CMB-S4 Systems Engineering

Robert Besuner*[a], Jessica N. Aguilar[a], Zeeshan Ahmed[b], Kam Arnold[c], Amy N. Bender[d], Bradford Benson[e], Julian Borrill[a], John E. Carlstrom[f], Nick Emerson[g], Brenna Flaugher[e], John C. Groh[a], Gunther Haller[b], Kelly Hanzel[a], John Kovac[h], Matthaeus Leitner[a], Kevin Long[a], Laura Newburgh[i], Elliot Newman[a], Hogan Nguyen[e], Erik Nichols[f], Michael D. Niemack[j], Mauricio E. Pilleux[k], John E. Ruhl[l], Joseph H. Silber[a], James Strait[a], Aritoki Suzuki[a], John G. Thayer[b], Jeff Zivick[f],
for the CMB-S4 Project and the CMB-S4 Collaboration
[a]Lawrence Berkeley National Laboratory, Berkeley, CA, USA, [b]SLAC National Accelerator Laboratory, Menlo Park, CA, USA, [c]University of California San Diego, La Jolla, CA, USA, [d]Argonne National Laboratory, Lemont, IL, USA, [e]Fermi National Accelerator Laboratory, Batavia, IL, USA, [f]University of Chicago, Chicago, IL, USA, [g]University of Arizona, Tucson, AZ, USA, [h]Harvard University, Cambridge, MA, USA, [i]Yale University, New Haven, CT, USA, [j]Cornell University, Ithaca, NY, USA, [k]EONS SpA, Santiago, Chile, [l]Case Western Reserve University, Cleveland, OH, USA

ABSTRACT

The Cosmic Microwave Background Stage Four Experiment (CMB-S4) is a planned DOE/NSF ground-based experiment that will probe the entire history of the cosmos by performing millimeter-wave sky surveys to produce multi-wavelength sky maps in both intensity and polarization of unprecedented quality. To meet its ambitious and transformative science goals within a reasonable survey duration, CMB-S4 employs a rigorous Systems Engineering approach to ensure tight control of instrumental sensitivity, systematic error, and instrument down-time. This disciplined Systems Engineering framework is essential for managing the instrumental configuration within the multi-institutional structure of the project. We present an overview of the project's Systems Engineering approach, processes, tools, and status.

Keywords: Cosmology, Inflation, Light Relics, Gravitational Waves, Galaxy Clusters

1. INTRODUCTION

The Cosmic Microwave Background Stage Four Experiment (CMB-S4) was recently endorsed as the highest-priority major initiative by the 2023 Particle Physics Project Prioritization Panel (P5)[1]. CMB-S4 has four primary Science Goals, each aligned with a science theme: primordial gravitational waves and inflation; the dark Universe; mapping matter in the cosmos; and the time-variable millimeter-wave sky[2]. The CMB-S4 Project is designing the experiment within an effective Systems Engineering framework that ensures that the deployed system will meet the Science Goals within a reasonable survey duration, and that coordinates technical contributions from a widely distributed project team. CMB-S4 Systems Engineering is effectively a Project Management tool, managed from the Project Office, and functionally integrated with the project's programmatic tools[3,4].

The CMB-S4 experiment will deploy hundreds of thousands of transition edge sensor (TES) detectors distributed between small aperture telescopes (SATs) to probe temperature and polarization of the millimeter-wave sky at degree angular scales, and large aperture telescopes (LATs) to probe at arcminute angular scales. To achieve the Science Goals, the experiment will require unprecedented sensitivity and control of systematic uncertainties. In order to complete the survey within a reasonable time, maximizing observing efficiency (i.e. minimizing instrument downtime) is a high priority. Sensitivity, systematics, and observing efficiency are major drivers of the design, and the Systems Engineering framework is implemented to ensure they are understood and controlled at all levels, from the entire deployed experiment down to the detailed technical design of the subsystems and their components.

*rwbesuner@lbl.gov; phone 1 510 486-5698

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This paper focuses on CMB-S4's approach to managing its requirements and their flowdown, along with management and documentation of technical interfaces across the widely-distributed project team., The CMB-S4 Systems Engineering effort also includes management of technical trade studies, configuration management of the technical design, definition and execution of technical reviews, assessment of design maturity, and support of the simulation and modeling efforts that predict overall experiment performance.

