WBS 1.07.09 US Integration and Testing (SAT)

L3 Leads - Marion Dierickx and Akito Kusaka

Outline

- Presenter Introductions
- Key Contributors in this L3
- Breakdown of this L3
- Key Requirements
- Interfaces with other L3s
- Technical Design / Scope
- Prototyping Plans
- Response to Previous CDR Recommendations
- Risks and Mitigation Strategies
- Conclusion

Presenter Introductions

- Marion Dierickx (Harvard University)
  - Instrumentation development, Operations co-lead for the BICEP/*Keck* collaboration.
  - Four seasons as on-site lead at the South Pole for the BK team.
  - Also L3 Lead for SAT Integration & Commissioning at South Pole Site.
- Akito Kusaka (LBNL Senior Scientist and UTokyo Associate Professor)
  - Experiments in Chile: QUIET, ABS, POLARBEAR, Leadership role in Simons Observatory SAT, Data analysis and instrumentation for “r” measurements.

Key Contributors in this L3

Joseph Saba (LBNL), Cryogenics / Vacuum Vessel / Mechanical Engineering, integration facility planning

Paul Williams (LBNL), Cryogenics / Electronics / Detector systems, Validation and Verification

Ben Schmitt (UPenn), Optomechanical designs, BICEP Array Replacement Tower project

Ken McCracken (CfA), Optics Tube design & engineering/integration facility planning

The WBS for US I&T

1.07.09 US Integration & Testing

.01 Integration Test Design, Development, and Tool Procurement.
- Early development of I&T plans, facilities requirements, hardware, etc. Upgrades and preparation of existing facilities for I&T.

.02 Integrate, Test, Ship Prototype SAT
- Assembly and verification of the prototype SAT cryostat.

.03 Prototype Mount/SAT I&T
- Integration and testing of SAT system with telescope mount assembly.

.04 Integrate, Test, Ship SAT1
- Integration of the vacuum systems, refrigerators, optics and tubes.
- Vacuum and cryogenic testing.
- Integration and testing of focal plane array.
- Disassemble, pack & ship to Port Hueneme

.05 Integrate, Test, Ship SAT2
- Same workflow as SAT1

.06 Integrate, Test, Ship SAT3
- Same workflow as SAT1

.07 Design/Construct crates for SAT Focal Plane

Reorganization in progress

Key Driving Requirements for US I&T

- Schedule - Ship 1 SAT system in 2031 and 2 SAT systems in 2032.
    - *Key focus is on timely delivery as project schedule evolves.*
- End product requirements - satisfy QA, verification and validation of performance prior to shipping.
- EHS - early identification, planning and execution (e.g. lifting procedures, crane training/certification, etc.)
- Plan for addressing these requirements:
    - Perform I&T at two sites (to handle large volume of work and maximize engagement from Stage-3 projects).
    - Leverage early BART mount process and hardware in order to validate interfaces.
    - Integration with Prototype SAT will inform the I&T process.

CQ1

Interfaces

Within SAT L2:

- **Cryostat, Mount**: mass, dimension and bolt pattern for lifting, supporting, and handling.
- **Optics, focal plane, etc**: bolt pattern for lifting and mounting.

External to SAT L2:

- **Detector Modules and Readout**: Schedule and handling procedures.
- **Sites, South Pole**: Schedule, facility needs, knowledge transfer for on-site I&C. Validate I&C plans to be implemented at Pole.

1.07.01 - Management	1.07.02 - Cryostat Prototyping	1.07.03 - Cryostats	1.07.04 - Optics Stack Prototyping	1.07.05 - Cold Optics	1.07.06 - Calibration Equipment	1.07.07 - Telescope Mount Assembly	1.07.08 - Telescope Ground Shield	1.07.09 - US Integration and Testing	L3 Element
									1.07.01 - Management
			M,E,T,O		M,O		O	M,E,T,O	1.07.02 - Cryostat Prototyping
				M,E,T,O	M,E,T,O	M,E	M	M,E,T,O	1.07.03 - Cryostats
					M,O		O	M,E,T,O	1.07.04 - Optics Stack Prototyping
					O			M,E,T,O	1.07.05 - Cold Optics
						M	M,O	M,O	1.07.06 - Calibration Equipment
							M,O	M,E,T,O	1.07.07 - Telescope Mount Assembly
								M,O	1.07.08 - Telescope Ground Shield
									1.07.09 - US Integration and Testing

Interface type key	
M	mechanical
E	electrical, data, control, telemetry
T	thermal
O	optical

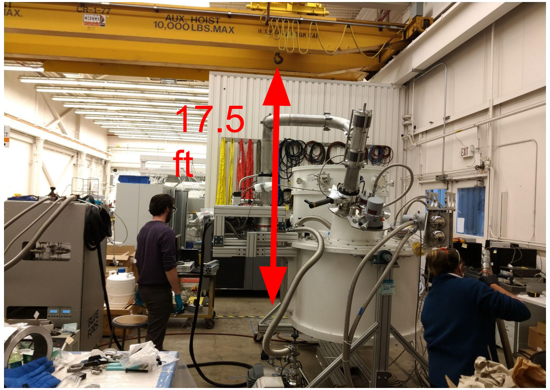
CQ1,2

Technical Design / Scope

Similar facilities exist at LBNL and at the CfA

Facility / equipment list of requirements:

- Two I&T centers
- Support for vacuum and cryogenic systems.
  - Power, cooling loop, pressurized air as necessary.
  - Simultaneous operation / integration of 2 cryostats per center.
- High bay capacity
  - Cryostat assembly / testing space ~ 120 m^2
  - Additional working space / clean room area for subassembly work.
- Crane capacity
  - 6 metric tons, 3.8 meter under hook height.
- Clean room
  - For focal plane inspection and assembly.



