Mission Planning Updates

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Overall Context for Mission Planning

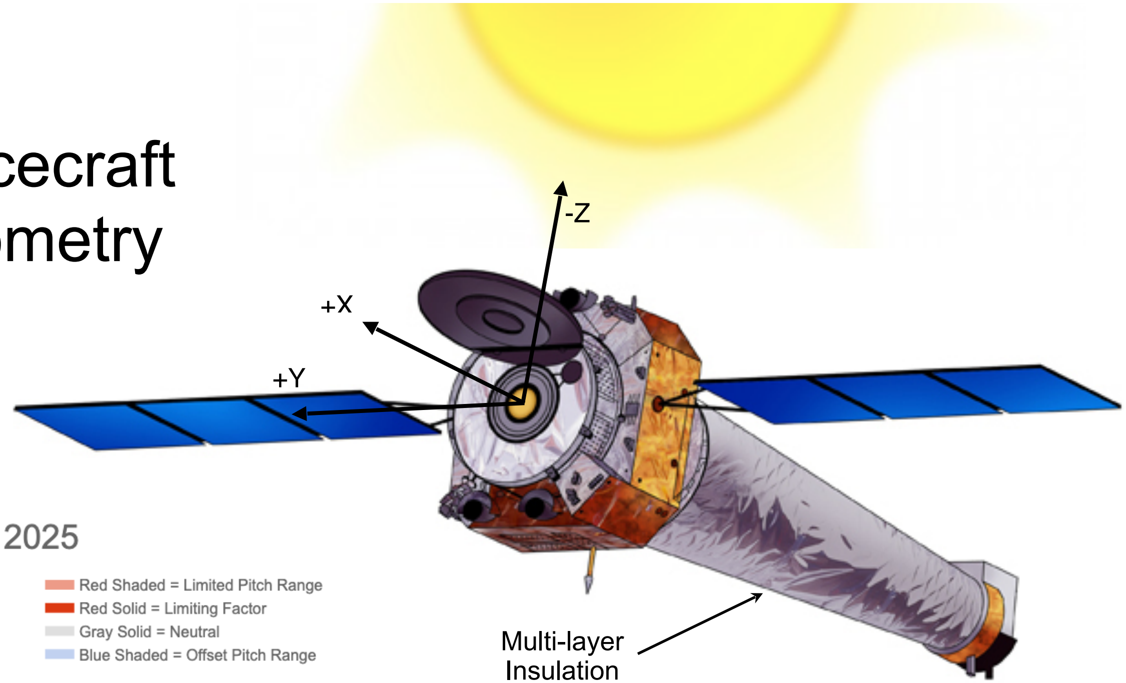
Goal:
Maximizing the science return of the mission in the presence of constraints:

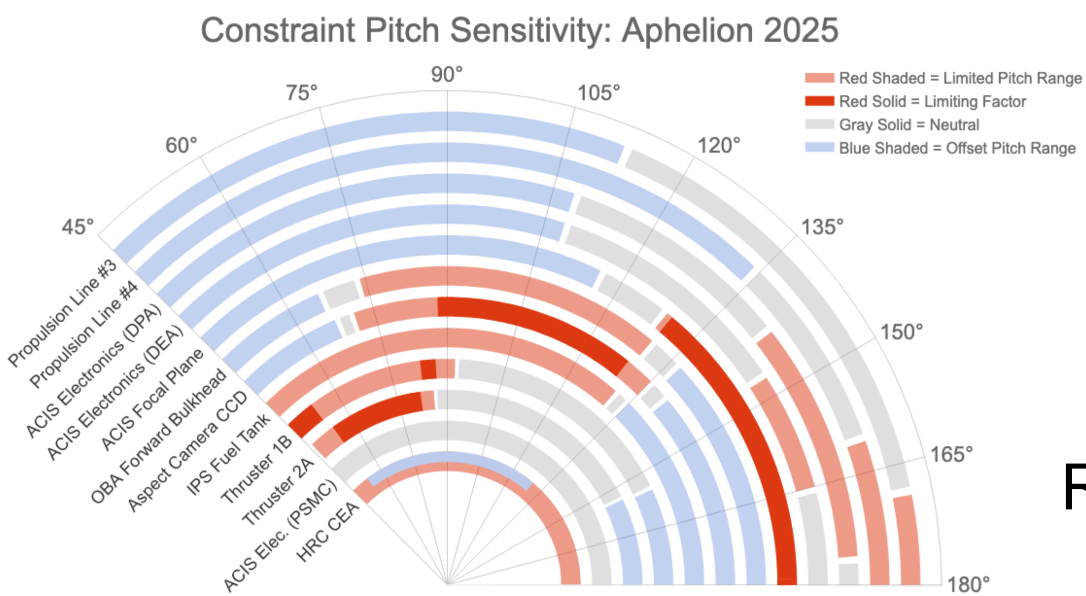
Observation constraints, e.g.,
- coordination
- time windows
- continuity of observations
- monitoring series and observation grouping
- roll constraints
- phase constraints

