SYSTEMATICS DICTIONARY

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ABSTRACT

A summary of systematics.

1 INTRODUCTION

The signal timestream registering in our detectors can be approximated by the following expression

$$\begin{aligned} d_i = K * \bigg(& n_i + g_i \int d\nu A_e(\nu) F(\nu) \int d\Omega P(\theta_i, \phi_i) \\ & \times [I(\theta_i, \phi_i) + \gamma_i (Q(\theta_i, \phi_i) \cos(2\psi_i) + U(\theta_i, \phi_i) \sin(2\psi_i))] \bigg) + \tilde{n}_i \end{aligned} \tag{1}$$

where $K*$ represents a convolution with the detector time response, n_i is the noise, which we assume is uncorrelated with signal, $A_e(\nu)$ represents the effective area of the telescope, $F(\nu)$ is the spectral responsivity, and $\tilde{n}_i$ represents noise terms that are not convolved by the detector response, including readout noise.

The above expression is in many ways incomplete. For example, it does suggest that the Stokes I, Q, and U parameters are frequency independent, which is certainly incorrect. The sky signal is generally composed of astrophysical signals with varying frequency dependence. This includes the CMB itself, thermal emission from dust, and synchrotron radiation. A CMB telescopes will observe the sky convolved with its beam function, $P(\theta, \phi)$.

2 OPTICS

2.1 Systematic/Property Name

DESCRIPTION: Description of systematic effect, including relevant equations and parameterization for TWGs. Note that each variable in each equation should be defined. This should include where we expect to get the value of this variable from (TWG, literature, etc.)

PLAN TO MODEL AND/OR MEASURE: Plan to model/measure effect

UNCERTAINTY/RANGE: This section should include the uncertainty of known parameters and/or the expected range of parameters for consideration

PARAMETERIZATION: This section should include the parameterization of figures of merit and the output to the SWGs.

2.2 Beam ellipticity

DESCRIPTION: Many CMB experiments are designed to have angular sensitivity that can be described by an azimuthally symmetric two-dimensional Gaussian function

$$P(\mathbf{x}) \propto \exp(-\mathbf{x}^2/2\sigma^2), \tag{2}$$

where σ represents the width of the beam. Optical aberrations will lead to asymmetries in the angular sensitivity which can often be captured by assuming that the Gaussian beam width is different along the two axis of a Cartesian coordinate system centered on the peak response

$$P(x,y) = \frac{1}{2\pi\sigma_x\sigma_y} \exp(-\frac{1}{2}[x^2/\sigma_x^2 + y^2/\sigma_y^2]). \tag{3}$$

This is referred to as an elliptical Gaussian function. The σ_x and σ_y parameters are the widths of the elliptical Gaussian beam along its two principal axes. The beam full width at half maximum (FWHM) can be defined

$$\theta_{\mathrm{FWHM}} = \sqrt{8\sigma_x\sigma_y \log(2)}. \tag{4}$$

We define beam ellipticity as

$$e = (\sigma_x - \sigma_y)/(\sigma_x + \sigma_y) \tag{5}$$

The beam ellipticity quantifies the extent to which the symmetry of the detector spatial response is broken. A highly elliptical beam response suggests that the detector signal response at any given time is dependent on the orientation of your detector relative to the signal on the sky; in other words, your scan strategy.

The spherical harmonic transform of an elliptical Gaussian beam is discussed in [1]. Let's try [2].

PLAN TO MODEL AND/OR MEASURE: Beam widths and ellipticities are extracted from beam maps which are acquired through scanning of a terrestrial source placed in the far-field of the optical system or by observing astrophysical point-sources such as the planets in our solar system.

UNCERTAINTY/RANGE: Insert text

PARAMETERIZATION:

2.3 Beam cross-polar response

DESCRIPTION: Insert text

PLAN TO MODEL AND/OR MEASURE: Insert text

UNCERTAINTY/RANGE: Insert text

PARAMETERIZATION: Insert text

2.4 Polarization Angle

DESCRIPTION: Sources of polarization angle systematics are varied and can be introduced several places in the instrument. To name a few examples, 1) a rotating elliptical beam (say in the case of a design incorporating bore-sight rotations) can cause T to P leakage, 2) off axis refractive optics influence the propagation of the polarization vectors according to their Fresnel coefficients leading to an instrumental polarization angle rotation and 3) in the presence of a HWP an apparent polarization angle rotation can arise from the detector time constants.

