SAT Cryostat Configuration Downselect
CMBS4-doc-737

SAT L2/L3 Project Team

Cryostat Configuration Task Force

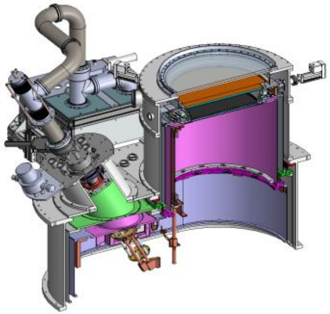
- In 2020 a Cryostat Configuration Task Force was formed to assess configurations of the Small Aperture Telescope Cryostats
- Team included:
  - Ben Schmitt, Joe Saba, John Kovac, Akito Kusaka, Fred Matsuda, Kirit Karkare, Robert Besuner, Tim Norton
- Alternatives studied included:
  - 1 - Single Tube Cryostats (“1 in 1”)
  - 2 - Three Tube Compact Cryostat (“3 in 1 - Compact”)
  - 3 - Three Tube Extended Cryostat (“3 in 1 - Extended”)
- Factors considered included:
  - Three alternative cryostat configurations
  - PT and DR cryocooler capacities and costs
  - Design, integration, and operation
  - Cryogenic and mechanical performance
  - Comparative optical shielding study

Cryostat Config Task Force Recommendation

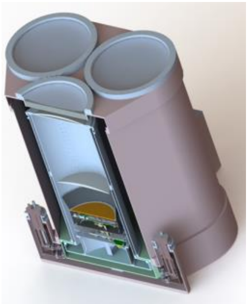
SOURCE: SAT Breakout - Annual Review (Aug 2020)

Recommendation for CMB-S4: Extended Hybrid Configuration

- Combines key advantages of both “1 in 1” and “3 in 1”
  - optical shielding advantage of “1 in 1”
  - lower power consumption & fewer DRs of “3 in 1”
- Assumption associated with the of the use of DR
  - Premise based on end-to-end cost savings of 25% fewer SATs
- Complexity in vacuum and cryogenics interconnect.
  - No heritage in the CMB field, but this is an engineering problem.
- 1K stage cooling capacity may not have generous margin.



SO SAT (1 in 1)



DSR Reference Design (3 in 1)

CMB-S4 Recommended Design
(Extended Hybrid)

SOURCE: SAT Breakout - Annual Review (Aug 2020)

Value Engineering - SAT cryostat config

Task Force (Dec 2019 - May 2020) studied three alternative cryostat configurations, evaluated PT and DR cryocooler capacities and costs, design, integration, and operation, cryo and mechanical performance, and comparative optical shielding study

X ALTERNATIVES										
Option	PC	PS	C	D	F	P	R	S	Comments	Rank
3 in 1 (extended)	**0**	**(+)**	**0**	**(-)**	**0**	**+**	**0**	**0**	**Single extended cryostat combines advantage of 1-in-1 in proven approach to shielding performance with advantage of 3-in-1 for lower costs, integration and power consumption. Engineering tradeoffs vs compact are relatively minor.**	**3**
1 in 1 (extended)	-	-	0	0	+	+	-	0	Individual cryostats allows extended geometry with advantages in proven approach to achieving shielding performance and flexibility, but at greater cost in number of cryostats and cryocoolers, integration and power consumption	1
3 in 1 (compact)	0	0	0	0	0	0	0	0	Single compact cryostat allows reduced number of cryostats and cryocoolers, integration and power consumption, but at increased risk to achieve shielding requirements	2

Performance Criteria:

PC: Project cost
PS: Project schedule
C: Complexity
P: Performance
D: Development risk
R: Reliability
F: Flexibility
S: Safety

Ranking Scale:

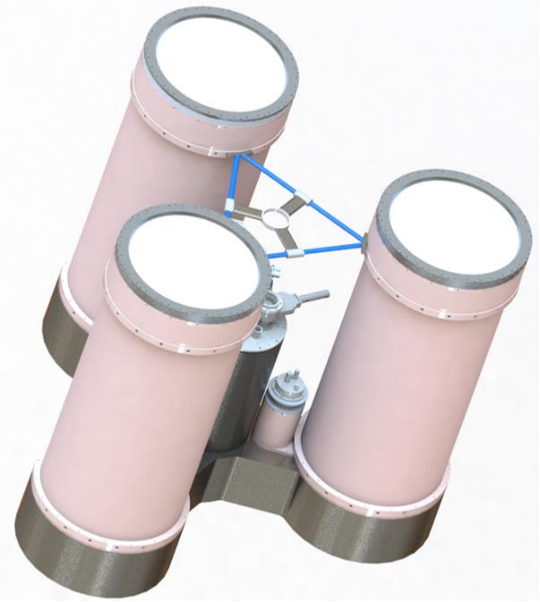
5 = Cost and performance improvement
4 = Cost or performance improvement
3 = Design suggestion
2 = Cost and scope or performance reduction