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

Chandra Thermal Restrictions

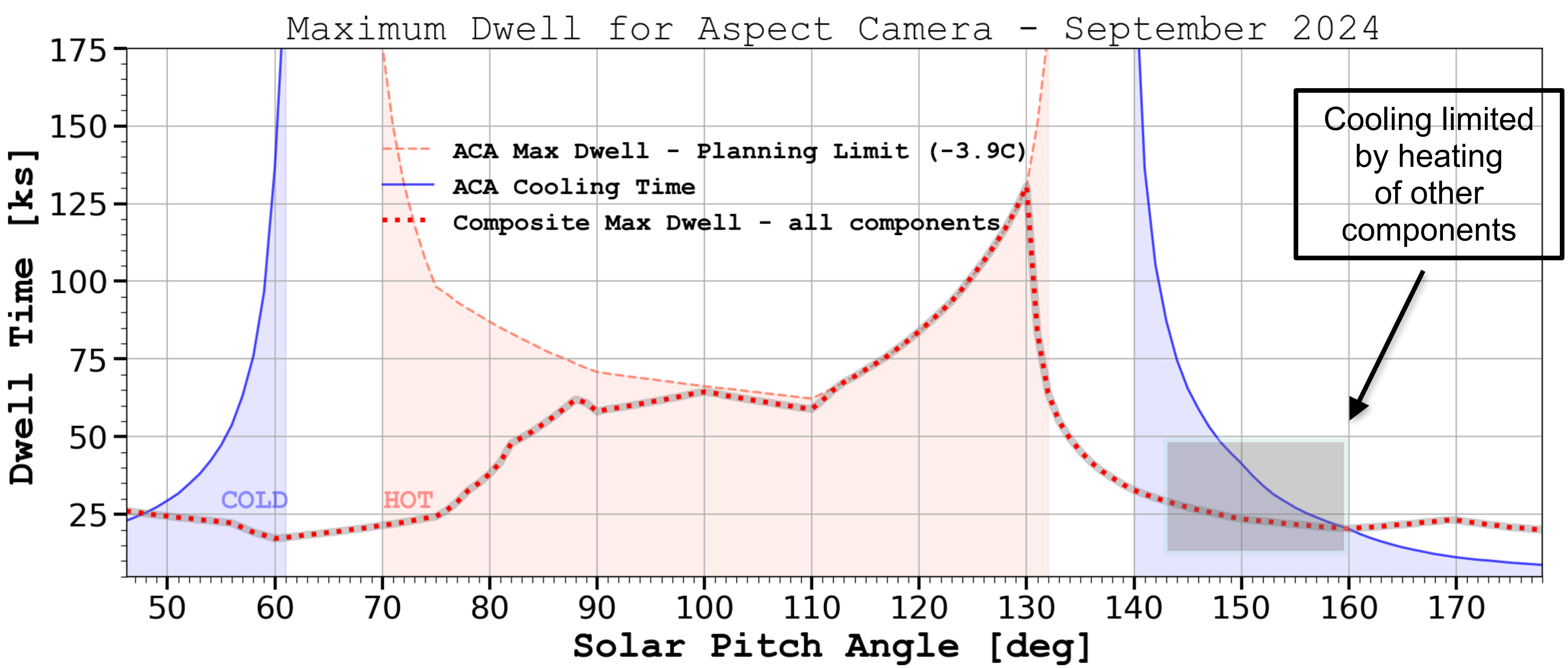
Spacecraft Geometry





Thermal Restrictions

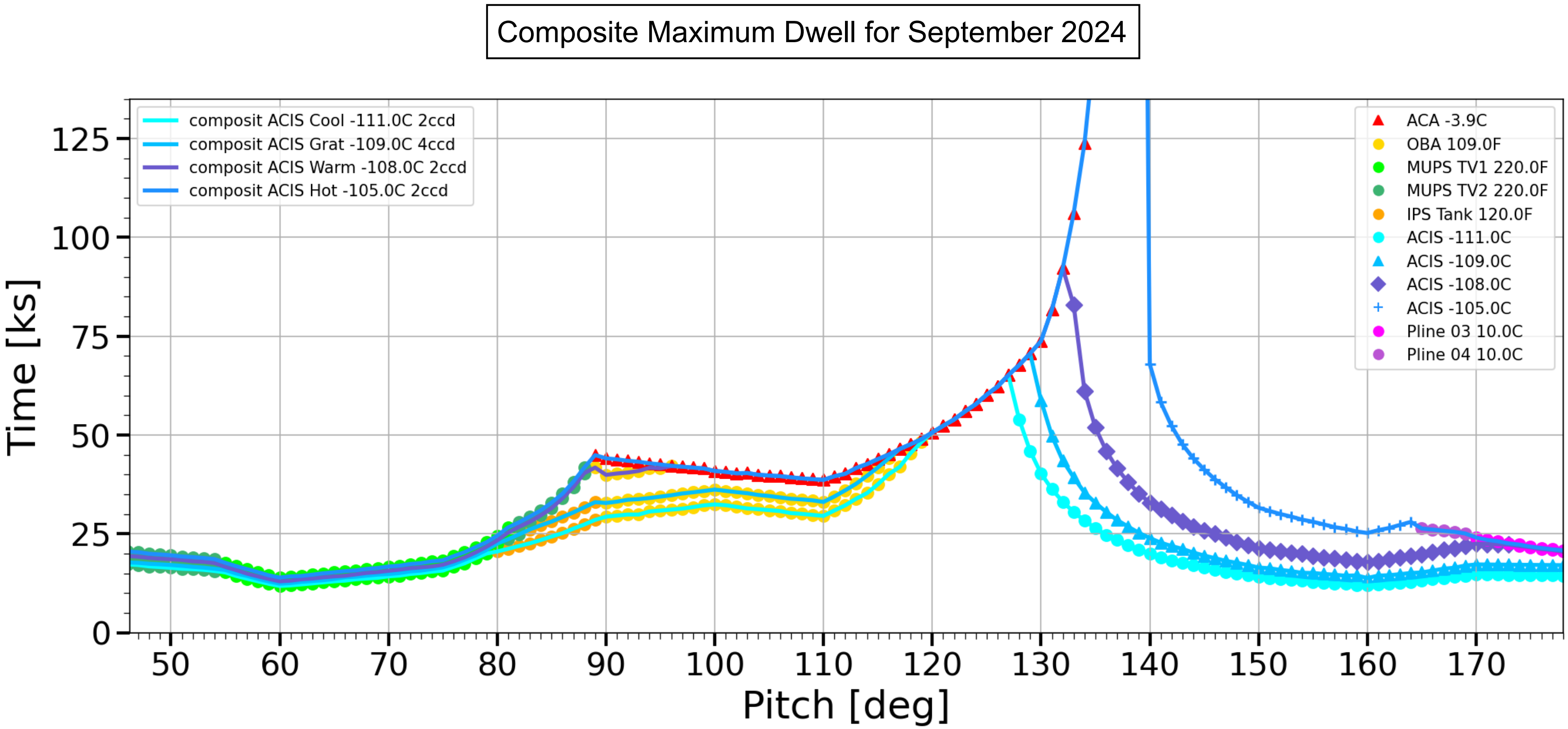
Thermal Balance: A Summary



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

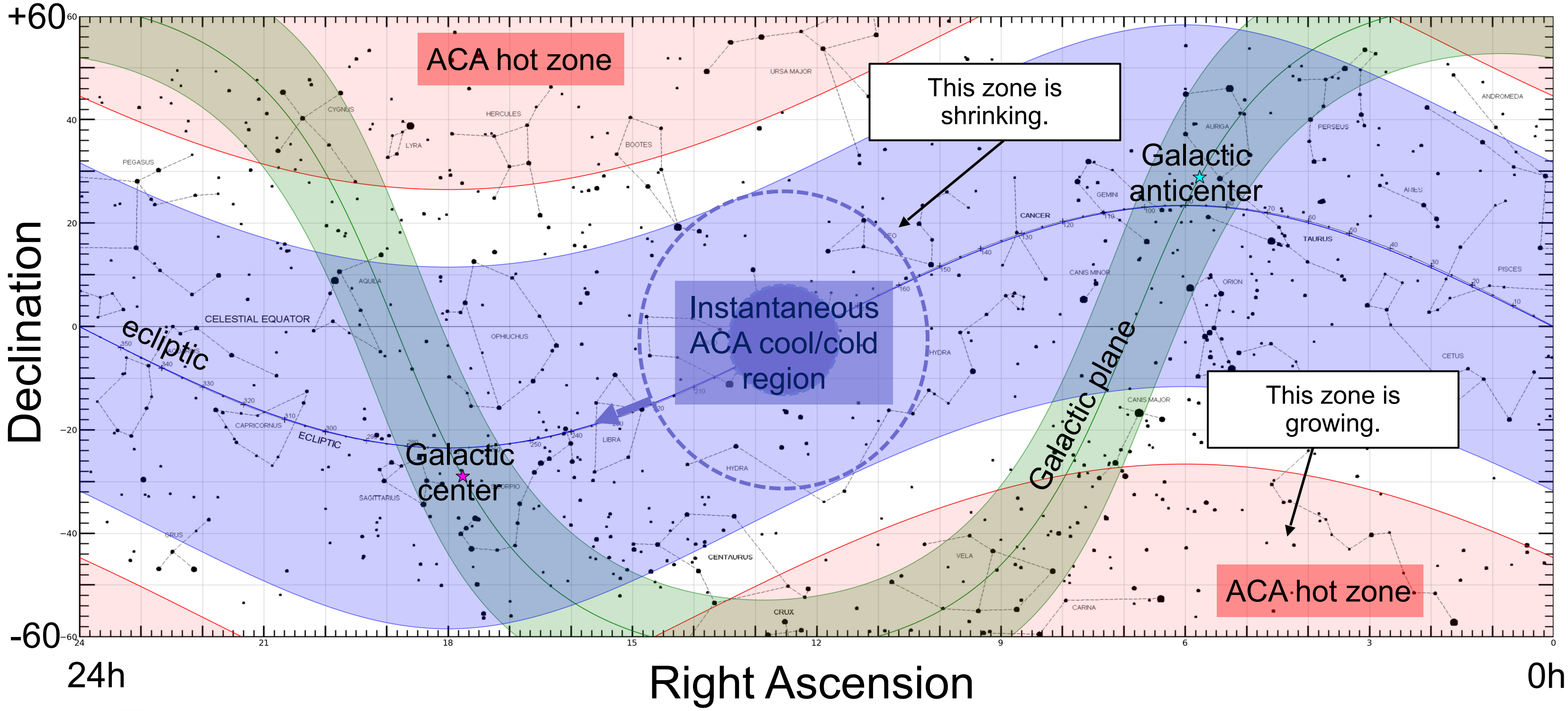
Blue: minimum cooling time required to return to state from which another max dwell possible

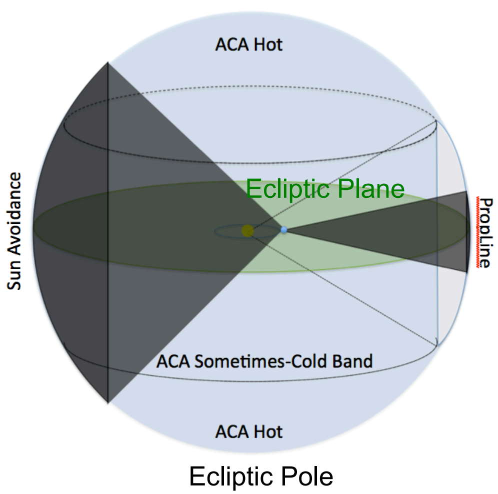
Thermal Balance: A Summary



- “Hot ACA” region (~ 90<pitch<130) now more favorable compared with other regions
- We continue to work hard to stay ahead of rising temperatures with component planning limit increases, wherever possible.

Constraints: Sky View





- The sometimes-cool/cold ACA/MUPS (-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

NEW Sky Distribution Metric

Segment: 34 limit: 5.30d, used 4.62d = 87.17% 21-Oct-2024 00h to 28-Oct-2024 00h (UT) antisun plot skybal plot

#Orbits: 2 Orbit Time: 458.08ks LTS Time: 397.85ks HRC Time: 32.00ks skybal: -70.50 #Targets: 17

Thermal Budget:		cold budget
aca	:	+44.0
mups	:	+49.8
ipstank	:	+84.1
dpa	:	+9.9
hrc	:	+141.5

momentum axes		momentum totals	
P_x :	+9.85	P_tot :	15.36
P_y :	-11.52	P_bal :	5.36
P_z :	+2.49		

