Mission Planning Updates

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On behalf of SOTMP:
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Overall Context for Mission Planning

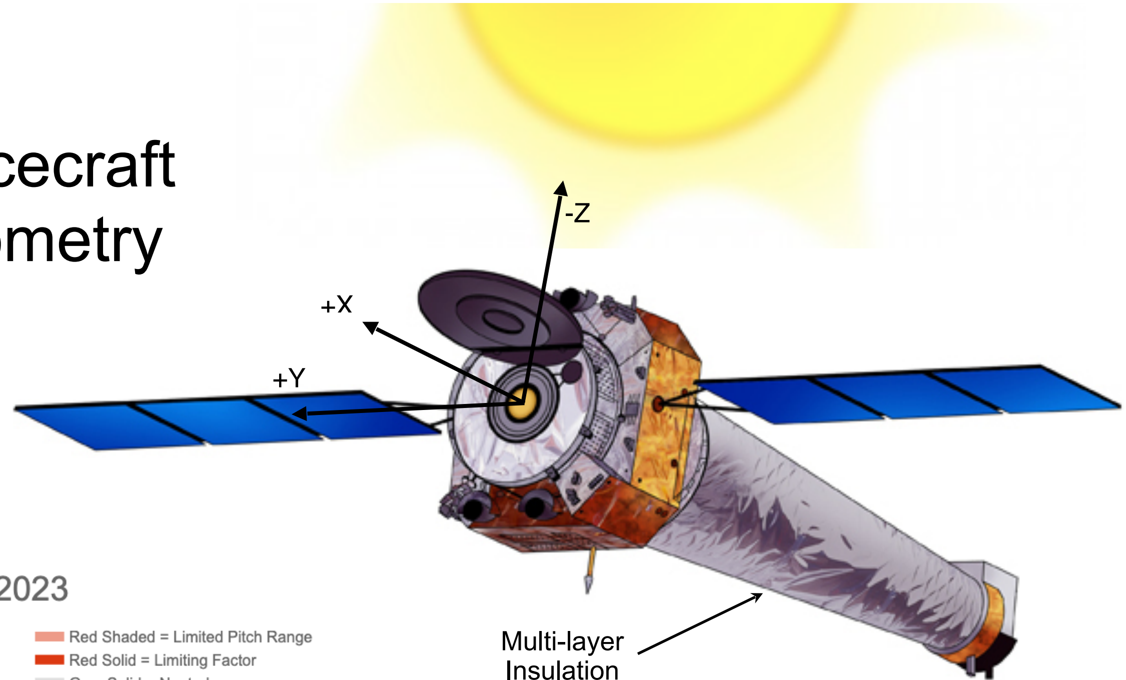
Goal:
Maximizing the science return of the mission in the presence of constraints:

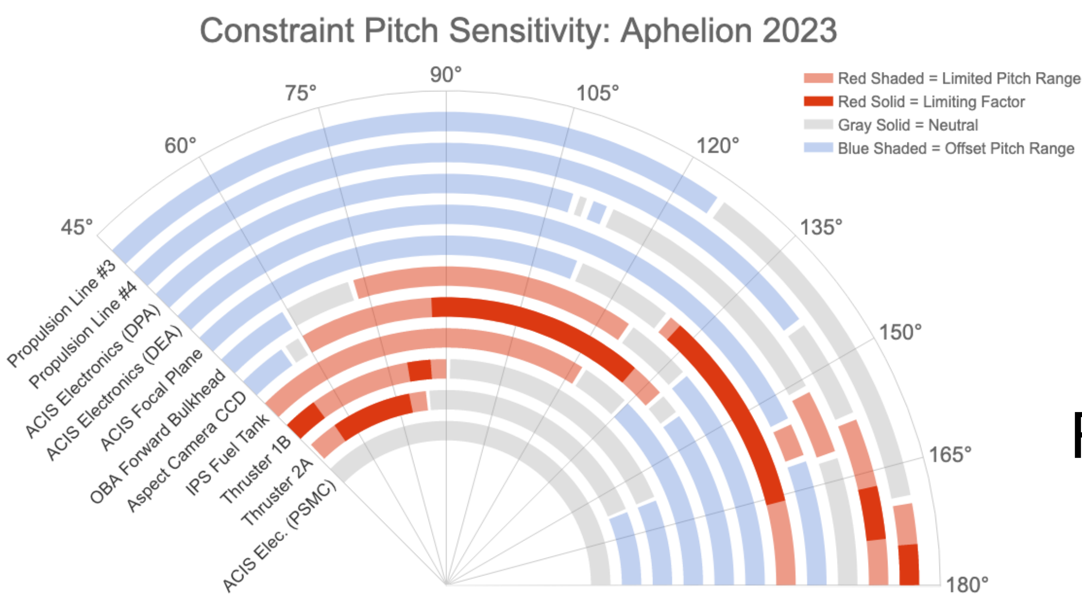
Observation constraints, e.g.,
- coordination
- time windows
- continuity of observations
- monitoring series and observation grouping
- roll constraints
- phase constraints

Engineering constraints, e.g.,
- *thermal constraints*
- star field constraints
- momentum management
- Sun, Moon, Earth, bright X-ray source avoidance

