Systems Engineering

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2024 Spring Collaboration Meeting
March 25, 2024

CMB-S4

Outline

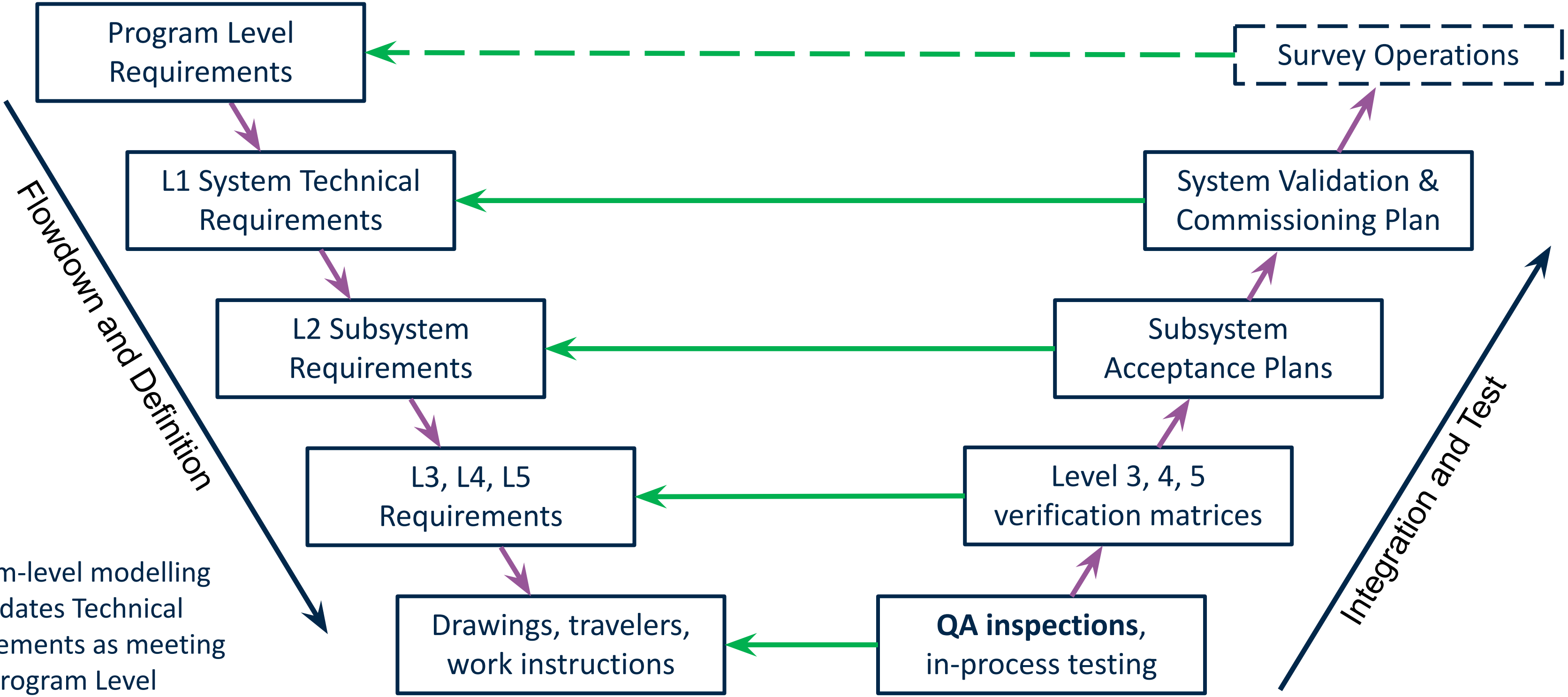
- Overview
- Current Status
- Next steps
- Summary

Major Systems Engineering Responsibilities

- Requirements management
- Interface management
- Technical resource allocations (e.g. mass or electrical power)
- Verifications
- Technical system modelling (performance predictions)
- Assessment and disposition of non-conformances (failures to meet requirements)

