CMB-S4 Systems Engineering Update

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(he/him/his)

CMB-S4 Collaboration Meeting
May 9-13, 2022

Outline

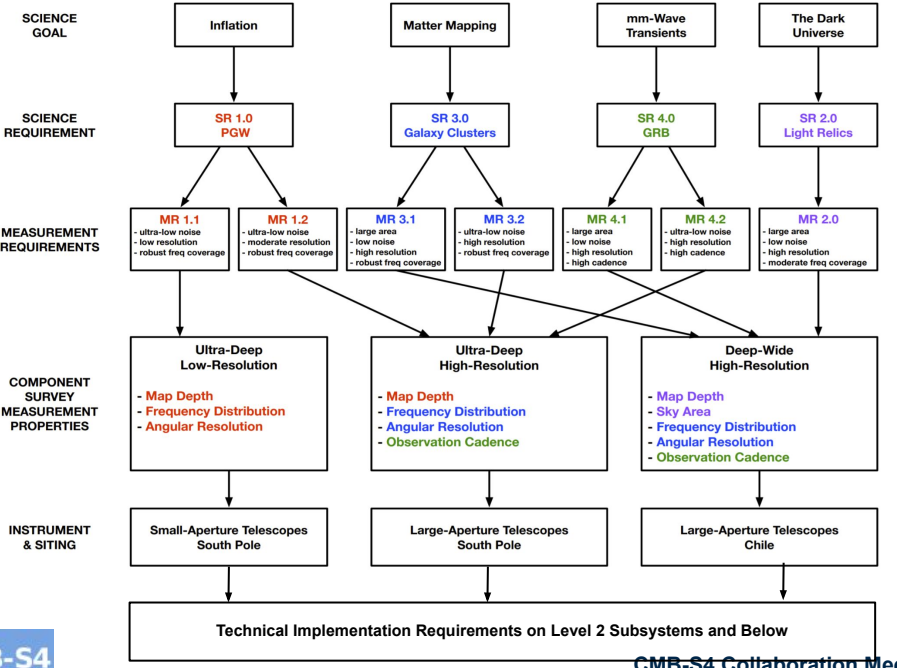
- Design Maturity
- Requirements
- Interfaces
- Performance margin
- AoA efforts
- Common Technologies

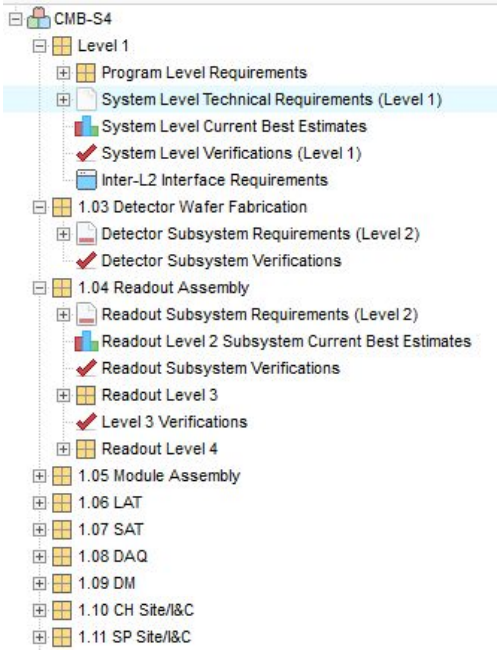
CMB-S4's Current Design Maturity

- All subsystems have conducted and passed Conceptual Design Reviews
- The project technical maturity
- The project overall is near Conceptual Design maturity, with areas of focus to continue on:
  - Requirements iteration / refinement
  - Performance margin assessment and improvement
  - Interface definitions
  - Verification / Acceptance plans