In 2022, the CMB-S4 Project and Collaboration performed an Analysis of Alternatives (AoA) that explored several options for different deployed distributions of SATs and LATs in the Chilean Atacama desert and at the South Pole. The experimental configuration underlying the examples shown in this paper is one of the alternatives studied, with Small and Large Aperture Telescopes deployed at the South Pole and Large Aperture Telescopes deployed in Chile. However, the Systems Engineering framework, along with the Project Management tools that are in place in the project are robust and suited to any eventual deployed configuration.

2. REQUIREMENTS MANAGEMENT AND FLOWDOWN

CMB-S4 requirements are defined and flowed down at all hierarchical levels of the project from the top-level Science Goals to technical requirements on elements within each subsystem, as illustrated in Figure 1.

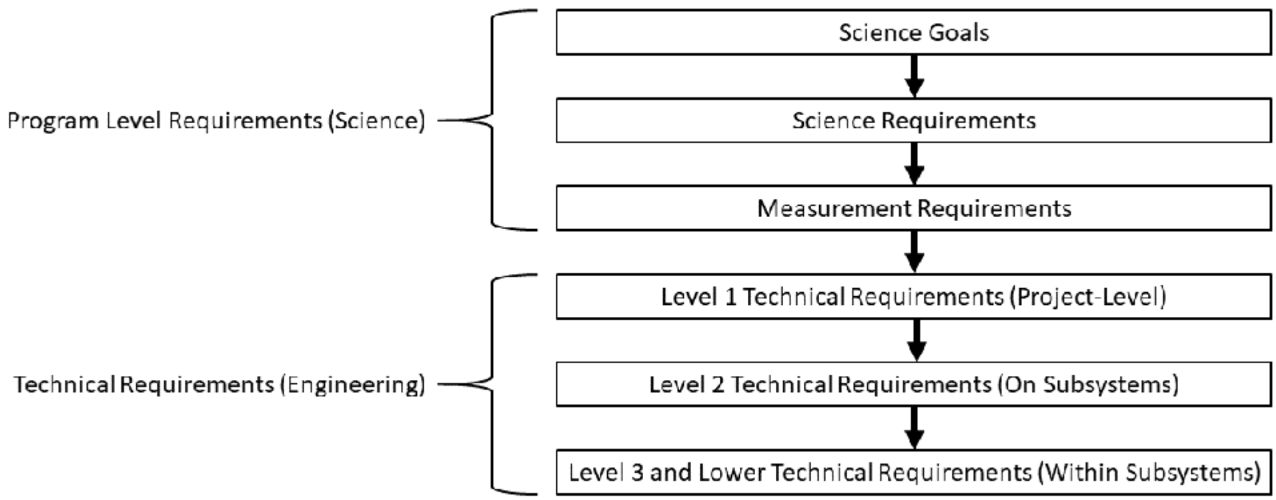

Figure 1: Hierarchy and flowdown of CMB-S4 requirements. The Program Level Requirements, which include Science Goals, Science Requirements, and Measurement Requirements are essentially scientific in nature, while the Technical Requirements from Level 1 and lower are predominantly related to engineering.

Requirements are managed using the Jama Connect software tool†. Jama Connect is a web-based requirements management tool that includes features that enable establishment of a hierarchical requirements structure with parent-child relationships that capture the flowdown of all the project's requirements. Figure 2 shows the overall organization of the CMB-S4 Requirements within Jama Connect.

† Jama Connect is a product of Jama Software, Portland, OR, USA. https://www.jamasoftware.com/