Prototyping Plans

A more aggressive cryogenic architecture was adopted as a result of the AoA.

Cryobus design changes are likely to make the assembly more complicated.

I&T and verification of the prototype cryostat:

- 3 test suites to verify cryostat design (more details on next slide)
- Risk mitigation for I&T planning
  - Reduce uncertainties in schedule, resource planning, and verification methods.
  - Reduce risks in handling sensitive components (e.g., focal plane, readout cables)

Test integration of a cryostat with a mount system in North America:

- Measurement (and mitigation) of receiver's sensitivity to effects induced by mount motion, such as vibration and magnetic field pickup.
- Validation of interfaces, including installation procedure.

CQ4

Prototyping Plans (Cont'd)

Suite 1 (11 months): Mitigating risks in cooling (0.1 K to 50 K) and assembly complexity

Goal: Ensure pulse tubes & cryobus achieve desired temperatures. Planning efforts draw from BA & SO commissioning procedures and lessons learned.

1. **Assembly:** rotational support frame, crane liftability, hand access, wiring, alignment
2. **Mechanical:** clearance, sag, strut load, manufacturing tolerance, vibration, vacuum
3. **Thermal:** IR load, MLI, struts, heat straps, cables, [0.1,1, 4, 50] K load curves, cooldown time tilt performance, power draw. DR and PTC performance test incl. realistic He hoses / connections.

→ Release of cryostat design for production following Suite 1

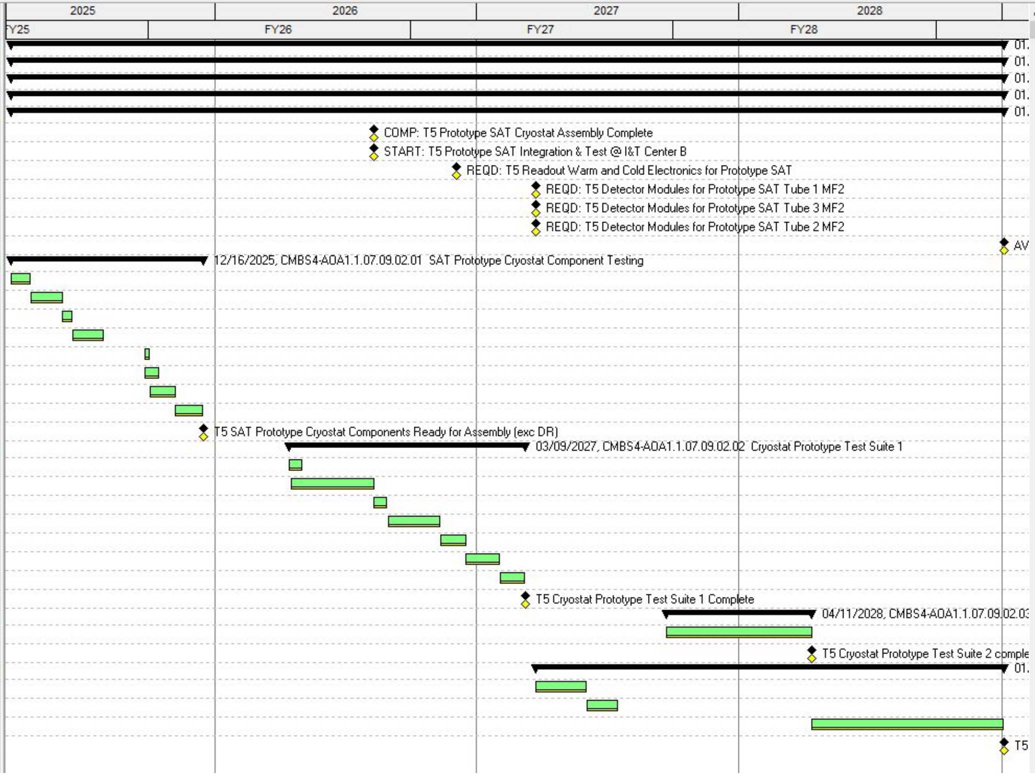
Suite 2 (6 months): Mitigating risks in RF and magnetic shielding