Systems Engineering - Requirements

- *The project exists to construct and deploy an experiment that will achieve the defined science goals*
- Requirements define the minimum performance of the experiment at all levels
- Requirements flow down from high-level science goals to all the way to technical implementation
- Meeting requirements at each level ensures the requirements at the next higher level are met
- Requirements are managed using the project's Jama requirements database (right)
- Development and refinement of all requirements includes regular workshops and a recent internal review





Project-Level (L2-L2) Interfaces Are Drafted And Maturing

- Interfaces are defined where subsystems meet
- As designs mature, interfaces are iterated, refined, and documented in Interface Control Documents (ICDs)
- Level of maturity of ICDs rated by Phase:
  - Phase 1: At Preliminary Design maturity--scope, boundaries and responsibilities defined.
  - Phase 2: Design-driven refinements to boundaries and responsibilities. Loads, flows, and functional requirements defined.
  - Phase 3: All details fully-documented. Subsystems can finalize their respective designs independently.
- Interfaces within Subsystems are also being developed

CMBS4-doc-469-v9: N-squared interface matrix

WBS 1.04 Readout	WBS 1.05 Module Assembly & Testing	WBS 1.06 Large Aperture Telescopes	WBS 1.07 Small Aperture Telescopes	WBS 1.08 Data Acquisition & Control	WBS 1.09 Data Management	WBS 1.10 Chile Site Infrastructure/I&C	WBS1.11 South Pole Site Infrastructure/I&C	← L2 Elements ↓
E (339)	M, E, T (463)	X	X	X	X	X	X	WBS 1.03 Detectors
	M, E, T (321)	M, E, T (318)	M, E, T (354)	E (324)	X	M, E, T (718)	M, E, T (719)	WBS 1.04 Readout
		M, T, O (345)	M, T, O (342)	X	X	M, E (721)	M, E (720)	WBS 1.05 Module Assembly & Testing
			X	M, E, T (333)	X	M, E, T (336)	M, E, T (330)	WBS 1.06 Large Aperture Telescopes
				M, E (351)	X	X	M, E, T (348)	WBS 1.07 Small Aperture Telescopes
					E (327)	M, E, T (417)	M, E, T (423)	WBS 1.08 Data Acquisition & Control
						M, E, T (426)	M, E, T (432)	WBS 1.09 Data Management
							X	WBS 1.10 Chile Site Infrastructure/I&C

(XXX) in cell indicates docdb number

Interface type key

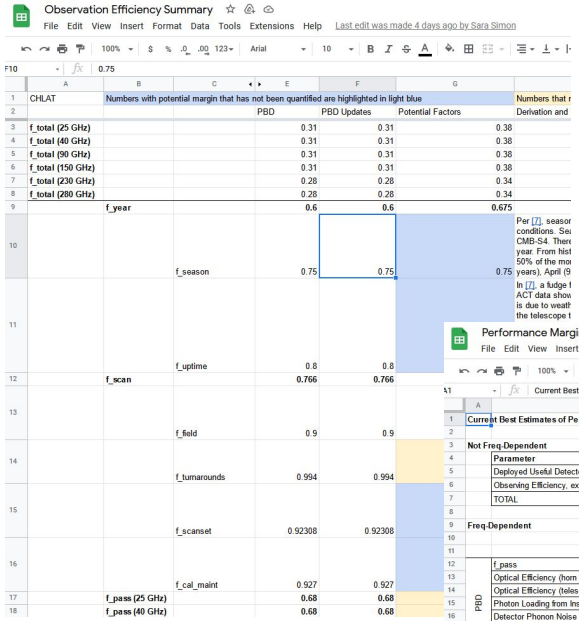
M	mechanical
E	electrical, data, control, telem
T	thermal
O	optical

ICD maturity phase color coding

X	no interface exists, no ICD req'd
	doc drafted, general xface params named
	more specific naming of xface params & boundaries
	most scope, boundaries, responsibilities defined
Phase 1	scope, boundaries, responsibilities defined
Phase 2	design-driven refinements
Phase 3	ICD complete

Performance Margin (more detail Thursday a.m.)