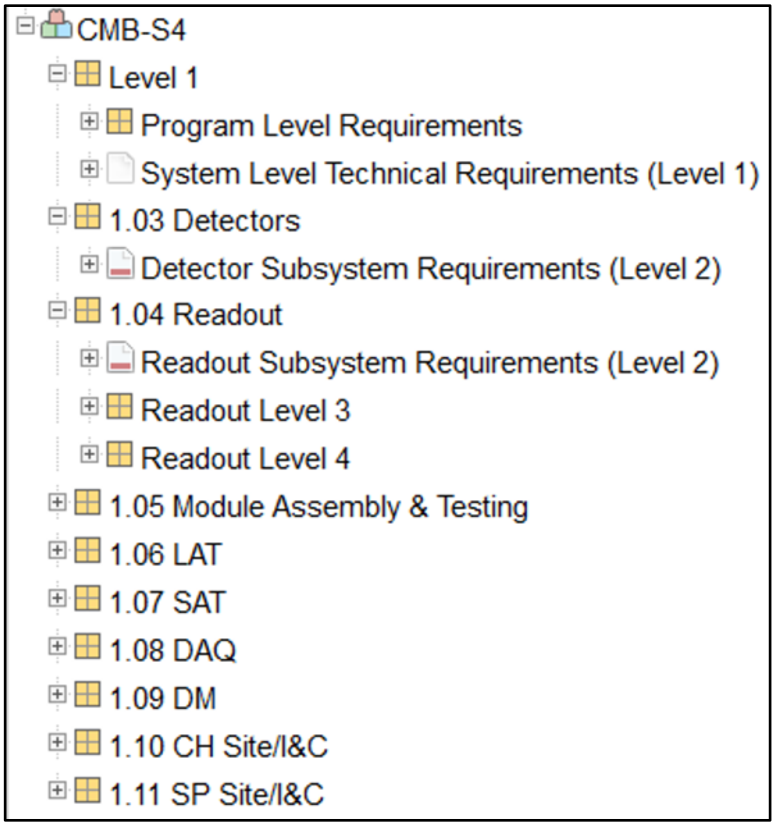

Figure 2 Partially expanded view of the structure of the CMB-S4 requirements in Jama Connect. Note that WBS 1.01 captures Project Management, and WBS 1.02 captured early R&D efforts that are now completed, so these two WBSs are not included in the requirements hierarchy. Structure is expanded for subsystems 1.03 and 1.04 only, however each of the other subsystems includes requirements at levels 3 and below, but for brevity are not expanded.

Within CMB-S4's implementation in Jama Connect, every requirement consists of fields that include the text of the requirement, a basis/rationale describing or linking to documentation of the basis for the requirement (such as a technical note or science analysis), a description of how the requirement is to be verified, and links to higher requirements from which the requirement flows (parents) and to lower requirements to which the requirements flows down (children). An illustrative example is shown in Figure 3. The project employs a workflow built in to Jama Connect for revision and approval of requirements.

