Small Aperture Telescopes PBD - plenary

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Tuesday March 9, 13:30 ET

SAT Parallel Agenda

SAT Baseline Design Discussion:

- Baseline Design Overview and Drivers - *John Kovac*
- Optics - *Abby Vieregg / Paul Grimes / Scott Paine*
- Cryostats - *Akito Kusaka / Joe Saba*
- Mount - *Clem Pryke*
- Groundshields and Exterior Baffles - *Ben Schmitt*
- Calibration - *Kirit Karkare*

SAT Zemax Lens Design Updates - *Fred Matsuda / Tony Stark*

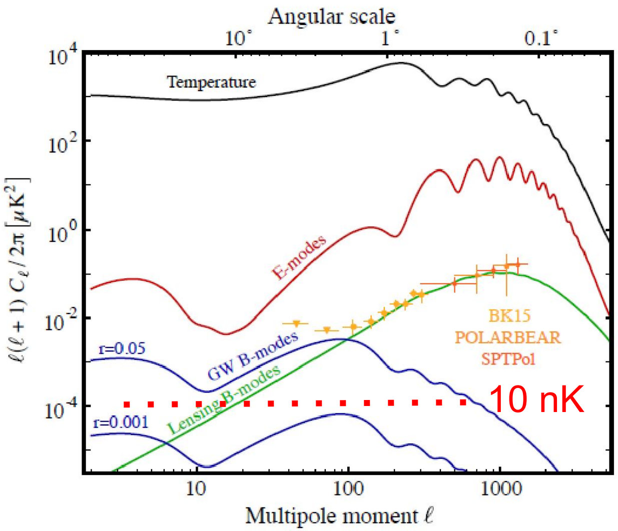
SAT Calibration Plan Updates - *Kirit Karkare*

SAT Overview / Intro to WBS

- Science Requirement (SR1) driving SAT design:
  - $r < 0.001$ at 95%, or detect $r > 0.003$ at 5σ confidence (from PLR)

- This means achieving < 10 nK for:
  - foreground separation
  - raw sensitivity
  - systematic control

…All are made **harder at degree scales** by 1/f noise & red-spectrum confusion signals



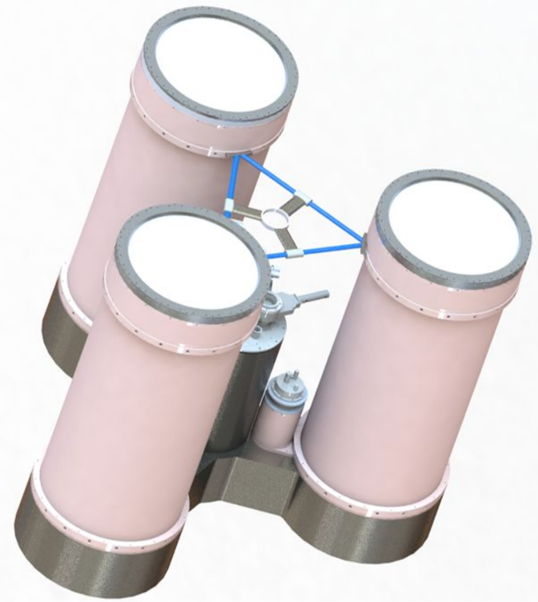
DSR (arXiv:1907.04473), Fig 6

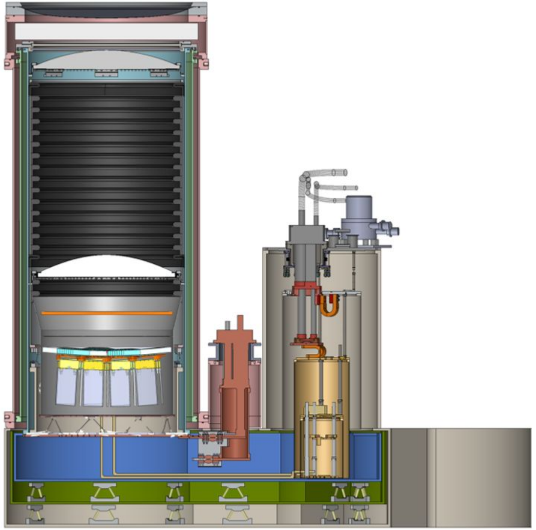
Why are SATs required?

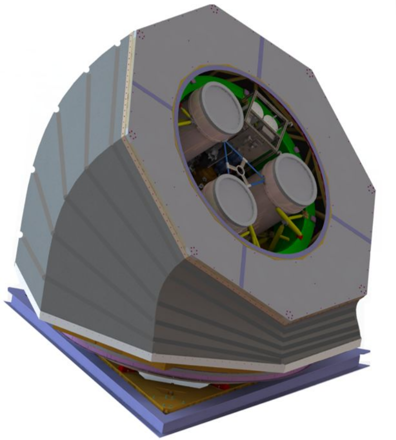
- **Intrinsic advantages:** efficient to integrate/test/deploy many detectors; stability of cryogenic optics; aperture filling calibrators; aperture filling modulation; superior sidelobe control and shielding
- **ONLY proven approach** for deep *r* measurement
- **SAT pBD builds on proven experience:** BICEP-style cryogenic refractors, while incorporating new technologies (e.g. dichroic horns, dilution fridges, and (for Chile) SO-derived HWPs) where they promise low risk & improved performance margin.

SAT Overview

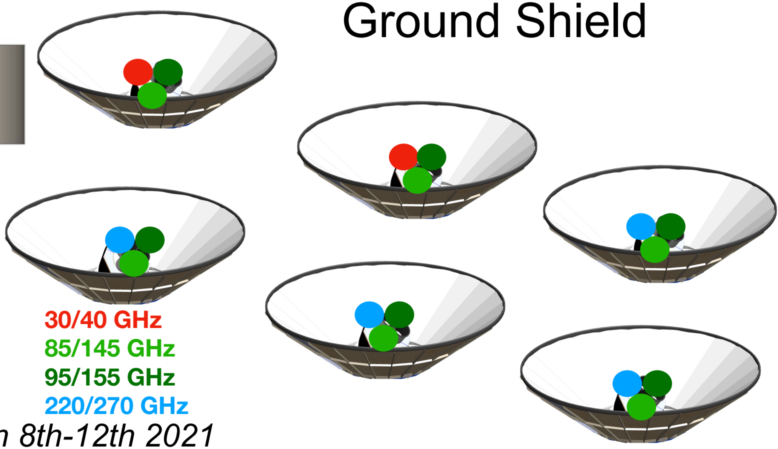
Cryostat System, Optics Tubes,
Integration & Test







Telescope Mount &
Ground Shield



SAT Overview (the project view)

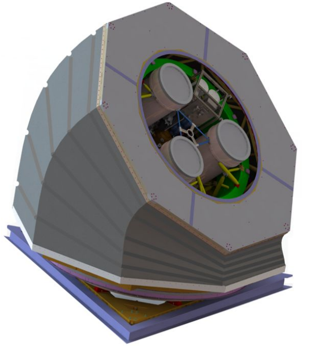
Lvl 2	Lvl 3	Lvl 4
1.07 Small Telescopes	1.07.01 - Small Telescopes Management	1.07.01.01 - Management
		1.07.01.02 - Reviews
	1.07.02 - Small Telescope Cryostats	1.07.02.01 - Cryostats
		1.07.02.02 - Refrigerators (incl Dilution Fridge)
		1.07.02.03 - Vacuum Systems
		1.07.02.04 - 100mK Stage Focal Plane Structure
		1.07.02.05 - Readout Wiring
		1.07.02.06 - Half Wave Plate Rotation Mechanism
		1.07.02.07 - Cryostat Installation & Test
		1.07.02.08 - Cryostat Crate & Ship
	1.07.03 - Cold Optics	1.07.03.01 - Lenses
		1.07.03.02 - AR Coatings
		1.07.03.03 - Filters
		1.07.03.04 - Vacuum Window
		1.07.03.05 - Half Wave Plate
		1.07.03.06 - Structure & Housekeeping
		1.07.03.07 - Cold Optics Tube Integration & Assembly
		1.07.03.08 - Cold Optics Crate & Ship
	1.07.04 - Telescope Mount Assembly	1.07.04.01 - Design/Procure/Fabricate
		1.07.04.02 - Crate & Ship
	1.07.05 - Telescope Ground Shield	1.07.05.01 - Design/Procure/Fabricate
		1.07.05.02 - Crate & Ship
	1.07.06 - Cryostat Prototype	
	1.07.07 - Optics Stack Prototype	
	1.07.08 - NO. Hemisphere Integration & Test	1.07.08.01 - Integregration Test Mgm't & Development
		1.07.08.02 - Integration, Test, Crate & Ship
		1.07.08.03 - Crate