- CMB-S4 aims to deliver unprecedented CMB science reach
- Performance margin helps assure the science goals will be met in the planned survey duration, even with risks and uncertainties
- Ongoing efforts are identifying areas where performance margin can be built
- Current areas of focus include
  - Observing efficiency (optimizing scan strategies and system up-time)
  - Fraction of deployed detectors that contribute to mapping (by rigorous detector fab process control and screening)
  - Use of low-ell data from SPLAT (to augment mapping from SATs)



Observation Efficiency Summary

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	A	B	C	E	F	G
1	CHLAT	Numbers with potential margin that has not been quantified are highlighted in light blue				Numbers that r
2				PBD	PBD Updates	Potential Factors	Derivation and
3	f_total (25 GHz)			0.31	0.31	0.38	
4	f_total (40 GHz)			0.31	0.31	0.38	
5	f_total (90 GHz)			0.31	0.31	0.38	
6	f_total (150 GHz)			0.31	0.31	0.38	
7	f_total (230 GHz)			0.28	0.28	0.34	
8	f_total (280 GHz)			0.28	0.28	0.34	
9		f_year		0.6	0.6	0.675	
10			f_season	0.75	0.75	0.75	Per [7], seasor conditions. Se CMB-S4. Ther year. From hist 50% of the mo years), April (9
11			f_uptime	0.8	0.8		In [7], a fudge f ACT data show is due to weatl the telescope t
12		f_scan		0.766	0.766		
13			f_field	0.9	0.9		
14			f_turnarounds	0.994	0.994		
15			f_scanset	0.92308	0.92308		
16			f_cal_maint	0.927	0.927		
17		f_pass (25 GHz)		0.68	0.68		
18		f_pass (40 GHz)		0.68	0.68		

Performance Margin Summary

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Current Best Estimates of Performance Margin relative to Preliminary Baseline Design

				PBD value	CBE value	ratio	margin		
	Not Freq-Dependent								
		Parameter							
		Deployed Useful Detector Fraction		0.8	0.9	1.125	13%		
		Observing Efficiency, excluding f_pass		0.459	0.562	1.22	22%		
		TOTAL				1.38	38%		
	Freq-Dependent								
				Band					
				LF_1	LF_2	MF_1	MF_2	HF_1	HF_2
PBD		f_pass		0.68	0.68	0.68	0.68	0.6	0.6
PBD		Optical Efficiency (horn to detector)		0.7	0.7	0.7	0.7	0.7	0.7
PBD		Optical Efficiency (telescope+optics tubes)		0.145	0.266	0.161	0.270	0.508	0.549
PBD		Photon Loading from Instrument	[Watts/Hz]	2.12E-23	3.22E-23	2.40E-23	5.31E-23	1.44E-22	2.02E-22
PBD		Detector Phonon Noise	[W/sqrt(Hz)]	2.85E-18	7.26E-18	8.40E-18	1.24E-17	2.63E-17	2.83E-17
PBD		Readout Noise	[W/sqrt(Hz)]	1.37E-18	4.31E-18	5.38E-18	9.78E-18	2.88E-17	3.42E-17
PBD		NumDetectors/wafer		96	96	864	864	864	864
CBE		f_pass		0.68	0.68	0.68	0.68	0.6	0.6
CBE		Optical Efficiency (horn to detector)		0.7	0.7	0.7	0.7	0.7	0.7
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CBE		NumDetectors/wafer		96	96	864	864	864	864
	Ratio of CBE mapping speed to PBD mapping speed for freq-dependent factors			1.00	1.00	1.00	1.00	1.00	1.00
	CBE Mapping speed margin for freq-dependent factors			0.00	0.00	0.00	0.00	0.00	0.00
	CBE Mapping speed margin including freq-dependent and non-freq-dependent params			38%	38%	38%	38%	38%	38%

