# BoloCalc User Manual
# Version 1.0

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## Contents

# 1 Quick Start

This section quickly covers whats needed to get `BoloCalc` up and running.

## 1.1 System Requirements

`BoloCalc` is to be run on a Linux and needs the following installed

1. Python v2.7.2
2. Numpy v1.8 or above

## 1.2 Code location

`BoloCalc` is stored on Charles Hill's GitHub account `chill90` within the repository `chill90/BoloCalc`. To clone a local copy of the repository, make sure that you have Git installed on your machine and run

```
git clone https://github.com/chill90/msCorr.git
```

All executables are stored at in the top-most directory

```
~/BoloCalc/
```

and all libraries are stored in the `src/` directory

```
~/BoloCalc/src/
```

## 1.3 Running `mappingSpeed.py`

The primary `BoloCalc` executable is called `mappingSpeed.py`, which 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, given some instrument configuration. `mappingSpeed.py` takes as input an experiment configuration directory, which is stored in `BoloCalc/Experiments` and has 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`. The `BoloCalc` repository comes with an example experiment that can be used to get started:

```
BoloCalc$ python2.7 mappingSpeed.py Experiments/ExampleExp/V0/
```

By default upon download, this execution will calculate one experiment realization, which should be shown by the status bar. The simulation parameters can be tuned in the `BoloCalc/config/simulationInputs.txt` After it has finished running, `mappingSpeed.py`

```
#***** Simulation Parameters *****
#
#----------------------------------------------------------------------------------------------------------
Parameter    | Value   | Description
#----------------------------------------------------------------------------------------------------------
Multiprocess | False   | Whether or not to use multiprocessing
#----------------------------------------------------------------------------------------------------------
Cores        | 1       | Number of cores to use for parallel processing. Positive integer
#----------------------------------------------------------------------------------------------------------
Verbosity    | 1       | Verbosity for printing logging messages to standard output. 0 for low, 1 for moderate, 2 for high
#----------------------------------------------------------------------------------------------------------
Experiments  | 1       | Number of Experiment MC realizations. Positive integer
#----------------------------------------------------------------------------------------------------------
Observations | 1       | Number of Observation MC realizations per experiment realization. Positive integer.
#----------------------------------------------------------------------------------------------------------
Detectors    | 1       | Number of Detector MC realizations per observation realization. Positive Integer.
#----------------------------------------------------------------------------------------------------------
Resolution   | 0.100   | Spectral resolution for integration over bands and spectra in GHz. Positive floating point value.
#----------------------------------------------------------------------------------------------------------
Foregrounds  | False   | Include Foregrounds? True or False
#----------------------------------------------------------------------------------------------------------
Correlations | True    | Include white noise correlations? True or False
#----------------------------------------------------------------------------------------------------------
```

generates several tables that display the calculated quantites for the simulated instrument. All files are named `sensitivity.txt`, but each is located at a different level of the experiment and therefore contains different information.

- `Experiments/ExampleExp/V0/sensitivity.txt`: contains the sensitivity combined by observation frequency of all telescopes in this experiment.
- `Experiments/ExampleExp/V0/Tel/sensitivity.txt`: contains the sensitivity combined by observation frequency of all cameras in this telescope.
- `Experiement/ExampleExp/V0/Tel/Cam/sensitivity.txt`: containst the sensitivity for each observation frequency in this camera.

### 1.4 Running `mappingSpeed_vary.py`

The other `BoloCalc` executable is called `mappingSpeed_vary.py`, which calculates the same output parameters as `mappingSpeed.py` (Section 1.3) given a passed instrument configuration

```
BoloCalc$ python2.7 mappingSpeed_vary.py Experiments/ExampleExp/V0/
```

and parameters to be varied, which are stored in `BoloCalc/config/paramsToVary.txt`. An example of the

```
# Telescope    | Camera      | Channel     | Optic              | Parameter          | Minimum     | Maximum     | Step Size
#------------------------------------------------------------------------------------------------------------------------------
Tel            | Cam         | 1           | Primary            | Spillover          | 0.000       | 0.050       | 0.010
#------------------------------------------------------------------------------------------------------------------------------
Tel            | Cam         | 1           | Aperture           | Temperature        | 1.000       | 5.000       | 1.000
```

Parameters are defined by row and have the following descriptors, which are organized by column:

- Column 1: Telescope in which the parameter is defined
  - Leave blanck if the parameter is defined in `config/foregrounds.txt`
- Column 2: Camera in which the parameter is defined
  - Leave blank if the parameter is defined in `Tel/config/telescope.txt`
- Column 3: Channel for which the parameter is deinfed
  - Leave blank if the parameter is defined in `Tel/config/telescope.txt` or `Cam/config/camera.txt`
- Column 4: Optic for which the parameter is defined
  - Leave blank **unless** the parameter is defined in `Cam/config/optics.txt`
- Column 5: Parameter name
- Column 6: Mininum parameter value to be calculated
- Column 7: Maximum parameter value to be calculated
- Column 8: Step size with which the parameter will be calculated over the range [Minimum, Maximum]

By default upon download, this execution will calculate one experiment realization for each parameter combination (see Section 1.3 for details on simulation inputs). The status bar will show progression towards calculating all combinations of parameters defined over the ranges

After it has finished running, `mappingSpeed.py` generates several tables that display the calculated quantites for the simulated instrument. All files are named `sensitivity.txt`, but each is located at a different level of the experiment and therefore contains different information.