seq#		obs	name	time	RA	dec	Roll	Range	Pitch	Range	SI	R	O	grat	observer	Type	AO	OR#	SF	TC	RC	PC	UC	PU	SC	Mlt	CRem	FP
201661		28733	NGC 2440	15.0	115.481	-18.209	79.8	75.4	86.9	92.3	HRC-I	-	-	NONE	Kastner	GO	25	0	N	N	N	N	N	N	N	N	Y	N/A
201686		28832	zeta Puppis	30.0	120.896	-40.003	85.1	79.0	79.2	82.7	ACIS-S	5	2	HETG	Gunderson	GTO	25	0	N	N	N	N	N	N	N	N	N	-105.0
291711		28381	Vega	1.0	279.237	38.786	288.7	294.9	84.2	81.0	HRC-S	-	-	NONE	Kashyap	CAL	25	0	N	Y	N	N	Y	N	N	N	N	N/A
291713		28383	Vega	1.0	279.237	38.786	288.7	294.9	84.2	81.0	HRC-S	-	-	NONE	Kashyap	CAL	25	0	N	Y	N	N	Y	N	N	N	N	N/A
402491		28037	SMC 2857	50.0	14.417	-71.988	348.8	342.5	97.0	94.1	ACIS-S	4	2	NONE	Ludwig	GO	25	0	N	N	N	N	N	N	N	N	N	-105.0
503455		28052	Crab Nebula	10.0	83.632	22.018	91.6	91.4	123.6	130.5	ACIS-S	2	0	NONE	Romani	GO	25	0	N	Y	N	N	N	N	N	N	N	-111.0
503474		28071	AT2024qfm	40.0	350.348	11.942	271.5	276.3	145.4	139.0	ACIS-S	2	0	NONE	MARGUTTI	TOO	25	0	N	S	N	N	N	N	N	P	N	-105.0
601591		28097	UM 351	25.0	24.594	1.901	353.0	326.0	171.2	166.4	ACIS-S	5	3	NONE	Irwin	GO	25	0	N	N	N	N	N	N	N	N	N	-105.0
601617		28547	NGC1512	30.0	60.976	-43.349	39.7	31.9	117.1	117.8	ACIS-S	5	3	NONE	Lehmer	GO	25	0	-1.2	N	N	N	N	N	N	N	N	-108.0
601621		28551	NGC7496	30.0	347.447	-43.428	317.6	312.9	115.7	110.2	ACIS-S	5	3	NONE	Lehmer	GO	25	0	N	N	N	N	N	N	N	N	N	-108.0
601622		28860	LEDA407	15.0	1.430	-50.115	333.4	327.5	115.6	111.2	HRC-S	-	-	LETG	Burwitz	GTO	25	0	N	N	N	N	N	N	N	N	N	N/A
704636		29501	NSA 91579	11.9	180.857	33.146	32.7	38.3	49.8	55.1	ACIS-S	4	2	NONE	Baldassare	GO	24	0	-6.3	N	N	N	N	N	N	N	N	-105.0
704981	H	28590	Abell 370	30.0	39.960	-1.586	48.9	27.1	161.2	163.5	ACIS-I	4	0	NONE	Bogdan	GO	25	0	-3.5	N	N	N	N	N	N	N	N	-111.0
704981	H	28591	Abell 370	30.0	39.960	-1.586	48.9	27.1	161.2	163.5	ACIS-I	4	0	NONE	Bogdan	GO	25	0	-3.5	N	N	N	N	N	N	N	N	-111.0
704981	H	28603	Abell 370	30.0	39.960	-1.586	48.9	27.1	161.2	163.5	ACIS-I	4	0	NONE	Bogdan	GO	25	0	-3.5	N	N	N	N	N	N	N	N	-111.0
705100		28291	SDSS J005824.75+0041	19.0	14.603	0.687	312.6	306.0	165.1	158.5	ACIS-S	2	0	NONE	Risaliti	GO	25	0	-5.3	N	N	N	N	N	N	N	N	-105.0
802120		28676	SpARCS J105111+58180	30.0	162.797	58.301	43.3	48.4	77.2	82.0	ACIS-I	4	0	NONE	Hlavacek-Larrondo	GO	25	0	-1.9	N	N	N	N	N	N	N	N	-108.0

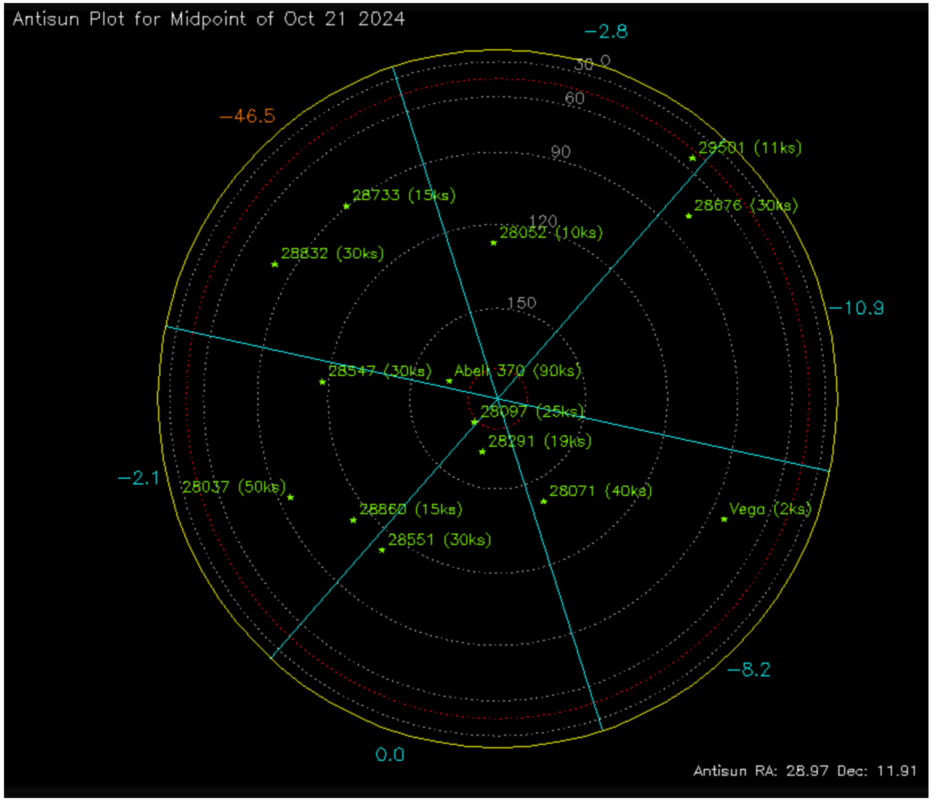
Cycle Stars Constraints Coordinations

- 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 in the process than just a few years ago.
- The Cycle 26 LTS has been delayed by budget uncertainties, but is now under construction. Fortunately, we were able to extend the Cycle 25 LTS into December 2024.

Tool / Process Updates

A New "Sky Balance" Metric

- Maneuvering has become increasingly important for detailed weekly planning, due to smaller observation durations and a greater number of splits.
- Previously, the sky distribution of targets in a given week was not quantitatively considered when constructing the Long Term Schedule.
- Developed a metric to quantify the "goodness" of the sky distribution of a collection of targets. The LTS is now designed to keep this metric below some (empirically determined) critical value each week.
- Consider total *negative* thermal impact in each of 6 (optimally chosen) sectors.
- Significantly reduced the typical amount of "dropped time" each week, leading to a much more stable LTS.



Tool / Process Updates

Machine Readable ORLs

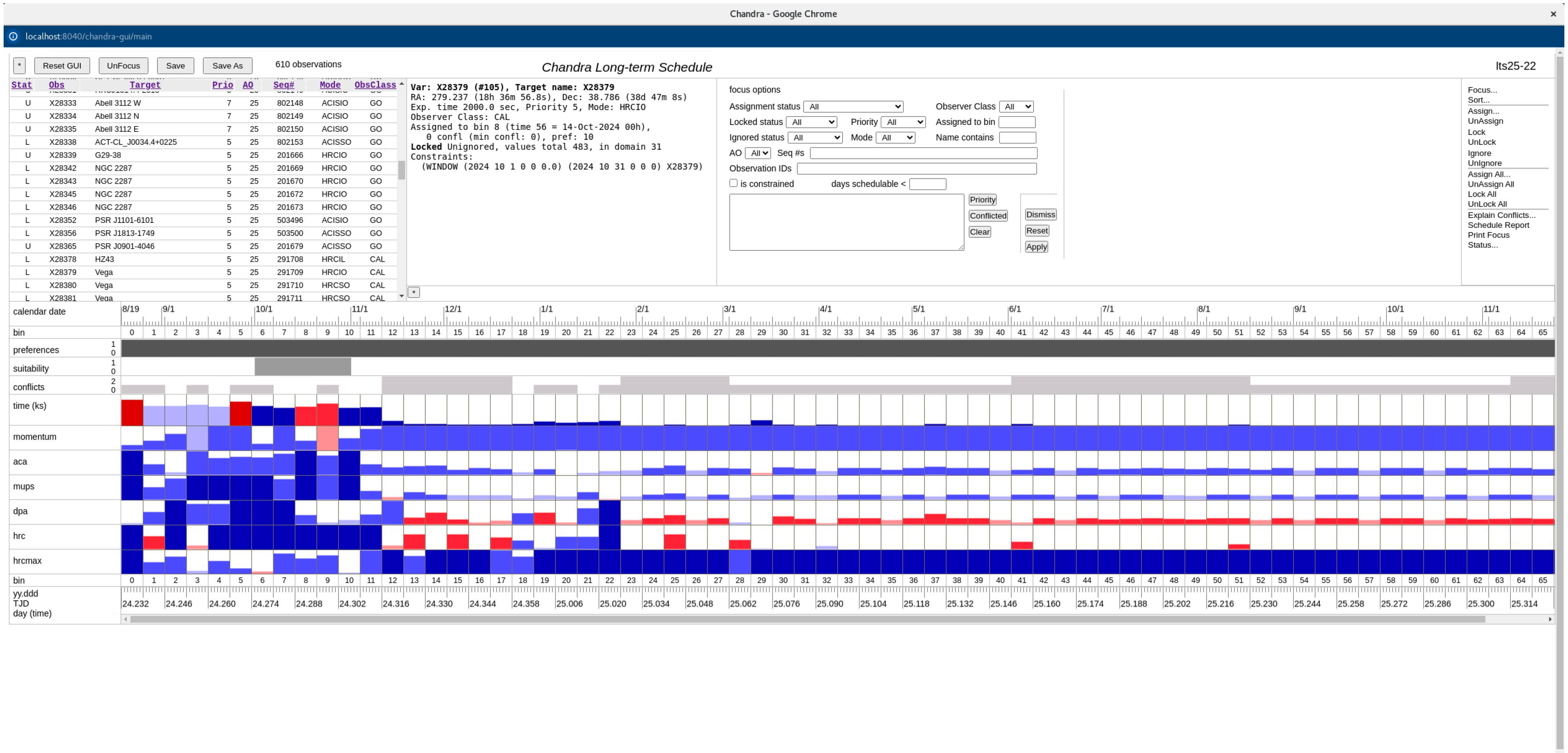
- We have implemented a new machine-readable ORL format, built around YAML formatted key/value pairs.
- This allows automated checking of most scheduling constraints during detailed weekly planning.
- It also sets the groundwork for eventually developing assistive scheduling software, which would help automate the building of weekly schedules (similar to what has been done with Spike for the LTS).

