Chile Alternatives

What would it take to meet our r goal from Chile?

Overview

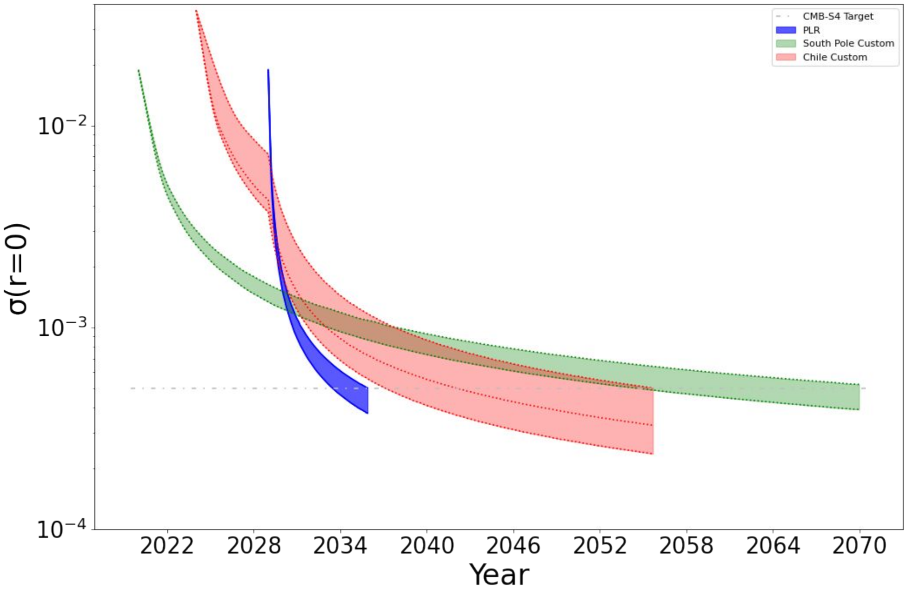
Julian Borrill

Background

- CMB-S4 has been generating suites of r forecasts for the South Pole and Chile sites - separately and in combination - since the 2017 CDT report.
- Our current forecasts are generated by the **Low-Ell BB AWG**, scaled from BICEP/Keck achieved performance, and were published as our first peer-reviewed collaboration paper “CMB-S4: Forecasting Constraints on Primordial Gravitational Waves” https://arxiv.org/abs/2008.12619 (ApJ 926, 1)
- Our conclusion was that the best return on effort (in detector-years) was to site all SATs at the South Pole, relentlessly focused on the Southern Hole.
- Limiting operations to 7 years requires
  - 150K detectors on 18 SPSATs (r + foreground cleaning)
  - 130K detectors on 1 SPLAT (delensing + synchrotron guard)

Assessment of Alternatives

- Scaling with SAT+LAT effort from current CMB-S4 forecasts lets us quickly compare configurations (baseline, extended Stage 3, alternative Stage 4)
- https://webapp.cmb-s4.org/Science-With-Effort
- Example:
  - CMB-S4 (Project Level Requirements)
  - SPO
  - SO + CMB-S4 (SATs in Chile)
- Line widths represent uncertainties
  - Foregrounds
  - Sensitivity

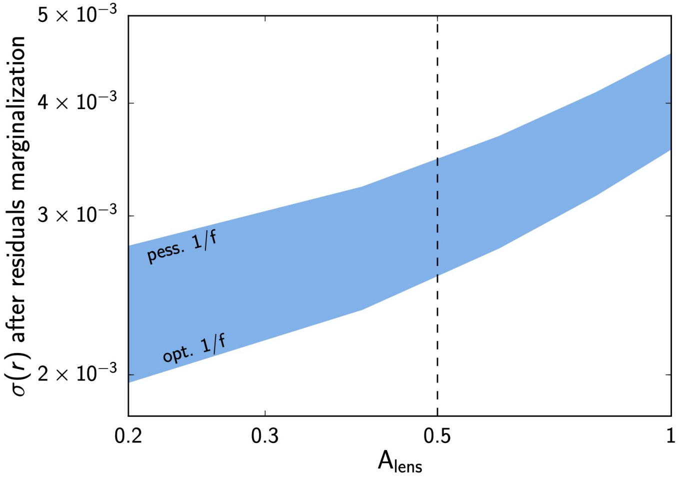


SO SATs & r-Forecasts

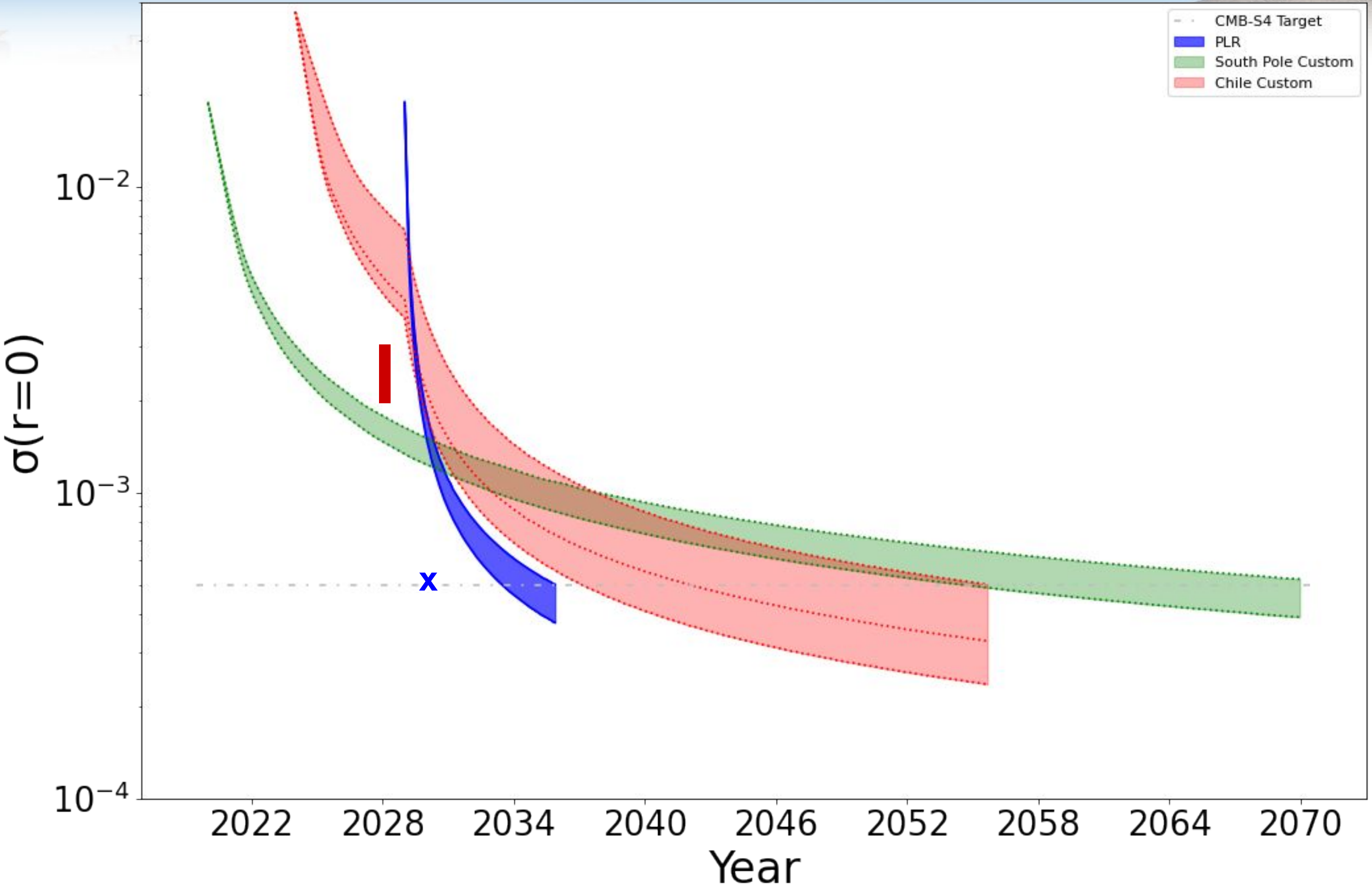
Photo from Saturday by Evelyn, SO safety officer

3 Simons Observatory SATs are being installed as we speak - real Chile SAT data will be invaluable.

Published SO r-forecasts are significantly more optimistic, for Chile ...



… and for the South Pole.



Current Situation

- SO forecasts are significantly more optimistic for both South Pole and Chile, requiring ~40% of the effort at each site.
- All forecasts necessarily include approximations and assumptions.
- To produce robust, agreed, forecasts, to the agency deadlines, we must quickly resolve the discrepancy and hone our approximations/assumptions.
- Given the scope and deadlines we have set up a tiger team to:
    1. Resolve forecasting code discrepancies
    2. Characterize Chile site-specific inputs
    3. Generate additional forecasts for r from Chile (and Pole as necessary)
    4. Document for robust internal and external review
- The project will then use this to assess possible alternative configurations.

Tiger Team

- Forecasting codes: David Alonso, Colin Bischoff*, Josquin Errard
- Survey strategies & atmospheric modeling: Reijo Keskitalo
- Observing efficiencies: Sara Simon
- Foregrounds: Susan Clark, Brandon Hensley
- Delensing: Raphael Flauger*, Marius Millea
- Sensitivity: Jeff McMahon, John Ruhl
- Data presentation: Cooper Jacobus
- Coordination: Julian Borrill, John Carlstrom

* Past or present Low-Ell BB AWG co-convener

Additional Project Considerations

- What are the site-specific risks for SATs in Chile and what additional R&D would be required to address them?
  - SAT L2 Scientist: John Kovac
- What are the Site Infrastructure/Commissioning issues for SATs in Chile?
  - Chile Site L2 Scientist: Kam Arnold

1. Resolve Forecasting Code Discrepancies

David Alonso, Colin Bischoff, Josquin Errard

Description of methods

1. [Bischoff] Parametric likelihood following BICEP analysis -- used for CMB-S4 r forecasting in Science Book, ApJ paper, CDT, DSR, PBDR, etc. (code mostly from V. Buza)
    a. Bandpower covariance matrix scaled from BK achieved results. Scale factors based on ideal per-detector NET, number of detector-years, sky fraction. Also adjusts the foreground contribution to bandpower covariance based on frequency bands, foreground models.
    b. Bandpower covariance matrix can also be described by N_l for each frequency plus effective fsky for signal, noise, and signal x noise.
    c. Fisher analysis to derive sigma(r), along with uncertainty on foreground model parameters. Foreground model includes decorrelation parameters for dust and synchrotron.
2. [Alonso] Similar bandpower-based component separation code. Option to use moment expansion instead of decorrelation (used here).
    a. Not really a forecasting code, but the final stage of the B-mode pipeline.
    b. Requires input bandpowers and covariance, so forecasts depend on assumptions behind those.
    c. Moments is a generalisation of decorelation (accounts for structure in spatial beta variation)

Description of methods

3. [Errard] Forecasting parametric map-based framework following Stompor et al. (2009,2016), Errard et al. (2011,2019) and its publicly available implementation in ***fgbuster*** (fgbuster.github.io)

a. Adjustment of parametric SEDs from observed foregrounds-only frequency maps (aka optimization of the spectral likelihood);

b. Estimation of the noise spectrum after component separation and foreground residuals

c. Cosmological likelihood on {r, Alens}

xForecast

R. Stompor, JE and D. Poletti (PRD 2016, 1609.03807)

simulation of observation with CMB + any foregrounds

↓

spectral analysis using simple scaling laws (e.g. power-law synchrotron and gray body dust)

$$\langle \mathcal{S}_{spec} \rangle = -\mathrm{tr} \sum_p \left\{ (\mathbf{N}_p^{-1} - \mathbf{P}_p)\left(\hat{\mathbf{d}}_p \hat{\mathbf{d}}_p^t + \mathbf{N}_p\right)\right\}$$

↓

estimation of statistical and systematic foregrounds residuals

$$\begin{aligned} C_\ell^{\rm res} \simeq\ & \otimes_\ell(\tilde{\mathbf{y}},\tilde{\mathbf{y}}) + \otimes_\ell(\tilde{\mathbf{y}},\tilde{\mathbf{z}}) + \otimes_\ell(\tilde{\mathbf{z}},\tilde{\mathbf{y}}) \\ & + \mathrm{tr}\left[\boldsymbol{\Sigma}\ \otimes_\ell(\tilde{\mathbf{Y}}^{(1)}, \tilde{\mathbf{Y}}^{(1)})\right] \end{aligned}$$

↓

propagation of these to the estimation of tensor-to-scalar ratio *r*

$$\langle \mathcal{S}^{par}\rangle = \mathrm{tr}\,\mathbf{C}^{-1}\mathbf{E} + \ln\det\mathbf{C}$$

Results comparison for South Pole

- Started with PBDR baseline configuration with 18 SATs at Pole plus SPLAT (residual Alens = 0.0655).
- Initial attempt at forecasting based on experiment configuration (number of detectors, NETs, hit map) showed a large discrepancy between methods.
- Discrepancy mostly goes away once all three methods are using common assumptions about frequency map sensitivity.
    - Colin and David use common bandpower covariance matrix. Josquin uses N_l plus hit map.