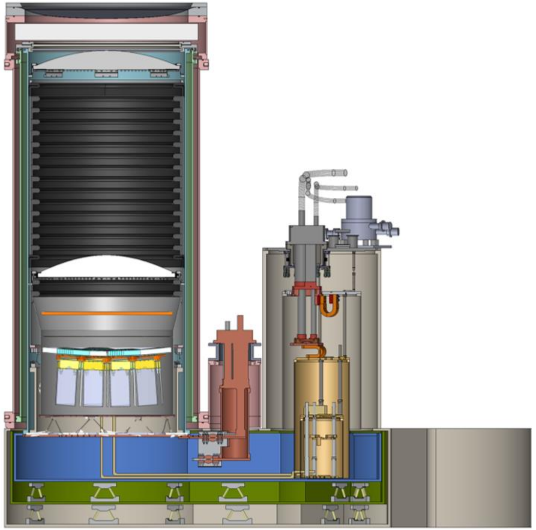
Evaluation Criteria

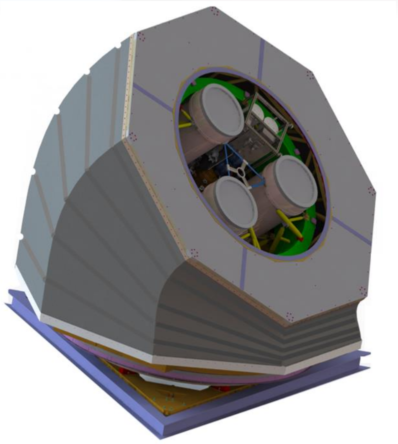
+ : Significant improvement
0 : Neutral
- : Significant reduction

SAT Overview

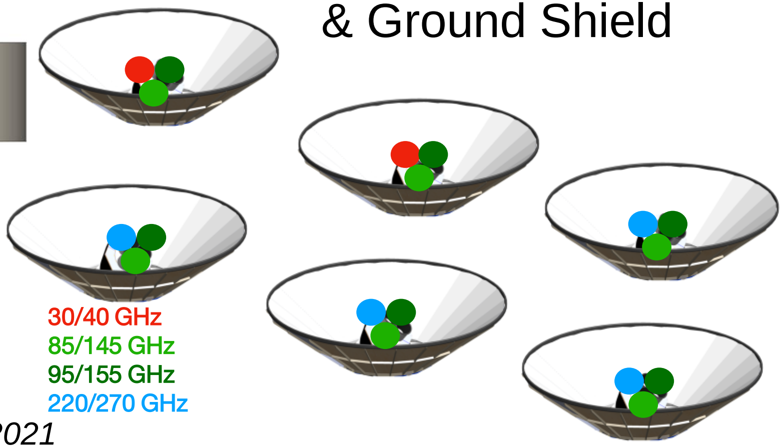
Cryostat System, Optics Tubes, Integration & Test







Telescope Mount & Ground Shield



SOURCE: SAT Plenary - Annual Review (Aug 2020)

SAT Requirements

Science Requirements

Required uncertainty on r

Measurement Requirements

- 8 frequency bands for foreground removal
- Sufficiently low statistical uncertainties
- Systematic uncertainties < statistical uncertainties
- Low-frequency noise suppressed

Instrument Requirements

- SAT detector counts / freq band
- Optics – aperture size/field of view
- Optical loss (bulk / reflective)
- Cryogenic performance
- E&M shielding
- Sidelobe levels
- Groundshields
- Mount pointing, 360 boresight rotation
- Mount scan speed, HWP

SOURCE: Collaboration Meeting Plenary (Mar 2021)

1.07 SAT Requirements

1.07 SAT CMB-S4 Requirements

A. SAT

	Initial Trace	Description of Requirement		
ID	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=1036198956
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

SOURCE: Collaboration Meeting Plenary (Mar 2021)