Perhaps 1) and 3) are best left to their respective sections on beams and time constants. Here we focus on 2), namely instrumental polarization errors and detector polarization angle rotations. Understanding this instrumental polarization error has implications not only for measuring CMB polarization, but for placing constraints on Cosmic Polarization Rotation (CPR).

A global polarization rotation is degenerate with a CPR angle and affects the power spectra as described in [3]. Analytic description of instrumental rotation is challenging, necessitating the use of optical modeling and experimental techniques for calibration of final detector angles (absolute and relative) and systematic rotations from the optics.

PLAN TO MODEL AND/OR MEASURE: We should plan to both model and measure the detector polarization angles. Calibration should be performed before deployment and during observations. This can be done with a lab calibrator as well as an astrophysical polarized source. Polarized sources already used as references include Tau A (the Crab Nebula) and Cen A.

When considering a lab source, placing a well known polarization calibrator in the far field is preferred, though difficult in practice. Proposed ideas include flying a source (whether tunable or wide band) on a drone or on a CalSat to place it in the far field. Alternative calibrators require placement in the near field and include sparse/dense wire grid polarizers or dielectric sheets [2, 4].

Modeling of the polarization rotation angle appears feasible and has been used on ACTPol using Code V [4]. This should be checked with physical optics calculations, but can be performed on a proposed telescope design.

UNCERTAINTY/RANGE: Angle offsets $\sim 1^\circ$ produce spurious B-mode signal at the same level as primodial B-modes for a tensor to scalar ratio $r \sim 0.005$ as well as nonzero EB and TB cross-correlations [5]. Currently employed calibration methods provide calibration to at best 0.5° [6]. Calibration to better than 0.05° would allow for constraints on CPR of order one degree to greater than 15σ [6].

PARAMETERIZATION:

3 SPECTRAL RESPONSE FUNCTION

3.1 Bandpass mismatch

DESCRIPTION: Different detectors might have different bandpasses. The total power received by a detector is the sum of each component coming from the sky integrated over the bandpass of the detector. Given that each component have a different spectrum, the calibration of the detectors are component dependent. For each component k and bolometer b, we can define a transmission coefficient

$$C_k^b = \frac{\int S_k(\nu)F(\nu)}{\int S_{CMB}(\nu)F(\nu)}. \tag{6}$$

These corrections factors to the gain should be applied whenever the signal has a different frequency dependance than the CMB. In practice, this will result in a mis-calibration like effect for all the foregrounds, producing temperature-to-polarization and polarization-to-polarization leakage.

PLAN TO MODEL AND/OR MEASURE: Spectral measurements for each detector should be performed in the laboratory and in the field once the telescope is installed. Using external foregrounds maps as templates, the leakage maps can be computed and subtracted. However, this method is limited by our knowledge of the foregrounds, and the external available data. Simulations to estimate the level of leakage and set a constraint on the differential bandpasses should be performed.

UNCERTAINTY/RANGE: This section should include the uncertainty of known parameters and/or the expected range of parameters for consideration

PARAMETERIZATION: This section should include the parameterization of figures of merit and the output to the SWGs.

4 POLARIZATION MODULATORS

4.1 Differential Optical Properties of a HWP

DESCRIPTION: Differential transmission, reflection and emissivity creates a 2f component in a polarimeter exploiting a rotating HWP

PLAN TO MODEL AND/OR MEASURE: Plan to model: HFSS model of the metamaterial HWP or data literature from Sapphire HWP. Plan to measure: differential transmission and reflection: FTS measurements; differential emissivity: HWP emissivity measurements at different temperatures (liquid nitrogen, room temperature and temperatures higher than room temperature).

UNCERTAINTY/RANGE: Transmission and reflection measured at room temperature scaled to cryogenic temperatures, same for differential emissivity.

PARAMETERIZATION: 12 Mueller matrix top left components of a real HWP or eq. (7) and (8) in

4.2 Thermal HWP Effects

DESCRIPTION: HWP thermal gradient and thermal fluctuations. A not uniform HWP temperature and its temporal fluctuations create a spatial and time dependent 2f signal.

PLAN TO MODEL AND/OR MEASURE: Model: thermal finite element analysis of a HWP thermalized with a suitable heat sink and with a realistic time variable loading. Measure: cryogenic measurements of the thermal gradients.

UNCERTAINTY/RANGE: Realistic model of the time variation of the loading.