The Systems Engineering "V" Diagram

- **Requirements are defined in finer detail at lower and lower levels of the system, then verified at higher and higher levels of integration.**
- **Verification definition and Quality Assurance planning are integral parts of requirements development**



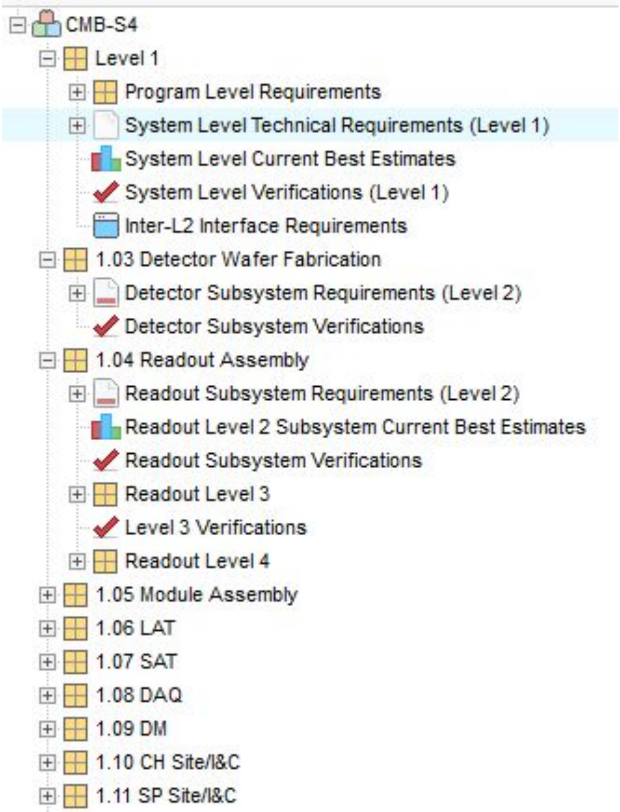
System-level modelling validates Technical Requirements as meeting Program Level Requirements

Requirements And Technical Budgets Define Experiment Performance And Reflect The Project Baseline

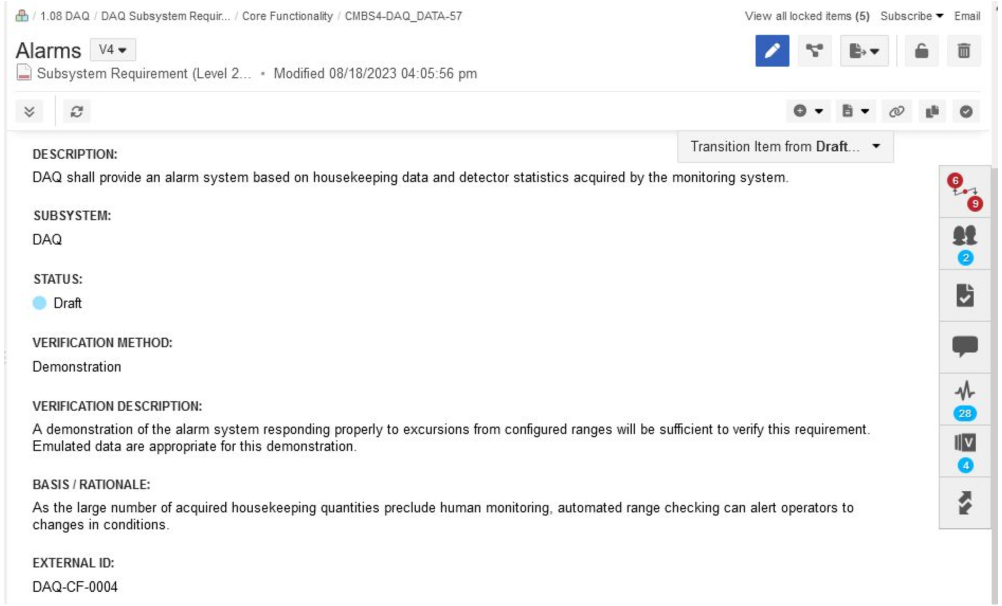
- Requirements
  - Minimum performance measure that a subsystem or component must meet
  - Hierarchical, flowed down from Science Goals to Technical Requirements