Support of Analysis of Alternatives

- Help define technical implementations for various experimental configurations (e.g. differences in hardware deployed in Chile vs South Pole)
- Parameterize resources needed, with the Preliminary Baseline Design as the starting point, e.g. electrical power needs:

CMB-S4 Electrical Power Needs v2

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Item	Quan at Chile Site	Max power each (kW)	Steady-state power each (kW)	basis (e.g. mfgr docs, eng'g analysis, test data)	Notes	Total max power in Chile (kW)	Total SS power in Chile (kW)
disk array	1	2.2	1.65	https://www.dell.com/en-us/work/shop/dell-emc-storage/powervault		2.2	1.65
server	1	0.5	0.375	https://i.dell.com/sites/csdocuments/Product_Docs/en/poweredge		0.5	0.375
rack UPS	1	0.125	0.125	https://www.dell.com/en-	See https://www.eng-tips.com/viewthread	0.125	0.125
TOTAL						2.825	2.15
	0.75	one possible value for average/peak power, taken from https://www.intel.com/content/dam/doc/white-paper/resources-xeon-measuring-processor-p					

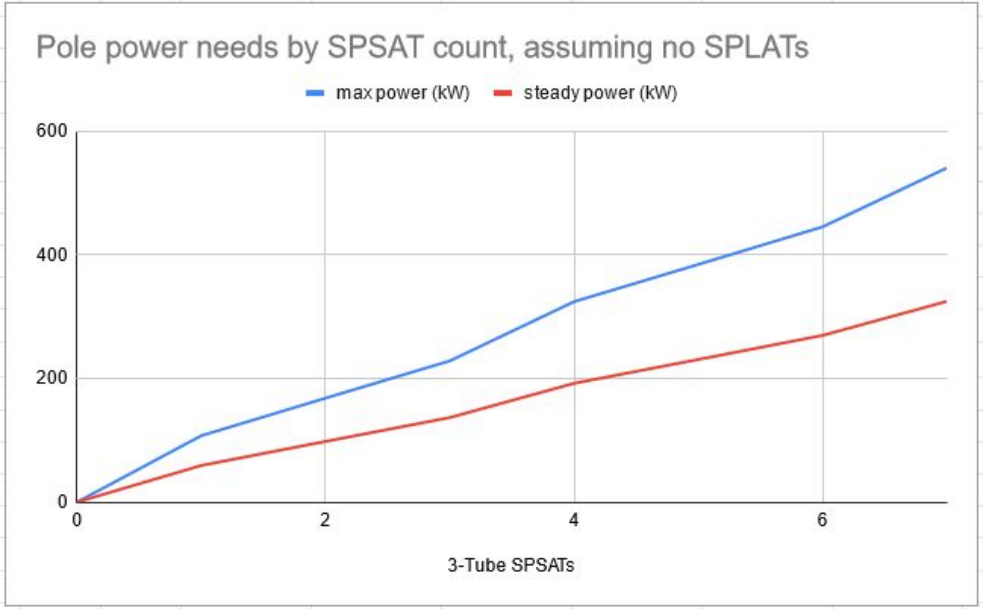
BOE discussed further in https://docs.google.com/spreadsheets/d/1_CVOTlMbvPp_aiGp5-c7oMsdopnijj0xUVLEpKF8Kfl/edit#gid=0

Item	Quan at Pole Site	Max power each (kW)	Steady-state power each (kW)	basis (e.g. mfgr docs, eng'g analysis, test data)	Notes	Total max power at Pole (kW)	Total SS power at Pole (kW)
disk array	8	2.8	2.1	https://i.dell.com/sites/d	data sheet does not specify max vs. stea	22.4	16.8
compute nodes	40	0.5	0.375	https://i.dell.com/sites/c	data sheet does not specify max vs. stea	20	15
rack UPS	6	0.125	0.125	https://www.dell.com/en-	See https://www.eng-tips.com/viewthread	0.75	0.75
TOTAL						43.15	32.55
	0.75	one possible value for average/peak power, taken from https://www.intel.com/content/dam/doc/white-paper/resources-xeon-measuring-processor-p					