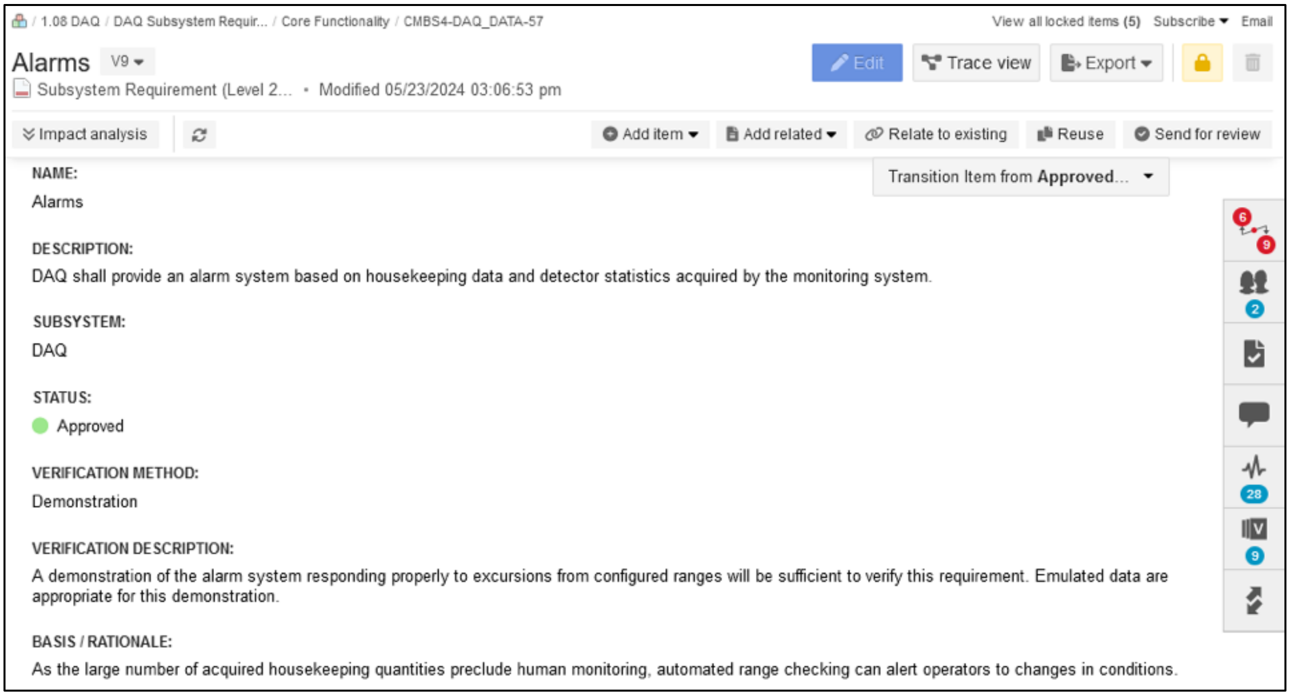

Figure 3: Screenshot of a requirement from CMB-S4's Jama Connect tool. The quantities of parent and child requirements for this DAQ requirement are denoted by the 6 and 9 numbers in red near the upper right.

The CMB-S4 project is organized with a single Project Office which is Level 1 in the project's work breakdown structure (WBS), and nine Level 2 Subsystems: Detectors; Readout; Module Assembly and Testing; Large Aperture Telescopes (LAT); Small Aperture Telescopes (SAT); Data Acquisition and Control (DAQ); Data Management (DM); Chile Infrastructure, Integration and Commissioning (CH Site/I&C); and South Pole Infrastructure, Integration and Commissioning (SP Site/I&C). The organization and hierarchy of the technical requirements match the project WBS, so that the managerial leads within each WBS element are responsible for ensuring that their deliverables meet the requirements on that WBS element. Acceptance packages for each Level 2 Subsystem, as well as for lower levels in the WBS, will largely consist of documentation of the verifications of the requirements within that WBS.

The Level 1 requirements consist of Program Level Requirements and System Level Technical Requirements. Within the Program Level Requirements, there are three hierarchical tiers: Science Goals, Science Requirements, and Measurement Requirements, as illustrated in the left pane of Figure 4. The Science Goals are qualitative statements of the science reach of the experiment. These then flow down to the Science Requirements, which quantitatively define the experiment's science reach in terms of cosmological and astrophysical parameters. The Science Requirements then flow down to Measurement Requirements of the on-sky performance that the experiment must meet in order to achieve the Science Requirements. There is not a unique set of measurements that can enable meeting the Science Requirements, so the Measurement Requirements are developed in parallel with the experiment and survey designs.