- Performance Budgets
  - System-level performance requirements are realized by flowdown of resources/parameters that are allocated (as requirements) among subsystems or components
  - These budgets are to be managed at a high level and include margin that can be allocated as needed from L1
  - CMB-S4 performance budgets include:
    - Systematics
    - Instantaneous Sensitivity
    - Observing Efficiency (including uptime/downtime)
    - Electrical power
    - Magnetic/RF shielding
    - Data Bandwidth
    - Beam quality

CMB-S4 Technical Requirements Are Managed Using Jama web-based tool

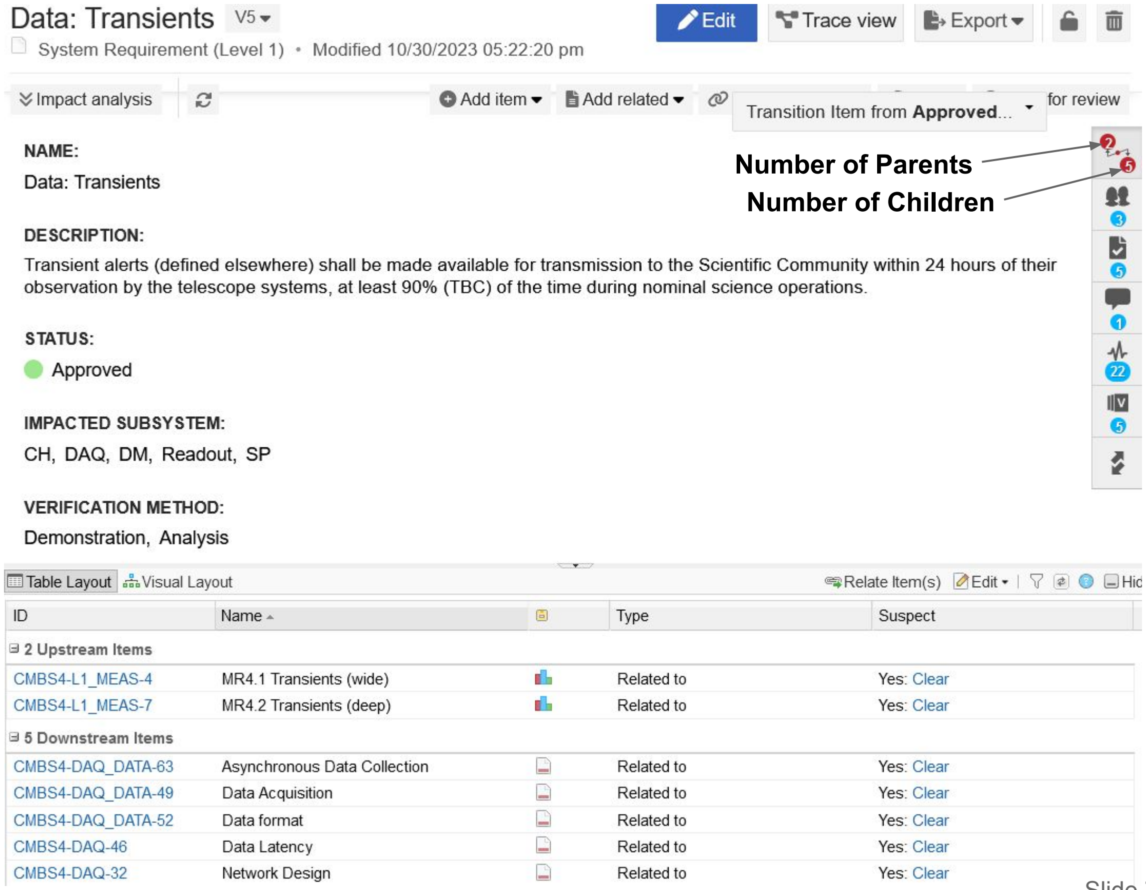


- Requirements at each level are traceable to the level above
- Requirement hierarchy captured as shown to left
- Revision and approval workflow is all within Jama
- All requirement entries include the requirement, **verification/QA**, and **traceability** to parents / children
- **The more detail in the Verification Description and Basis/Rationale, the better, ideally with links to detailed test plans or analyses that justify the requirement values**