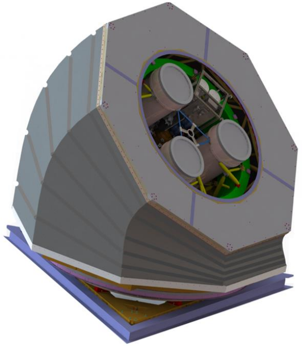
SAT Cryostats Draw on Successful Heritage

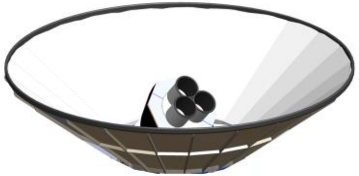
Example:

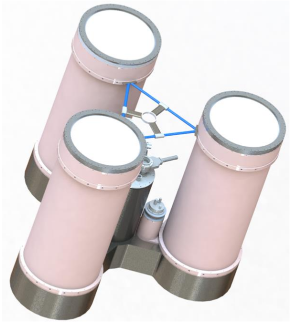
Cryogenic backend is the same approach used for BICEP Array

Preliminary Baseline Design Summary

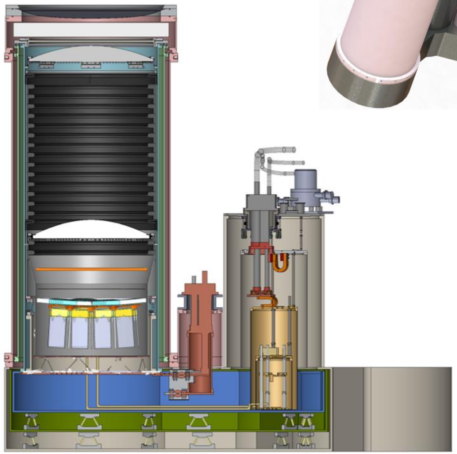
- Preliminary Baseline Design for SATs
  - 6 mounts + groundshields at Pole
  - 6 cryostats, each with 3 optics tubes (18 total)
    - Optics design heritage from BA and SO
  - Option of HWPs, allowing additional use in Chile
- North American Integration and Test



