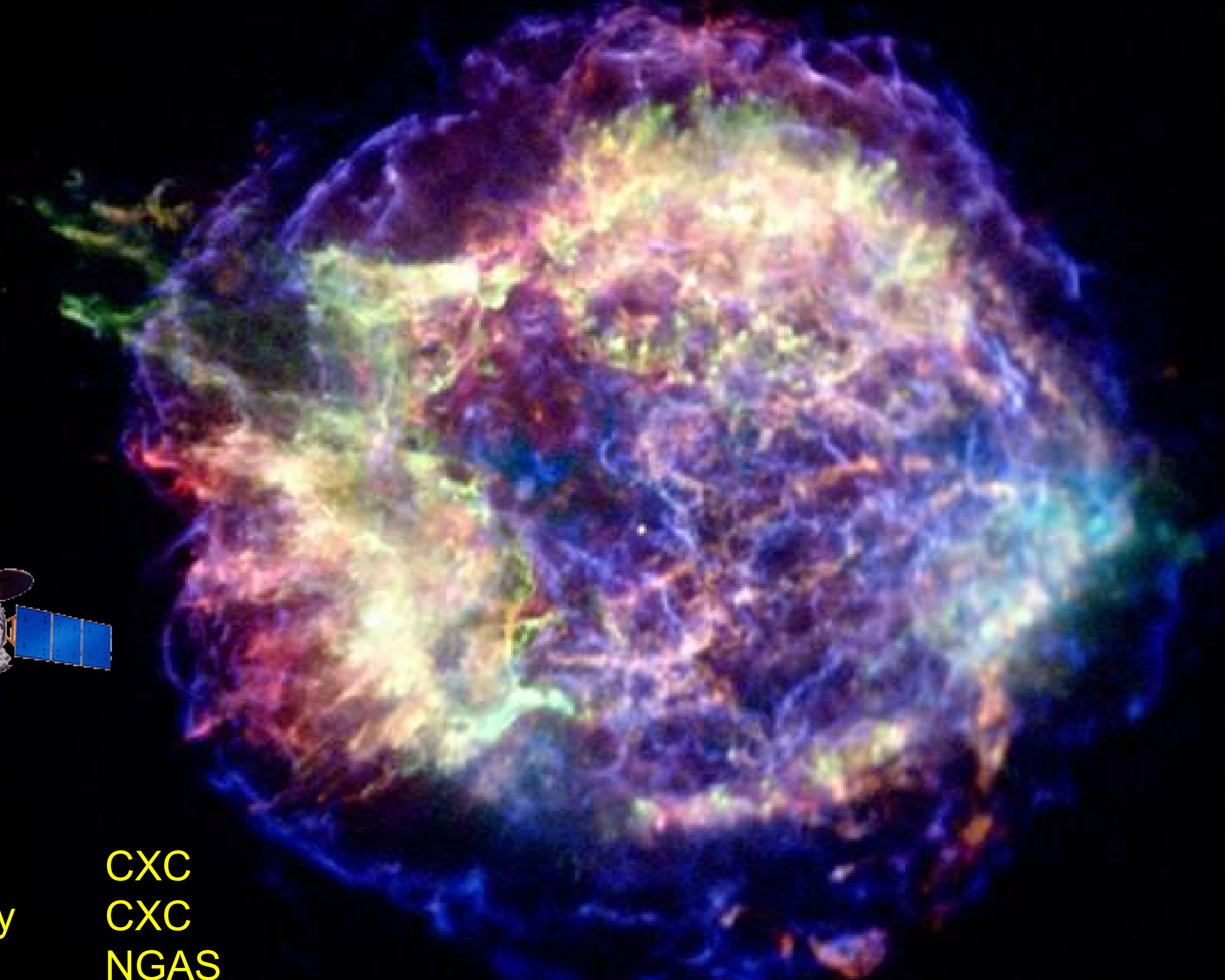
State of the ACA 2013





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Jean Connelly CXC
Eric Martin NGAS
Star Selection and Acquisition Working Group

Nov. 21, 2013

Mission Statement and Agenda

Mission Statement

The State of the ACA is a forum for presenting to the community the status of the Aspect Camera Assembly and related or dependent subsystems, including on-board PCAD attitude control and ground aspect reconstruction. The goal is to define the actions necessary to address current and future issues and thereby maintain the high-quality of the Chandra science mission.

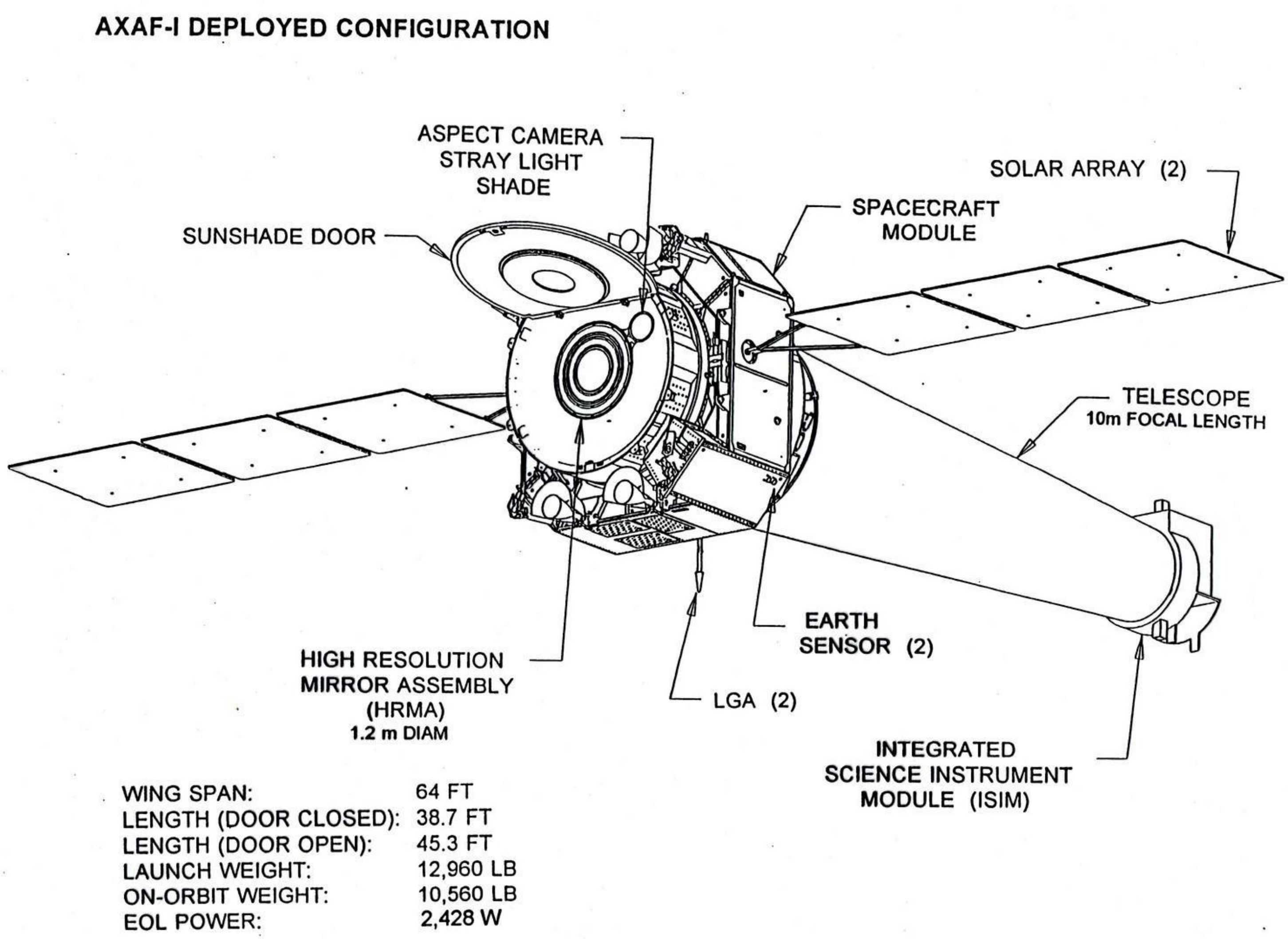
Top-level Agenda

- ACA overview - *Hardware, operations and requirements*
- ACA monitoring and trending - *What we know and how we know it*
- ACA operational issues - *Current, near and long term*
- ACA B-side - *Potential checkout and use*
- Recovery from complete ACA failure - *What if the worst happens?*
- Action list for FOT and SOT related to the ACA

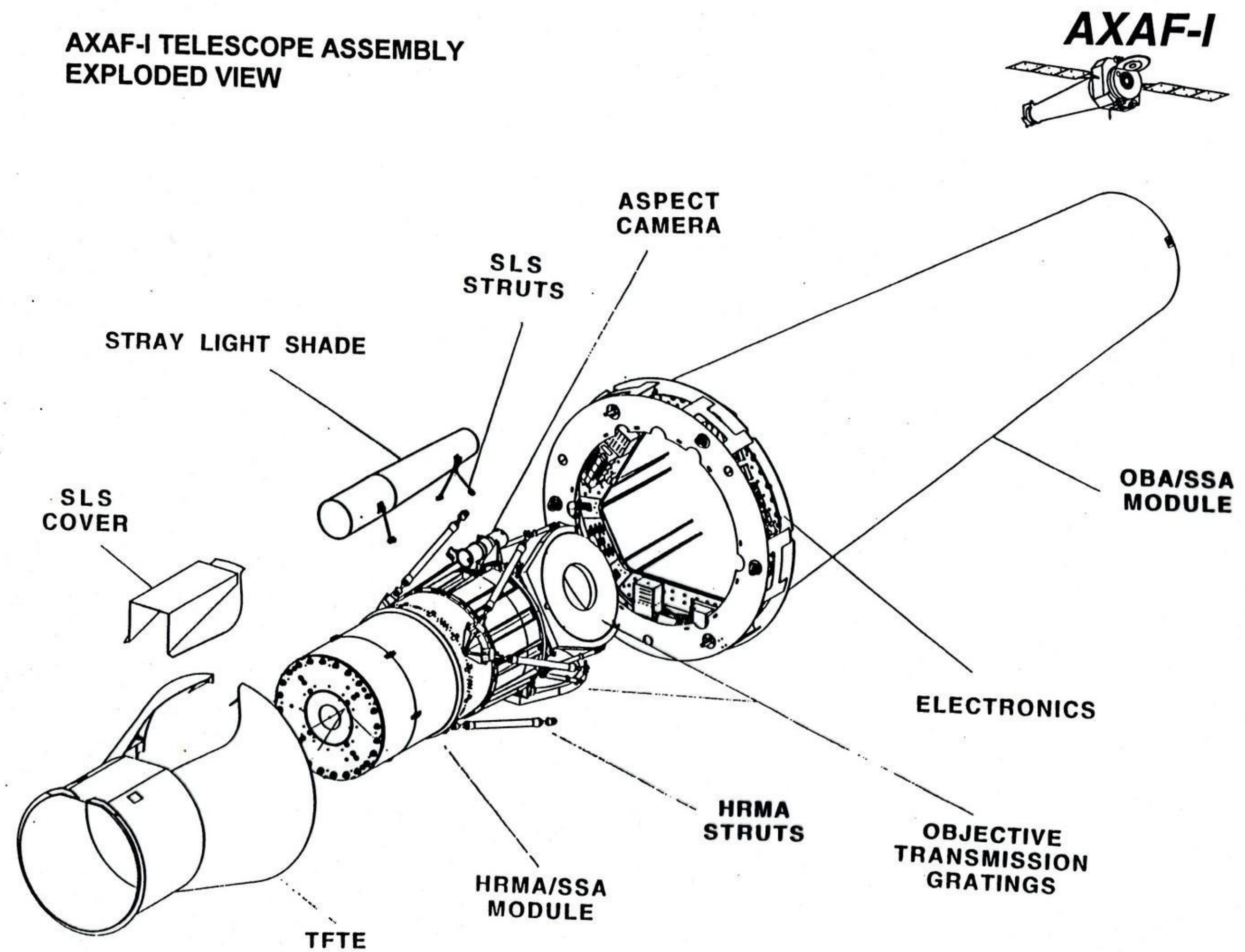
ACA overview

- Aspect Camera Assembly (ACA) is a 4.5” star tracker built by Ball
- Price: ~ $20M
- ACA, gyros, and reaction wheels are basis for PCAD
  - Star positions to OBC for realtime spacecraft control
  - Image data for post-facto aspect reconstruction

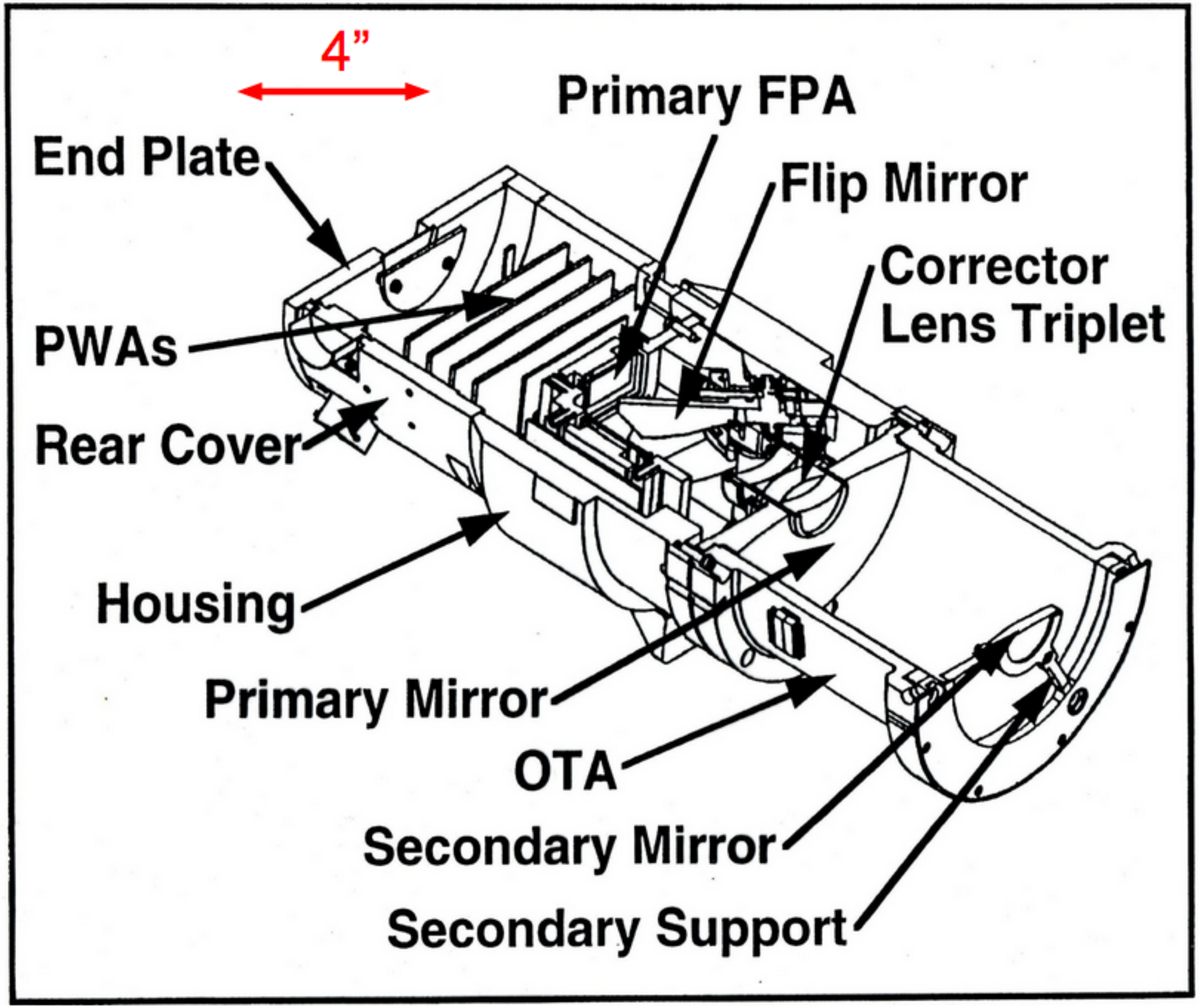
Chandra deployed configuration



ACA in Chandra exploded view



ACA close-up


4”
Primary FPA
End Plate
Flip Mirror
Corrector
Lens Triplet
PWAs
Rear Cover
Housing
Primary Mirror
OTA
Secondary Mirror
Secondary Support

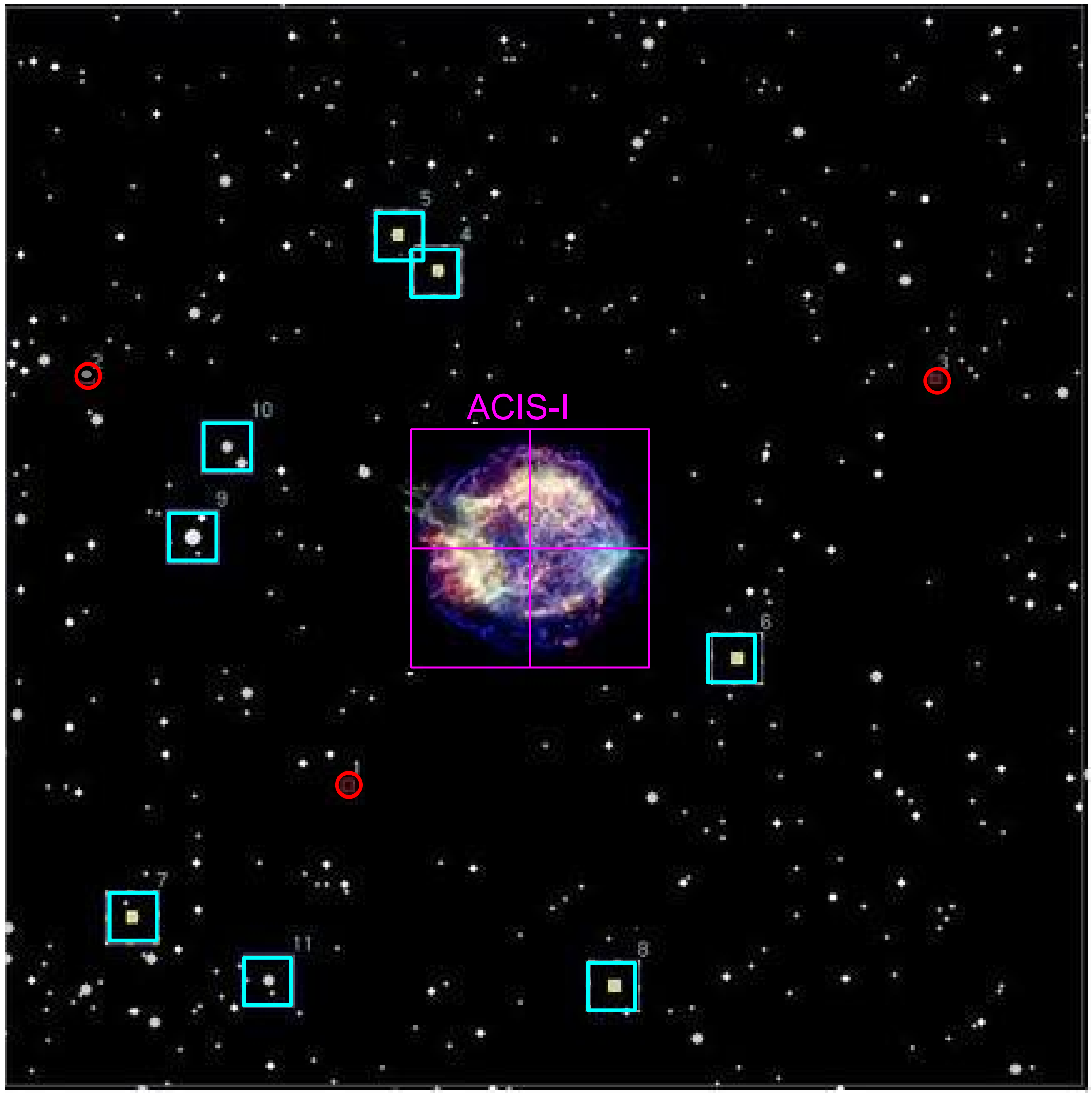
ACA Configuration

System Parameters

- ACA Components
  - Stray Light Shade (SLS)
  - Aspect Camera (AC)
  - Processor Electronics Assembly (PEA) x2
- Dimensions and Mass
  - SLS: 0.41m diameter, 2.34m length, 9kg
  - AC: 0.18m diameter, 0.42m length, 11.3kg
  - PEA: 9kg each
- Power
  - 20W average
- Processor
  - 1750A compatible
  - FORTH source code (in DM06)
  - 32KB PROM, 64KB RAM
  - 2 x 1280B EEPROM in AC
- Optics
  - Cassegrain telescope, with refractor triplet
  - Focal length: 991mm
  - 0.11m aperture, f/9
  - No redundancy in optics
  - 2 focal plane detectors, single-strung to PEAs
  - Flip mirror mechanism for using redundant focal plane
- Focal Plane
  - TK1024 CCD
  - 1024x1024 pixels
  - pixel size: 24μm x 24μm
  - nominal plate scale: 5"/pixel
  - active FP cooled to -10C, using Peltier thermo-electric cooler
  - 4 electrical quadrants, with individual pre-amp readouts

Variable now

As the ACA sees the sky



1.4 degrees

ACA Image Telemetry

NORTHROP GRUMMAN

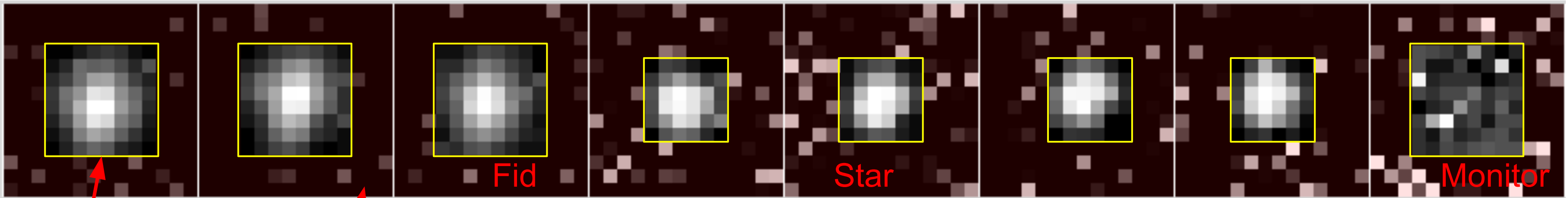


Image readout

Dark current background

Time	176267425.35
Date	2003:215:03:09:22.166

slot	0	1	2	3	4	5	6	7
QUALITY	0	0	0	0	0	0	0	0
MJF	47656	47656	47656	47656	47656	47656	47656	47656
MNF	32	32	32	24	24	24	24	24
INTEG	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70
GLBSTAT	0	0	0	0	0	0	0	0
COMMCNT	0	0	0	0	0	0	0	0
COMMPROG	0	0	0	0	0	0	0	0
IMGFID1	1	1	1	0	0	0	0	0
IMGNUM1	0	1	2	3	4	5	6	7
IMGFUNC1	1	1	1	1	1	1	1	2
IMGSTAT	0	0	0	0	0	0	0	0
IMGROW0	-186	367	-77	-428	33	-377	138	2
IMGCOL0	-347	33	163	455	-162	-150	-257	12
IMGSCALE	238	184	214	32	32	32	32	32
BGDAVG	19	20	22	0	0	0	0	1
IMGFID2	1	1	1	0	0	0	0	0
IMGNUM2	0	1	2	3	4	5	6	7
IMGFUNC2	1	1	1	1	1	1	1	2
BGDRMS	5	8	12	2	2	1	2	2
TEMPCCD	-15.2	-15.2	-15.2	-14.8	-14.8	-14.8	-14.8	-14.8
TEMPHOUS	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6
TEMPPRIM	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6
TEMPSEC	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2
BGDSTAT	253	255	255	63	223	223	245	255

Time step
- 1.025
- 2.05
- 4.1
- 8.2
- 16.4
- 32.8
- 131.2
- 1049.6

Resume

Next

- Forward
- Reverse

Delay

0

0
500
1000
1500
2000

Quit

ACA normal operations

- ACA operational parameters
  - 1.4 x 1.4 degree field of view
  - 1.696 second integration time
  - 10.6 mag limiting magnitude (nominal in 2013)
  - Track and centroid up to 8 images (5 stars and 3 fid lights)
- ACA normal operations consists of the sequence:
  - Maneuver to new attitude in Normal Maneuver Mode
  - Acquire acquisition stars to establish fine attitude
  - Perform one-shot attitude update
  - Acquire guide stars and fid lights
  - Maintain attitude and dither (8-20 arcsec) in Normal Point Mode while tracking guide stars
- To support this:
  - Ground prepares catalogs of acquisition stars (well-separated from nearby stars) and guide stars (optimized for on-board control and ground aspect).
  - Ground sends maneuver commands and *star catalogs* to the OBC via command loads
  - OBC sends commands to ACA at the right time