Suite 3 (11 months): Pre-production detector & readout integration into cryostat

CQ4

Cryostat Prototype I&T P6 Schedule

Activity ID	Activity Name	Planned Duration	Planned Start	Planned Finish
CMBS4-AOA1 Working File AOA-1 - Cosmic Microwave Background - Stage 4 CD-1 Planning - AOA-1 WHAT IF		934d	03/24/2025	01/03/2029
CMBS4-AOA1.1 Cosmic Microwave Background - Stage 4 Master Project		934d	03/24/2025	01/03/2029
CMBS4-AOA1.1.07 Small Telescopes		934d	03/24/2025	01/03/2029
CMBS4-AOA1.1.07.09 U.S. Integration & Test		934d	03/24/2025	01/03/2029
CMBS4-AOA1.1.07.09.02 Integrate, Test, Ship Prototype SAT		934d	03/24/2025	01/03/2029
MS5_SAT_I&T_1007	COMP: T5 Prototype SAT Cryostat Assembly Complete	0d		08/10/2026
MS5_SAT_I&T_1012	START: T5 Prototype SAT Integration & Test @ I&T Center B	0d	08/11/2026	
MS5_SAT_I&T_1004	REQD: T5 Readout Warm and Cold Electronics for Prototype SAT	0d	12/04/2026	
MS5_SAT_I&T_1001	REQD: T5 Detector Modules for Prototype SAT Tube 1 MF2	0d	03/24/2027	
MS5_SAT_I&T_1002	REQD: T5 Detector Modules for Prototype SAT Tube 3 MF2	0d	03/24/2027	
MS5_SAT_I&T_1003	REQD: T5 Detector Modules for Prototype SAT Tube 2 MF2	0d	03/24/2027	
MS5_SAT_I&T_1123	AVAIL: T5 SAT Prototype Integration and test complete	0d		01/03/2029
CMBS4-AOA1.1.07.09.02.01 SAT Prototype Cryostat Component Testing		186d	03/24/2025	12/16/2025
SAT_0792_3120	Design PTC tilt test cryostat	20d	03/24/2025	04/18/2025
SAT_0792_3125	Fabricate PTC tilt test cryostat	30d	04/21/2025	06/02/2025
SAT_0792_3130	Vacuum verify PTC tilt test cryostat	10d	06/03/2025	06/16/2025
SAT_0792_3140	Write control & analysis scripts for PTC tilt test	30d	06/17/2025	07/29/2025
SAT_0792_3150	Assemble PTC tilt test setup	5d	09/26/2025	10/02/2025
SAT_0792_3160	SAT prototype cryostat window testing	13d	09/26/2025	10/14/2025
SAT_0792_3170	PTC load curve and tilt tests	25d	10/03/2025	11/06/2025
SAT_0792_3190	SAT prototype conductivity and thermal diode testing	25d	11/07/2025	12/15/2025
MS5_SAT_PROT_1006	T5 SAT Prototype Cryostat Components Ready for Assembly (exc DR)	0d	12/16/2025	
CMBS4-AOA1.1.07.09.02.02 Cryostat Prototype Test Suite 1		220d	04/15/2026	03/09/2027
SAT_0792_3220	SAT prototype DR verification	13d	04/15/2026	05/01/2026
SAT_0792_3210	Assemble SAT Cryostat Prototype	80d	04/17/2026	08/10/2026
SAT_0792_3230	Vacuum verification	14d	08/11/2026	08/28/2026
SAT_0792_3240	PTC verification with SAT	51d	08/31/2026	11/10/2026
SAT_0792_3250	DR verification in SAT	24d	11/11/2026	12/16/2026
SAT_0792_3260	Dummy Optics Tube installation	25d	12/17/2026	02/01/2027
SAT_0792_3270	Cooldown and load test with window open	24d	02/02/2027	03/08/2027
MS5_SAT_PROT_1008	T5 Cryostat Prototype Test Suite 1 Complete	0d	03/09/2027	
CMBS4-AOA1.1.07.09.02.03 Cryostat Prototype Test Suite 2		133d	09/22/2027	04/11/2028
SAT_0792_3280	Cryostat Prototype Test Suite 2 (Magnetic Shielding, Cryo under Optical load)	133d	09/22/2027	04/10/2028
MS5_SAT_PROT_1009	T5 Cryostat Prototype Test Suite 2 complete	0d	04/11/2028	
CMBS4-AOA1.1.07.09.02.04 Cryostat Prototype Test Suite 3		440d	03/24/2027	01/03/2029
SAT_0792_3080	Integration of Focal Plane Array (detectors, Cold RO, cabling) for Prototype SAT	50d	03/24/2027	06/02/2027
SAT_0792_3100	Testing of Focal Plane Arrays for Prototype SAT	30d	06/03/2027	07/15/2027
SAT_0792_3290	Cryostat Prototype Test Suite 3 (Detector testing, NFBM, NFPolCal)	180d	04/11/2028	01/02/2029
MS5_SAT_PROT_1010	T5 Cryostat Prototype Test Suite 3 complete	0d	01/03/2029	



CQ6

Response to Previous CDR Recommendations

R2

- **Revisit schedule for Integration & Test,** R2 Schedule (RT-121): Revisit the schedule with the goal of including adequate time for Integration & Test, especially as funding profile and levels become clearer.
  - Response: Refinement of the schedules and goals of integration & test is an ongoing iterative process. The integration process and schedule are being modified in parallel with updates to the design, including the revised cryostat architecture. There is also active feedback from the Calibration L3 WBS as well as the South Pole Integration and Commissioning WBS under the South Pole Site L2. We expect the I&T schedule will need to evolve subject to project-level inputs, including schedule targets for detector delivery and SAT deployment. We are in the process of developing a bottom-up understanding of the minimum adequate time required for I&T of production cryostats, considering risks which can and cannot be retired at the prototype stage.
  - Response summary: We continue to refine the I&T plan, subject to evolving and uncertain funding and timing outlooks.

R8

- **Refine Northern Hemisphere calibration and verification plans,** CDR R8 (RT-128): The integration and test plan needs to be further developed to include calibration and verification of performance at Northern Hemisphere sites. This should be accomplished by CD-2.
  - Response: The South Pole Integration & Commissioning Plan for Small Aperture Telescopes System (CMBS4-doc-729) was developed in order to lay out commissioning steps for each SAT system. This document details the prerequisite state of readiness of SAT subsystems in North America prior to shipping, including: cryogenic performance; thermal and vacuum-cycling survival; detector and readout characterization; diagnostics; and mount mechanical capabilities for I&C support, mount / receiver integration. Before CD-2, development of Northern Hemisphere Integration & Testing efforts will include procedures for each measurement and for test sequencing for each SAT system at each I&T site. Development of these procedures will also inform the specs for calibration equipment.
  - Response summary: The South Pole I&C plan will inform lab I&T plans and procedures, as well as calibration equipment specs.

CQ10

Cryostat Assembly and Validation

R2, R8

Procedures and resources are in planning, including interfaces with other L3s.

