

BoloCalc Quick Reference Guide

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1 Input Parameter Guide

1.1 Experiment Parameters

1.1.1 `foregrounds.txt`

- **Dust Temperature**
 - Definition: T_d in Equation 45
 - Description: Modified dust blackbody temperature
 - Units: [K]
 - Allowed Values: Floating point value between $[0.000, +\infty)$
 - Suggested Default: 19.70 ± 0.000 K
- **Dust Spec Index**
 - Definition: n_d in Equation 45
 - Description: Spectral index of the modified blackbody dust spectrum
 - Units: [NA]
 - Allowed Values: Floating point value between $(-\infty, +\infty)$
 - Suggested Default: 1.500 ± 0.000
- **Dust Amplitude**
 - Definition: A_d in Equation 45
 - Description: Amplitude of the modified blackbody dust spectrum at the scale frequency
 - Units: [MJy sr⁻¹]
 - Allowed Values: Floating point value between $[0.000, +\infty)$
 - Suggested Default: $1 \times 10^{-2} \pm 0.000$
- **Dust Scale Frequency**
 - Definition: ν_d in Equation 45
 - Description: Scale (or pivot) frequency for the modified blackbody dust spectrum
 - Unit: [GHz]
 - Allowed Values: Floating point value between $(0.000, +\infty)$
 - Suggested Default: 353.0 ± 0.000
- **Synchrotron Spec Index**
 - Definition: n_s in Equation 44
 - Description: Spectral index of the synchrotron power law spectrum
 - Unit: [NA]

- Allowed Values: Floating point value between $(-\infty, +\infty)$
- Suggested Default: -3.000 ± 0.000
- **Synchrotron Amplitude**
 - Definition: T_s in Equation 44
 - Description: Amplitude of the synchrotron power law spectrum at the scale frequency in brightness temperature
 - Unit: [K_{RJ}]
 - Allowed Values: Floating point value between $(0.000, +\infty)$
 - Suggested Default: $1.000 \times 10^{-3} \pm 0.000$
- **Sync Scale Frequency**
 - Definition: ν_s in Equation 44
 - Description: Scale (or pivot) frequency for the synchrotron power law spectrum
 - Unit: [GHz]
 - Allowed Values: Floating point value between $(0.000, +\infty)$
 - Suggested Default: 30.00 ± 0.000

1.2 Telescope Parameters

1.2.1 `telescope.txt`

- **Site**
 - Description: Site at which the telescope observes, which defines the atmospheric profile
 - Allowed Values: “Atacama,” “Pole,” “McMurdo” (balloon), “Space,” “Room” (300 K blackbody), or “CUST” (custom atmosphere file). See section 2.14.3 for more details about handling of the atmosphere.
- **Elevation**
 - Definition: θ_{tel} in Equation 53
 - Description: Telescope boresight elevation
 - Units: [deg] above the horizon
 - Allowed Values: Floating point value with step size 1.0 between [20, 90]
 - Suggested Default: 50.00 ± 0.000
- **PWV**
 - Description: Precipitable water vapor of the atmosphere through which the telescope observes in millimeters
 - Units: [mm]
 - Allowed Values: Floating point value with step size 0.1 between [0.0, 8.0]
 - Suggested Default: 1.000 ± 0.000
- **Observation Time**
 - Definition: t_{obs} in Equation 43
 - Description: For how long the telescope will operate in years. Note that observation efficiency is a separate parameter
 - Units: [yr]
 - Allowed Values: Floating point value between $(0.000, +\infty)$
 - Suggested Default: 3.000 ± 0.000
- **Sky Fraction**
 - Definition: f_{sky} in Equation 43
 - Description: (Effective) fraction of the full sky observed by this telescope
 - Units: [NA]
 - Allowed Values: Floating point value between $(0.000, 1.0]$
 - Suggested Default: 0.700 ± 0.000
- **Observation Efficiency**
 - Definition: η_{obs} in Equation 43

- Description: Fraction of the total operation time during which the telescope is making science observations
- Units: [NA]
- Allowed Values: Floating point value between (0.000, 1.000]
- Suggested Default: 0.800 ± 0.000
- **NET Margin**
 - Definition: M in Equation 34
 - Description: Agnostic factor which multiplies all NETs for this telescope. Useful for incorporating contingencies.
 - Units: [NA]
 - Allowed Values: Floating point value between (0.000, $+\infty$)
 - Suggested Default: 1.000 ± 0.000