On-board and Post-facto Aspect

On-board and Post-facto

ACA tracks stars to establish spacecraft *attitude*

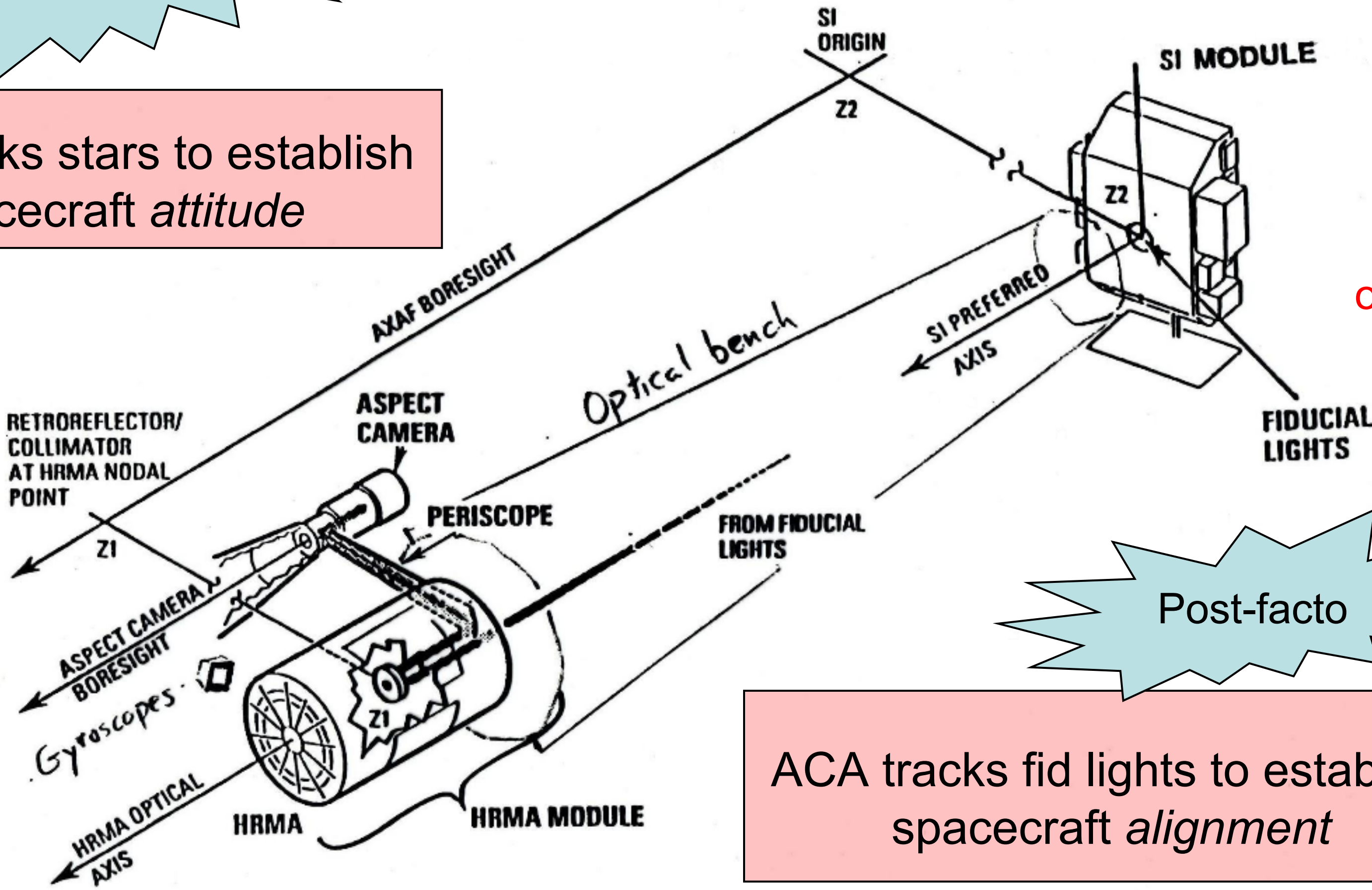


Figure 4.2-1. Aspect Determination Hardware and Alignment Axes

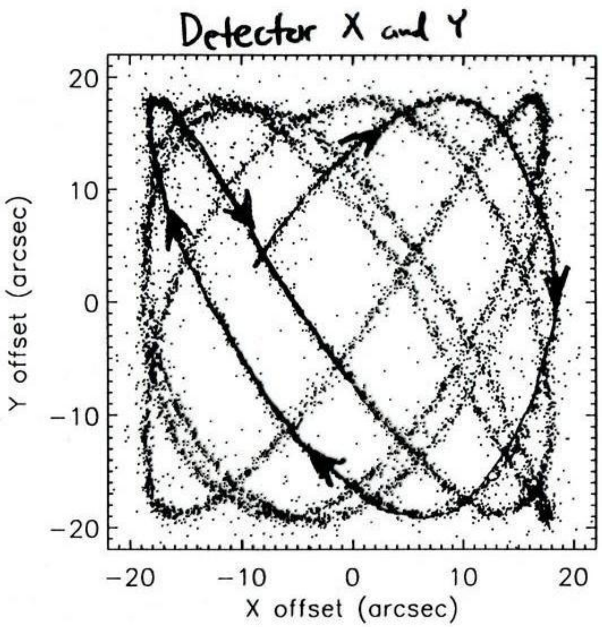
Red LEDs on focal plane

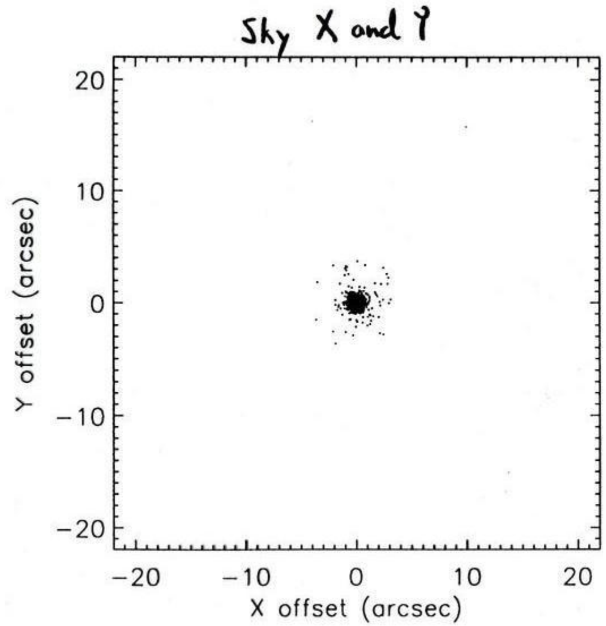
Post-facto

ACA tracks fid lights to establish spacecraft *alignment*

Post-facto aspect

- Aspect solution is a time-history of the exact pointing attitude and spacecraft alignment.
- Allows conversion from detector pixel coordinate to sky position (RA, Dec) for each detected photon.
- Also required for creation of observation exposure maps.





Requirements and capabilities

Key requirements from Level II Project Requirements Document:

Description	**Requirement**	**Actual**
Celestial location Error circle in X-ray astrometry	1.0” (RMS radius)	0.6”
Image reconstruction Effective blurring of X-ray PSF	0.5” (RMS diam)	0.3”
Absolute celestial pointing X-ray source position on detector	30.0” (99%, radial)	11.8”
PCAD 10 sec pointing stability Attitude control error (jitter)	0.1” (95% of std. dev. samples)	0.057” (pitch) 0.053” (yaw)

ACA monitoring and trending overview

The cornerstone of ACA operations is monitoring and trending

- Broad range of analysis done by four teams[1] with complementary emphasis - *FOT PCAD*, *SOT MTA*, *CXCDS ops,* and *SOT Aspect*.
- FOT PCAD is the front line for ACA and gyro health issues and emphasizes on-board control.
- SOT MTA monitors immediate ACA health and configuration issues and does direct telemetry trending.
- CXCDS ops performs V&V (automated + visual as needed) on each observation to ensure the aspect meets requirements.
- SOT Aspect is focused on longer time scales and complex derived quantities that relate to post-facto aspect and ACA health.

[1]**The teams**: *FOT PCAD*: Eric Martin, Amanda Arvai and Ken Gage
SOT MTA: Scott Wolk and Brad Spitzbart
CXCDS ops: Joy Nichols and the ops team (Beth, Craig, Doug, Jen)
SOT Aspect: Tom Aldcroft and Jean Connelly

ACA monitoring and trending status

ACA subsystem	H/W	Process	Comment
PCAD SSE daily review	●	●	Two eyes every weekday
PCAD 10 sec stability trending	●	●	Quarterly
ACA thermal (CCD and housing)	●	●	Auto-monitoring, monthly review
Dark current: warm pixels	●	●	Three times per year
Dark current: flickering pixels	●	●	Last analysis 2008 (no further data avail)
Acquisition star success	●	●	Nightly update, monthly review
Guide star tracking success	●	●	On-board and post-facto
Image reconstruction per obsid	●	●	CXCDS ops V&V
Image reconstruction trending	●	●	Monthly review
ACA response	●	●	2013 analysis (not automated)
Celestial location	●	●	Monthly (ground cal. files need update)
ACA alignment	●	●	Nightly update via fids, monthly review
ACA high-background anomaly	●	●	Monthly review, minor software issues
Absolute celestial pointing	●	●	Fids + CXC aimpoint trending

H/W: Status of hardware reflected in the ACA subsystem analysis, including "lack of knowledge" as an issue.
Process: Status of ground software or process for performing ACA subsystem analysis.

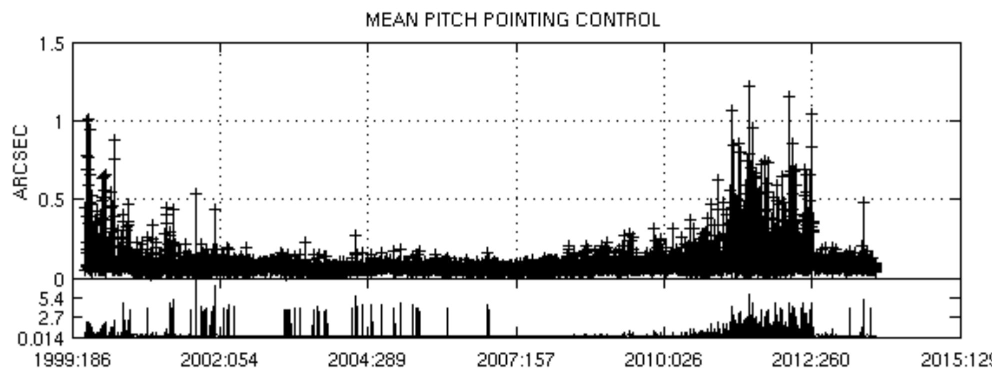
● No issue ● Minor issue / low impact ● Significant issue / impact ● Failure

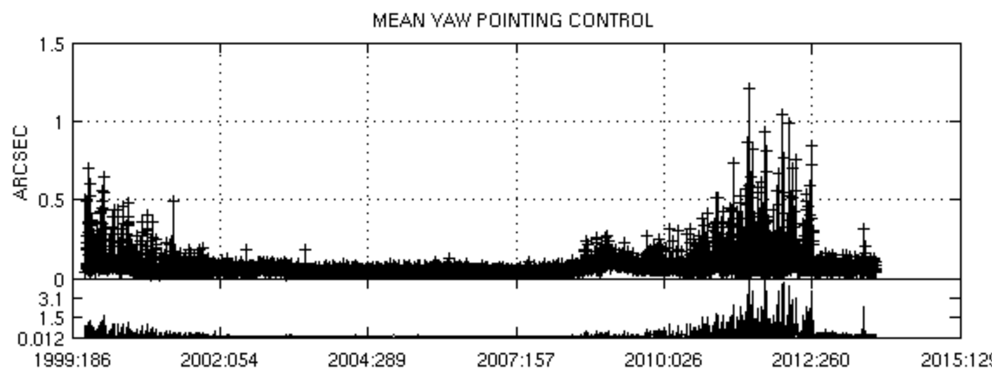
PCAD SSE daily review

- One-shot attitude updates (which are based on identification of acquisition stars)
  - Follows every transition into Normal Pointing mode (NPM)
  - NPM is only PCAD mode that uses stars for attitude estimation (Kalman filter) and control
  - Updates should be < 80 arcsec, in general
- Fine Sun Sensor / Coarse Sun Sensor angles and comparison
  - CSS-derived Sun position should be within 4 deg of that from FSS
- Gyro bias
  - Only updated in NPM (output of Kalman filter)
  - Variation should be < 0.005 arcsec/sec, in general
- Daily pointing control and stability (see following slide)
- Number of stars recognized/identified by OBC
- Number of stars used by onboard Kalman filter (automated alerts for durations > 60 seconds with < 2 Kalman stars)

PCAD Control and Stability

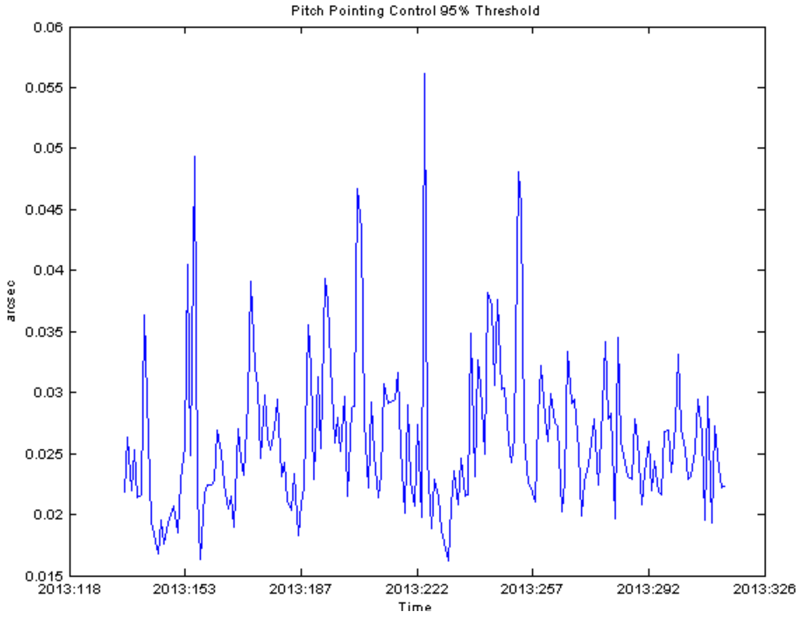
- Pointing control requirement: per-axis attitude errors < 4 arcsec, outside of maneuvers, momentum dumps, and perigee passages
- Plot shows daily mean and standard deviation for pointing control over entire mission (including perigee passages)
  - Gravity gradient effects cause cyclical spikes every few days in average error trace
- 2010-2012 increase in values is due primarily to increased gravity gradient effects because of decreased perigee altitude
- Spacecraft ephemeris updates every orbit resulted in decrease since late 2012

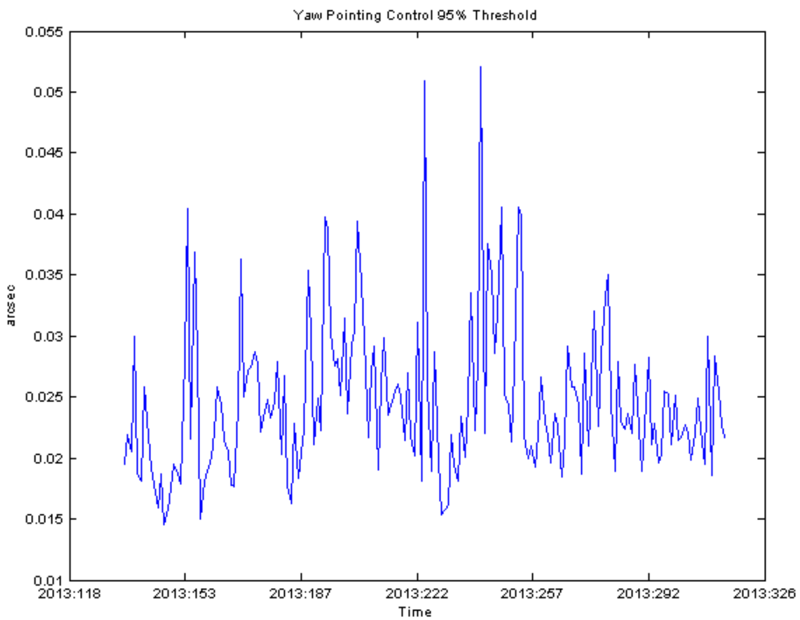




PCAD Control and Stability

- Pointing stability is essentially standard deviation of 10 sec samples of attitude error
  - Program requirement: 95% of 10 sec stability samples < 0.12 arcsec
- Plots show pointing stability for a 6-month period and are typical throughout mission
- Variation in pointing control and stability is primarily due to gyro bias excursions and quality of onboard star catalogs
  - Total number of stars available for use by onboard Kalman filter
  - Stars intermittently acquired or identified by OBC which drop in and out of use by onboard Kalman filter

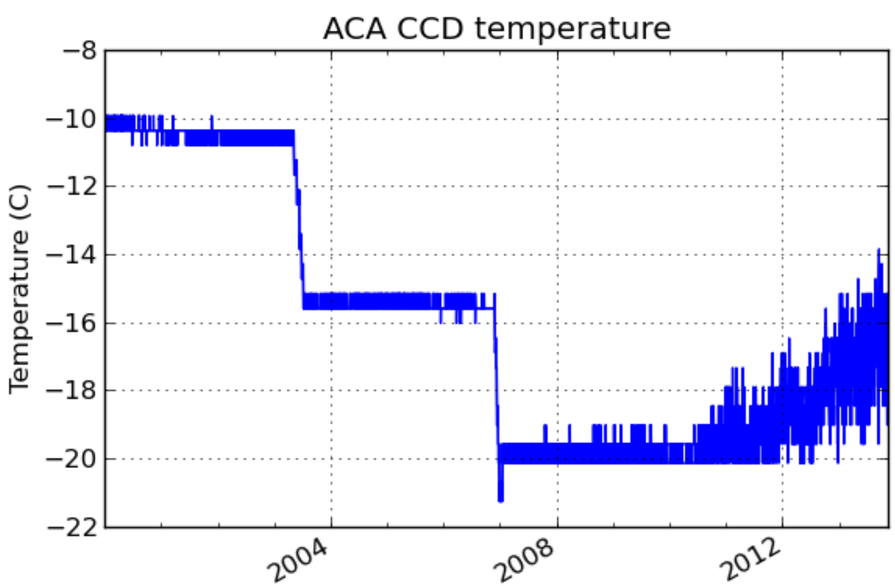


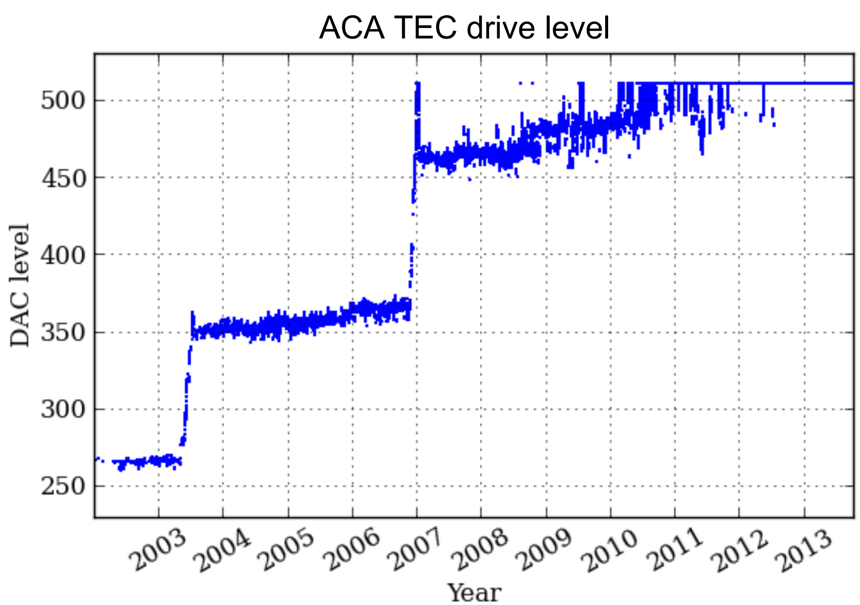


ACA thermal (CCD and housing) trending

- TEC keeps the CCD below the ambient ACA housing temperature
- Desired CCD temperature of -19 C was maintained 2007 through ~2011
- Increasing ACA housing temperature (due to overall spacecraft heating) outstripping TEC control authority and the CCD has lifted off its setpoint.
- *Ball has no concerns about indefinitely maintaining the TEC at maximum drive level.*

Increasing CCD temperature is a root cause of many ACA issues

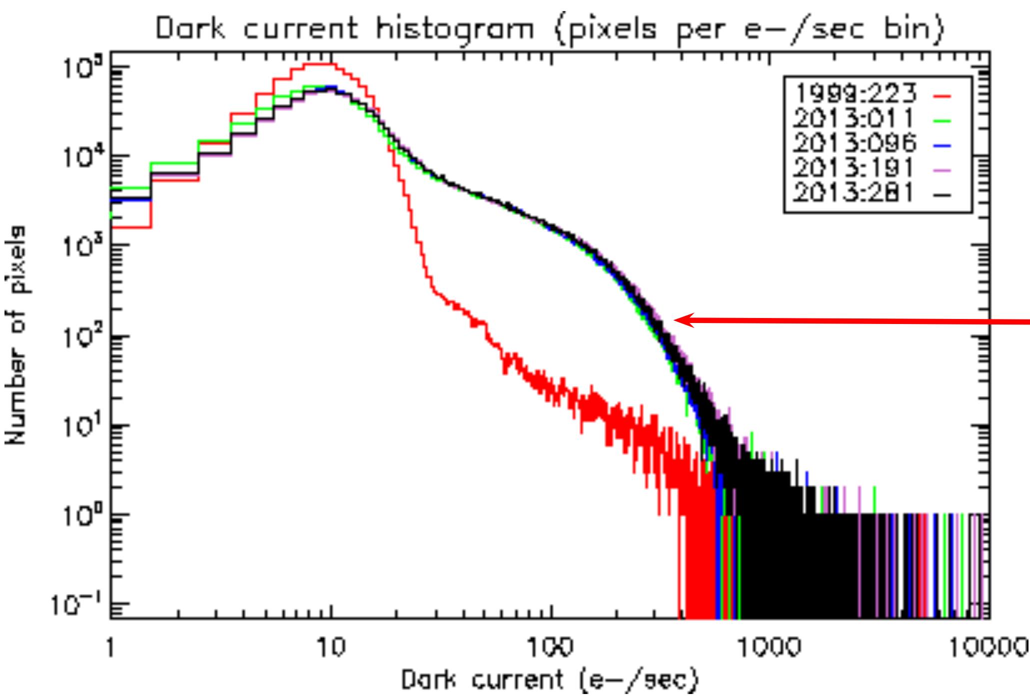




Dark current: warm pixels

- Approximately four times per year a full-field dark current calibration is performed.
- No shutter and significant readout time. Requires multiple readouts for two integration times (5 sec and 10 sec).
- Requires a total of 3 hours of realtime 512K comm during perigee.

Increasing warm pixels is a root cause of many ACA issues

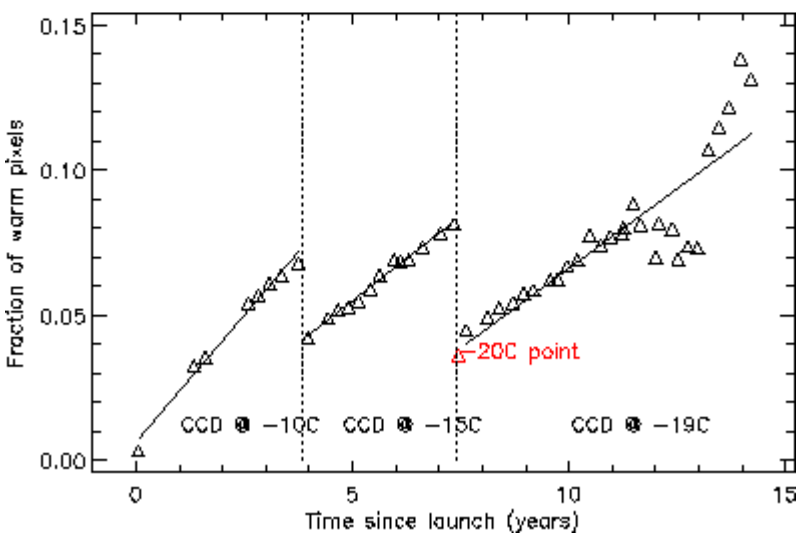


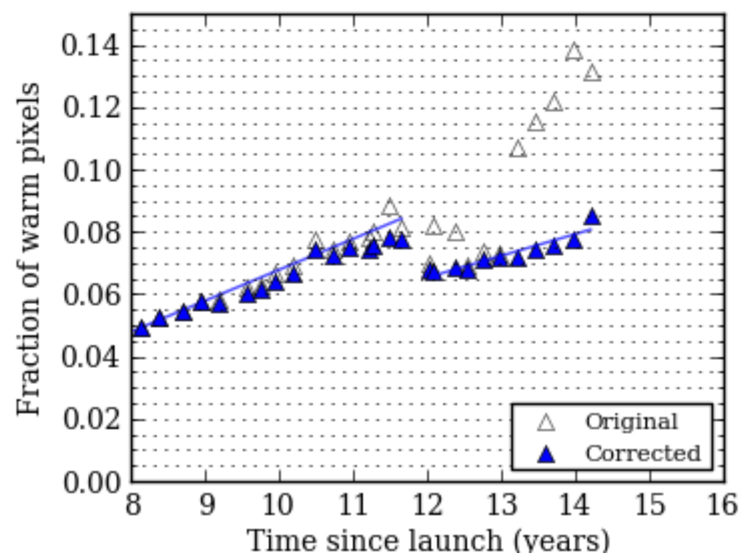
Warm pixels (*aka* dark-current non-uniformity) are the main source of centroiding noise.

Dark current *doubles* for each 6 degC temperature increase.