Method	No decorrelation	With fg decorrelation
1 - Bischoff	3.9e-4	5.3e-4
2 - Alonso	3.7e-4	5.9e-4 (moment exp.)
3 - Errard	4.2e-4	5.5e-4 (multipatch w/ nside=8)

2. Characterize Chile Site-Specific Inputs

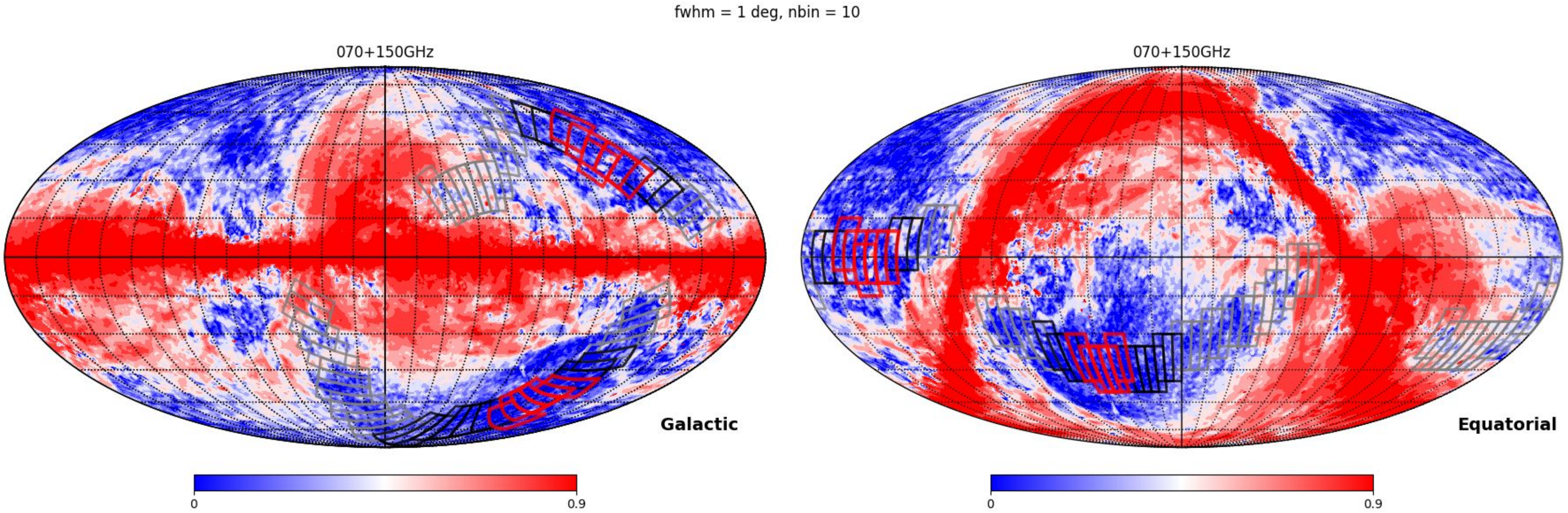
Chile SAT Sky Surveys

Reijo Keskitalo

Aims

- Develop representative scanning strategies for immediate forecasting needs
- Simulate the scanning strategies into estimates of achieved noise depth, accounting for realistic penalties from
    - Sun/Moon avoidance
    - Seasonal weather patterns
    - Loading with observing elevation
    - Mode loss from filtering
- Understand the benefits and limitations of the site in terms of observing strategy

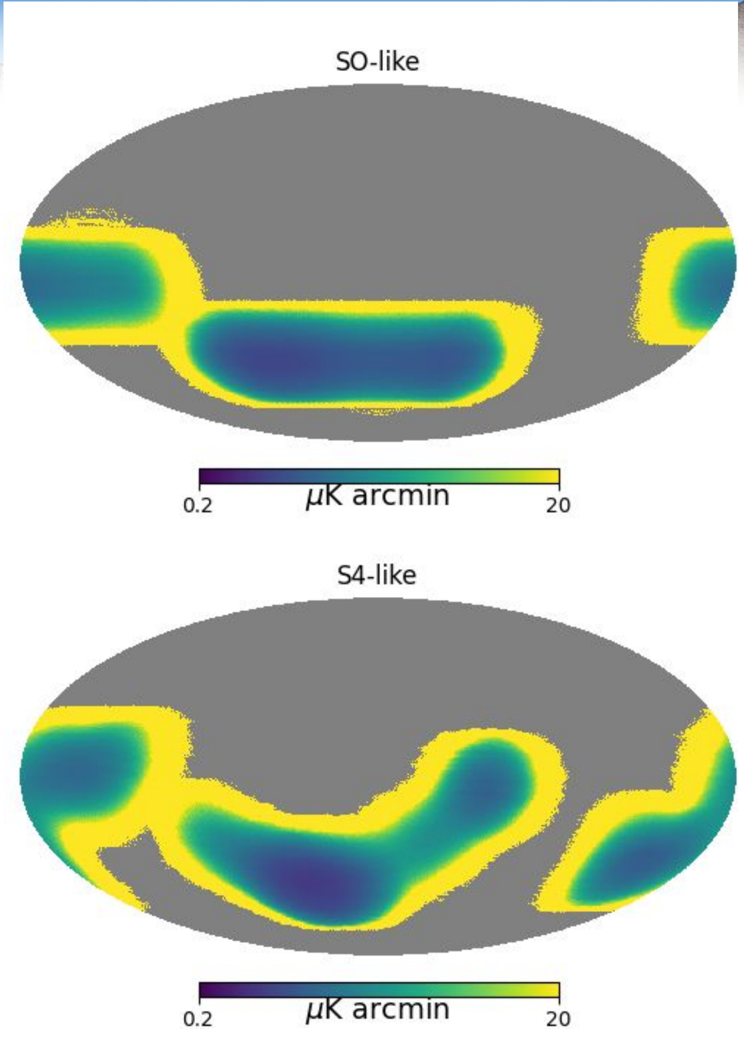
Find the cleanest sky for the deep field



The composite map combines temperature and polarization intensity of both dust and synchrotron.

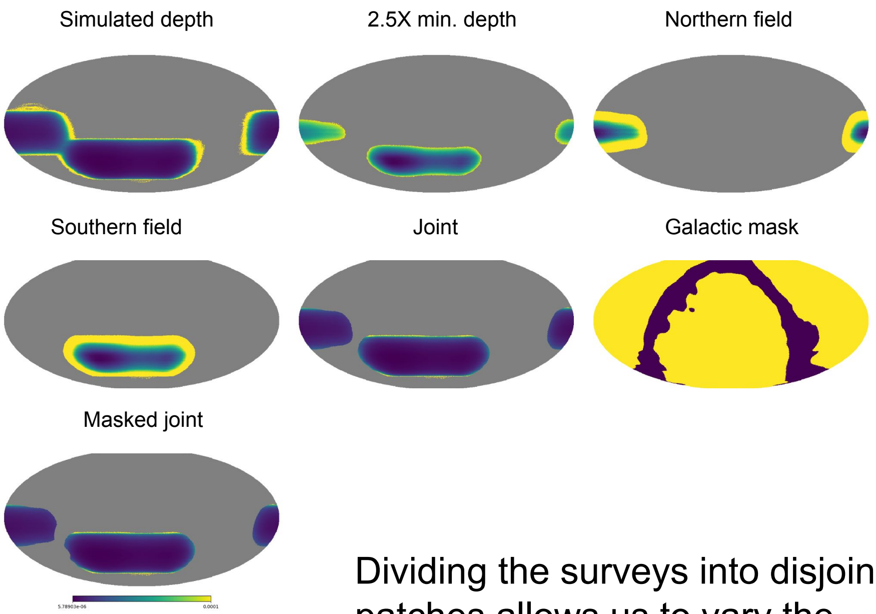
Two different observing strategies (1/2)

- It is difficult to focus a large FOV into a narrow field, especially when the field rises and sets
- SO-like strategy produces more uniform depth over a wider field
- S4-like strategy achieves a deeper primary field

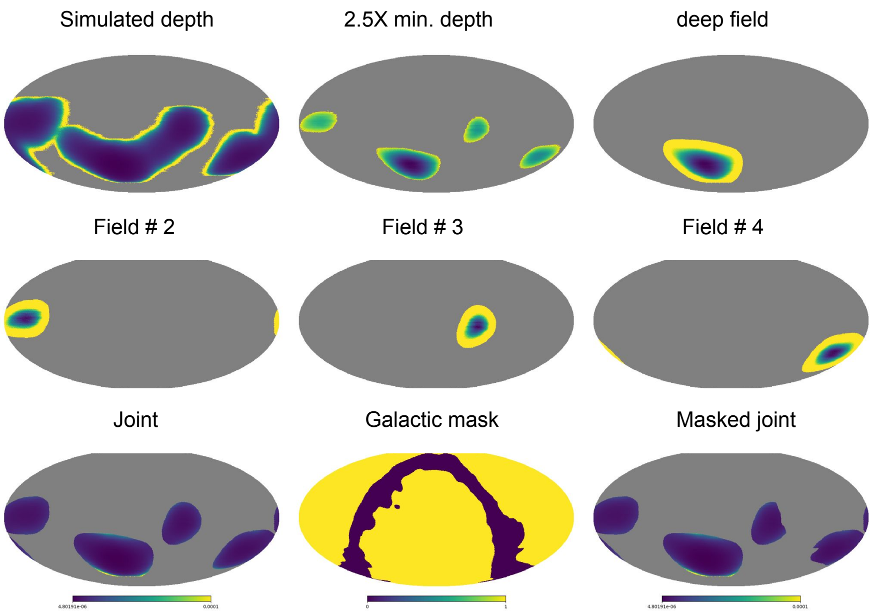


Two different observing strategies (2/2)

SO-like



S4-like



Dividing the surveys into disjoint patches allows us to vary the foreground and/or lensing residuals in each patch.

Observing Efficiency

Sara Simon *(she/her)*

Non-frequency dependent quantities

- Observation strategy group made initial estimates last year
- Use the CHLAT values (derived from ACT) for most quantities
- Derive the field efficiency and turnarounds from scan strategies

Factor	Value	Reasoning
f_season	0.75	Same as CHLAT
f_uptime	0.80	Same as CHLAT
f_field	(0.793, 0.709)	Derived from scan strategy (S4, SO-style), 45° Sun/Moon avoidance
f_turnaround	(0.947, 0.954)	Derived from average scan strategy throw, speed, and same acceleration as SPSAT
f_scanset	0.92	Same as CHLAT
f_cal_maint	0.92	Same as CHLAT

Frequency-dependent quantities

- Use the CHLAT values for PWV cuts
- Scale the CHLAT data quality cuts at ~90 GHz by frequency-dependent ratio from BK
- LF bands use data quality value at ~90 GHz (conservative)

Factor	Value	Reasoning
f_quality(LF, 85, 95 GHz)	0.80	Same as CHLAT
f_quality(145, 155 GHz)	0.79	CHLAT quality cuts at 90 GHz scaled by f_quality(150)/f_quality(90) from BK
f_quality(220 GHz)	0.56	CHLAT quality cuts at 90 GHz scaled by f_quality(220)/f_quality(90) from BK
f_quality(280 GHz)	0.39	CHLAT quality cuts at 90 GHz scaled by f_quality(280)/f_quality(90) from BK
f_PWV(LF, MF)	0.85	PWV<3 (same as CHLAT)
f_PWV(HF)	0.75	PWV<2 (same as CHLAT)

~10-26% total efficiency depending on the band, captured in efficiency spreadsheet

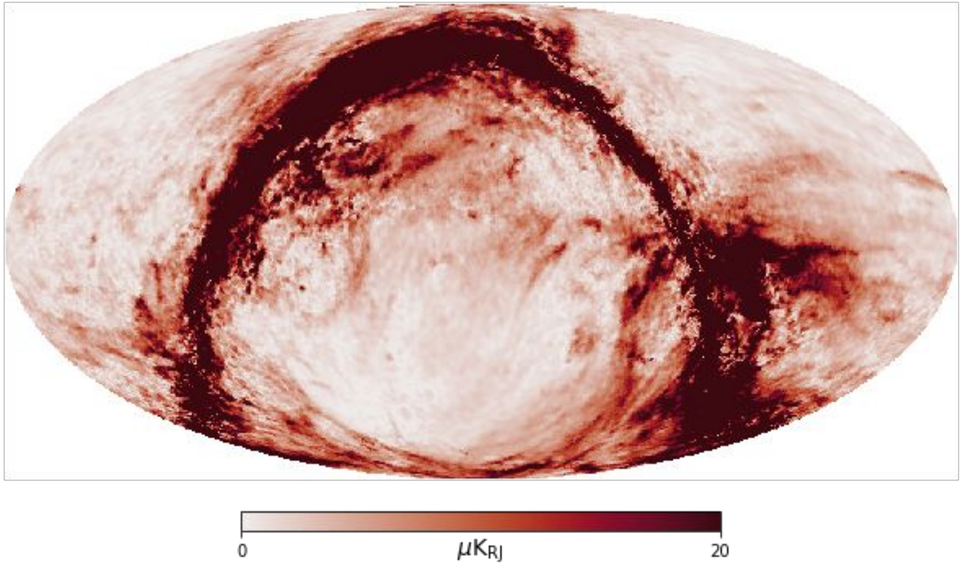
Foregrounds

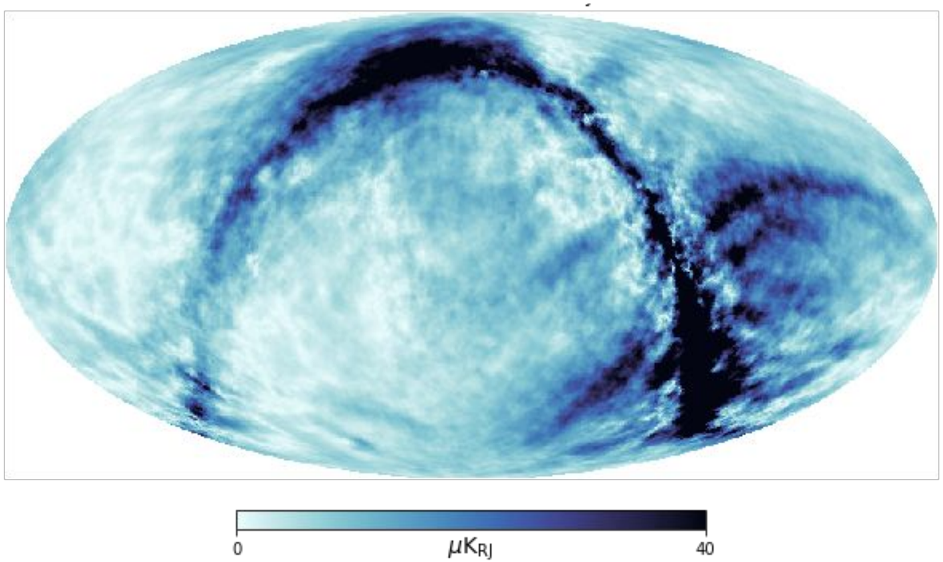
Susan Clark, Brandon Hensley

Foreground Models

- New suite of models implemented in PySM
  - Improved emission templates based on latest component separation analyses
  - Stochastic small-scale fluctuations in amplitudes as well as spectral parameters
  - Log-pol tensor formalism → non-Gaussianity
  - “Layer model” (MKD) with line of sight frequency decorrelation
- Basis of three sky models (all consistent with current data):
  - Optimistic: Small-scale fluctuations in amplitudes only, no decorrelation
  - Best Guess: Parameter maps based on component separation with extrapolation to small scales in both amplitudes and spectral parameters
  - Pessimistic: Near maximum allowed decorrelation for dust emission, line of sight dust SED variations, AME polarization, synchrotron curvature
- Available now on Github if you are interested in using these models: https://github.com/galsci/pysm
- More detailed presentation of models in session on Friday