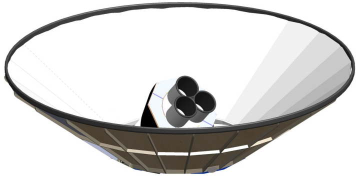
1.07 SAT Requirements (now tracked in Jama)

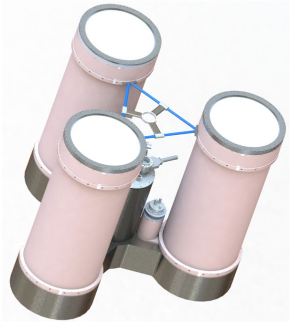
ID	Initial Trace Driving Measurement Requirement1	Title	Requirement	Basis/Rationale
SAT-0110	MR1.1	Sensitivity (white noise)	Equivalent white noise sensitivity shall meet or exceed actual in-the-field achieved performance of BICEP/Keck telescopes scaled to the following specifications: Frequency: 30, 40, 85, 95, 145, 155, 220, 270 GHz # detectors: 592, 592, 21336, 21336, 21336, 21336, 34376, 34376	https://docs.google.com/spreadsheets/d/1i_GU6hZKhxmBb64vhgr4rkRrERvl8Lz5YaZO0-dWjn0/edit?ts=5be076a9&pli=1#gid=1036196956
SAT-0120	MR1.1	Sensitivity (1/f noise)	Low-frequency excess noise as a function of multipole in integrated maps shall not exceed the specification curve, given as a function of multipole.	https://cmb-s4.org/wiki/index.php/Expected_Survey_Performance_for_Science_Forecasting
SAT-0130	MR1.1	Sensitivity (spurious pickup, e.g. mag field)	Spurious (non-optical) signal power in integrated polarization maps shall not exceed 10% of the final statistical uncertainty on the angular power spectrum at any multipole from 40 to 200.	https://cmb-s4.org/wiki/index.php/Expected_Survey_Performance_for_Science_Forecasting
SAT-0100	MR1.1	Beam size	Beam resolution shall meet or exceed the following maximum FWHM sizes: Frequency: 30, 40, 85, 95, 145, 155, 220, 270 GHz FWHM : 72.8, 72.8, 25.5, 22.7 25.5 22.7 13.0 13.0 arcmin	https://cmb-s4.org/wiki/index.php/Expected_Survey_Performance_for_Science_Forecasting
SAT-0150	MR1.1	Beam sidelobe	Spurious signal power from sidelobe pickup in integrated polarization maps shall not exceed 10% of the final statistical uncertainty on the angular power spectrum at any multipole from 40 to 200.	https://cmb-s4.org/wiki/index.php/Expected_Survey_Performance_for_Science_Forecasting
SAT-0160	MR1.1	Beam leakage	Spurious signal power from temperature to polarization leakage in integrated polarization maps shall not exceed 10% of the final statistical uncertainty on the angular power spectrum at any multipole from 40 to 200.	https://cmb-s4.org/wiki/index.php/Expected_Survey_Performance_for_Science_Forecasting
SAT-0170	MR1.1	Survey redundancy	Boresight rotation shall be 0-360 degrees	Permits full polarization coverage with systematic cross-checks
SAT-0180	MR1.1	Power consumption	Total SAT power consumption on site shall not exceed 300 kW	South Pole generation plant and fuel constraints, ref. site planning discussions with OPP/ASC and SPO, final number TBC
SAT-0190	MR1.1	Mass	All shipping pieces shall be < 24,000 lbs	compatibility with LC130 shipment
SAT-0200	MR1.1	Shipping envelope	All pieces shall ship within triple airforce pallet envelope, 252x96x104"	compatibility with LC130 shipment
SAT-0210	MR1.1	Footprint	Groundshield diameter shall not exceed 20m	compatibility with South Pole facility plan, including snow drifting maintenance
SAT-0220	MR1.1	Environmental	wind: survival 70 m/s, operation 30 m/s; seismic survival 0.3g; temperature survival & operation -90C	Wind and seismic dominated by Chile, Temperature dominated by Pole
SAT-0230	MR1.1	Observing range	Mount motion shall allow 24h observation of primary field with boresight center pointings between declination -50 to -60, as viewed from South Pole	https://cmb-s4.org/wiki/index.php/Expected_Survey_Performance_for_Science_Forecasting
SAT-0240	MR1.1	Observing efficiency	80% on-source efficiency, defined as fraction of seconds during observing season which contribute to CMB map integration	Typical of achieved performance for successful SATs, e.g. https://arxiv.org/pdf/1403.4302.pdf

Preliminary Baseline Design Summary

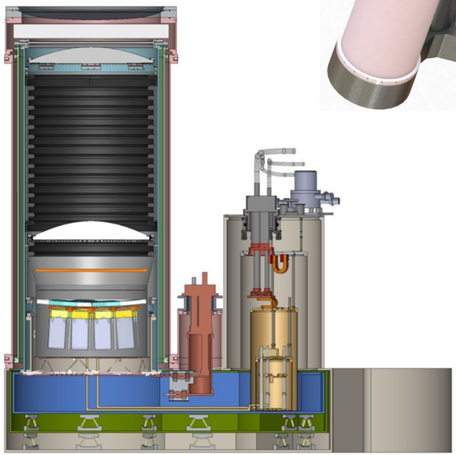
- Preliminary Baseline Design for SATs
  - 6 mounts + groundshields at Pole
  - 6 cryostats, each with 3 optics tubes (18 total)
    - Optics design heritage from BA and SO
  - Option of HWPs, allowing additional use in Chile
- North American Integration and Test







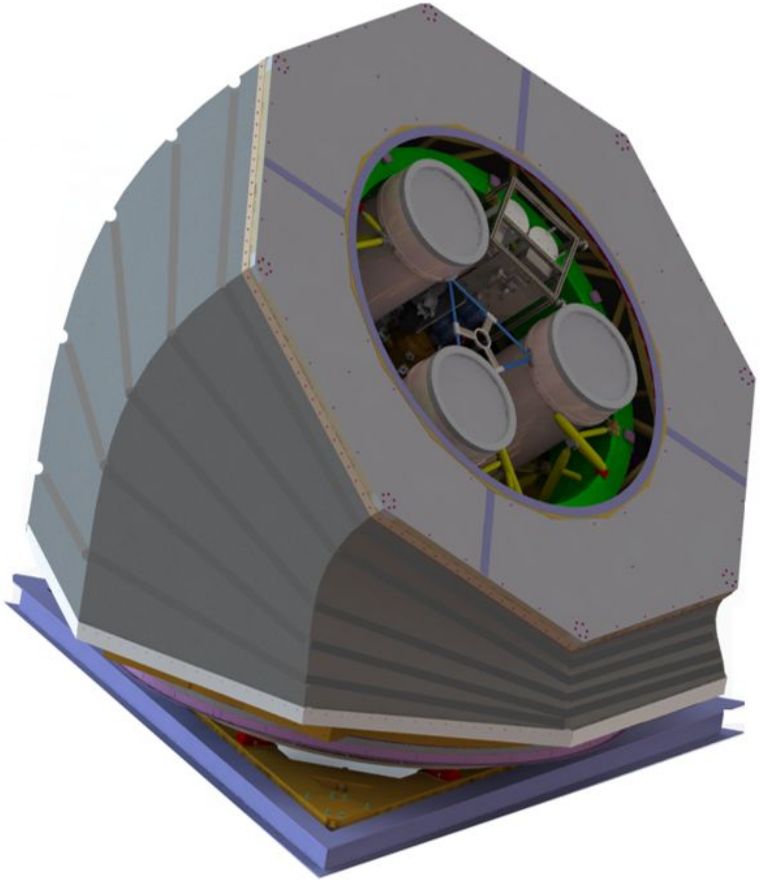
Bands	Lenses	Horns / Module	Modules / Tube	Tubes
30 / 40	2x 63cm HDPE	12	12	2
85 / 145	2x 63cm HDPE	147	12	6
95 / 155	2x 63cm HDPE	147	12	6
220 / 270	2x 46cm Silicon	469	12 (> 9 active)	4
		totals:	154,560 detectors / 18 tubes	