Dark current: warm pixels

- Detailed analysis performed:
  - Mean, median, mean of undamaged population
  - Intrinsic dark current trending
  - Warm (>100, 200 e^-/sec) and hot (>2000, 3000 e^-/sec) fraction
  - Trending warm (>100) pixel fraction
  - Hot pixel list generated for use in MP star selection
- Reports archived at *http://cxc.harvard.edu/mta/ASPECT/dark_cal/*
- Reviewed by Star Working Group

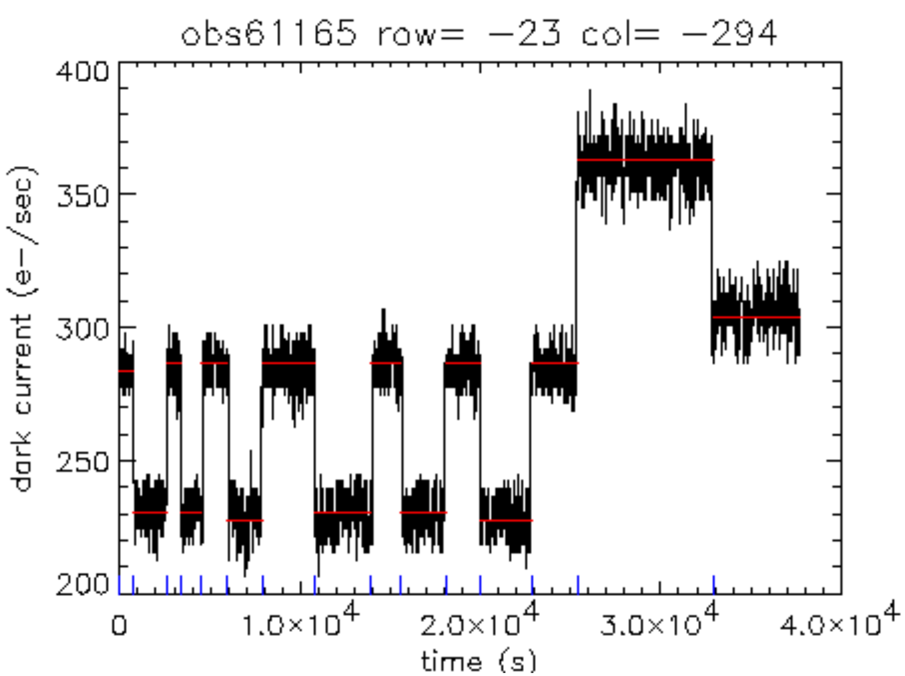


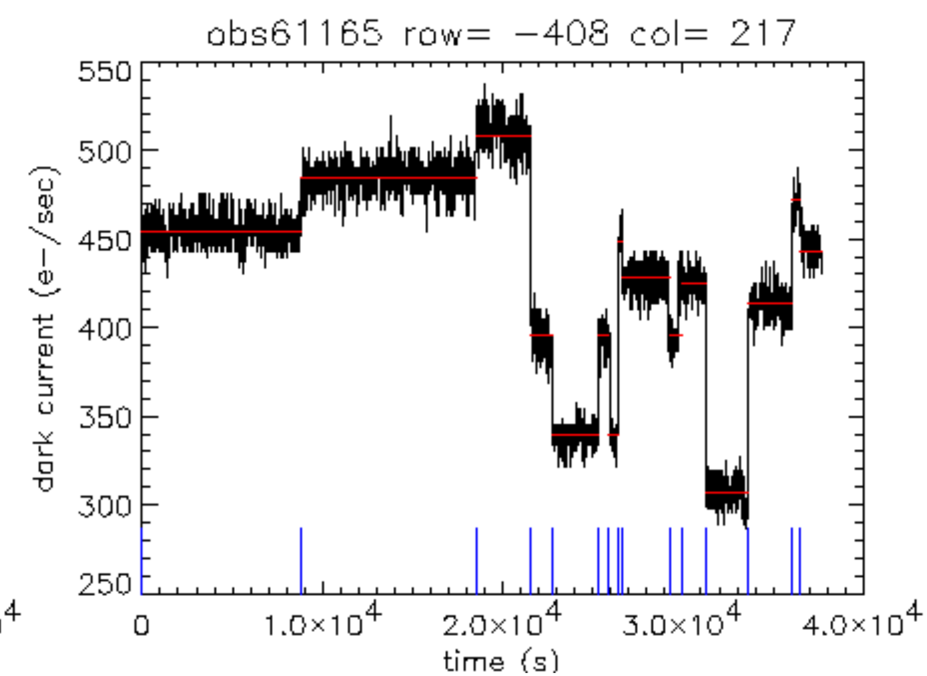


Dark current: flickering pixels

- For added challenge: warm pixels also randomly “flicker” between different values on time scales of 2-20 ksec.
- Analysis in *http://cxc.harvard.edu/mta/ASPECT/flicker_2002/*
- Generating a static dark map from calibrations is not useful.
- Ground aspect uses on-the-fly warm pixel detection.
- Follow-up study in 2008 confirmed no change in behavior

  http://cxc.harvard.edu/mta/ASPECT/flick_pix_2008/





ACA Acquisition and Tracking Success

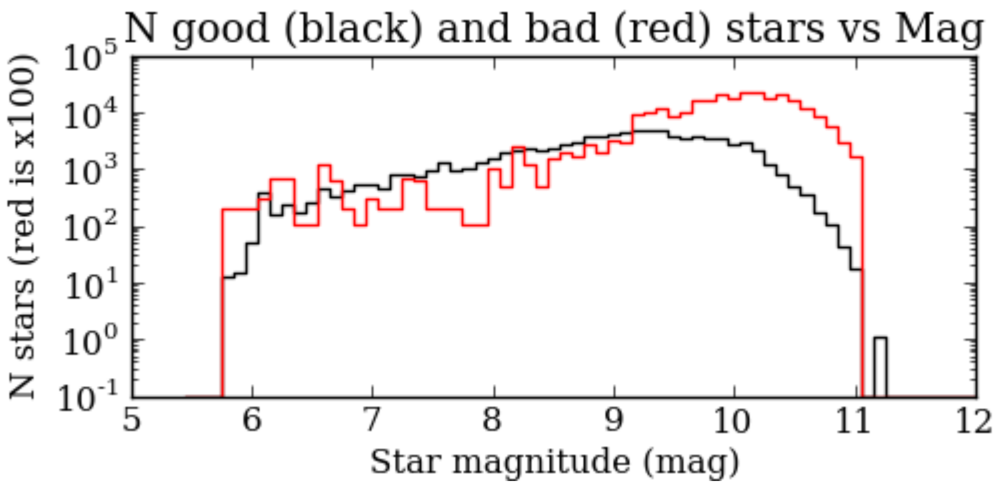
The SOT aspect team carefully tracks the status of every commanded acquisition and guide star.

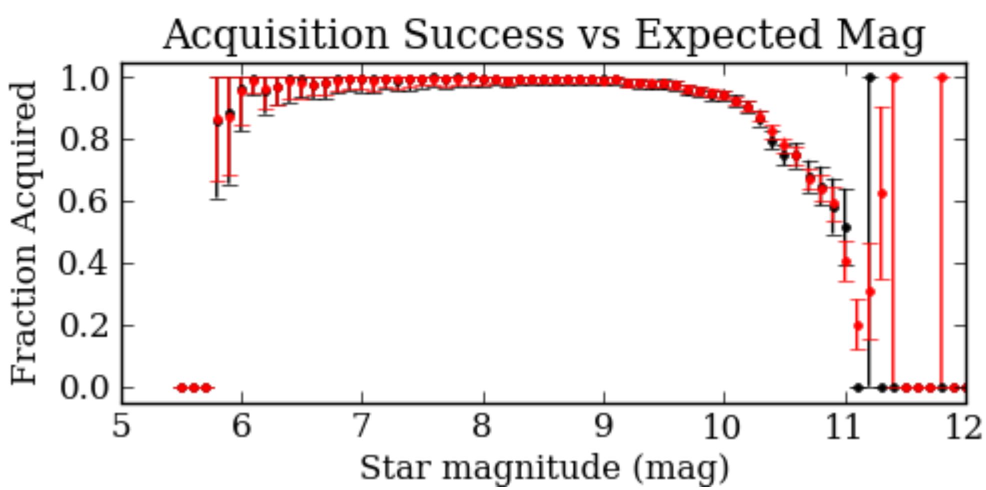
- All relevant information from the “life-cycle” of a star is retained:
  - Mission planning info (schedule, command load)[1]
  - Commanded star catalog values (y, z, search box, etc)
  - ACA review warnings and metadata
  - Key AGASC information (RA, Dec, color, mag_aca, etc)
  - Observed acquisition (ACA and OBC acq status, magnitude)
  - Observed guide star tracking (magnitude, track fraction, ..)
  - Guide star V&V (mean and RMS centroid deviations)
- Nightly processing jobs download data and telemetry from the CXC archive and generate derived data products.
- Data then stored in tables within a Sybase relational database.
- Summary info and plots available for intervals: month, quarter, semi-annual, annual, mission since 2003, mission.

[1]Ensuring the accuracy of our mission planning info table in the face of replans, stoppages, and pseudo-random naming conventions is a substantial challenge!

Acquisition star success

Mission since 2007 acq statistics





Mission since 2007 faint acq failures

		failed_acq	
	N Stars	stars	rate
10.0-10.1	3013	220	0.07
10.1-10.2	2802	232	0.08
10.2-10.3	1806	190	0.11
10.3-10.4	1108	189	0.17
10.4-10.5	831	185	0.22
10.5-10.6	574	143	0.25
10.6-10.7	314	98	0.31
10.7-10.8	214	69	0.32
10.8-10.9	117	44	0.38

Oct-2013 monthly report

Acq Stats Report - 2013-M10

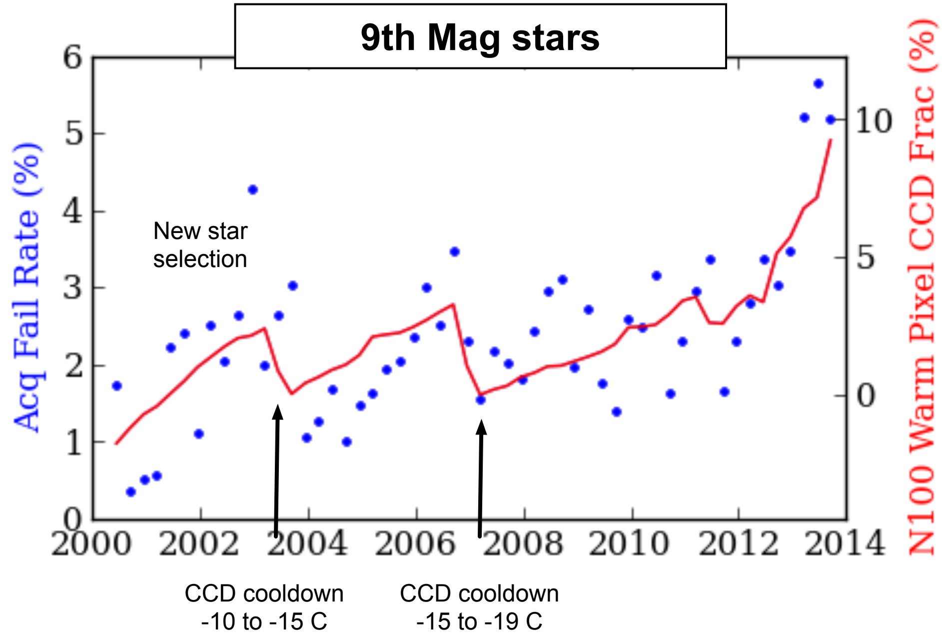
01-October-2013 through 01-November-2013

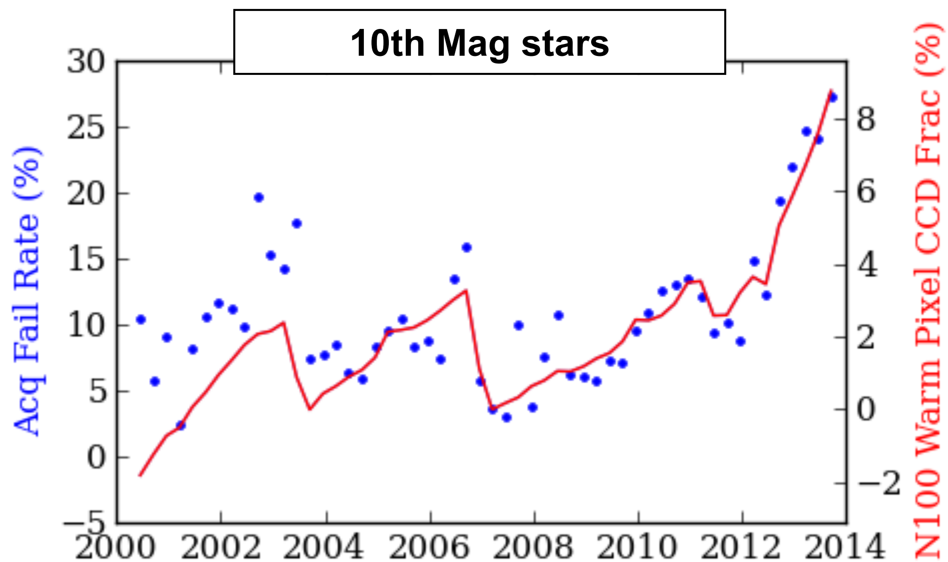
TSTART	TSTOP
2013:274:00:00:00.000	2013:305:00:00:00.000

		failed_acq					
		stars				rate	
	n stars	actual	pred.	P Less	P More	actual	pred.
report	1032	56	40	0.993	0.010	0.054	0.039

Acquisition star success trending

- Trends in acquisition failure rate are strongly affected by CCD temperature.
- Apparent correlation with warm pixel fraction (N > 100 e-/sec)
- *Red line: Scale * N100 + Offset*
- Extrapolate? More later.





Guide star tracking success

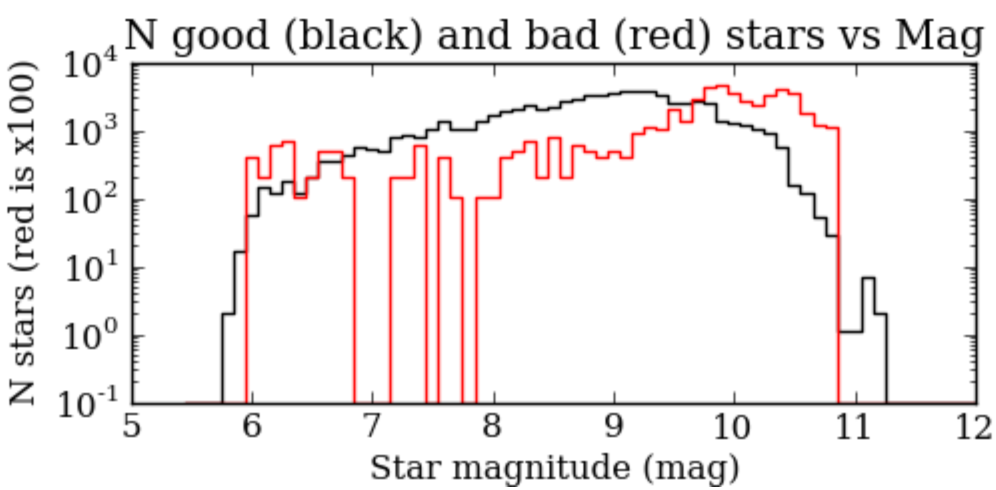
As for acquisition there are monthly plots and stats that get reviewed by the star working group.

For guide stars there are three key metrics:

Bad track	ACA not tracking star for > 5% of observation.
Failed track	Star never tracked
OBC bad status	OBC rejecting star for kalman filter for > 5% of observation[1]

[1]The OBC rejects stars for the kalman filter if the centroid residual is too large or if an ACA bad image status flag is set (ionizing radiation, multiple stars, defective pixel, or saturated pixel)

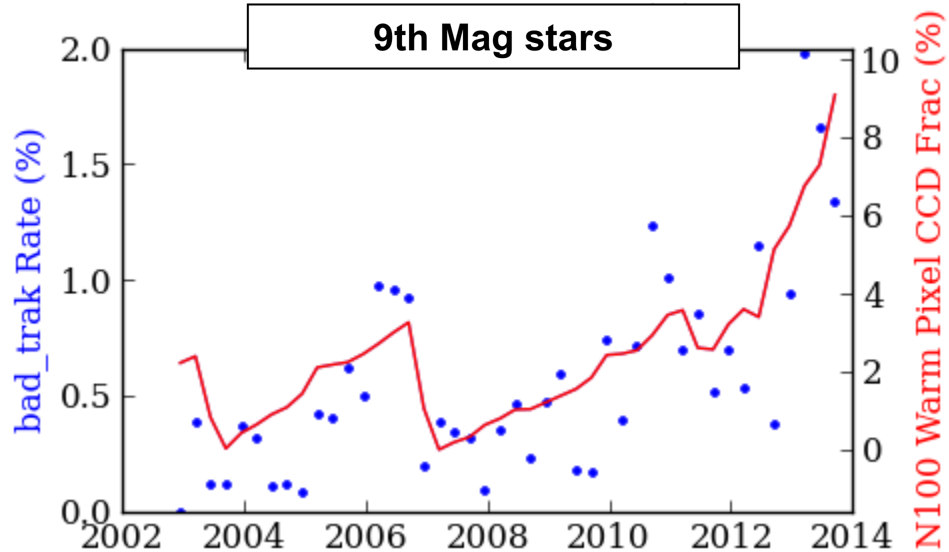
Mission since 2007 guide star statistics



		bad_track		no_track		obc_bad_status	
	N Stars	stars	rate	stars	rate	stars	rate
10.0 - 10.1	1257	27	0.021	1	0.001	466	0.371
10.1 - 10.2	1173	25	0.021	2	0.002	420	0.358
10.2 - 10.3	999	25	0.025	0	0.000	445	0.445
10.3 - 10.4	837	44	0.053	0	0.000	417	0.498
10.4 - 10.5	301	26	0.086	1	0.003	180	0.598
10.5 - 10.6	209	40	0.191	1	0.005	130	0.622
10.6 - 10.7	74	11	0.149	0	0.000	54	0.730
10.7 - 10.8	63	16	0.254	0	0.000	46	0.730
10.8 - 10.9	2	0	0.000	0	0.000	0	0.000

Guide star tracking success trending

- Guide star trends show similar trend with warm pixel fraction.
- *Recall: an observation of a single guide star is assigned “bad track” if the star is not tracked more than 5% of the observation.*
- Although we record the actual fraction of time a star is tracked, it is useful for analysis to classify a guide star as “good” or “bad” based on the bad track status.
- These plots show the percentage of stars that are “bad track”.
- *Red line: Scale * N100 + Offset*



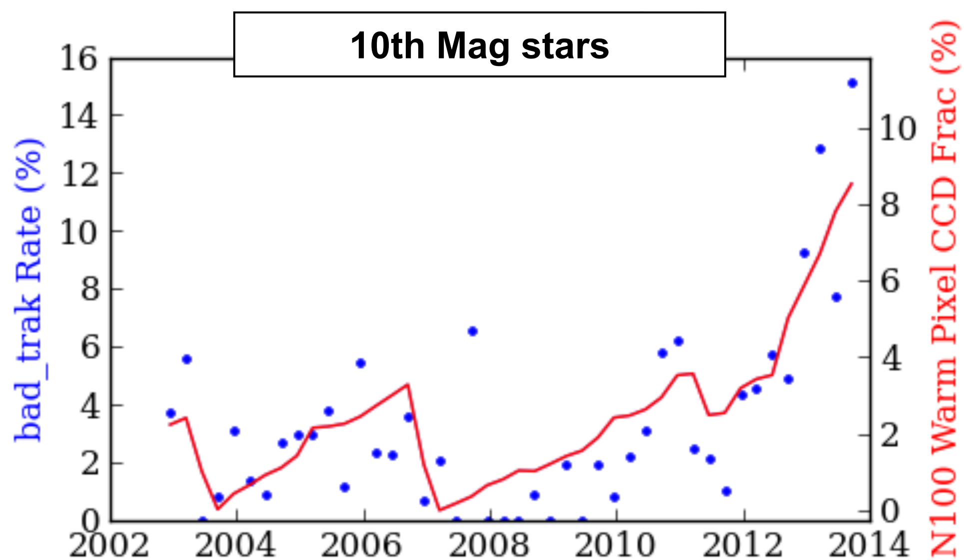
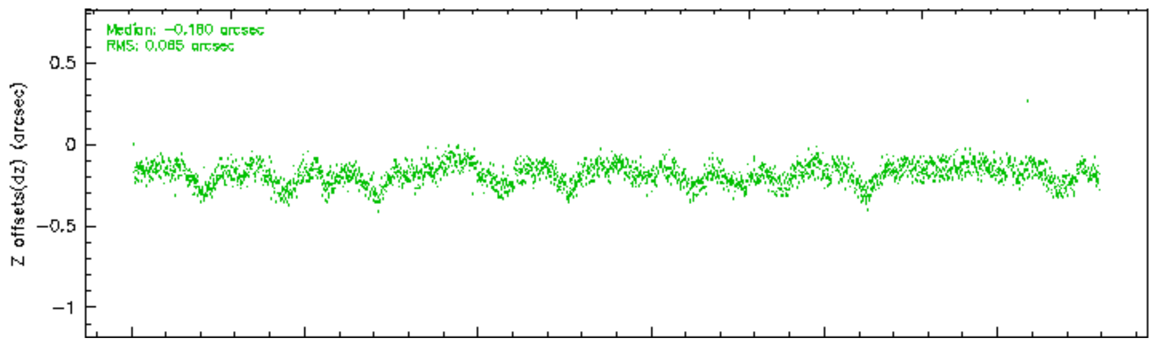


Image reconstruction per obsid

- The aspect pipeline is robust and successfully processes most observations without operator intervention.
- Standard processing V&V checks that aspect solution meets requirements.
- Manual review by CXCDS ops and SOT aspect as necessary.

Typical centroid residuals



Dither period

Hot pixel centroid residuals

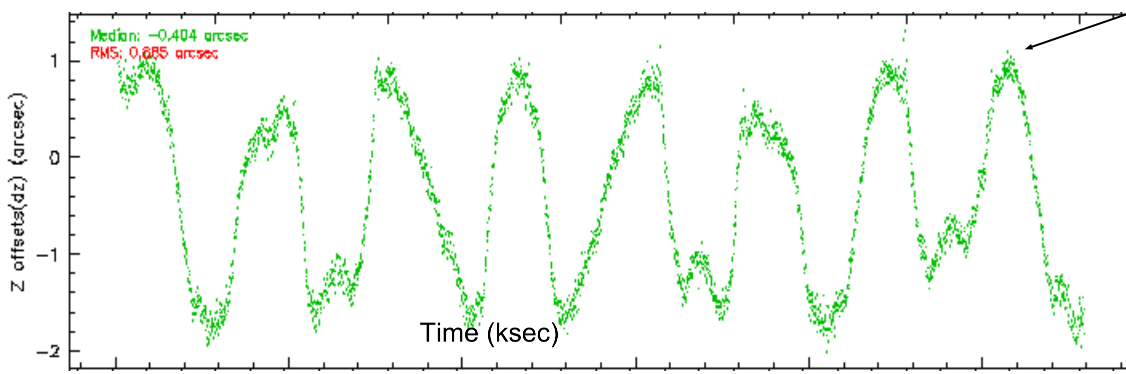
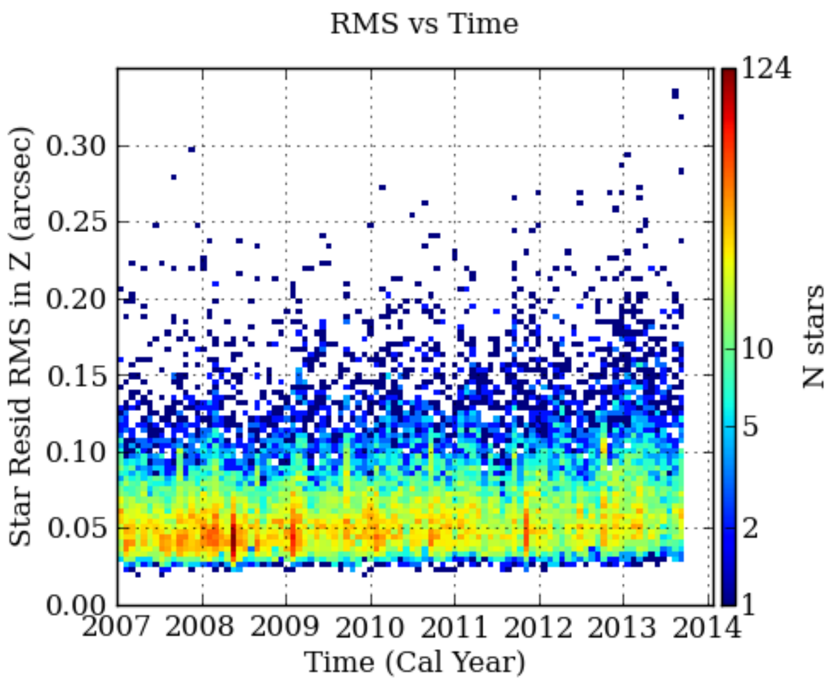
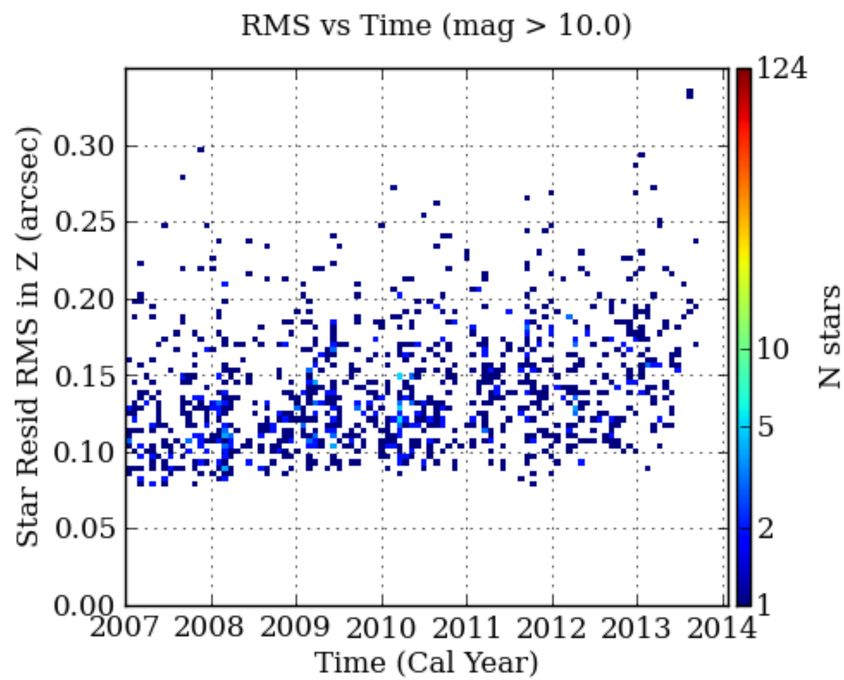


Image reconstruction trending

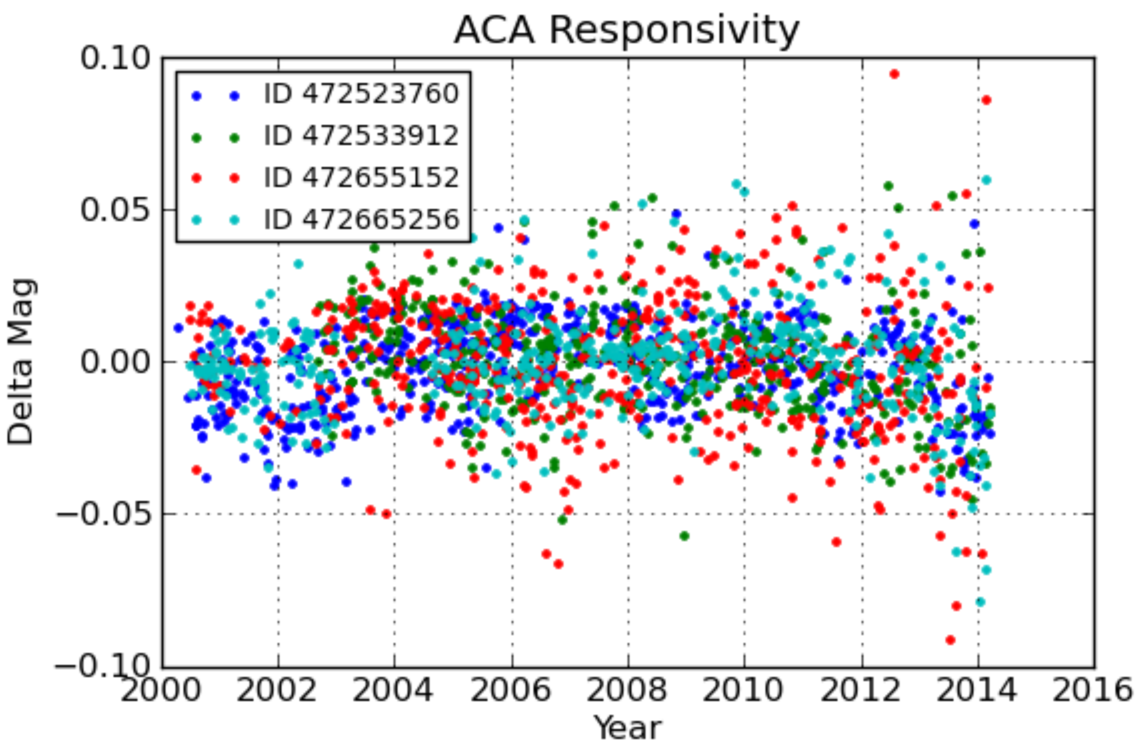
- V&V tool calculates star centroid residuals from aspect solution
- The 68% value of radial residual for each guide star is stored.
- Plot below shows a detectable but non-impacting trend.





