CHillCalc2 User Manual
Version 0

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2018-01-28

Contents

1 Getting Started

This section covers the basic information needed to get started using `CHillCalc2`.

1.1 System Requirements

To run CHillCalc, you need

1. Python v2.7
2. Numpy v1.8 or above

1.2 Source code location

`CHillCalc2` is stored on Sara Simons git account `smsimon` within the repository `smsimon/sensitivity_calculators`. All relevant files are stored within the top-most directory of the repo:

```
~/ sensitivity_calculators/SO_SensitivityCalculator/CHillCalc2/
```

For the rest of this document, we will refer to this directory as simply `CHillCalc2`.

1.3 Setting the environment

There are two files used to set the environment. If operating in a bash environment, run

```
CHillCalc2$ source env.sh
```

If operating in a C shell environment, run

```
CHillCalc2$ source env.csh
```

This adds `CHillCalc/src`, which contains all custom python modules, to the `$PYTHONPATH` such that executables them.

1.4 Running `mappingSpeed.py`

There is one executable in CHillCalc called `mappingSpeed.py` that calculates optical power, noise equivalent power (NEP) contributions from photon noise, bolometer thermal carrier noise, readout noise, per-detector noise equivalent temperature (NET), array NET, mapping speed, and map depth. `mappingSpeed.py` takes as input an experiment configuration directory, which are stored in `CHillCalc/Experiments` and have the following structure:

```
CHillCalc/
 |-- Experiements/
 |     |-- Experiment 1/
 |     |     |-- Experiment Design 1/
 |     |     |-- Experiment Design 2/
 |     |     |-- ...
 |     |-- Expierment 2/
 |     |-- ...
```

To calculate the sensitivity an experiment, pass its `Experiment Design` directory to `mappingSpeed.py`. For example:

```
CHillCalc2$ python mappingSpeed.py Experiments/SimonsObservatory/V3/
```

Note that you need to put a slash at the end of the experiment directory for the executable to properly interpret the input.

1.4.1 mappingSpeed_params.txt

`mappingSpeed.py` also takes several input parameters which are stored in

```
CHillCalc2/config/mappingSpeed_params.txt
```

Below is a list of the parameters listed in `mappingSpeed_params.txt`.

- **Cores**
  - *Description*: Number of cores to pool for parallel processing
  - *Allowed Values*: Positive integer between $[1, +\infty)$
  - *Default Value*: 1
- **Verbosity**
  - *Description*: Logging verbosity. 0 to print all output, 1 to print some output, 2 to print little output
  - *Allowed Values*: Integer between [0, 2]
  - *Default Value*: 1
- **Experiments**
  - *Description*: Number of experiment realizations to Monte Carlo; each experiment has independently-sampled parameters defined in`foregrounds.txt`, `program.txt`, `camera.txt`, and `optics.txt`.
  - *Allowed Values*: Positive integer $[1, +\infty)$
  - *Default Value*: 1
  - If 1, assume central value for all parameters defined in `foregrounds.txt`, `program.txt`, `camera.txt`, and `optics.txt`.
- **Observations**
  - *Description*: Number of independently-sampled [Elevation, PWV] values per experiment realization
  - *Allowed Values*: Positive integer $[1, +\infty)$
  - *Default Value*: 1
- **Detectors**
  - *Description*: Number of independently-sampled parameters defined in `channels.txt` per observation
  - *Allowed Values*: Positive integer $[1, +\infty)$
  - *Default Value*: 1
  - If 1, assume central value for all detector parameeters
- **Elevation**
  - *Description*: Use this elevation for all [Elevation, PWV] samples
  - *Allowed Values*: A floating point value between [30, 75] deg

    - *Default Value*: 60.0
    - If "NA," elevations are to be drawn from either `elevation.txt` or default probability distribution function
- **PWV**
    - *Description*: Use the same PWV for all [Elevation, PWV] samples
    - *Allowed Values*: A floating point value between [0.0, 8.0] mm
    - *Default Value*: 1.0
    - If "NA," PWV values are to be drawn from the PWV probability distribution function for the Atacama observation site
- **Resolution**
    - *Description*: Frequency resolution of integrals over spectra
    - *Allowed Values*: A positive floating-point value between (0.0, 20.0] GHz
    - *Default Value*: 0.1
- **Correlations**
    - *Description*: Whether to impose white noise correlations when calculating array NET
    - *Allowed Values*: "True" or "False"
    - *Default Value*: "True"

2 Defining an Experiment

There are many parameters that define the input experiment. In this section, we go through them by input file.

2.1 Directory Layout

The experiment directory is meant to be easily generalizeable to various kinds of experiments and telescopes. Below is an overview of the file structure.

```
CHillCalc2/Experiements/[Experiment Name]/[Experiment Design]
 |-- config
 |    |--foregrounds.txt
 |--Telescope 1/
 |    |-- config/
 |    |    |-- program.txt
 |    |    |-- elevation.txt
 |    |    |-- [Custom Atmospheric Profile] (optional)
 |    |-- Camera 1/
 |    |     |-- config/
 |    |          |-- camera.txt
 |    |          |-- channels.txt
 |    |          |-- optics.txt
 |    |          |-- Bands/
 |    |              |-- Optics/
 |    |              |    |-- [Optic Band File 1] (optional)
 |    |              |    |-- [Optic Band File 2] (optional)
 |    |              |    |-- ...
 |    |              |-- Detectors/
```

```
|     |                    |-- [Detector Band File 1] (optional)
|     |                    |-- [Detector Band File 2] (optional)
|     |             |-- ...
|     |-- Camera 2/
|     |-- ...
|-- Telescope 2/
|-- ...
```