Receiver Design Overview

- SAT design will draw directly on design heritage from BICEP3, BICEP Array, and Simons Observatory Small Aperture Telescope Receivers

SAT Design Overview



- "In considering changes for the baseline design compared to the small-aperture telescopes that have achieved previous deep r measurements, we have incorporated new technologies—e.g. dichroic detectors, dilution refrigerators, and (if small-aperture telescopes are deployed to Chile) cryogenic half-wave plate modulators—where there is a consensus that they promise improved performance while adding little technical risk."
- In design choices we attempt to distinguish
  - *engineering issues:* those that can be fully developed and demonstrated in the lab to retire risk
  - *science issues:* those whose impact on successfully meeting the measurement and science requirements must be judged with comparison to direct experience of making deep B-mode maps.
- Most aspects of cryostat design are primarily engineering issues because we are confident our design choices can be fully validated in the lab.
- Examples of science issues include beam and sidelobe optical performance, polarization modulation approach, ground pickup and shielding, and other systematic effects <u>where instrumental and environmental couplings are complex enough to require field validation for any fundamental change of approach</u>. For design choices that impact these issues we have endeavored to <u>stay close to and to build upon proven experience, guided by comparative testing.</u>

Optics

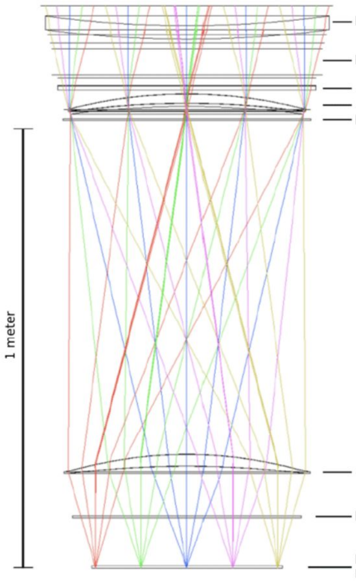
Abby Vieregg, Paul Grimes, Scott Paine

Cold Optics

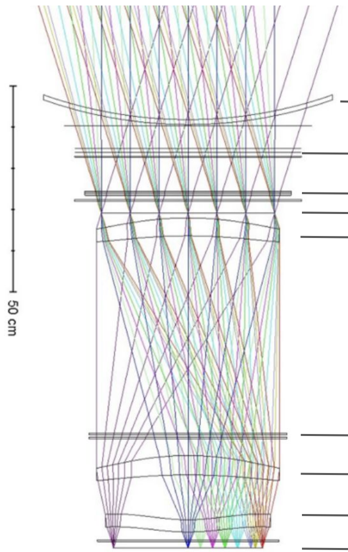
- Critical component for reaching target $\sigma(r)$
  - Need to control polarization systematics and optical efficiency
- While there is lots of heritage to draw on, this is a major R&D item for SATs and laying out baseline configuration
  - Mass production capability is an added requirement to a S4-ready technology.
- On our timeline: assessment for identification of baseline and alternative optics choices
- Many components in common with LAT cold optics

Cold Optics Heritage

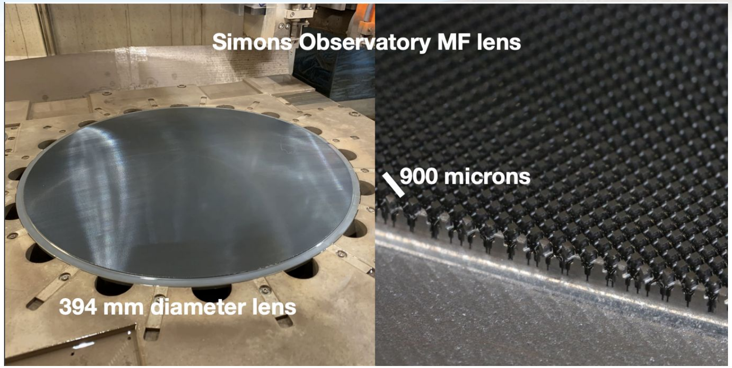
BICEP3



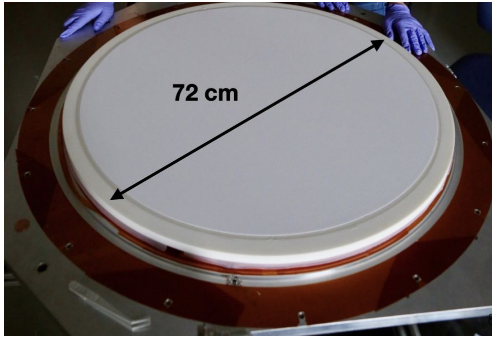
Simons Observatory



Silicon AR Example (Michigan/Chicago)



Alumina AR Example (Illinois)



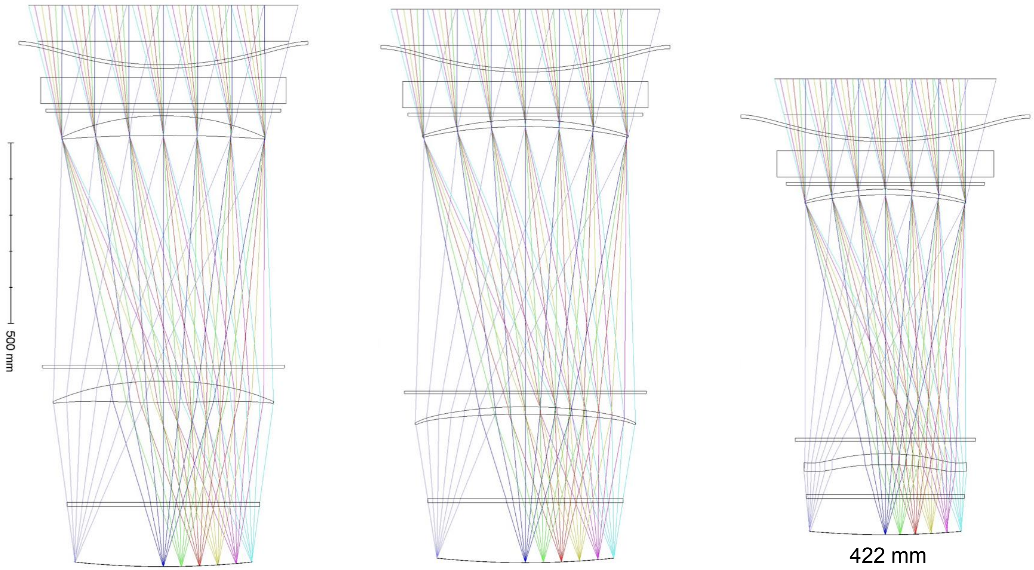
AR coating is a major R&D item.
Technology shared with LAT.

Optics design based on matured study.