Updated Spike GUI

- The GUI tool that for many years we used for weekly planning needed to be replaced, as it was based on an obsolete, unmaintained protocol.
- Working with developers at STScI, we now have a web browser based tool, that is not only maintainable, but tracks various thermal and other constraints accurately when working on scheduling.
- This tool has significantly streamlined weekly planning and LTS maintenance for SOTMP.

Tool / Process Updates

Updated Spike GUI



Tool / Process Updates

Notable Temperature Limit Increases

- As of the Fall 2023 CUC Meeting, we did not expect any further significant temperature limit increases for the MUPS, severely limiting maximum dwell times at forward sun pitch angles.

- Subsequently, a detailed engineering investigation revealed that allowing the MUPS to reach significantly higher temperatures was very likely to be safe. As a result, we are in the midst of a series of planned step increases to this limit.

- This has been a massive boon for scheduling, and for Chandra's maximum dwell time capabilities.

- Furthermore, thanks to a significant calibration effort, we have identified classes of observations that can be done at higher ACIS focal plane temperatures, greatly improving scheduling flexibility. For Cycle 25 ACIS obs:

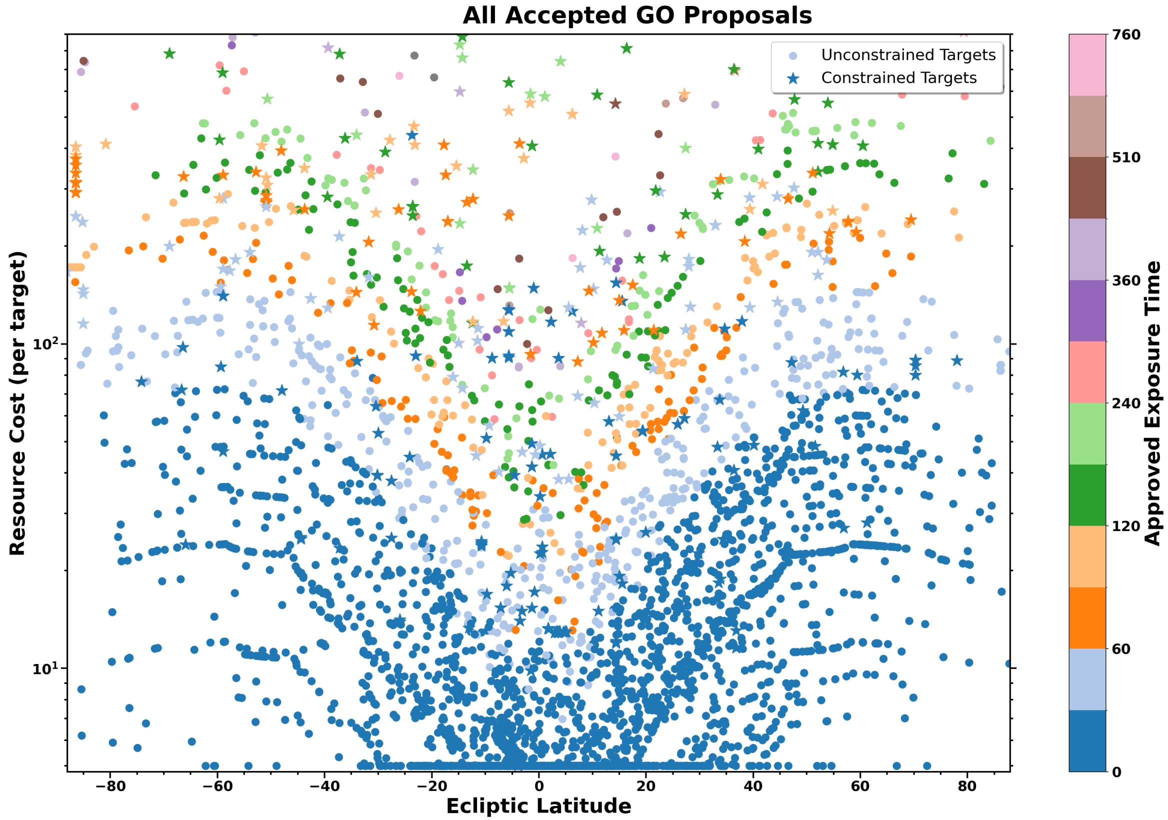
    - -105 C FP Limit: 31%
    - -108 C FP Limit: 18%
    - -109 C FP Limit: 4%
    - -111 C FP Limit: 47%

Tool / Process Updates

New Thermal Database

- Calculation of the thermal impact of a given observation on the various satellite components depends on the solar pitch angle, the instrument setup, and the science requirements.
- Previously, these impacts were calculated on the fly, which is expensive when one wants to know the impact of a given observation (or set of observations) on each thermal component throughout the year, e.g., when deciding where to place a new observation in the LTS.
- We have implemented a new thermal database, which pre-calculates these values for all ObsIDs throughout the year. The database is automatically updated when a new observation is created, or when a relevant parameter for an existing observation is updated.
- This drastically reduces the runtime of the code used for LTS construction and weekly maintenance, improving the efficiency of these tasks.

Resource Cost

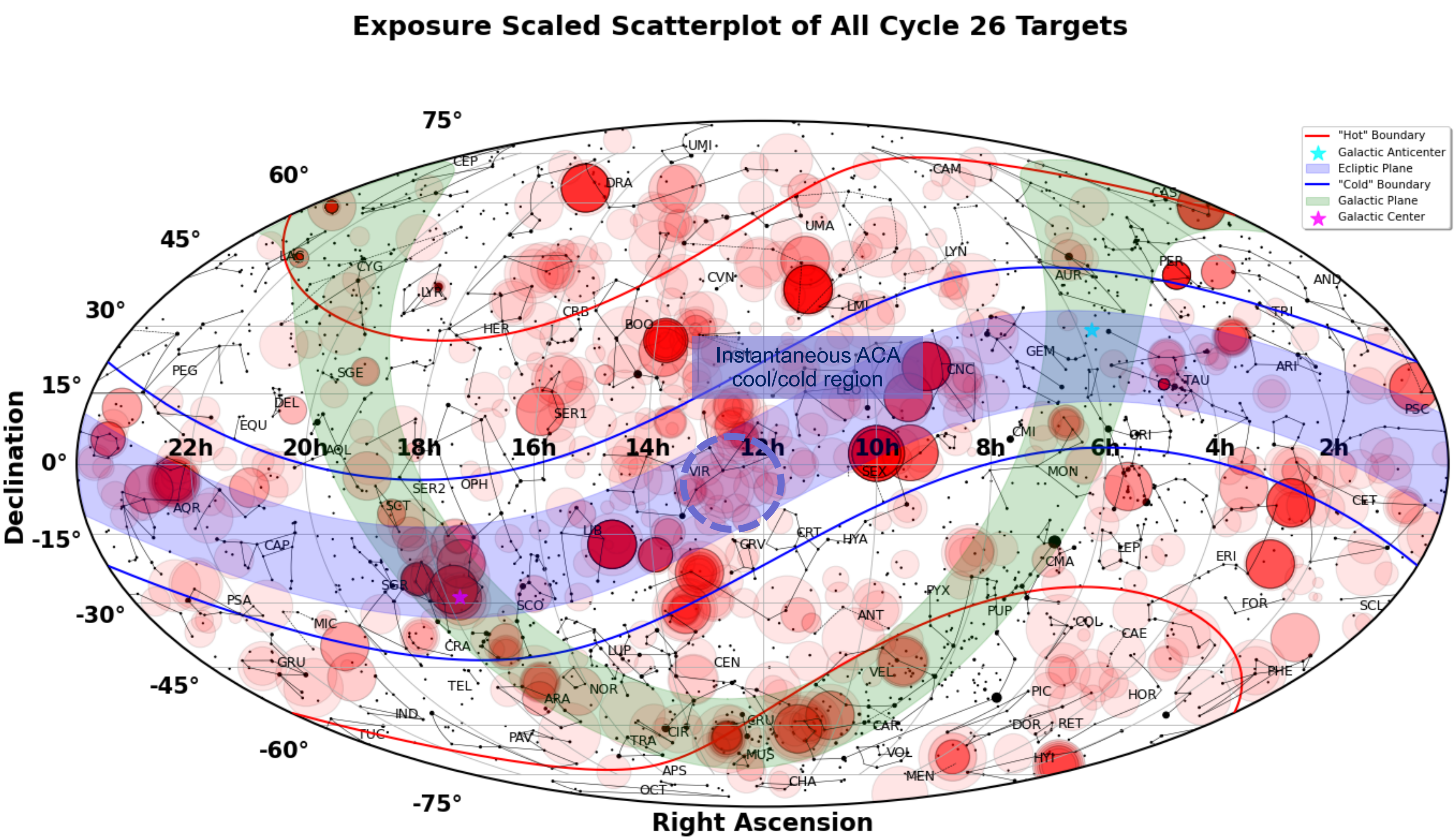


Resource Cost (RC) values for observing programs from *Chandra* Cycles 14-26. Starred targets have science observing constraints, circles are unconstrained.