Each experiment definition has four layers:

1. Experiment
   - Composed of (multiple) telescopes
   - All telescopes in a given experiment see the same galactic foregrounds
2. Telescopes
   - Composed of (multiple) cameras
   - All cameras in a given telescope see the same atmosphere
   - All cameras in a given telescope have the same scan strategy
3. Cameras
   - Composed of (multiple) frequency channels
   - All frequency channels in a given camera have the same camera parameters
   - All frequency channels in a given camera see the same optical chain
4. Channels
   - Each channel has independent detector and optical element parameters

These layers allow telescopes to added to an experiment in an arbitrary location, each with arbitrary cameras, each with arbitrary frequency channels.

2.2 Parameter Definitions

All parameters in `CHillCalc2` are defined with a central value and an error bar. Parameter variation is assumed to be sampled from a Gaussian distribution, which is a useful first-order approximation.

Parameters defined `foregrounds.txt`, `program.txt`, `camera.txt`, and `channels.txt` have the following format:

```
Mean +/- Std Dev
```

The following formatting rules should be followed for the code to work robustly and the tables to render neatly:

1. All central values and standard deviations should have five characters. For instance, `1.000` and `10.00` are valid, while `10.000` is not.

2. All central values and standard deviations should be separated by ` +/- `, noting the spaces on either side of the $+/-$ sign

Parameters defined in `optics.txt` are defined for multiple bands in multi-chroic cameras and therefore follow a different format:

```
[Mean for Band 1, Mean for Band 2, ...] +/- [Std Dev for Band 1, Std Dev for Band 2, ...]
```

In a similar way to with the single values, the following formatting rules should be followed for the code to work robustly and the tables to render neatly:

1. All central values and standard deviations should have five characters. For instance, `1.000` and `10.00` are valid, while `10.000` is not.

2. All arrays of central values and arrays of standard deviations should be separated by ` +/- `, noting the spaces on either side of the $+/-$ sign

2.3 Experiment Parameters

The experiment is comprised of an arbitrary set of telescopes, which are assumed to see the same cosmos, including power from the CMB and galactic foregrounds.

2.3.1 `foregrounds.txt`

The below list overviews the parameters defined in `foregrounds.txt`, the file that defines the galaxy through which the telescope must observe the CMB. This cosmos will be the same for all telescopes.

- **Dust Temperature**
  - *Description*: Dust modified blackbody temperature
  - *Allowed Values*: Floating point value between $(0.0, +\infty)$ K
  - *Default Value*: 19.70
- **Dust Spec Index**
  - *Description*: The spectral index of the dust modified blackbody spectrum
  - *Allowed Values*: Floating point value between $(-\infty, +\infty)$
  - *Default Value*: 1.50
- **Dust Amplitude**
  - *Description*: Amplitude of the dust modified blackbody spectrum
  - *Allowed Values*: Floating point value between $(0.0, +\infty)$
  - *Default Value*: 2×10^{-3}
- **Dust Scale Frequency**
  - *Description*: Scale frequency for the dust modified blackbody spectrum
  - *Allowed Values*: Floating point value between $(0.0, +\infty)$
  - *Default Value*: 353.0 GHz
- **Synchrotron Spec Index**
  - *Description*: Spectral index of the synchrotron power law spectrum
  - *Allowed Values*: Floating point value between $(-\infty, +\infty]$
  - *Default Value*: 2×10^{-3}
- **Synchrotron Amplitude**
  - *Description*: Amplitude of the synchrotron power law spectrum
  - *Allowed Values*: Floating point value between $(0.0, +\infty)$
  - *Default Value*: 6×10^{3}

2.4 Telescope Parameters

In the following sections, we will overview the input parameters for each of the telescope input files.

2.4.1 `program.txt`

The below list overviews the parameters defined in `program.txt`, the file that defines programmatic inputs to the telescope.

- **Observation Time**
  - *Description*: How long this telescope will observe
  - *Allowed Values*: Floating point value between (0.0, $+\infty$) years
  - *Default Value*: 3.0
- **Sky Fraction**
  - *Description*: What fraction of the sky this telescope will observe
  - *Allowed Values*: Floating point value between (0.0, 1.0]
  - *Default Value*: 0.7
- **Observation Efficiency**
  - *Description*: What fraction of the observation time will the telescope be actually observing
  - *Allowed Values*: Floating point value between (0.0, 1.0]
  - *Default Value*: 0.8
- **NET Margin**
  - *Description*: Agnostic factor which multiplies the detector NETs for this telescope
  - *Allowed Values*: Floating point value between (0.0, $+\infty$)
  - *Default Value*: 1.0

2.4.2 `elevation.txt`

`elevation.txt` is an optional file that defines the elevation probability distribution function (PDF), which is determined by the scan strategy of the telescope. The first column is the elevation above the horizon in degrees, and the second column is the fraction if time spent at that elevation.

The probabilities should add up to one, and if they don not, the fraction will be determined by the provided probability divided by the sum of the provided probabilities.