1.3 Camera Parameters

1.3.1 `camera.txt`

- **Boresight Elevation**
 - Definition: θ_{cam} in Equation 53
 - Description: Camera boresight elevation with respect to the telescope boresight elevation
 - Units: [deg] above telescope boresight
 - Allowed Values: Floating point value between $[-40.00, +40.00]$
 - Suggested Default: 0.000 ± 0.000
- **Optical Coupling**
 - Definition: ξ in Equations 36 and 35
 - Description: An overall coupling factor for all detectors pixels in this camera
 - Units: [NA]
 - Allowed Values: Floating point value between (0.000, 1.000]
 - Suggested Default: 1.000 ± 0.000
- **F Number**
 - Definition: F in Equation 46
 - Description: (Effective) F-number at the focal plane
 - Units: [NA]
 - Allowed Values: Floating point value between (0.000, $+\infty$)
 - Suggested Default: 2.000 ± 0.000
- **Bath Temperature**
 - Definition: T_{bath} in Equations 18, 20, and 19
 - Description: Focal plane temperature
 - Units: [K]
 - Allowed Values: Floating point value between (0.000, $+\infty$)
 - Suggested Default: 0.100 ± 0.000

1.3.2 `channels.txt`

- **Band ID**
 - Description: The identification for this frequency channel
 - Suggested Default: 1
 - Every channel within a camera needs to have a unique Band ID. **We strongly recommend that you index your bands in ascending order in `channels.txt`, using the Band ID parameter.**
- **Pixel ID**
 - Description: Pixel identification for this frequency channel

- Suggested Default: 1
- **As of BoloCalc v0.10.0, this parameter no longer has meaning. That said, it can be useful for organizing which detector channels share a detector pixel, in the case of multichroic pixels.** You can delete the parameter from your `channels.txt` file if you like.
- **Band Center**
 - Definition: ν_c in Equation 1
 - Description: Central frequency for this frequency channel
 - Units: [GHz]
 - Allowed Values: A floating point value between (0.000, $+\infty$)
 - Suggested Default: 150.0 ± 0.000
- **Fractional BW**
 - Definition: f_{BW} in Equation 1
 - Description: Fractional arithmetic bandwidth for this frequency channel
 - Units: [NA]
 - Allowed Values: A floating point value between (0.000, 2.0]
 - Suggested Default: 0.300 ± 0.000
- **Pixel Size**
 - Definition: D_{pix} in Equation 46
 - Description: Detector pixel size (or equivalently, pixel spacing) for this frequency channel
 - Units: [mm]
 - Allowed Values: A floating point value between (0.000, $+\infty$)
 - Suggested Default: 6.800 ± 0.000
- **Num Det per Wafer**
 - Definition: $N_{det/waf}$ in Equation 57. Note that detector yield is an independent parameter.
 - Description: Number of detectors per detector wafer for this frequency channel
 - Units: [NA]
 - Allowed Values: An integer value between [0, $+\infty$)
 - Suggested Default: 542
 - Note that this parameter does not accept a spread
- **Num Waf per OT**
 - Definition: $N_{waf/OT}$ in Equation 57
 - Description: Number of wafers per optics tube (camera) for this frequency channel
 - Units: [NA]
 - Allowed Values: An integer value between [0, $+\infty$)
 - Suggested Default: 7
 - Note that this parameter does not accept a spread
- **Num OT**
 - Definition: N_{OT} in Equation 57
 - Description: Number of optics tubes (cameras) which contain detector wafers that have detectors of this frequency channel
 - Units: [NA]
 - Allowed Values: An integer value between [0, $+\infty$)
 - Suggested Default: 1
 - Note that this parameter does not accept a spread
- **Waist Factor**
 - Definition: w_f in Equation 46
 - Description: Ratio of pixel diameter to pixel Gaussian beam waist
 - Units: [NA]
 - Allowed Values: A floating point value between [2.0, $+\infty$)