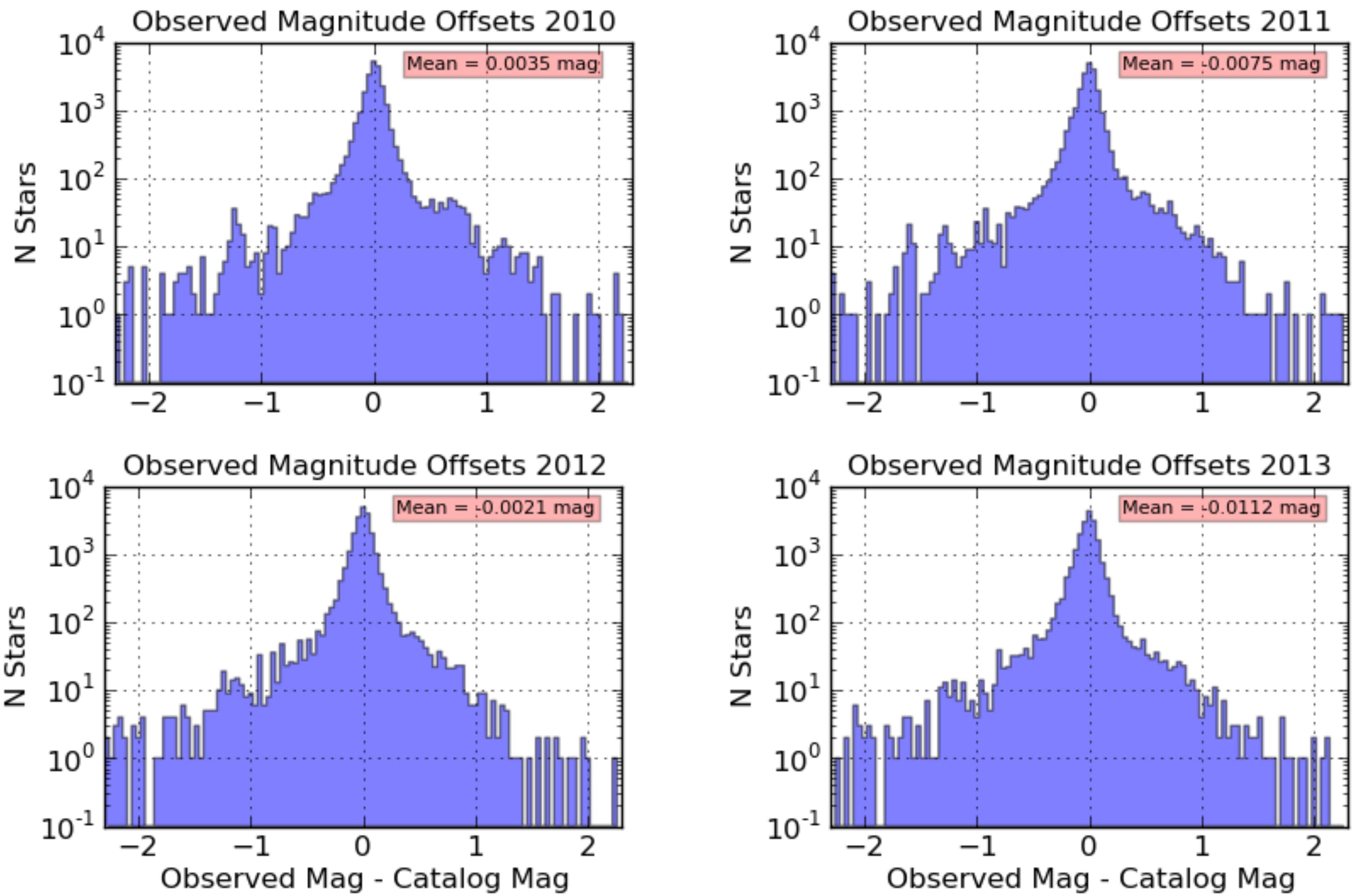
ACA Response

- Trend in ACA response is analyzed using repeat observations of guide stars (from Ar Lac and Capella).
- Apparent trend at the level of ~0.005 mags/year since 2011.
- Includes potential effects from contamination (CCD and mirrors), change in readout gain, and warm pixels.
- Not an issue operationally.



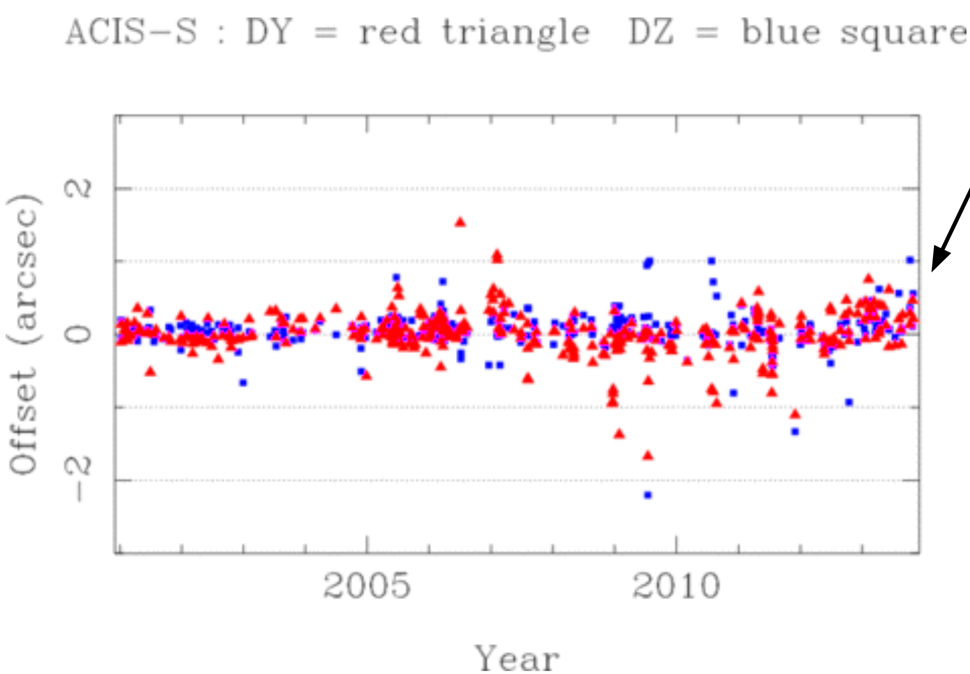
ACA Response

- Statistical analysis of mag error for acq. and guide stars shows no trend.

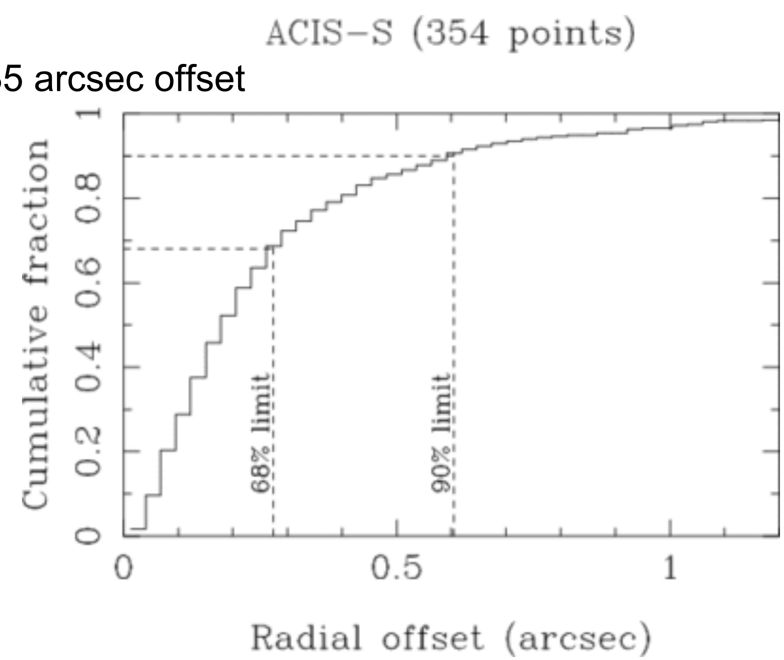


Celestial location

- Automated tools examine all “suitable” observations for X-ray sources with optical/IR/radio counterparts having accurate astrometry.
- Results stored in database and plotted monthly.

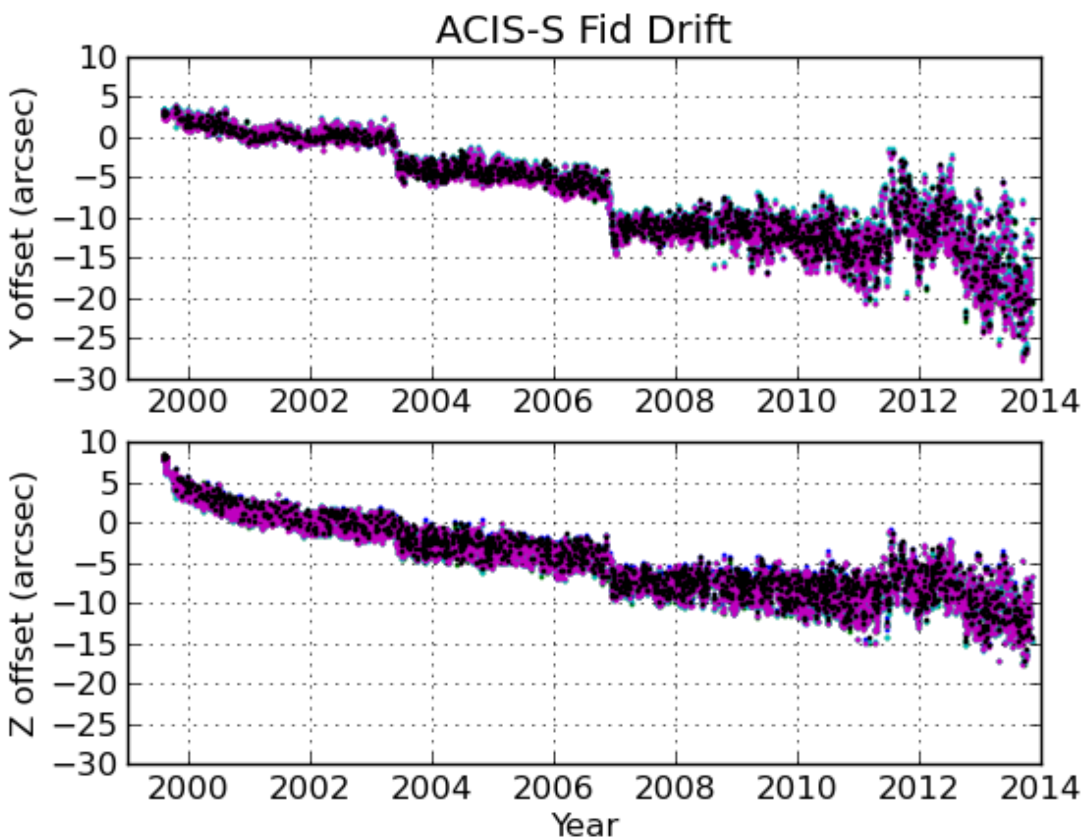


0.35 arcsec offset



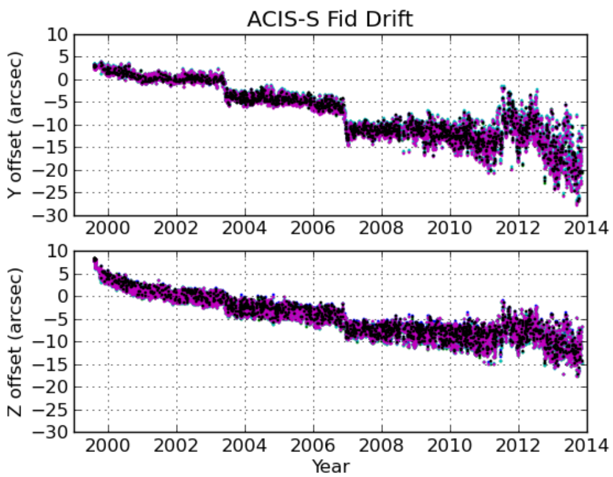
ACA alignment and celestial pointing

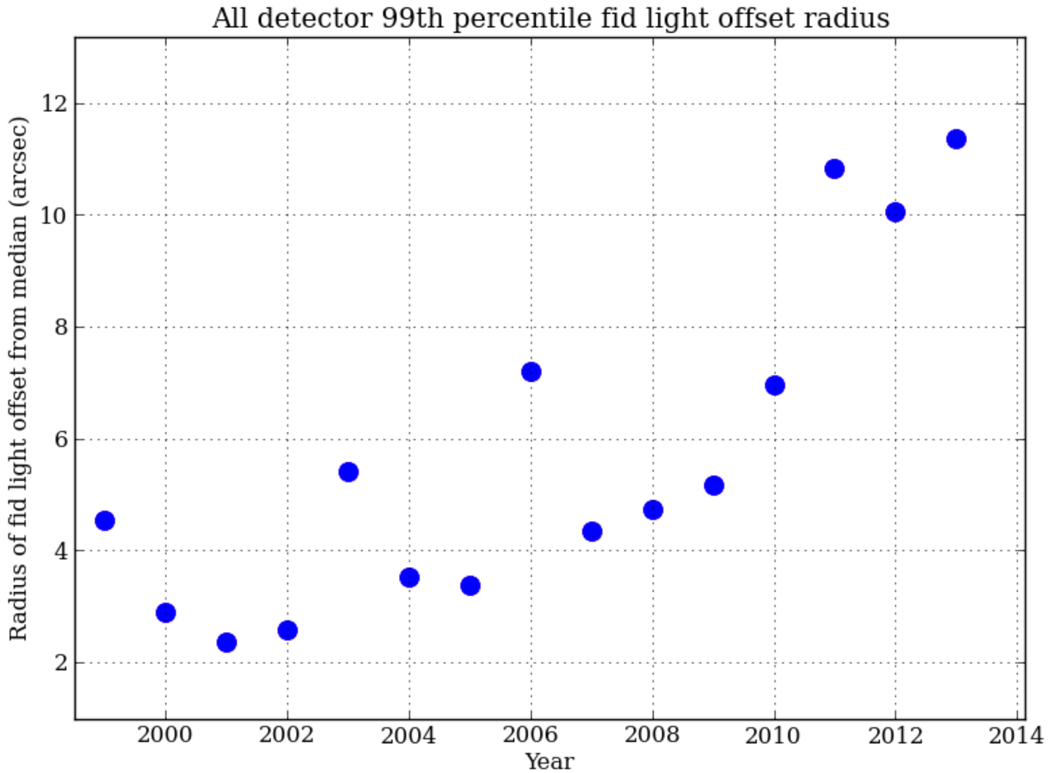
- Automated software extracts fid light statistics from aspect pipeline outputs for each obsid.
- Trend in mean reflects alignment of ACA with respect to HRMA/SIM
- Trend in scatter reflects spacecraft thermal issues.
- Scatter over ~1 year timescale indicates absolute celestial pointing after "calibrating" detector aimpoints.



ACA alignment and celestial pointing

- Celestial pointing is becoming noticeable.
- Level of uncertainty undesirable for certain grating observations (avoiding node boundaries for LETG / ACIS-S).



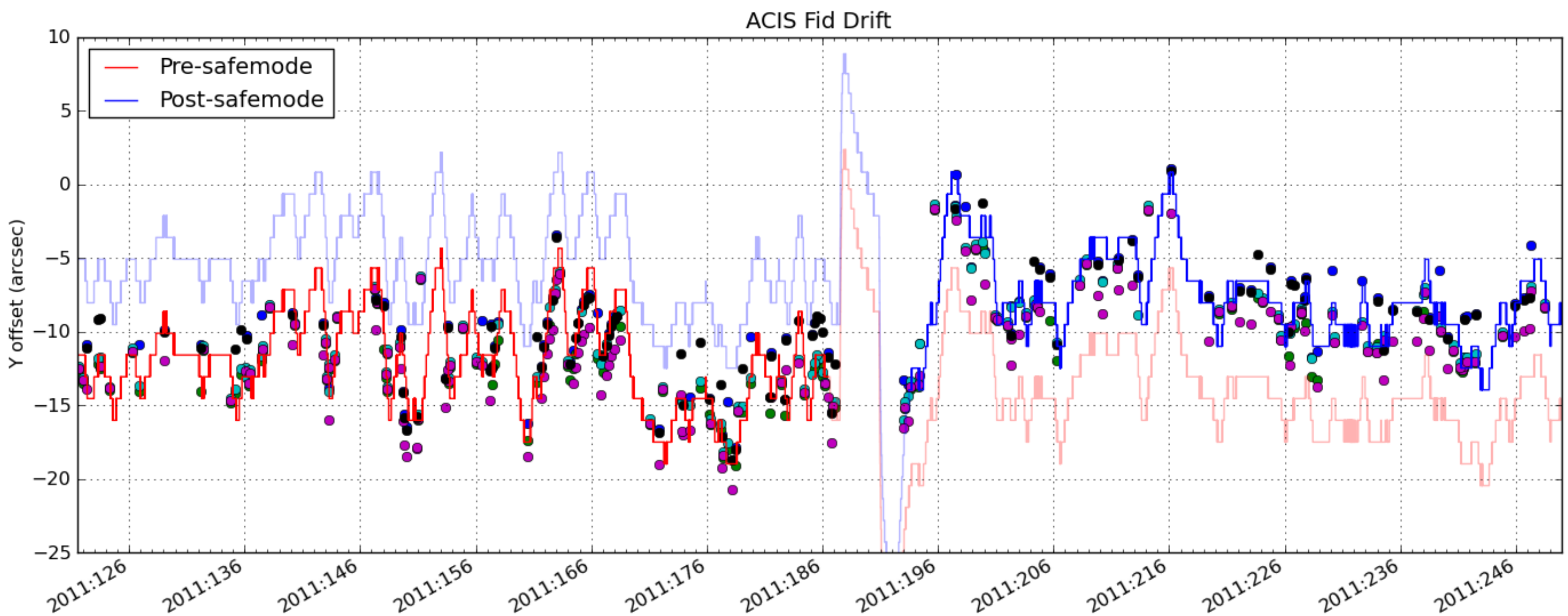


ACA alignment and celestial pointing

During a period of extended heating coinciding with the 2011:188 safe mode dwell at normal sun, the ACA mount alignment shifted by about 7 arcsec.

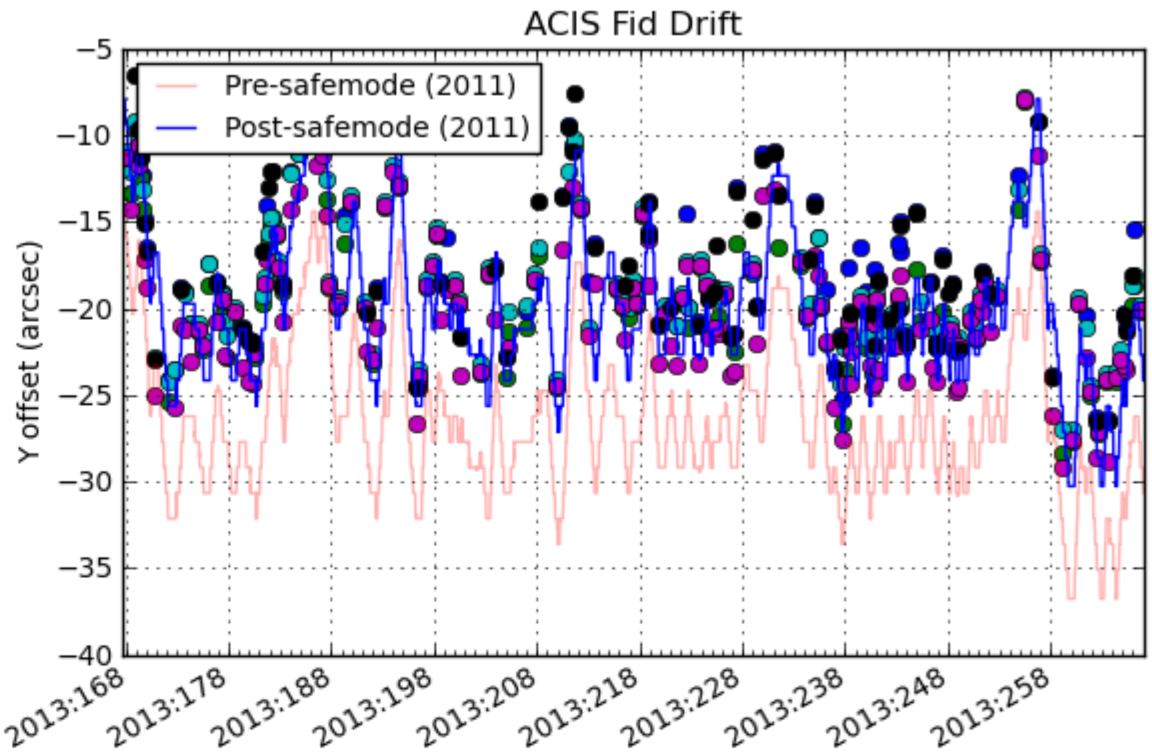
The following plot shows:

- Alignment as measured by fid light positions (dots)
- Empirical model of alignment based on $T_{ACA\_housing}$ * *scale* + *offset*
- System alignment is dominated by local ACA alignment rather than



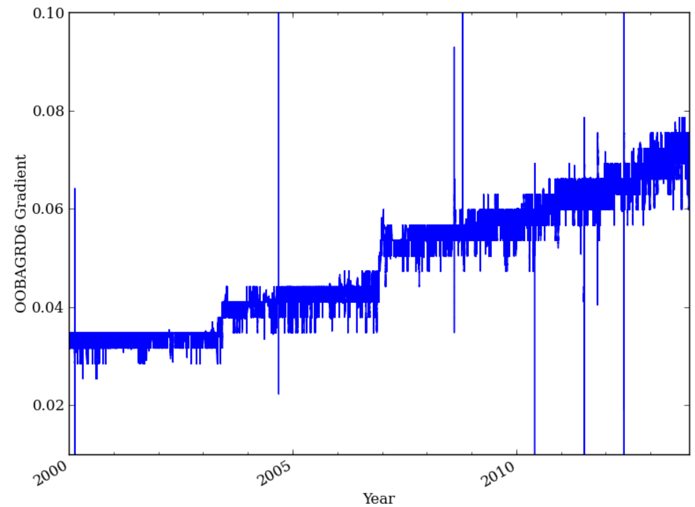
ACA alignment and celestial pointing

- No further change since 2011:288.
- This is monitored monthly.