Requirements flow down and traceability

- High level requirements flow down to requirements on subsystems and lower
- Each requirement has at least one parent from which it flows
- Requirements impacted by changes or non-conformances are easily identified through parent-child traceability



Parent Requirements

Child Requirements

Survey Margin

- Survey margin is the difference between the experiment's defined baseline survey duration and our projections of experiment performance
  - Baseline survey duration is the time in which we promise the Measurement Requirements will be met. Level 1 Technical Requirement:

> **DESCRIPTION:**
>
> The experiment shall be designed to meet Measurement Requirements MR1.1, MR1.2, MR2.0, MR3.1, and MR3.2 within a survey duration no longer than ten years.

  - Projections of the time required to complete the Measurement Requirements are based on simulations, modelling, and analysis of our current baseline instrument design (e.g. AoA studies and Data Challenges)
- Survey margin enables us to accommodate uncertainties in modelling or in actual performance of the system
  - As the designs mature and actual hardware is tested, some elements may not meet their assumed performance levels, and these non-conformances will be assessed, considering available margin, to determine whether to accept or mitigate

Interfaces

- Interfaces are defined where subsystems meet
- As designs mature, interfaces are iterated, refined, and documented in Interface Control Documents (ICDs)
  - Allows teams to work independently, with interfaces mutually understood
  - Currently exist in Google Docs
  - Now being folded into the Jama Connect requirements management tool
- Plan to get ICDs approved in Jama before NSF CDR
- A high priority topic for the May Workshop
- Actively being matured by subsystem teams

CMBS4-doc-469-v10: 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 (several)	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

Status of Requirements

- Program Level Requirements (Science Goals, Science Requirements, Measurement Requirements) are all approved.
- 23 of 51 Level 1 Technical Requirements are approved
- 302 Level 2 Technical Requirements exist, all require approval
- 631 Level 3 Technical Requirements exist, all require approval
- statistics:

Subsystem	L2 reqts	approved L2 reqts	L3 reqts	approved L3 reqts
DET	72	0	0	0
RO	8	0	171	0
MAT	30	0	19	0
SAT	28	0	76	0
LAT	38	0	136	0
DAQ	22	0	65	0
DM	16	0	1	0
Chile	59	0	38	0
SP	29	0	125	0
Project	302	0	631	0

Significant work remains to complete definition and flowdown of requirements (much of which depends on effort from scientists and the Collaboration)

- Many requirements include TBDs that need firm values
- Some important high level requirements are only generally defined, with descriptions of what still needs to be done to complete them and to flow them down to technical requirements
- Some key requirements drive overall survey performance and flow down to many technical areas. These need work to refine and finalize
    - Systematics
        - Need to define and flow down to instrument and calibration requirements
    - Instantaneous Sensitivity
        - Flows down to optics, modules, detectors, including required percentage of operating detector channels (aka yield)
    - Observing efficiency
        - Flows down to survey strategy, maintenance plans, calibration plans, reliability requirements, etc

Systematics requirements are currently defined mostly qualitatively, with statements about work still to do

NAME:

Systematics

DESCRIPTION:

The integrated SPLAT system side-lobe response within 2 (TBC) degrees from boresight shall be dominated by diffraction from the clear aperture illumination; features in the diffraction sidelobe response from any gaps in the reflectors or other sources must be subdominant. On angular scales that could couple to the ground (> 40 degree from the boresight), the sidelobe features on 2 (TBC) degrees or smaller scales shall not cause features in the map at levels greater than predicted from the primordial B-mode signal. All other aggregated systematic errors for the integrated SPLAT 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, magnetic fields, and electromagnetic interference. This requirement will be factorized into multiple, quantitative requirements in the future.

