r forecasting for the AoA and beyond

Colin Bischoff (he/him)

CMB-S4 Collaboration Meeting
April 3-6, 2023

CMB-S4

Ingredients for r forecasting

- Raw sensitivity of the frequency maps. Survey weight in units of μK^{-2} scales linearly with total number of detector-years.
- Sky coverage, i.e. effective number of modes.
- Level of delensing, depends on sensitivity (and fidelity) of LAT maps.
- Foreground cleaning / separation. Multiple methods possible, making different assumptions about foregrounds.
- Systematics, which can contribute spurious B-mode power (additive) or affect signals present in the maps (multiplicative).

All of these ingredients are critically important to achieve $\sigma(r)$=5e-4. Can't neglect any of them and complicated trade-offs exist.

How r forecasting was carried out for forecasting paper, DSR, etc

- **Raw sensitivity of frequency maps:** Scale from achieved survey weight of BICEP/Keck by number of detector-years, adjusting for ideal detector NET, beam size, and frequency bands. This preserves BICEP sensitivity hits from detector yield / non-ideality, observing efficiency, cuts, etc.
- **Effective number of modes:** Simulations of scan strategy provide sky coverage for CMB-S4. Scale the BICEP/Keck effective number of modes by the ratio of noise-effective fsky, which captures a realistic estimate for mode loss from filtering.
- **Residual lensing power:** Calculated from LAT noise forecasted. Validated on map-based sims by Julien Carron and Sebastian Belkner (paper in prep).
- **Foreground cleaning:** Forecasts assumed a model that is consistent with BICEP observations (plus a little complication). Tested with map-based sims using a range of foreground models.
- **Systematics:** Instrument design closely follows BICEP example. Assume that we will match or exceed that systematic control after lots and lots of work.

The Analysis of Alternatives problem

- Limitations on infrastructure at South Pole forced us to rescope from an original plan that consisted of six 3-shooter SATs plus one SPLAT, all at the Pole.
- **Critical that we still achieve our science target, $\sigma(r)$=5e-4.**
- Narrowed down parameter space to three alternatives:
  - Alt 1: Three 3-shooter SATs plus SPLAT, all at the Pole.
  - Alt 2: Four 3-shooter SATs at Pole, but no SPLAT. Add additional CHLATs for delensing.
  - Alt 3: Nine 3-shooter SATs in Chile with smaller apertures and HWP. Add a third CHLAT (or more) to assist with delensing.
- For any of these configurations, we can extend the survey duration beyond the nominal seven years.
- For all alternatives, we still have the two original CHLATs to carry out the non-r CMB-S4 science.

How did we update the r forecasting?

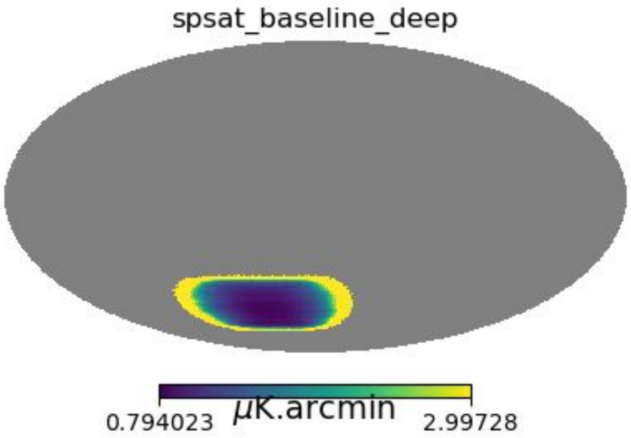
- The long history of BICEP/Keck operations provides a reliable estimate of survey weight per detector-year achievable from the South Pole (in each frequency band). We don’t have a similar reference for Chile.
- Appendix A of the DSR took a simple approach:
  - Table A-4 assumed equal survey weight per detector-year from the two sites. Other factors (sky area, delensing, foregrounds) still lead to differences between Chile and Pole r forecasts.
  - Table A-5 assumed that SATs in Chile would achieve only 50% as much survey weight per detector-year as SATs at Pole.
- For AoA, we quantified some survey weight / efficiency factors while ignoring ones that are poorly understood. Improved precision… but with what accuracy?
- Forecasts need to account for foreground variation across the sky regions observed from Chile.

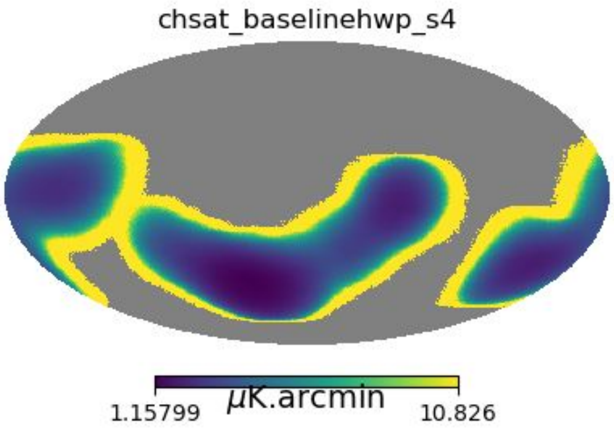
How did we update the sensitivity forecast? (1/3)

- Sara Simon led Observing Strategy group to collect information about efficiency factors. Focus on factors that might differ between alts 1,2 (Pole) vs alt 3 (Chile). Most important factors *that differ between sites* are:
  - Lose some time in Chile for Sun/Moon avoidance
  - Lose some time in Chile when PWV > 3 mm (> 2 mm for 220/270 GHz)
  - Lose some time in Chile for downtime / recovery from storms
  - SAT with HWP can scan slower, spend less time on turnarounds
- We have some knowledge about atmospheric differences between the two sites:
  - Chile site is at higher altitude
  - Chile site has higher median PWV and broader distribution of PWV
  - We don’t know much about “sky noise”, i.e. amplitude and scale of atmospheric fluctuations

How did we update the sensitivity forecast? (2/3)

- Using the inputs from the previous slide, Reijo simulated depth maps for the three alternatives.
    - Simulations obeyed the observing strategy / efficiency factors compiled by Sara.
    - Simulations used John Ruhl's detector NET model that accounts for atmospheric differences between the sites and varies with observing elevation and PWV values that are drawn from site-specific distributions.