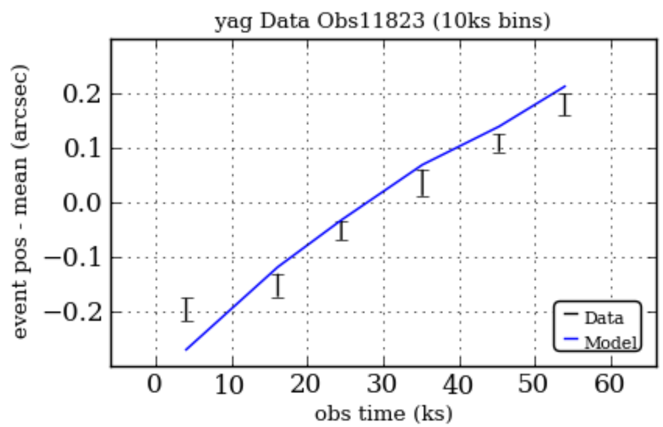


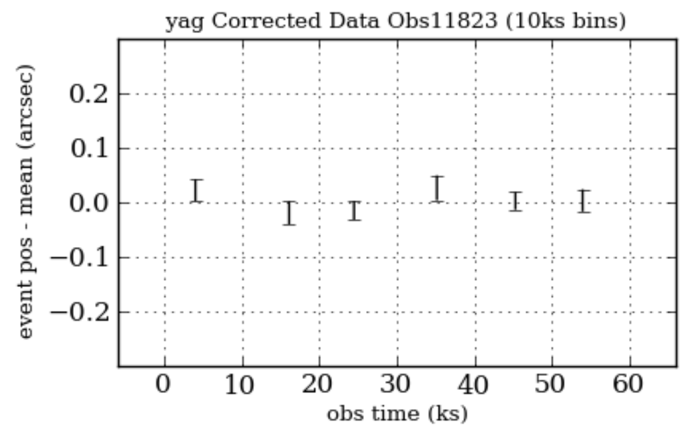
Aspect FTS periscope drift

Thermal gradients in the fiducial transfer system periscope can introduce uncompensated aspect offsets.



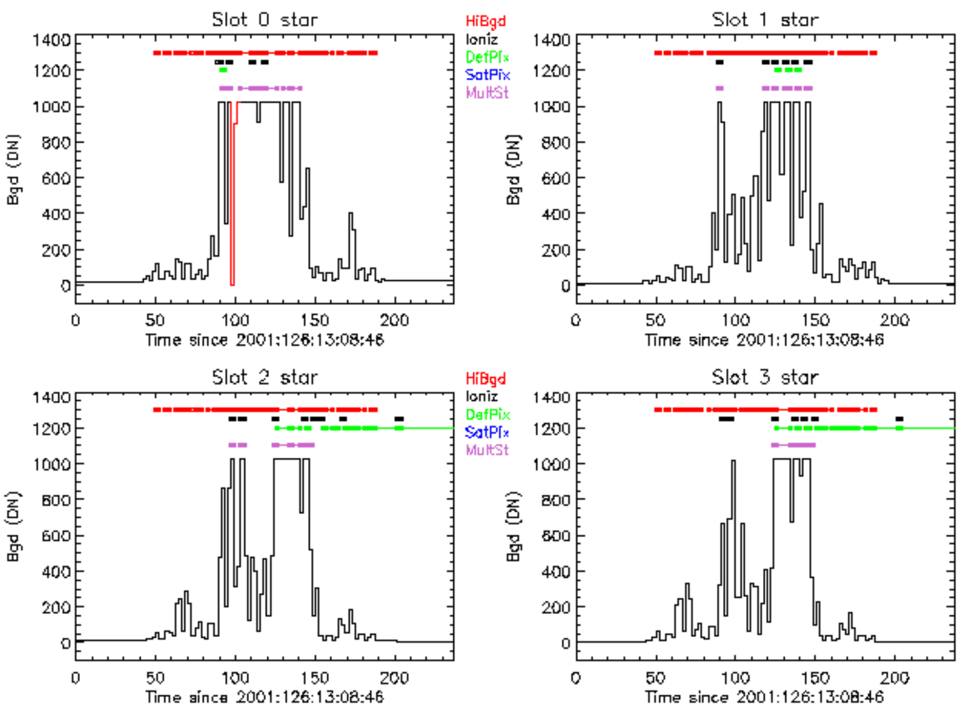
- Magnitude of gradient and daily swings (evident as “noise”) is increasing.
- Highest delta-gradients produce observable drift in X-ray source locations of up to 0.5 arcsec.
- Long (>40ks) observations with bright sources to calibrate a model which determines Y/Z offsets/corrections using the gradients.
- Model was then implemented in the ground aspect pipeline.





ACA high-background anomaly

- From launch through ~2001 the ACA occasionally experienced episodes of anomalously high background.
- No operational impact.
- Incidence and severity much reduced since 2001.
- After similar phenomenon caused by Jupiter just outside FOV, suspect some sort of debris as cause.



ACA operational issues

- Key areas of concern (root causes)
  - CCD radiation damage
  - Increasing CCD temperature
- Current and near-term risks
- Long-term risks for the 25-year mission
- Mitigation steps for issues

Key areas of concern (root causes)

Collective assessment of data from trending analysis shows two root areas of concern for ACA operational performance:

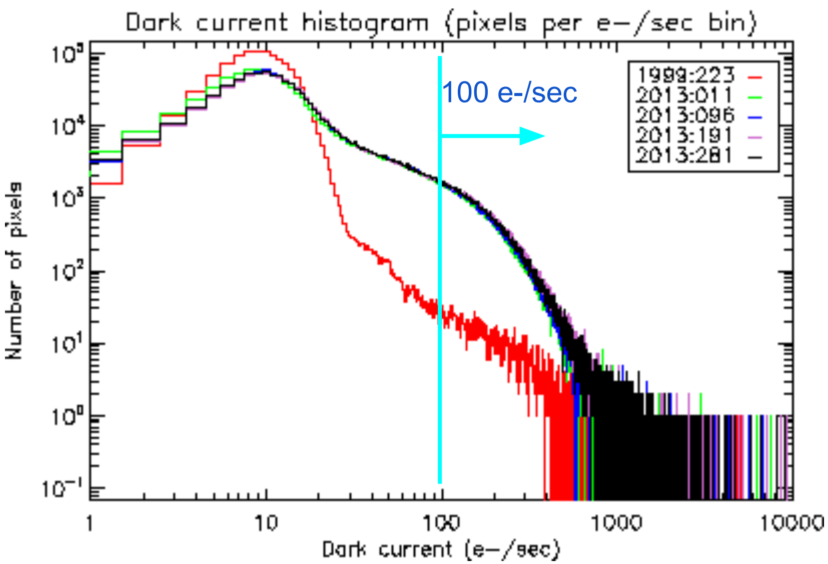
- Ongoing radiation damage of CCD pixels
- Increasing CCD temperature

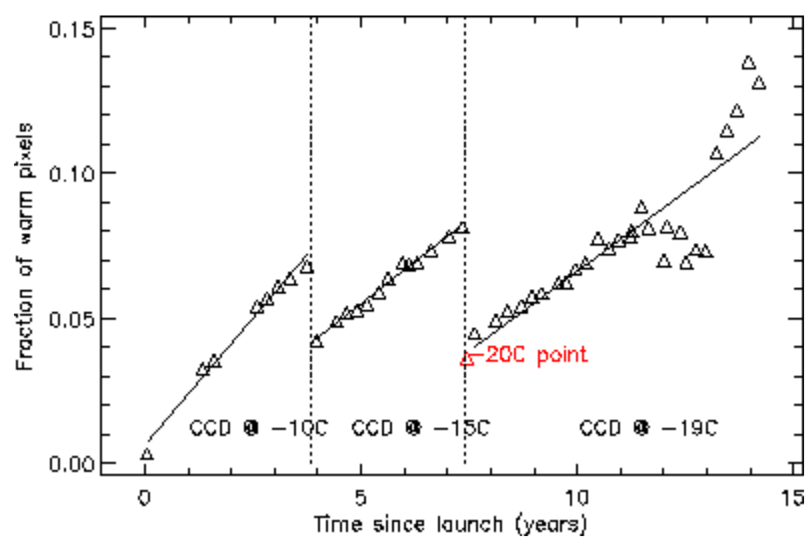
The two are physically independent but coupled in performance predictions. *Dark current doubles for each 6 C increase.*

Note that radiation damage to the **PEA** has been examined as part of a general radiation study and no particular concerns were identified.

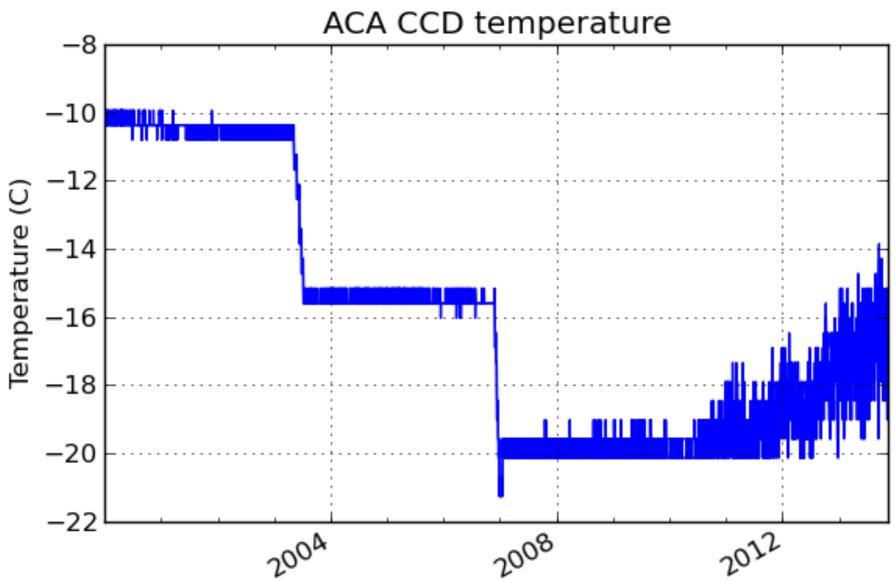
Ongoing radiation damage of CCD pixels

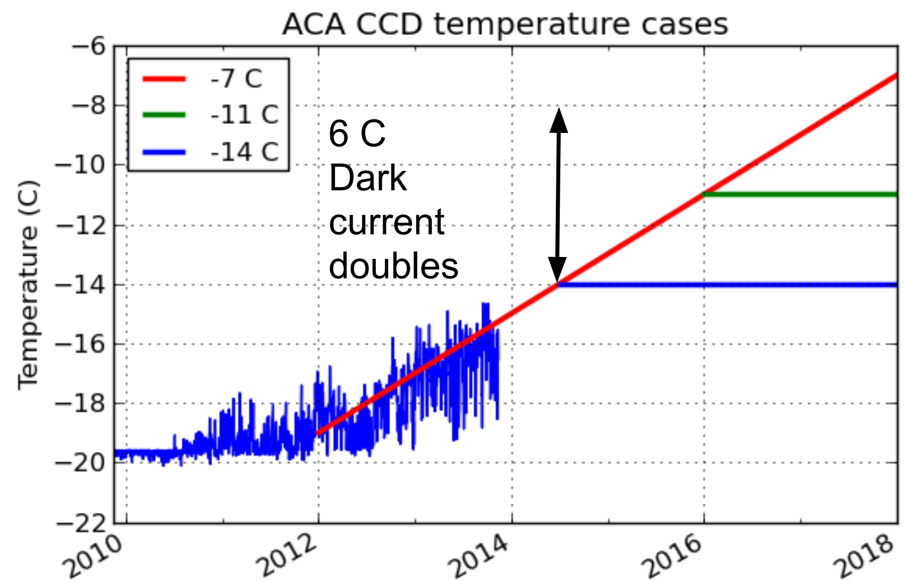
- Radiation damage to the CCD is due to ionizing particles which damage the semiconductor and allow a leakage current.
- It is useful to characterize damage by the fraction of pixels with a dark current exceeding a certain threshold.
- Threshold of 100 e-/sec correlates with other observables.





Increasing CCD temperature



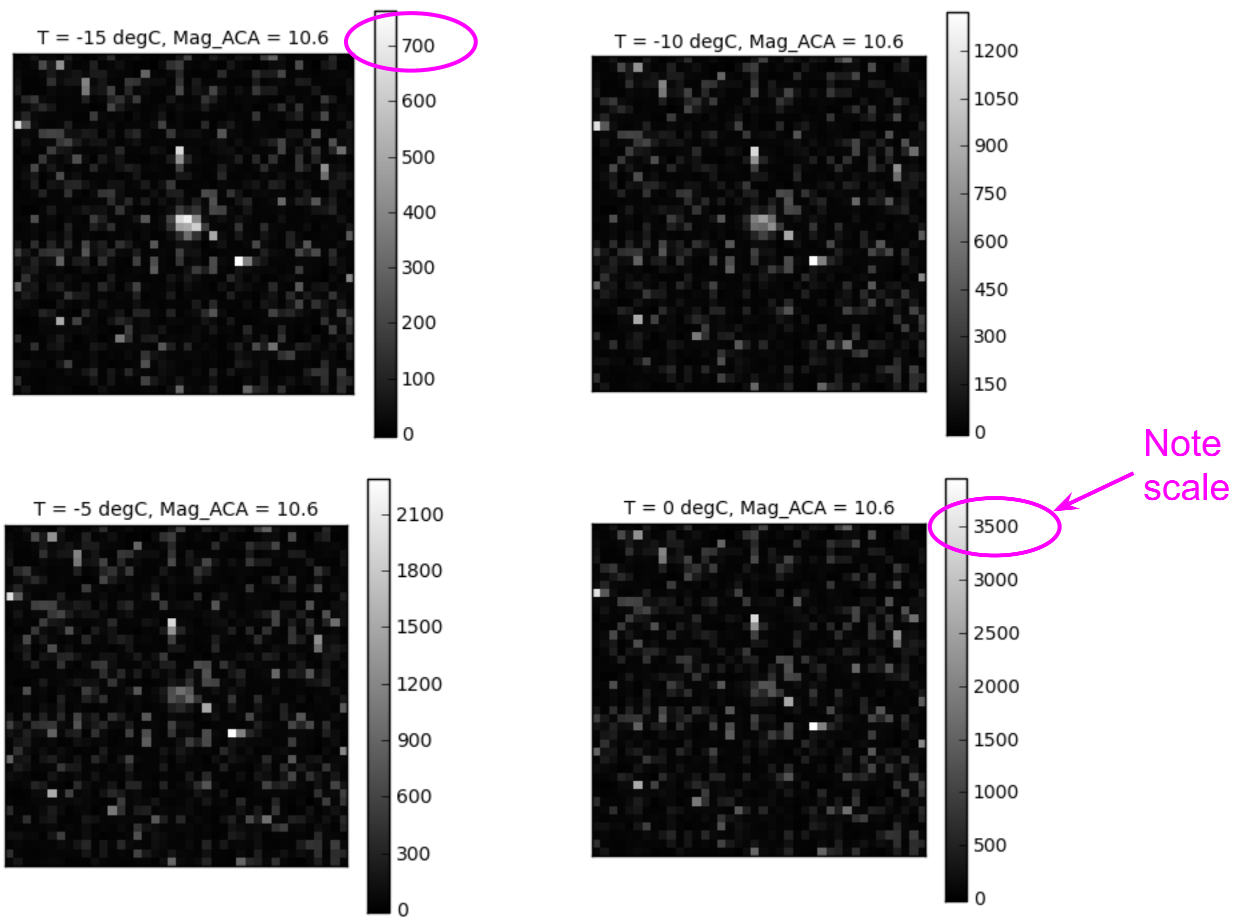


From trending define three analysis cases for CCD temperature at 2018-Jan:

- -14 C (blue, aggressive temperature constraint)
- -11 C (green, moderate constraint)
- -7 C (red, continue current linear trend)

Visual guide to warm pixels and limiting magnitude

- Increasing warm pixels makes tracking faint stars more difficult
- At the current epoch (2013) a 10.6 mag star (shown below) fades into the noise somewhere around T_{CCD} = -5 to 0 C



Current and potential risks

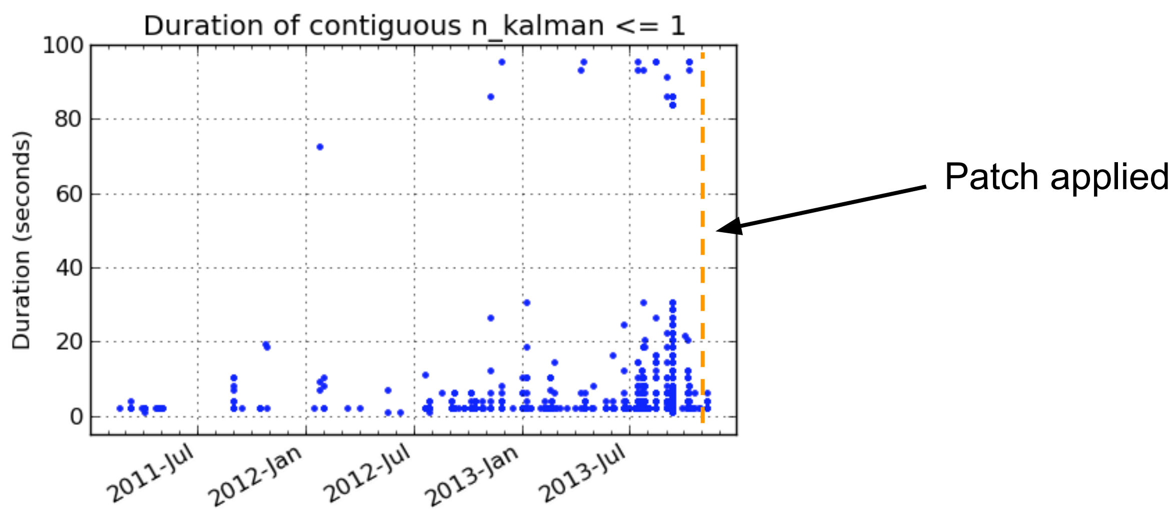
Trend of increasing CCD radiation damage and temperature has system-level risks which are currently occurring or possible in the future.

- On-board control
  - Loss of Kalman stars (which are successfully re-acquired) leads to loss of science
  - Loss of Kalman stars and failed re-acquisition leads to bright star hold or normal sun mode (BSH or NSM)
  - Failed star acquisition leads to BSH or NSM
  - Poor guide star tracking leads to BSH or NSM
- Ground aspect
  - Degraded image reconstruction impacts science
- Mission planning
  - Reduced ACA limiting magnitude leads to restrictions on pointing attitude due to insufficient guide or acquisition stars
  - ACA CCD thermal constraint impacts mission planning

In the following charts we discuss each risk along with near-term predictions of impact and potential mitigations.

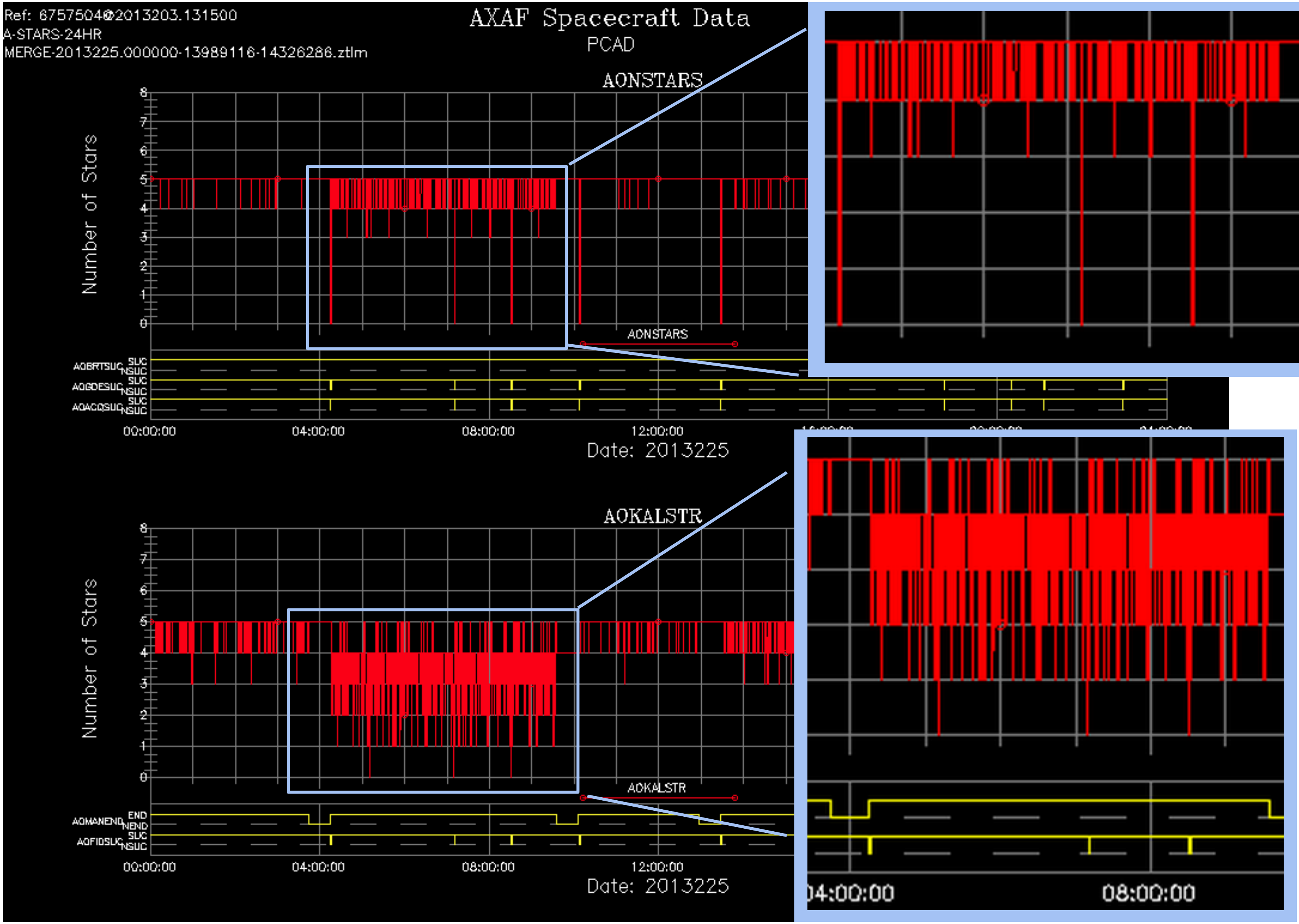
On-board control - Loss of Kalman stars

- PEA supplies a status flags for each readout: defective pixel (DP), ionizing radiation, multiple stars, saturated pixel.
- OBC ACA processing rejects a guide star readout if flags are set.
- PEA bug (known since early mission) causes DP to be set incorrectly, resulting in occasional loss of stars to the Kalman filter (see next slide).
- With increasing frequency in 2013 this led to star reacquisition events.



- Detailed analysis performed to establish that it would be safe to ignore the defective pixel flag
- In Oct-2013 the OBC was patched to ignore defective pixel flag.