Suite 1

SAT Cryostat initial verification
Personnel: 3-4 people (2 postdocs, 1-2 technicians)
Total time: 208 days

1. Cryostat Assembly and Vacuum verification (19 days)
    a. Personnel
        i. 2 postdocs
        ii. 2 technicians
    b. Goals
        i. Leak checking of all welds and o-rings
        ii. Verify MLI pumping speed
    c. Equipment:
        i. SAT
        ii. SAT cart
        iii. Scroll and turbo pumps
        iv. Leak checker, leak checking hoses, helium
        v. Blank offs for window, PTC, DR, etc
    d. Schedule
        i. Unpacking and assembly of SAT vacuum shell (10 days)
        ii. Pumping (4 days)
        iii. Leak checking (2 days)
        iv. Vent to atmosphere and open (3 days)
2. PTC verification in SAT (60 days)
    a. Personnel
        i. 2 postdocs
        ii. 1-2 technicians

Validation items, durations, and personnel are being estimated. Further iterations are needed for:

- Cryostat assembly procedure with new cryobus design (ongoing)
- Critical path analysis.
- Interface with calibration equipment L3, South Pole Site Integration & Commissioning L3.
- Availability of prototype detector modules and readout systems.

Risks and Mitigation Strategies

Risks in the receiver design: gain feedback through prototyping

- Assembly issues, fit, complexity (cryostat L3)
- Vibration - integration test with mount, cryostat and detectors L3s
- Magnetic, RF and electric pickup - I&T with cryostat L3 as well as detectors, readout and modules L2s.

Schedule risks

- Component delivery: prototyping will inform procurement schedules.
- Process uncertainty - e.g. pumpout & cooldown: prototype the process, plan for multiple cycles, refine and validate the plan.

Technical risks in I&T

- Interfaces: verification will occur prior to I&T - e.g., readout should deliver a system that is validated as a full chain prior to delivery.
- Uncertainty in the I&T process itself: reduce by prototyping
    - E.g. vacuum failure (leak) → mitigation: cryostat acceptance test at the Cryostat L3.

CQ4

Conclusions

The SAT team has a wealth of experience integrating, testing, and deploying CMB instrumentation throughout the evolution of this experimental field.

The SAT I&T plan is at an appropriate level of maturity and is based on experience with similar CMB telescopes.

SAT prototyping is planned to reduce risk for the production system.

Schedule and resources for SAT I&T and Shipping are implemented in the CMB-S4 P6 resource-loaded schedule.

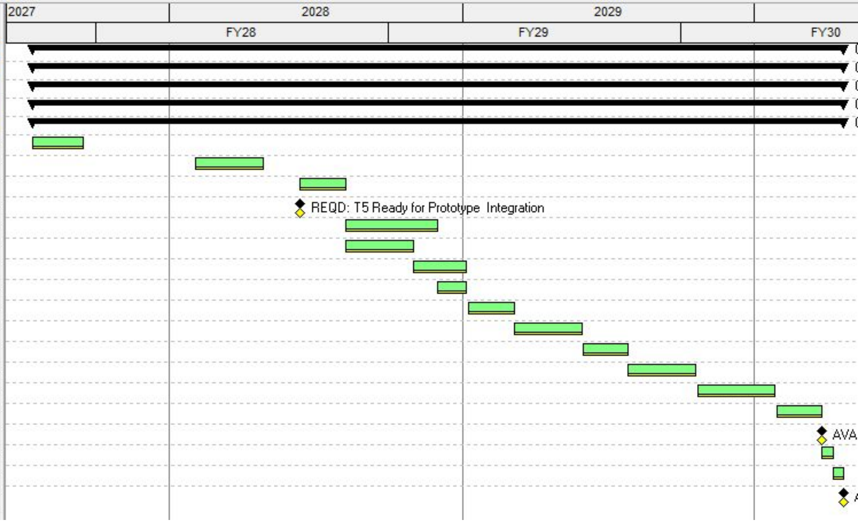
Next steps are to update and iterate on planning, schedule and resources; refine process flows; and continue learning from ongoing experiments' efforts.

Backup Slides

Prototype Mount/SAT I&T

Scopes in this section are being worked on; some of the scopes will be transferred to the Mount L3.