Chandra Thermal Restrictions

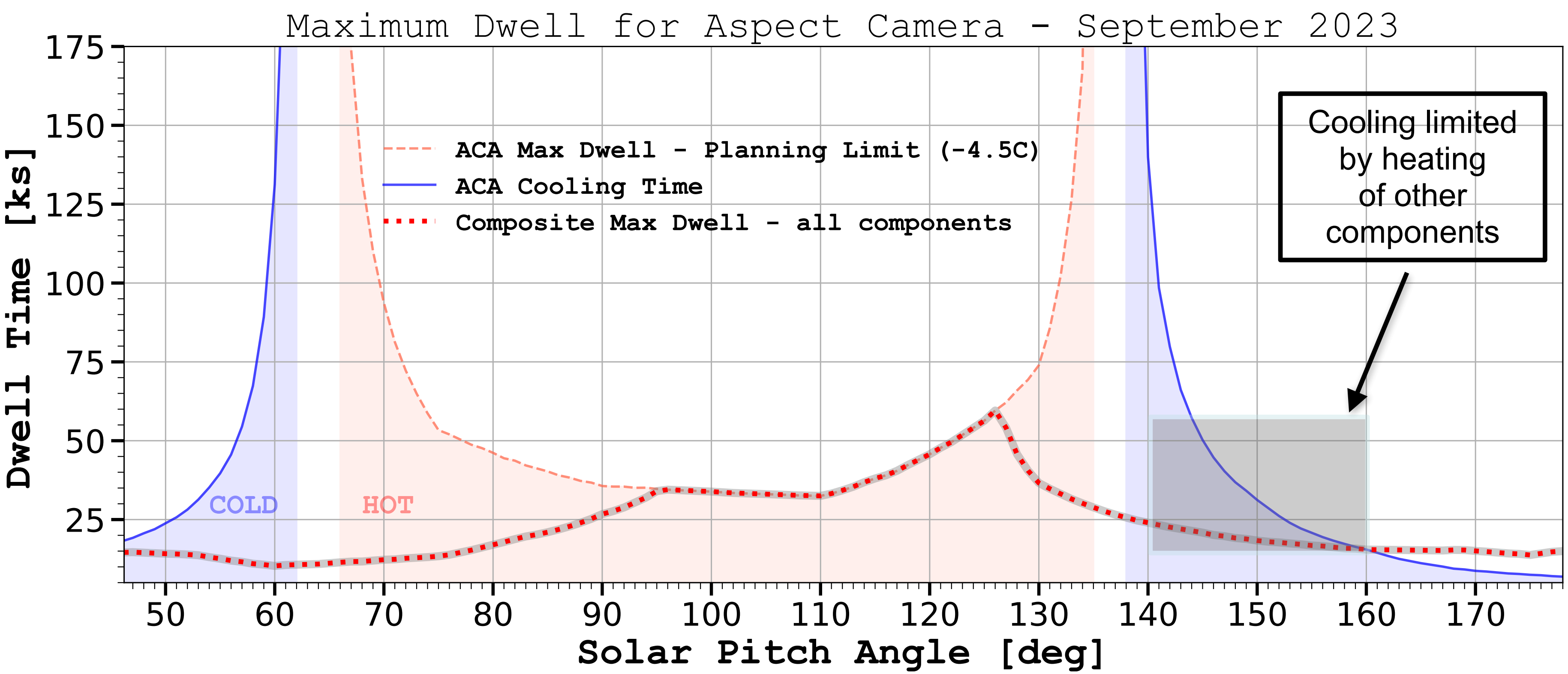
Spacecraft Geometry





Thermal Restrictions

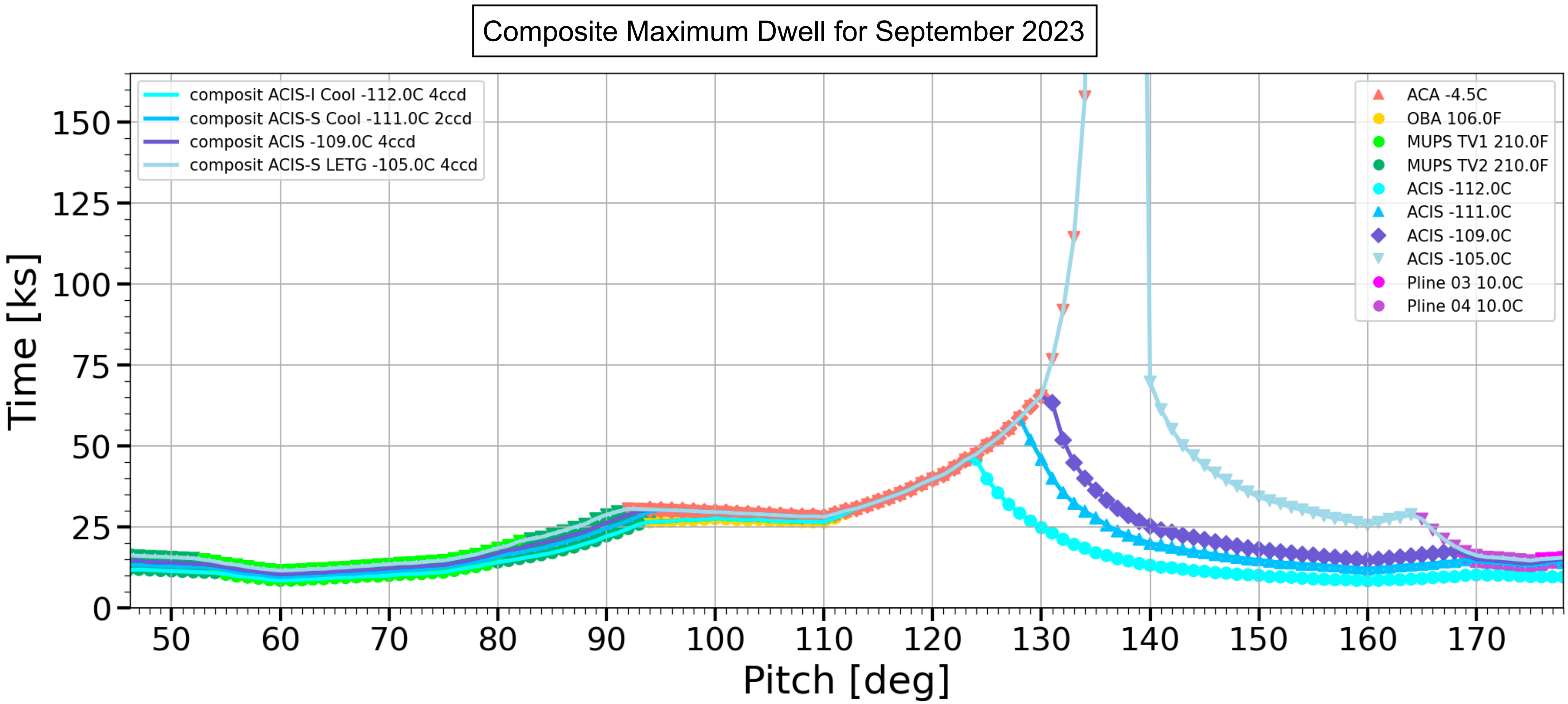
Thermal Balance: A Summary



Red: maximum exposure before exceeding temperature limit (dotted is **composite** for all components).

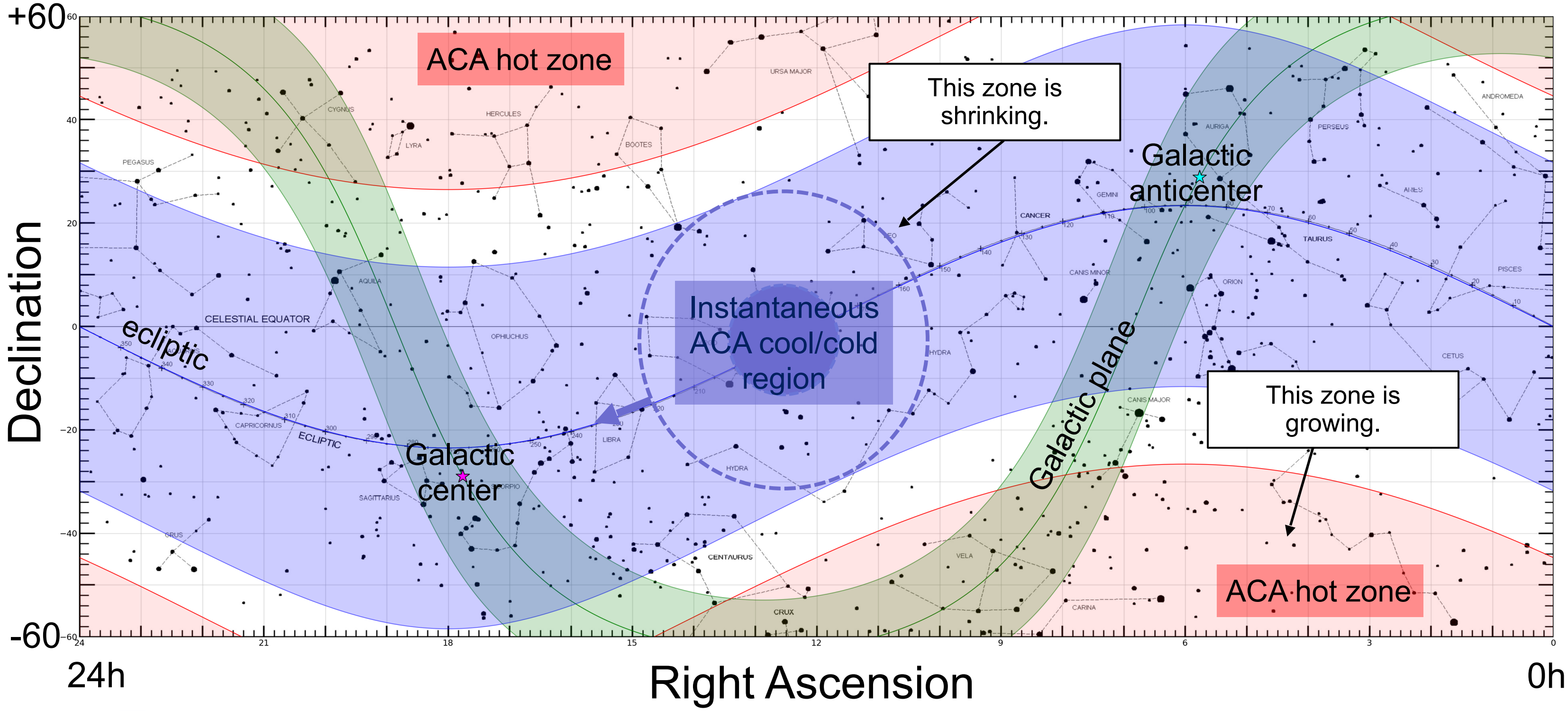
Blue: minimum cooling time required to return to state from which another max dwell possible

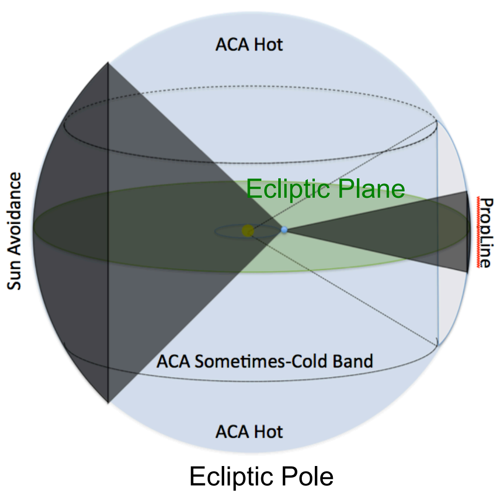
Thermal Balance: A Summary



- “Hot ACA” region (~ 90<pitch<130) now more favorable compared with other regions
- We have been working hard to stay ahead of rising temperatures with component planning limit increases, but that can only go so far….
- The MUPS thruster valve limits are not expected to increase significantly, which places tight and *permanent* limits on the maximum dwell time below 90 deg (and rising) pitch

Constraints: Sky View





- The sometimes-cool/cold ACA (-Z) region covers a band in the sky
- Although the story is no longer dominated by the ACA (rather by MUPS vs ACIS), the anti-Sun region is still extremely valuable for thermal management
- The cool region is shrinking and the hot ones are growing with time

Impact on the Long Term Schedule

Thermal balance

Momentum balance

Segment: 35 limit: 5.95d, used 5.28d = 88.74% 09-Oct-2023 00h to 16-Oct-2023 00h (UT) antisun plot

#Orbits: 3 Orbit Time: 486.73ks LTS Time: 454.00ks #Targets: 16

Thermal Budget:	cold budget
aca :	+129.5
mups :	-2.4
ipstank :	+39.0
dpa :	+154.0
hrc :	-4.5

momentum axes		momentum totals	
P_x :	+2.99	P_tot :	6.90
P_y :	-3.81	P_bal :	-7.65
P_z :	+4.92		

seq#		obs	name	time	RA	dec	Roll Range		Pitch Range		SI	R	O	grat	observer	Type	AO	OR#	SF	TC	RC	PC	UC	PU	Mlt	CRem	FP
402412	H	27975	LMC Deep Field 06	13.0	83.208	-67.033	68.7	61.8	92.4	92.2	ACIS-I	6	2	NONE	Antoniou	GO	24	0	N	N	N	N	N	N	N	N	-112.0
503344		25512	SNR 1987A	29.0	83.867	-69.270	69.2	62.3	91.3	90.9	HRC-S	–	–	LETG	Park	GO	24	0	N	Y	N	N	N	N	N	N	N/A
503399		26639	SN 2023ozo	50.0	244.771	-1.907	276.1	280.3	51.0	44.8	ACIS-S	2	0	NONE	Chornock	TOO	24	0	N	S	N	N	N	N	N	N	-109.0
704435	H	25865	DELS J091054.53-0414	10.5	137.727	-4.235	85.7	82.5	55.9	62.2	ACIS-I	5	1	NONE	Wang	GO	23	0	N	N	N	N	N	N	N	N	-109.0
704435	H	25867	DELS J091054.53-0414	30.0	137.727	-4.235	85.7	82.5	55.9	62.2	ACIS-I	5	1	NONE	Wang	GO	23	0	N	N	N	N	N	N	N	N	-109.0
704435	H	25875	DELS J091054.53-0414	32.0	137.727	-4.235	85.7	82.5	55.9	62.2	ACIS-I	5	1	NONE	Wang	GO	23	0	N	N	N	N	N	N	N	N	-109.0
704435	H	25890	DELS J091054.53-0414	35.0	137.727	-4.235	85.7	82.5	55.9	62.2	ACIS-I	5	1	NONE	Wang	GO	23	0	N	N	N	N	N	N	N	N	-109.0
704651		27130	Slug nebula	30.0	13.012	1.023	350.6	316.5	175.0	169.5	ACIS-I	6	2	NONE	Vito	GO	24	0	N	N	N	N	N	N	N	N	-109.0
704651		27131	Slug nebula	20.0	13.012	1.023	350.6	316.5	175.0	169.5	ACIS-I	6	2	NONE	Vito	GO	24	0	N	N	N	N	N	N	N	N	-109.0
704651		27134	Slug nebula	30.0	13.012	1.023	350.6	316.5	175.0	169.5	ACIS-I	6	2	NONE	Vito	GO	24	0	N	N	N	N	N	N	N	N	-109.0
704663		26742	SDSS J002343.86+1418	25.0	5.933	14.307	223.7	249.4	168.6	164.8	ACIS-S	5	3	NONE	Comerford	GO	24	0	-4.9	N	N	N	N	N	N	N	-109.0
705103		28294	AT2018fyk	50.0	342.567	-44.865	322.5	317.4	122.0	116.7	ACIS-S	2	0	NONE	Pasham	TOO	24	0	N	R	N	N	N	N	N	N	-109.0
801946		27937	MOOJ1506+5137	13.5	226.586	51.617	323.2	330.9	64.0	64.3	ACIS-I	4	0	NONE	Connor	GO	23	0	N	N	N	N	N	N	N	N	-112.0
801971		25764	A1068	36.0	160.186	39.953	42.0	46.7	55.4	61.0	ACIS-S	5	3	NONE	Markevitch	GO	23	0	N	N	N	N	N	N	N	N	-111.0
801971		25767	A1068	30.0	160.186	39.953	42.0	46.7	55.4	61.0	ACIS-S	5	3	NONE	Markevitch	GO	23	0	N	N	N	N	N	N	N	N	-111.0
802029		26915	PSZ2 G107.83-45.45	20.0	1.898	16.117	230.3	249.4	164.5	160.6	ACIS-I	5	1	NONE	Mantz	GO	24	0	N	N	N	N	N	N	N	N	-109.0

Cycle

Stars

Constraints

Coordinations

Constructing the LTS is extremely challenging. Auto-scheduling software, developed in cooperation with a software team at STScI, allowed the continued generation of efficient schedules. The initial schedule for "Cycle 25" was completed in September 2023, much earlier than just a few years ago.