On-board control - Loss of Kalman stars

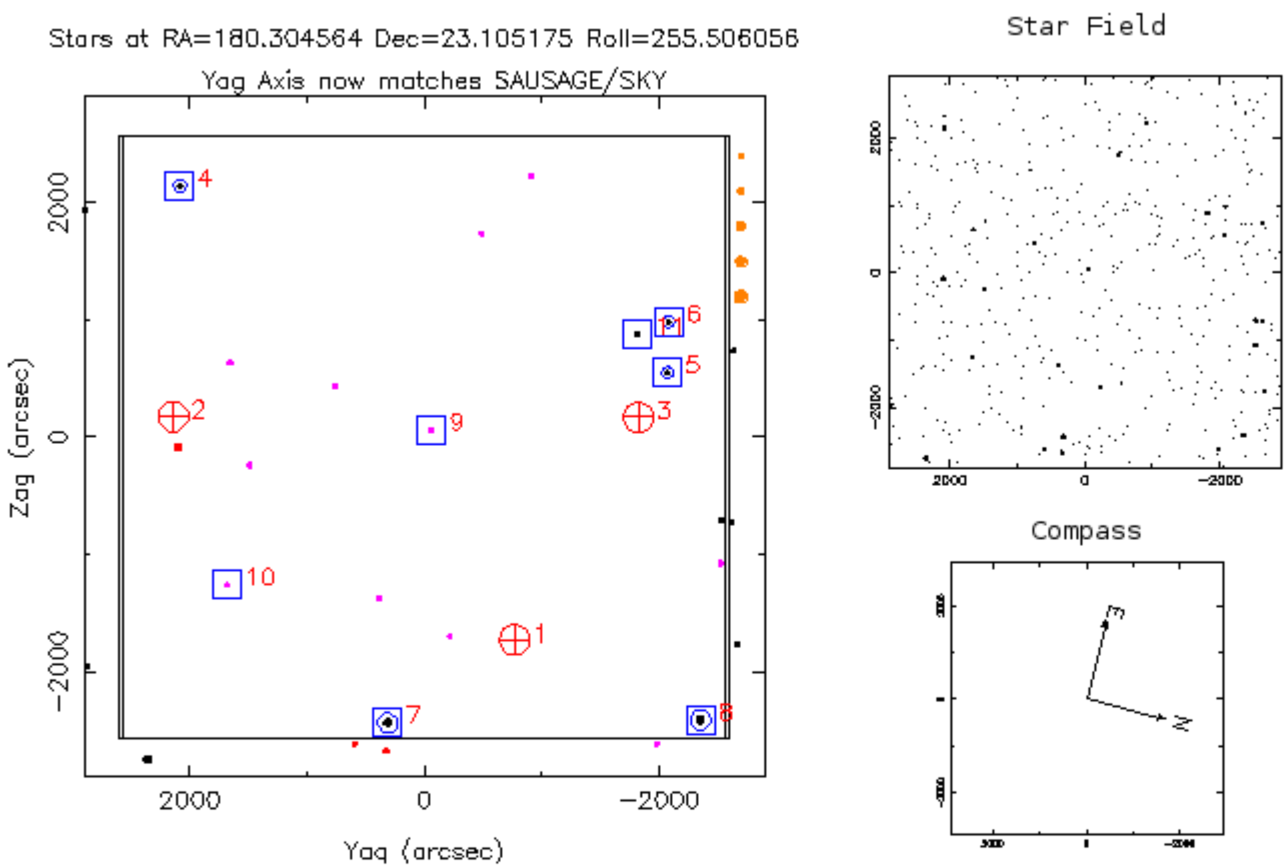


On-board control - Loss of Kalman stars

- Failed reacquistion scenarios:
  - High radiation
  - Nearby optically bright source (moving or not)
- OBC continues to filter out images with ionizing radiation, multiple stars and saturated pixel flags set
- Sufficiently bright optical source can render one or more quadrants of CCD "unusable", i.e., no stars will be acquired there
- Safing expected to result in Normal Sun mode, rather than Bright Star Hold
  - Stars in OBC catalogs usually among brightest in ACA field of view
  - If (re)acquisition of catalog stars fails, acquisition of "bright" stars is unlikely to succeed
- Recovery operations may result in loss of science time
- Solar radiation levels monitored at all times
  - Radiation sufficient to disrupt ACA star acquisition or tracking is most likely high enough to trigger safing action by onboard Radiation Monitor
- Optically bright sources known to be in or near ACA field of view (e. g., Venus) accounted for in mission planning
  - Catalog star selection avoids potential CCD trouble spots
  - Number of stars to acquire/track may be increased vs. number of fid lights

On-board control - star acquisition

- First part of every observation is acquiring up to 8 stars to establish fine attitude.
- As a case study consider obsid 11762: (http://occweb.cfa.harvard.edu/twiki/Aspect/ObsId11762)
- Star catalogs are evaluated with the output of the starcheck tool:



On-board control - star acquisition

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OBSID: 11762 SDSS J1201+2306   ACIS-S SIM Z offset:0   (0.00mm) Grating: NONE
RA, Dec, Roll (deg):   180.304564   23.105175   255.506056
Dither: ON Y_amp= 8.0 Z_amp= 8.0 Y_period=1000.0 Z_period= 707.1
BACKSTOP GUIDE_SUMM OR MANVR DOT MAKE_STARS TLR

MP_TARGQUAT at 2010:204:23:36:51.701 (VCDU count = 4709297)
Q1,Q2,Q3,Q4: 0.12467386 -0.77431091 0.60027422 0.15674788
MANVR: Angle= 112.40 deg Duration= 2159 sec Slew err= 43.9 arcsec

MP_STARCAT at 2010:204:23:36:53.344 (VCDU count = 4709304)

IDX	SLOT	ID	TYPE	SZ	MINMAG	MAG	MAXMAG	YANG	ZANG	DIM	RES	HALFW	PASS	NOTES
[1]	0	2	FID	8x8	5.797	7.000	8.000	-773	-1741	1	1	25		
[2]	1	4	FID	8x8	5.797	7.000	8.000	2140	166	1	1	25		
[3]	2	5	FID	8x8	5.797	7.000	8.000	-1826	160	1	1	25		
[4]	3	189268760	BOT	6x6	5.797	9.876	11.734	2082	2142	20	1	120	a2g3	
[5]	4	260320616	BOT	6x6	5.797	10.342	11.844	-2074	548	20	1	120	a3g4	
[6]	5	260318824	BOT	6x6	5.797	10.521	12.766	-2084	984	20	1	120	a3g4	
[7]	6	260180632	BOT	6x6	5.797	8.731	10.234	312	-2433	20	1	120	aX	
[8]	7	260182104	BOT	6x6	5.797	8.733	10.234	-2357	-2410	20	1	120	aX	
[9]	0	260323048	ACQ	6x6	5.797	10.733	12.234	-62	63	20	1	120	a4	
[10]	1	260185712	ACQ	6x6	5.797	10.805	12.312	1677	-1260	20	1	120	a4	c
[11]	2	260325616	ACQ	6x6	5.797	10.385	12.047	-1818	879	20	1	120	a3	

>> WARNING: [9] Magnitude. 10.733
>> WARNING: [10] Magnitude. 10.805
>> WARNING: [5] Magnitude. 10.342
>> WARNING: [6] Magnitude. 10.521
>> WARNING: [10] Marginal star. B-V = 0.700, Mag_Err = 0.41, Pos_Err = 0.20
>> WARNING: [11] Magnitude. 10.385

Probability of acquiring 2,3, and 4 or fewer stars (10^x):   -4.770 -3.106 -1.926
Acquisition Stars Expected : 5.99

On-board control - star acquisition

Post-game analysis with Mica:

- Retrieves telemetry and processed products from the CXCDS archive
- Stores these products in a Ska file archive for speed and convenience
- Creates report pages: “most of what you need to know about an observation”
- https://icxc.harvard.edu/aspect/mica_reports/11/11762/index.html

IDX	SLOT	ID	TYPE	SZ	MAG	YANG	ZANG	NOTES	OBC_ID	MAG_OBS	TRAK %
1	0	2	FID	8x8	7.000	-773	-1741			6.812	100
2	1	4	FID	8x8	7.000	2140	166			6.875	100
3	2	5	FID	8x8	7.000	-1826	160			6.875	100
4	3	189268760	BOT	6x6	9.876	2082	2142	a2g3	NOID	11.062	90
5	4	260320616	BOT	6x6	10.342	-2074	548	a3g4	ID	10.312	100
6	5	260318824	BOT	6x6	10.521	-2084	984	a3g4	NOID	11.250	91
7	6	260180632	BOT	6x6	8.731	312	-2433	aX	ID	8.750	100
8	7	260182104	BOT	6x6	8.733	-2357	-2410	aX	ID	8.750	100
9	0	260323048	ACQ	6x6	10.733	-62	63	a4	ID	10.625	
10	1	260185712	ACQ	6x6	10.805	1677	-1260	a4c	NOID	11.688	
11	2	260325616	ACQ	6x6	10.385	-1818	879	a3	NOID	11.062	

On-board control - star acquisition

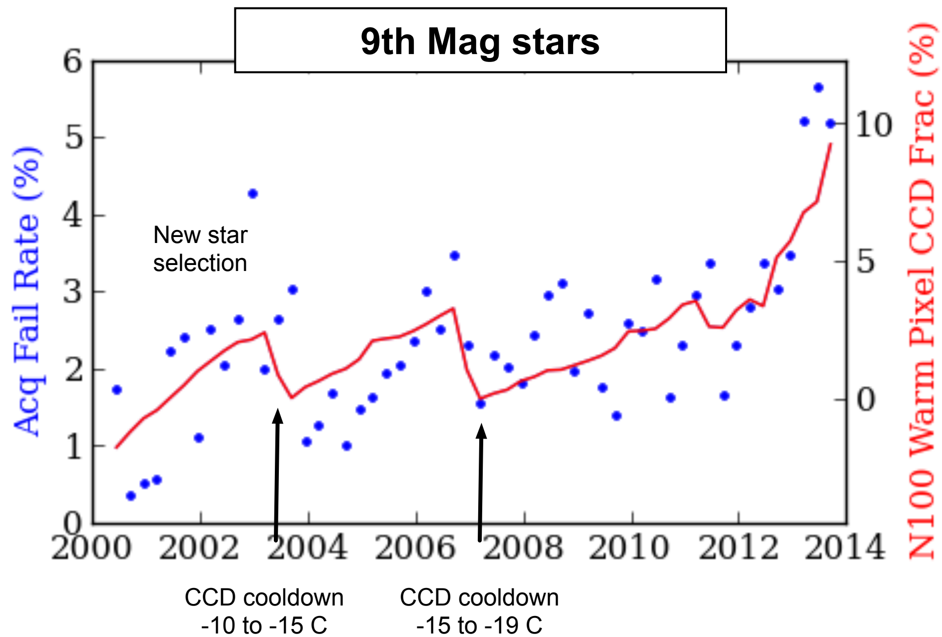
- Trends in acquisition failure rate correlate well with warm pixel fraction N100 (N > 100 e-/sec)
- *Red line: Scale * N100 + Offset*

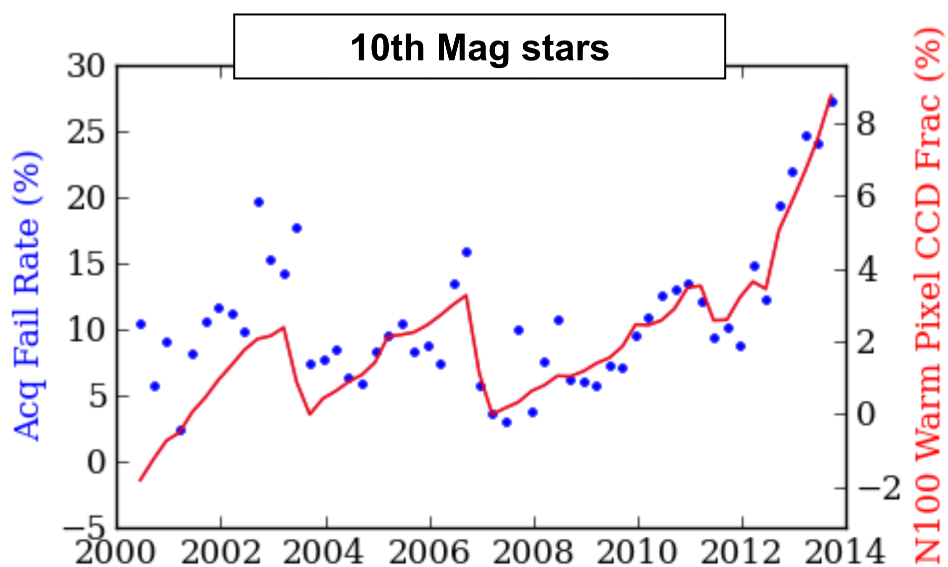
Can we predict future performance as a function of magnitude, time and CCD temperature?

- Find Scale(mag), Offset(mag)
- Find N100(time, temperature)

P_{acq} = *Scale * N100 + Offset*

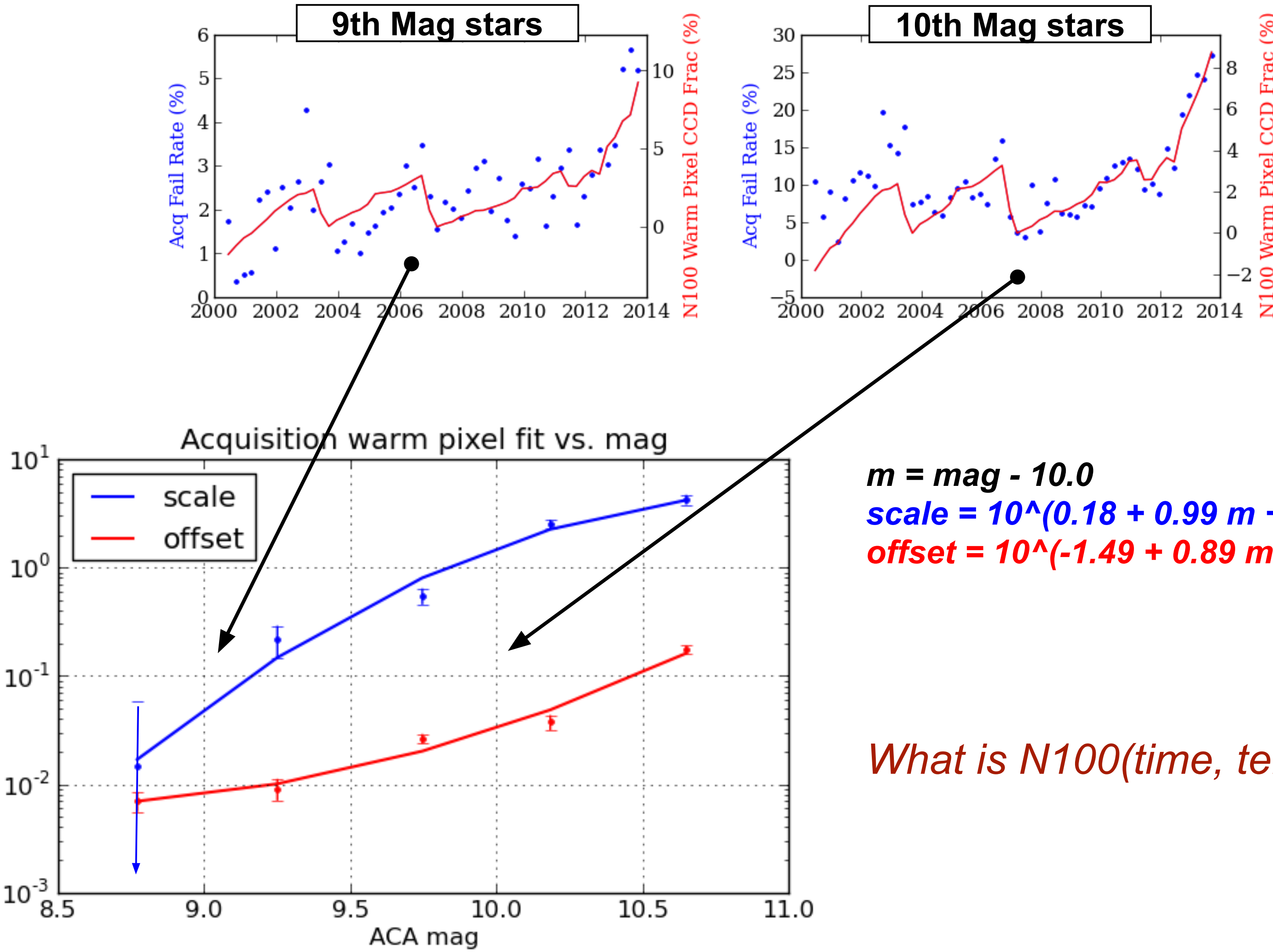
** N100 is always normalized by 1024^2*





On-board control - star acquisition

- Use Sherpa to fit scale and offset for mission data in 0.5 mag bins



m = mag - 10.0

scale = 10^(0.18 + 0.99 m + 0.49 m^2)

offset = 10^(-1.49 + 0.89 m + 0.28 m^2)

What is N100(time, temperature)?

Computing the predicted dark current distribution

In order to make near-term predictions of the coupled effect of radiation damage and temperature increases, an empirical model of ACA CCD radiation damage has been developed.

- Assumes:
  - Incident damage as a sudden increase in the dark current of a single pixel
  - Constant rate of damage with a fixed spectral shape
  - Exponential temperature sensitivity with dark current ~ $K^{(T - T0) / m}$
- Calibrated using mission dark cal data.
- Gives a good fit to all data.
- Forms the basis of ACA performance *predictions*, and in particular allows computation of *N100(time, temperature)*

Coupling CCD radiation damage and temperature

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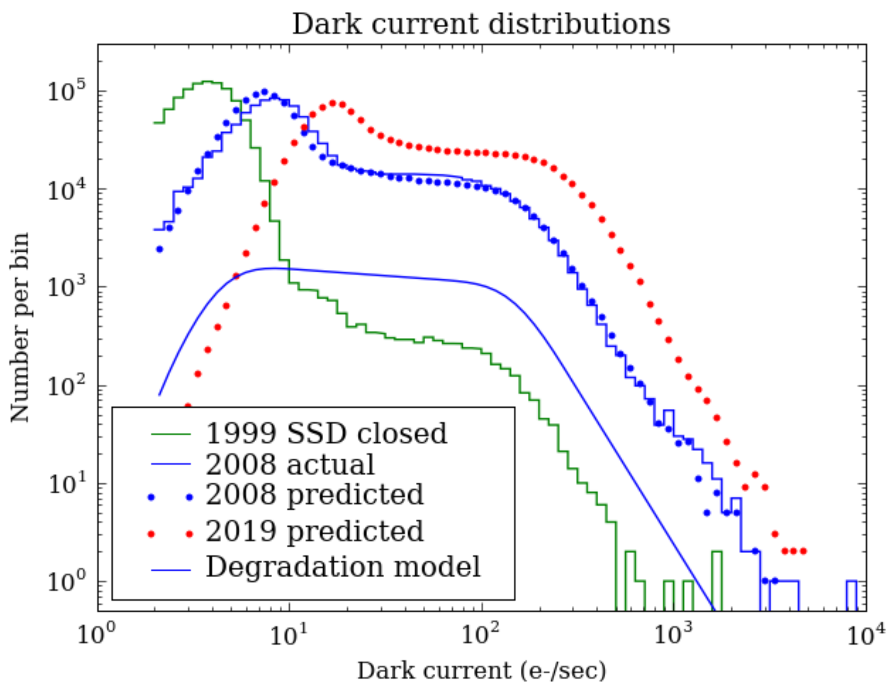
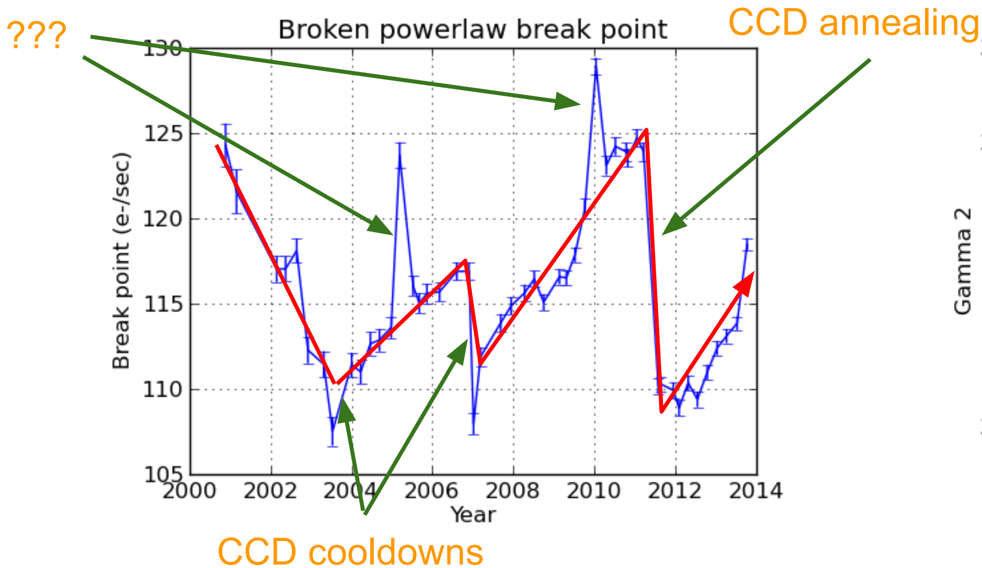
Dark current model details

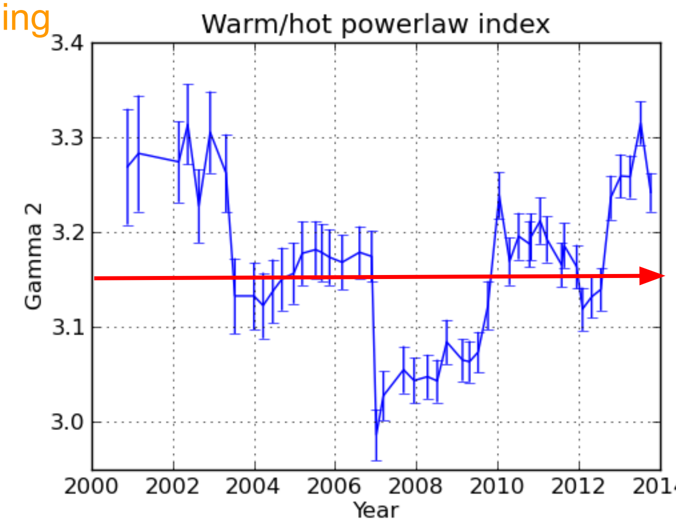
- For each epoch, model the distribution as a smoothed broken power-law.
- Parameters: Gamma1, Gamma2, Break point, Amplitude
- For warm pixel analysis the gaussian peak is ignored and Gamma1 is frozen at a constant value.

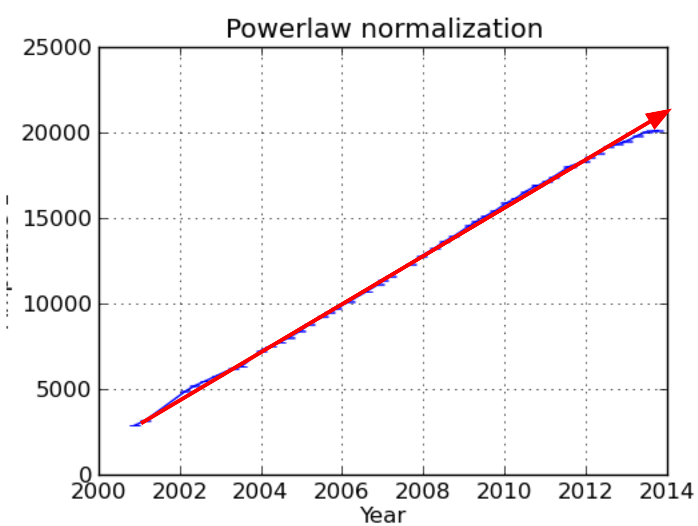


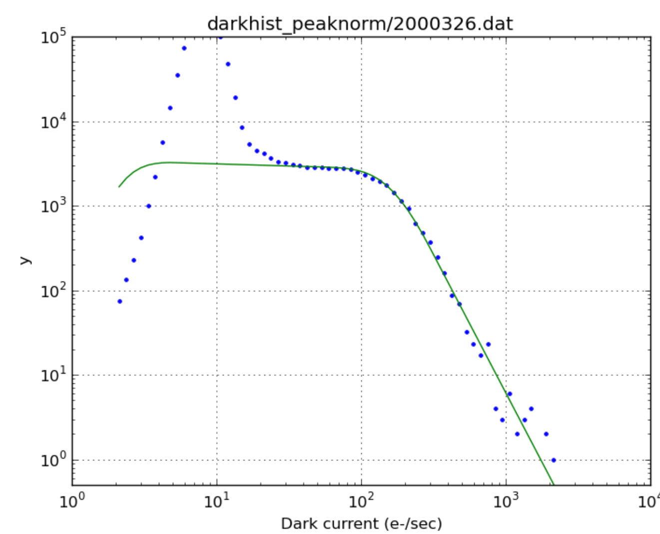
Coupling CCD radiation damage and temperature

Fit model using Sherpa, then create piecewise linear approximations to parameter fits, *and extrapolate.*





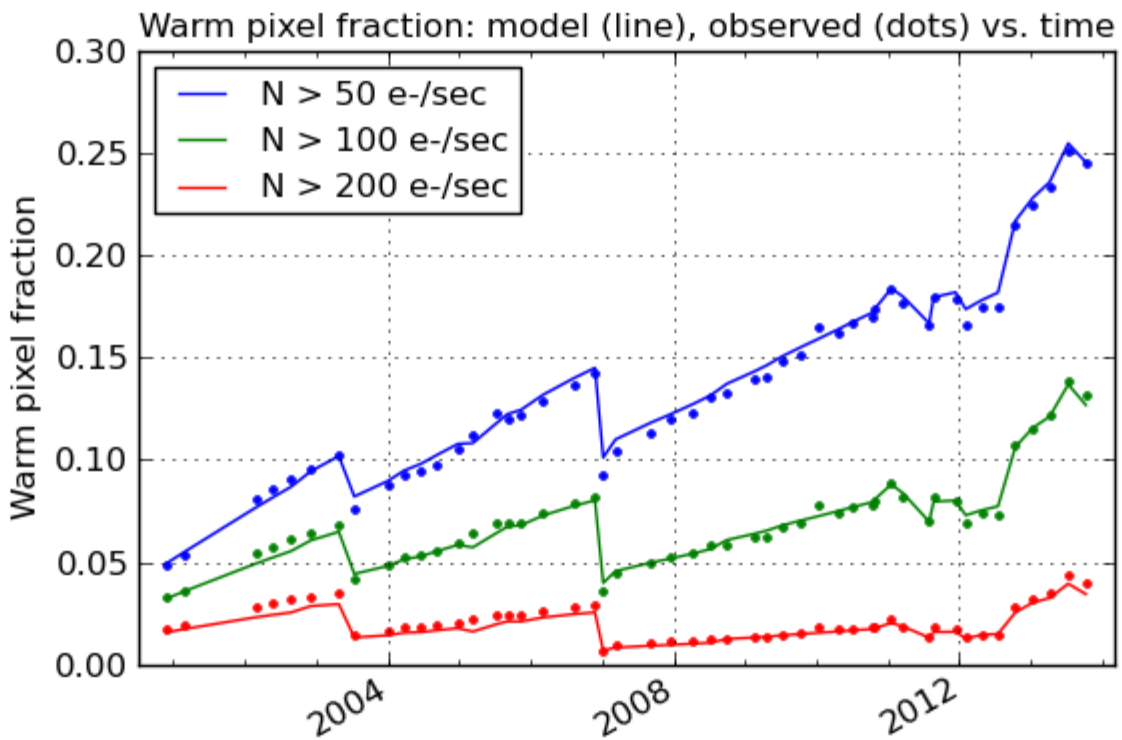




[Animation Link]

Coupling CCD radiation damage and temperature

<u>How accurately does the model predict historical warm pixel data?</u>



Coupling CCD radiation damage and temperature

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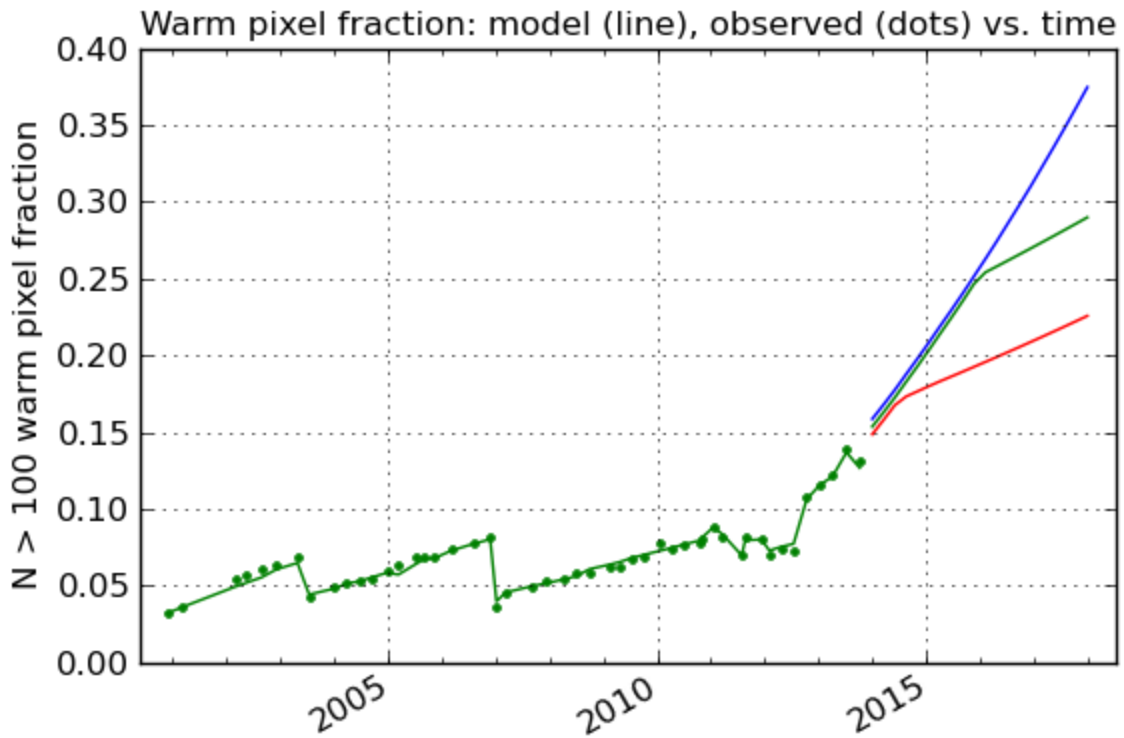
What is the predicted N > 100 fraction for three analysis cases?