Activity ID	Activity Name	Planned Duration	Planned Start	Planned Finish	WBS
CMBS4-AOA1 Working File AOA-1 - Cosmic Microwave Background - Stage 4 CD-1 Planning - AOA-1 WHAT IF		685.0d	07/14/2027	04/22/2030	
CMBS4-AOA1.1 Cosmic Microwave Background - Stage 4 Master Project		685.0d	07/14/2027	04/22/2030	
CMBS4-AOA1.1.07 Small Telescopes		685.0d	07/14/2027	04/22/2030	
CMBS4-AOA1.1.07.09 U.S. Integration & Test		685.0d	07/14/2027	04/22/2030	
CMBS4-AOA1.1.07.09.03 Prototype Mount/SAT I&T		685.0d	07/14/2027	04/22/2030	
SAT_0792_5000	Prepare UMN highbay	44.0d	07/14/2027	09/14/2027	CMBS4-AOA1.1
SAT_0792_5010	Mount Prototype steel assembly at UMN	60.0d	02/02/2028	04/26/2028	CMBS4-AOA1.1
SAT_0792_5020	Prepare for Prototype Integration & Test at Mount Integration Site	40.0d	06/12/2028	08/07/2028	CMBS4-AOA1.1
MS5_SAT_5020	REQD: T5 Ready for Prototype Integration	0.0d	06/12/2028		CMBS4-AOA1.1
SAT_0792_5030	Mount integration test with Prototype with cryogenics including DR	80.0d	08/08/2028	11/30/2028	CMBS4-AOA1.1
SAT_0792_5040	Mount drive system install, tune, test - Prototype	60.0d	08/08/2028	10/31/2028	CMBS4-AOA1.1
SAT_0792_5050	Mount dummy receiver hoist checkout - Prototype	40.0d	11/01/2028	01/05/2029	CMBS4-AOA1.1
SAT_0792_5060	Mount env boot install - Prototype	20.0d	12/01/2028	01/05/2029	CMBS4-AOA1.1
SAT_0792_5070	Install HRJ's and helium hoses - Prototype	40.0d	01/08/2029	03/06/2029	CMBS4-AOA1.1
SAT_0792_5080	Receiver arrives and load - Prototype	60.0d	03/07/2029	05/30/2029	CMBS4-AOA1.1
SAT_0792_5090	Verify cryo performance under el/dk - Prototype	40.0d	05/31/2029	07/26/2029	CMBS4-AOA1.1
SAT_0792_5100	Install electronics on receiver and establish readout - Prototype	60.0d	07/27/2029	10/19/2029	CMBS4-AOA1.1
SAT_0792_5110	Detector testing on mount - Prototype	60.0d	10/22/2029	01/25/2030	CMBS4-AOA1.1
SAT_0792_5120	Install environmental boot and verify - Prototype	40.0d	01/28/2030	03/25/2030	CMBS4-AOA1.1
MS5_SAT_5010	AVAIL: T5 SAT Prototype Mount and SAT Integration and test complete	0.0d		03/25/2030	CMBS4-AOA1.1
SAT_0792_5130	Packing of Mount Assembly (one of two)	10.0d	03/26/2030	04/08/2030	CMBS4-AOA1.1
SAT_0792_5140	Shipping of SAT Mount Assembly (one of two) to Port Hueneme CA NonLabor	10.0d	04/09/2030	04/22/2030	CMBS4-AOA1.1
MS5_SAT_5030	AVAIL: T5 South Pole Mount Assembly (one of two) AVAILABLE for Shipping to	0.0d		04/22/2030	CMBS4-AOA1.1