Tool / Process Updates

Star Field Constrained Targets

- Increasing aspect camera temperatures mean higher detection limits for guide stars. This means some star fields have become extremely difficult to do, with narrow yearly windows (roll angle ranges) when they are observable
- The aspect camera flight software was patched in May 2023 to use new dynamic background algorithm, improving sensitivity for guide stars. The effect is equivalent to 1-1.5 degree cooling, a significant benefit for planning
- However, the problem will worsen over time, with some star fields expected to become unobservable in the near future

Star Field Checker Web Tool introduced in AO25

- Fewer proposals with difficult star fields were submitted
- Processing time and memory usage per target is non-negligible, raising issues if large numbers of targets submitted at once (e.g., if incorporated in CPS and many proposers use it just before deadline)
- Queueing system, target list input, and inclusion in CPS all in development for next year

Tool / Process Updates

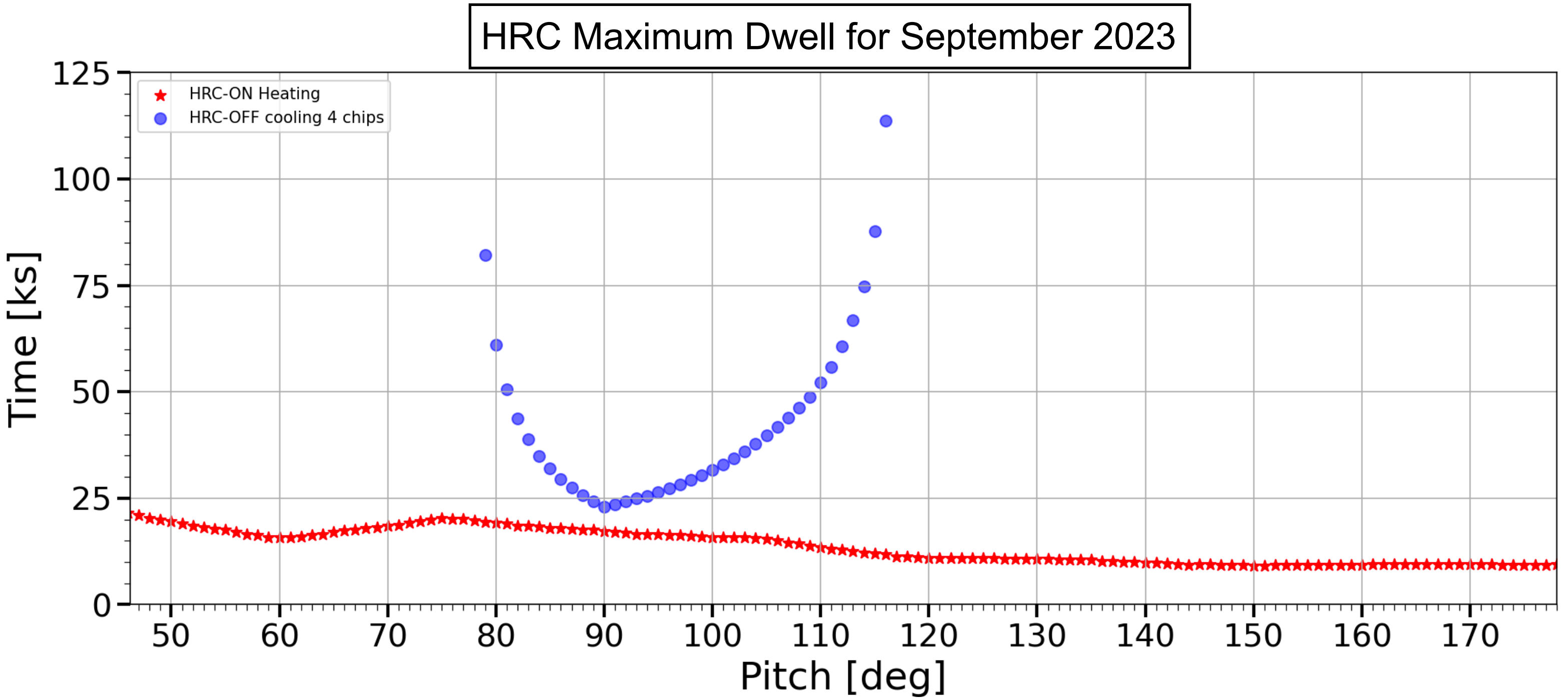
Assistive scheduling tools for flight planners

- As thermal limits become more constraining, it is becoming more difficult and time consuming to build the final schedule for each week. Similar problem to constructing the yearly LTS
- We have begun experiments to determine practicality of developing assistive scheduling tools for flight planners
- Complexity and trade-offs involved means tools can only ever be *assistive*, not fully *automatic*
- Goal is to speed up process by generating set of outline schedules which offer a good starting point for a planner to build on
- A new machine readable OR list format has been defined, containing all quantifiable constraints. This is required for input to assistive scheduling tools, but is also helpful for normal planning.

Tool / Process Updates

HRC Thermal Models

- HRC returned to normal operations in April 2023, but with important thermal limitations. HRC *heats at all pitch angles* while switched on, and only cools effectively in a narrow pitch range while switched off.
- Observations limited to ~14.5 ks, with at least 30 ks cooling time required between observations. Typically this allows 2-3 observations per orbit.
- Significant impact on planning and building the LTS, but we have developed HRC thermal models to account for these limitations



Tool / Process Updates

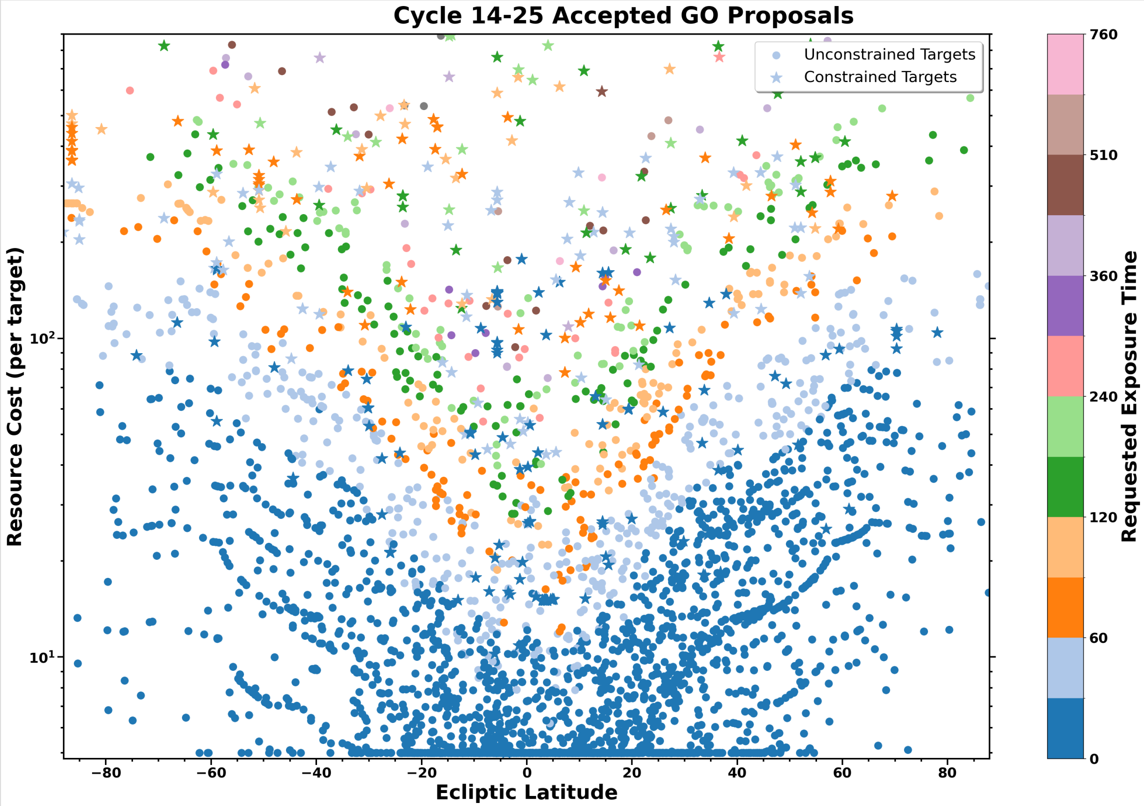
High Ecliptic Latitude (HEL) Time Limit

- Investigation into impact of observing time at high ecliptic latitudes ($|\beta| > 55°$), using auto-scheduler to determine how HEL affects difficulty of building LTS
- Decreased dominance of ACA temperature limitations and need for mid-pitch ACIS targets to allow HRC cooling makes HEL time more beneficial
- HEL time available through peer review increased to 4 Ms in cycle 25, but not all was used
- Likely to decline in future cycles as MUPS becomes the limiting factor

ACIS Focal Plane Temperature Limit Increase

- ACIS FP limit increased to -105 C approved for small number of ACIS-S HETG observations with SIM-Z < 0.6mm
- Use of -105 C limit expected to expand as calibration at this temperature improved