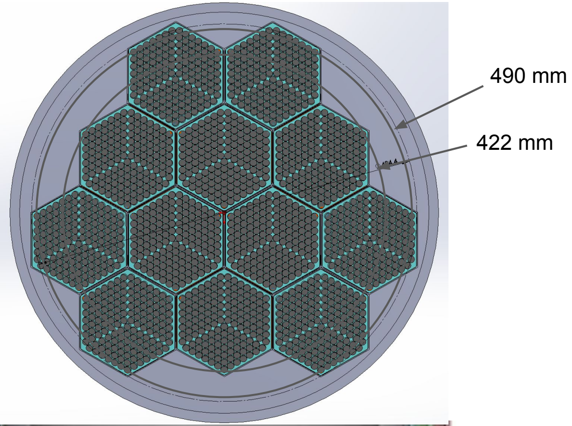
SAT lens design

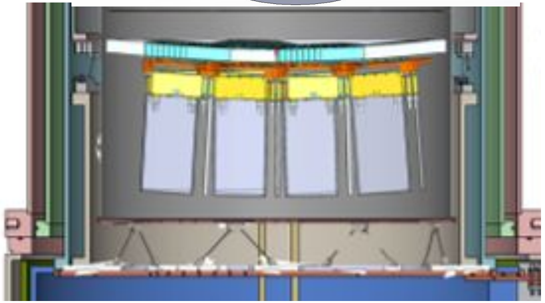
- ZEMAX candidate baseline designs advanced by Fred Matsuda, Tony Stark
- Recent development: **slightly curved focal surface** (r = 2.4 m) dramatically improves performance of two-lens designs

HDPE | Alumina | Silicon



490 mm | 490 mm | 422 mm





Baseline optics stack

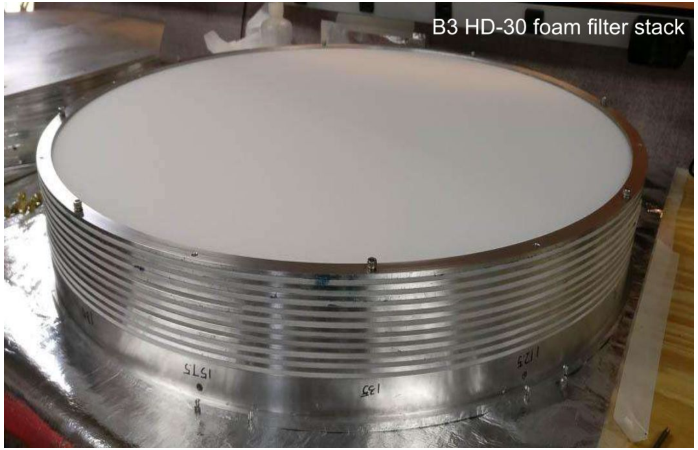
Element	Temperature	Material	AR coat	Diameter (clear, mm)	Thickness (center, mm)	IR power (transmitted)
window	290 K	HDPE	bonded plastic	740	20	172 W
filter1 (scattering)	250-140K	foam		717	12×3	12.5 W
filter2 (absorbing)	50K	alumina	bonded plastic	634	10	160 mW
filter3 (absorbing)	4K	nylon	bonded plastic	620	7.5	2.04 mW
30/40, 85/145 & 95/155 GHz baseline lens design						
lens1 (objective)	1K	HDPE	bonded plastic	570	55	503 μW
aperture stop	1K	tapered absorber		560		
lens2 (field)	1K	HDPE	bonded plastic	610	59	18 μW
220/270 GHz baseline lens design						
lens1 (objective)	1K	silicon	diced	445	16	1160 μW
aperture stop	1K	tapered absorber		440		
lens2 (field)	1K	silicon	diced	445	30	85 μW
low pass edge filter	0.1K	metal mesh		520	~ 8	

Table 3-18: Summary of small-aperture telescope optics elements for the baseline optics design. The window and filter configurations are identical for all bands. The baseline design assumes HDPE lenses for the lower three bands and silicon lenses for the highest frequency band; while HDPE or alumina lenses allow more throughput, current uncertainty in their loss and anti-reflection performance in this band drive this baseline choice.

RT-MLI and low-pass edge (LPE) Filters

- Zotefoam scattering filters
- Thermal and LPE filters fabricated at Cardiff
  - Up to 675 mm diameter thermal filters available
  - Up to 500 mm diameter LPE filters available

Keith Thompson



Carole Tucker

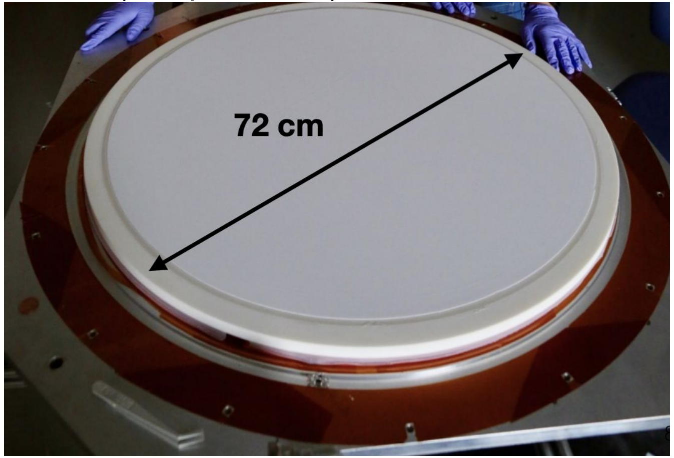
150GHz band 6.8cm-1 LPE filter
at 500mm OD, March 2020

Anti-Reflection Coating of Alumina

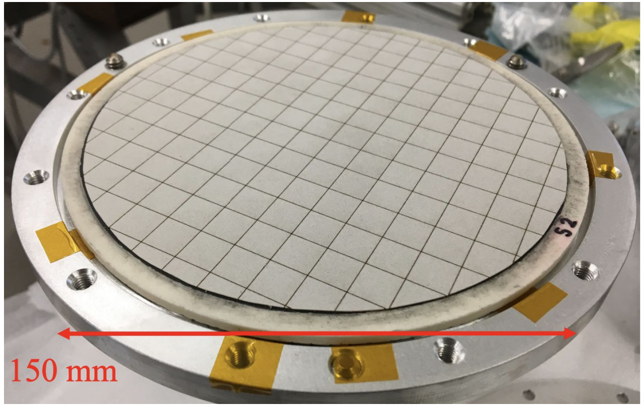
- Various technologies deployed or in development: Laminate (plastic and epoxy), epoxy, thermal spray, laser, metamaterial

Laminate Epoxy coating
(Thompson/Dierickx)

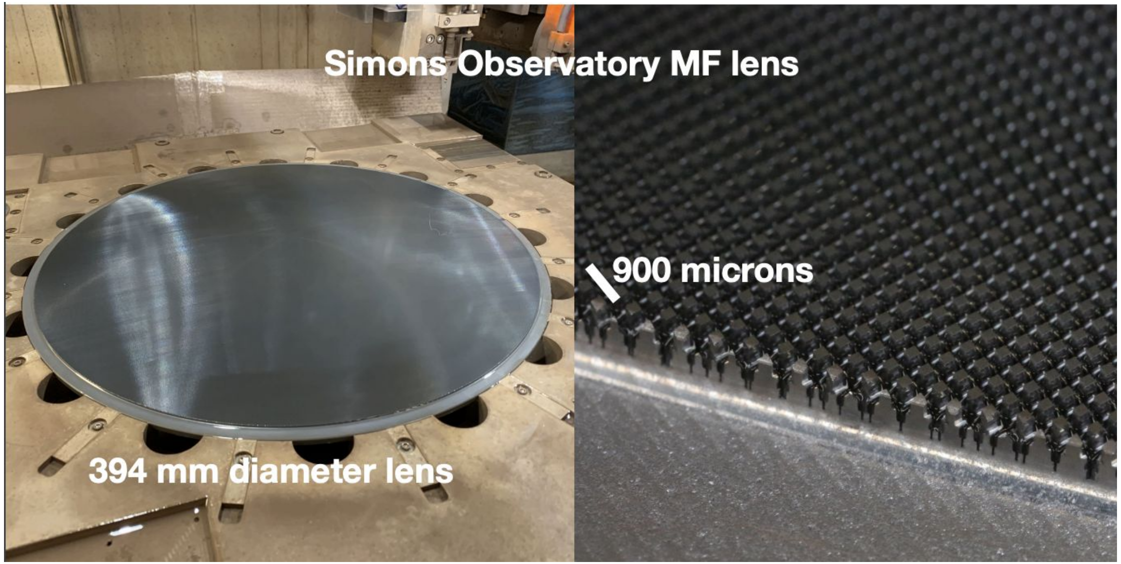
Laminate Plastic coating
(Joaquin Vieira)