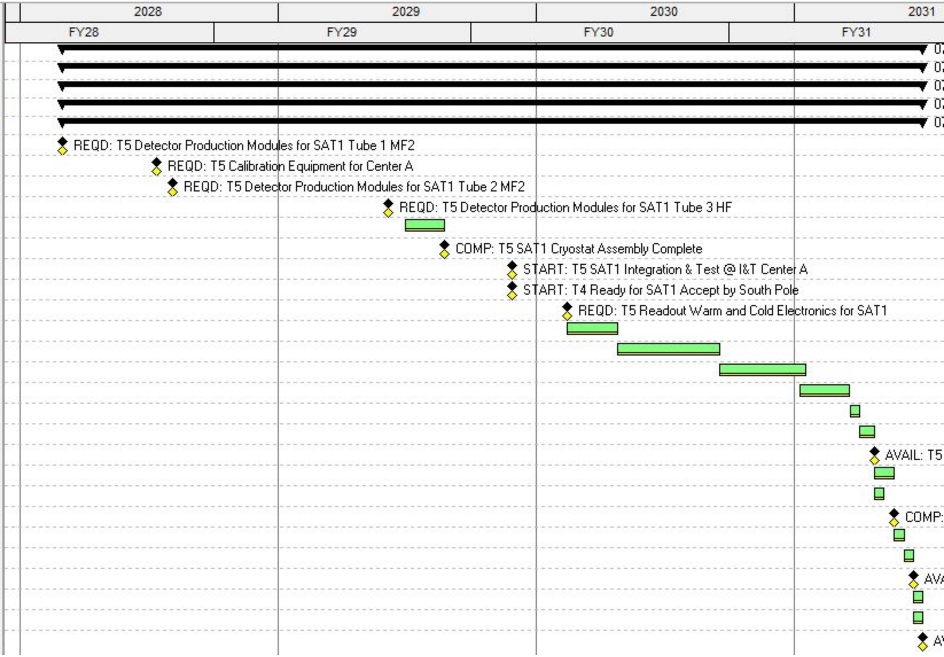


CQ6

SAT 1 I&T

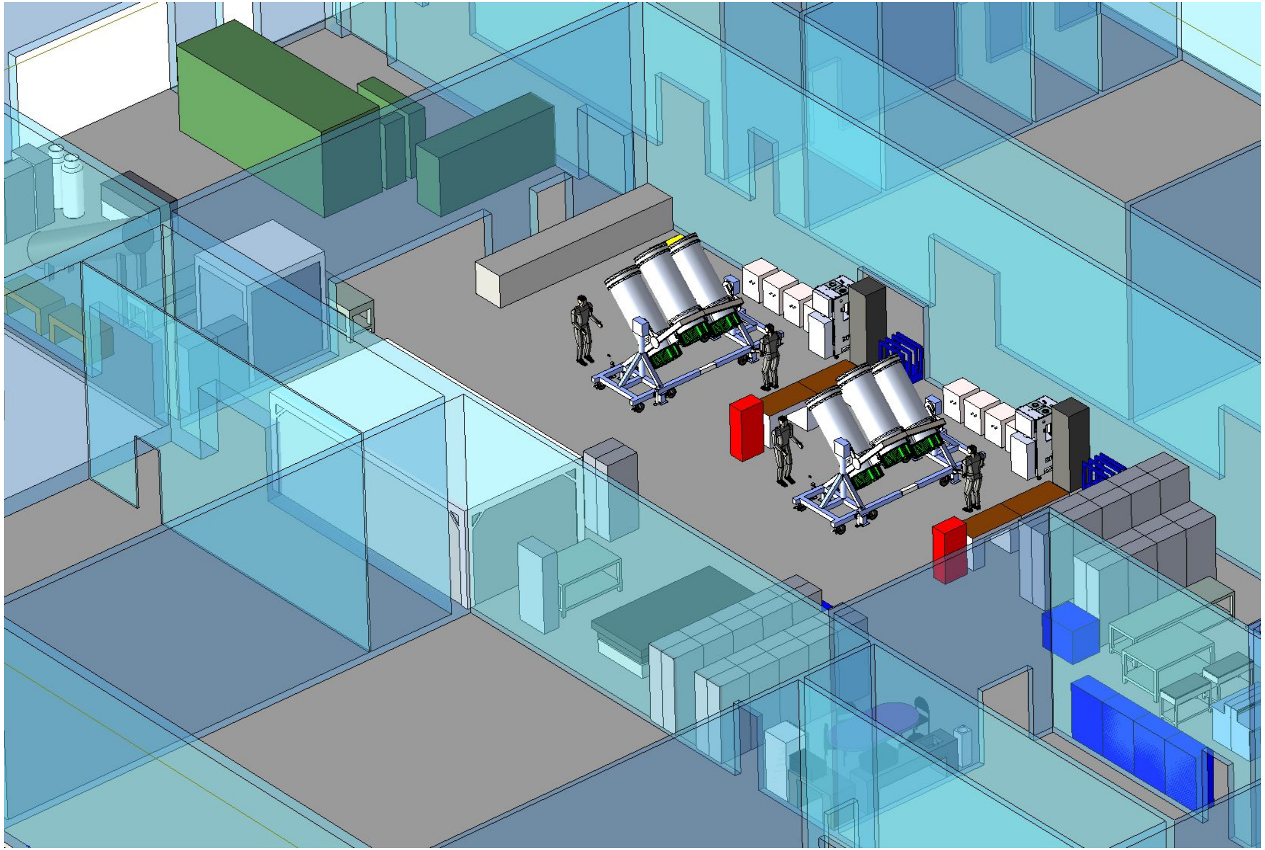
Bottom-up schedule for production cryostat I&T, based on prototype prototype cryostat plan, will be incorporated into P6 before the Director's Review.

Activity ID	Activity Name	Planned Duration	Planned Start	Planned Finish
CMBS4-AOA1 Working File AOA-1 - Cosmic Microwave Background - Stage 4 CD-1 Planning - AOA-1 WHAT IF		833.0d	03/01/2028	07/02/2031
CMBS4-AOA1.1 Cosmic Microwave Background - Stage 4 Master Project		833.0d	03/01/2028	07/02/2031
CMBS4-AOA1.1.07 Small Telescopes		833.0d	03/01/2028	07/02/2031
CMBS4-AOA1.1.07.09 U.S. Integration & Test		833.0d	03/01/2028	07/02/2031
CMBS4-AOA1.1.07.09.04 Integrate, Test, Ship SAT1		833.0d	03/01/2028	07/02/2031
MS5_SAT_I&T_1044	REQD: T5 Detector Production Modules for SAT1 Tube 1 MF2	0.0d	03/01/2028	
MS5_SAT_I&T_1049	REQD: T5 Calibration Equipment for Center A	0.0d	07/11/2028	
MS5_SAT_I&T_1058	REQD: T5 Detector Production Modules for SAT1 Tube 2 MF2	0.0d	08/04/2028	
MS5_SAT_I&T_1050	REQD: T5 Detector Production Modules for SAT1 Tube 3 HF	0.0d	06/05/2029	
SAT_0792_1000	Assemble and Test SAT1 Cryostat Tubes (1-3)	40.0d	06/29/2029	08/24/2029
MS5_SAT_I&T_1028	COMP: T5 SAT1 Cryostat Assembly Complete	0.0d		08/24/2029
MS5_SAT_I&T_1037	START: T5 SAT1 Integration & Test @ I&T Center A	0.0d	11/28/2029	
MS5_SAT_I&T_1122	START: T4 Ready for SAT1 Accept by South Pole	0.0d	11/28/2029	
MS5_SAT_I&T_1034	REQD: T5 Readout Warm and Cold Electronics for SAT1	0.0d	02/14/2030	
SAT_0792_1010	Assembly of Readout and Housekeeping electronics, wiring, and support equipm	50.0d	02/14/2030	04/25/2030
SAT_0792_1020	SAT1 Integration & Test @ I&T Center A	100.0d	04/26/2030	09/17/2030
SAT_0792_1040	Vacuum and Cold Testing of SAT1	80.0d	09/18/2030	01/17/2031
SAT_0792_1030	Optics tube integration and testing	50.0d	01/10/2031	03/20/2031
SAT_0792_1050	Integration of Focal Plane Array (detectors, Cold RO, cabling) for SAT1	10.0d	03/21/2031	04/03/2031
SAT_0792_1060	Testing of Focal Plane Arrays for SAT1	15.0d	04/04/2031	04/24/2031
MS5_SAT_I&T_1126	AVAIL: T5 SAT1 Integration and test complete	0.0d		04/24/2031
SAT_0792_1070	Disassembly of Systems SAT1 in preparation for Shipping	20.0d	04/25/2031	05/22/2031
SAT_0792_1080	End to End testing of SAT1 in preparation for FY30 Shipping deadline	10.0d	04/25/2031	05/08/2031
MS5_SAT_I&T_1060	COMP: T5 SAT1 Ready to Pack	0.0d		05/22/2031
SAT_0792_1090	Packing of Cryostat Crate for SAT1	10.0d	05/23/2031	06/05/2031
SAT_0792_1100	Packing of Focal Plane for SAT1	9.0d	06/06/2031	06/18/2031
MS5_SAT_I&T_1061	AVAIL: T5 SAT1 ready to Ship to Port Hueneme CA	0.0d		06/18/2031
SAT_0792_1110	Shipping of SAT1 to Port Hueneme CA Labor	10.0d	06/19/2031	07/02/2031
SAT_0792_1120	Shipping of SAT1 to Port Hueneme CA NonLabor	10.0d	06/19/2031	07/02/2031
MS5_SAT_I&T_1062	AVAIL: T5 SAT1 onsite at Port Hueneme CA	0.0d		07/02/2031