Resource Cost

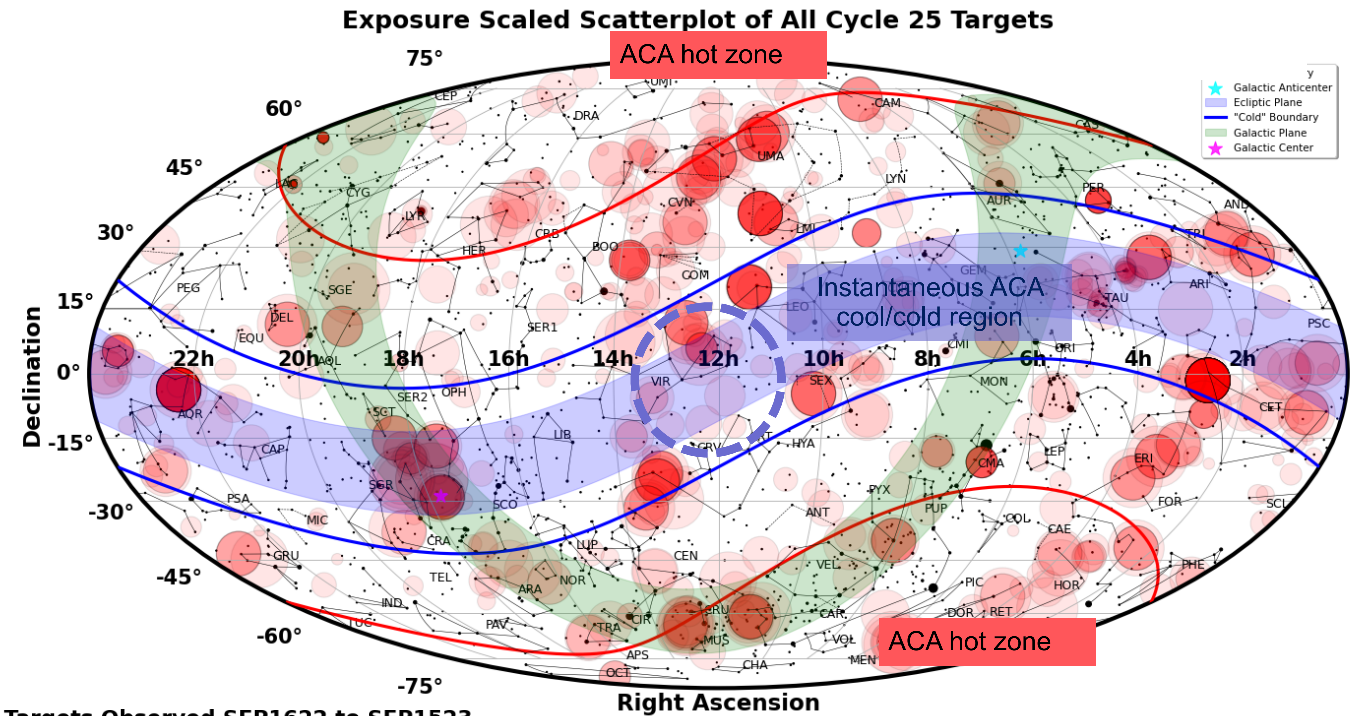


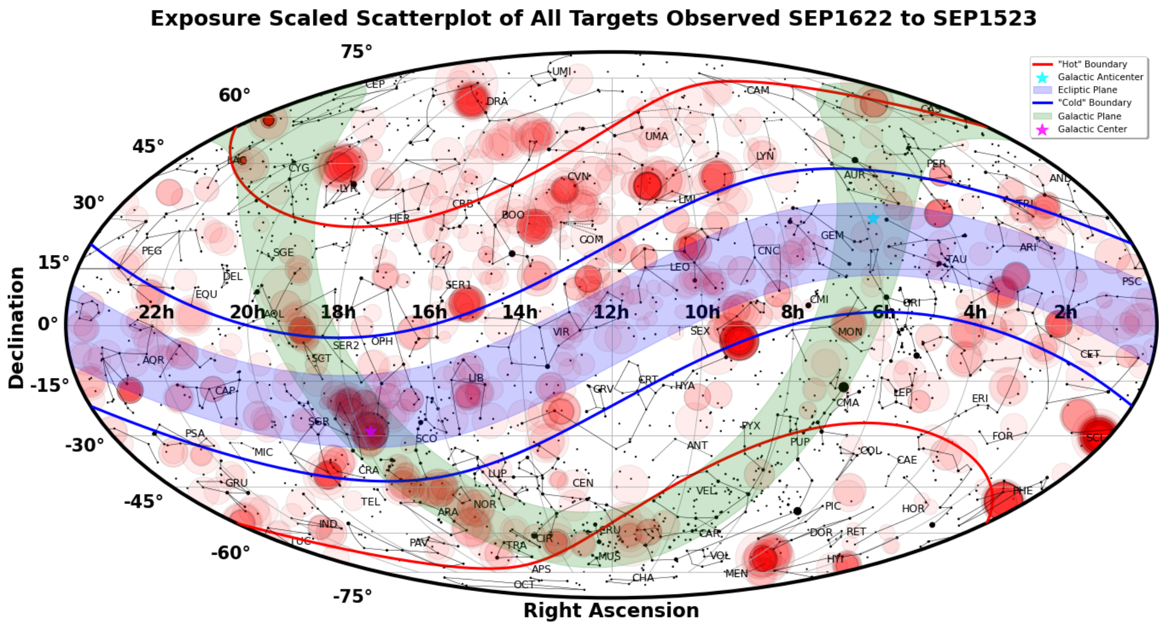
Resource Cost (RC) values for observing programs from *Chandra* Cycles 14-25.
- Circles represent observations without constraints, for which RC values depend only on ecliptic latitude (X-axis) and exposure time (color bar).
- Stars represent to targets with observing constraints.

- Introduced in cycle 22.
- Replaces "constraint categories" (easy/average/difficult) used in previous cycles.
- Calculated for all non-TOO targets.
- On current (arbitrary) scale, peer review assigns total cost ~27,000.
- For Cycle 26: minor fixes, and pitch weighting changes to not as strongly disfavor HEL targets.

- Prototype resource-cost-like scoring for TOOs developed.
  - Currently only the number of triggers by category are tracked, so a fast 100 ks TOO is equivalent to a fast 1 ks TOO.
  - Prototype already useful in highlighting difficult or infeasible TOO proposals

Target Distributions





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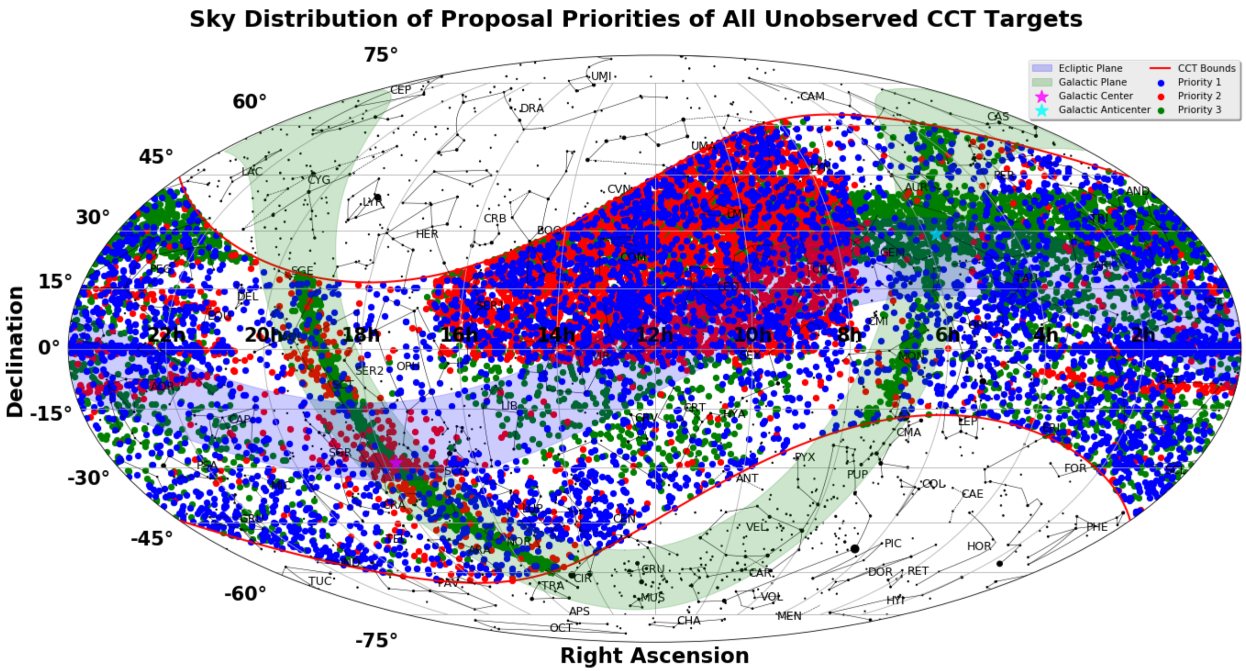
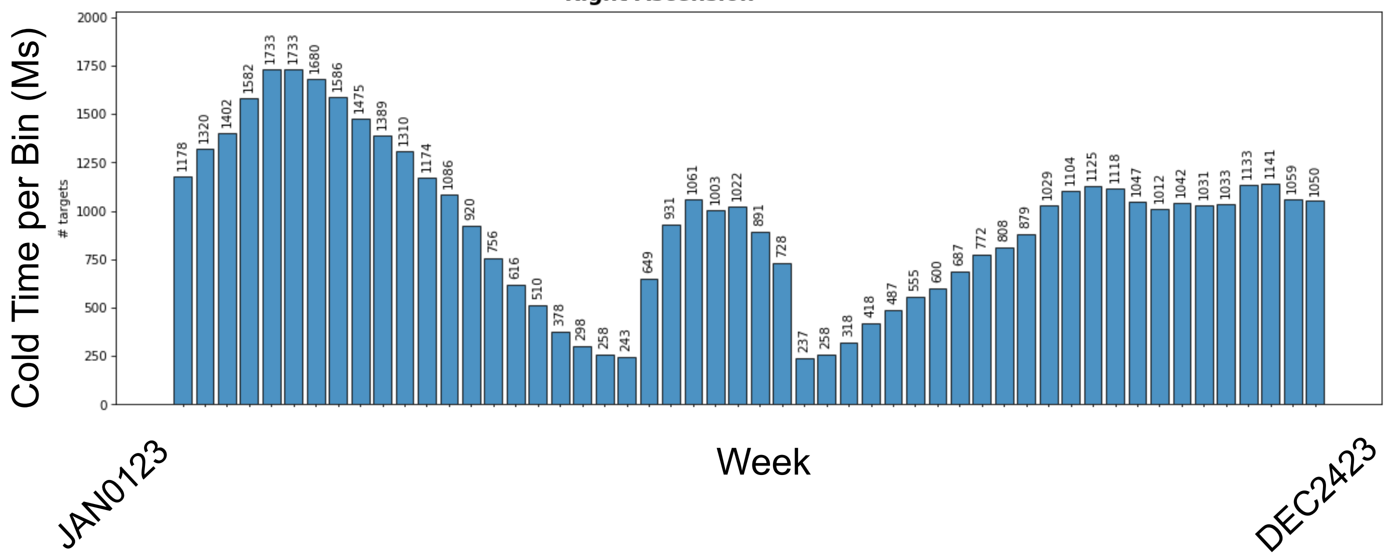
Chandra Cool Targets (CCTs)