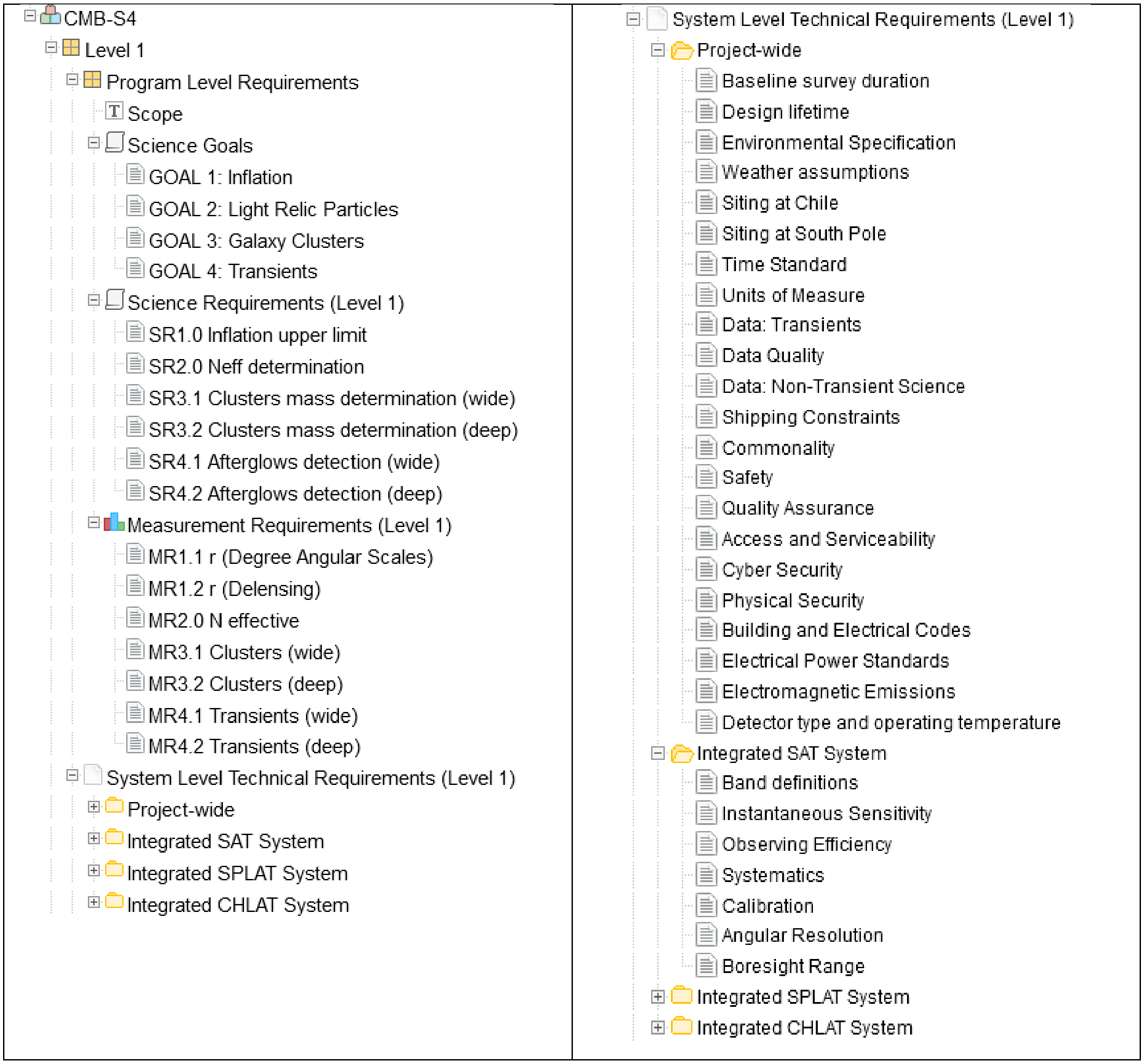

Figure 4: Expanded structure of top level requirements. The Program Level Requirements are expanded in the left frame. The Level 1 Technical Requirements are expanded in the right frame. Note that the Integrated SPLAT (South Pole Large Aperture Telescope) System folder and the Integrated CHLAT (Chile Large Aperture Telescope) System folder have the same requirements named in their folders as the Integrated SAT (Small Aperture Telescope) System, but with different values of parameters.

An example of the flowdown of Program Level Requirements is for the Inflation science:

- Science Goal: Test models of inflation by measuring or putting upper limits on r, the ratio of tensor fluctuations to scalar fluctuations.
- Science Requirement: CMB-S4 shall test models of inflation by putting an upper limit on r of $r \leq 0.001$ at 95% confidence if $r = 0$, or by measuring r at a 5σ level if $r > 0.003$.
- Measurement Requirements then define required integrated noise levels as a function of multipole and frequency, along with the sky area over which those noise levels are to be met, for both degree-angular-scale polarization maps and arcminute-scale delensing probes (details omitted for brevity).

The Measurement Requirements (MR) flow down to technical requirements at Level 1 and below. The Program Level Requirements capture the experiment's scientific reach, based on scientific analyses and forecasts, while the technical requirements govern performance and implementation of the experiment, which are largely engineering-related. The Measurement Requirements define in quantitative terms what the experiment must produce during its survey, and the Technical Requirements define the minimum performance of the experiment that will meet those Measurement Requirements.

The Level 1 System Level Technical Requirements are categorized in 4 folders in Jama Connect (see right pane of Figure 4), with one folder for requirements that apply across the experiment and one folder each for the different types of telescope systems (Small Aperture Telescopes, South Pole Large Aperture Telescope, and Chile Large Aperture Telescopes). Note that in this context the "telescope system" refers to all the deployed hardware and software that integrate together for each type of telescope, including the telescopes themselves, along with elements from the other subsystems such as detector modules, and readout elements. The right pane of Figure 4 shows the Level 1 Technical Requirements that apply project-wide, along with those for the Small Aperture Telescopes. The same set of requirements apply for each of the three telescope systems, with different parameter values for each. The Level 1 Technical Requirements flow down to Level 2 Subsystem Requirements which in turn flow down within the subsystems, to finer and finer elements of the experiment.