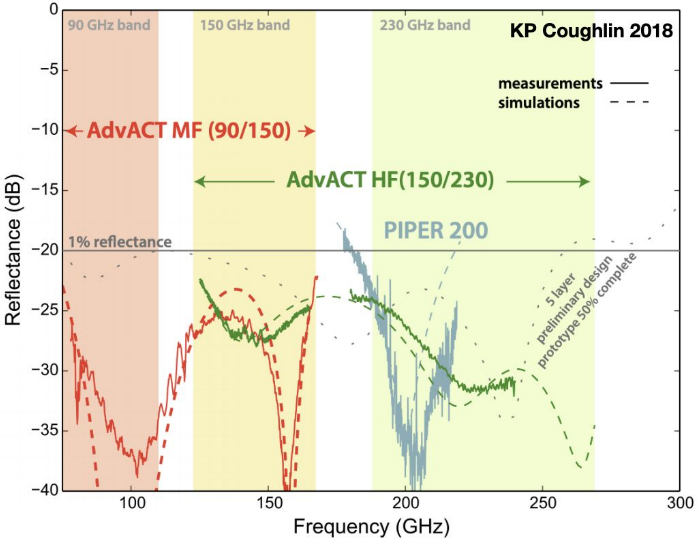


Epoxy coating
(Charlie Hill)



Anti-Reflection Coating of Silicon





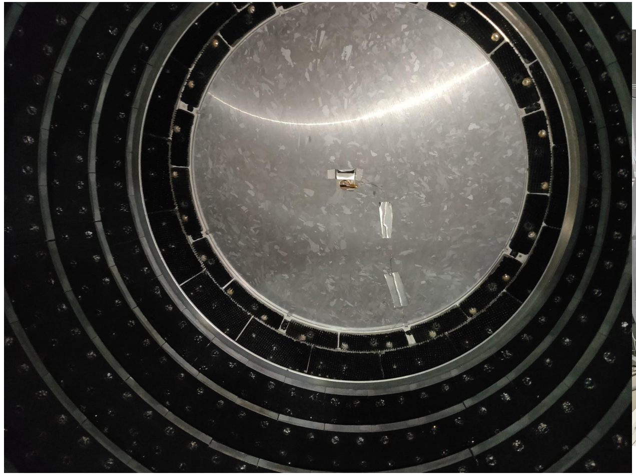
Joey Golec

- Metamaterial AR coating of silicon lenses at U. Michigan
  - Technology deployed for Adv ACTPol
  - Up to 46 cm diameter lens fabrication in process for Simons Observatory SAT

Cryogenic Baffles - Sidelobe Control

BICEP Array

Simons Observatory



Images from Kenji Kiuchi

- HR-10-coated baffle rings in 4K optics tube suppress sidelobes measured in previous BICEP receivers

- Deep cryogenic baffles with pyramidal-shaped absorbers made from carbon-loaded plastic material in 1K optics tube for sidelobe suppression

Cryostats

Akito Kusaka, Joe Saba

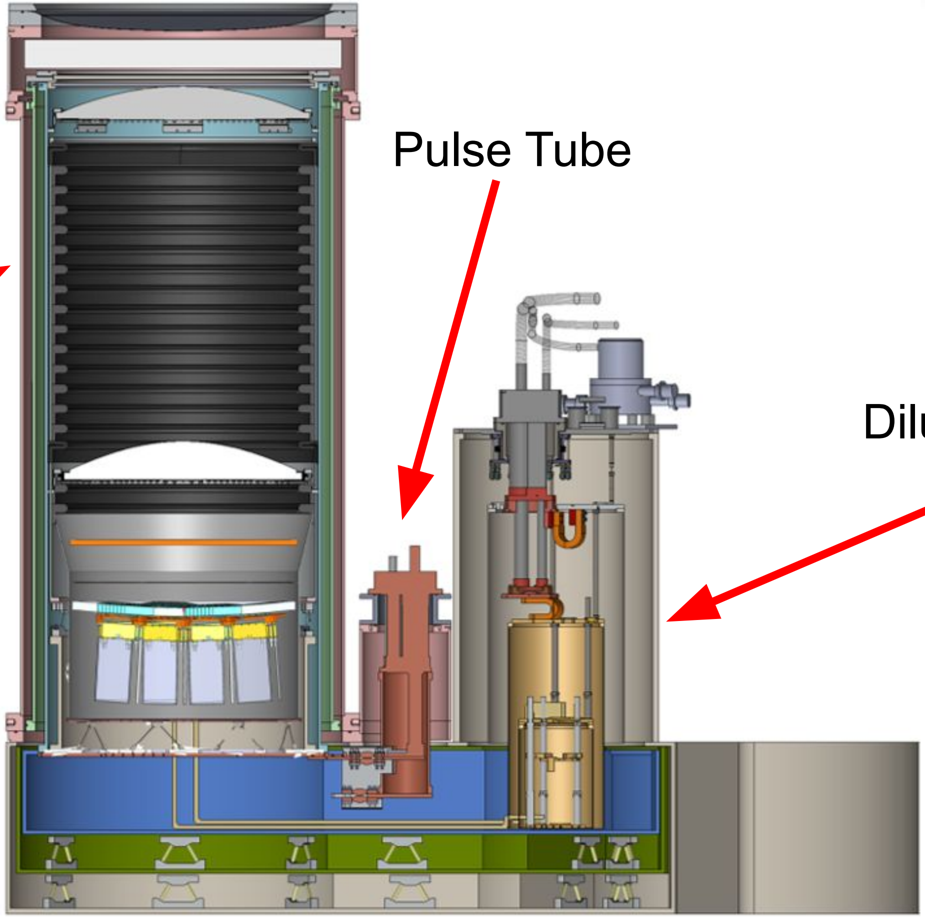
Receiver Cross-Section

Pulse Tube

Receiver Tube (optics tube and focal plane)

Dilution Refrigerator

Bus Cryostat



SAT Cryostats Draw on Successful Heritage

Example:

Cryogenic Bus Assembly is based on BICEP Array Heritage

Cryostat design progress

In the process of advancing the design maturity.
Several key interfaces w/ other WBS and other subcomponents are identified.

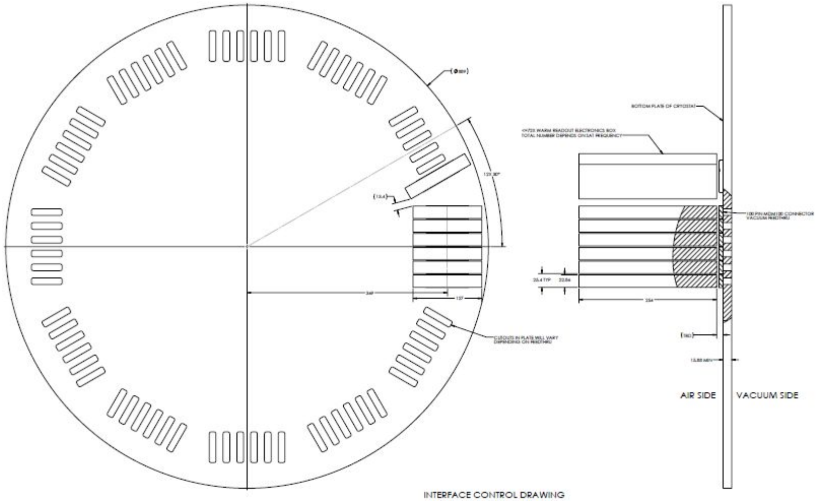
- Readout : Hermetic flanges and wirings are unlikely to be the constraining factor. -Room for 72 warm readout modules underneath each optics tube
- Optics Tube spacing :
  - Warm baffling wants the tubes be spaced apart.
  - The existing mount design constrains the maximum cryostat OD and optics tube OD.
- Optics Tube OD : interfacing to the lens diameter, radiation shield, cryo baffling.
- Detector modules : the focal plane packing density (gap between modules) is key interface to the optics, the optics tube diameter, and the detector module WBS.