BOE discussed further in https://docs.google.com/spreadsheets/d/1V1udyFb4BeDvJw2XKiYdXxo37JrmM9VeHfuMjntavU/edit#gid=0 and https://docs.google.com/spreadsheets/d/185CN-lltj

scaling model from the first link in the BOE cell above:

	count	power	
SPLAT samples/s =	3.60E+07		
SAT samples/s =	166666.6667	per tube!	
baseline pole samples/s	3.90E+07		
baseline pole disks needed	8	(exactly)	
disks needed per SPLAT	7.38		
disks needed per CHLAT	0.31	(420 TB needed in baseline divided by the max capacity of MD1280 divided by 2 CHLATs in baseline)	
disks needed per SPSAT cryostat	0.10	per 3-tube cryostat!	
disks needed per CHSAT cryostat	0.004	per 3-tube cryostat!	scale relative to disks/CHLAT as for SPLAT - SPSAT
baseline compute nodes	40	(exactly)	



Common Technologies - Technical areas that are relevant in multiple areas of the project

- Goals:
  - Leverage the experience of the S4 team and others
  - Apply lessons learned
  - Avoid redundant work
  - Apply uniform engineering approaches to common technical areas
- Approach:
  - Identify technical areas that span multiple subsystems, and which consolidation of effort can help achieve the above goals
  - Project-wide approaches to be documented and made readily accessible to all
- Some identified common technical areas:
  - Thermal engineering
    - Material properties (generate a single common database)
    - Thermal interfaces
    - Thermal isolation / mechanical support
    - Rapid cooldown systems
  - Optical Technologies
    - Materials and antireflection treatements
    - Baffling and absorption/scattering treatements
  - Magnetic / Radio Frequency shielding

Next Steps

- Support AoA
- Continue performance margin efforts
- Continue development of requirements and interfaces
- Support ongoing R&D