How did we update the sensitivity forecast? (3/3)

- These depth maps allow us to calculate the **relative survey weight** between our different alternatives. This allows us to account for certain factors that we think we understand or can estimate -- atmospheric contributions to NET, observing strategy differences -- but other factors are assumed to be the same (because we don't know any better).

Rel. survey weight: 9 SATs in Chile vs 3 SATs at Pole	**25 GHz**	**40**	**85**	**95**	**145**	**155**	**230**	**280**
	1.5	2.4	2.2	1.9	1.4	1.3	1.2	1.1

How did we update the fsky and delensing?

- Depth maps also define the sky coverage for the different alternatives.
  - We still scale the effective number of modes from BICEP to capture mode loss from filtering.
- Delensing options become complicated (but forecasts still follow the same methodology)
  - For alt 1, the SPLAT carries out a deep survey to delens the SAT maps
  - For alt 2, we get some delensing from the wide-field survey but found that we needed to either add three new CHLAT dedicated to delensing or else one new CHLAT but then convert all three to a hybrid delensing/wide-field survey.
  - For alt 3, we get some delensing from the wide-field survey and add one new CHLAT that focuses on delensing the four sub-fields observed by the Chile SATs.

How did we update the foregrounds?

- In Alt 3, the sky coverage is spread out across four sub-fields that have significantly different foreground levels. Assuming foregrounds consistent with BICEP observations is not valid for this configuration.
- Instead, we used three foreground models provided by Pan-Ex Galactic Science. These models are qualitatively similar to what has been used in Low-ell BB map-based sims (but not in Fisher forecasting):
    - Low-complexity model with no variation of foreground spectral parameters
    - “Best estimate” model with spectral parameter maps derived from data
    - High-complexity model with multi-layer dust, sync curvature, etc
    - Further updates have been made to these models since the AoA review to improve their agreement with data.
- Two different methods for handling foregrounds in forecast:
    - Colin used BICEP-style parametric likelihood for foreground separation
    - Raphael used harmonic-space ILC

How did we update the systematics?

- Regarding systematics, we still believe that following a conservative, well-tested instrument design will allow us to control systematics at the necessary level (with lots and lots of work).
- However, for alt 3 it is believed that rapidly rotating half-wave plates are needed to suppress unpolarized sky noise in Chile. This is a departure from BICEP experience.
  - HWP also limit the aperture size, which affects the detector NETs.
- We chose not to pursue configurations that pack more detectors into SAT focal planes. These configurations would improve receiver NET but could lead to unknown sidelobe systematics.
- Some concern exists about our ability to shield the SATs from mountains in Chile, which reach up to 15 degrees elevation as seen from the site.

Using SPLAT data at low ℓ

- The SPLAT telescope design (Three-Mirror Anastigmat) includes multiple features that were chosen to improve systematics control at large angular scales:
  - Monolithic primary mirror eliminates panel gaps could cause wide angle scattering
  - Boresight rotation enables systematics cross-checks and partial cancelation of some systematics in the full maps.
- For alt 1, we considered the impact of including SPLAT data at low ℓ for the r constraint (in addition to using it for delensing).
  - The shape of SPLAT N_ℓ curves was based on SPT-3G achieved noise.
  - Survey weight is scaled from BICEP/Keck under the assumption that analysis for B modes at ℓ ~ 80 will require similar filtering, cuts, etc.

AoA forecasts: years to reach σ(r)=5e-4

Alternative	Low-complexity		Best estimate		High-complexity	
	Colin	Raphael	Colin	Raphael	Colin	Raphael
1, w/out SPLAT	11.7	10.4	11.7	14.2	14.7	38.6
1, w/ SPLAT	9.3	7.7	9.0	10.7	10.9	25.8
2, (2+3)xCHLAT	11.5	9.8	11.4	16.4	14.0	34.4
2, 3xCHLAT-hybrid	14.1	12.3	13.7	20.1	>15	41.3
3, (2+1)xCHLAT	18.5	9.9	20.2	13.7	18.1	16.4

- Forecast methods disagree on the impact of high complexity foregrounds
- Forecast methods disagree on alternative 3
- But both methods favor alternative 1, especially if low ℓ SPLAT data is usable

Next steps

- Need to get to the bottom of forecast inconsistencies
  - Analyze map-based sims to validate Fisher forecasts and check for biases.
  - Include additional analyses as cross-checks: Ghosh/Delabrouille, others?
- Update foreground models based on recent work by Pan-Ex Galactic Science.
- Explore design optimizations:
  - What is the best distribution of LF, MF, and HF tubes for alts 2, 3? (Colin and Raphael forecasts didn’t agree on this)
  - For alt 1, does it make sense to move some LF sensitivity from SAT to SPLAT?
  - Optimize weight masks (was done for DSR but not for AoA)
- Keep an eye out for a CMB-S4 project proposal to tie up these loose ends, properly document the AoA forecasts, and publish the result.
  - Work will take place in the Low-ℓ BB Analysis Working Group.