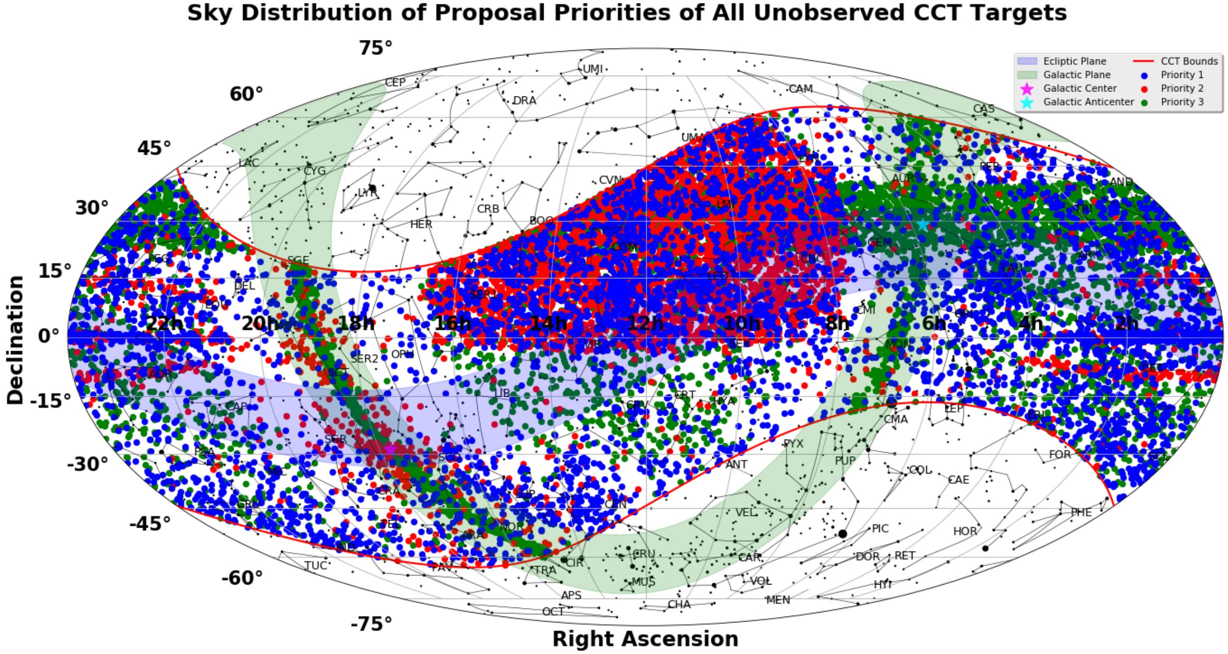
- Introduced in cycle 22.
- Replaces "constraint categories" (easy/average/difficult) used in previous cycles.
- Calculated for all non-TOO targets.
- On current (arbitrary) scale, peer review assigns total cost ~27,000.
- For Cycle 26: minor fixes, and pitch weighting changes to not as strongly disfavor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



Chandra Cool Targets (CCTs)



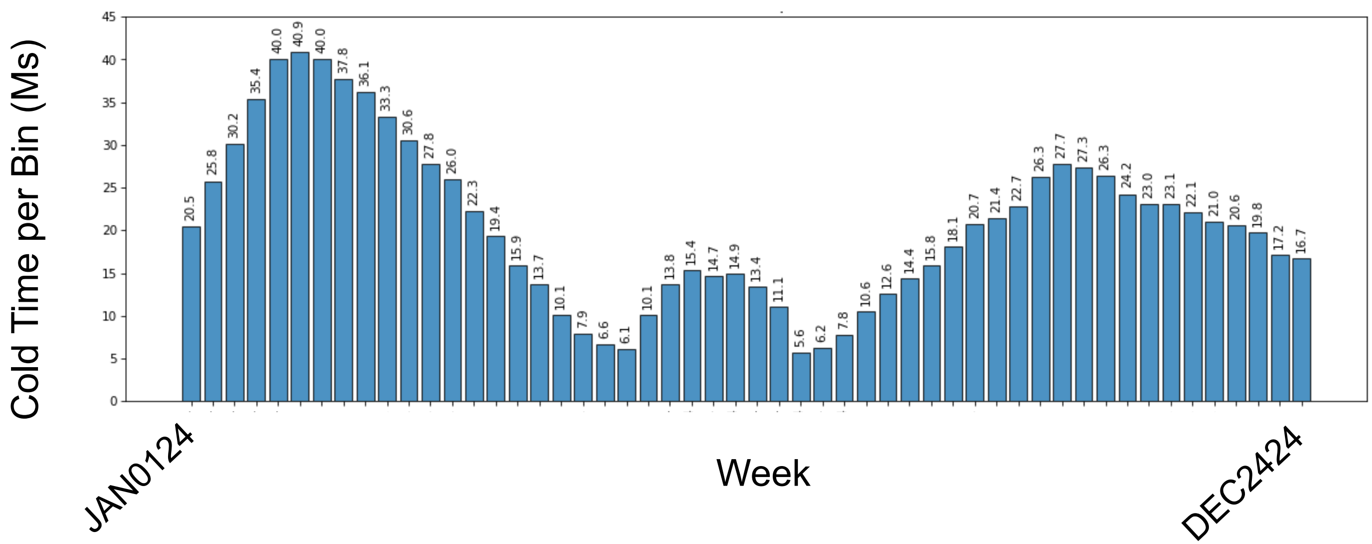
- 22 programs
- Include:

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



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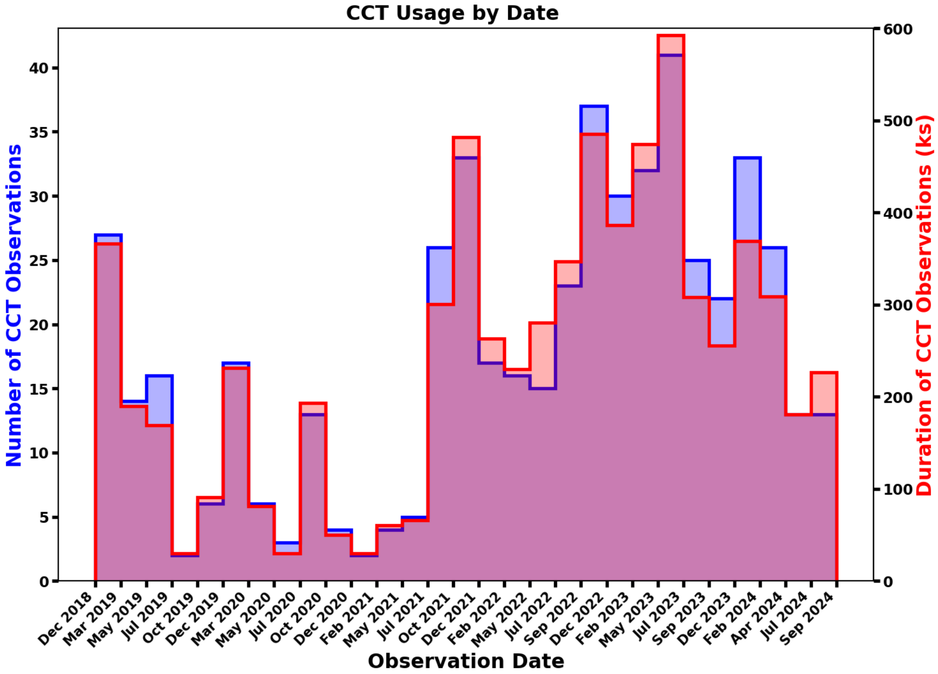
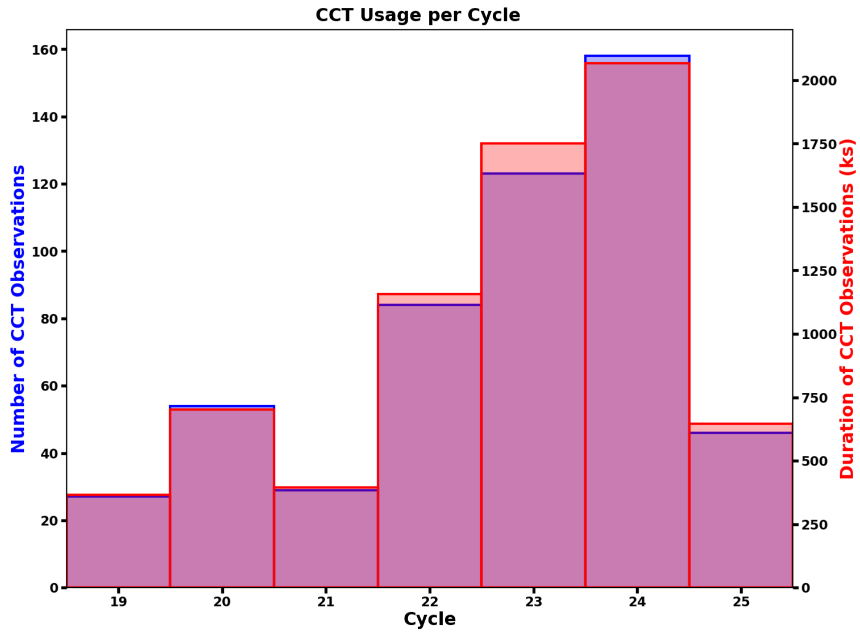
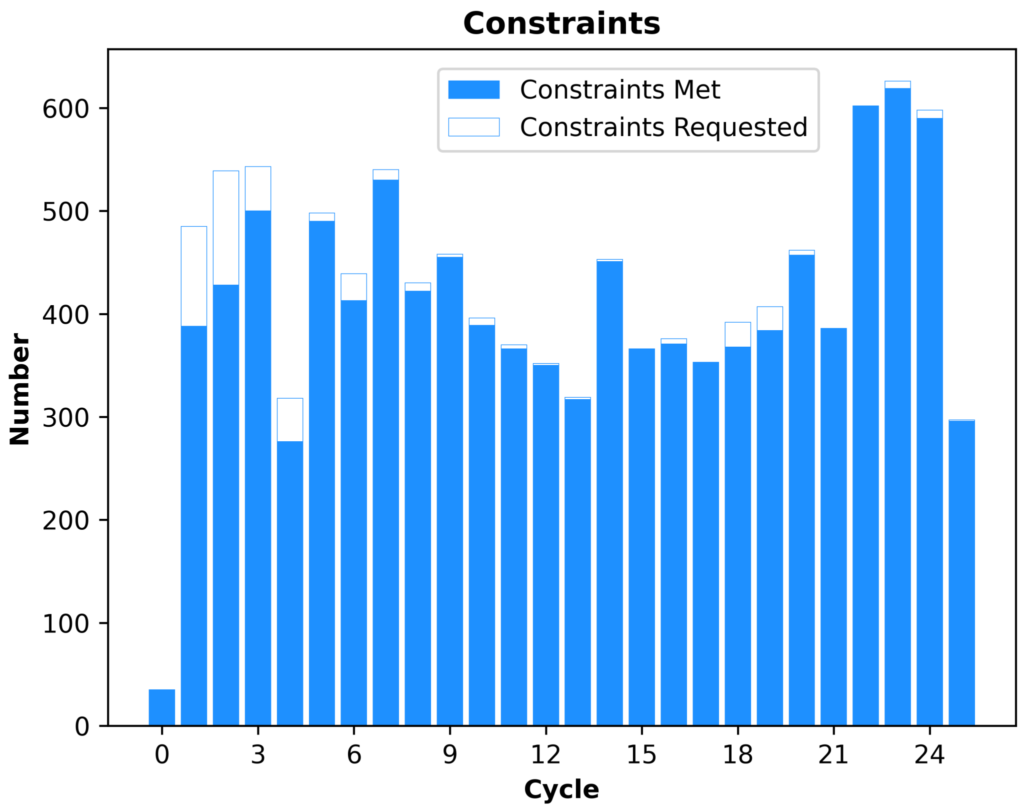




