WBS 1.07.06 - Calibration Equipment

L3 Lead - Kirit S. Karkare

Outline

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- Key L3 contributors
- Breakdown of this L3
- Key Requirements
- Interfaces with other L3s
- Technical Design / Scope
- Prototyping Plans
- Conclusion

Presenter Introduction

Kirit S. Karkare

- Staff scientist in CMB group at SLAC/KIPAC
- 12 years experience in SAT instrumentation
- Graduate work in Harvard CMB lab working on BICEP/Keck Array, continued as postdoc at UChicago/Fermilab
- Calibration hardware design/fabrication and measurements at South Pole
- Led analysis of instrumental systematics in BICEP *r* constraints

Key Contributors in this L3

- Clara Verges (CfA), Calibration requirements study
- Colin Bischoff (Cincinnati), Calibration requirements study
- Keith Thompson (Stanford), FTS design
- Brodi Elwood (CfA), Near-field beam mapper design
- Matthew Petroff (CfA), Cold load design

General inputs: James Cornelison, Marion Dierickx, Nick Galitzki, John Kovac, Fred Matsuda, Jeff McMahon, Paul Williams, many more…

Description of L4 WBSs

Build, test, and deliver calibration hardware used for NA testing and South Pole

1.07.06.01	Hardware interfaces design	**1.07.06.07**	Far-field flat mirror
1.07.06.02	Aperture-filling load	**1.07.06.08**	Far-field thermal chopper
1.07.06.03	Near-field beam mapper	**1.07.06.09**	Amplified microwave source
1.07.06.04	Fourier transform spectrometer	**1.07.06.10**	Helmholtz coil
1.07.06.05	Near-field polarization calibrator	**1.07.06.11**	RF sources and monitoring
1.07.06.06	Calibration mast	**1.07.06.12**	Star camera

Needed (first) for NA prototype and production cryostat testing, then at Pole

Needed at Pole

Each L4 comprises design, prototype, procurement/assembly, and crating/shipping to the appropriate site

Key Driving Requirements for Calibration

Calibration equipment will be used for:

- Testing during cryostat/optics prototyping
  - E.g. optics stack sidelobe testing
- Validation of SAT performance during commissioning
  - System-level verification
- Measuring basic instrument parameters to well-defined precision
  - Needed to make CMB maps: bandpasses, beam shapes, pol angles…
- Probing instrumental systematics
  - Needed to constrain *r*: deep beam maps, sidelobe pickup…

Each measurement sets different requirements on individual pieces of cal hardware, e.g.:

- To measure main beams to -40 dB, we need a far-field thermal chopper presenting a load of (250-77 K) with a 24” aperture, spinning at 16 Hz, observing for X hours
- A major thrust of current activity in this L3 is setting these calibration requirements and connecting them to hardware requirements, scaling from achieved calibrator performance

CQ1

Inter-L3 Interfaces

Within SAT L2:

- **Cryostat**: Mounting flanges
- **Optics**: Optical coupling to FPU
- **Mount**: Mounting with multiple tubes, electrical/data feedthrough
- **Ground shield**: Mirror mounting and storage, door to pass equipment through, crane
- **I&T**: Schedule and measurements needed for acceptance

External to SAT L2:

- **Sites**: Placement of SAT towers, network connections
- **DAQ**: Auxiliary data inputs

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

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

CQ2

Equipment Needed for Prototyping and NA Integration

- Generally equipment for lab measurements, but some can also be used on-site at South Pole
  - Aperture-filling load (1.07.06.02)
  - Near-field beam mapper (1.07.06.03)
  - Fourier Transform spectrometer (1.07.06.04)
  - Near-field polarization calibrator (1.07.06.05)
  - Helmholtz coil (1.07.06.10)
- Prototyping most of these in the next year, then moving to production
- Designs mostly straightforwardly adapted from existing SAT equipment
  - Some minor R&D (e.g. FTS optical coupling)
- Parallel work: hardware interfaces design (mounting, electrical connections, etc. - 1.07.07.01)
  - Thinking about dimensions for multiple equipment on the mount at the same time