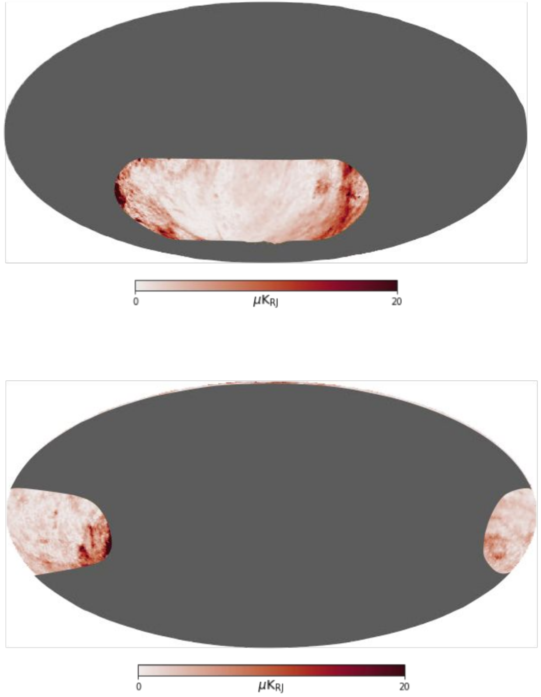
Foreground Models


353 GHz P

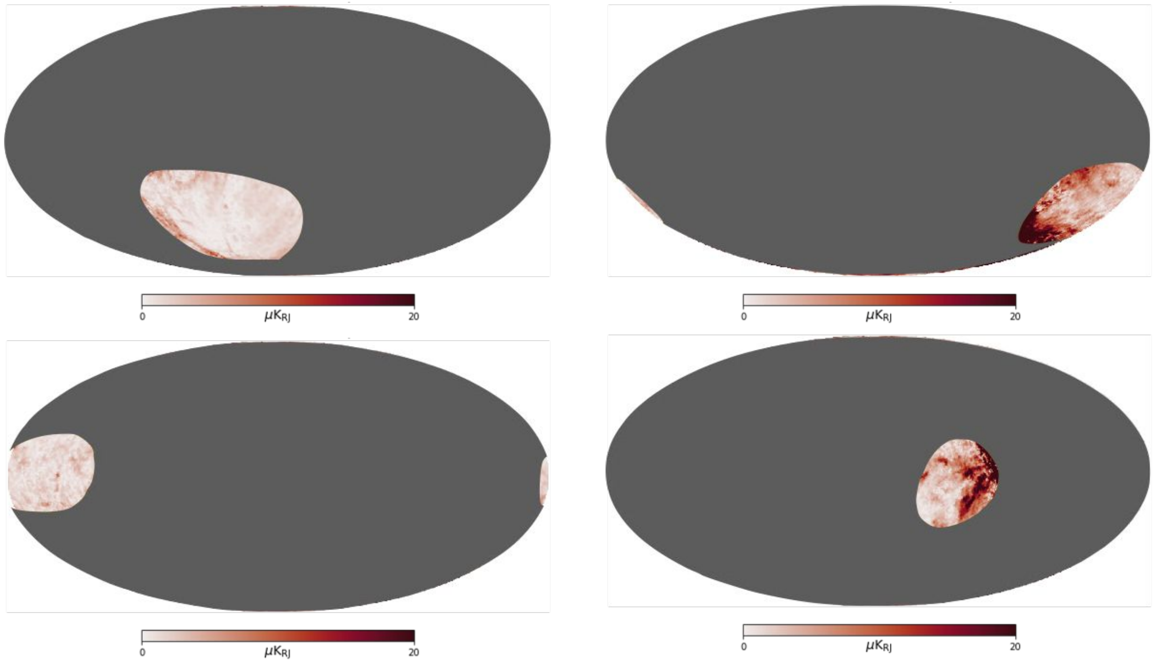

30 GHz P

Foreground Models and Observing Strategies

SO-Like



S4-Like



Delensing

Raphael Flauger, Marius Millea

Delensing

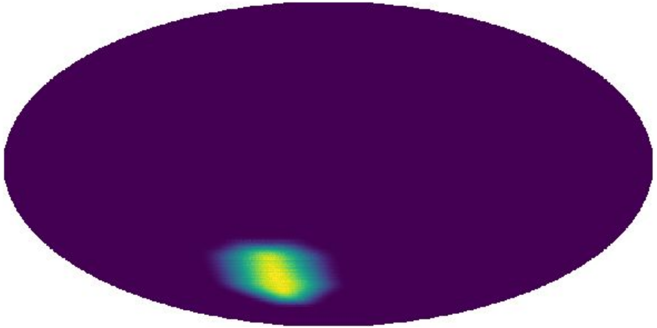
- Forecast methodology
  - For a given LAT configuration, survey, and foreground model, LAT frequency cross-spectra are computed and a spectral ILC is performed.
  - For the LAT ILC signal and noise spectra

$$
\begin{aligned}
N_\ell^{\phi\phi} &= \left[\frac{1}{2\ell+1}\sum_{\ell_1\ell_2}|f^{EB}_{\ell_1\ell_2\ell}|^2\left(\frac{1}{C^{B_{\rm res}}_{\ell_1}+N^{BB}_{\ell_1}}\right)\left(\frac{(C^{EE}_{\ell_2})^2}{C^{EE}_{\ell_2}+N^{EE}_{\ell_2}}\right)\right]^{-1}\\
C^{B_{\rm res}}_{\ell_1} &= \frac{1}{2\ell_1+1}\sum_{\ell_2\ell}|f^{EB}_{\ell_1\ell_2\ell}|^2\left[C^{EE}_{\ell_2}C^{\phi\phi}_\ell-\left(\frac{(C^{EE}_{\ell_2})^2}{C^{EE}_{\ell_2}+N^{EE}_{\ell_2}}\right)\left(\frac{(C^{\phi\phi}_\ell)^2}{C^{\phi\phi}_\ell+N^{\phi\phi}_\ell}\right)\right]
\end{aligned}
$$

    are iterated to determine A_L.
  - The result is used to determine sensitivity to r for a given SAT configuration.
- This has previously been compared to map-based delensing and has been found to agree well.
- An optimal joint determination is available for small sky areas but has not yet been used for AoA.

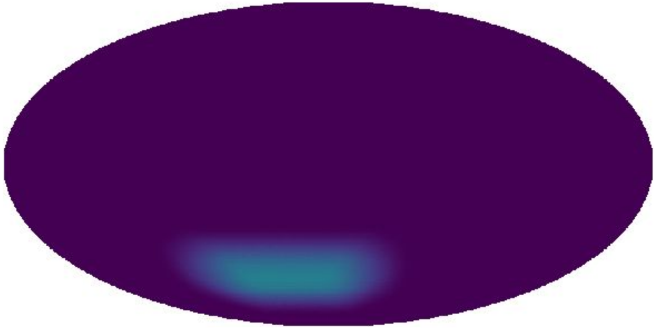
Surveys under consideration

- South Pole LAT to delens South Pole SATs (pole deep)



A_L= 0.049

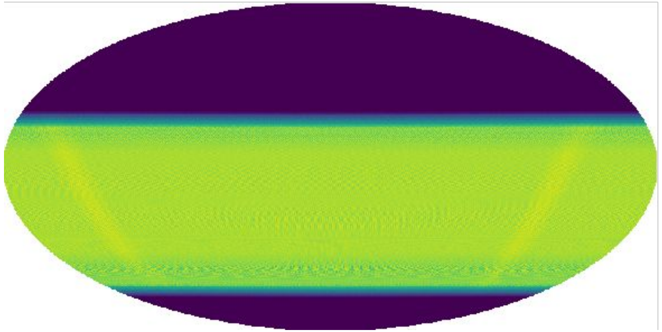
- South Pole LAT to delens Chile SATs (pole wide)



A_L= 0.073 for deep patch
(A_L= 0.27 for other Chile patches)

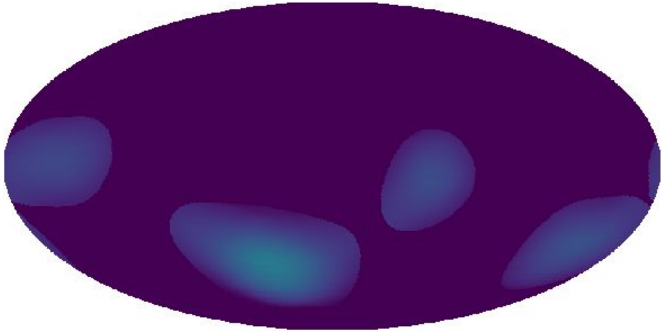
Surveys under consideration

- 3rd Chile LAT participating in wide area survey to delens Chile LATs



$A_L = 0.23$

- 3rd Chile LAT dedicated to delensing Chile SATs



Work in progress

3. Generate (Initial) Results

Initial Surveys

- Having achieved convergence between the codes we can now apply them all to a first set of Chile surveys (and equivalent South Pole surveys)
- The Chile surveys will have:
  - 2 SAT survey strategies: SO-like and S4-like (including loading & efficiency implications) split into 2 & 4 patches to allow for foreground & delensing variation
  - 3 galactic foreground models: optimistic, best-guess, pessimistic
  - 2 delensing options based on the siting/survey of the 3rd LAT: in Chile doing the legacy survey, at the South Pole doing a wider Southern Hole survey
- The South Pole survey will have
  - 1 SAT survey strategy: PBD regenerated with the same methodology as CHSATs
  - 3 galactic foreground models: optimistic, best-guess, pessimistic
  - 1 delensing option: PBD SPLAT
- Initially the instrument properties will be assumed to be the same at both sites, scaled from BICEP/Keck

Sensitivity, Atmosphere & Half-Wave Plates

John Ruhl, Jeff McMahon

The sensitivity question:

What noise vs ell (N_ell) can we achieve in Chile, for a given number of detector-years?

There are several factors feeding into this:

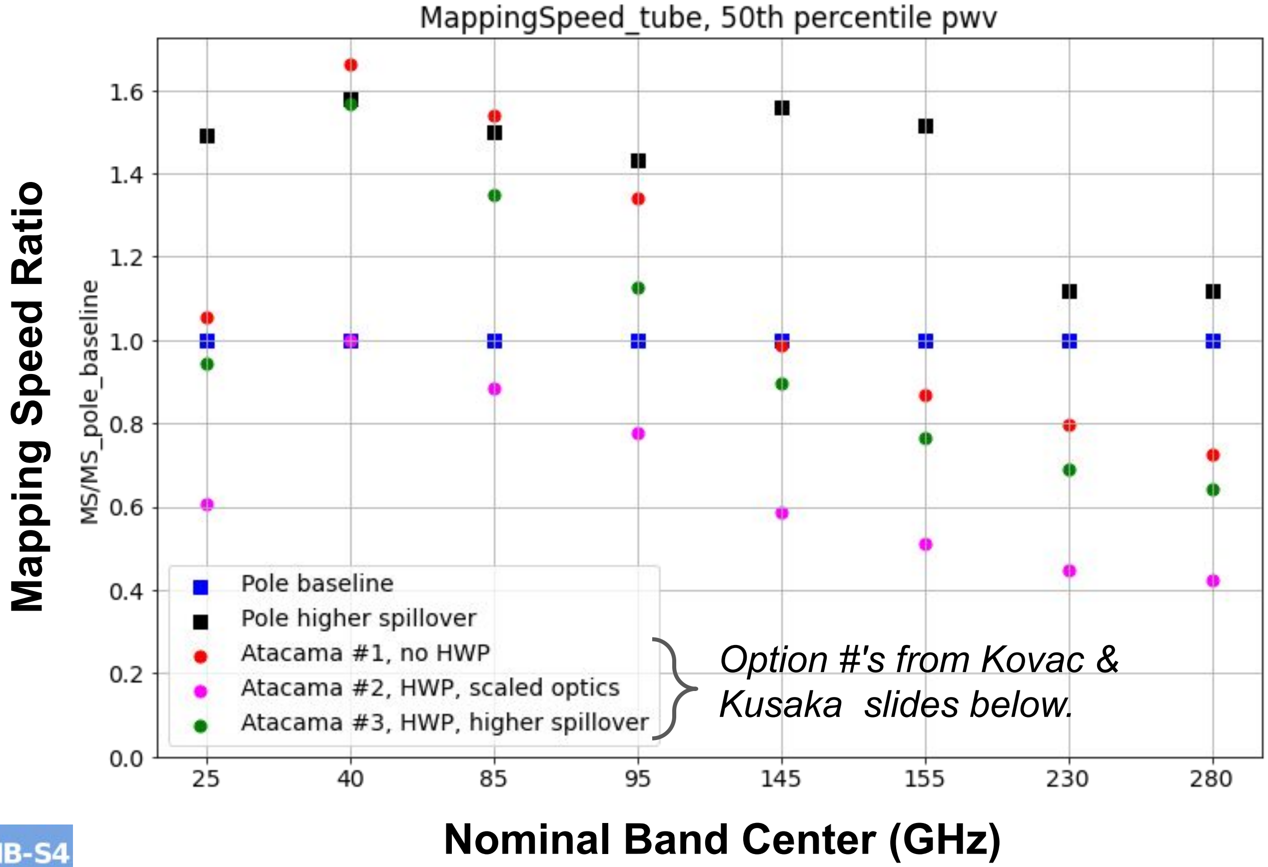
- Individual detector "white noise" sensitivity, including variations in pwv and distribution of pwvs during observations

- Number of good hours of data one can profitably use per year. This is related to:
    - Level of atmospheric ΔI fluctuations during possible observing times.
    - The instrument's ability to reject those with some form of polarization modulation or differencing.