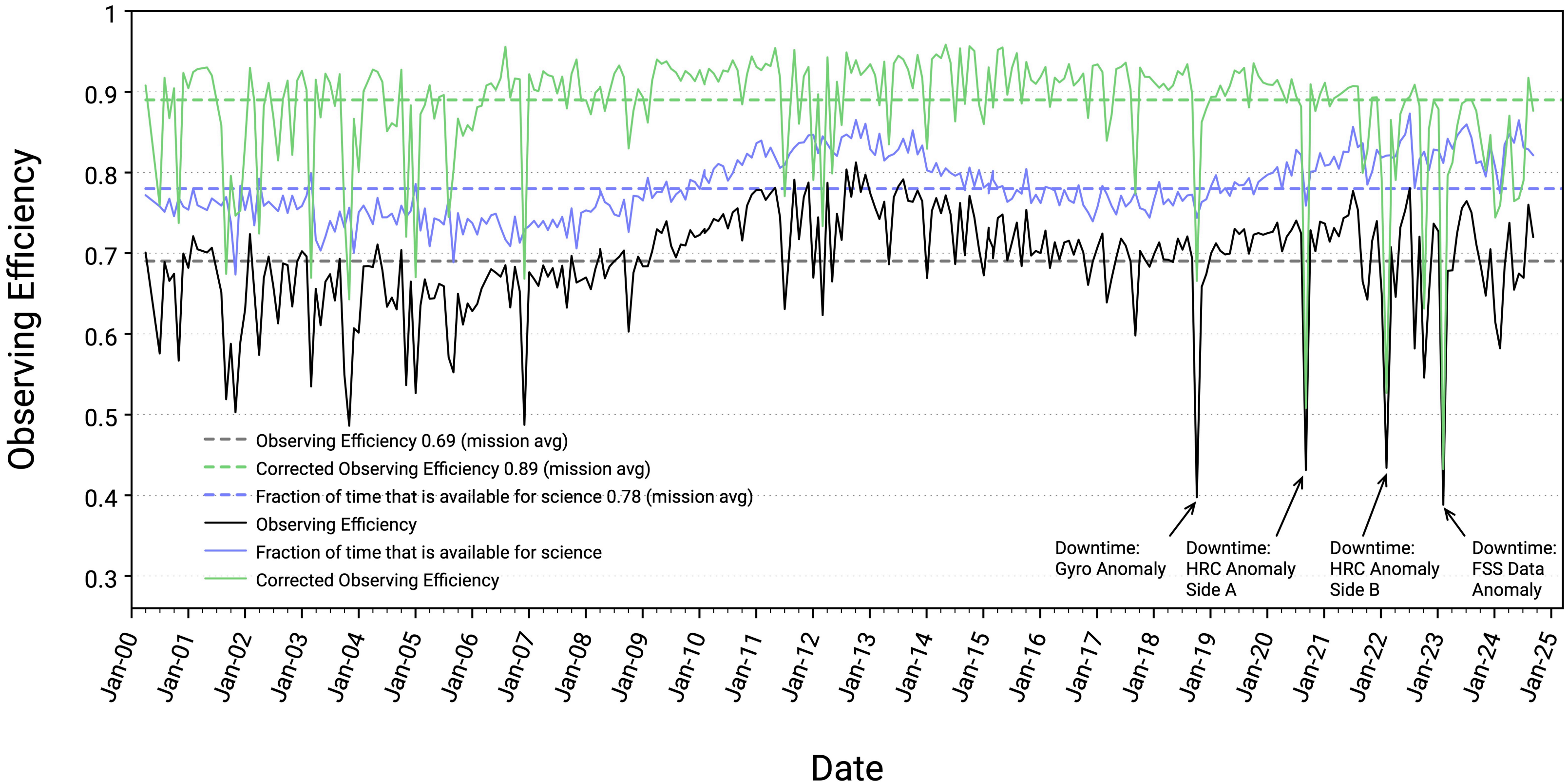
CCT usage has increased in recent years, although this is probably partially driven by recovery from operational events (e.g., HRC power anomaly, IU reset, Fine Sun Sensor issue), and by large programs with particularly difficult star fields observed prior to the ACA flight software patch

Science Constraints



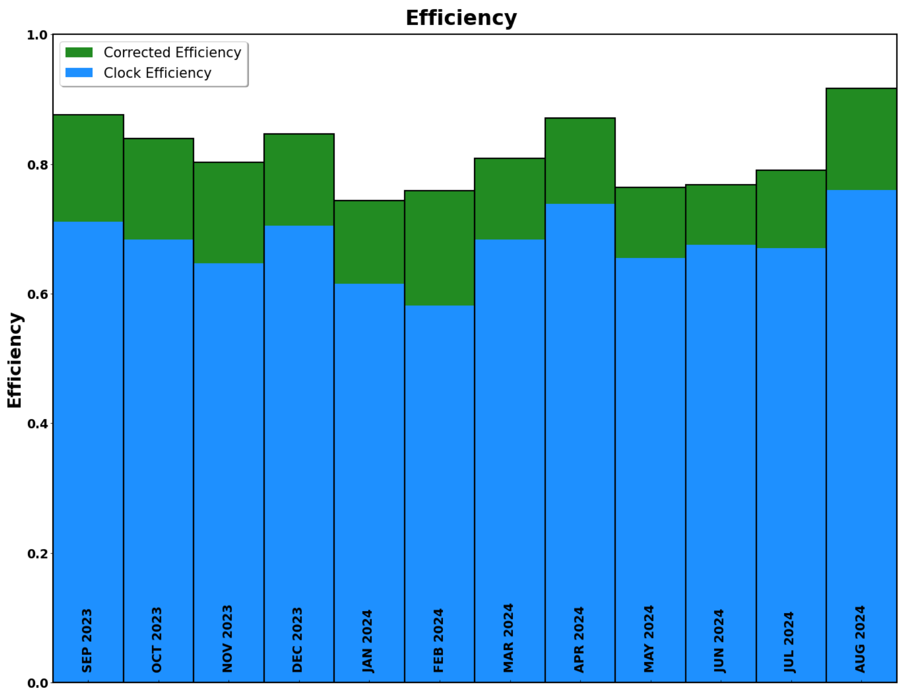
- Difficulty associated with meeting constraints is increasing due to spacecraft thermal limitations (e.g., decrease in maximum dwell times, increasing number of star field constrained targets).
- However, we continue to meet approved observing constraints successfully.
- Most missed constraints are due to solar flares and other operational events that lead to schedule interruptions.

Mission Efficiency History

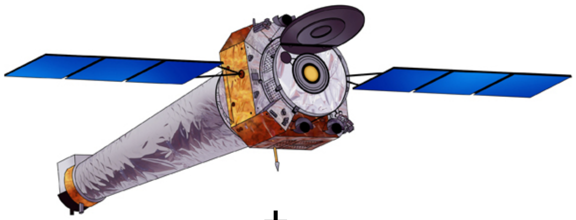


- The “corrected efficiency” (the fraction of available science time we spend observing, green line) has dropped somewhat in recent years. This is largely driven by shorter observation durations (which means more maneuver time), and the use of “intermediate attitudes” to help mange thermal issues.
- Nonetheless, the corrected efficiency remains high, and the wall-clock efficiency is consistent with the mission average.