Cryostat design progress

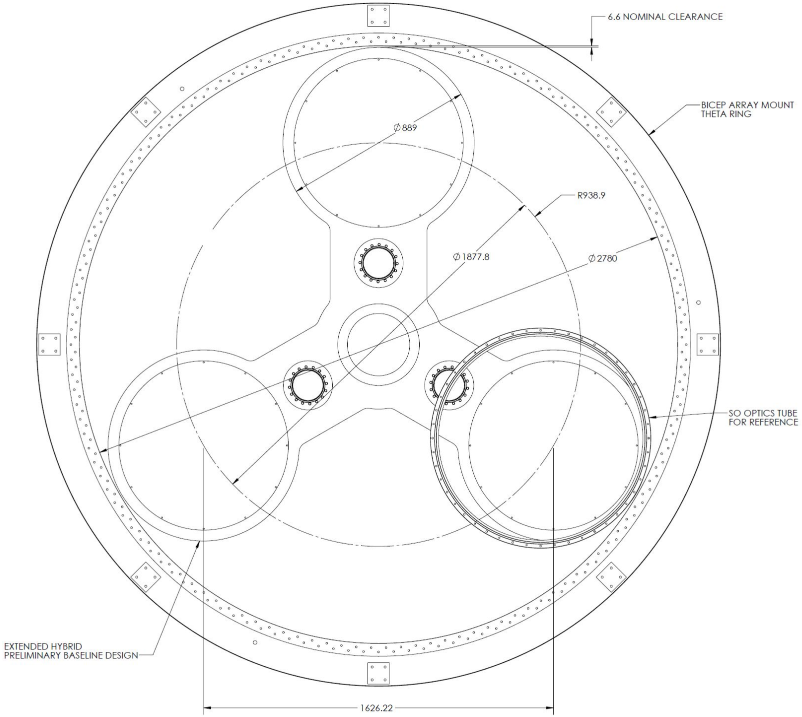
SAT WBS Internal Interfaces N^2

Detector Module Assembly	Readout - Cryo Electronics (by detectors, 100mK)	Readout - Cold Electronics (4K, 50K)	SAT - Cryostat (incl. Cryogenics, Optics)	Readout - Warm Electronics (~300K)	SAT - Telescope Mount	SAT - Telescope Ground Shields	DAQ - Observation Control System	Site - South Pole Infrastructure	Integration & Commissioning	**CMB-S4 Smal Aperture Telescopes - N^2 Diagram - SAT Interfaces** Key: M - Mechanical, E - Electrical, T - Thermal, O - Optical
	M, E, T	M, E, T	M, T, O						M, E, T	Detector Module Assembly
		E	M, T							Readout - Cryo Electronics (by detectors, 100mK)
			M, T	E						Readout - Cold Electronics (4K, 50K)
				M, E, T	M	O	E	M, E, T	M, E, T	SAT - Cryostat (incl. Cryogenics, Optics)
					M		E			Readout - Warm Electronics (~300K)
							M, E	M, E	M, E, T	SAT - Telescope Mount
								M	M	SAT - Telescope Ground Shields
								M, E, T	M, E, T	DAQ - Observation Control System
									M, E, T	Site - South Pole Infrastructure
										Integration & Commissioning

Cryostat design progress

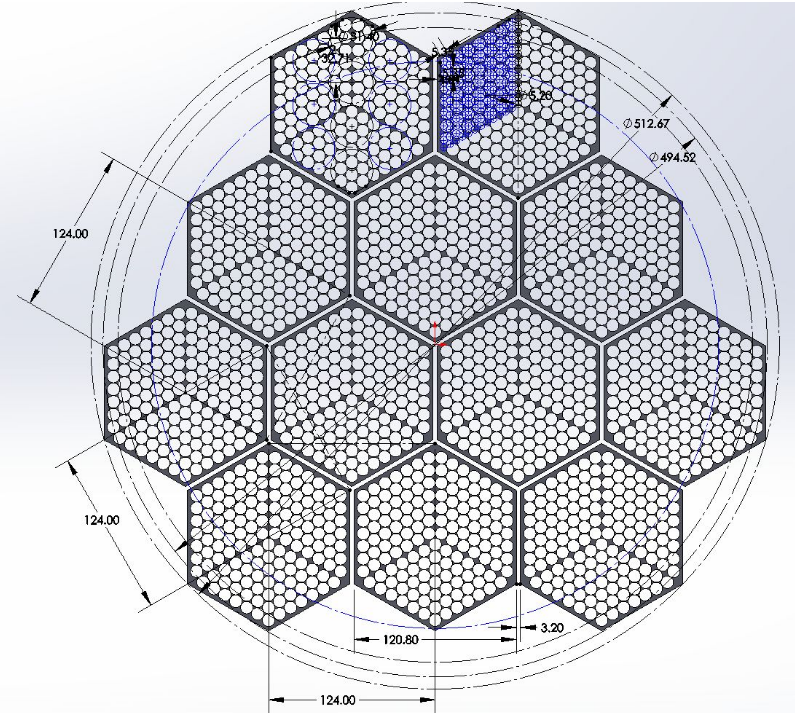


Interface: Readout vs. optics tube diameter

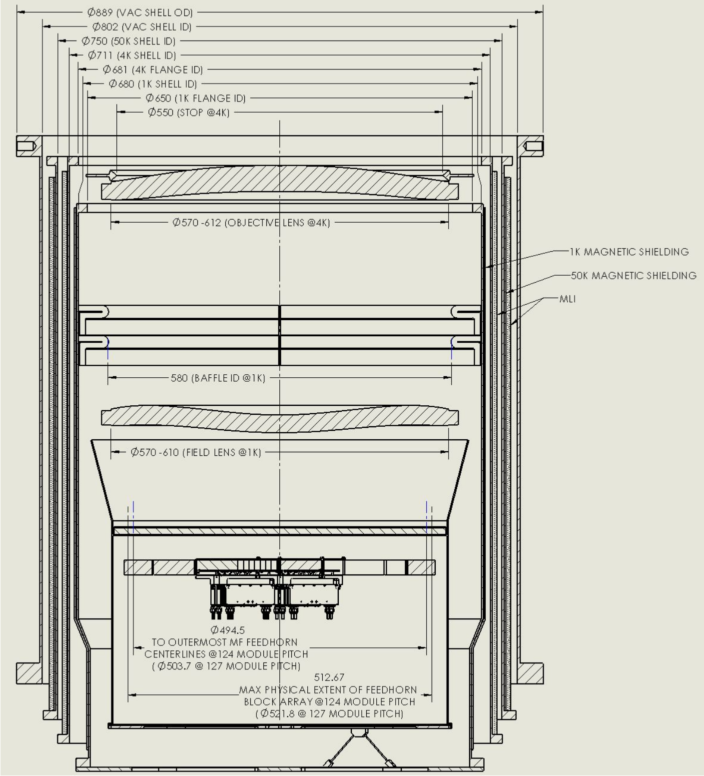


Interface: OT diameter/spacing vs. mount vs. warm baffle

Cryostat design progress



[Focal plane diameter vs. module spacing]



Optics tube / radiation shield vs. lens OD vs. focal plane

Mount

Clem Pryke

Baseline Design/Requirements - Mounts

- **Baseline Design:**
  - Draws on BICEP Array mount heritage
  - BICEP Array mount successfully deployed between Nov 2019 - Jan 2020, and now successfully operating at the Amundsen-Scott South Pole Station
- **S4-SAT Mount Requirements:**
  - Needs to accommodate a single three-tube SAT receiver, rather than four individual BA-type receivers (design updates to allow rear-loading underway)
  - SAT receiver must include mounting points for strut interfaces to the mount structure (similar to BICEP Array)
  - Mount must also accommodate the DR gas handling system and provide sufficient mounting volumes for warm readout interfaces.