- Ability to control other factors that lead to 1/ell in maps.

SAT white noise sensitivities

for various configurations (Pole and Chile), relative to Pole baseline.



Option #'s from Kovac & Kusaka slides below.

Mapping speed per tube

Optics and bolometer prescriptions same for all options.

Site-specific atmosphere

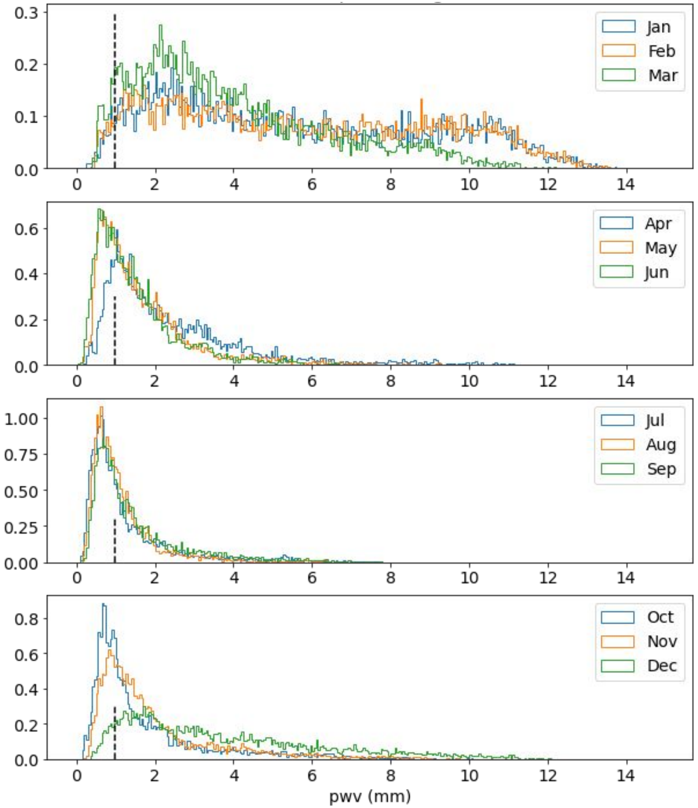
Psat = 2.5*Poptical

HWP model: same as alumina filter, but 4mm thick, 55K

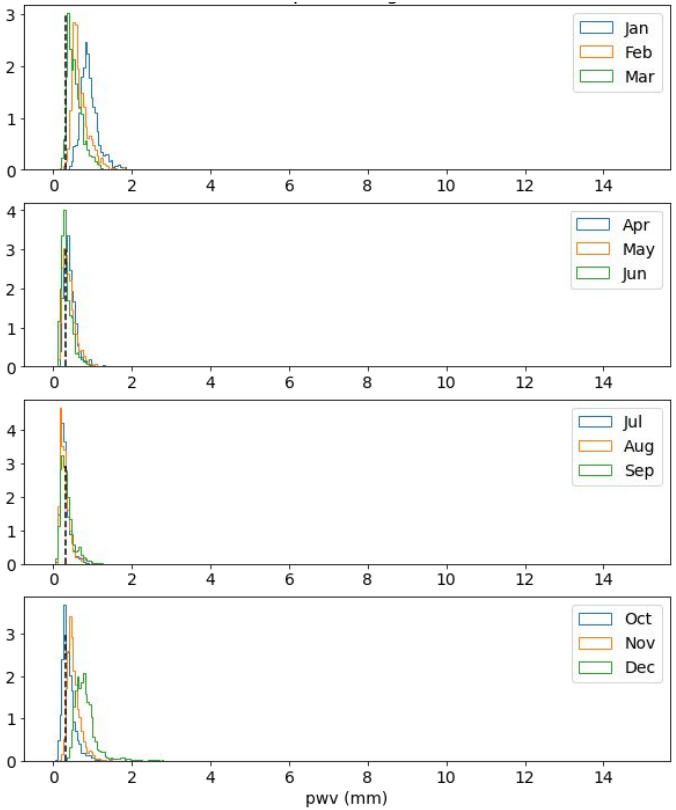
Spillovers on cold stop from P. Grimes.

PWV histograms

Atacama

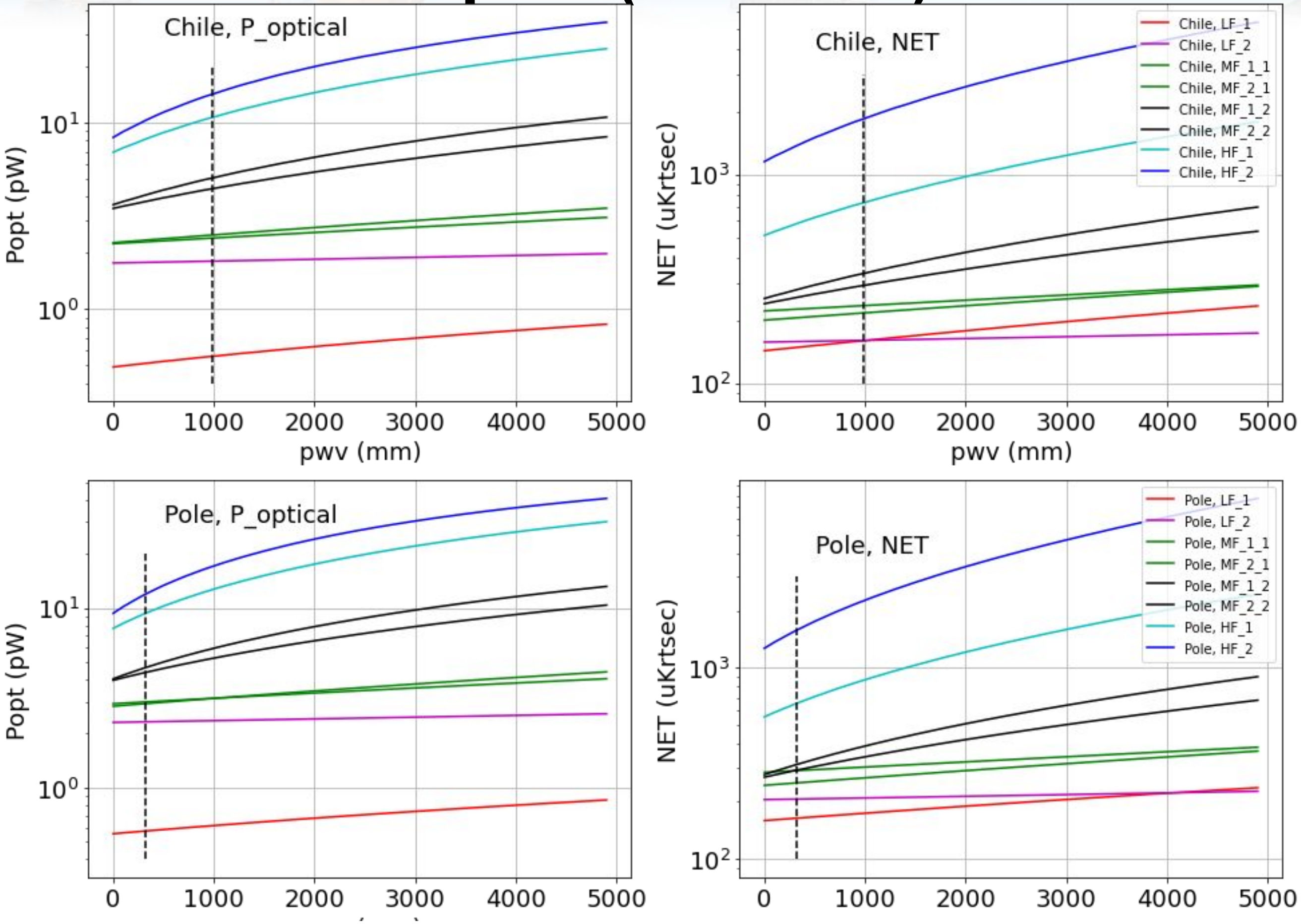


South Pole



dashed lines: S4 design input: 50th percentile pwv from Kuo, https://arxiv.org/pdf/1707.08400.pdf, for 8-month observing season at each site.

SAT Popt and NET vs pwv (baseline)

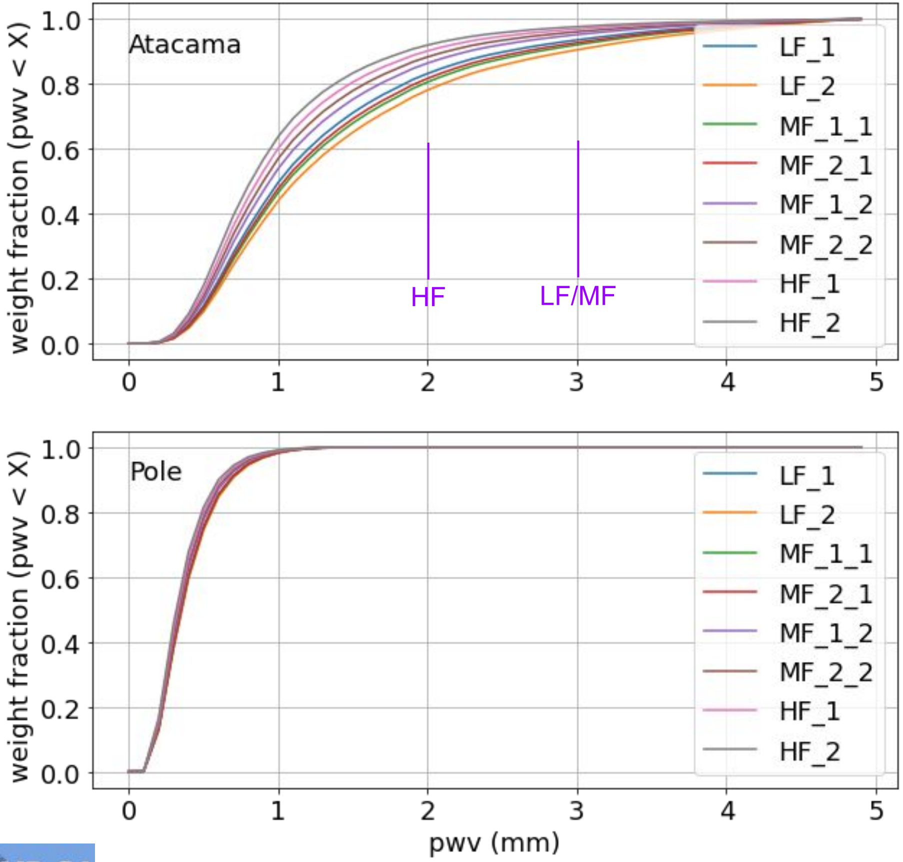


pwv (microns)

pwv (microns)

SAT weight (in Chile) depends a bit on pwv cut

Note: weight \propto mapping speed \propto 1/(NET^2*)*



For this example:

Omit Chile Jan/Feb/March.
Omit Pole Nov/Dec/Jan.

Calculate weight(pwv) by appropriate use of pwv histogram and NET(pwv).

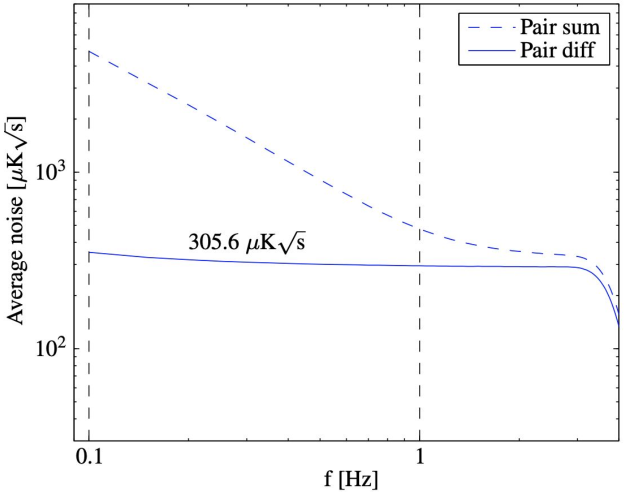
Result:

- ~ All Pole weight is below 1mm.
- Above 2mm, Chile weight has weak dependence on pwv cut.

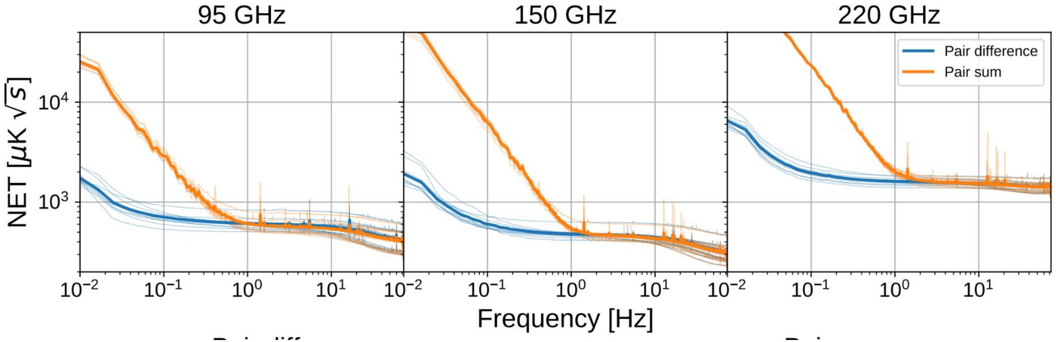
This analysis knows nothing about turbulence.