Below is a made-up example of correct formatting for `elevation.txt`. Notice that each row is separated by a commented line of hyphens, while each colum is separated by a vertical bar.

```
#*****Elevation Distribution******
#
Elevation     | Probability
#---------------------------
[deg]         | NA
#---------------------------
```

```
30.0          | 0.100
#---------------------------
40.0          | 0.100
#---------------------------
50.0          | 0.300
#---------------------------
60.0          | 0.400
#---------------------------
70.0          | 0.100
#---------------------------
```

If `elevation.txt` is not found in `[Telescope Name]/config/`, then the code defaults to the PB2 wedding cake scan strategy, defined oosely as of 2017.

```
#Default to the PB2 wedding cake scan strategy
self.elVals = np.array([30.00, 35.21, 45.52, 47.74, 49.97,
                        50.00, 52.19, 54.41, 55.00, 56.63,
                        58.86, 60.00, 61.08, 63.30, 65.52])
self.elFrac = np.array([10.02, 10.02, 00.82, 00.82, 00.82,
                        31.99, 00.82, 00.82, 19.85, 00.82,
                        00.82, 19.87, 00.82, 00.82, 00.82])*un.pctToDec
```

2.4.3 `atm.txt`

There is an option to override the code's handling of the atmosphere by providing a custom atmospheric profile. The atmsophere file must be in `[Telescope Name]/config/`, and the filename must have the form `atm_[Elevation]deg_[PWV]um.txt`. For example, a valid filename is `atm_60deg_1000um.txt`.

The atmosphere file should have four columns, delimited by white space:

1. Frequency [GHz]
2. Optical Depth
3. Planck Temperature [K]
4. Transmission

```
| Frequency [GHz] | Optical Depth | Planck Temp [K] | Transmission |
```

Note that the temperature is in Planck units, not Rayleigh-Jeans. The passed frequency range needs to be large enough to cover the frequency bands observed by the telescope with at least a 15% buffer on the bandwidths of the highest and lowest bands.

Below is an example of an atmospheric profile generated using the AM simulation code and a configuration file designed using the 10-year MERRA dataset for the Chajnantor Observatory.

```
1.0000000e+01 3.664259e-03 3.589557e+00 9.963424e-01
1.0020000e+01 3.667538e-03 3.590339e+00 9.963392e-01
1.0040000e+01 3.671011e-03 3.591163e+00 9.963357e-01
1.0060000e+01 3.674741e-03 3.592043e+00 9.963320e-01
1.0080000e+01 3.678826e-03 3.593001e+00 9.963279e-01
1.0100000e+01 3.683414e-03 3.594069e+00 9.963234e-01
1.0120000e+01 3.688744e-03 3.595301e+00 9.963181e-01
1.0140000e+01 3.695220e-03 3.596788e+00 9.963116e-01
```

```
1.0160000e+01 3.703583e-03 3.598698e+00 9.963033e-01
1.0180000e+01 3.715317e-03 3.601374e+00 9.962916e-01
1.0200000e+01 3.733976e-03 3.605660e+00 9.962730e-01
...
```

2.5 Camera Parameters

In the following sections, we will overview the input parameters for each of the camera input files.

2.5.1 `camera.txt`

`camera.txt` defines parameters that are the same for all frequency bands observed with this camera. The file must be located within `[Telescope Name]/[Camera Name]/config/`.

- **Optical Coupling**
  - *Description*: How well the incident light on the focal plane couples to the pixel apertures
  - *Allowed Values*: Floating point value between (0.0, 1.0]
  - *Default Value*: 1.0
- **F Number**
  - *Description*: The focal ratio at the focal plane
  - *Allowed Values*: Floating point value between (0.0, $+\infty$)
  - *Default Value*: 2.0
- **Bath Temp**
  - *Description*: The temperature of the focal plane
  - *Allowed Values*: Floating point value between (0.0, $+\infty$) K
  - *Default Value*: 0.100

2.5.2 `channels.txt`

`channels.txt` defines the parameters of the frequency bands and detectors that are observing in this camera. The file must be located within `[Telescope Name]/[Camera Name]/config/`.

- **Band ID**
  - *Description*: The idenfitication number for this band
  - *Allowed Values*: An integer value between [1, $+\infty$)
  - *Default Value*: 1
  - Cannot have two bands with same Band ID on the same pixel
- **Pixel ID**
  - *Description*: The identification number for the pixel this band observes from
  - *Allowed Values*: An integer value between [1, $+\infty$)
  - *Default Value*: 1
- **Band Center**
  - *Description*: The central frequency for this band

- *Allowed Values*: A floating point value between (0.0, $+\infty$) GHz
- *Default Value*: 145.0