PARAMETERIZATION: HWP thermal fluctuations: $\Delta_{\mathrm{HWP}}(x, y, t)$ with (x, y) the spatial coordinates of the HWP and t the time.

4.3 HWP Beam Systematics

Started By Sean Bryan

DESCRIPTION: Putting a HWP skyward of every optical element cures a range of beam and polarization systematics. However, putting a HWP inside the optical system induces some beam and polarization systematics of its own, and fails to cure some systematics you'd think it would. Thus, careful consideration is needed.

PLAN TO MODEL AND/OR MEASURE: Modeling would entail ray tracing and physical optics for a non-planar or non-uniform AR coated HWP. It would also require calculating the impact of non-uniform AR coatings or optical properties. Non-normal incidence effects...might matter...might focus the beam...ask ABS people on the theory side, and PB/ACT people on the experience side.

Also model how these beam systematics show up in the rapid-rotation demodulation. Even with an optimal mapmaker, ignoring this effect would mean they will show up likely as I-P and Q-U leakage beams with very funny structure. (Investigate making an optimal mapmaker for this..? Would definitely require data since the dipole-quadrupole small-distortion beam formalism may not apply here.)

In general, CST is commercial software that can model diffraction, without too much CPU time, from very funny shaped large structures (like struts and baffles and things). Putting the HWP into that model to get some of these beam systematics might be interesting.

Measurements, in principle, would be done with a long campaign of beam maps taken at a large set of HWP angle. And/or, in the case of a rapid modulator, very slow beam maps taken with several modulation cycles per beam scanned (unlike in science mode where we can scan fast). The source is TBD, a sky source seems like it would be slow, and informally in the meeting people were saying that a source on a mast will be difficult because it requires tilting the telescope to a low elevation that's mechanically difficult.

UNCERTAINTY/RANGE: Very uncertain "prior" on this, could be no effect, could be huge and a showstopper.

PARAMETERIZATION: Leverage existing beam formalisms? Leverage Maria, Sean, Tom E-H, others, work on polarization non-idealities of the HWP, but combine it with beam formalisms?

5 TIME CONSTANTS

Detector time-response features can be probed by scanning quickly over bright objects such as planets, but our ability to probe such features might be limited by the maximum scan speed of the telescope mount. TES bolometers are instrinsicly quite fast 1 ms time-response. Features due to variation in scan speed might be visible in maps with sufficient integration. Additionally, when using a HWP, changes in time constant can change the apparent polarization angle, which must be corrected for.

6 CROSSTALK

DESCRIPTION: The frequency multiplexing readout has crosstalk due to the finite width of the LC resonators. Crosstalk from one bolometer to another due to coupling in the multiplexed readout will lead to polarization and temperature leakage from a point outside the main beam, creating a localized, polarized near side lobe. Crosstalk is strongest in bolometer channels that share a SQUID in the frequency-domain multiplexed readout, and are closest together in bias frequency.

PLAN TO MODEL AND/OR MEASURE: Planet observations (beam maps). POLARBEAR assumed constant level of crosstalk between neighbour bolometers. We may want to have a spatial distribution across the focal plane for more realism.

UNCERTAINTY/RANGE:

PARAMETERIZATION:

7 GAIN MISMATCH

7.1 Time variation

DESCRIPTION: Depending on the technique used to calibrate the thermal-response of the timestream, there might be several science scans taken in between two calibration measurements. In between two calibration measurements, the thermal calibration of each detector might drift (*time variation*) from its initial value, and significantly. A possible procedure to correct for time variation over the duration of a science scan is to interpolate our gains between measurements of the thermal calibration source taken at the beginning and end of the observation periods. Obviously this technique is not perfect and will lead to some residual.

PLAN TO MODEL AND/OR MEASURE: In order to understand the impact of potential errors in this interpolation, we can for example construct a set of gains based only on the initial (or final) calibration measurement thus use no interpolation. Say now that a simulated map with no B-modes is "observed," producing timestreams using the non-interpolated gain model, and then reconstructed using the interpolated analysis gain model. The level of resulting C_ℓ^{BB} (null to start with) quantifies the difference in these gain models in power spectrum space, and thus puts an upper limit on the impact of the drifts.

(Sean Bryan Addition)

For Spider TES camera, and maybe Keck/BICEP I'm not sure, we would inject small electrical signals into the detectors regularly. We called this Bias Steps, it's written up in peoples' theses, but they might be embargoed, but if there's interest I'm sure that bit can be released. This, combined with lab measurements proving that it correlated well with actual gain, was very convienient.