Observation Scheduling



Coordinated Observations



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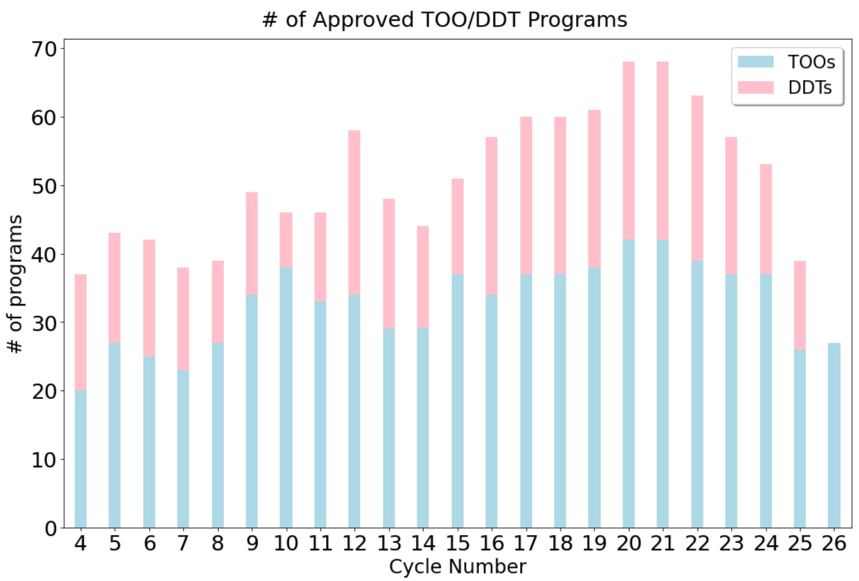
JWST, HST, NuSTAR, Swift, XMM, IXPE, NICER, VLA, ALMA, EHT, Hobby-Eberly

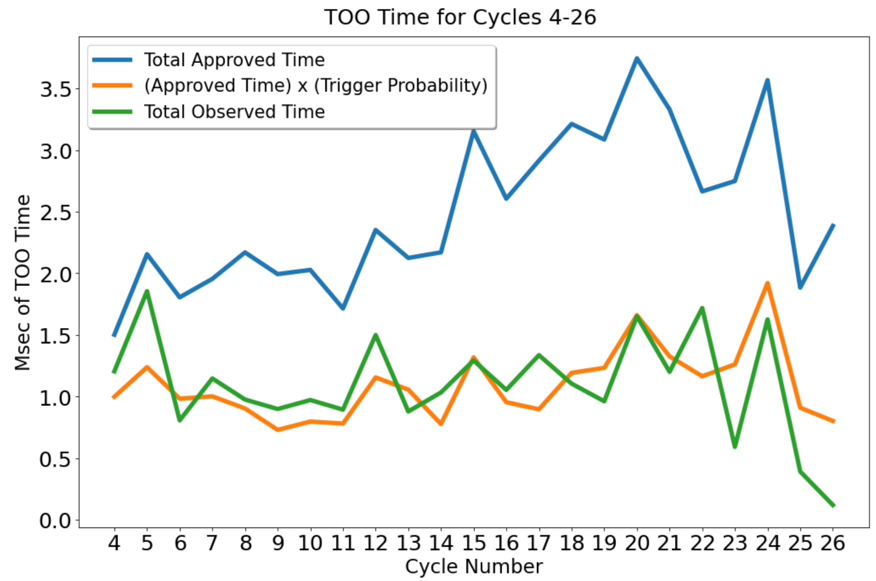
From Sep. 16, 2023 - Sep. 15, 2024:

- Scheduled: 1437 observations (21.6 Ms)
- Executed:
  - 63 TOO observations (924 ks)
  - 35 DDT observations (597 ks)
    - ✧ interrupted 4 operating loads for TOO/DDT support

- Chandra Coordinations (Sep. 16 2023 - Sep. 15 2024):
  - 90 observations for 1.47 Ms

TOO/DDT Observations: Historical Performance





Historical TOO/DDT performance has been very steady despite evolving thermal constraints.

- 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 complicates both 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, TOO/DDT response, and science constraint compliance that are on par with mission history.
- There are no known barriers to the continued successful and efficient operation of Chandra for years to come.

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

<u>Completed in Cycle 23:</u>

- 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

Coming Up in Cycle 24:

• 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

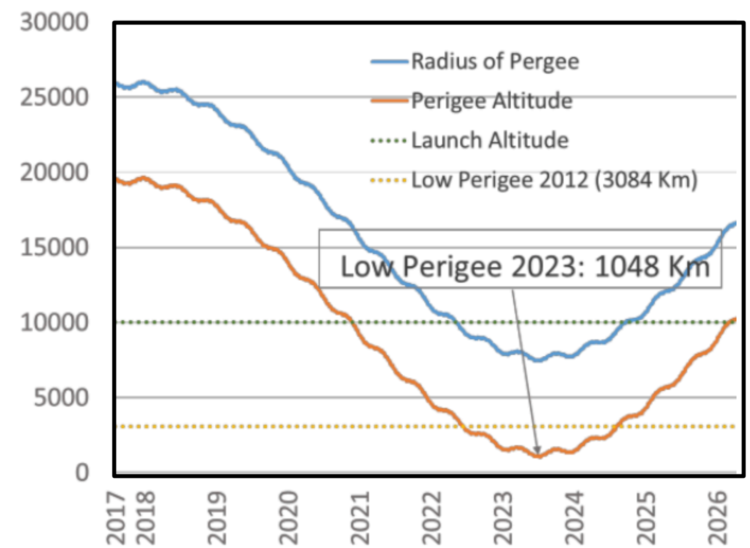
Snapshot of Planning Process

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)					

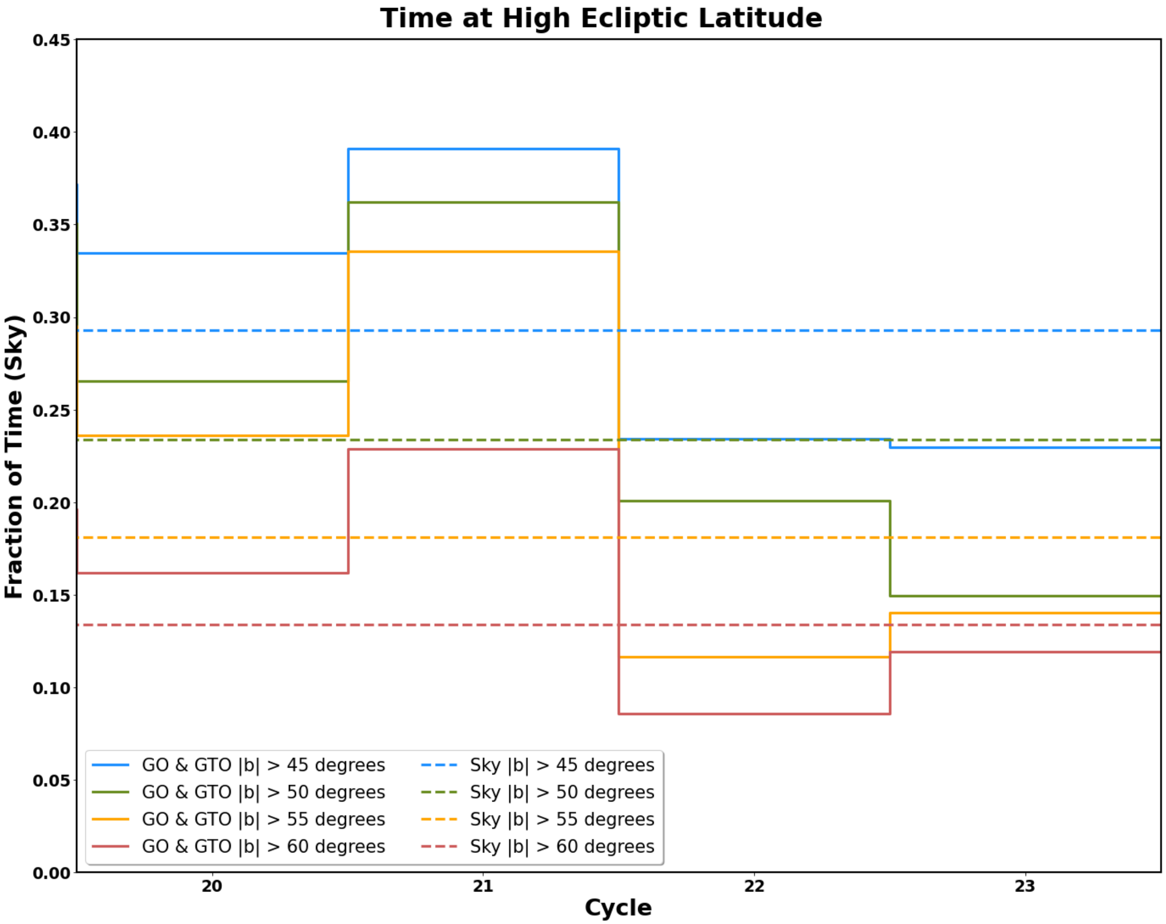
Tool/Process/Limit Updates

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.