- **Fractional BW**
  - *Description*: Fractional arithmetic bandwdith for this band
  - *Allowed Values*: A floating point value between (0.0, 2.0]
  - *Default Value*: 0.276
- **Pixel Size**
  - *Description*: Size of the pixel via which this band is observing
  - *Allowed Values*: A postive floating point value between (0.0, $+\infty$) mm
  - *Default Value*: 6.8
- **Num Det per Wafer**
  - *Description*: Number of detectors per wafer within this band
  - *Allowed Values*: An integer value between [1, $+\infty$)
  - *Default Value*: 542
- **Num Waf per OT**
  - *Description*: Number of wafers with this band per camera
  - *Allowed Values*: An integer value between [1, $+\infty$)
  - *Default Value*: 7
- **Num OT**
  - *Description*: Number of cameras in this telescope observing at this frequency
  - *Allowed Values*: An integer value between [1, $+\infty$)
  - *Default Value*: 1
- **Waist Factor**
  - *Description*: The ratio of the gaussian beam waist coming from the pixel aperture to the pixel aperture diameter for this band
  - *Allowed Values*: A floating point value between [2.0, $+\infty$)
  - *Default Value*: 3.0
- **Det Eff**
  - *Description*: Efficiency of the detector from the entry point of the pixel aperture to the bolometer
  - *Allowed Values*: A floating point value between (0.0, 1.0]
  - *Default Value*: 0.700
- **Psat**
  - *Description*: Saturation power of the bolometer
  - *Allowed Values*: A floating point value between (0.0, $+\infty$] pW
  - *Default Value*: “NA”
  - If “NA,” use “Psat Factor” to calculate “Psat”
- **Psat Factor**
  - *Description*: Safety factor used to caculate saturation power from optical power
  - *Allowed Values*: A floating point value between (0.0, $+\infty$)
  - *Default Value*: 3.0
  - If “Psat” is “NA,” calculate $P_{sat} = P_{opt} \times$ “Psat Factor$''$

- **Carrier Index**
  - *Description*: Thermal carrier index for bolometer leg conductivity
  - *Allowed Values*: A floating point value between (0.0, $+\infty$)
  - *Default Value*: 2.7
- **Tc**
  - *Description*: Bolometer superconducting transition temperature
  - *Allowed Values*: A floating point value between (0.0, $+\infty$) K
  - *Default Value*: 0.159
  - If "NA," use "Tc Fraction" to calculate "Tc"
- **Tc Fraction**
  - *Description*: Factor used to calculate transition temperature from the bath temperature
  - *Allowed Values*: A floating point value between (1.0, $+\infty$)
  - *Default Value*: "NA"
  - If "Tc" is "NA," calculate $T_c = T_b \times$ "Tc Fraction$''$"
- **Yield**
  - *Description*: Fraction of deployed detectors that are observing. This is also commonly referred to as "end-to-end" yield.
  - *Allowed Values*: A floating point value between (0.0, 1.0]
  - *Default Value*: 0.700
- **SQUID NEI**
  - *Description*: SQUID noise equivalent current
  - *Allowed Values*: A floating point value between (0.0, $+\infty$) pA/$\sqrt{\text{Hz}}$
  - *Default Value*: "NA"
  - If "NA," "Read Noise Frac" is used to calculate readout noise
- **Bolo Resistance**
  - *Description*: Bolometer resistance
  - *Allowed Values*: A floating point value between (0.0, $+\infty$) Ω
  - *Default Value*: "NA"
  - If "NA," "Read Noise Frac" is used to calculate readout noise
- **Read Noise Frac**
  - *Description*: Fraction of the total NEP that is due to readout noise
  - *Allowed Values*: A floating point value between [0.0, $+\infty$)
  - *Default Value*: 0.100
  - If "SQUID NEI" or "Bolo Resistance" are "NA," then calculate readout NEP as $NEP_{\text{read}} = \sqrt{(1 + (\text{“Read Noise Frac''}))^2 - 1} \times \sqrt{NEP_{\text{ph}}^2 + NEP_{\text{g}}^2}$. If "NA," readout noise is zero.

2.5.3 `optics.txt`

`optics.txt` defines the parameters the frequency bands and detectors that are observing in this camera. The file must be located within `[Telescope Name]/[Camera Name]/config/`.

- **Element**
  - *Description*: Name of optical element
  - *Allowed Values*: Any string
  - *Default Value*: "Element"
  - "Primary," "Mirror," "Aperture," and "Stop" trigger additional calculations and therefore must be used purposefully
- **Temperature**
  - *Description*: Temperature of the optical element
  - *Allowed Values*: An floating point value between (0.0, $+\infty$)
  - *Default Value*: 4.0
- **Absorption**
  - *Description*: Fractional power attenuation due to absorption within the optical element
  - *Allowed Values*: A floating point value between [0.0, 1.0)
  - *Default Value*: 0.000
  - If "NA" ...
    - If "Mirror" or "Primary" is in "Element," "Conductivity" is used to calculate ohmic losses in the reflective optical element
    - If "Mirror" or "Primary" is not in "Element," "Thickness," "Index," and "Loss Tangent" are used to calculate dielectric loss in the refractive optical element
- **Reflection**
  - *Description*: Fractional power lost due to reflection at the optical element
  - *Allowed Values*: A floating point value between [0.0, 1.0)
  - *Default Value*: 0.000
  - If "NA" ...
    - If "Mirror" or "Primary" is in "Element," "Surface Rough" is used to reflection loss in the reflective optic
    - If "Mirror" or "Primary" is not in "Element," relfection is assumed be zero
- **Thickness**
  - *Description*: Thickness of the optical element
  - *Allowed Values*: A floating point value between (0.0, $+\infty$) mm
  - *Default Value*: "NA"
  - If "Absorption" is "NA," ...
    - If "Thickness" is "NA," absorption is assumed be zero
    - If "Thickness" is not "NA,"
      - If "Mirror" or "Primary" is in "Element," this parameter is ignored
      - If "Mirror" or "Primary" is not in "Element," this parameter is used to calculate dielectric loss in the refractive optic
  - If "Absorption" is not "NA," this parameter is ignored
- **Index**
  - *Description*: Index of refraction of the optical elemet