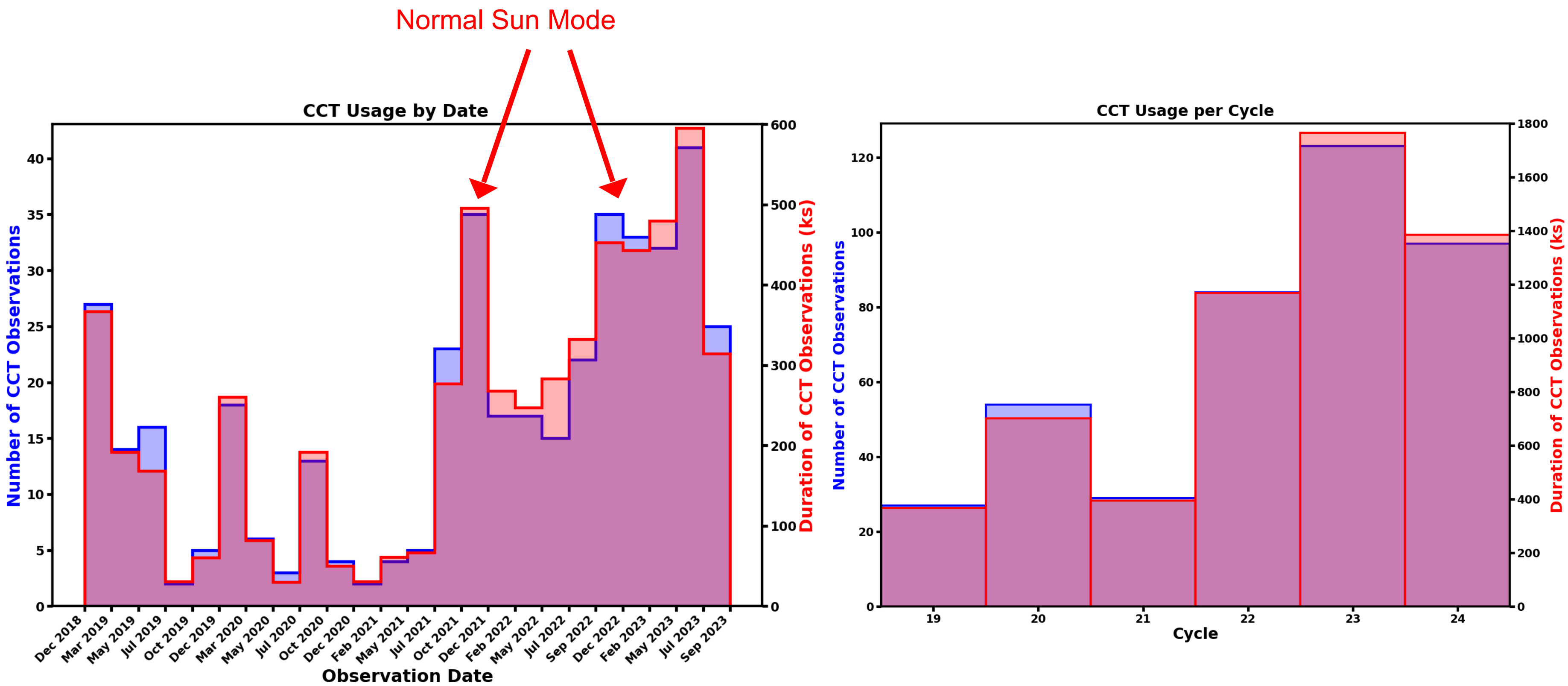
- 22 programs
- Include:

galaxy clusters, ULXs quasars, AGN, HMXBs CVs, SFRs, cool stars, survey counterparts, radio galaxies, star clusters, Fermi sources, dwarf galaxies, symbiotic stars

10 ks ≤ t ≤ 35 ks; |b| < 40º

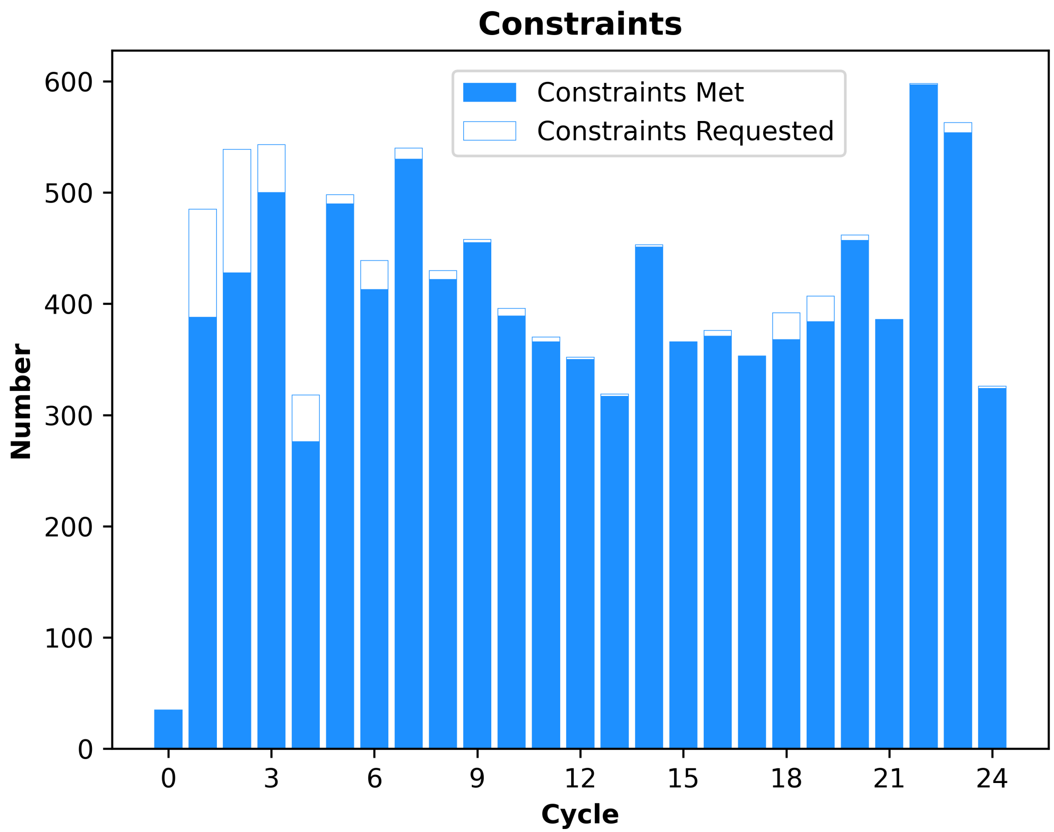
- Includes:
  - ~19,000 targets
  - ~400 Ms in time
- Adequate cooling time in any week

Chandra Cool Targets (CCTs)



CCT usage has increased over the past year, although this is probably partially driven by recovery from operational events (e.g., IU reset, Fine Sun Sensor issue) and by large programs with particularly difficult star fields observed prior to the ACA flight software patch

Science Constraints

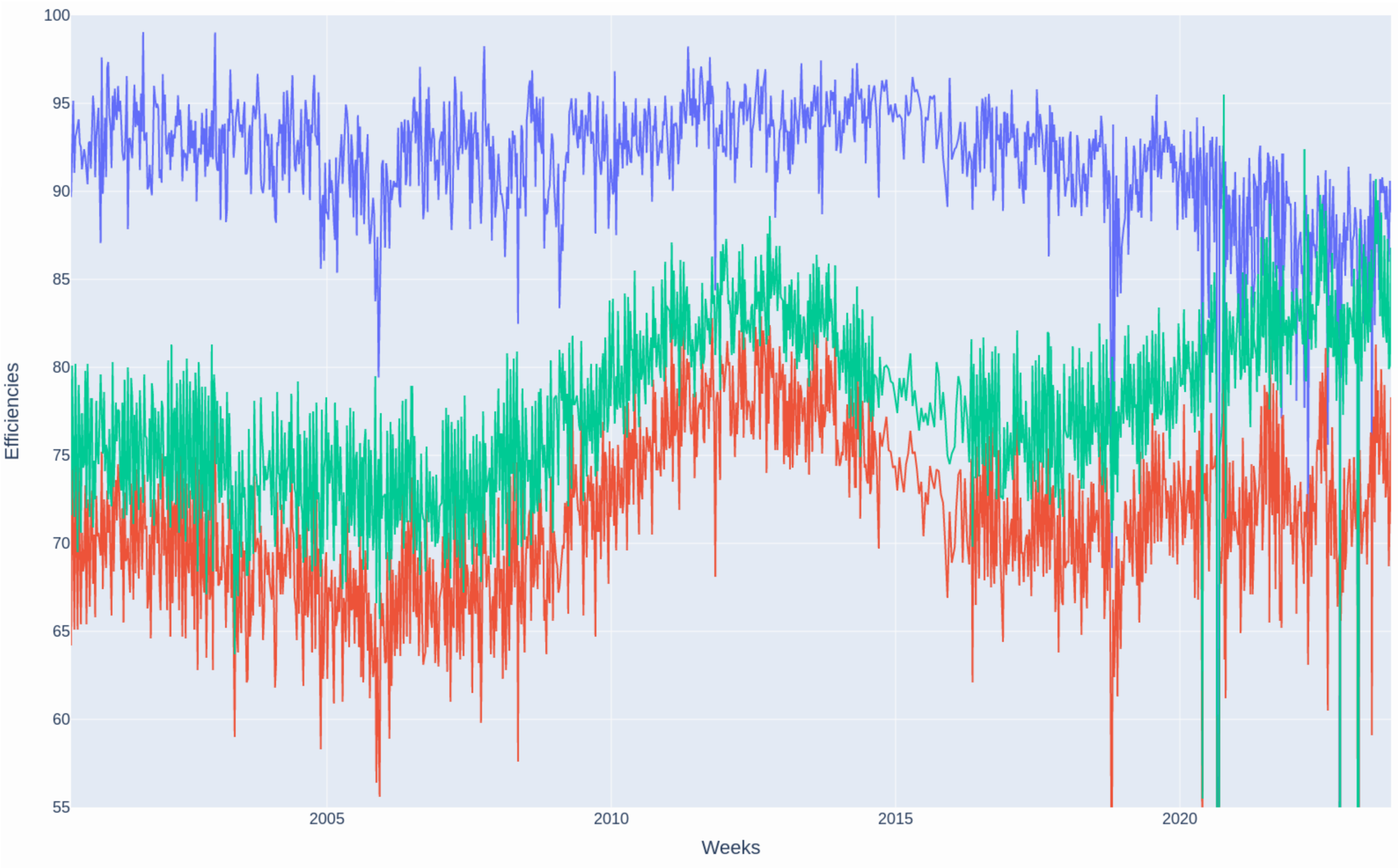


- Difficulty associated with meeting constraints is increasing due to spacecraft thermal limitations (e.g., decrease in maximum dwell times, increasing number of star field constrained targets)