Rejecting Atmospheric ΔI fluctuations in timestreams

Detector-differencing has worked well at the South Pole, at least a factor of ~20 in ΔT units
(Not known if residual 1/f is from ΔI atmosphere or other effects)



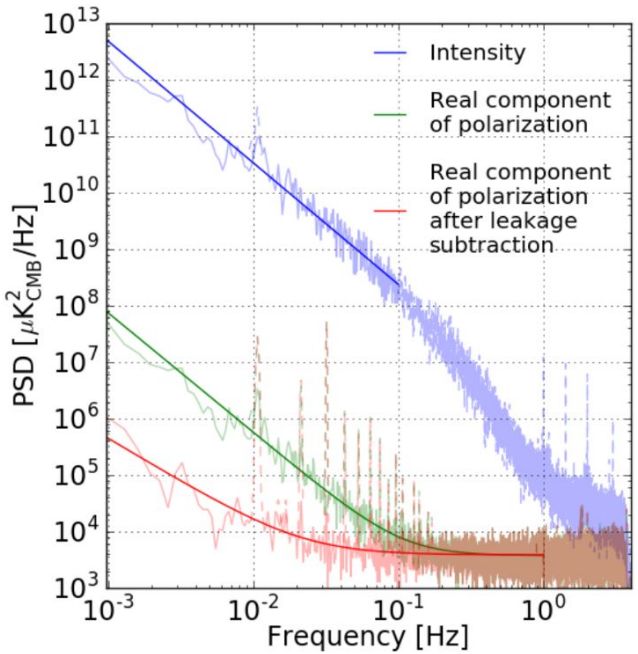
Bicep2, 150GHz



SPT-3G

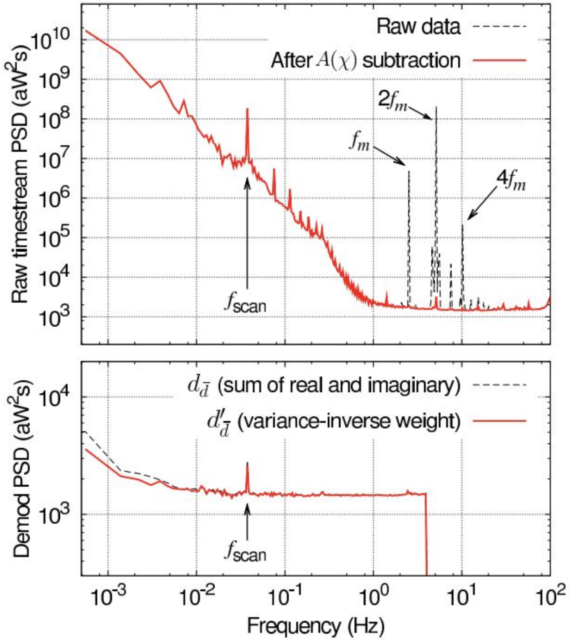
Rejecting Atmospheric ΔI fluctuations in timestreams

Continuously rotating HWPs have been shown to reject atmospheric ΔI fluctuations by a factor of ~100 in ΔT units.



Polarbear

https://arxiv.org/pdf/1702.07111.pdf



ABS

https://arxiv.org/pdf/1310.3711.pdf

How large are the ΔI fluctuations at each site, over all intended observing times?

We don't know for sure.

(A number of previous studies suggest Chile fluctuations are significantly worse, but we don't have a good handle on the actual factor. This shows up, for example, in our ACT/SPT experience-driven forecast 1/ell knees, which are higher for the CHLAT survey than for the SPLAT survey).

We plan to look at ACT and SPT data to better quantify this factor, in the near future.

Useful Detector-hours per year

(or weight/detector/year, etc)

We can look at data cuts in previous experiments (Act/SPT), but there is not a long history of large-angular-scale measurements in Chile to compare with Bicep/Keck, to well-inform atmospheric noise cut estimates.

We can look at achieved weights by various experiments, and rate them by:

1. per detector-year, using the total total calendar time from start to stop of observations. This factors in all lost observing time or weight due to maintenance, breakdowns, and weather, as well as differences in per-detector sensitivity.
2. per detector-running-hour, using the number of hours where the instrument was running, but not necessarily on the field.
3. per detector-on-field-hour, using the number of hours the instrument was pointed at the field.
4. varieties of the above including factors accounting for dead detector fraction, and/or detector NETs

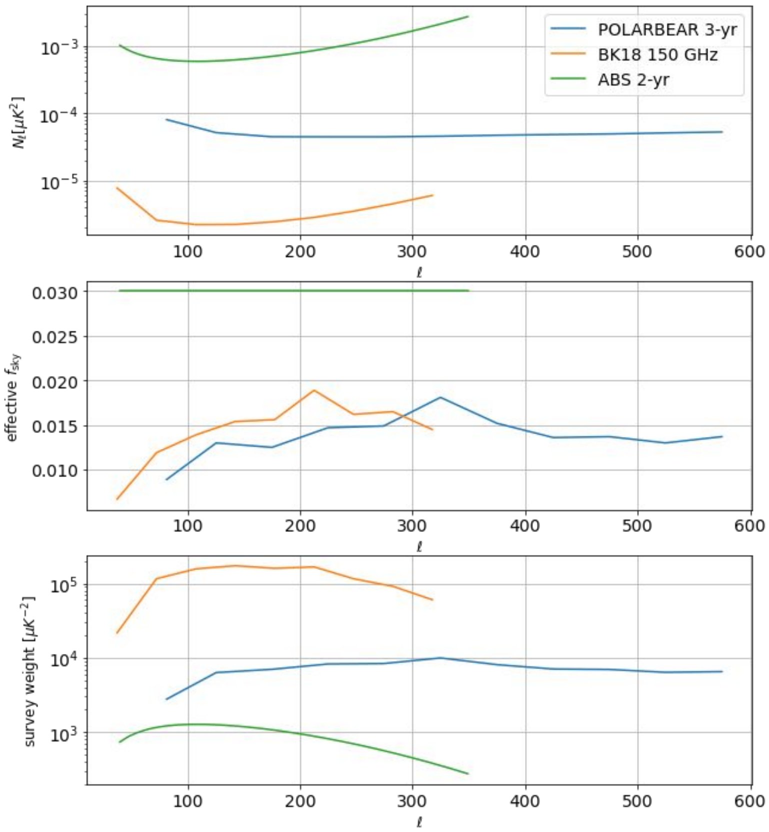
Useful Detector-hours per year

(or weight/detector/year, etc)

Case #1: BK favored by ratio of 10.
Case #2: *(working to get numbers)*
Case #3: *(working to get numbers)*
Case #4: *(need to think about what matters…)*

That ratio falls as you consider/allow more factors, but with significant uncertainty because the Chile HWP experiments do not have a long baseline.

Other factors



Plot code+data from Colin Bischoff

N_ell

Sky Area

Total Weight

HWPs have enabled Chile experiments to achieve impressive N_ell shapes.

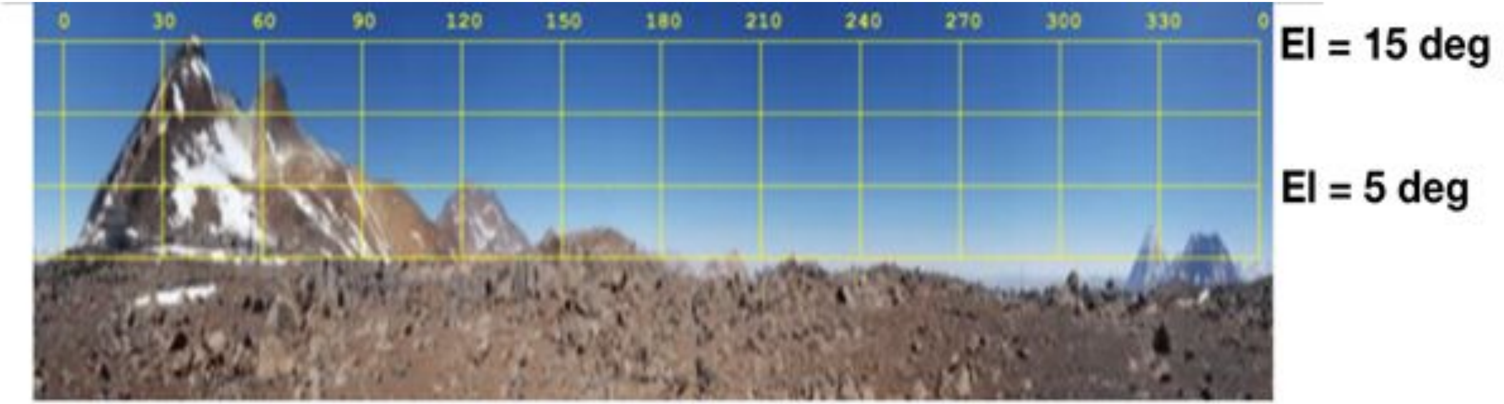
However, they are still a factor of 10 or more below the Bicep/Keck total weight, so there remains the risk that other things may come into play.

CMB-S4 will dig deeper than Bicep/Keck, so this kind of concern applies to any design, but at different magnitudes

Risks and R&D

John Kovac, Akito Kusaka

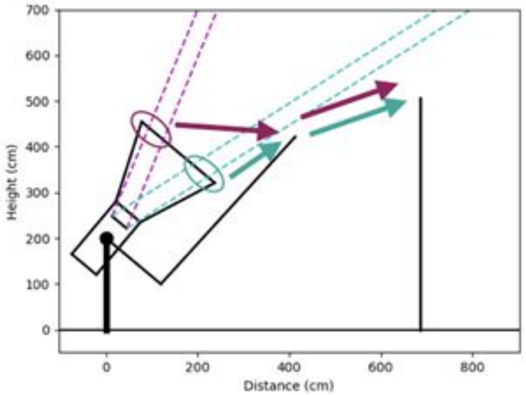
Distribution of Terrain at Chilean Site



The closest mountain (Cerro Toco) peaks at around elevation ~15 degrees from horizon, NE of site. Mountains that are further away peak at around elevation ~5 degrees from horizon. Approximately half of the azimuth range contains mountains that rise above the horizon.

Relaxed Double-Diffraction Criteria

From the Simons Observatory (SO) shielding study, we have adopted a “relaxed” version of the double-diffraction criteria due to that fact that extremely large ground shields are required to satisfy the full double-diffraction criteria. The relax double-diffraction criteria only has one difference. The relaxed criteria allows the diffraction off the top of the forebaffle to be able to “see” the top portion of Cerro Toco, but not the horizon or further off mountains. The diffraction off the top of the forebaffle is much smaller and sub-dominant compared to the diffraction off the bottom of the forebaffle which will be blocked in the relax criteria. Also sidelobes due to forebaffle scattering may also “see” the top portion of Cerro Toco.



Shielding geometry (Study by Fred and Kirit)

Option 1

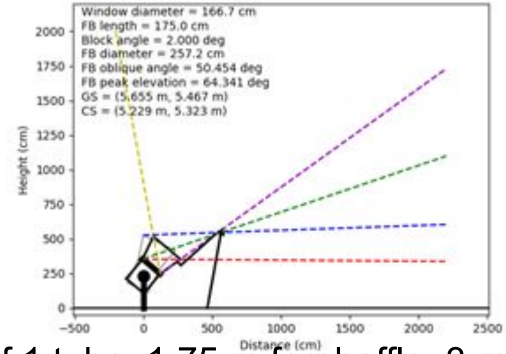
- Forebaffle: 1.75 m (same)
- Ground shield: R=15.6 m, H = 6.9 m

Option 2

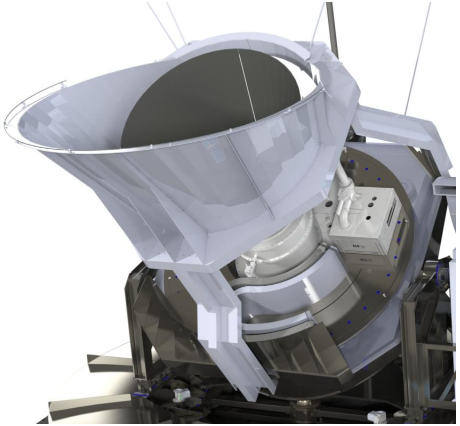
- Forebaffle: 1.75 m (same)
- Tertiary: 2 m (added)
- Ground shield: R=12.1 m, H = 6.6 m

Both w/ Relaxed double-diffraction criteria

Study by F. Matsuda and K. Karkare



Example of 1 tube, 1.75 m forebaffle, 3 m tertiary



Example from Simons Observatory

Optics Alternatives for Chile

Slides by Paul G.

Option 1 - No changes	**Option 2 - HWP w/ scaled optics**	**Option 3 - HWP with hard stop**
Deploy Optics designed for Pole with no changes. Can migrate to Option 3 if measurements show that HWP is necessary.	Redesign optics to balance HWP aperture limitations with edge taper and spillover. ***Assume linear scaling of Pole design to smaller aperture here***	Add HWP to Optics design for Pole. Install smaller aperture stop to control illumination of HWP.
+ No impact on modules + No impact on optics + No impact on detector counts + No work to redeploy to Pole	+ No impact on modules + Reduced scattering from aperture stop vs Option 3 + Better optical systematics vs Option 3 + Thinner, smaller lenses	+ No impact on modules + Minimal impact on optics + No impact on detector counts + Reversible
- Risk that atmospheric fluctuations are too large	**- Significantly Reduced detector count** - Need to replace optics before redeploying to Pole	- High edge taper - **Higher beam/sidelobe risk** - Increased scattering from aperture stop - High spillover

Optics parameters by option - MF 1

Slides by Paul G.

	Option 1 (as for pole)		**Option 2** (scaled optics)		**Option 3** (HWP w/ stop)	
	Low	**High**	**Low**	**High**	**Low**	**High**
Nominal F/#	1.45		1.45		1.845	
Aperture	560 mm		440mm		440mm	
Focal Plane Diameter	428 mm		336 mm		428 mm	
Feedhorn Count	1542		1008		1542	
Edge Taper	-8.69 dB	-16.58 dB	-8.69 dB	-16.58 dB	-5.15 dB	-11.60 dB
Spillover	16.2%	6.5%	16.2%	6.5%	31.8%	12.8%
Beam FWHM	25.5’	25.5’	~32’*	~32’*	~30’*	~30’*
Stop Scattering	x1	x1	x1	x1	x2.26	x3.14

*Beam size for Option 2 and 3 needs optics simulation to be accurate.

Other changes for sensitivity calcs

Slides by Paul G.