- *Allowed Values*: A floating point value between [1.0, $+\infty$)
- *Default Value*: "NA"
- If "Absorption" is "NA," ...
  - If "Index" is "NA," absorption is assumed be zero
  - If "Index" is not "NA,"
    - If "Mirror" or "Primary" is in "Element," this parameter is ignored
    - If "Mirror" or "Primary" is not in "Element," this parameter is used to calculate dielectric loss in the refractive optic
- If "Absorption" is not "NA," this parameter is ignored

- **Loss Tangent**
  - *Description*: Loss tangent of the optical element
  - *Allowed Values*: A floating point value between [0.0, $+\infty$)
  - *Default Value*: "NA"
  - If "Absorption" is "NA," ...
    - If "Loss Tangent" is "NA," absorption is assumed be zero
    - If "Loss Tangent" is not "NA,"
      - If "Mirror" or "Primary" is in "Element," this parameter is ignored
      - If "Mirror" or "Primary" is not in "Element," this parameter is used to calculate dielectric loss in the refractive optic
  - If "Absorption" is not "NA," this parameter is ignored
- **Conductivity**
  - *Description*: Electrical conductivity of the optical element
  - *Allowed Values*: A floating point value between (0.0, $+\infty$)
  - *Default Value*: "NA"
  - If "Absorption" is "NA," ...
    - If "Conductivity" is "NA," absorption is assumed be zero
    - If "Conductivity" is not "NA,"
      - If "Mirror" or "Primary" is in "Element," this parameter is used to calculate dielectric loss in the reflective optic
      - If "Mirror" or "Primary" is not in "Element," this parameter is ignored
  - If "Absorption" is not "NA," this parameter is ignored
- **Surface Rough**
  - *Description*: Surface roughness of the optical element
  - *Allowed Values*: A floating point value between [0.0, $+\infty$)
  - *Default Value*: "NA"
  - If "Reflection" is "NA," ...
    - If "Surface Rough" is "NA," absorption is assumed be zero
    - If "Surface Rough" is not "NA,"
      - If "Mirror" or "Primary" is in "Element," this parameter is used to calculate the reflection loss due to Ruze Scattering in the reflective optic
      - If "Mirror" or "Primary" is not in "Element," this parameter is ig-

nored

  - If “Reflection” is not “NA,” this parameter is ignored
- **Spillover**
  - *Description*: Fractional power that spills over the optical element
  - *Allowed Values*: A floating point value between [0.0, 1.0)
  - *Default Value*: “NA”
  - If this parameter is “NA,” spillover is assumed be zero
- **Spillover Temp**
  - *Description*: The effective temperature that the spilled power lands on
  - *Allowed Values*: A floating point value between [0.0, $+\infty$)
  - *Default Value*: “NA”
  - If “NA,” spillover is assumed to land at “Temperature,” the temperature of the element itself
- **Scatter Frac**
  - *Description*: Fraction of the reflected power that is scatterd out of the propogation mode
  - *Allowed Values*: A floating point value between [0.0, 1.0]
  - *Default Value*: “NA”
  - If “NA,” scattering is assumed to be zero.
- **Scatter Temp**
  - *Description*: The effective temperature that the scattered power lands on
  - *Allowed Values*: A floating point value between [0.0, $+\infty$)
  - *Default Value*: “NA”
  - If “NA,” scattered power is assumed to land at “Temperature,” the temperature of the optical element itself

2.6 Custom Bands

By default, `CHillCalc2` assumes top hat bands for all detectors and optical elements, whose height is determined soley by the mean and standard deviation of the end-to-end optical efficiency. However, custom bands can be input for any optical element.

The general file format for all band files is the same:

```
| Frequency [GHz] | Mean Efficiency | Standard Deviation (optional) |
```

Each column is separated by a vertical bar, and the final column, which contains the error bars, can be omitted. If only two columns are present, all stand deviations are assumed to be zero.

An example of a made-up detector bandpass text file, which is space-delimited, is shown below:

```
70.     0.000   0.000
75.     0.500   0.100
80.     0.700   0.100
85.     0.650   0.100
90.     0.700   0.100
100.    0.800   0.100
```

```
105.    0.600   0.100
110.    0.700   0.100
115.    0.500   0.100
120.    0.000   0.000
```

2.6.1 Detectors

Detector band files are stored in

```
[Telescope Name]/[Camera Name]/config/Bands/Detectors/
```

The band is identified using its filename, which must have the format `[Camera Name][Band ID].txt` for text files, or `[Camera Name][Band ID].csv` for comma-separated value files; both file formats work equally well. For example, to load a text file for a camera named "MF" (in the directory `[Telescope Name]/MF/` and a Band ID "1," the file name should be `MF1.txt`. Note that for a multi-chroic camera, there should be multiple band files, one for each frequency channel.

2.6.2 Optics

Optics band files are stored in

```
[Telescope Name]/[Camera Name]/config/Bands/Detectors/Optics/
```

The band is identified using its filename, which must have the format `[Optical Element Name].txt` for text files, or `[Optical Element Name].csv` for comma-separated value files; both file formats work equally well. For example, to load a text file for an optical element named "Lens1," the file name should be `Lens1.txt`. Note that there is only one band file for optical elements, even in multi-chroic cameras, as all detectors are all frequencies see the same bandpass. Also note that you can apply the same band to multiple optical elements by duplicating matching names in `optics.txt`.