- However, we continue to meet approved observing constraints successfully

- Most missed constraints are due to solar flares and other operational events that lead to schedule interruptions

Mission Efficiency History



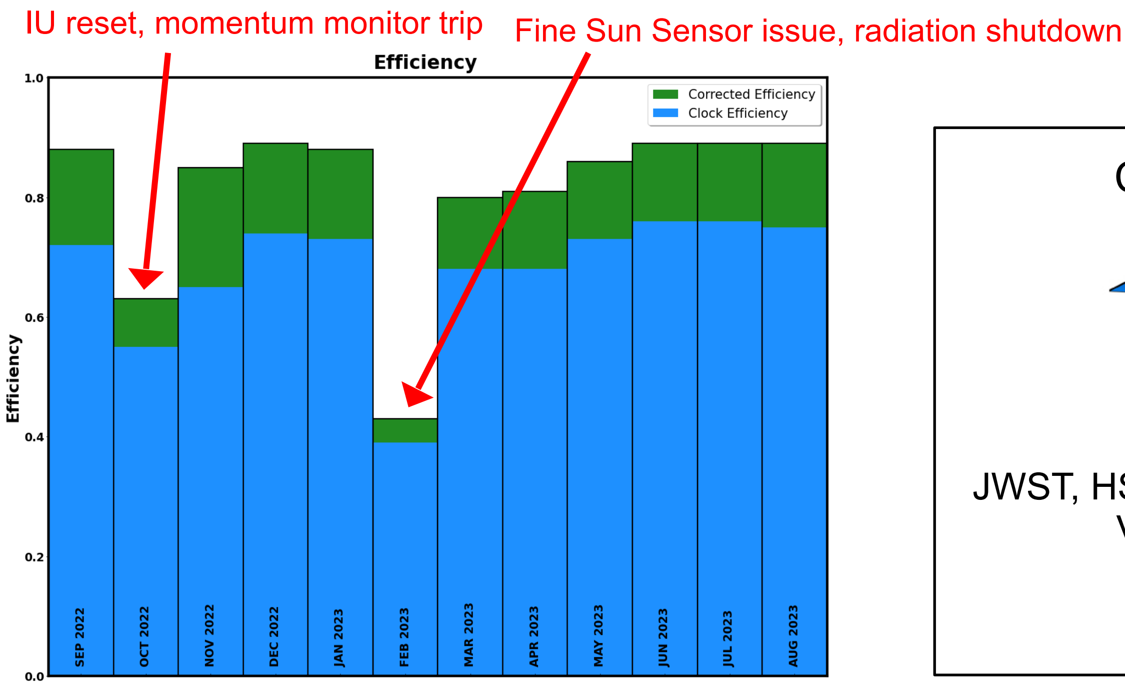
Science time/above radzone time.

Above radzone time/wallclock time.

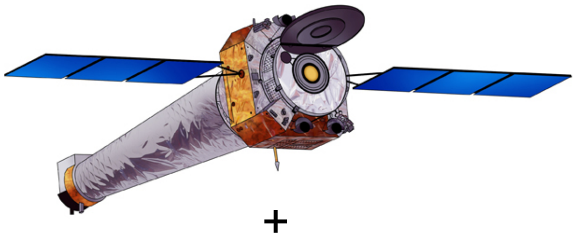
Science time/wallclock time.

E. O'Sullivan (Chandra Mission Planning)

Observation Scheduling



Coordinated Observations



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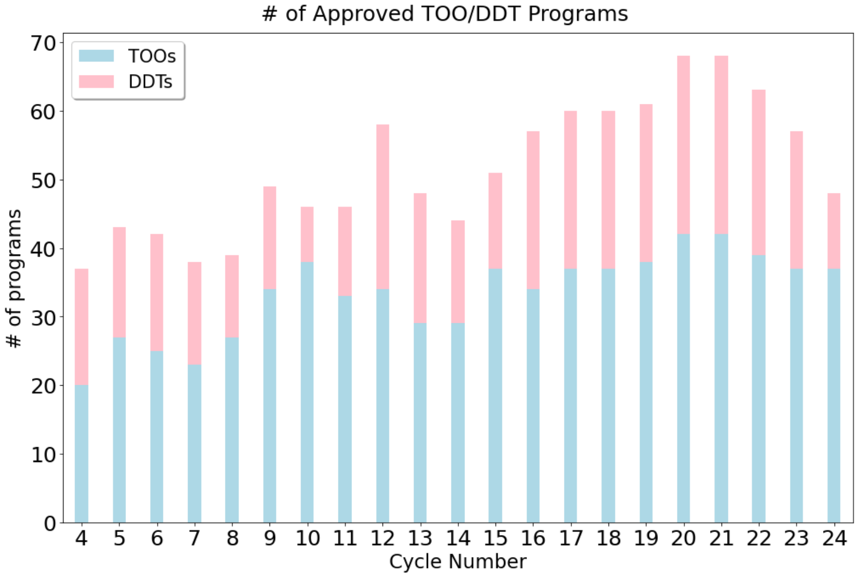
JWST, HST, NuSTAR, Swift, XMM, IXPE, NICER, VLA, ALMA, EHT, Hobby-Eberly

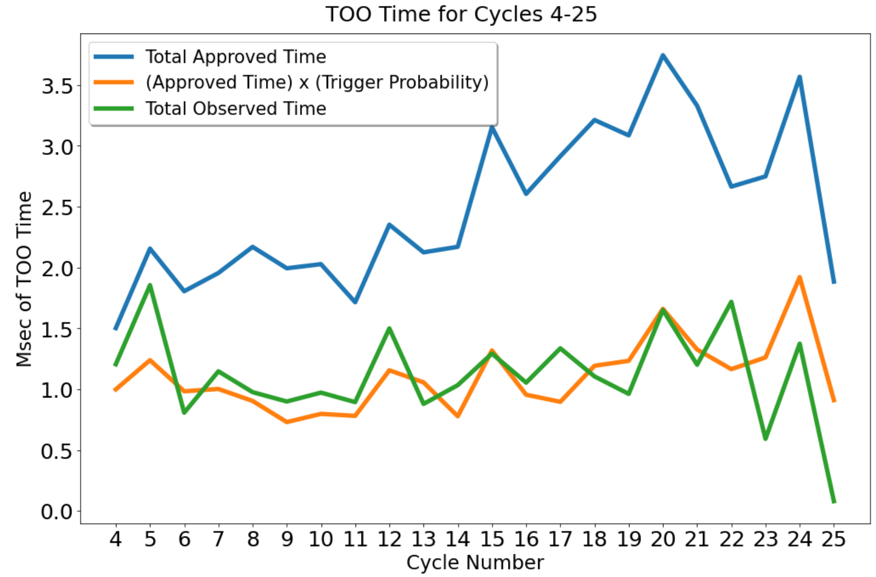
From Sep. 16, 2022 - Sep. 15, 2023:

- Scheduled: 1383 observations (21.6 Ms)
- Executed:
  - 71 TOO observations (1.36 Ms)
  - 33 DDT observations (475.9 ks)
    - ✧ interrupted 3 operating loads for TOO/DDT support

- Chandra Coordinations (Sep. 16 2022 - Sep. 15 2023):
  - 50 observations for 798.7 ks

TOO/DDT Observations: Historical Performance





Historical TOO/DDT performance has been very steady despite evolution of thermal constraints over more than a decade.

- This has been done by continued development of tools and procedures, and this process continues for both regular planning and TOOs.
- We anticipate continued support at levels similar to historical levels

Summary

- The overall temperature increase of Chandra continues to limit the amount of time we can observe at any given solar pitch angle, due to the temperature limits of the various components
- This greatly complicates constructing the long term schedule and detailed weekly planning, e.g. due to component temperature limits and increases in the detection threshold of the aspect camera
- The effects of this heating are mitigated, as much as possible, by several proactive software, procedure, and policy changes
- Despite increasing challenges, observing metrics remain favorable, with observing efficiency, and TOO/DDT response, and science constraint compliance that are on par with mission history

Backup Slides

Star Field Constrained Targets

- Increased aspect camera temperatures means a higher detection limit for guide stars
- Some star fields have become extremely difficult to do, with narrow yearly windows (roll angle ranges) when they are observable
- These “star field constrained” targets make up the majority of our most difficult programs to schedule
- The aspect camera flight software was patched in May 2023 to use new dynamic background algorithm, improving sensitivity for guide stars. The effect is equivalent to 1-1.5 degree cooling, a significant benefit for planning
- However, the problem will worsen over time, with some star fields expected to become unobservable in the near future

Tool/Process Updates

Star Field Checker Tool

- Star field checker webtool was released for AO 25
- Fewer proposals with difficult star fields were submitted
- Processing time and memory usage per target is non-negligible, raising issues if large numbers of targets submitted at once (e.g., if incorporated in CPS and many proposers use it just before deadline)
- Queueing system, target list input, and inclusion in CPS all in development for next year

Tool/Process/Limit Updates

TFTE Heater Set-point Change

- It was realized that lowering the set-point temperature for the Telescope Forward Thermal Enclosure (TFTE) heater provided unexpected thermal relief for the ACA.
- New set-point temperature was quickly implemented
- This likely "recovered" 1-2 years worth or nominal ACA heating

Tool/Process/Limit Updates

ACIS Heater Set-point Investigation

- ACIS investigated the potential benefits of lowering the set-point at which the ACIS heater turns on. If the ACIS focal plane is allowed to reach a lower temperature, then the maximum dwell time after reaching this lower limit may be improved.
- After a detailed investigation, it was determined that exploratory observations would be required to answer this question definitively
- Unfortunately, this study found that lowering the ACIS set-point temperature did not significantly improve subsequent max-dwell capabilities

Tool/Process/Limit Updates

- History of recent thermal limit changes

Model	Date of most recent update	Planning limit relaxations in past year
ACA	2022 Feb	- 5.8 C -> -5.2 C
MUPS	2020 Apr	210 F Limit Unchanged
OBA	2022 Jan	Non-LETG Limit unchanged 103 F Separate LETG limit 102 F
Tank	2021 Oct	115F -> 120 F
PLINE	2020 May	50 F Limit Unchanged
DEA	2022 May	37.5C -> 38.5 C
ACIS FP	2022 Nov	ACIS-I: -112C -> -109 C* ACIS-S: -111C -> -109 C* *when calibration allows

Sample of Significant Planning Efforts

Completed in Cycle 23:

- Sgr A* - 100 ks, including
  - Tightly coordinated with the EHT

- Galactic Center mosaic - 1.7 Msec; CMZ Molecular Cloud - 900 ks
  - 2.6 Msec all in the same part of the sky (same “good” and “bad” pitch windows)

- Abell 2029 - 150 ks
  - Extremely difficult star field
  - No workable "first order" solution, at any temperature. Required special consultation with the ACA team.
  - Ultimately led to very tight observing windows with extra ACA cooling.