STATUS:

Review

IMPACTED SUBSYSTEM:

DAQ, Detector, DM, LAT, Module Assembly, Readout, SP

VERIFICATION METHOD:

Analysis

VERIFICATION DESCRIPTION:

Documentation of heritage experiments in addition to analysis and documentation of CMB-S4 improvements, including verification of the far sidelobe response levels by simulation of the integrated CMB-S4 SPLAT optical and baffling system using conservative models of the polarized ground emission as measured by BICEP / Keck experiments.

BASIS / RATIONALE:

Initial performance simulations of CMB-S4 SPLAT are based on achieved SPT performance. The overall achieved SPT 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 predicted performance improvements.

Current draft SPLAT and CHLAT Top-Level Instantaneous Sensitivity requirements are captured quantitatively

- Technical requirements on components must combine (in analyses) to meet these L1 requirements

NAME:

Instantaneous Sensitivity

DESCRIPTION:

The instantaneous sensitivity for each band, defined as noise-equivalent temperature (NET), of the integrated SPLAT system shall be no larger than the following values, by band (in microKelvin root seconds): 39.5, 19.6, 11.6, 1.97, 1.56, 5.13, and 11.5 for ULF, LF_1, LF_2, MF_1, MF_2, HF_1, and HF_2, respectively.

STATUS:

Review

IMPACTED SUBSYSTEM:

DAQ, Detector, LAT, Module Assembly, Readout, SP

VERIFICATION METHOD:

Test, Analysis

VERIFICATION DESCRIPTION:

Performance modelling and commissioning plan.

BASIS / RATIONALE:

Ensure mapping speed to meet Measurement Requirements in the required survey duration.

Current draft SAT system Instantaneous Sensitivity requirement needs (ongoing) work to be made quantitative

Transition item from **Review...**

DESCRIPTION:

The instantaneous sensitivity for each band, defined as the noise-equivalent temperature (NET), of the integrated SAT system, shall be no larger than the levels required to meet Measurement Requirement MR1.1 within the Survey Duration defined in SYS-PRJ-010, accounting for the Observing Efficiency defined in SYS-SAT-050 and the Weather Assumptions defined in SYS-PRJ-040.. (Specific sensitivity requirement values by band and by contributing factor are to be determined. This requirement will be factorized into multiple, quantitative requirements in the future).

STATUS:

Review

IMPACTED SUBSYSTEM:

DAQ, Detector, Module Assembly, Readout, SAT, SP

VERIFICATION METHOD:

Test, Analysis

VERIFICATION DESCRIPTION:

Performance modeling and commissioning plan.

BASIS / RATIONALE:

Performance simulations of CMB-S4 SATs are based on scaling of B/K performance. The overall achieved B/K instantaneous sensitivity is being documented and will be analyzed to add quantitative values to this requirement and to identify performance parameters that can confidently be improved. Any such identified improvements will be implemented as updated requirements, with analysis and/or prototyping to justify and document expected performance improvements.

Current Draft Top level Observing Efficiency requirements refer to ongoing work that is informing technical requirements and design

Observing Efficiency

DESCRIPTION:

The integrated SAT 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 XX% (to be determined, starting with equal to achieved BICEP/Keck performance of ~11%, but with weather impacts removed, 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, non-weather-dependent noise weighting in map making, and expected non-weather-dependent data cuts .

VERIFICATION DESCRIPTION:

Documentation of heritage experiments and documentation of projected CMB-S4 improvements.

BASIS / RATIONALE:

Performance simulations of CMB-S4 SATs are based on scaling of B/K performance. The overall achieved B/K 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.

Sara Simon leads the breaking down and documenting of observing efficiency. Iteration is needed with technical team to refine factors.