Continuing along a flowdown thread that originates with the Inflation Science Goal, the maximum integrated noise levels defined in MR1.1 and MR1.2 flow down to several Level 1 Technical Requirements. We highlight in particular the requirements on the Integrated Telescope Systems that govern Instantaneous Sensitivity, Observing Efficiency, and Systematics, listing some of the key technical areas and requirements that are important to meeting each:

The Instantaneous Sensitivity of each Integrated Telescope System, integrated over time and sky area mapped, enables meeting the Sensitivity Measurement Requirements. The Instantaneous Sensitivity Level 1 Requirements flow down to numerous Requirements on the Level 2 Subsystems and lower. Some key requirements and implementation details at Level 2 and below that flow directly from Instantaneous Sensitivity include:

- Optical Design and Material Selection by the Telescope Subsystems, which directly impact the fraction of incoming light that reaches the Detector Modules.
- Efficient and optimized coupling to detector wafers via Feedhorns and Coupling Wafers from the Module Assembly and Test Subsystem.
- Detector technology and parameters to minimize noise, including employing Transition Edge Sensors operating at a base temperature of 100 milliKelvin.
- Low-noise Readout elements, including the use of cryogenic Superconducting QUantum Interference Devices (SQUIDs)[5].
- Minimum fraction of functioning detector channels, factorized as yield requirements on each of detector wafers, readout elements, and electrical signal interconnects.
- Siting the telescopes at high and dry locations with good access to regions of the sky with minimal contamination from galactic foregrounds.

Observing Efficiency Requirements define the fraction of available calendar time that usable on-sky data are collected by each Integrated Telescope System (not accounting for weather which is separately tracked). The experiment's observing efficiency directly impacts the number of years required to meet the Measurement Requirements. Factors comprising the overall observing efficiency requirement include these effects which drive specific technical requirements within subsystems:

- Frequency and duration of instrument calibration campaigns: Drives planning of calibration activities, design and quantities of calibration equipment, and on-site personnel requirements.
- Intervals and duration of planned shutdowns and maintenance activities: Drives use of reliability analysis to define inspection, preventative maintenance and replacement plans, design for efficient serviceability, on-site staffing requirements, and cooldown time requirements.
- Forecasts of impacts of unplanned maintenance and interruptions of electrical power or data utilities: Drives thorough reliability analysis, system redundancy where beneficial, design for serviceability and replacement of

critical elements, specification of high-reliability components, pre-deployment lifetime testing, cooldown time requirements, and provision of appropriate types and quantities of spare components.

- Efficiency of the sky scanning strategy: Drives requirements on ranges of azimuth, elevation, and boresight rotation over which the systems (including cryostat refrigeration) must perform, telescope drive dynamic capabilities (azimuthal and elevation rotation speeds and accelerations), and consequent stiffness and natural frequency requirements on the instrumentation carried by the telescopes.

Limiting Systematics to be below levels that would contaminate or bias the science data at the levels required in the Science Requirements drives numerous technical implementation requirements, which include:

- Requirements on calibration precision are necessary to ensure proper characterization of actual instrumental parameters that affect the maps that are generated from the scans, including: centers of frequency bands in the integrated systems, beam shapes as-deployed (including near sidelobes), detector time constants, detector gains, effective polarization angles, and polarization measurement efficiency.
- Requirements on non-signal pickup from far sidelobes drive implementation of ground shields and baffles, detailed design of the camera optics, and location and height of the deployed telescope systems relative to geographic features and other nearby human-made structures.
- Requirements that limit magnetic fields and electromagnetic interference that reach the detectors and readout elements drive shielding requirements for the telescope cryostats, the readout components, and the detector module assemblies themselves.