For the NIKA LEKID camera, the NIKEL readout electronics monitored both on and near-resonance frequencies. That way when the DC loading, and therefore the gain, would change, this was monitored in realtime. Every single TOD sample had a corresponding gain measurement, which was nice because there didn't need to be interpolation. If SO uses LEKIDs, we should implement something like this. If we use DfMUX bolometers, we should see if a complimentary technique can be invented.

(End Sean Bryan Addition)

(Loic Maurin Addition)

Bias Steps (described by Sean) are currently used in ACTPol for calibration. They can be performed quite often and do not perturb the detectors much (limited loss of data). Nevertheless, they do not provide an accurate responsivity for all detectors, so we identify a set of detectors for which the BS are accurate to set the gain, and flat-field the other detectors using the atmospheric signal.

Atmospheric signal is strongly dominant at low frequency and provide a real time relative calibrator. Difficulties arise from its modeling (at 1st order, the atmosphere is seen as homogeneous by the array; substructures should be taken into account to improve accuracy of the method though) and from the degeneracy between the atmosphere signal and thermal fluctuations in the cryostat.

(Loic Maurin Addition)

UNCERTAINTY/RANGE:

PARAMETERIZATION:

7.2 Differential gain

DESCRIPTION: Miscalibrations of relative bolometer gains in a pixel pair will "leak" temperature signal into Q and U. This effect is particularly enhanced if we subtract two bolometers within pairs to obtain the polarized part of the timestream. If we just deconvolved timestreams (using rotating HWP), we might not really care about this?

(Loïc addition)

I am not sure to understand the last comment.

(end Loïc addition)

PLAN TO MODEL AND/OR MEASURE: Leakage from gain mismatch can be computed using the formalism described in [7]. Simulations for various scanning strategies should be performed.

These simulations will be useful not only to estimate the precision we need for the gain but also for the polarization efficiencies and detector orientations.

8 SPURIOUS SIGNAL AND NOISE

9 ATMOSPHERIC EFFECTS

10 PAPERS ON SYSTEMATICS

There exist a number of useful papers that discuss characterization of systematics and their potential effects on CMB experiments. The following list is by no means exhaustive.

Papers that discuss systematics in the context of particular experiments

BICEP2 COLLABORATION (2015) BICEP2 III: Instrumental Systematics

- Instrument and systematic characterization for the BICEP2 experiment
- Topics: beams, pointing, crosstalk, ghost beams, polarization angles, detector transfer functions, EMI, etc.

POLARBEAR COLLABORATION (2014) A Measurement of the Cosmic Microwave Background B-Mode Polarization Power Spectrum at Sub-Degree Scales with POLARBEAR

- B-mode measurement by POLARBEAR. Sec. 7 describes in detail the systematic instrumental effects, and their evaluation.
- Topics: Differential gain, gain drifts, beams, pointing, crosstalk, polarization angles, polarization efficiency, HWP dependency, etc.

FRAISSE ET AL. (2011) SPIDER: Probing the Early Universe with a Suborbital Polarimeter

- In many ways a continuation of the work presented in Takahasi et al. Some additions include taking a look at polarized sidelobes.

TAKAHASHI ET AL. (2009) Characterization of the BICEP Telescope for High-Precision Cosmic Microwave Background Polarimetry

- Description of paper content

ROSSET ET AL. (2010) Planck pre-launch status: High Frequency Instrument polarization calibration

- Setting constraints on the relative calibration for gains, polarization efficiencies and polarization angles in the focal plane needed to achieve Planck goals in terms of T,E,B leakage.

Papers that provide a general discussion of systematics associated with CMB experiments

KEATING, SHIMON, YADAV (2012) Self-Calibration of CMB Polarization Experiments

- This paper describes a method that calibrates the polarization angles by enforcing **EB** and **TB** to zero.
- Topics: polarization angles

HANSON, LEWIS, CHALLINOR (2010) Asymmetric Beams and CMB Statistical Anisotropy

- Discussing mathematical tools that allow one to propagate beam asymmetries into effects on CMB power spectra.
- Topics: beams

SHIMON ET AL. (2008) CMB Polarization Systematics Due to Beam Asymmetry: Impact on Inflationary Science

- Topics: beams

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[5] Paolo de Bernardis and Silvia Masi. Cosmic microwave background and cosmic polarization rotation: An experimentalist view. *International Journal of Modern Physics D*, 25(11):1640012, 2016.

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