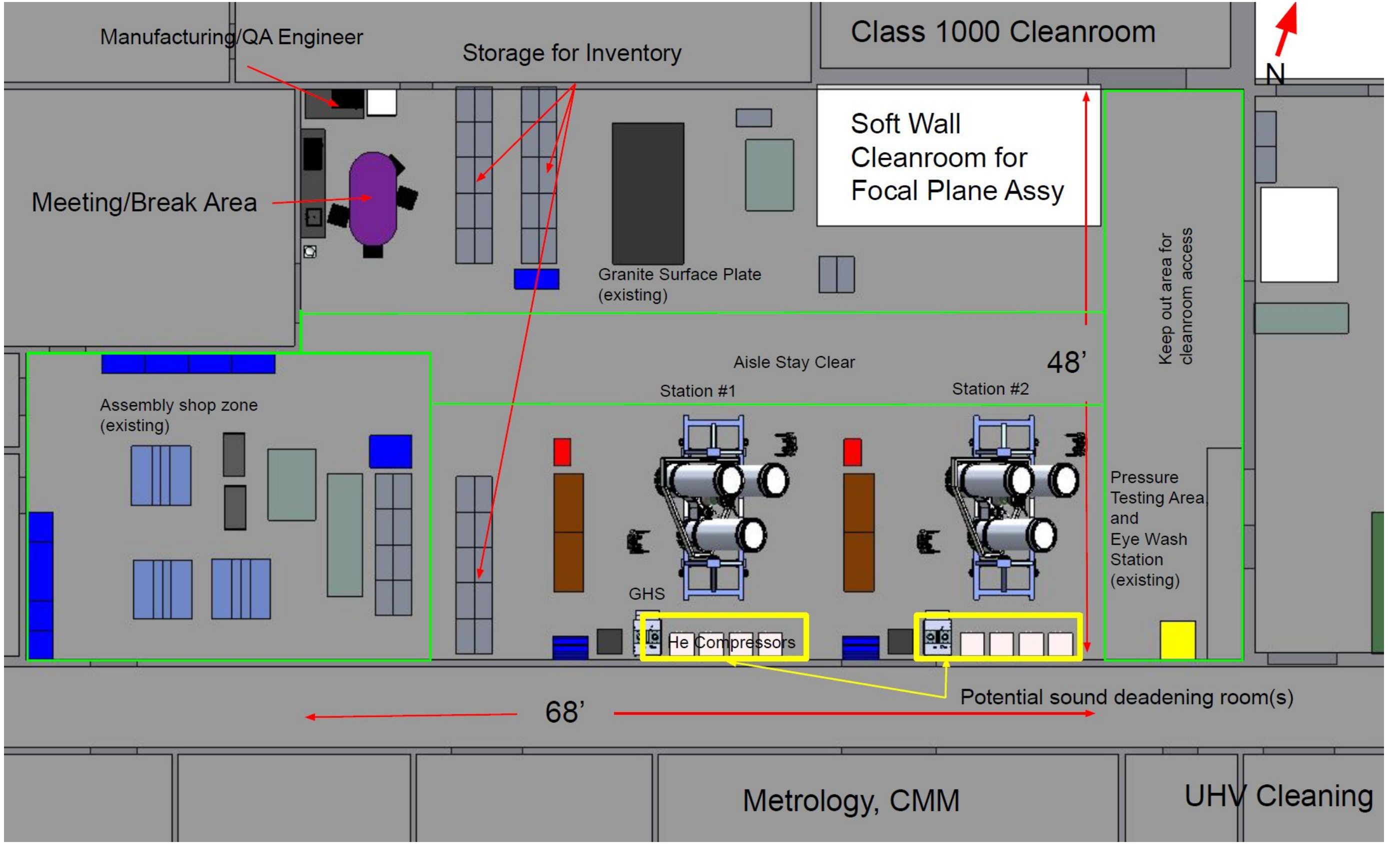


CQ6

Integration & Testing Site Design



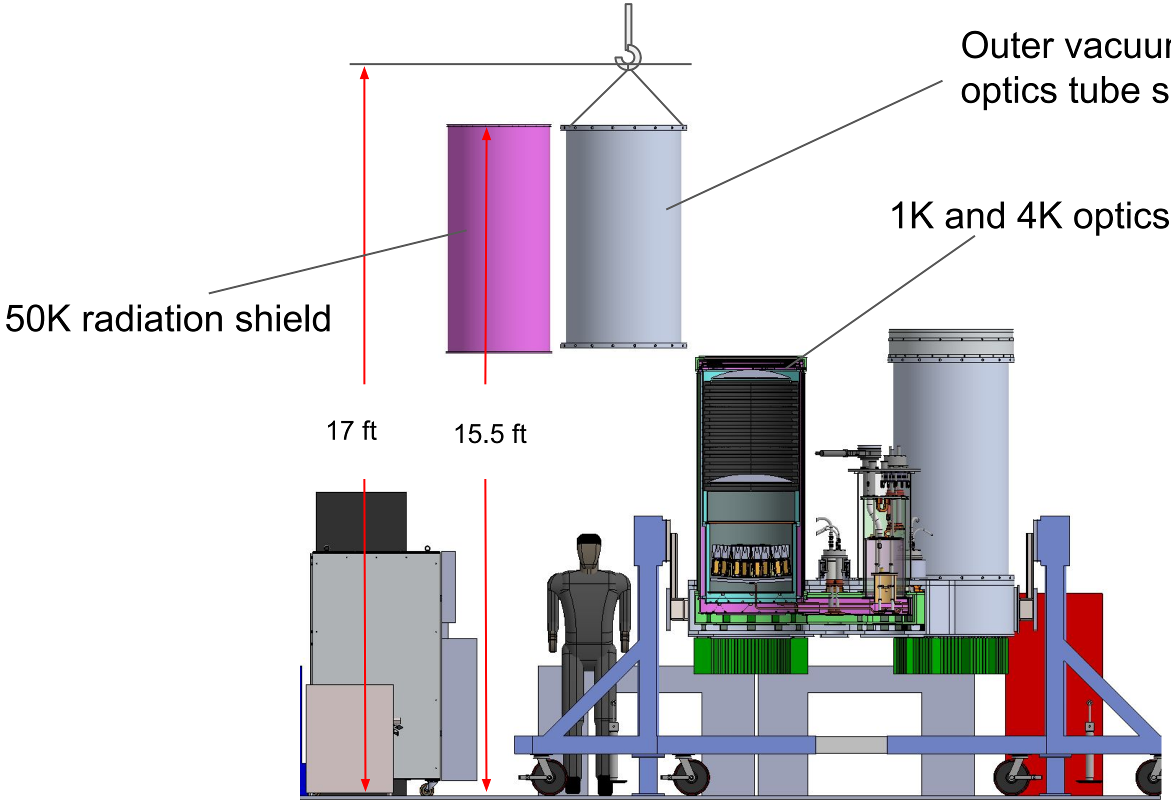
Integration & Testing Site Design



The floor plan consists of:

- 2 integration areas
  - 620 sq ft, similar to the pole lab space.
- Staging and pre-assembly area.

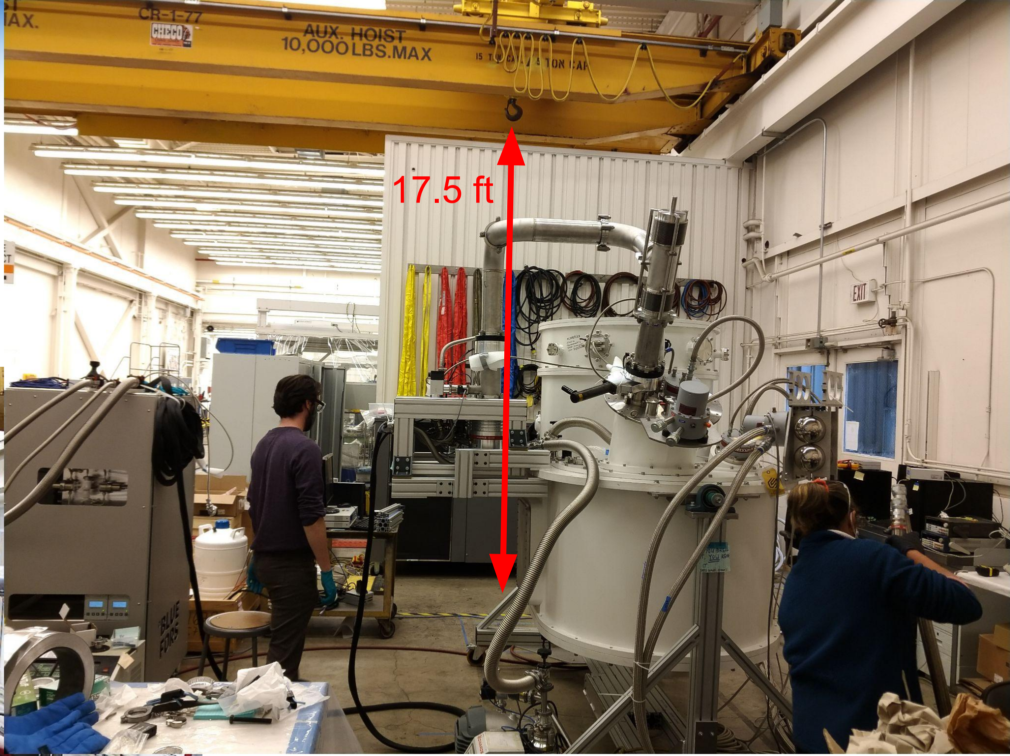
Integration & Testing Site Design



Height and crane requirement: 17 ft in order to install the outer shells of the optics tube section.
There is an option to modify the cart and reduce the hook-height requirement.

Crane capacity: 3 metric tons to lift the entire cryostat.

This is the LBNL West Highbay in the same building (the opposite end of Building 77). Similar height and width, but longer than the East Highbay shown in the CAD views on previous slides.



The Simons Observatory SAT under integration in the LBNL building 77 East Highbay.

Similar facilities exist at the CfA.

I&T Infrastructure Requirements

Largest power consumer: PTC compressor.

- Each PT410 requires:
  - Electrical Power: 200/230 OR 460 VAC 3PH / 8.4kW
  - Cooling water: 2.3 GPM (9 LPM) @ 80°F (27°C)
  - Dedicated receptacle, NEMA L15-50 twist lock (230), or NEMA L16-30R twist lock (460)
  - Noise: 70 dBA each (x8 = 79 dBA). Shielding or distancing from the workers to be considered.

Total: 8 compressors (worst), 3 compressors (nominal per cryostat)

- 8 compressors: 67.2 kW electrical / 18.4 GPM cooling water
- 3 compressors: 25.2 kW electrical / 6.9 GPM cooling water

Dilution Refrigerator (DR) gas handling system (GHS): 2 of them at maximum

- 220 VAC single phase / 20A dedicated breaker / NEMA L6-20R receptacle.
- Compressed Air (BlueFors DR GHS): > 5 bar, 70 PSI