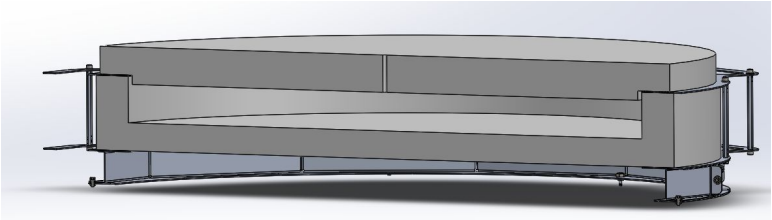
Aperture-Filling Load

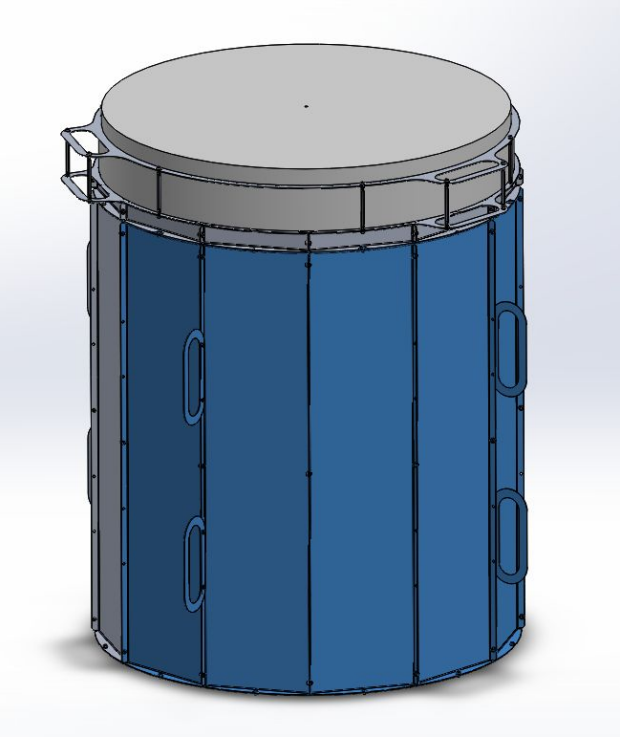
Present a 300 or 77 K blackbody load to detectors

Used to measure optical efficiency and noise

Can also be used with a forebaffle-shaped cylinder to measure loading vs solid angle

Design in hand (Matthew Petroff), prototype now being built at SLAC to be tested on BICEP Array receiver in August 2023



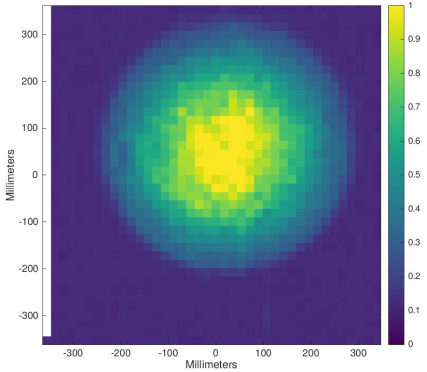


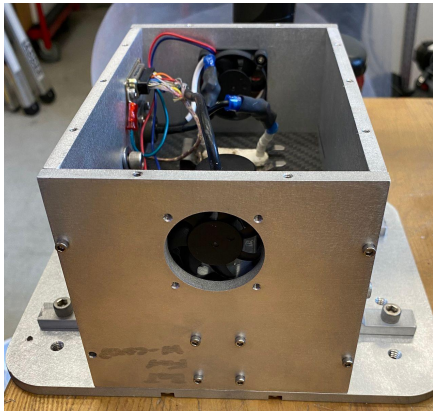
Near-Field Beam Mapper

Measure beams in the aperture plane with a chopped thermal source mounted on an XY stage