Heritage: BICEP Array Mount Integration and Deployment

BICEP Array Mount @ UMN
(Aug 2020)

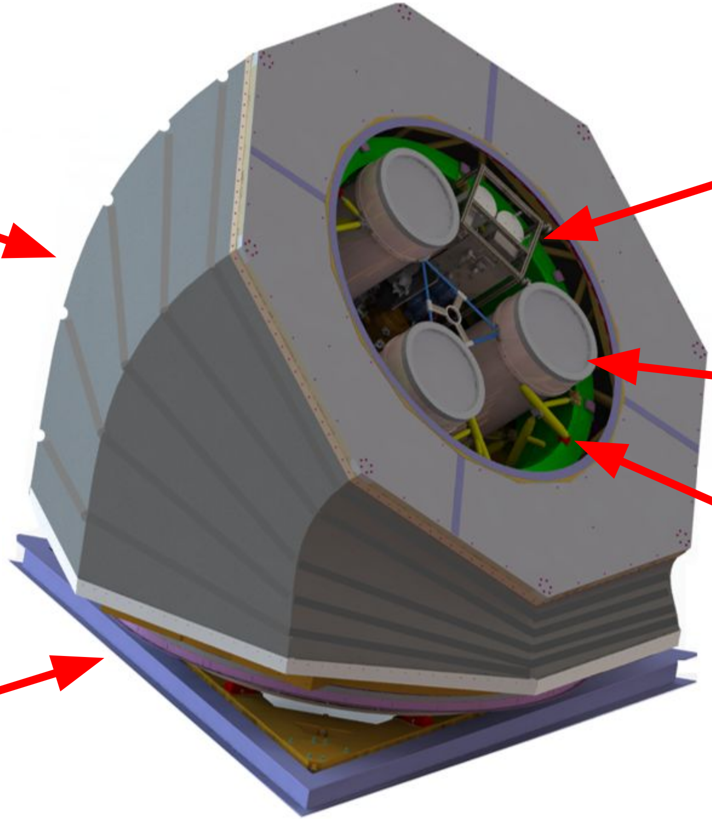
BICEP Array Mount @ Pole
(Jan 2020)

SAT Mount Parameters

Parameter	Value	Notes
Mass of instrument	up to 4500 kg	includes cryostat, DR system, electronics, forebaffle
Motion	3 axis	full boresight rotation of instrument and forebaffle
Scan pointing knowledge	< 15 arcsec rms	$< 1/20$th beamwidth at $\lambda = 1$ mm
Scan speed AZ/EL/TH	$5/1/1$ deg s^{-1}	≈ 3 deg s^{-1} on the sky for fast diff. measurements
Scan accel. AZ/EL/TH	$3/1/1$ deg s^{-2}	turnaround efficiency
Range AZ/EL/TH	$\infty/45\ldots110/\infty$	continuous AZ desirable
Shipping envelope	standard double pallet	deployment via C-130 / standard vehicles
Mount mass	< 25 tons	includes instrument, comoving forebaffle and scoop
Survival: wind	$70\,\mathrm{m\,s^{-1}}$	Chile dominates
Survival: seismic	$0.3\,\mathrm{g}$	Chile dominates
Survival: temperature	-90 C	Pole dominates

SAT Mount Overview

Flexible Environmental Enclosure



DR Gas Handling System

SAT Receiver

Receiver - Mount Interface Struts

Interface to SAT Tower (Sites)

Ground Shields and Exterior Baffles

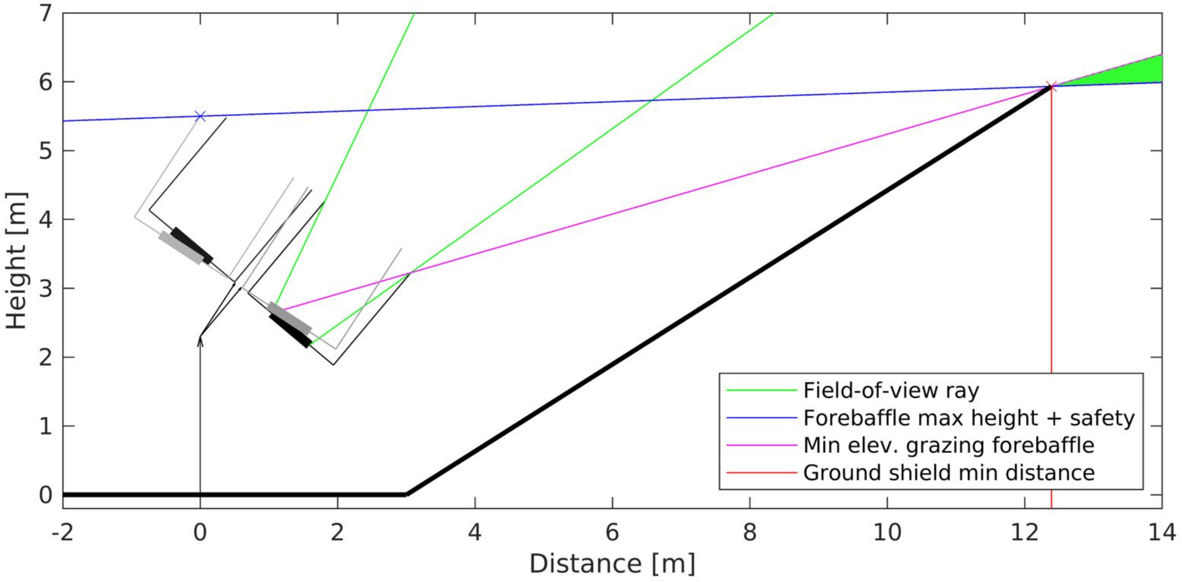
Ben Schmitt

Ground Shield

Under double-diffraction criterion, at 50 degrees minimum elevation, we find that the SAT receiver can be shielded with:

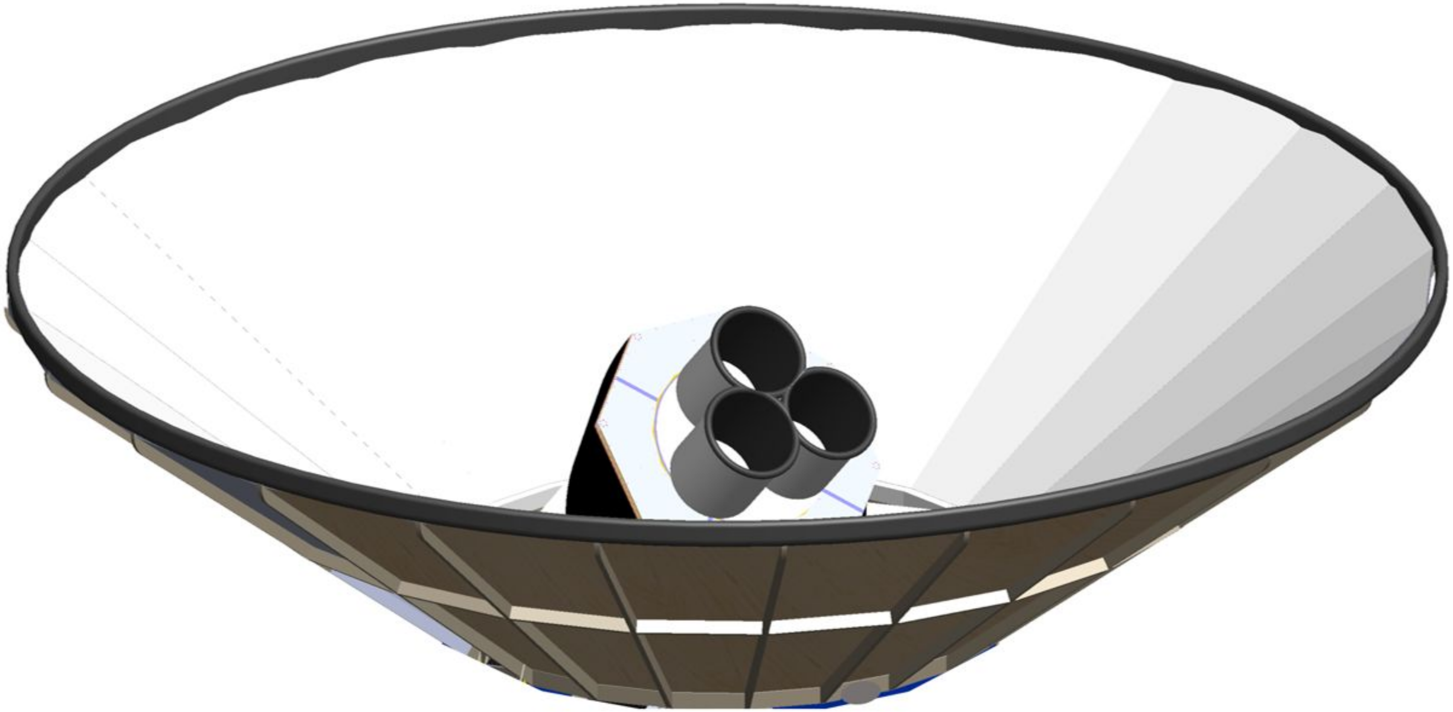
- **<u>Forebaffle</u>**: 1.75 m tall, 0.8 m radius
- **<u>Ground Shield</u>**: 5.9 m tall, 12.4 m radius

Smallest achievable ground shield size for a 2-shield scenario (given the max forebaffle size allowed)



Ground Shield

Cylindrical Warm Forebaffles: key element of systematics control.