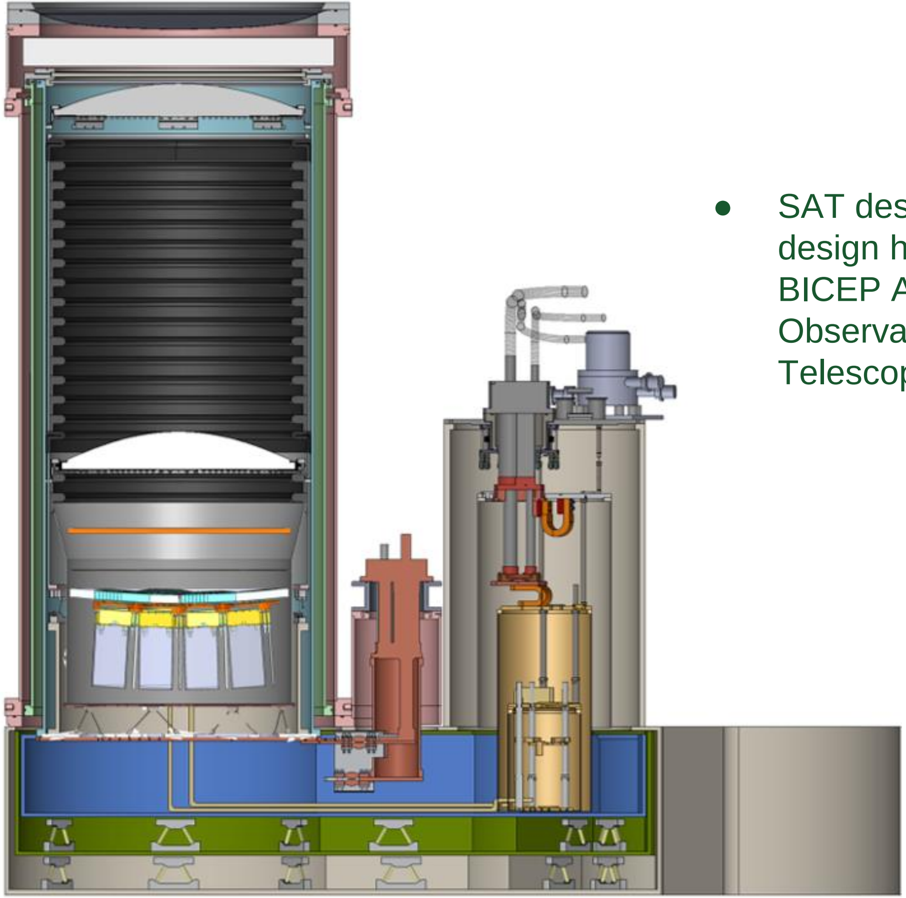




Bands	Lenses	Horns / Module	Modules / Tube	Tubes
30 / 40	2x 63cm HDPE	12	12	2
85 / 145	2x 63cm HDPE	147	12	6
95 / 155	2x 63cm HDPE	147	12	6
220 / 270	2x 46cm Silicon	469	12 (> 9 active)	4
		totals:	154,560 detectors / 18 tubes	

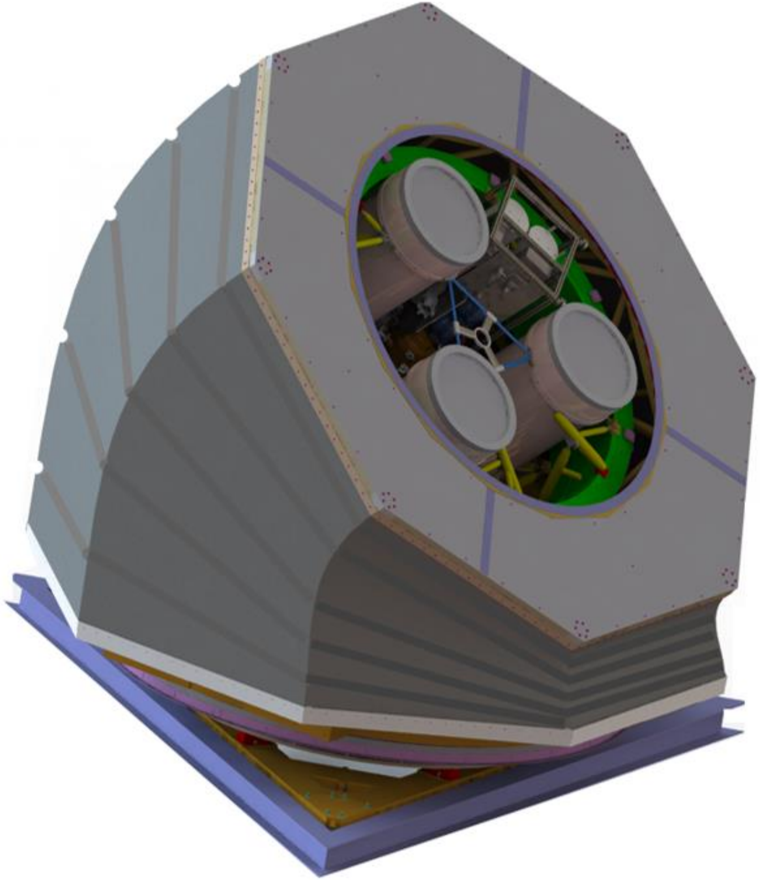


Receiver Design Overview



- 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 where instrumental and environmental couplings are complex enough to require field validation for any fundamental change of approach. For design choices that impact these issues we have endeavored to stay close to and to build upon proven experience, guided by comparative testing.

SOURCE: SAT Plenary - Annual Review (Aug 2020)