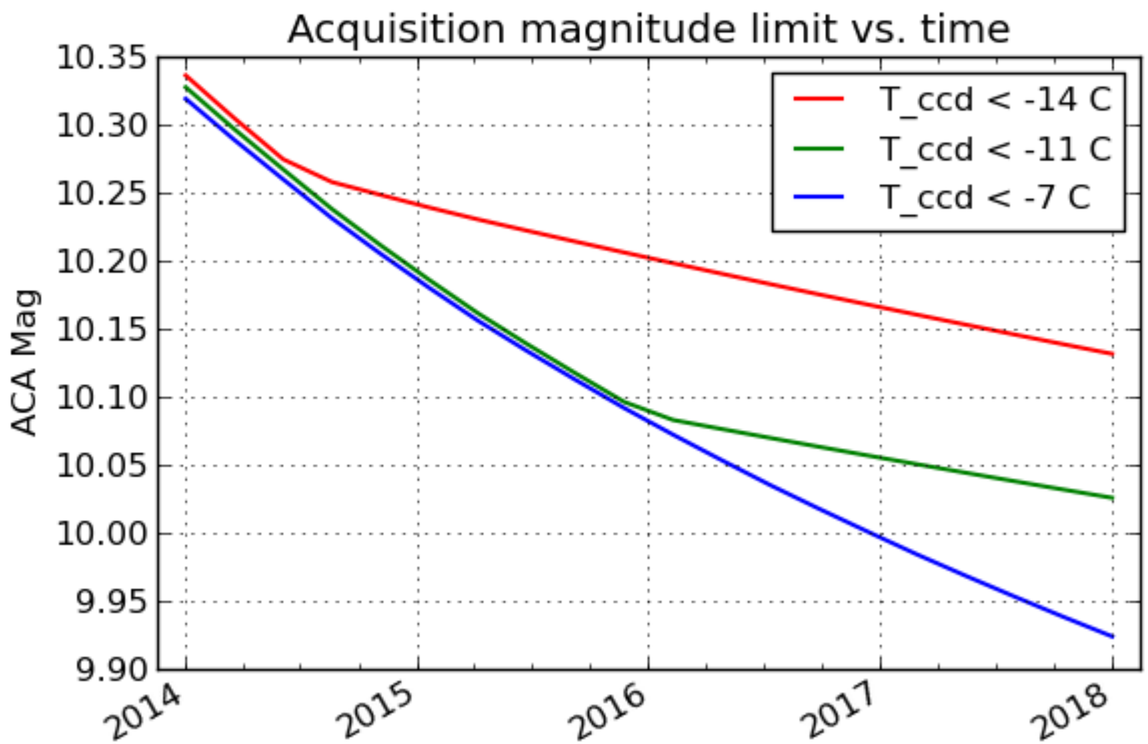
T_CCD < -14 C (red), -11 C (green), -7 C (blue)



On-board control - star acquisition

Let's predict future performance as a function of magnitude, time and CCD temperature!

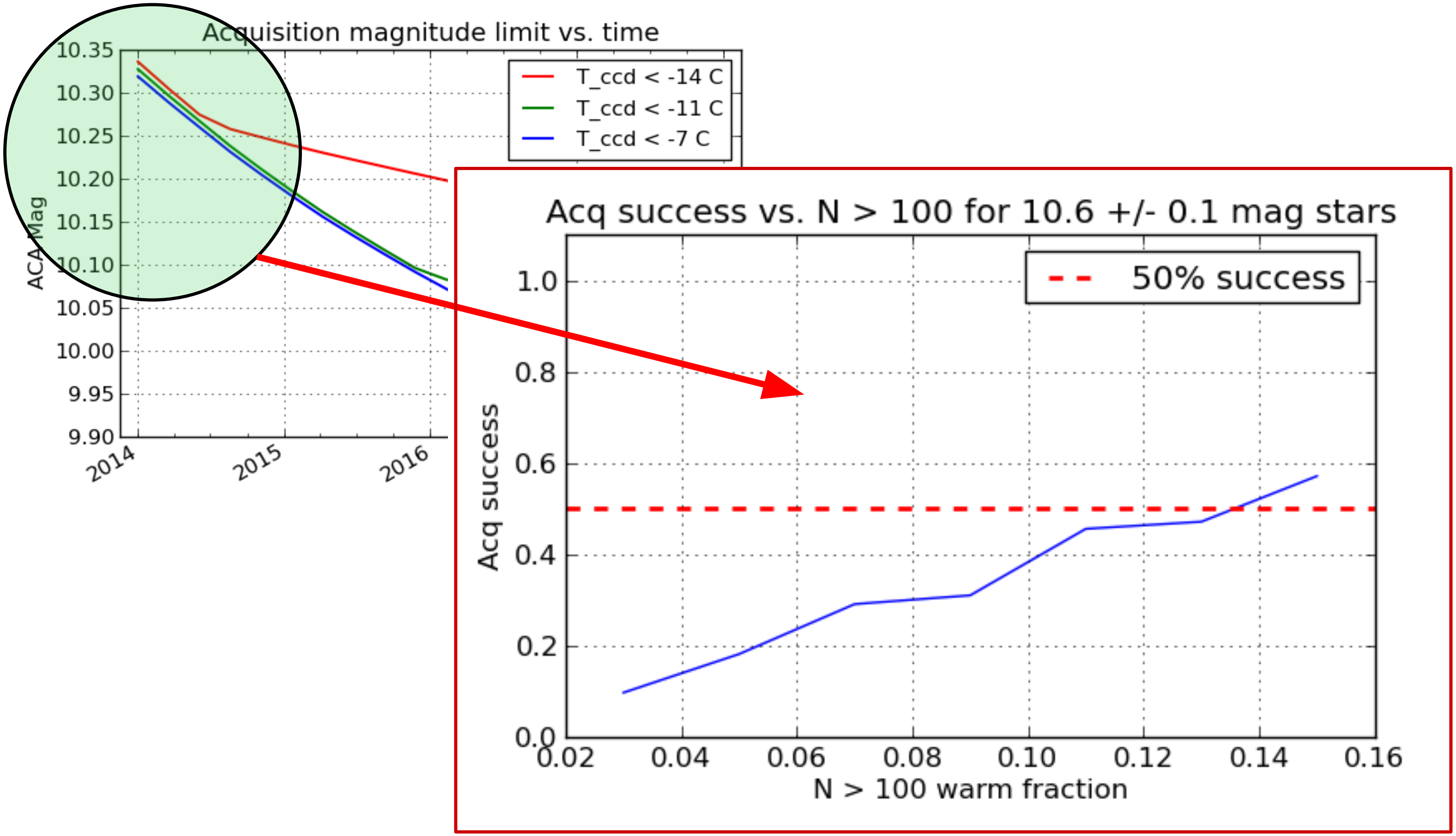
Define acquisition limiting magnitude as the magnitude where P_{acq} = 50%.
Solving for *Scale(mag) * N100(time, temperature) + Offset(mag) = 0.5* gives:



On-board control - star acquisition

Q: Aren't we still using 10.6 as the magnitude limit for acquisition stars?

A: Yes, and that is a bit optimistic at this point:



Put it all together to predict the fraction of the sky with good acquisition catalogs

- Definition of a "good" acquisition catalog depends on the accepted level of risk for a failed acquisition sequence (and subsequent safing action).
- Historically we have had significant margin, with no failed acquisitions (due to a poor catalog) in over 20000 observations.

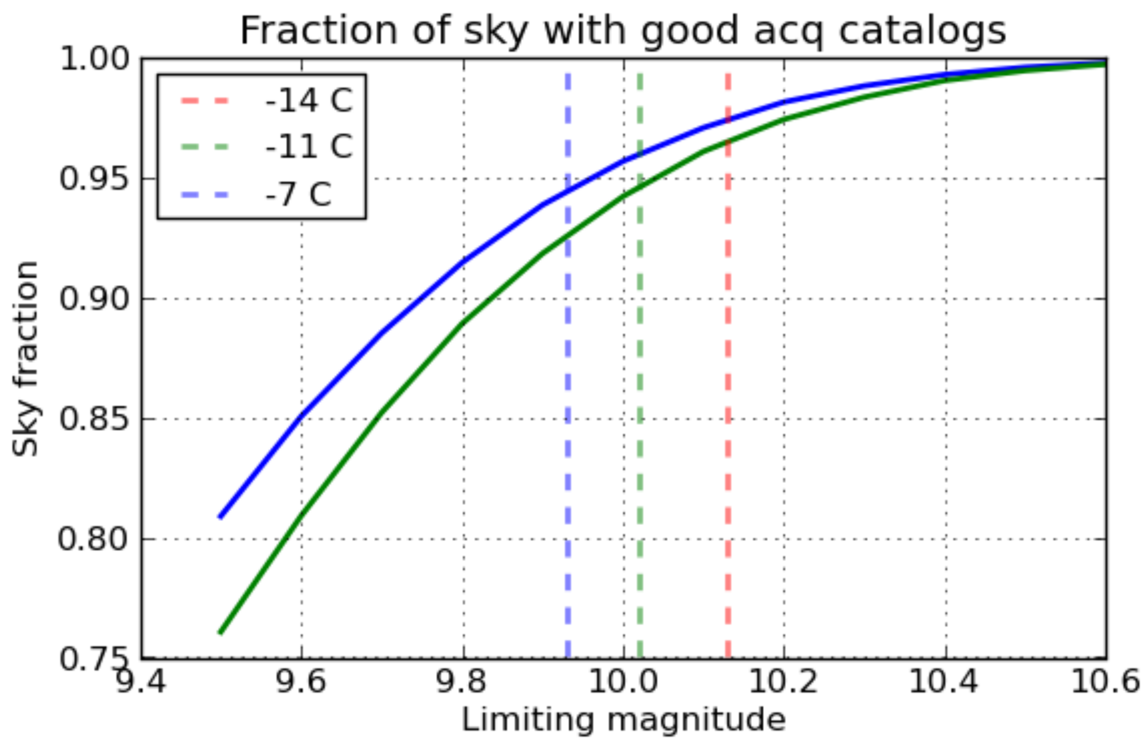
Assume a magnitude limit of M_{lim} (where P_{acq} = 50%).
Define three minimum star counts:

$N_{0.6}$: Number of solid stars, brighter than M_{lim} - 0.6 mag
$N_{0.3}$: Number of decent stars, brighter than M_{lim} - 0.3 mag
$N_{0.0}$: Number of marginal stars, brighter than M_{lim}

A good acquisition catalog then has (conservative case):
$N_{0.6}$ >= 2 (at least 2 solid stars)
$N_{0.3}$ >= 3 (which includes the 2 solid stars)
$N_{0.0}$ >= 5 (which includes the 3 solid / decent stars)

Put it all together to predict the fraction of the sky with good acquisition catalogs in Jan 2018.

Sample the AGASC 1.6 star catalog at 50000 positions over the sky and compute whether the available stars comprise a “good” catalog for acquisition.



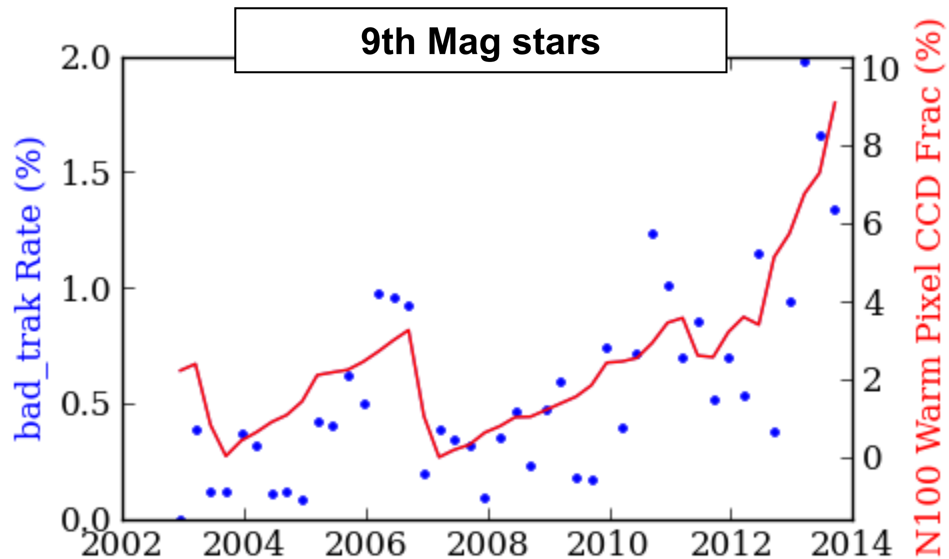
Green is conservative case ($N_{0.6}$ >= 2, $N_{0.3}$ >= 3, $N_{0.0}$ >= 5)
Blue is higher risk case ($N_{0.6}$ >= 2, $N_{0.3}$ >= 3, $N_{0.0}$ >= 4)

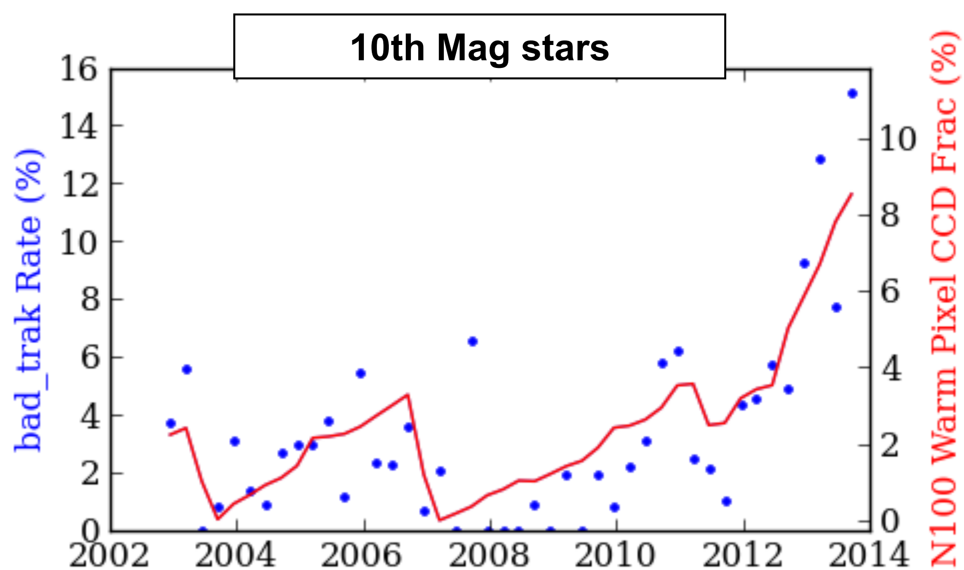
On-board control - guide star tracking

- As with acquisition, trends in guide star tracking correlate with warm fraction N100 (N > 100 e-/sec)
- *Red line: Scale * N100 + Offset*
- *Blue dots: bad track fraction*

Reminder: “bad track” means a star was tracked less than 95% of the observation.

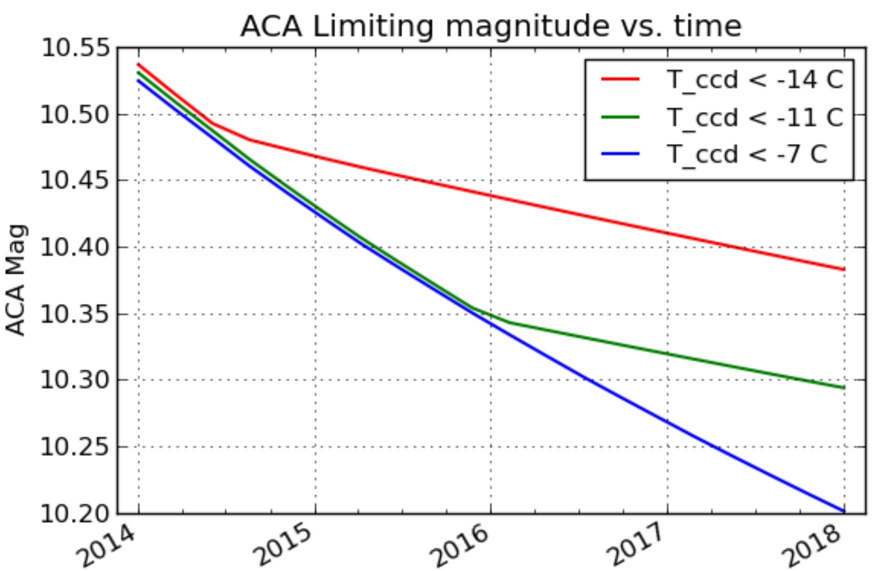
This is a yes/no similar to asking if a star was acquired.

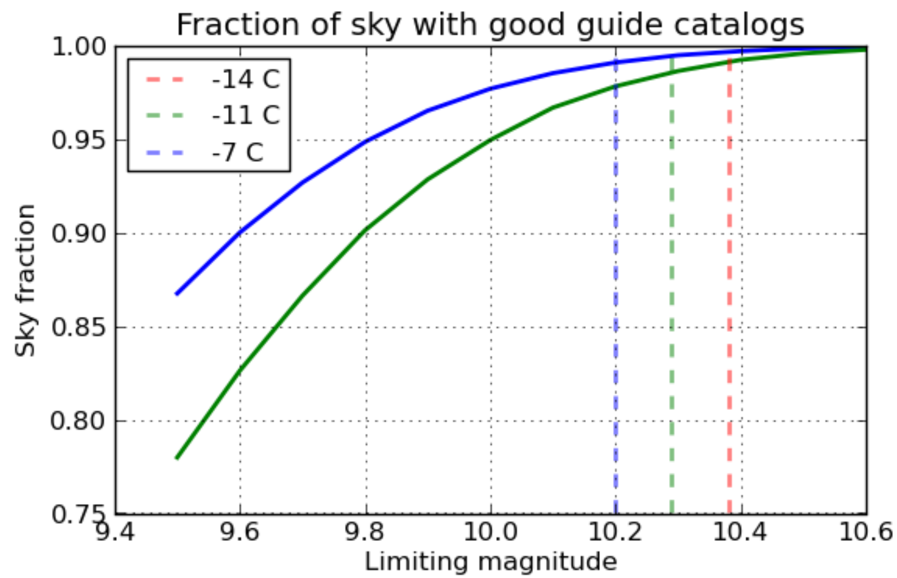




On-board control - Guide star tracking

- Guide star limiting magnitude is defined as the magnitude where
  *P(bad_track) = Scale(mag) * N100 + Offset(mag) = 50%*
- *Compute fraction of sky with good guide catalogs in Jan 2018.*

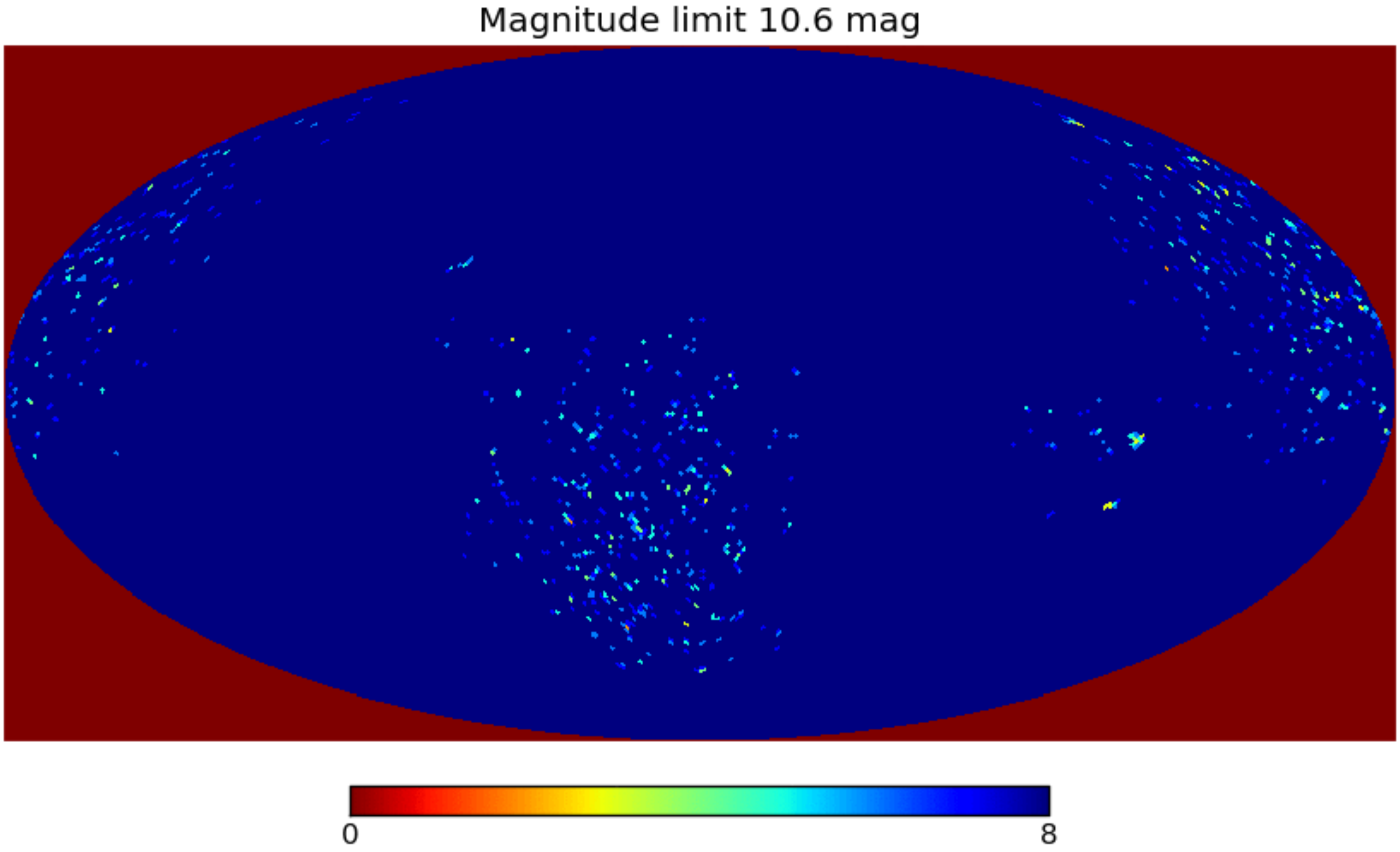




Green is conservative case ($N_{0.6}$ >= 1, $N_{0.3}$ >= 3, $N_{0.0}$ >= 5)
Blue is higher risk case ($N_{0.6}$ >= 1, $N_{0.3}$ >= 2, $N_{0.0}$ >= 4)