- QSO J0041-4936 - 150ks; PSZ2G358.98-67.26 - 4.9 ks; 2MASX J15114125+0518089 - 60 ks
  - All severely star field constrained, difficult to schedule, with short allowable windows

- B1152+199 - 50 ks
  - 5 x 10 ks, monitor series with a monthly cadence that also has a difficult star field.

Sample of Significant Planning Efforts

<u>Coming Up in Cycle 24:</u>

- Sgr A* - 100 ks
  - Tightly coordinated with the EHT

- Abell 2029 - 275 ks; SIG A2029 - 170ks:
  - Extremely difficult star field

- QSO J0041-4936 500ks; MCXCJ0216.3-4816 - 25ks; SDSS J114907.15+004104.3 - 3.1ks
  - All severely star field constrained, difficult to schedule, with short allowable windows

- Some likely challenging approved Cycle 24 TOO programs

Note that the story regarding the toughest programs to schedule has largely become about “star field constrained” targets

TOO/DDT Responses and Planning

- Very Fast TOO response times could be delayed by up to10 hours beyond historical times in order to pre-cool.
- Anti-TOOs are TOOs
  - Pulling a TOO or its follow-up after scheduling requires a similar effort as starting a new TOO.

- Approach to TOO follow-ups has been changed effective cycle 22
  - Now, follow-ups schedulable at time of trigger count as ½ trigger against the cycle quota; follow-ups that depend on results of an earlier TOO are proposed as separate TOOs
- TOO/DDT programs delay GO observations.
  - Harsh reality is that bumped targets can no longer routinely be rescheduled into a nearby week.

TOO/DDT Observations: Planning Impacts

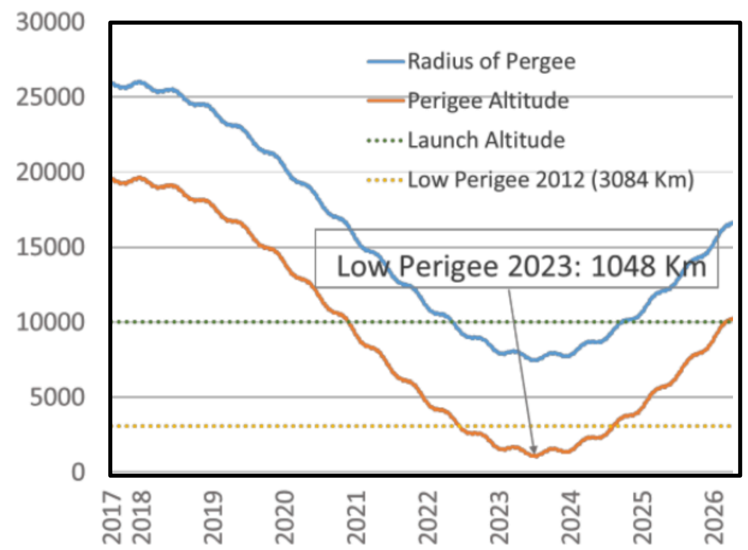
Snapshot of Planning Process

Week	Monday	Tuesday	Wednesday	Thursday	Friday	Weekend
Schedule Planning	SOTMP Reviews LTS Bin		Preliminary Schedule Build			
	On-call for previous week's loads, performing all FOTMP Reviews					
Preliminary Schedule	Finalize Preliminary Schedule		Internal FOTMP Prelim Review ---- Rebuild Prelim*	ACA Pre-review of Prelim ---- Rebuild Prelim*	Deliver Prelim to SOTMP ---- SOTMP Review	
Schedule Review	SOTMP Delivers Final ORL ---- FOT Builds Final Schedule	FOTMP Builds Official Loads ---- FOTMP Review	Loads Released for Review ---- Load Review	Subsequent Load Builds and Load Reviews, if necessary.		
Schedule Running	LOADS ONBOARD AND RUNNING (Planner who built loads is on-call, performing all FOTMP reviews, and already starting the next schedule's first week)					

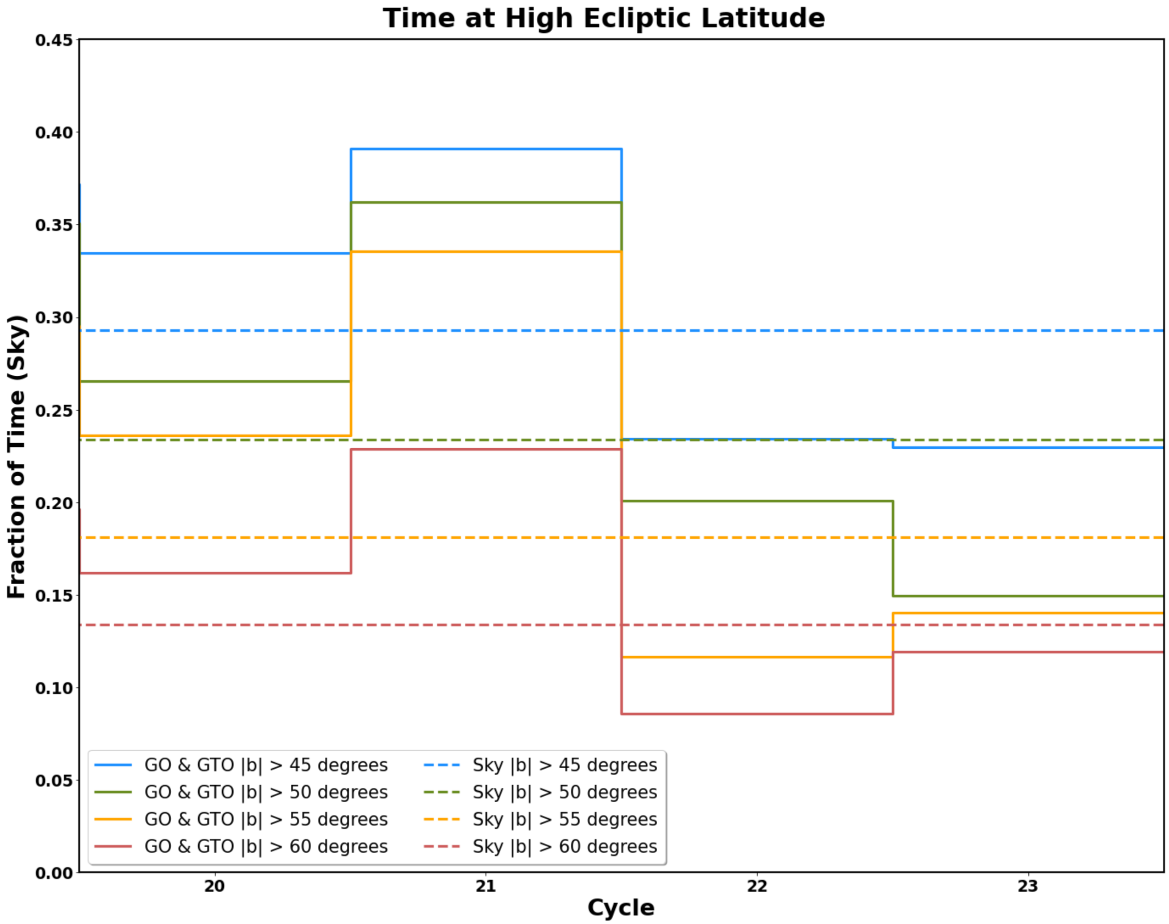
Tool/Process/Limit Updates

Momentum Management

- Chandra will reach its lowest perigee altitude in 2023, requiring an increase in the use of the thrusters to unload momentum.
- Degradation of the A-side thrusters was observed after ~700 “warm starts”, resulting in a switch to the B-side thrusters in 2013.
- Goal is to budget warm starts to stay under this limit of 700 through low-perigee.
- Developed software to estimate the momentum accumulation per axis for any observation, allowing the “momentum balance” to be calculated for every week.
- Momentum is now balanced week by week when laying out the LTS, as is done for thermal.