Beam maps probe receiver health and can be compared to optics simulations

Prototype built (Brodi Elwood) and tested on BICEP Array receivers in 2022





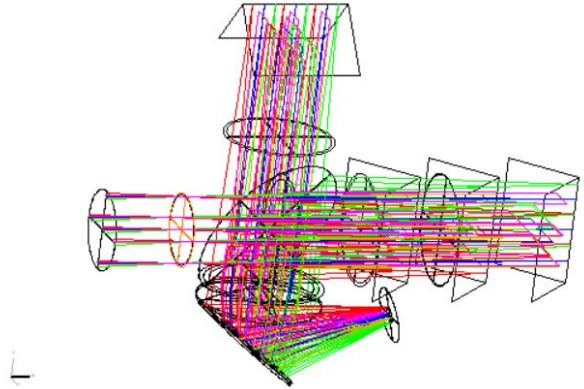
Fourier Transform Spectrometer

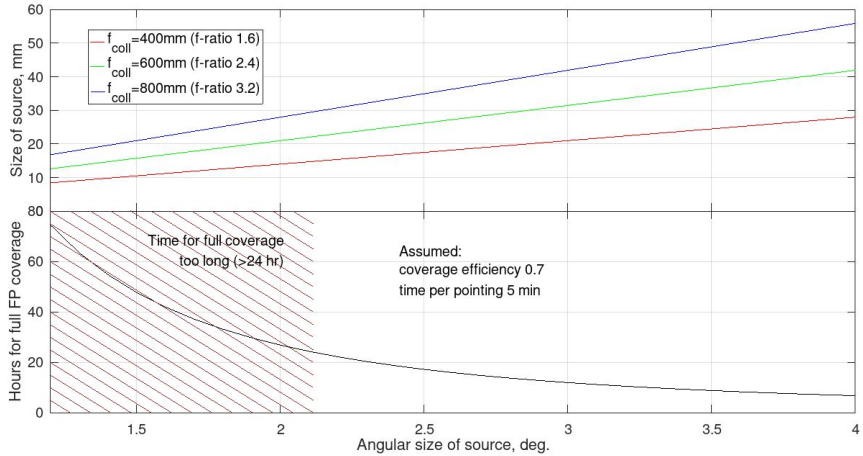
Measure detector spectral response

Optical design in place (Keith Thompson), starting to build prototype at Stanford

Lots of ongoing modeling work to understand:

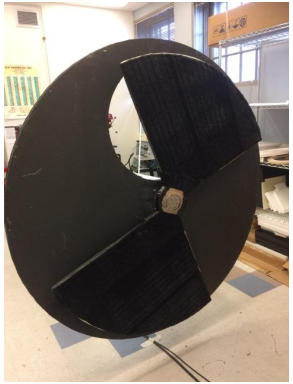
- Spectral resolution requirements (may change with band)
- Systematics associated with suboptimal aperture illumination and off-axis rays





Equipment Needed in the Field

- Calibration mast (1.07.06.06)
- Far-field flat mirror (1.07.06.07)
- Far-field thermal chopper (1.07.06.08)
- Amplified microwave source (1.07.06.09)
- RF sources and monitoring (1.07.06.11)
- Star camera (1.07.06.12)



For the equipment needed for critical systematics tests (mast+mirror+chopper+amplified source), we are baselining an extrapolation of the existing BK beams strategy.

We are also analyzing archival BK data to understand where the existing strategy may not adequately address S4 requirements, and plan to coordinate with BICEP Array and pSAT to perform measurements that can determine whether this strategy is sufficient.

- E.g., ground shield stability and geometry (affects calibration mast/mirror design)

2021 CDR Recommendation R1.1 Overall

- **Perform systematic-error analysis of existing BICEP/Keck data,** CDR R1.1 Overall (RT-118): In order to identify legacy elements of the SAT design that do not adequately address the CMB-S4 requirements, we recommend an S4-focused systematic-error analysis of existing BICEP/Keck data by the time of CD-1. An example of such an analysis would be in the context of quantifying the amplitude and stability of azimuth-synchronous signals from the ground or stationary ground shield. Beyond this, all elements of the L2 and L3 SAT requirements list (CMBS4-doc-755-v1) that can be investigated with existing data should be. This work will require significant effort by the BICEP/Keck team and they should be supported in this effort by the S4 project.
- RESPONSE: In addition to the longstanding, ongoing analysis of systematics in BICEP/Keck data (the latest of which was published in October 2021 with a focus on residual beam mismatch, polarized point sources, noise bias mis-estimates, and bandpass uncertainty), we are now planning projects that specifically probe aspects of the SAT design and calibration strategy that have not yet been adequately studied. This includes an effort to connect the achieved precision in calibration measurements to systematic uncertainties and their effects on sigma(r) - now approved as a CMB-S4 technical report - and a dedicated study of ground shield pickup. While there has not yet been funding for these efforts, there is an SPO LOI making BK data available to CMB-S4 for this work. We intend to make significant progress in these efforts before CD-1.