Calibration

Kirit Karkare

(more discussion later)

Calibration Apparatus

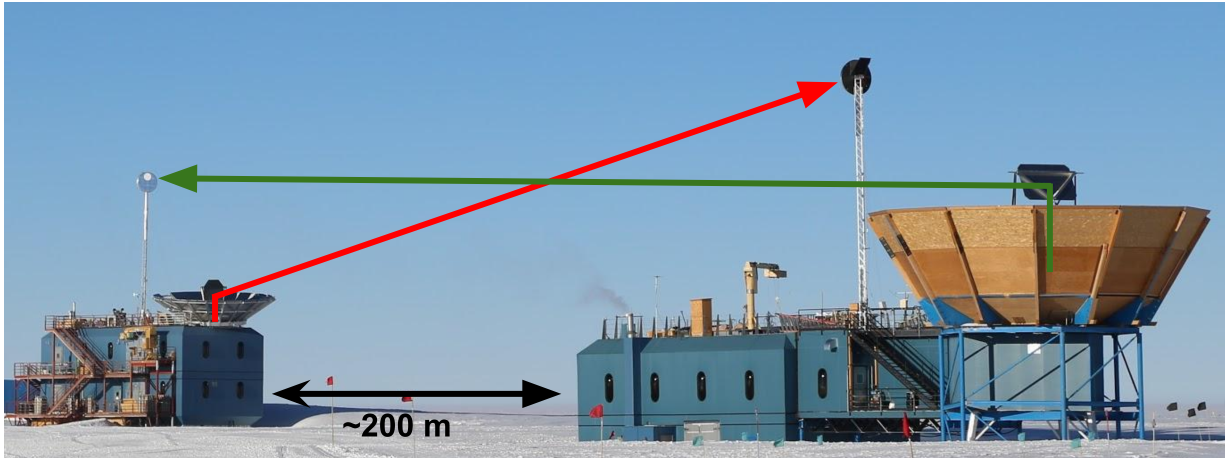
Based on experience from previous generations of SATs, design specialized hardware to

- Validate SAT performance during commissioning
  - Do responsivity, beam shapes, etc. look reasonable?
- Measure instrument parameters to well-defined precision, in lab and *in situ*
  - Bandpasses, beam shapes, polarization angles…
- Probe potential instrumental systematics relevant to the *r* measurement
  - T->P, E->B, sidelobe pickup…

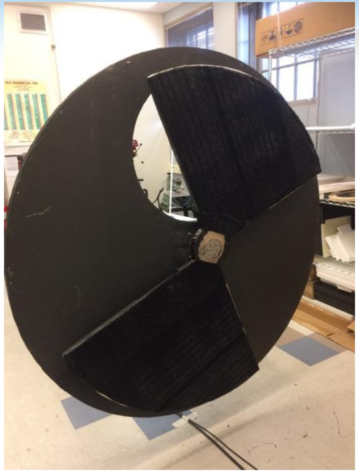
Calibration should be built into the SAT design and schedule!

- Mounting points (in lab and *in situ*), cranes...
- Should understand measurement SNR to plan calibration campaigns

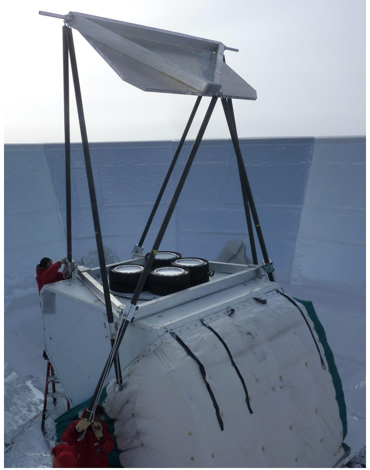
Calibration Apparatus



Far-field measurements using a redirecting flat mirror and source on mast

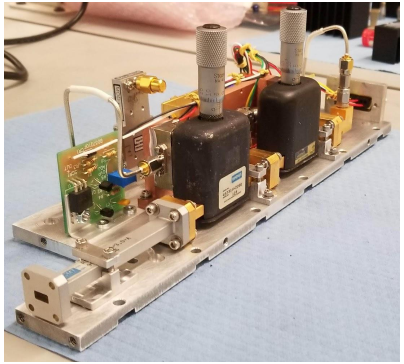


Thermal chopper
24” aperture



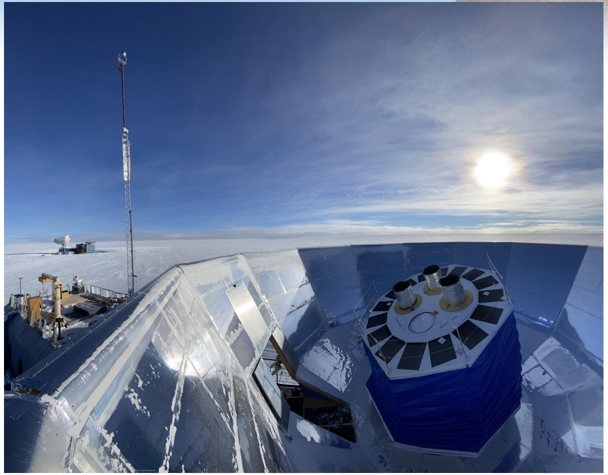
Far-field flat mirror

Calibration Apparatus

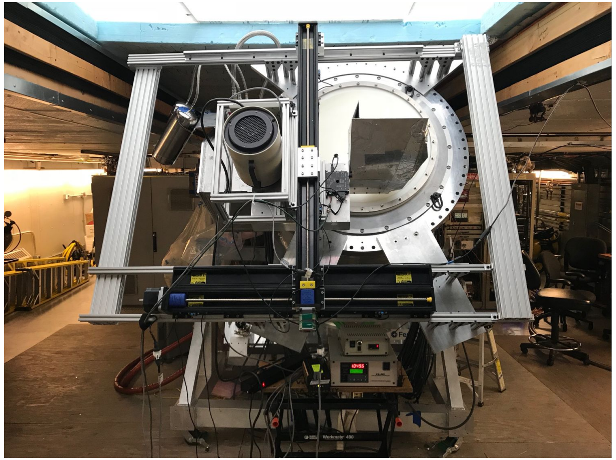


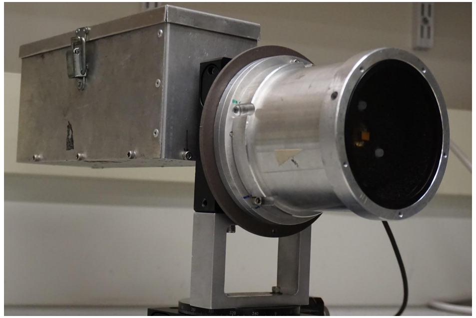
Amplified broad spectrum
noise source

Far sidelobe
measurements



FTS measurements
(multi-axis optical
coupling)





Rotating polarized source
(referenced to gravity)

Path to CD-1 (this year's priorities)

Ongoing and upcoming key activities to advance design.

- Cryostat design
  - Hybrid design in progress, burning down engineering risks (this type of cryostat has not been deployed before)
  - By CD-1, conceptual design mature, ready for prototyping
- Cryostat prototyping
  - This R&D will burn down risks in cryogenics and assembly process.
- Cold Optics
  - Addresses technical risks in material losses, scattering, absorption, and AR technologies, as well as the production throughput of the AR coating (Alumina, HDPE and Silicon)
  - By CD-1, process risks retired & conceptual design mature, ready for prototyping
- Optics Prototyping
  - Beam and sidelobe are the top performance risks in the project. This prototyping R&D will burn these risks.

Conclusions

- Thanks to lots of collaboration input, SAT design maturity has advanced
  - We have a good understanding of key/driving interfaces, especially dimensional ones
    - Allows parallel design development of cryostat, optics, shields, mount, calibrators

- PBDR text will continue to be refined
  - We solicit suggestions from the collaboration
  - (We need to add appropriate references to heritage work! Please help us.)

- SAT WG meetings every other Monday
  - Great chance to contribute to technical design choices

Rest of SAT parallel will be dedicated to:

- SAT Zemax Lens Design Updates - *Fred Matsuda / Tony Stark*
- SAT Calibration Plan Updates - *Kirit Karkare*