The definition and flowdown of CMB-S4's requirements is a collaborative effort, with engagement and inputs from across the project team and the CMB-S4 Science Collaboration, coordinated by the Systems Engineers. The Science Goals, Science Requirements, and Measurement Requirements were largely developed by the scientific leadership of the project, along with members of the Science Collaboration, with significant inputs from across the technical team to help iteratively frame the Measurement Requirements so that they correspond with the planned technical implementation of the experiment. The development of the Technical Requirements has relied on the broad and deep expertise of the project team, with Subsystem Lead Scientists actively working with Systems Engineers to define requirements and verifications that are sufficiently specific to meet higher level requirements and general enough to allow flexibility in implementations. Requirements development and management work across the project is facilitated by weekly project-wide Technical Meetings, bi-weekly Subsystem meetings, and regular Project Workshops. Approval of all requirements at Level 2 and lower requires approvals by not only the Project Office but also the lead scientist and manager of the affected subsystem. Jama Connect is actively used not only by the project's Systems Engineers, but also by project management and technical leads from all the Subsystems.

3. INTERFACE DEVELOPMENT AND MANAGEMENT

The CMB-S4 team is widely distributed, with responsibilities for major deliverables assigned to groups at numerous different institutions. Clear, precise, and unambiguous definitions of the scope boundaries and technical details of the interfaces between subsystems and within subsystems are essential. The interface details between CMB-S4 Level 2 Subsystems are captured in Interface Control Documents (ICDs). The inter-subsystem ICDs are identified in the "N-squared" interface matrix shown in Figure 5. The letter 'X' in a cell indicates that there is no interface between the two subsystems. The letters within the boxes for extant interfaces indicate the types of interfaces that exist, the numbers indicate the project's internal document number for each, and the fill color indicates the phase of maturity of each ICD. At this time, all of the inter-subsystem ICDs have complete definitions of the scope boundaries and responsibilities between subsystems, and they capture the technical details of the interfaces beyond Conceptual Design maturity, though the project is technically in the Conceptual Design phase (not yet having had a DOE CD-1 Review or NSF Conceptual Design Review). ICDs between Level 3 WBS areas within the Level 2 Subsystems are also under development, managed within their respective Level 2 WBS areas by Subsystem managers and Project Systems Engineers.

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

Figure 5: CMB-S4's Interface Matrix illustrating which Level 2 Subsystems interface with which other Subsystems, the types of interfaces that exist in each, the project document number of each Interface Control Document (ICD), and the maturity level of each ICD. All of the inter-subsystem interfaces are currently at Phase 2, with all scope, boundaries and divisions of responsibilities defined, and with ongoing increases in level of detail captured. All of the ICDs are well beyond Conceptual Design maturity.

The ICDs are currently in the form of controlled project documents that contain all the definitions and technical details. The project is in the process of folding the content of the ICDs into the Jama Connect tool. In Jama Connect, the technical definitions of inter-subsystem interfaces will be captured within the Level 1 Technical Requirements, managed by the Systems Engineers in the Project Office, with approvals of the Project Office and the leaders of the relevant Subsystems. These will then flow down to specific technical requirements, with verification plans, within the Level 2 Subsystems, so that they are equivalent to Level 2 Technical Requirements on each Subsystem, and with the other Level 2 Technical Requirements, they will form the basis of the Acceptance Packages for the Subsystems. A similar structure will be in place for interfaces between deliverables at Level 3 and lower.

4. CONCLUSION

Systems Engineering processes and tools are in place and being effectively employed across the CMB-S4 project. Interfaces within the experiment are well-defined and maturing in parallel with the designs of the elements that comprise the overall systems. Requirements are defined at all levels from overall Science Goals down to the technical details, with complete definition of the requirements lineage that each requirement is flowed down from. This approach makes clear the relevance of each requirement to meeting the overall Science Goals and clear definition of the deliverables, performance thresholds, and success criteria of all elements of the experiment at every level. Systems Engineering on CMB-S4 is not a distinct aspect of the technical work on the project, but is fully integrated as the project's approach to defining, designing, building, and commissioning the experiment as a team. The approach and tools that are in place are actively used by the project team to help enable us to achieve our common goals though we are widely distributed across different institutions and have different skillsets and experience. This well-established Systems Engineering framework, along with the CMB-S4 team's familiarity and effectiveness working within it, will help ensure the project is well-positioned to efficiently design and build the experiment regardless of possible re-configuration.

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DISCLAIMER

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