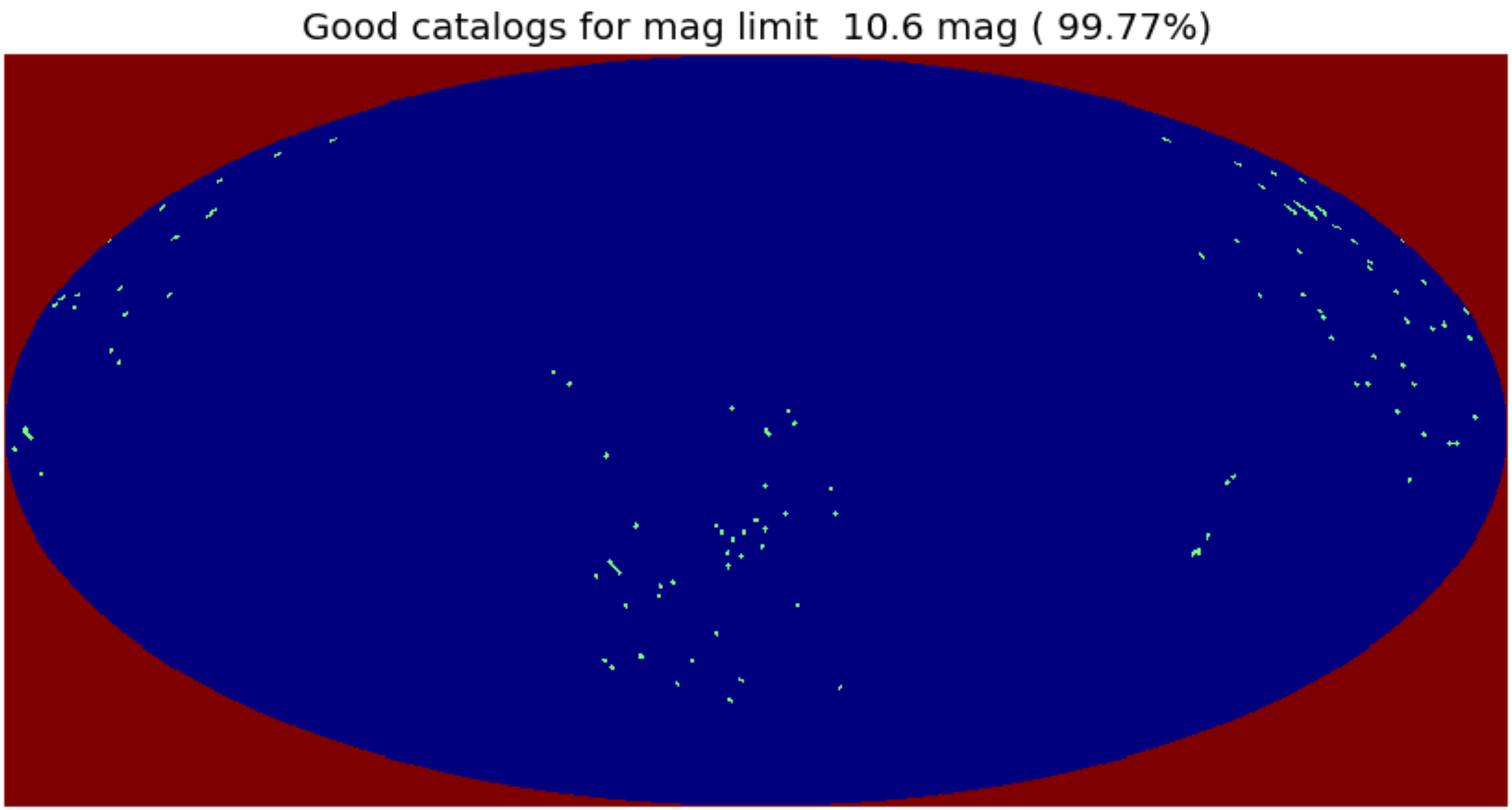
Mission planning - ACA limiting magnitude

This visualization shows the number of guide stars in the ACA FOV brighter than the given magnitude limit. *[Animation link]*



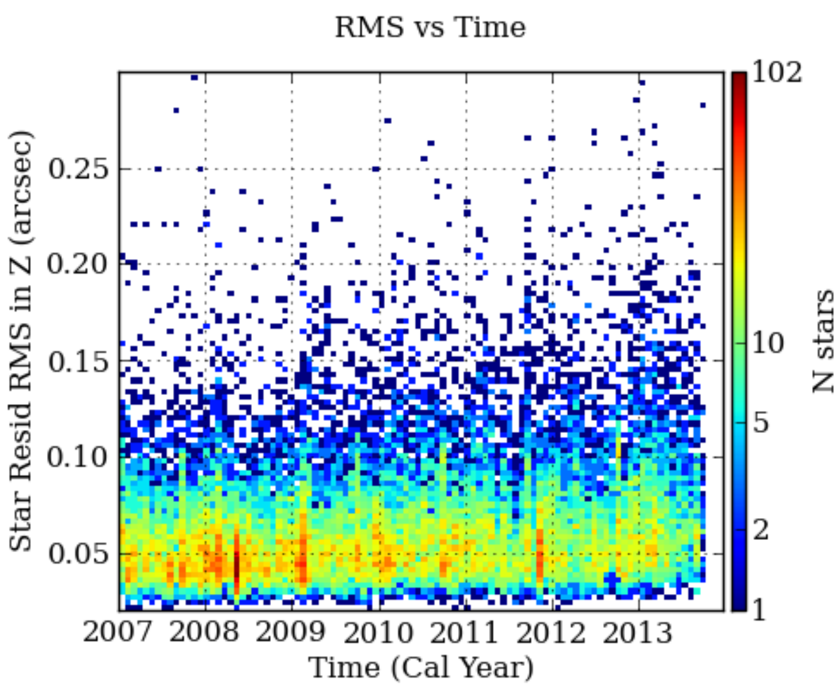
Mission planning - ACA limiting magnitude

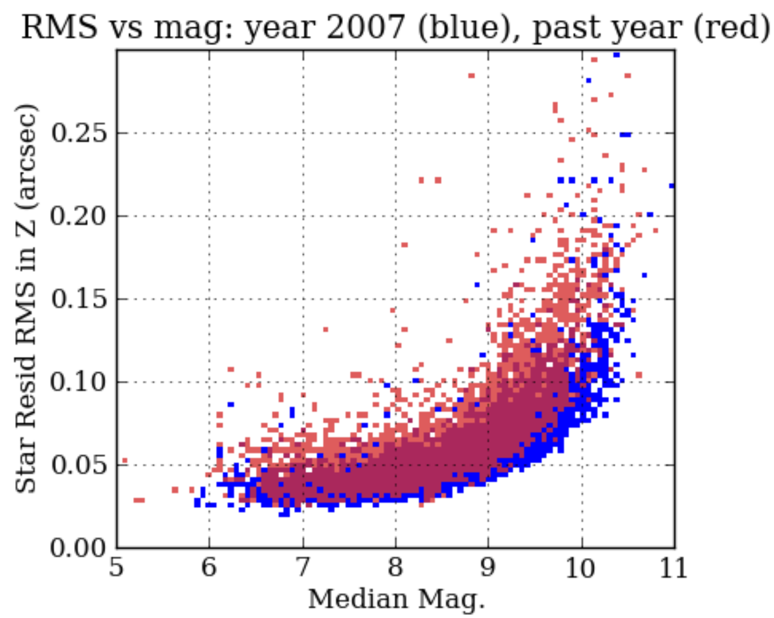
This shows the sky area with good acquisition catalogs (blue) or not good catalogs (green) for the $N_{0.6}$ >= 2, $N_{0.3}$ >= 3, $N_{0.0}$ >= 4 case. *[Animation Link]*



Ground aspect - Degraded image reconstruction

- As noted in previous trending discussion there is a noticeable effect in primary aspect data.
- Downstream impact on X-ray image PSF not expected to be observable, though detailed analysis is not available.

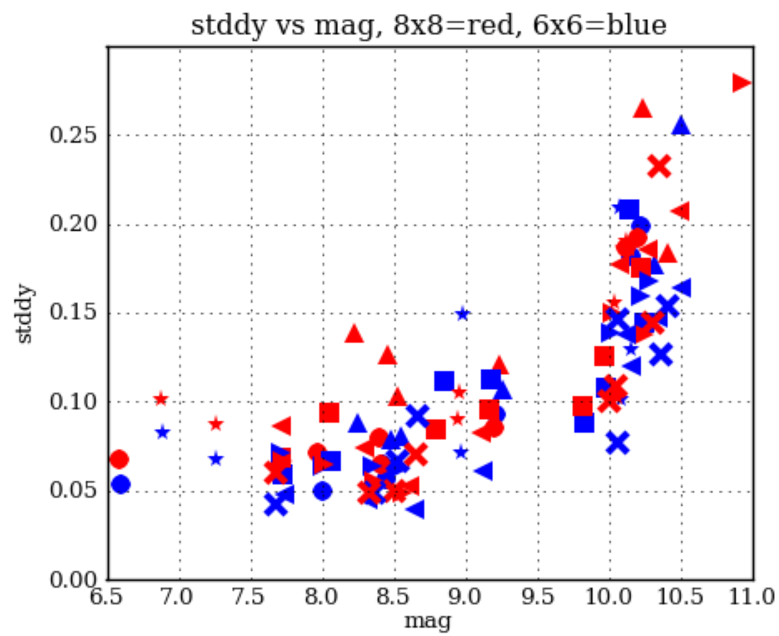




Ground aspect - Degraded image reconstruction

Warm and hot pixels are the primary cause of degraded centroiding.

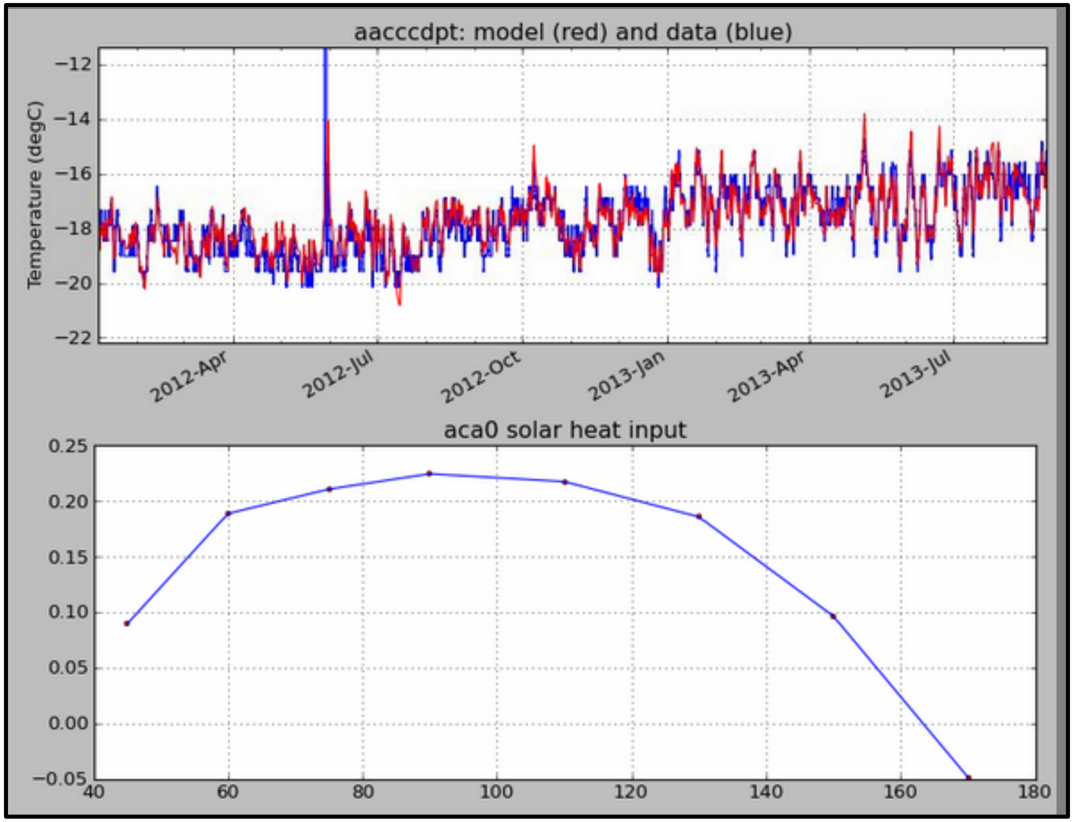
- One mitigation option is to use an 8x8 pixel readout window which provides better data for *on-the-fly dark current subtraction*, where dark current is measured during observation using edge pixels.
- Given the ~5 arcsec PSF for stars, 8x8 gives cleaner dark measurement.
- As part of a pathfinder study, a series of test obsids were run in late 2012 with 6x6 and 8x8 readouts used on the same sets of stars.
- Results in the plot show no significant change in centroid performance, but *without* an improved on-the-fly algorithm.
- This dataset will be used in future algorithm studies, which could include a PEA patch for on-the-fly dark current subtraction.



Individual star aspect solution residuals. Same stars have same symbols in red (8x8) and blue (6x6)

Mission planning - ACA thermal constraint

- As a control mechanism for all of the previously identified risks, we have implemented a mission planning constraint on the predicted ACA CCD temperature for weekly loads: $T_{CCD} < -14$ C
- Accurate to about +/- 1 C (90%).
- “Real” constraint is complicated: depends on detailed star catalog and influences probability of a safing action.



Long-term risks for the 25-year mission

NORTHROP GRUMMAN

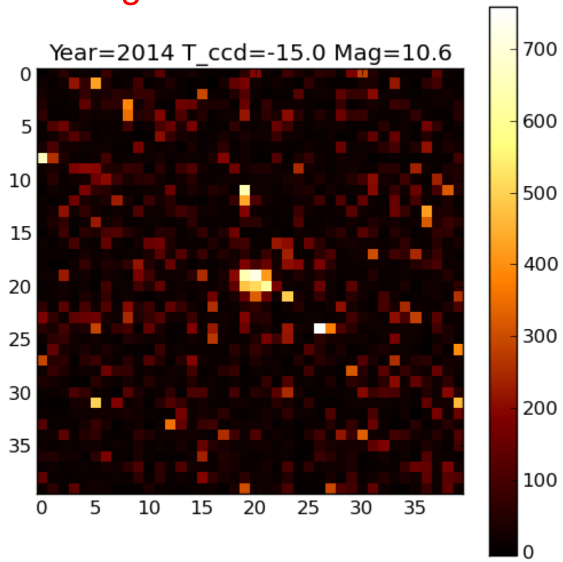
No life limiting factors -- by starting now we will prepare for the serious challenges.

- Acquisition and guide performance at 25 years (2024)
- Checking out the B-side PEA
  - CCD might be less damaged because it has been at room temperature
  - Preparing for possible A-side ACA failure
- Continuing the mission for failure of both A and B-side ACA.

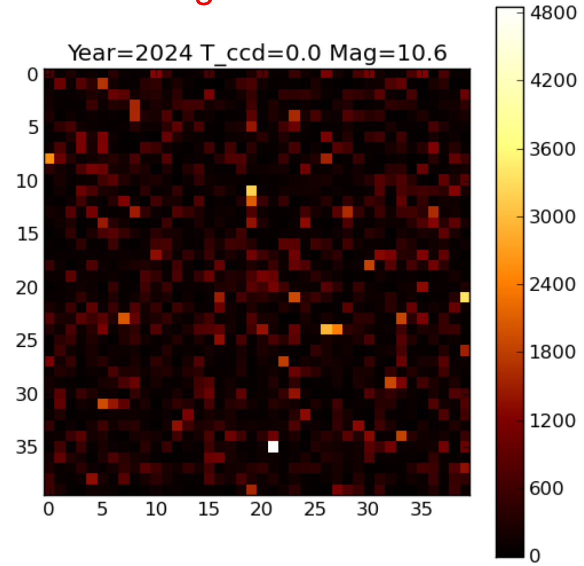
Guide and acquisition at 25 years

- Substantial uncertainty in the thermal environment at 25 years
- Some uncertainty in dark current and related performance because damage will no longer be in the linear regime.
- Plenty of opportunity for more sophisticated analysis, but start simple:
  - N100 extrapolations don’t work since they rely on linear dark current.
  - Instead, roughly estimate limiting magnitude at 25 years by doing a by-eye comparison of simulated images.
  - Image on right illustrates that 10.6 mag will not be feasible at 25 years.

Reference: 2014
T_{CCD} = -15 C
Mag = 10.6



25 years: 2024
T_{CCD} = 0 C
Mag = 10.6

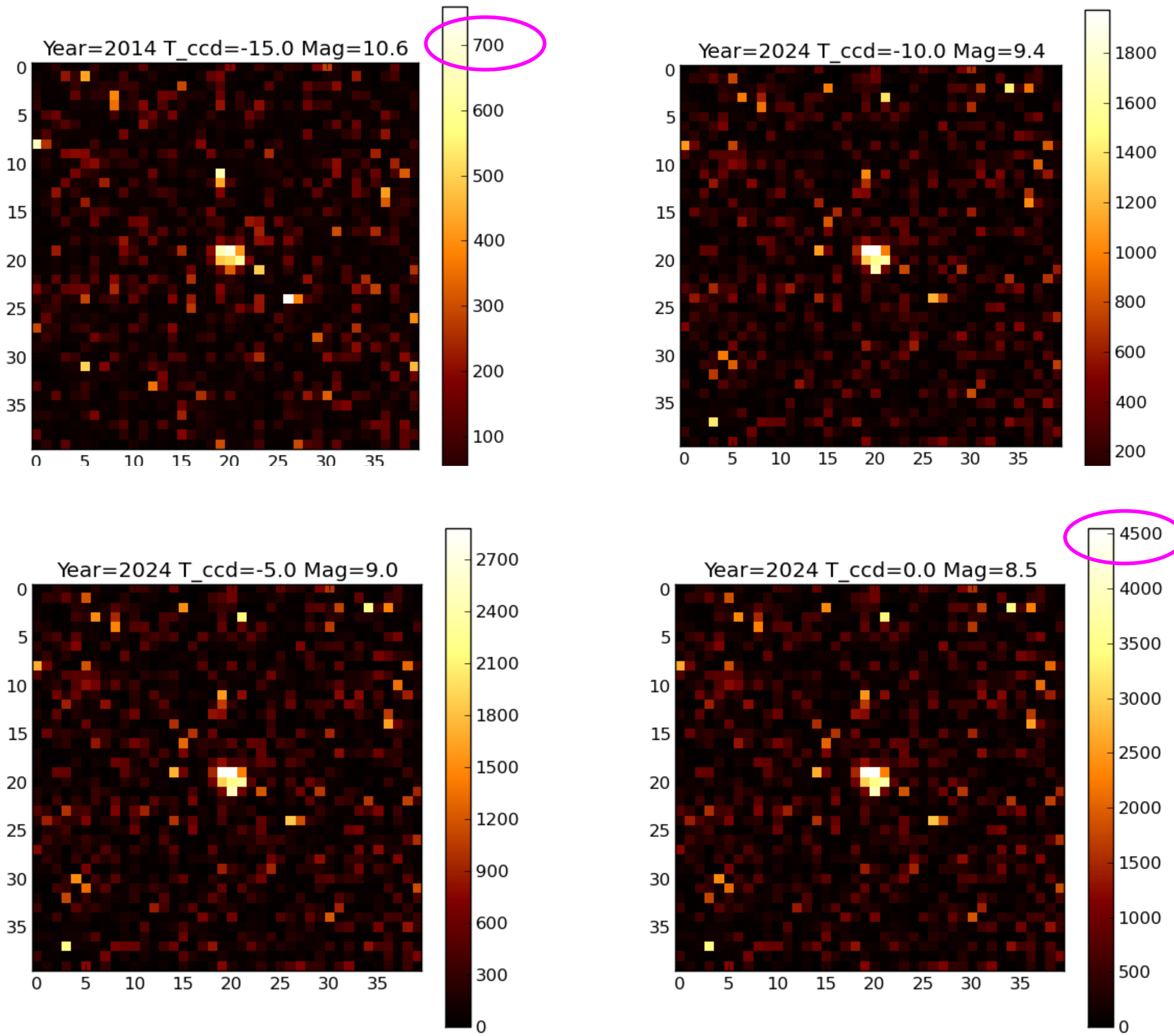


Guide and acquisition at 25 years

25 year images for three temperature cases visually matched to the reference by varying Mag

Reference
2014

25 years
T_ccd = -10 C
Mag = 9.4



Note
scale

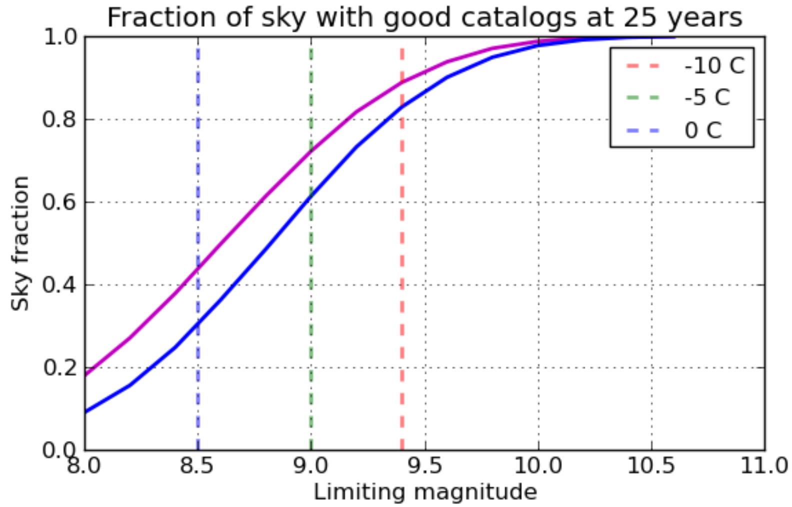
25 years
T_ccd = -5 C
Mag = 9.0

25 years
T_ccd = 0 C
Mag = 8.5

Guide and acquisition at 25 years

With continuing innovation the aspect system can support a 25 year mission:

- Brighter limiting magnitudes will reduce the available sky fraction
- Mitigate with:
  - Perform temperature-sensitive planning
  - Implement less disruptive response to failed acquisition or lost guide stars
  - Patch PEA to improve centroiding in the presence of warm pixels
  - Gyro hold and (where possible) X-ray self-calibration.
  - Integrate star requirements with proposal planning / evaluation and LTS generation (choose optimal roll). Note Galactic plane is mostly OK.



Blue is guide star “higher risk” case ($N_{0.6}$ >= 1, $N_{0.3}$ >= 2, $N_{0.0}$ >= 4)

Magenta is corresponds to $N_{0.6}$ >= 1, $N_{0.3}$ >= 2, $N_{0.0}$ >= 3

Checking out and swapping to the ACA B-side

- CARD PCAD-C-010 requires that only one PEA may be powered on at a time in order to avoid loss of meaningful telemetry and potential damage to Aspect Camera electronics
- Telemetry from PEA-2
  - Not available in science formats (1 or 2)
  - Format 4 does provide telemetry for PEA-2 as well as PEA-1
  - Patch to CTU EEPROM required for PEA-2 telemetry to be available in science formats
- May be possible to perform dark current measurements on B-side CCD using telemetry format 4 (needs further investigation)
  - Would require turning off PEA-1 and turning on PEA-2
  - Would not require insertion of flip mirror
  - Expect that B-side CCD may be less damaged (because it has been at much higher temperature than A-side)
- Switch to B-side if A-side fails:
  - Turn off PEA-1 and turn on PEA-2
  - Insert flip mirror
  - Patch CTU EEPROM
  - Calibrate ACA

Continuing the science mission with failed ACA

- Normal Maneuver mode (gyro hold) used for science observations
- Large impact to pointing control and stability, and post-facto aspect determination

Recovery options depend on FSS availability

- FSS + Gyro + X-ray self-calibration
  - FSS output quantized to about 15 arcsec [1]
  - Would require large dither amplitude for gyro bias estimation
  - Degeneracy about Sun line
  - On-board bias updates (based on maneuvers)
  - Bright X-ray point sources can be used for ground corrections to gyro bias (both on-board and post-facto)
  - Use FSS measurements closed-loop to prevent attitude change due to large gyro bias excursions
- Gyro + X-ray self-calibration
  - Bright X-ray point sources can be used for gyro bias estimation
  - Use CSS measurements closed-loop to prevent attitude change due to large gyro bias excursions
  - May want to fix solar array angles in NMM to enhance usefulness of CSS measurements

[1] See http://occweb.cfa.harvard.edu/twiki/Aspect/FssVersusAspectSolution for further info on FSS versus aspect solution sun pitch

Summary of mitigation steps for issues

- Adjust star catalog and dither
  - Use 6 guide stars and 2 fid lights
  - Adjust image window size (8x8 instead of 6x6)
  - Increase dither amplitude
- Constraints
  - Mission planning constraint on ACA CCD temperature [DONE]
  - Potential proposal constraints (star field evaluator?)
- Software patches
  - OBC: Ignore ACA defective pixel flag [DONE]
  - PEA: Weighted centroiding
  - PEA: On-the-fly warm pixel detection
  - OBC: Reacquire lost fid lights
  - OBC: Drop intermittently acquired/identified stars
  - OBC: Reduce Kalman positional threshold to filter spurious centroids
- CXCDS software updates
  - Improved on-the-fly warm pixel detection using 8x8 pixel images
  - Time-variable dark map to handle flickering
- Activate flip mirror and use B-side (PEA and CCD)

Action list summary

Prioritized actions for SOT and FOT aspect are as follows:

- Increase the ACA CCD planning limit in 1 C per 3-month steps and evaluate performance at each step.
- Update the CXCDS alignment calibration (celestial location).
- Develop a formal probabilistic method for assessing star catalogs and associated risk of a safing action. Estimate uncertainties using historical data and predict near term performance.
- Include probability assessment for each star catalog in the ACA review tool including temperature and time.
- Update the ACA star and fid light distortion maps to improve celestial location accuracy.
- Develop and evaluate improved dark current subtraction code for ground processing.
- Investigate weighted centroiding algorithms for PEA.
- Identify code changes for OBC patches (fids, stars, centroids).

Summary

- A robust monitoring and trending system is in place.
- A reliable model of CCD dark current has been developed.
- Key ACA issues have been examined with high fidelity out to 2018.
  - Negligible degradation of post-facto image reconstruction.
  - No significant reduction in on-board control margin.
  - Increasing CCD temperature and dark current has a manageable near term impact.
- Explored issues for the 25 year timeframe and identified strategies to enable a continued excellent science mission.
- Identified mitigation options for current issues.
- Developed a list of near term actions and priorities.