Receiver Design Overview

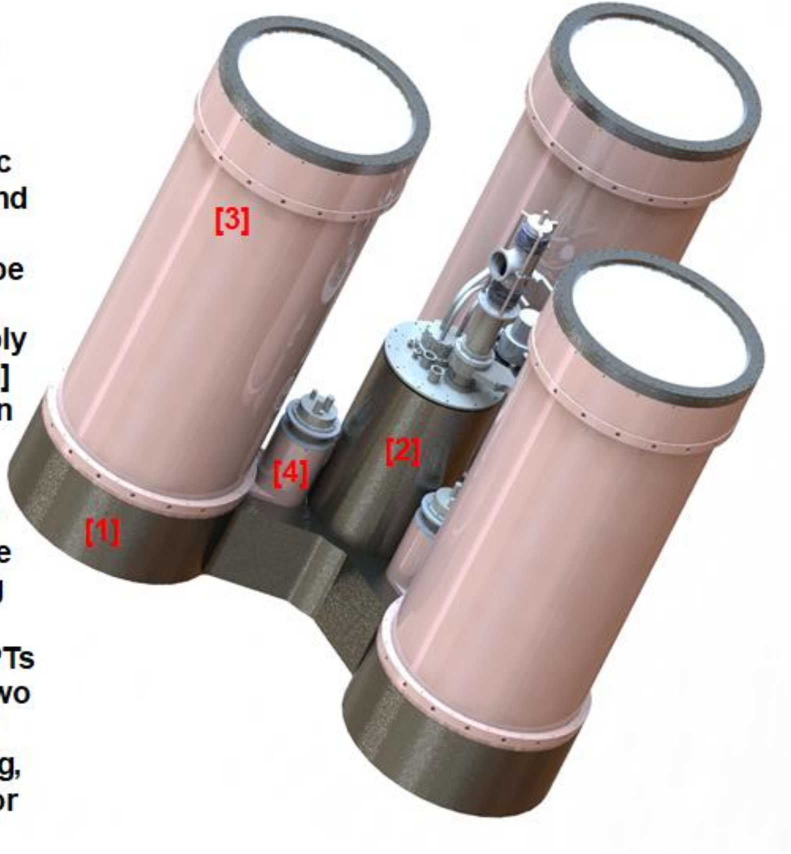
Extended Hybrid Consists of:

[1] Single Cryogenic Bus Cryostat Backend

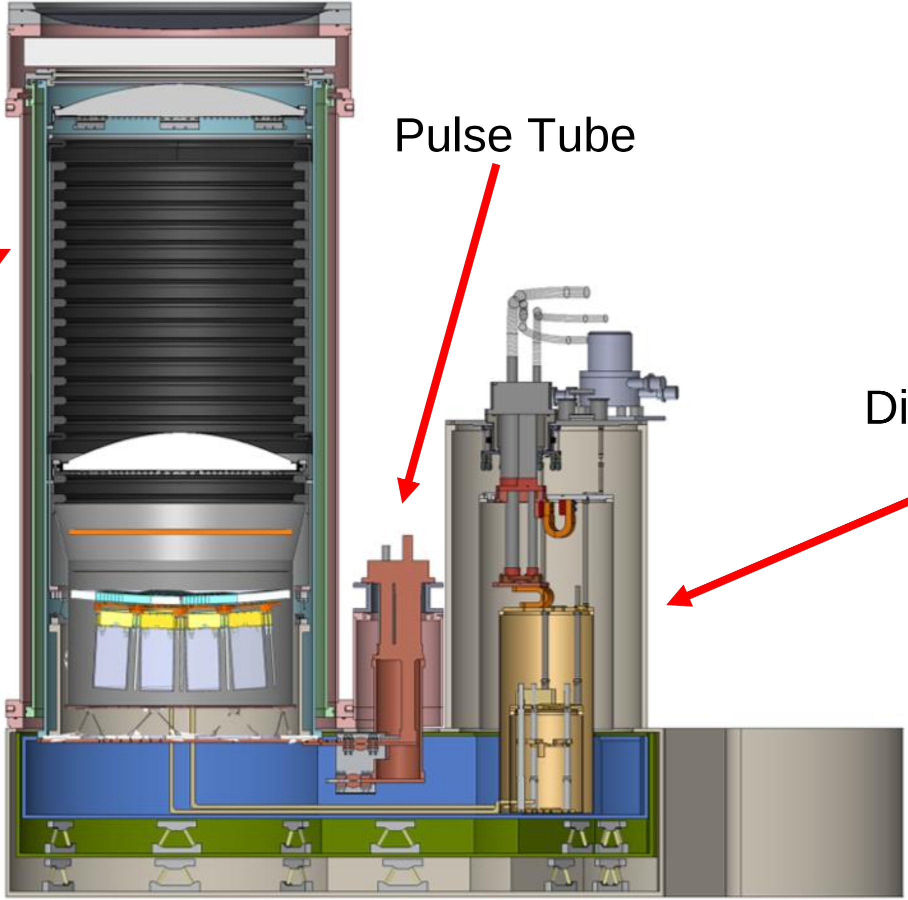
[2] Central Pulse Tube Backed Dilution Refrigerator Assembly [1K, 100mK cooling] (Bluefors DR used in SO SAT shown)

[3] Three Receiver Tubes with Separate Magnetic Shielding

[4] Three Additional PTs [50K, 4K cooling → two likely needed for receiver tube cooling, one perhaps used for rapid cooldown]