- Recommendation summary: Perform systematic-error analysis of existing BICEP/Keck data, (2021 CDR R1.1)
- Response summary: We intend to make significant progress in these efforts before CD-1.

CQ10

2021 CDR Recommendation R1.3 Overall

- **Coordinate with the BICEP Array about telescope validation data,** CDR R1.3 Overall (RT-120) : If mining the existing data identifies legacy SAT design elements where the S4 team needs more validation data, then we recommend the S4 team coordinate with the BICEP Array team to perform the measurements required to determine whether legacy designs can limit systematic errors to the levels identified in CMBS4-doc-755-v1. (See also Calibration recommendations).
- Response: As our understanding of systematics in existing BICEP data as applied to the CMB-S4 SATs matures, and we identify areas where more validation data are needed, we will work with the BICEP Array team to take the relevant measurements. This could include e.g. different ground shield geometries.

- Recommendation summary: Coordinate with the BICEP Array about telescope validation data, CDR R1.3
- Response summary: We will identify areas where on-sky data can help us and will work with the BA team to collect such data.

CQ10

Systematics Requirements Analysis

We have started a CMB-S4 analysis project, "**Systematics Forecasting for SATs"** (Clara Verges, Colin Bischoff, Kirit Karkare) to set calibration requirements for σ(r) < 5e-4

Generic tool that injects systematics templates into the likelihood framework, so their effects can be modeled in the context of a multicomponent analysis

Templates to be generated for various classes of expected systematics (main beam T→P leakage, bandpass mismatch, crosstalk, etc), based on real measurements

Measurement requirements (e.g., depth of beam maps) can then be connected to hardware requirements (e.g., how many masts/mirrors, size of mirrors/choppers) and calibration strategy, scaling from existing BK measurements.

Status: Basic framework is set up, can replicate results from CMB-S4 *r* forecasting paper. Should have preliminary requirements for beam maps in the next few months.

2021 CDR Recommendation R7: Calibration

- **Re-evaluate calibration data and plans,** CDR R7 (RT-127): The existing BICEP/Keck calibration data should be analyzed in detail to determine if the baseline SAT calibration and systematic mitigation program is likely to be sufficient. Any potential weak points need to be identified and solutions should be designed by the time of CD-1. If new calibration equipment and techniques are motivated, then the project should support the BICEP Array team in implementing and testing them. This should be completed by CD-2.
- Response: As a part of the now-approved CMB-S4 Technical Report ("Framework for Instrumental Systematics Forecasting for SATs"), we are using archival BICEP calibration data to quantify the depth of calibration measurements needed for CMB-S4's r limits. This will allow us to determine whether the existing calibration program is sufficient, and whether new equipment is needed, on a ~several-month timescale. If necessary, we will explore new calibration scenarios using BICEP Array as a test platform.

- Recommendation summary: Re-evaluate calibration data and plans, CDR R7
- Response summary: In order to complete our cal plans and equipment specs, we are studying archival BICEP cal data to quantify the depth of cal measurements needed to reach CMB-S4's r requirements.

CQ10

Conclusions

We have a strong team with extensive experience in calibration, all of whom are working this with existing Stage 3 experiments.

We are working closely with other L3s, especially SAT I&T, to ensure that the hardware we build is sufficient for the required testing plan.

We have started building prototypes for in-lab calibration measurements, which will be tested on SAT-like receivers in the next year.

A comprehensive calibration requirements study is in the works, which will help us refine the required equipment and calibration strategy at South Pole.