Backup

Project-Wide L1 Technical Requirements Apply to The Entire Experiment

Item Type	ID	Name	Impacted Subsystem	Description	Basis / Rationale	Verification Method	Verification Description
Folder		Project-wide					
System Requirement (Level 1)	SYS-PRJ-010	Baseline survey duration	CH,DAQ,Detector,DM,LAT,Module Assembly,Readout,SAT,SP	All elements of the experiment shall be designed to meet their performance requirements assuming a survey duration of 7 years.	Survey duration as a design parameter.	Analysis	System-level performance modelling of the experiment is to be used to evaluate survey margin against the required duration. Survey margin to be determined for two cases: 1) assuming all performance-related requirements are exactly met and 2) using Current Best Estimates of all performance-related parameters.
System Requirement (Level 1)	SYS-PRJ-020	Design lifetime	CH,DAQ,Detector,DM,LAT,Module Assembly,Readout,SAT,SP	All deployed elements shall have a design lifetime of 15 years of operation or greater in the environment in which they are deployed.	Ensure survival for planned survey duration plus margin.	Analysis	Technical analyses of lifetime/reliability of the design, lifetime testing where appropriate, published specifications for purchased components.
System Requirement (Level 1)	SYS-PRJ-030	Environmental Specification	CH,DAQ,Detector,DM,LAT,Module Assembly,Readout,SAT,SP	All elements of CMB-S4 shall be designed to meet the (to be written) environmental specification, defining survival and operating ranges of temperatures, pressures, humidities, shipping, seismic, and other environmental factors.	Set design criteria.	Analysis	Technical analyses of the design, environmental testing where appropriate, published specifications for purchased components.
System Requirement (Level 1)	SYS-PRJ-040	Weather assumptions	CH,DAQ,Detector,DM,LAT,Module Assembly,Readout,SAT,SP	Performance assessments of the deployed experiment over the duration of the survey shall assume degradation due to weather (by band) based on historical data as documented in CMBS4-doc-XXX (to be written)	Account for weather in survey performance predictions. Historical weather data should be assessed by month or week of the year to optimize planned shutdown scheduling.	Analysis	Ensure there is a well-defined set of weather assumptions, which is uniformly applied to performance assessments.
System Requirement (Level 1)	SYS-PRJ-050	Siting at Chile	CH,DAQ,Detector,DM,LAT,Module Assembly,Readout	There shall be an observing site in the Atacama of Chile with an Integrated CHLAT System (encompassing all deployed large aperture telescopes, receivers, detectors, etc at the site) for the CMB-S4 Wide Field Survey, with infrastructure sufficient to support deployment and operation of CMB-S4, including but not limited to office and laboratory space, electrical power, maintenance/repair capabilities, and data storage/transmission capabilities.	Specify location and define the overall needs, which then are flowed down to more specific implentation requirements, such as electrical power budgets, etc.	Demonstration	Documentation package including site plans, resource loaded schedule, technical budgets, etc.
System Requirement (Level 1)	SYS-PRJ-060	Siting at South Pole	DAQ,Detector,DM,LAT,Module Assembly,Readout,SAT,SP	There shall be an observing site with an Integrated SAT System (encompassing all deployed small aperture telescopes, receivers, detectors, etc at the site) and Integrated SPLAT System (encompassing the deployed large aperture telescope and all deployed receivers, detectors, etc at the site) at the South Pole for the CMB-S4 Inflation Survey, with infrastructure sufficient to support deployment, and operation of CMB-S4, including but not limited to office and laboratory space, electrical power, maintenance/repair capabilities, and data storage/transmission capabilities.	Specify location and define the overall needs, which then are flowed down to more specific implentation requirements, such as electrical power budgets, etc.	Demonstration	Documentation package including site plans, resource loaded schedule, technical budgets, etc.

L1 Requirements On “Integrated Telescope Systems” Govern Technical Performance Of All Deployed Elements Of CHLAT, SPLAT, And SAT