Receiver Cross-Section



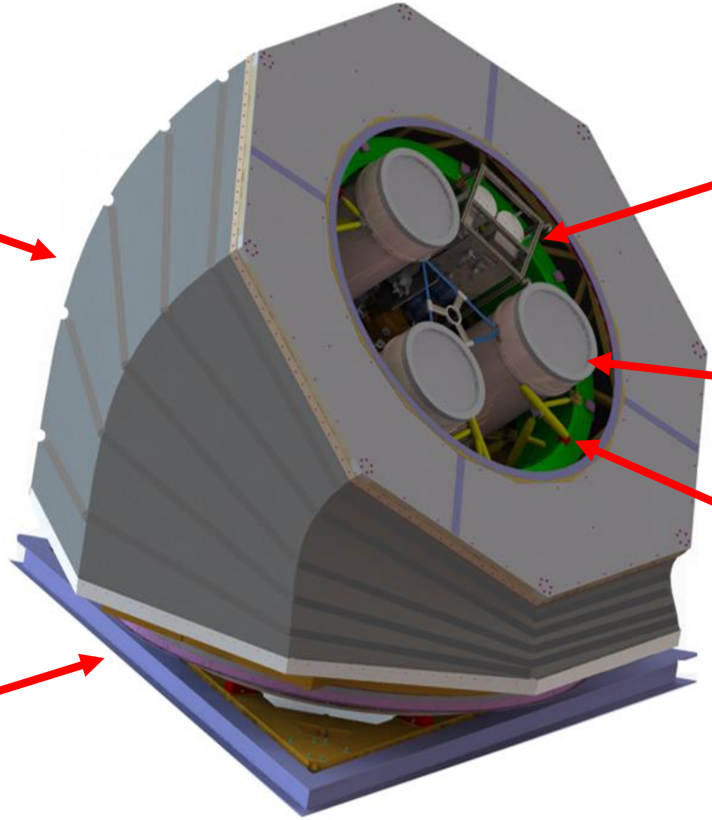
Pulse Tube

Receiver Tube (optics tube and focal plane)

Dilution Refrigerator

Bus Cryostat

SAT Mount Overview

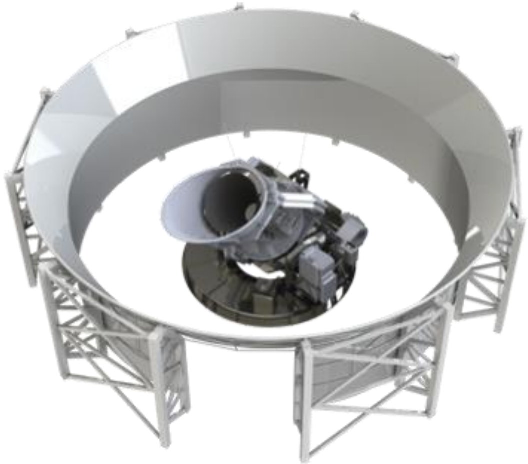


Warm Baffling

- Controlling far-sidelobe response to ~300 K ground is critical - to constrain *r* we are attempting to measure nK-level fluctuations!
  - SATs have typically used multiple levels of shielding to prevent far sidelobes from coupling to the ground/Galaxy
- “Double diffraction” criterion: ground radiation must diffract twice before entering any optics tube window
- For 3-Tube and Extended Hybrid SAT configurations, studied the sizes of various shields needed to enforce the “double-diffraction” criterion
  - Forebaffle: co-moving with Az / El / Boresight, can be absorptive or reflective
  - Ground shield: fixed, reflective
  - Tertiary shield: co-moving with Az (possible El), can be absorptive or reflective
- Sites differ in terrain complexity
  - South Pole: terrain near horizon
  - Chile: terrain below El < 5 deg, Cerro Toco mountain peak ~15 deg
    - “Relaxed” double-diffraction used for Chile

SOURCE: SAT Optics Parallel - Annual Review (Aug 2020)

BICEP and Simons Observatory Examples



BICEP Array

4 optics tubes in one mount

Separate forebaffles: 1 m

Ground shield: R = 7.6 m (DASI legacy)