Observation Efficiency Summary

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A1 fx SAT

	A	B	C	E	F	G	H	I
1	SAT	Numbers with potential margin that has not been quantified are highlighted in light blue						Numbers that may need further vetting/confirmation
2				PBD	AoA Numbers/D(	PBD Updates	Potential Factors	Derivation and Discussion
3	**f_total (25 GHz)**			0.24	0.32	0.29	0.32	
4	**f_total (40 GHz)**			0.24	0.32	0.29	0.32	
5	**f_total (85, 95 GHz)**			0.24	0.32	0.29	0.32	
6	**f_total (145,155 GHz)**			0.24	0.31	0.29	0.31	
7	**f_total (230 GHz)**			0.17	0.22	0.21	0.22	
8	**f_total (280 GHz)**			0.12	0.15	0.14	0.15	
9		**f_year**		**0.478**	**0.648**	**0.692**	**0.692**	
10			f_season	0.586	0.750	0.750	0.750	PBD: Typicaly season dates for the SAT are April 1-November 1. Typically it ha difficult to observe when the South Pole is open due to RF environment (~Nov1- March is often used for a beam calibration campaign, but if the configuration is between years (i.e. no additional detectors/changes), we may not need to do be calibration campaign every year. There could be some additional margin in the s dates, but it would require more study with current BICEP/Keck data. ***For PBD Updates/AoA/Potential Margin: Assume the calibration month is gained ba month of observing time from the break because of different operational s of S4.***
11			f_weather_event	1.0	1.0	1.0	1.0	
12			f_availability	0.816	0.864	0.922	0.922	PBD: From [1], the total f_year is 0.478. Using the value of f_seasons, we can f_uptime. f_uptime here includes time lost from fridge cycles and mechanical d Additionally the historical data from BICEP 3 included regular maintenance and calibration time in this number, so these would need to be broken down and inc f_cal_maint below. Separating this value into mechanical downtime, fridge cylin and regular calibration and maintenance will require further study, but there is m gain here. *For AoA: This uptime was from BICEP 3, so 6/72 hours were used f cycling. ~2 hr of that time is used for snow sweeping, so assume we recover 4/ by using DR.* This gives an uptime of 0.864. PBD Updates/Potential Margin: As gain the 4 hours from fridge cycling back as we did in the AoA numbers, but m hours of time every 72 hours for snow sweeping to the f_cal_maint number. Als 1.5 hours every two weeks for star camera calibration and 10 minutes every 6 s for skydips to f_cal_maint
13		**f_scan**		**0.707**	**0.679**	**0.591**	**0.636**	
								PBD: The Sun and Moon avoidance are negligible for the SATs during the 7 mor

Definitions CHLAT SPLAT SPSAT Definitions_old CHLAT_old SPLAT_old SPSAT_old AOA_CHS/

CMB-S4

Electrical Power Budgets and Instrument Thermal Analyses

- A technical priority is increasing the fidelity of and confidence in the cryostat thermal analyses
- Electrical power for cryostat cooling is a major driver for the electrical power required at the Sites, particularly for the South Pole, where available power is a significant constraint that we don’t have complete control over
- We need to have high confidence that the experiment will be able to perform within the electrical power allocated
- Thermal analyses and early prototyping are needed to ensure we have included sufficient pulse tube cooling and dilution refrigerator capacity in our designs

Project Technical Workshop May 1-3 to address topics important for agency reviews and near-term work

Some high priority topics:

- Interface definitions
- Definition and allocation of magnetic and RF shielding requirements
- Cryostat thermal analyses
- Electrical power budgets
- On-Site Installation, Verification, and Commissioning plans

Work to be done

- Factorize Systematics into contributors and allocate as quantitative requirements on elements of the experiment
- Continue to factorize Sensitivity contributors and allocate as quantitative requirements on elements of the experiment
- Continue iterating observing efficiency requirements and technical implementations to meet them
- Understand impacts of non-conforming or underperforming components on overall survey performance
  - e.g. lower efficiency in one band than expected/required or lower yield on a particular wafer or wafer type, etc.
  - This facilitates assessment of whether to accept or remediate non-conforming items

Summary

- The Project is using Systems Engineering tools to define the technical performance of the CMB-S4 Experiment
- We are technically well-positioned for upcoming NSF and DOE project reviews
- There is a lot more work needed from both the Project and the Collaboration to better define and flow down requirements for all the instrumentation
- The project team is encouraged to continue to actively document technical performance at all levels in the Requirements