	Option 1 (as for pole)	**Option 2** (scaled optics)	**Option 3** (HWP w/ stop)
Half wave plate loss	No Change	Add HWP loss	Add HWP loss
Lens thickness	No Change	Reduce thickness by 0.75	No Change
Photon correlation term	No Change	No Change	Slight increase (from 1.9 to 1.5 Fλ)
Forebaffle Loading	No Change	Add HWP scattering	Add HWP scattering Increased due to higher aperture stop scattering to forebaffle
Internal Baffle Loading	No Change	No Change	Increased due to higher aperture stop scattering to walls of cryostat in front of Objective Lens

Suggested HWP loss, scattering and temperature

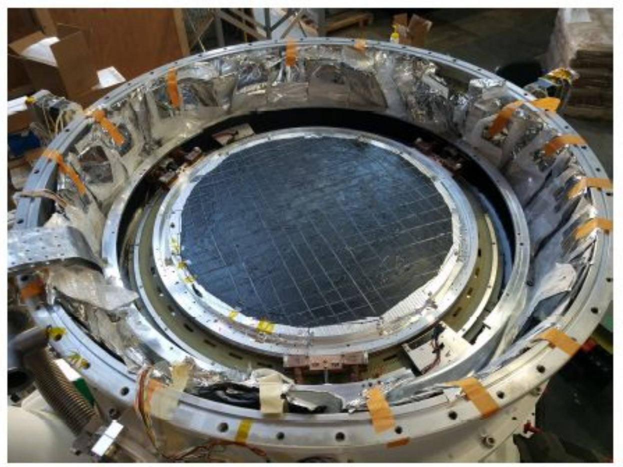
Loss and scattering: the same AR coating (2 surfaces) as Alumina filter, and 4mm thick Alumina.

Rationale: these are dominated by the AR coating and potentially Alumina. Use consistent technology.

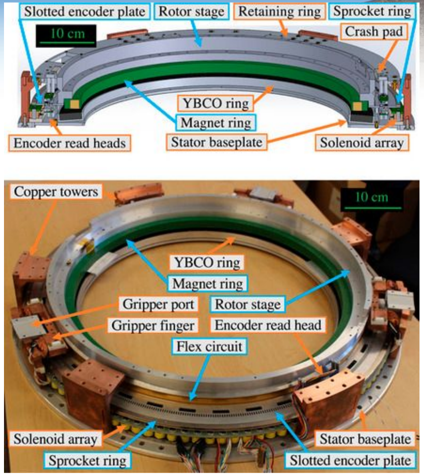
HWP temperature: 40K filter temperature + 15K

Conservative assumption from SO HWP; PB2b does better (https://doi.org/10.1063/5.0029006)

Half-wave plate



SO HWP rotation mechanism.



SA HWP rotation mechanism.

HWP rotating mechanism: high-Tc superconducting mag-lev bearing. Virtually no limit on the aperture size.

Optical stack: three-layer sapphire stack with AR coating layers.
  Sapphire diameter limited to 505 mm for current technology.
    Metamaterial possible to expand diameter, R&D needed.
  AR coating : conservative: glue AR-coated Alumina on.
    Some technology can direct AR coat on Sapphire.

Half-wave plate - systematics mitigation

- Atmospheric Fluctuations
  - Mitigated: additive fluctuations.
  - Not mitigated: multiplicative fluctuations. (incl. non-linearity driven by atmospheric fluctuations. This exists in pair-diff as well.)
  - (https://doi.org/10.1063/1.4862058, https://doi.org/10.1117/12.2232280)
- Polarized Beam Systematics
  - Mitigated: diff. response of detectors and elements between HWP and detectors.
  - Not mitigated: 40 K filter and window (but a large scale common mode)
  - (https://doi.org/10.1063/1.4962023, https://doi.org/10.48550/arXiv.1808.07442)
- Polarized Sidelobe Systematics
  - Mitigated: pol. sidelobe due to aperture stop diffraction, pol. sidelobe due to differential illumination on warm baffle/shield.
  - Not mitigated: sidelobe polarization due to baffle/shield diffraction and scattering.
- Crosstalk-induced pol. leakage
  - Mitigated: Crosstalk between “X” and “Y” detectors becomes P → P leakage.

SAT implementation in Chile risks, existing database (1)

Atacama B-mode Search (SAT: 25 cm aperture, cryogenic mirrors; warm HWP)

- CMB power spectrum results
- HWP beam systematics mitigation
- HWP atmospheric fluctuation mitigation

POLARBEAR (MAT: 2m aperture, warm mirrors; warm HWP)

- CMB power spectrum results 1, results 2
- HWP atmospheric fluctuation mitigation

QUIET (MAT: 1.4m aperture, warm mirrors; phaseswitch modulation)

- CMB power spectrum results 1 (40 GHz), results 2 (90 GHz)

Simons Observatory SATs (first light 2023~2024)

- 42 cm aperture, equipped with cryogenic HWP

SAT implementation in Chile risks, existing database (2)

But there remains large uncertainty in the actual factors limiting achievable performance.

Site-dependent differences include dramatically different out-of-field pickup and atmospheric noise.

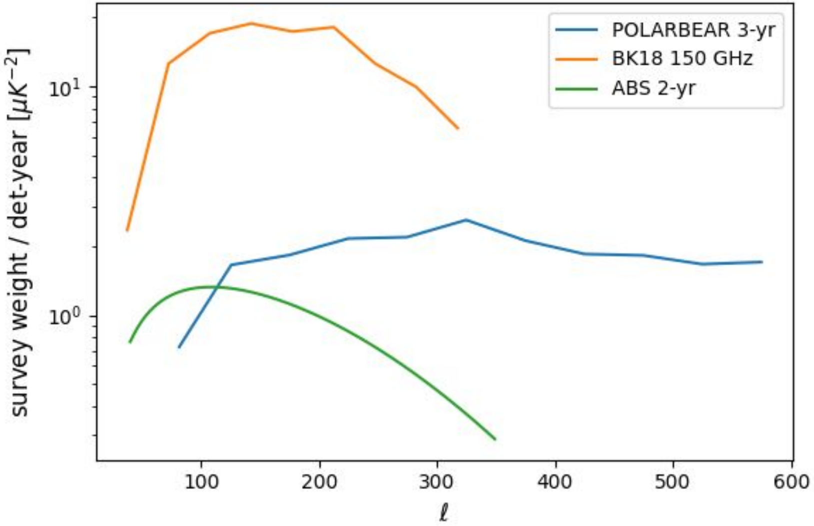
HWP modulation can mitigate polarized 1/ell from

1. Unpolarized atmosphere in main beam
2. Sidelobes in zero-diffraction directions

These are also relevant for Pole SATs, but *are not what currently limits* their polarized 1/ell performance.

Compared to these, polarized atmosphere and ground pickup from single and double-diffraction directions are suspected to be greater limiting factors for Pole SAT.

- Diffracted pickup expected to be worse in Chile and is not (obviously) mitigated by the HWP
- HWP-specific systematics introduce new risks to evaluate:
  - freq. dependence of bandpass, pol angle, efficiency
  - HWP non-uniformities → false 4f, 1/ell
- Without deep-map empirical characterization, hard to model/predict the impact on shielding requirements and ultimately achievable 1/ell performance



Survey Weight per detector-year at 150 GHz
C. Bischoff, CMB-S4 Science Council Logbook, 8 April 2022

Evaluation of Alternatives / Necessary prototyping efforts

- The **white noise** and **survey coverage** factors can be easily analyzed
  - Can be calculated for Optics Alternatives 1, 2, and 3 to immediately place a lower bound on the number of SATs in Chile needed to equal the baseline (6 SATs / 18 tubes) at Pole, for each of those alternatives.
- Chile vs. Pole differences in ground pickup and atmospheric noise lead to additional uncertainty in **achievable sensitivity per tube, particularly at large scales (1/ell)**.
  - Current gap between Pole vs Chile end-to-end achieved performance leaves room for this additional factor to be potentially very large.
- Experience* has shown that full-season deep maps from site, with specific proposed technical approach, are needed to narrow such uncertainties to < 2x
  - Reduction/cleaning of deep, full-season maps needed to assess trade between systematics and 1/ell
- A deployment of an S4 prototype SAT in Chile for 1-2 seasons operation, prior to finalizing required number and design of Chile SATs would seem prudent
  - Achieved performance with e.g. option 3 and option 1 vs Pole SAT baseline could be judged
  - SO SATs may offer information on one point design, but need full-season, full efficiency, deep, cleaned maps
  - Requirement differences for design, including shielding and calibrations, could also be validated

* “Experience over hope.” - Jim Yeck

Site Infrastructure Implications

Kam Arnold

Outline

- Status of requirements from SAT and assumptions for current layouts
- Resources of concern and their status
- Candidate layouts
- Alternate sites

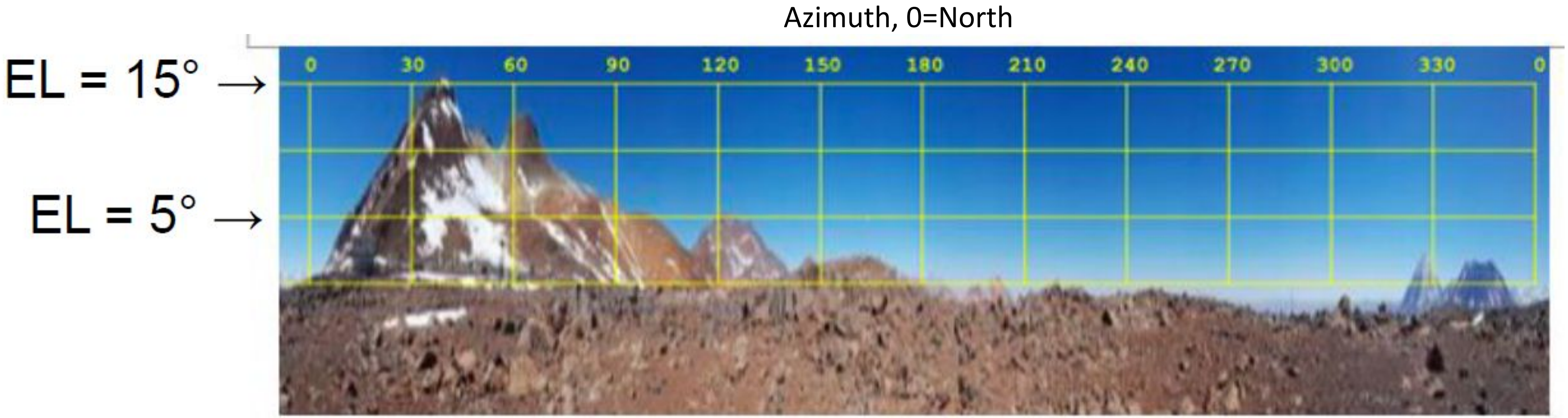
Status of requirements from SAT and assumptions for current layouts

- SAT-Pole ICD: [doc-348]
- Key JAMA Requirements on layout:
  - SPSITE-49: SAT telescopes shall have a clear field-of-view 2 degrees above the upper lip of the ground shield
  - CHILE-11: Other facilities/instruments will not block the LAT observations above 10 degrees elevation, as measured from the elevation axis of the LAT (currently 10 meters high)
- BART drawings
  - BART Replacement Tower (30% Construction Documents), Ditesco, 3/10/2022
  - BART Structural Design, Louis Becker Consulting Engineer, 3/7/2022

Resources of concern and their status

- Power: there is no issue with scaling the power plant up (through a capacity of 3 MW compared to the current <1 MW). The lifecycle power cost is reasonably characterizable as a cost per kWh.
    - Note: we are considering a photovoltaic power plant in a separate trade study. There is little interplay between that trade study and the AoA. They are similar in cost and parameterizable by kWh in all cases
- Cooling: cost scales with number of compressors, no scaling break point
- Data: Fits within 10 Gbps connection, available now. If we needed more bandwidth than this we could get it. See detailed slide
- Lab space: we would include new SAT assembly lab space under the SATs. See more in the candidate layouts
- Real estate cost: land cost scales with project cost [annual cost=$40k+(project cost)/1000]
- **Clear Horizon**: The baseline Chile site has horizon blockage to the north and northeast
- **Usable area:** see this in the upcoming layouts

Clear Horizon at Cerro Toco



- No horizon blockage above 2 degrees for az>145 and az<10.
  - Given that the science scans are so focused on the southern patch, does this satisfy our requirement for 2 degrees?
- Relaxing the requirement to 5 degrees would expand the “clear” azimuth to az>90 and az<10.

SAT layout constraints

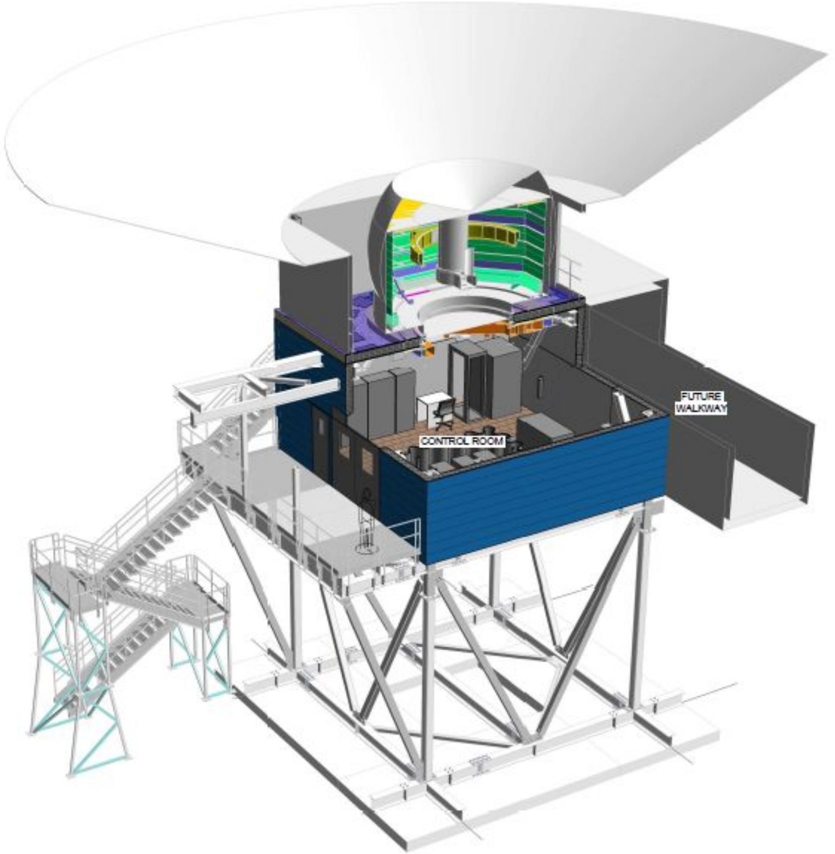
Pole layout is to have SATs on towers with control room underneath them, connected to assembly space by a walkway. These structures are 17 meters high.