Simons Observatory SAT

Single optics tube per mount

Forebaffle: 1.7 m

Tertiary Shield: ~ 2.2 m

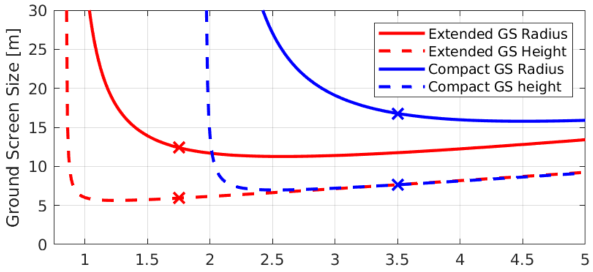
Ground Shield: R ~ 8.2 m

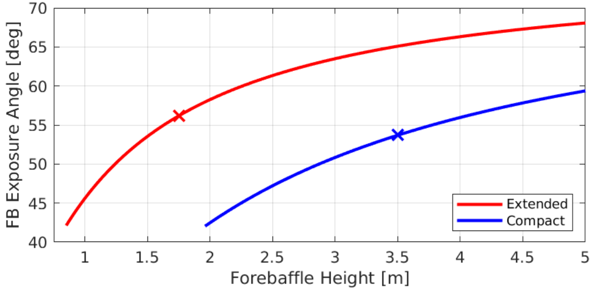
SOURCE: SAT Optics Parallel - Annual Review (Aug 2020)

Two Shield Comparisons

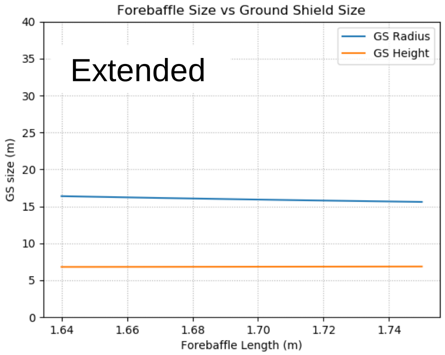
For various forebaffle heights, calculate minimum ground shield radius and height needed to satisfy double-diffraction criterion for extended and compact configurations

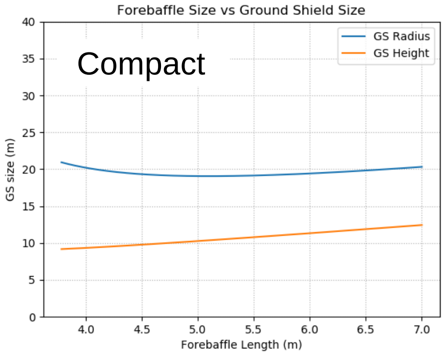
South Pole





Chile



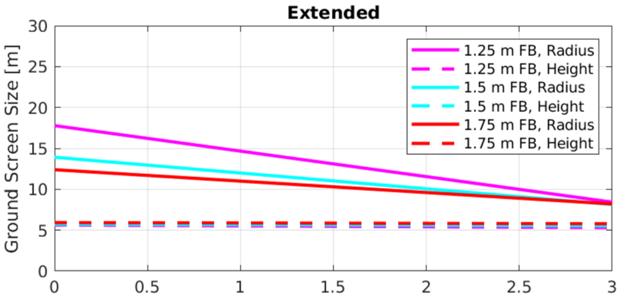


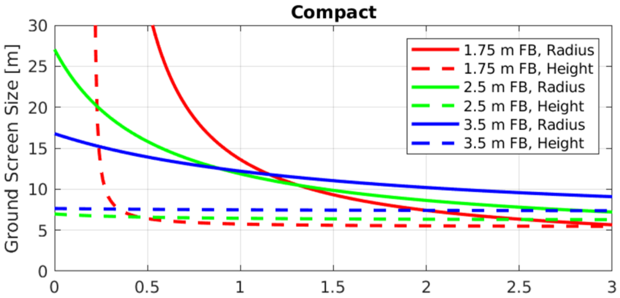
SOURCE: [SAT Optics Parallel - Annual Review (Aug 2020)]

Three Shield Comparisons

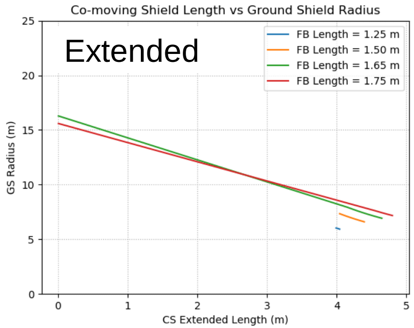
For several fixed forebaffle heights, add a tertiary shield, and calculate minimum ground shield radius and height as before. *Generally results in smaller ground shields.*