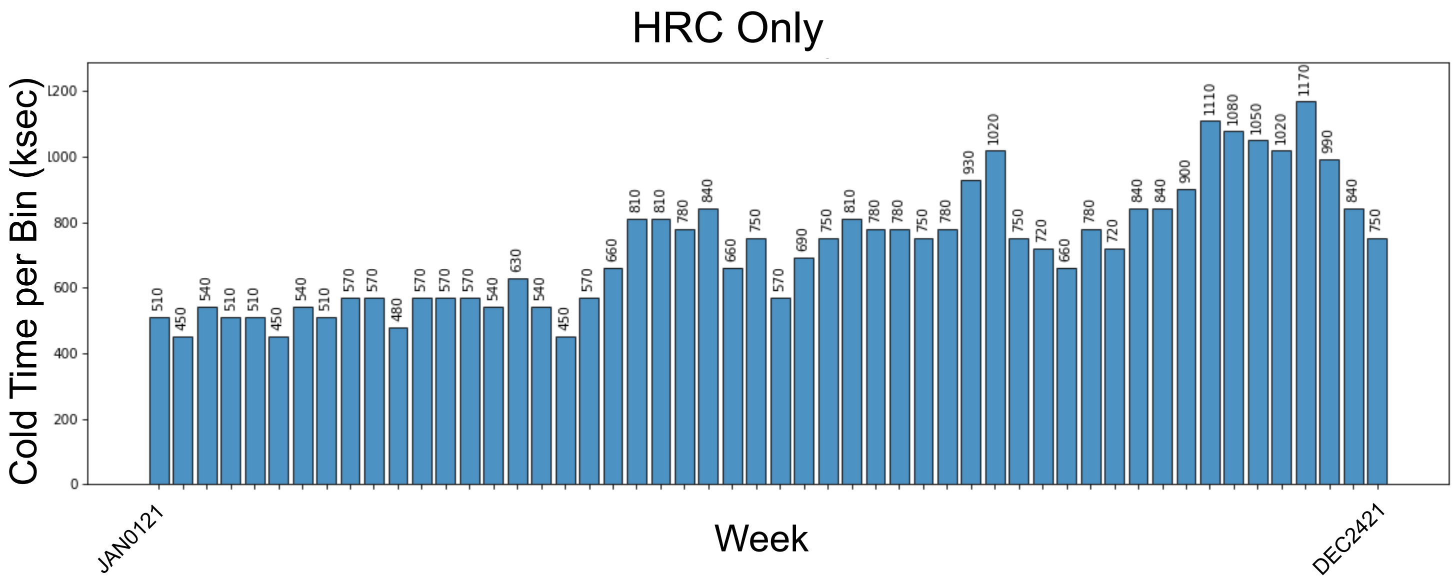
Target Distribution: Cycle 22



- For several cycles, the CXC has been limiting high ecliptic latitude time in large programs only.
- This has not proven adequate: target times at high β have ended up *above* their proportionate share of sky area.
- Consequences include very long (~6 month) LTS development times and programs that extend far into subsequent cycles.
- Cycle 22+, with high-latitude time limited for *all* targets, finally achieves high-latitude target times somewhat below their proportionate sky area.

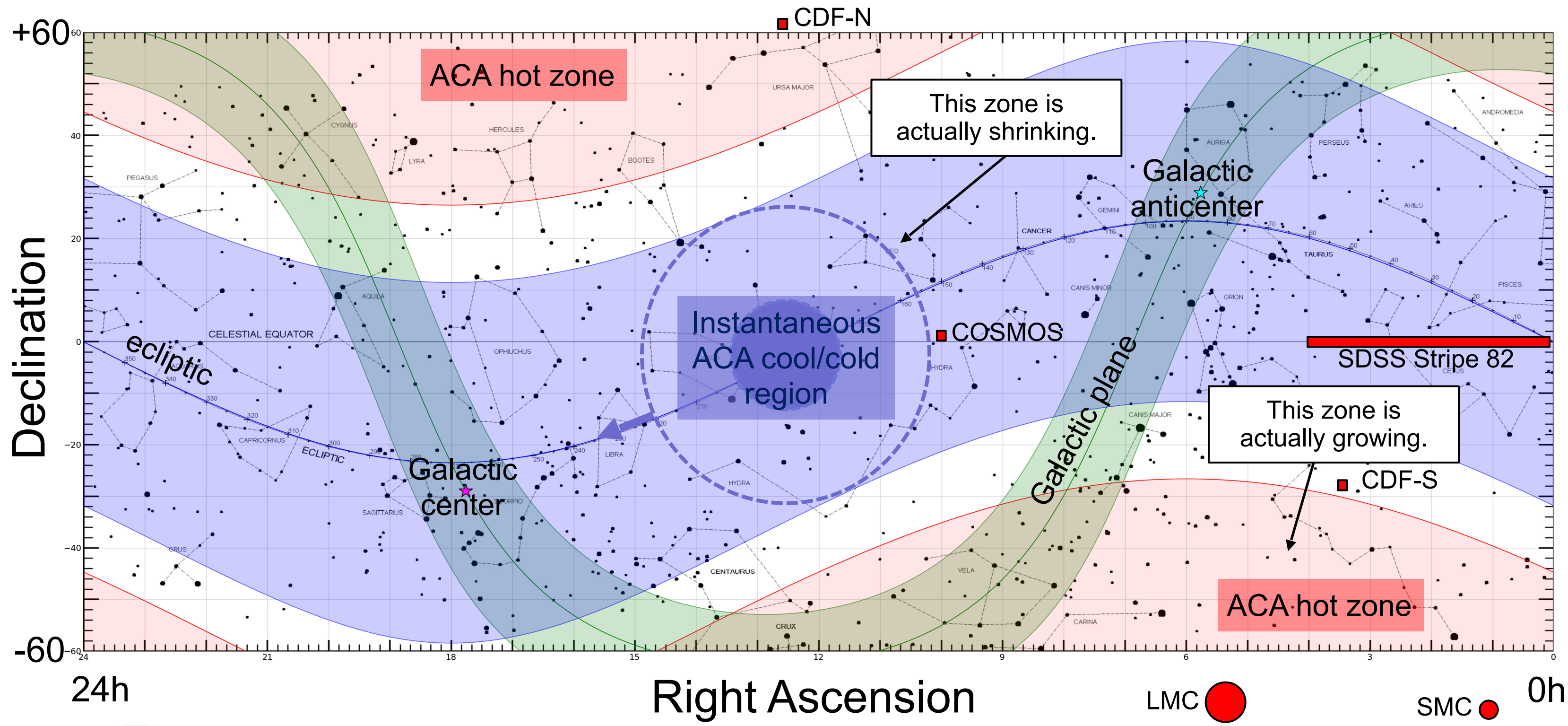
- Due to “catching up” with time from earlier cycles and the decreased relative importance of ACA heating, we ***may*** be able to increase the time limit on high latitude targets, <u>but low-latitude time is still crucial for cooling</u>.

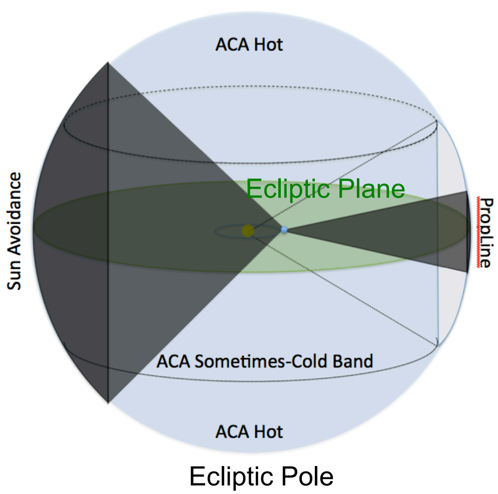
Chandra Cool Targets (CCTs)



- Recall that cold HRC observations are particularly useful for thermal management, since ACIS is the main limiting factor at high pitch angles.
- There is a good amount of HRC cold time per week remaining in the CCT program.
- However, **all** of these remaining observations are 30 ks, which is typically longer than desired for nominal planning, since it can unnecessarily displace time from GO programs or unbalance the ACIS heating budget for the week.

Constraints: Sky View





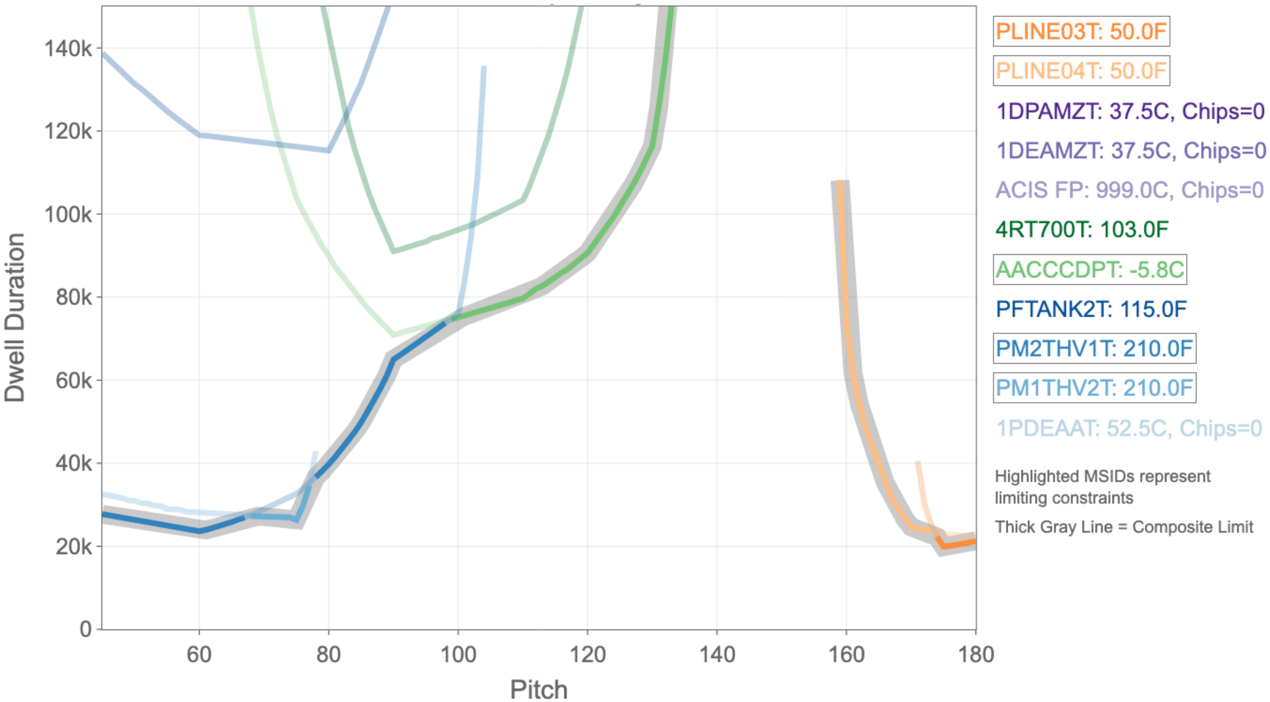
- Sometimes-cool/cold ACA (-Z) region covers large sky area.

  - Many well-known fields can provide some cooling; others always heat the ACA.

  - The cool regions are shrinking and the hot ones are growing.

Future Thermal Needs

Composite Maximum Dwell with No ACIS Chips (Aphelion 2022)



- Most limiting components cool at high pitch angles, except ACIS.
- Therefore, turning off all ACIS chips greatly increases the maximum dwell at high pitch angles (limited at the highest pitch angles by the propulsion lines)

- This means that HRC observations are especially useful for cooling most thermal components (and useful at other pitch angles for cooling ACIS).
- We expect HRC observations to become more and more useful as the global average temperature of the spacecraft continues to rise.