SATs still need to be high in Chile if they are near the LATs.

Satisfying the existing horizon blockage requirements means:

2	deg	minimum elevation angle of LAT seen from SAT groundscreen
10	deg	minimum elevation angle of SAT see from LAT elevation axis
18	m	maximum height of LAT
10	m	height of LAT elevation axis
16.7	m	Height of SAT groundshield at minimum distance
38.5	m	minimum distance from LAT to SAT

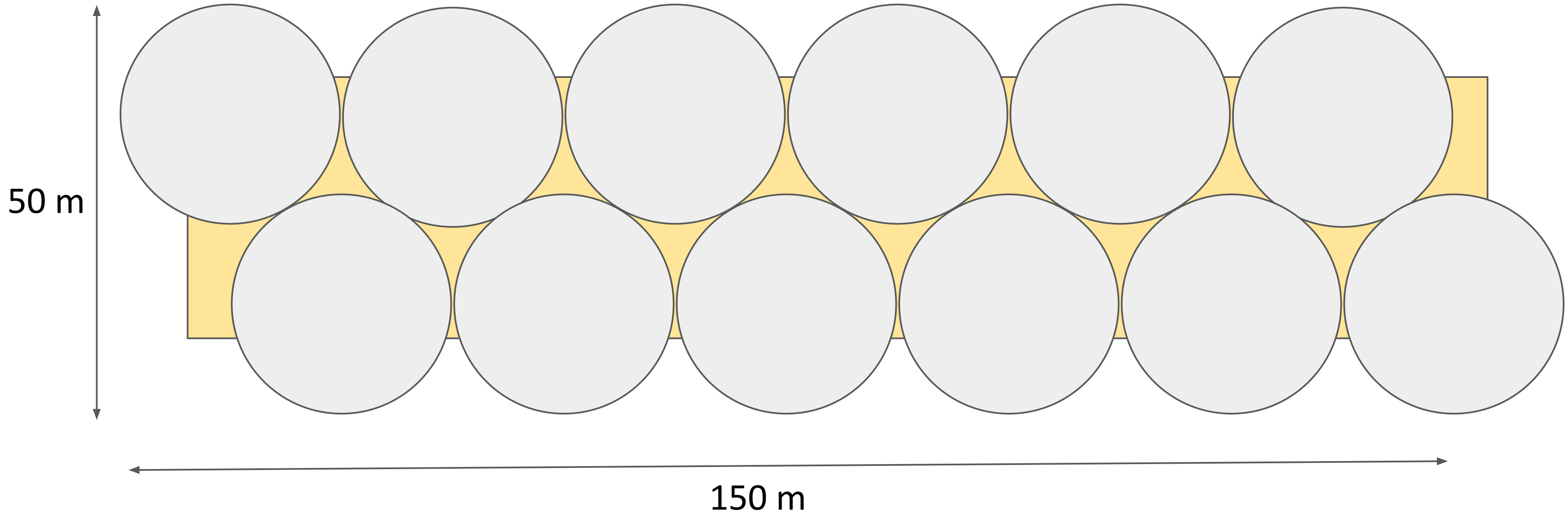
This is not a very restrictive minimum distance. As we move farther from the LAT than this, then there is more flexibility in the height of the SATs



Candidate SAT Structure design

- Ground shields are 25 m in diameter; can be placed next to each other
- With them close-packed, we can take advantage of the centralized space underneath them.
  - Control rooms (under the telescope mount and ground shield) are directly connected to a shared central workspace.
    - Footprint scales with number of SATs
  - The central space must allow for integrating all the SAT receivers that you would be deployed at one time
    - SATs are then directly hoisted up into the center of their groundshields, which are above the integration space
  - Utilities are provided by a separate utilities yard as currently planned in the Chile design.
  - This scheme is scalable if more SATs need to be supported (extend the pattern).

Top view of SAT building concept

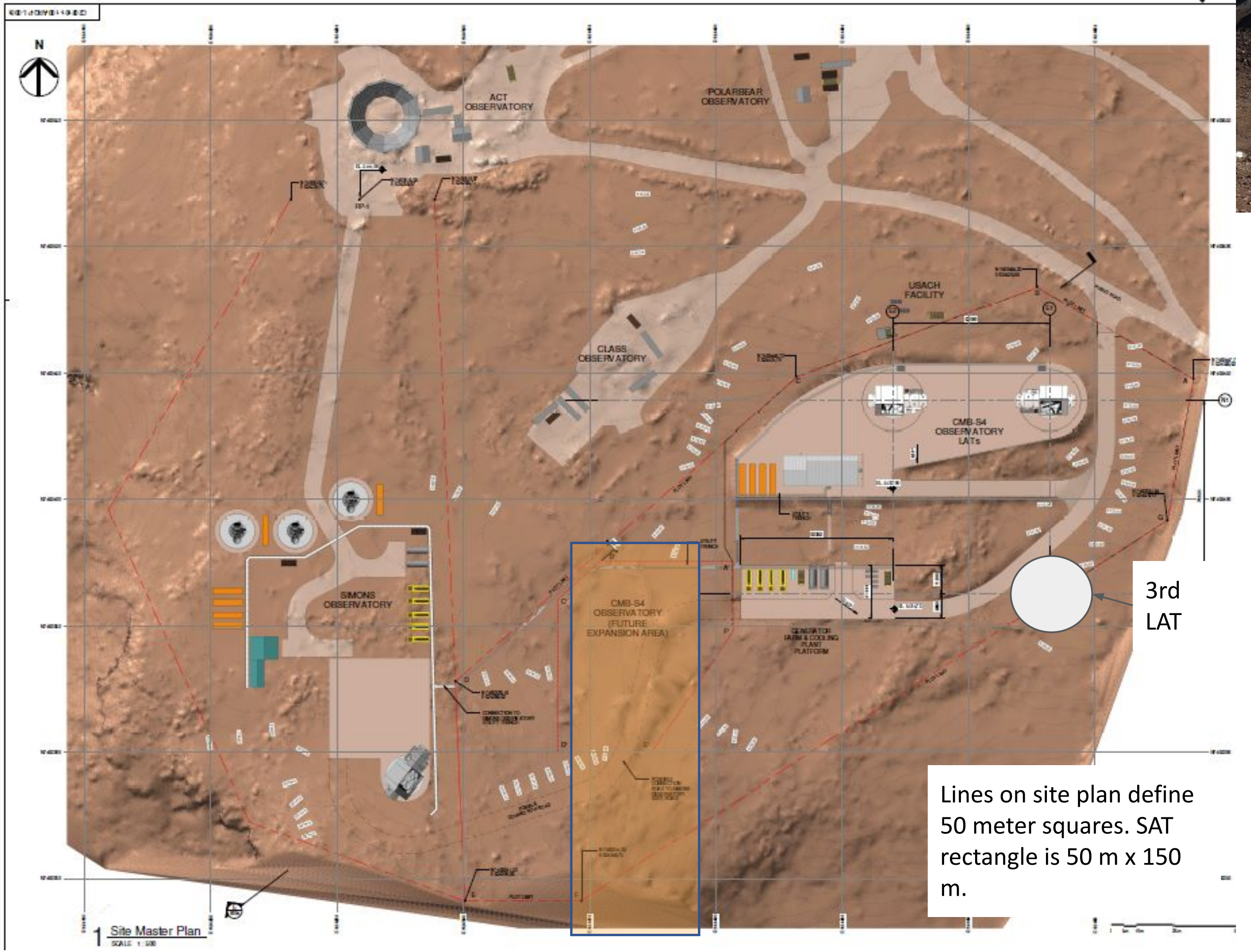


- Hoist points below the center of each SAT (on 25 meter centers)
- Provides a significant amount of integration space between the hoist points. Total area of building to be determined in more detailed design. Could be a central narrower building with wings that go out to each SAT, for example.
- Top floor provides an instrument space. People move to the top floor in elevators
- Electrical & Cooling provided by central plant as in current Chile plan, with that plant enlarged as necessary

Candidate Layout A

Land where SATs go is lower than S4 and SO LATs. Horizon blockage calculations would need to be re-done taking that into account. However, note also that the S4 LATs are to the northeast and maybe we don't have a strict a requirement there. The SO LAT is the one that needs more consideration. In this layout it is about 60 meters away from the groundshield lip of the nearest SAT, significantly farther than the minimum distance defined by the horizon blockage criteria.

Note that we need to define a minimum distance between the SATs and the possible heat plumes from the generator and cooling plant, and distance from CLASS



3rd LAT

Lines on site plan define 50 meter squares. SAT rectangle is 50 m x 150 m.

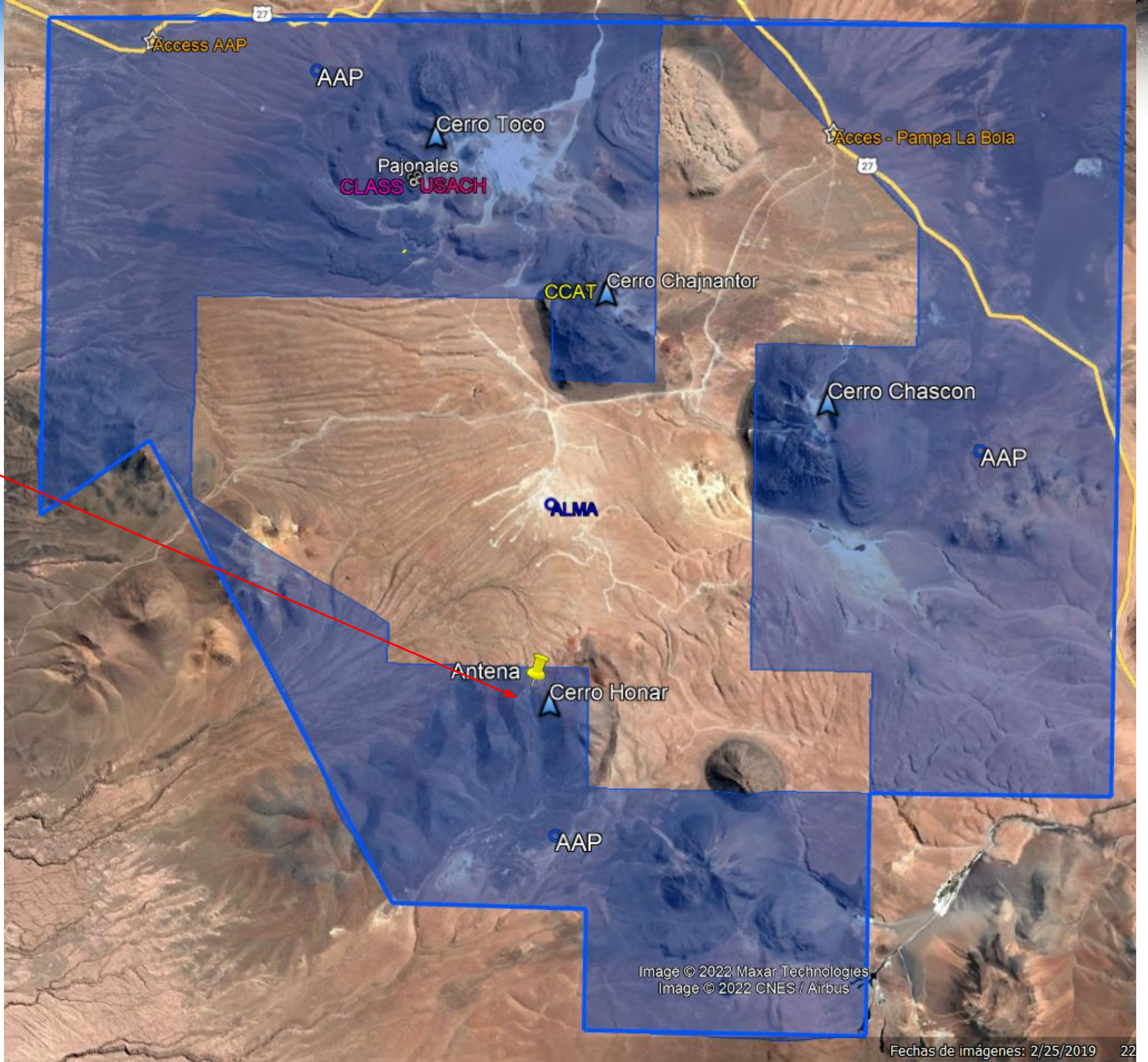
If Horizon blockage by Toco is unacceptable

Cerro Honar

- Lower North horizon blockage
- Characterized by CCAT, TMT
- Used by ALMA as a remote calibrator station
- Has line-of-site for free-space optical to either ALMA AOS or Toco site.
- Is not considered extreme altitude (in contrast with the Chajnantor summit site)

Comments on this site:

- Would we put all CMB-S4 equipment here?
- Farther from San Pedro, and the road goes through the ALMA concession
- Need to rely on free-space data link. This would be fine for SATs, but if all the LATs were here the technology may be more difficult
- Could not leverage cooperation with existing experiments



Views from Cerro Honar

Need to do a survey, but we think the horizon blockage is below 2 degrees in every direction

Source: *Cornell Caltech Atacama Telescope (CCAT), Feasibility/Concept Design Study*. Final Report, January 2006 (link)

Figure 10.2.4. View from the Honar Ridge to the North UIT Chajnantor and Chascon on Front