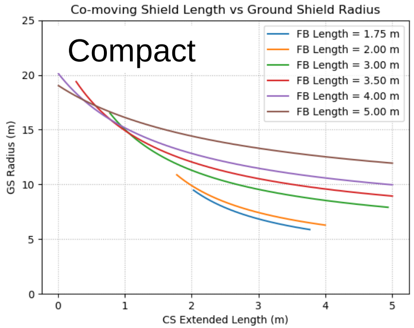
South Pole





Chile





Warm Baffling Conclusions

- With two shields, Extended configuration allows for smaller forebaffle and ground shield
- With three shields, Compact configuration allows for slightly smaller ground shield
  - Potential optical complexities of tertiary shield are not yet well-understood

- Relaxed double-diffraction criterion for Chile is similar to South Pole
  - Chile only requires 2~3 m larger ground shield sizes
  - SO SAT adopts relaxed double-diffraction criterion

- **Result of study:** extended configuration preferred. Major tech driver for cryostat configuration downselect.

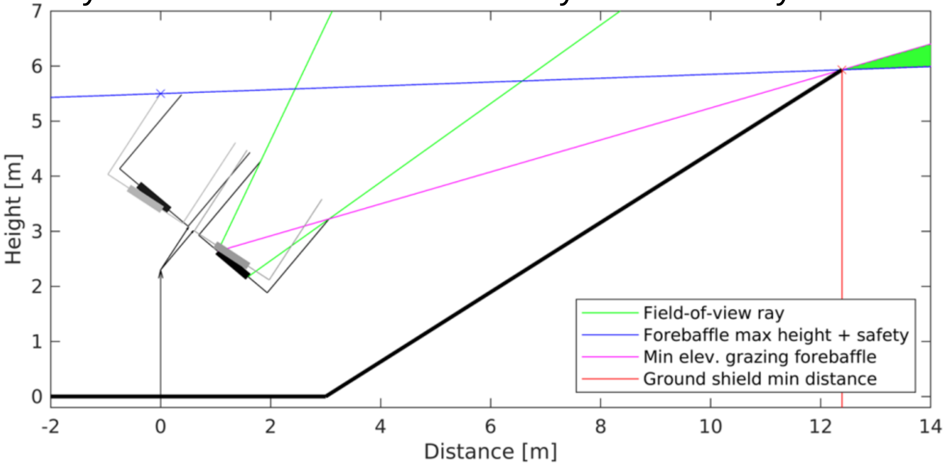
Ground Shield

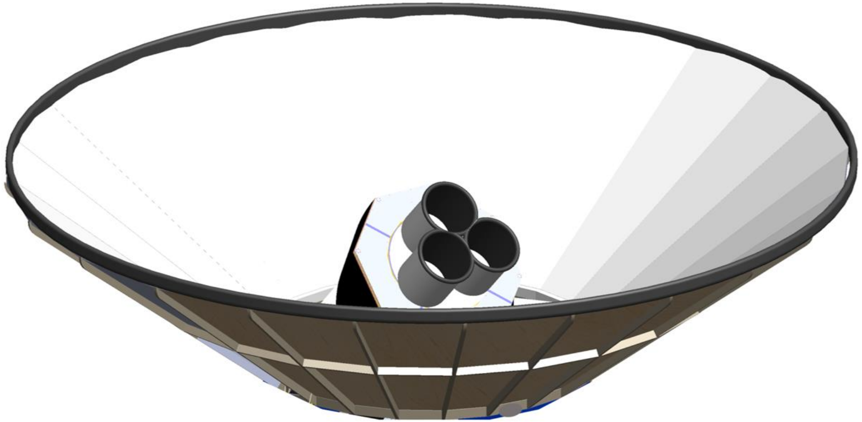
Under double-diffraction criterion, at 50 degrees minimum elevation, we find that the SAT receiver can be shielded with:

- **Forebaffle**: 1.75 m tall, 0.8 m radius
- **Ground Shield**: 5.9 m tall, 12.4 m radius

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

Cylindrical Warm Forebaffles: key element of systematics control





Backup/Reference Slides

- SAT Cryostat Configuration Selection Overview - April 2021
- SAT Plenary Slides - Collaboration Meeting - March 2021
- SAT Parallel Slides - Collaboration Meeting - March 2021
- SAT Plenary Slides - Annual Review - Aug 2020
- SAT Breakout Slides - Annual Review - Aug 2020
- SAT Cryostats Parallel - Annual Review - Aug 2020
- SAT Optics Parallel - Annual Review - Aug 2020