- `Experiments/ExampleExp/V0/sensitivity.txt`: contains the sensitivity combined by observation frequency of all telescopes in this experiment.

- `Experiments/ExampleExp/V0/Tel/sensitivity.txt`: contains the sensitivity combined by observation frequency of all cameras in this telescope.

- `Experiement/ExampleExp/V0/Tel/Cam/sensitivity.txt`: containst the sensitivity for each observation frequency in this camera.

### 1.5 Contact

Please send any comments, requests, questions, or bugs to Charles Hill at `chill@lbl.gov`.

## 2 Defining an Experiment

BoloCalc has a modular object-oriented structure, which allows for arbitrary mixtures of sites, telescopes, cameras, optics, focal planes, and detectors. A BoloCalc project has the parent-child structure shown in Fig. 1 and is built with four layers: experiments, telescopes, cameras, and channels, which are defined in Tab. 1. Each experiment can have an arbitrary set of telescopes (at different sites), each telescope an arbitrary set of cameras, and each camera an arbitrary set of channels.

| Layer | Definition |
|---|---|
| Experiment | An assemblage of CMB telescopes. |
| Telescope | A platform that carries and points one or more cameras. It observes at a specified site with a specified observation strategy and can include warm reflectors. |
| Camera | A cryostat that houses cryogenic optics, filters, and detectors. Multiple cameras can be mounted on the same telescope. |
| Channel | A frequency band observed by some set of detectors within a camera. A multichroic camera will have multiple channels. |

Table 1: Definitions of the layers used to build a BoloCalc project.

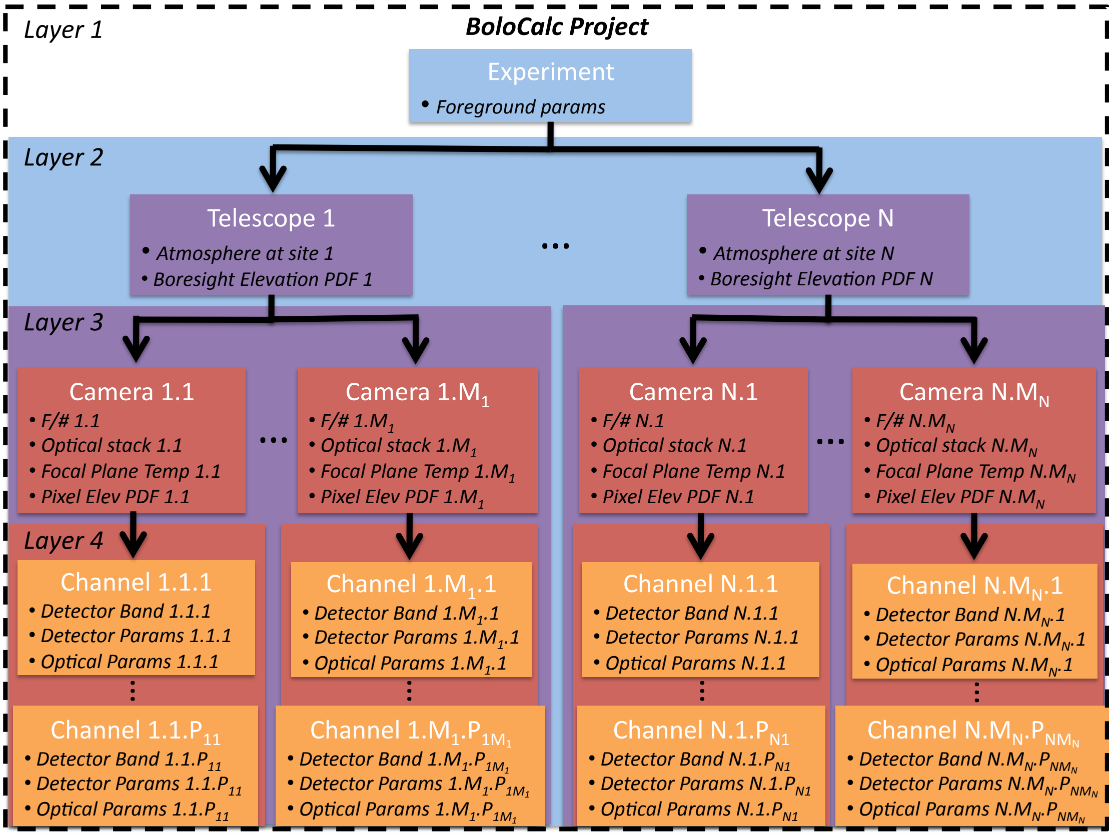


Figure 1: Layout of a BoloCalc project.