View to N

Figure 10.2.5. View from the Honar Ridge to the West

View to W

Figure 10.2.6. View from the Honar Ridge to the south

View to S

Site Constraints Back-Up Slides

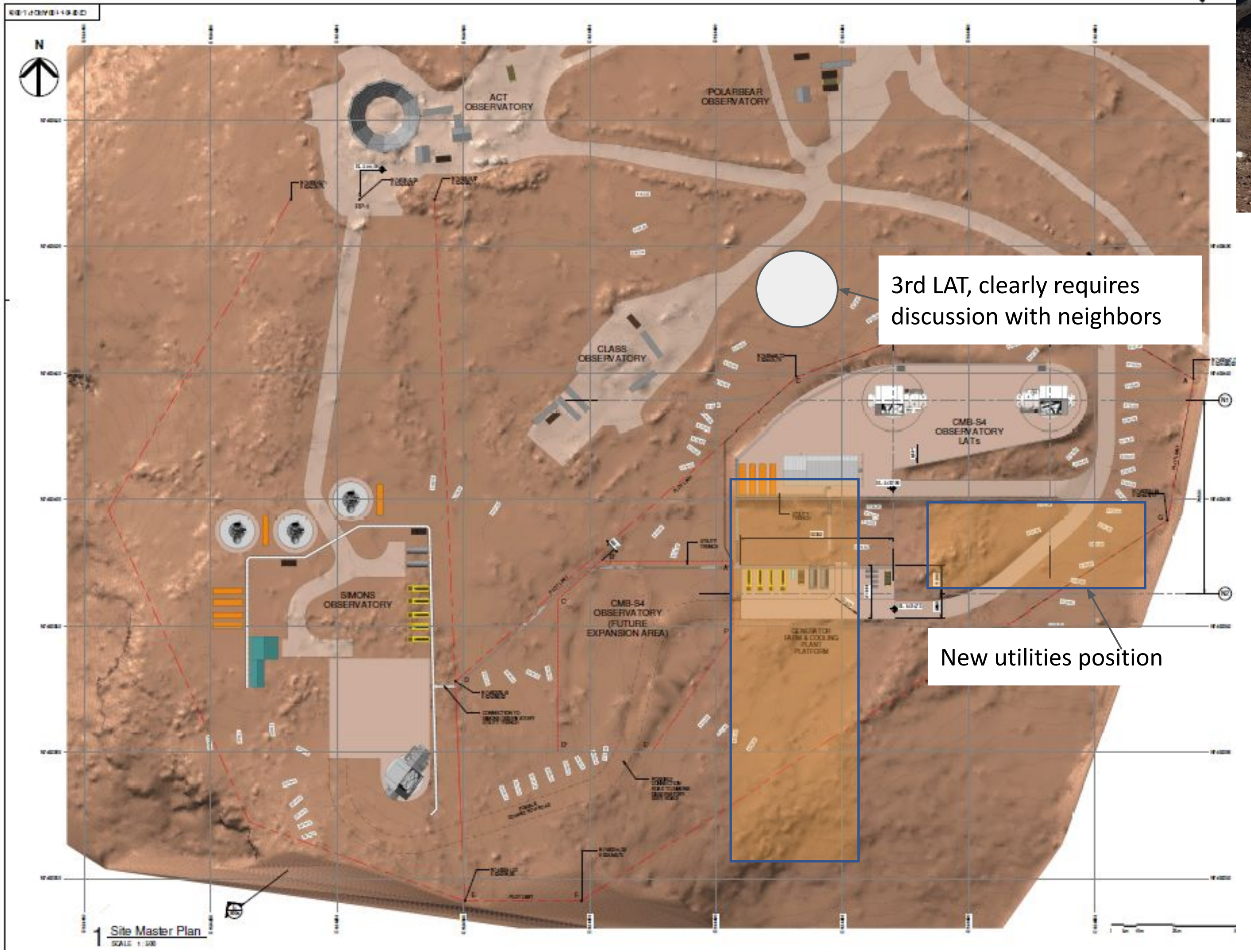
Data

- Current Chile need is 1.3 Gbps, satisfied in a 5 Gbps or 10 Gbps allocation.
- Current SAT data rate for 6x3 SATs is 0.57 Gbps. We assume twice this number of SATs, so total data for the three sats is 1.04 Gbps.
- If we assume another LAT with 0.65 Gbps, then the total data rate needed from Chile to North America is 2.5 Gbps
- 2.5 Gbps can be accommodated within one 10 Gbps connection, or we could work with REUNA to provision more if necessary.

Candidate Layout B

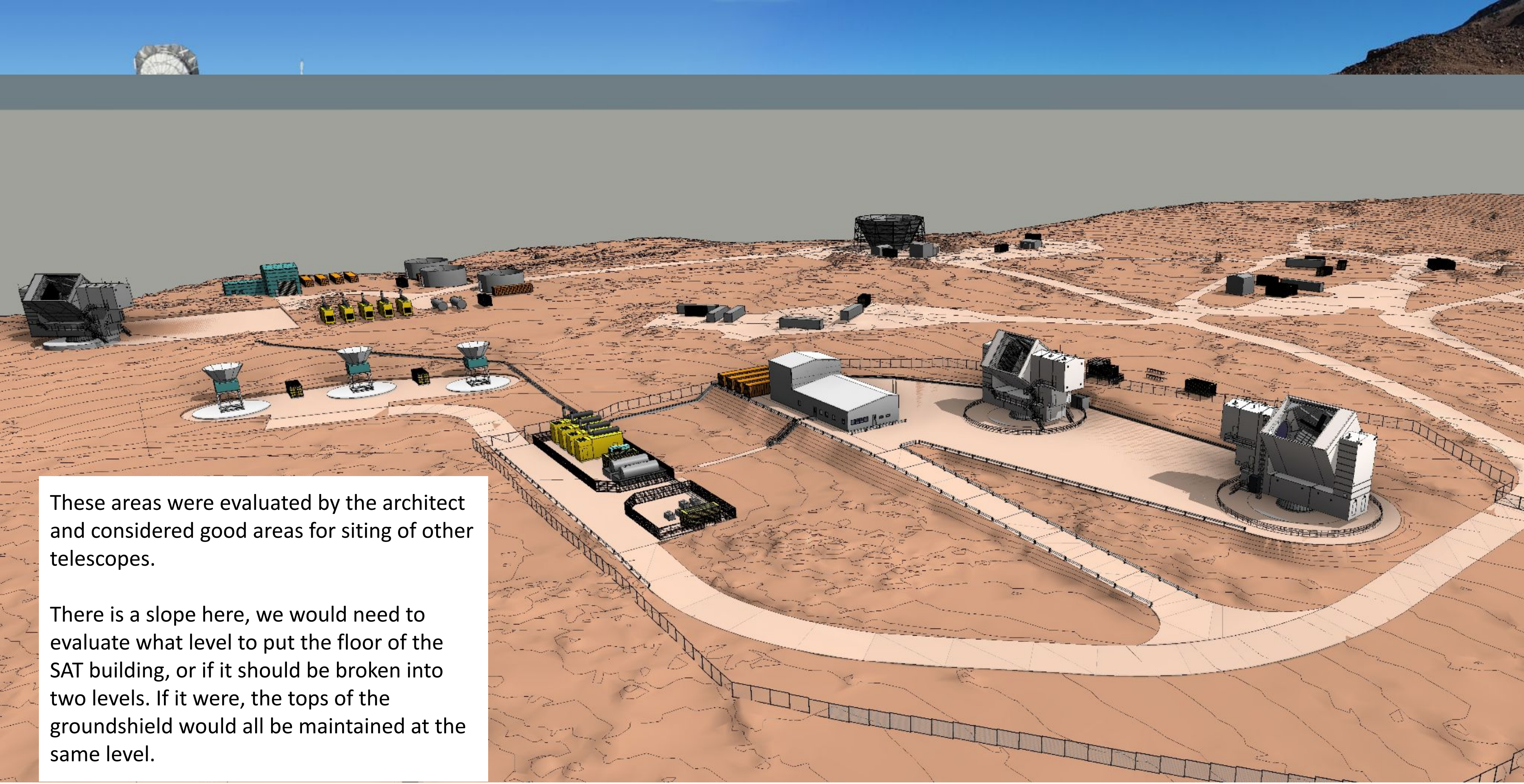
Move utilities to the East so that the S4 SATs can be moved farther from the SO LAT and the CLASS telescopes

Remove high bay and office from existing Chile plan, and house all that in the building under the SATs



3rd LAT, clearly requires discussion with neighbors

New utilities position

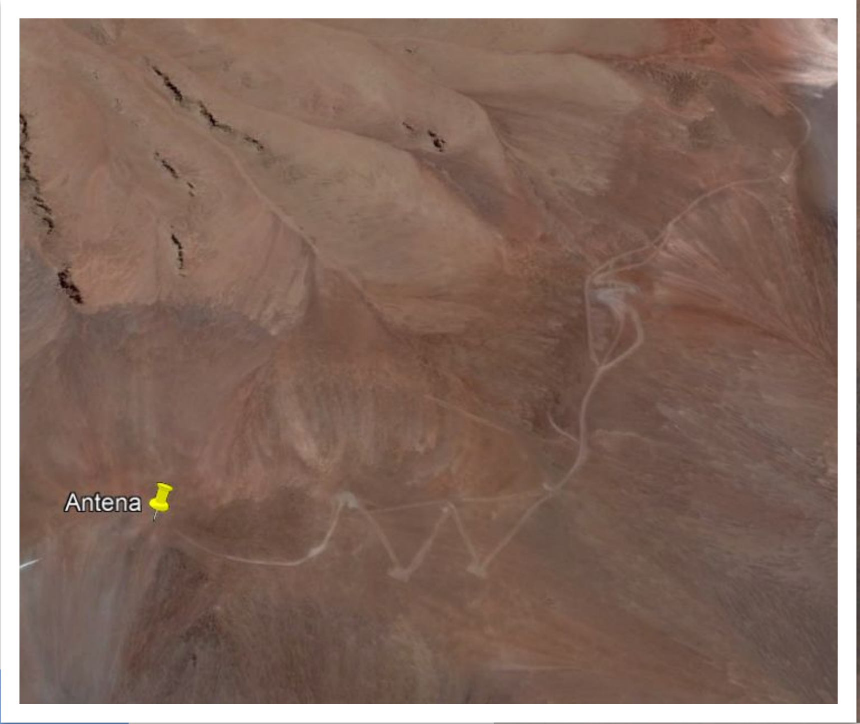


These areas were evaluated by the architect and considered good areas for siting of other telescopes.

There is a slope here, we would need to evaluate what level to put the floor of the SAT building, or if it should be broken into two levels. If it were, the tops of the groundshield would all be maintained at the same level.

Cerro Honar


Antena
Image © 2022 CNES / Airbus
Image © 2022 Maxar Technologies
Google Earth
Fechas de imágenes: 3/31/2016 23°03'30.33" S 67°44'14.22" O elevación 5032 m alt. ojo 10.37 km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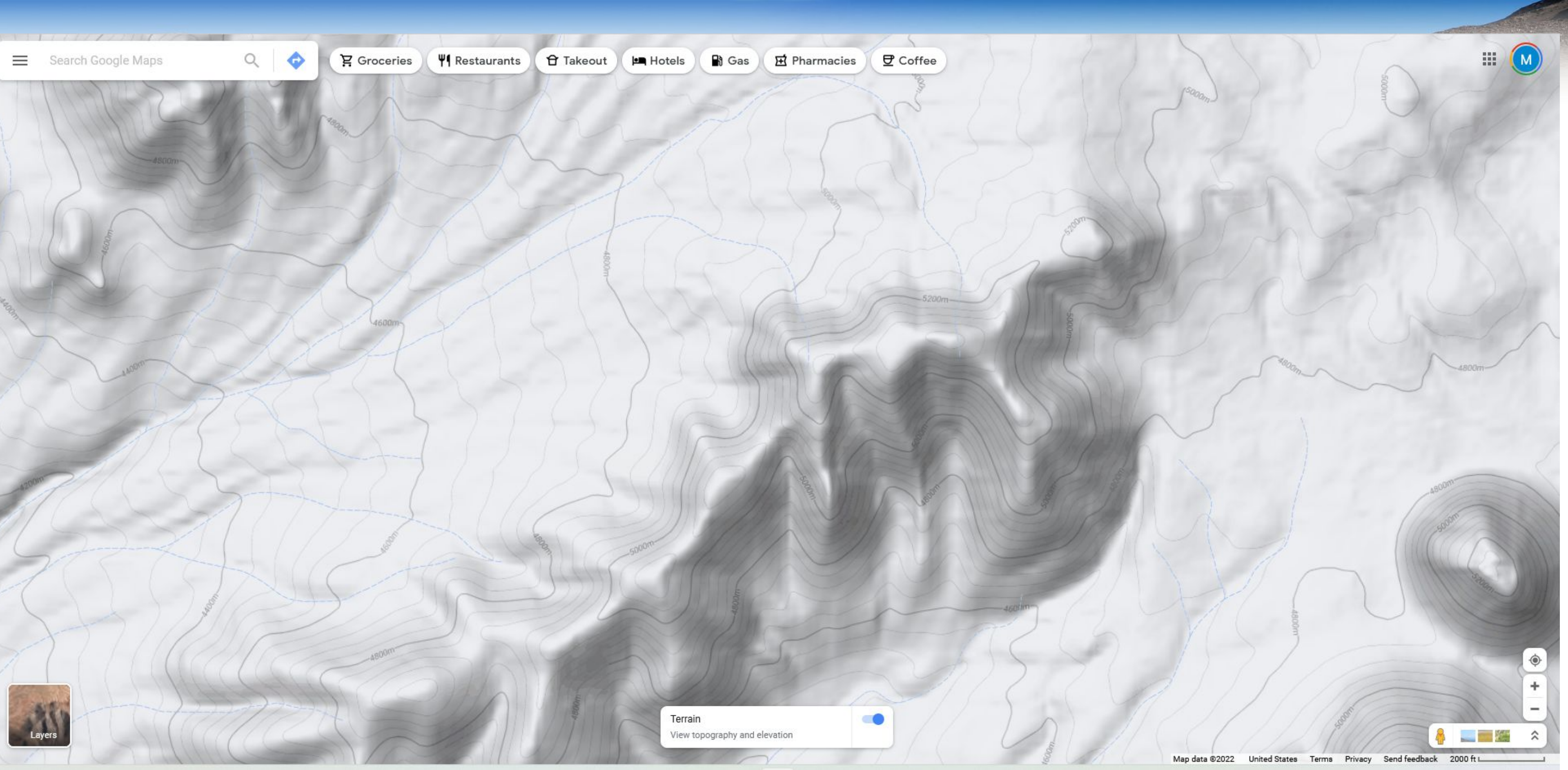
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Hotels
Gas
Pharmacies
Coffee
M
4800m
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4200m
5000m
5200m
5700m
Layers
Terrain
View topography and elevation
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CMB-S4

Slide Title

- Slide text