Item Type	ID	Name	Impacted Subsystem	Description	Basis / Rationale	Verification Method	Verification Description
Folder		Integrated CHLAT System					
System Requirement (Level 1)	SYS-CHL-010	Instantaneous Sensitivity	CH,DAQ,Detector,LAT,Module Assembly,Readout	The instantaneous sensitivity for each band, defined as noise-equivalent temperature (NET), of the integrated CHLAT system shall be no worse than (numerically larger than) the following values, by band (in microKelvin root seconds): 15.6, 8.35, 1.30, 1.42, 4.57, and 11.16 for LF_1, LF_2, MF_1, MF_2, HF_1, and HF_2, respecively	Ensure mapping speed to meet Measurement Requirements in the required survey duration.	Test,Analysis	Performance modelling and commissioning plan.
System Requirement (Level 1)	SYS-CHL-020	Band definitions	CH,Detector,LAT,Module Assembly,Readout	The integrated CHLAT system nominal frequency bands shall be as follows (all frequencies in GHz): 21.5 ≤ LF_1 ≤ 30.0; 30.0 ≤ LF_2 ≤ 47.5; 77.0 ≤ MF_1 ≤ 106.0; 128.0 ≤ MF_2 ≤ 169.0; 197.9 ≤ HF_1 ≤ 256.1; 256.0 ≤ HF_2 ≤ 315.	Conform to bands in Measurement Requirements and achieve instantaneous sensitivity requirements.	Test	Component/Subsystem/System-level testing and calibration
System Requirement (Level 1)	SYS-CHL-030	Number of deployed detectors	CH,DAQ,Detector,DM,LAT,Module Assembly,Readout	The total number of detectors deployed in the integrated CHLAT system (including non-functioning detectors which are accounted for as yield in other requirements) by band shall be no fewer than: 1536, 1536, 93312, 93312, 43148, and 43148 for bands LF_1, LF_2, MF_1, MF_2, HF_1, and HF_2, respectively.	Conform to bands in Measurement Requirements and achieve instantaneous sensitivity requirements. Accounts for all detectors on both deployed large aperture telescopes sited in Chile.	Inspection	Documentation of the Baseline.
System Requirement (Level 1)	SYS-CHL-040	Detector type and characteristic	DAQ,Detector,DM,LAT,Module Assembly,Readout	The detectors deployed in the integrated CHLAT system shall be transition edge sensors with a nominal transition temperature of 160 mK for science observations.	Maximize instantaneous sensitivity	Test	Detectors to be lab tested at operating temperatures
System Requirement (Level 1)	SYS-CHL-050	Observing Efficiency	CH,DAQ,Detector,DM,LAT,Module Assembly,Readout	The integrated CHLAT system and its operational and maintenance plans shall be designed such that the predicted effective fraction of time that it collects survey-quality science data is no less than 20% (to be confirmed, equal to achieved ACT performance, being analyzed) of the time available during the survey that is not degraded by weather. The factors degrading the on-field time fraction include at a minimum: calibration time, planned maintenance, planned shutdown periods, best estimates of unplanned maintenance, scan efficiency, noise weighting in map making, deployed detector functioning fraction, and expected data cuts.	Observing efficiencies in performance simulations of CMB-S4 CHLAT are based on achieved ACT performance. The overall achieved ACT observing efficiency is being documented and will be decomposed further to requirements on those named factors and any others identified. Each of those requirements will be analyzed to identify performance parameters that can confidently be improved, and these identified improvements will be implemented as requirements, with analysis and/or prototyping to justify and document expected performance improvements.	Analysis	Documentation of heritage experiments and documentation of CMB-S4 improvements.
System Requirement (Level 1)	SYS-CHL-060	Systematics	CH,DAQ,Detector,DM,LAT,Module Assembly,Readout	Aggregated systematic error for the integrated CHLAT system shall be no worse than that achieved by SPT, including but not limited to error related to: band edge calibration, beam shape (including near sidelobes), detector time constants, detector gain calibration, polarization angle calibration, polarization efficiency, far sidelobes (including ground pickup), magnetic fields, and electromagnetic interference.	Performance simulations of CMB-S4 CHLAT are based on achieved ACT performance. The overall achieved ACT systematics performance is being documented and will be analyzed to identify systematics contributions that can confidently be improved, and these identified improvements will be implemented as requirements, with analysis and/or prototyping to justify and document expected performance improvements.	Analysis	Documentation of heritage experiments and documentation of CMB-S4 improvements.
System Requirement (Level 1)	SYS-CHL-070	Calibration	CH,DAQ,Detector,DM,LAT,Module Assembly,Readout	There shall be calibration equipment, planned calibration intervals, procedures, and any necessary features of the science instrumentation that enable the integrated CHLAT system to meet its observational performance requirements over its entire survey duration	Must maintain calibration to an appropriate level, which will require calibration hardware and software, definition of calibration intervals, required calibration accuracy, and features on the science instrumentation to facilitate this calibration (such as features to interface with calibration equipment and high-Tc calibration TESs).	Analysis	Technical documentation of designs and required/expected performance.
System Requirement (Level 1)	SYS-CHL-080	Angular Resolution	DM,LAT,Module Assembly,Readout	The FWHM beam size as delivered to the integrated SPLAT system detectors shall be no greater than the following values by band (in arcmin on-sky) : 7.4, 5.1, 2.2, 1.4, 1.0, and 0.9 for bands LF_1, LF_2, MF_1, MF_2, HF_1, and HF_2, respectively.	Meet resolution mapping measurement requirements	Test,Analysis	Optical/sidelobe modelling and commissioning plan.