3 Output Files

Running `mappingSpeed.py` generates several output files, which quantify the performance of the simulated experiment. Note that all examples in this document assume the Simons Observatory V3 configutation with no error bars for all parameters, with all observations at 60 deg elevation and 1 mm PWV.

3.1 Sensitivity Tables

`CHillCalc2` produces tables of outputs related to the white noise performance of the instrument. All sensitivity tables are in files named `sensitivity.txt`, and there are multiple tables generated at multiple directory tree levels, describing the performance of the camera, telescope, and entire experiment.

3.1.1 `Experiment/sensitivity.txt`

This file lists the following parameters:

- `Chan`
  - Frequency channel name `[Camera Name][Band ID]`
- `Frequency`
  - Central frequency of the frequency channel
- `Frac Bandwidth`
  - Fractional bandwidth of frequency channel
- `Num Det`
  - Total number of detectors deployed in this frequency channel, combined for all telescopes within the experiment
- `Array NET`
  - Aarray-averaged noise equivalent temperature of this frequency channel, combined for all telescopes within the experiment
- `Mapping Speed`
  - Mapping speed of this frequency channel, combined for all telescopes within the experiment
- `Map Depth`
  - Map depth achieved by this frequency channel, combined for all telescopes within the experiment

Note that if identical bands are shared between telescopes, the detectors are combined in this table, with the combined Array NET of that band is found by taking the inverse-variance average of the duplicated bands.

Below is an example of `sensitivity.txt` at the Experiment directory level:

Chan	Frequency	Frac Bandwidth	Num Det	Array NET	Mapping Speed	Map Depth
	[GHz]			[uK-rtSec]	[(uK^2 s)^-1]	[uK-arcmin]
LF1	27.0 +/- 0.0	0.222 +/- 0.000	444	24.37 +/- 0.00	0.0017 +/- 0.0000	40.4 +/- 0.0
LF2	39.0 +/- 0.0	0.462 +/- 0.000	444	14.08 +/- 0.00	0.0050 +/- 0.0000	23.3 +/- 0.0
MF1	93.0 +/- 0.0	0.376 +/- 0.000	14092	2.42 +/- 0.00	0.1706 +/- 0.0000	4.0 +/- 0.0
MF2	145.0 +/- 0.0	0.276 +/- 0.000	14092	3.04 +/- 0.00	0.1079 +/- 0.0000	5.0 +/- 0.0
UHF1	225.0 +/- 0.0	0.267 +/- 0.000	16836	5.54 +/- 0.00	0.0326 +/- 0.0000	9.2 +/- 0.0
UHF2	278.0 +/- 0.0	0.162 +/- 0.000	16836	13.28 +/- 0.00	0.0057 +/- 0.0000	22.0 +/- 0.0
Total			62744	1.76 +/- 0.00	0.3235 +/- 0.0000	2.9 +/- 0.0

Figure 1: Simons Observatory V3 experiment sensitivity, which combines the NETs from the Large Aperture Telescope and the Small Aperture Telescope. Both telescopes share wafers, and therefore have duplicates of each frequency band. The NETs are inverse-variace averaged in this sensitivity table for the entire experiment.

3.1.2 `Experiment/Telescope/sensitivity.txt`

This file lists

- `Chan`
  - Frequency channel name `[Camera Name][Band ID]`
- `Frequency`
  - Central frequency of the frequency channel
- `Frac Bandwidth`
  - Fractional bandwidth of frequency channel
- `Num Det`
  - Total number of detectors deployed in this frequency channel, combined for all cameras within the telescope
- `Array NET`
  - Aarray-averaged noise equivalent temperature of this frequency channel, combined for all cameras within the telescope
- `Mapping Speed`
  - Mapping speed of this frequency channel, combined for all cameras within the telescope
- `Map Depth`
  - Map depth achieved by this frequency channel, combined for all cameras within the telescope

Note that if identical bands are shared between cameras, the detectors are combined in this table, with the combined Array NET of that band is found by taking the inverse-variance average of the duplicated bands.

Below is an example of `sensitivity.txt` at the Telescope directory level:

Chan	Frequency	Frac Bandwidth	Num Det	Array NET	Mapping Speed	Map Depth
	[GHz]			[uK-rtSec]	[(uK^2 s)^-1]	[uK-arcmin]
LF1	27.0 +/- 0.0	0.222 +/- 0.000	222	43.21 +/- 0.00	0.0005 +/- 0.0000	71.6 +/- 0.0
LF2	39.0 +/- 0.0	0.462 +/- 0.000	222	22.14 +/- 0.00	0.0020 +/- 0.0000	36.7 +/- 0.0
MF1	93.0 +/- 0.0	0.376 +/- 0.000	6504	4.60 +/- 0.00	0.0473 +/- 0.0000	7.6 +/- 0.0
MF2	145.0 +/- 0.0	0.276 +/- 0.000	6504	5.71 +/- 0.00	0.0306 +/- 0.0000	9.5 +/- 0.0
UHF1	225.0 +/- 0.0	0.267 +/- 0.000	6084	12.63 +/- 0.00	0.0063 +/- 0.0000	20.9 +/- 0.0
UHF2	278.0 +/- 0.0	0.162 +/- 0.000	6084	30.30 +/- 0.00	0.0011 +/- 0.0000	50.2 +/- 0.0
Total			25620	3.37 +/- 0.00	0.0879 +/- 0.0000	5.6 +/- 0.0

Figure 2: Simons Observatory V3 Large Aperture Telescope sensitivity, which combines the NETs from the LF, MF, and UHF cameras.