Each layer of an experiment has several 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.

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

As stated in Section 2, an 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 `BoloCalc` are defined with a central value and an error bar. Therefore, all parameter variation is assumed to have an underlying Gaussian distribution, and all parameters are assumed to be uncorrelated.

Parameters defined `foregrounds.txt`, `telescope.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 as 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 the same celestial loading, 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 galactic parameters 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*: $2 \times 10^{-3}$
- **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*: $2 \times 10^{-3}$
- **Synchrotron Amplitude**
    - *Description*: Amplitude of the synchrotron power law spectrum
    - *Allowed Values*: Floating point value between $(0.0, +\infty)$
    - *Default Value*: $6 \times 10^{3}$

## 2.4 Telescope Parameters

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

### 2.4.1 `telescope.txt`

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

- **Site**
    - *Description*: Site at which the telescope observes, which defines the atmospheric conditions.
    - *Allowed Values*: Either "Atacama" or "Pole"
    - *Default Value*: "Atacama"
- **Elevation**
    - *Description*: Elevation at which the telescope observes.
    - *Allowed Values*: [20.0, 90.0] deg above the horizon
    - *Default Value*: 50.0 deg
    - If "NA," the elevation distribution defined in `Telescope/config/elevation.txt`, will be assumed.
- **PWV**
    - *Description*: PWV of the atmosphere through which the telescope observes.

- *Allowed Values*: [0.0, 8.0] mm
- *Default Value*: 1.0 mm
- If "NA," the PWV distribution defined in `Telescope/config/pwv.txt`, will be assumed.

- **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.

This file is only used if the parameter "Elevation" in `Telescope/config/elevation.txt` is defined to be "NA" (see Section 2.4.1 for more information about `telescope.txt`).

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

Below is a made-up example for `elevation.txt`. Notice that each row is separated by a commented line of hyphens, while each column 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
#---------------------------
```

### 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 atmosphere 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 in the atmosphere file 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. For instance, if you want to know the atmospheric loading in a band from 240 to 300 GHz, your atmosphere file should have values that go up to at least 345 GHz.

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/`.

- **Boresight Elevation**
  - *Description*: The elevation of the camera boresight with respect to the telescope boresight.
  - *Allowed Values*: Floating point value between (-40.0, 40.0] deg
  - *Default Value*: 0.0 deg
- **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 `elevation.txt`

`elevation.txt` is an optional file that defines the elevation distribution with respect to the camera boresight of pixels on the focal plane. It has the exact same structure as the file `Telescope/config/elevation.txt`, which instead defines the scan strategy and is described in section [**?**]. The first column is the elevation above the horizon in degrees, and the second column is the fraction if time spent at that elevation.

This file is only used if the parameter "Elevation" in `Telescope/config/elevation.txt` is defined to be "NA" (see Section 2.4.1 for more information about `telescope.txt`).

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
#---------------------------
```

### 2.5.3 `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, +∞)
- *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, +∞)
  - *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, +∞] 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, +∞)
  - *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, +∞)
  - *Default Value*: 2.7
- **Tc**
  - *Description*: Bolometer superconducting transition temperature
  - *Allowed Values*: A floating point value between (0.0, +∞) 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, +∞)
  - *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, $+\infty$) $\Omega$
  - *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.

### 2.5.4 `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 ignored
  - 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, BoloCalc 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

`BoloCalc` 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 2: 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 3: 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 4: Simons Observatory V3 Large Aperture Telescope MF Camera sensitivity.

### 3.2 Optical Power Table

`BoloCalc` 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.

## 4 Monte Carlo Simulation

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

- $N_{\mathrm{exp}}$ Experiment realizations
  - $N_{\mathrm{obs}}$ Observations per experiment realization

************************ MF 1 ************************

| Element | Power from Sky [pW] | Power to Detect [pW] | Cumulative Eff |
|---|---|---|---|
| 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 [pW] | Power to Detect [pW] | Cumulative Eff |
|---|---|---|---|
| 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 5: Simons Observatory V3 Large Aperture Telescope Mid-Frequency camera optical power tables. Each table is labeled by "[camera name] + [band name]."

    * $N_{\text{det}}$ Detector realizations per observation

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

- $N_{\text{exp}}$ = `Experiments`
- $N_{\text{obs}}$ = `Observations`
- $N_{\text{det}}$ = `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 `telescope.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/`