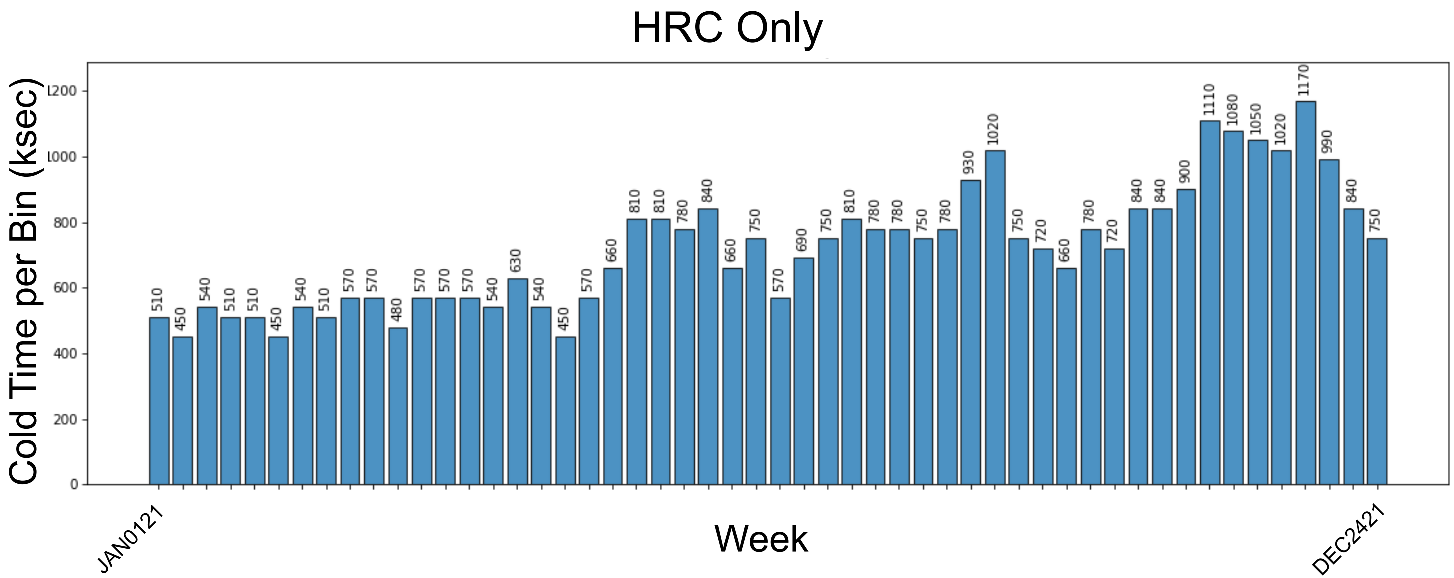
Target Distribution: Cycle 22



- 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)

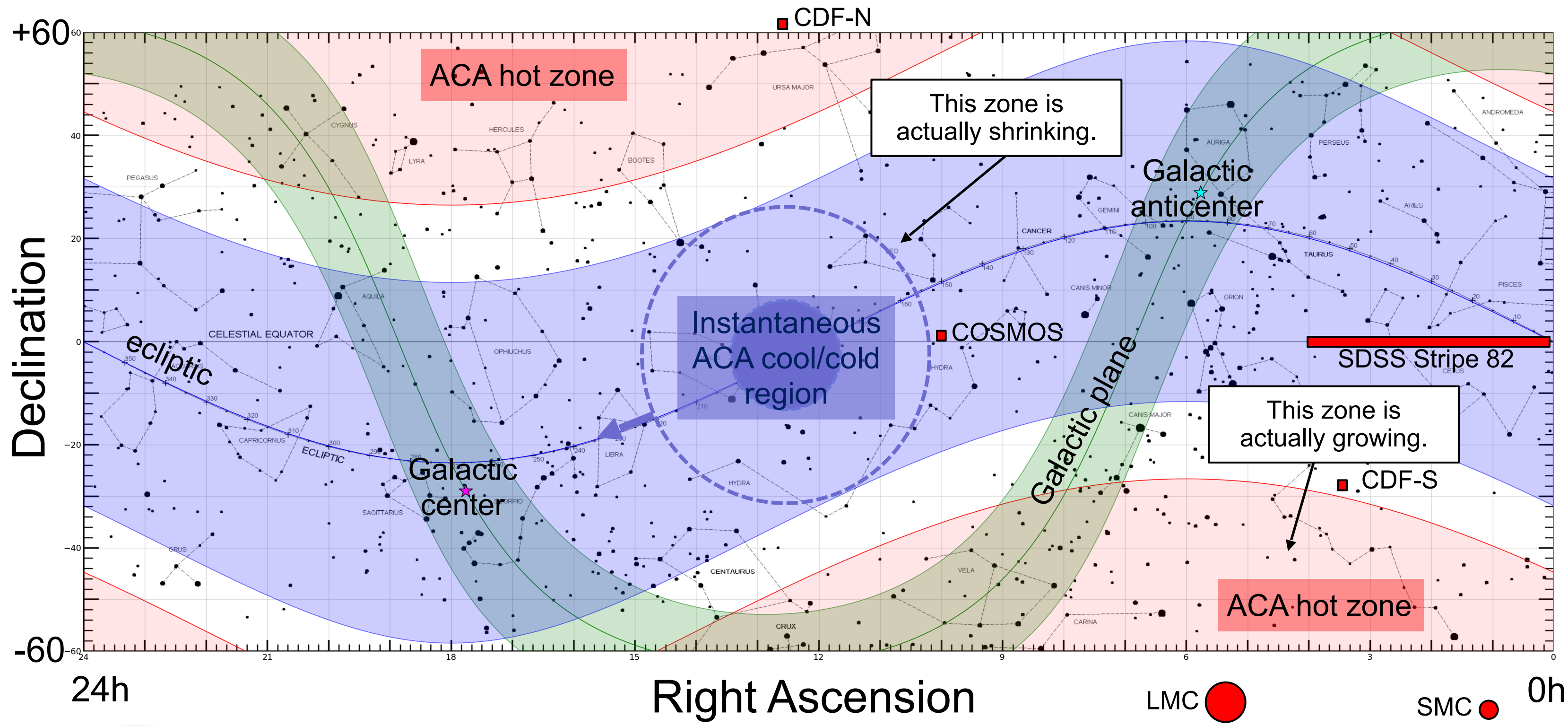


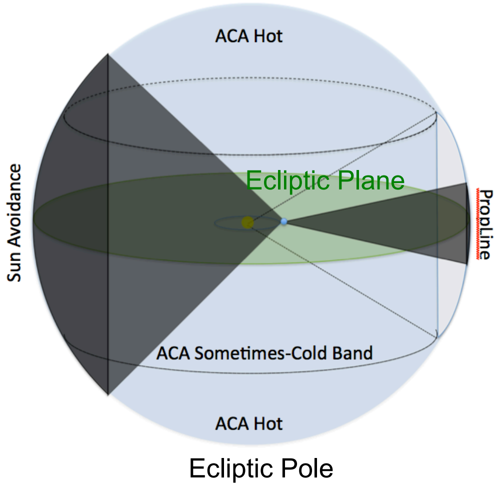
- Recall that cold HRC observations are particularly useful for thermal management, since ACIS is the main limiting factor at high pitch angles.

- 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



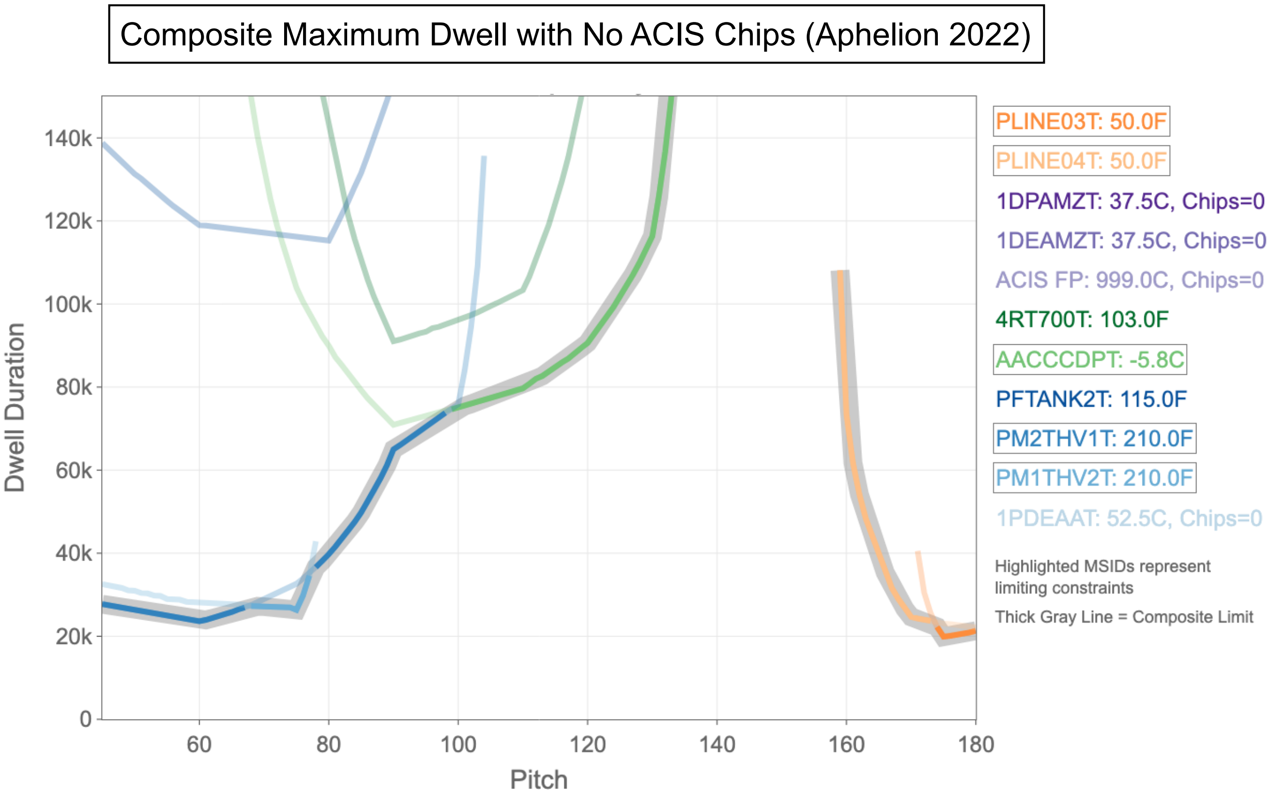


- Sometimes-cool/cold ACA (-Z) region covers large sky area.

  - 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



- 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.