3.1.3 `Experiment/Telescope/Camera/sensitivity.txt`

This file lists

- `Chan`

    - Frequency channel name `[Camera Name][Band ID]`
- `Frequency`
    - Central frequency of the frequency channel
- `Frac Bandwidth`
    - Fractional bandwidth of frequency channel
- `Num Det`
    - Total number of detectors deployed in this frequency channel, combined for all cameras within the telescope
- `Chan`
    - Frequency channel name `[Camera Name][Band ID]`
- `Lyot Efficiency`
    - Lyot stop spillover efficiency of the frequency channel
- `Optical Power`
    - Total optical power on detectors within this frequency channel
- `Photon NEP`
    - Noise-equivalent power due to photon noise for detectors within this frequency channel
- `Bolometer NEP`
    - Noise-equivalent power due to bolometer thermal carrier noise for detectors within this frequency channel
- `Detector NEP`
    - Total noise-equivalent power due to the combinatin of photon, thermal carrier, and readout noise for detectors within this frequency channel
- `Detector NET`
    - Per-detector noise-equivalent temperature for detectors within this channel
- `Array NET`
    - Aarray-averaged noise equivalent temperature of this frequency channel
- `Mapping Speed`
    - Mapping speed of this frequency channel
- `Map Depth`
    - Map depth achieved by this frequency channel

for every frequency channel in the provided camera.

Below is an example of `sensitivity.txt` at the Camera directory level:

Chan	Frequency	Frac Bandwidth	Num Det	Lyot Efficiency	Optical Power	Photon NEP	Bolometer NEP	Readout NEP	Detector NEP	Detector NET	Array NET	Mapping Speed	Map Depth
	[GHz]			[%]	[pW]	[aW/rtHz]	[aW/rtHz]	[aW/rtHz]	[aW/rtHz]	[uK-rtSec]	[uK-rtSec]	[(uK^2 s)^-1]	[uK-arcmin]
MF1	93.0 +/- 0.0	0.376 +/- 0.000	6504	35.30 +/- 0.00	1.89 +/- 0.00	20.93 +/- 0.00	10.88 +/- 0.00	0.00 +/- 0.00	23.59 +/- 0.00	283.1 +/- 0.0	4.60 +/- 0.00	0.0473 +/- 0.0000	7.6 +/- 0.0
MF2	145.0 +/- 0.0	0.276 +/- 0.000	6504	52.80 +/- 0.00	3.49 +/- 0.00	35.79 +/- 0.00	14.77 +/- 0.00	0.00 +/- 0.00	38.72 +/- 0.00	375.2 +/- 0.0	5.71 +/- 0.00	0.0306 +/- 0.0000	9.5 +/- 0.0
Total			13008								3.58 +/- 0.00	0.0780 +/- 0.0000	5.9 +/- 0.0

Figure 3: Simons Observatory V3 Large Aperture Telescope MF Camera sensitivity.

3.2 Optical Power Table

`CHillCalc2` also outputs tables of optical powers, including the the following information in columns:

- `Element`
  - Name of optical element, as defined within `optics.txt` for this camera
- `Power from Sky`
  - Power incident on this optical element from the sky side
- `Power to Detect`
  - Power emitted from this optical element which is seen by the detector
- `Cumulative Eff`
  - Cumulative Efficiency between this optical emenet and the detector

3.2.1 `Experiment/Telescope/Camera/opticalPower.txt`

Optical powers are listed for each channel in the camera, formatted as one table per frequency. Below is an example for the V3 Large Aperture Telescope Mid-Frequency camera.

MF 1

Element	Power from Sky	Power to Detect	Cumulative Eff
	[pW]	[pW]	
CMB	0.00 +/- 0.00	0.08 +/- 0.00	0.152 +/- 0.000
ATM	0.52 +/- 0.00	0.68 +/- 0.00	0.157 +/- 0.000
Primary	4.81 +/- 0.00	0.79 +/- 0.00	0.163 +/- 0.000
Mirror	9.48 +/- 0.00	0.04 +/- 0.00	0.164 +/- 0.000
Mirror	9.72 +/- 0.00	0.04 +/- 0.00	0.164 +/- 0.000
Window	9.96 +/- 0.00	0.11 +/- 0.00	0.166 +/- 0.000
IRShader1	10.45 +/- 0.00	0.02 +/- 0.00	0.167 +/- 0.000
IRShader2	10.58 +/- 0.00	0.02 +/- 0.00	0.167 +/- 0.000
IRShader1	10.70 +/- 0.00	0.02 +/- 0.00	0.167 +/- 0.000
IRShader2	10.80 +/- 0.00	0.02 +/- 0.00	0.167 +/- 0.000
AluminaF	10.89 +/- 0.00	0.00 +/- 0.00	0.171 +/- 0.000
IRShader1	10.69 +/- 0.00	0.01 +/- 0.00	0.171 +/- 0.000
IRShader2	10.71 +/- 0.00	0.00 +/- 0.00	0.171 +/- 0.000
AluminaF	10.72 +/- 0.00	0.00 +/- 0.00	0.175 +/- 0.000
LowPass1	10.51 +/- 0.00	0.03 +/- 0.00	0.186 +/- 0.000
Lens1	10.06 +/- 0.00	0.00 +/- 0.00	0.188 +/- 0.000
LowPass1	9.94 +/- 0.00	0.00 +/- 0.00	0.200 +/- 0.000
Lens2	9.35 +/- 0.00	0.00 +/- 0.00	0.203 +/- 0.000
Aperture	9.23 +/- 0.00	0.02 +/- 0.00	0.574 +/- 0.000
LowPass1	3.30 +/- 0.00	0.00 +/- 0.00	0.611 +/- 0.000
LowPass2	3.10 +/- 0.00	0.00 +/- 0.00	0.650 +/- 0.000
Lens3	2.91 +/- 0.00	0.00 +/- 0.00	0.659 +/- 0.000
LowPass1	2.88 +/- 0.00	0.00 +/- 0.00	0.701 +/- 0.000
Detector	2.70 +/- 0.00	0.00 +/- 0.00	1.001 +/- 0.000

MF 2

Element	Power from Sky	Power to Detect	Cumulative Eff
	[pW]	[pW]	
CMB	0.00 +/- 0.00	0.07 +/- 0.00	0.221 +/- 0.000
ATM	0.33 +/- 0.00	1.06 +/- 0.00	0.229 +/- 0.000
Primary	4.93 +/- 0.00	1.42 +/- 0.00	0.238 +/- 0.000
Mirror	10.69 +/- 0.00	0.18 +/- 0.00	0.239 +/- 0.000
Mirror	11.38 +/- 0.00	0.18 +/- 0.00	0.240 +/- 0.000
Window	12.07 +/- 0.00	0.35 +/- 0.00	0.245 +/- 0.000
IRShader1	13.27 +/- 0.00	0.04 +/- 0.00	0.246 +/- 0.000
IRShader2	13.42 +/- 0.00	0.04 +/- 0.00	0.246 +/- 0.000
IRShader1	13.55 +/- 0.00	0.03 +/- 0.00	0.246 +/- 0.000
IRShader2	13.67 +/- 0.00	0.03 +/- 0.00	0.246 +/- 0.000
AluminaF	13.76 +/- 0.00	0.01 +/- 0.00	0.252 +/- 0.000
IRShader1	13.52 +/- 0.00	0.01 +/- 0.00	0.252 +/- 0.000
IRShader2	13.54 +/- 0.00	0.01 +/- 0.00	0.252 +/- 0.000
AluminaF	13.56 +/- 0.00	0.00 +/- 0.00	0.258 +/- 0.000
LowPass1	13.29 +/- 0.00	0.05 +/- 0.00	0.274 +/- 0.000
Lens1	12.69 +/- 0.00	0.00 +/- 0.00	0.279 +/- 0.000
LowPass1	12.49 +/- 0.00	0.00 +/- 0.00	0.296 +/- 0.000
Lens2	11.75 +/- 0.00	0.00 +/- 0.00	0.302 +/- 0.000
Aperture	11.55 +/- 0.00	0.00 +/- 0.00	0.571 +/- 0.000
LowPass1	6.10 +/- 0.00	0.00 +/- 0.00	0.608 +/- 0.000
LowPass2	5.74 +/- 0.00	0.00 +/- 0.00	0.646 +/- 0.000
Lens3	5.39 +/- 0.00	0.00 +/- 0.00	0.658 +/- 0.000
LowPass1	5.30 +/- 0.00	0.00 +/- 0.00	0.700 +/- 0.000
Detector	4.98 +/- 0.00	0.00 +/- 0.00	1.000 +/- 0.000

Figure 4: Simons Observatory V3 Large Aperture Telescope Mid-Frequency camera optical power tables. Each table is labeled by "[camera name] + [band name]."

4 Monte Carlo Simulation

The Monte Carlo (MC) simulation iterates using a nest of the following structure:

- N_{exp} Experiment realizations
  - N_{obs} Observations per experiment realization
    - N_{det} Detector realizations per observation

The number of iterations performed at each level of the MC is determined by parameters in `CHillCalc2/config/mappingSpeed_params.txt`:

- N_{exp} = `Experiments`
- N_{obs} = `Observations`
- N_{det} = `Detectors`

If any of these parameters are set to one, then the mean value is taken for the parameters that vary with the experiment realization, observation, or detector realization, respectively.

Below is a list of parameters that vary with each layer of the MC tree:

- **Experiment Realizations**
  - All parameters in `foregrounds.txt`
  - All parameters in each `program.txt` file
  - All parameters in each `camera.txt` file
  - All parameters in each `optics.txt` file
  - Within all `channels.txt` files:
    - `Pixel Size`
    - `Waist Factor`
    - `Yield`
- All bands defined by files in `config/Bands/Optics/`
- **Observations**
  - PWV
  - Elevation
- **Detector Realizations**
  - Within all `channels.txt` files:
    - `Band Center`
    - `Fractional BW`
    - `Det Eff`
    - `Psat`
    - `Psat Factor`
    - `Carrier Index`
    - `Tc`
    - `Tc Fraction`
    - `SQUID NEI`
    - `Bolo Resistance`
    - `Read Noise Frac`
  - All bands defined by files in `config/Bands/Detectors/`