- Suggested Default: 3.000 ± 0.000
- **Det Eff**
 - Definition: η_{det} in Equations 11 and 5.
 - Description: The band-averaged detector optical efficiency
 - Units: [NA]
 - Allowed Values: A floating point value between (0.000, 1.000]
 - Suggested Default: 0.700 ± 0.000
- **Psat**
 - Definition: P_{sat} in Equations 20 and 28
 - Description: The detector saturation power for this frequency channel
 - Units: [pW/ $\sqrt{\text{Hz}}$]
 - Allowed Values: A floating point value between (0.000, $+\infty$)
 - Suggested Default: “NA”
 - If “NA,” then use **Psat Factor** f_{psat} Equation 54 to calculate P_{sat}
- **Psat Factor**
 - Definition: f_{psat} in Equation 54
 - Description: The ratio of saturation power to optical power for detectors within this frequency channel
 - Units: [NA]
 - Allowed Values: A floating point value between (0.000, $+\infty$)
 - Suggested Default: 3.000 ± 0.000
 - If parameter **Psat** is not “NA,” this this parameter is ignored
- **Carrier Index**
 - Definition: n in Equations 20 and 19
 - Description: Thermal carrier index for bolometer conductivity to the bath
 - Units: [NA]
 - Allowed Values: A floating point value between (0.000, $+\infty$)
 - Suggested Default: 2.700 ± 0.000
 - If parameter **G** is not “NA” and **Flink** is not “NA,” this parameter is ignored
- **Tc**
 - Definition: T_{oper} in Equations 20, 19, and 17
 - Description: Bolometer operating temperature
 - Units: [K]
 - Allowed Values: A floating point value between (0.000, $+\infty$)
 - Suggested Default: 0.165 ± 0.000
 - If “NA,” then use parameter **Tc Fraction** to calculate T_{oper}
- **Tc Fraction**
 - Definition: f_{oper} in Equation 18
 - Description: The ratio of bolometer operating temperature to bath temperature
 - Units: [NA]
 - Allowed Values: A floating point value between (0.000, $+\infty$)
 - Suggested Default: “NA”
 - If parameter T_c is not “NA,” then this parameter is ignored
- **Flink**
 - Definition: F_{link} in Equations 19 and 17
 - Description: Numerical factor that depends on the thermal carrier index
 - Units: [NA]
 - Allowed Values: A floating point value between (0.000, $+\infty$)
 - Suggested Default: “NA”
 - If “NA,” **Flink** is calculated using **Carroer Index** and Equation 19
 - This parameter was added in BoloCalc v0.9.0. If the parameter is absent from

- `channels.txt`, the assumed value is “NA”
- **G**
 - Definition: G in Equations 20 and 17
 - Description: Thermal conduction from the bolometer to the bath
 - Units: [pW / K]
 - Allowed Values: A floating point value between (0.000, $+\infty$)
 - Suggested Default: “NA”
 - If “NA,” G is calculated using the parameters **Carrier Index**, **Tc**, **Bath Temp**, and **Psat** and Equation 20
 - This parameter was added in BoloCalc v0.9.0. If the parameter is absent from `channels.txt`, the assumed value is “NA”
- **Yield**
 - Definition: Y in Equation 37
 - Description: Detector yield
 - Units: [NA]
 - Allowed Values: A floating point value between (0.000, 1.000]
 - Suggested Default: 0.700 ± 0.000
- **SQUID NEI**
 - Definition: **NEI** in Equation 28
 - Description: SQUID amplifier noise
 - Units: pA/ $\sqrt{\text{Hz}}$
 - Allowed Values: A floating point value between (0.000, $+\infty$)
 - Suggested Default: “NA”
 - If “NA,” then use parameter **Read Noise Frac** and Equation 29 to calculate NEP_{read}
- **Bolo Resistance**
 - Definition: R_{bolo} in Equations 26 and 28
 - Description: Bolometer operating resistance
 - Units: [Ω]
 - Allowed Values: A floating point value between (0.000, $+\infty$)
 - Suggested Default: “NA”
 - If “NA,” then use parameter **Read Noise Frac** and Equation 56 to calculate NEP_{read}
- **Resp Factor**
 - Definition: S_{fact} in Equations 28, 22, and 23
 - Description: Responsivity factor, which is set by bolometer operating loop gain
 - Units: [NA]
 - Allowed Values: A floating point value between (0.000, $+\infty$)
 - Suggested Default: 1.000 ± 0.000
 - If “NA,” then assume a value of 1
 - This parameter was added in BoloCalc v0.10.0. If the parameter is absent from `channels.txt`, the assumed value is “NA”
- **Read Noise Frac**
 - Definition: Δ_{read} in Equation 56
 - Description: Fraction of the total detector NEP that is due to readout noise
 - Units: [NA]
 - Allowed Values: A floating point value between [0.000, $+\infty$)
 - Suggested Default: 0.100 ± 0.000
 - If parameters **SQUID NEI** and **Bolo Resistance** are not “NA,” then this parameter is ignored

1.3.3 `optics.txt`

- **Element**
 - Description: Name of the optical element
 - Allowed Values: Any string, conventionally without spaces and in camel case format
 - RESERVED NAMES: “Primary” and “Mirror” trigger mirror calculations in Equation 51, and “Aperture,” “Stop,” and “Lyot,” trigger aperture stop calculations in Equation 46. Use these names with intentionality
 - NOTE: Each optical element name must be unique
- **Temperature**
 - Definition: T_i in Equation 8
 - Description: Temperature of the optical element
 - Units: [K]
 - Allowed Values: A floating point value between $(0.000, +\infty)$
- **Absorption**
 - Definition: ϵ_i in Equation 8
 - Description: Emissivity/absorptivity of the optical element
 - Units: [NA]
 - Allowed Values: A floating point value between $[0.000, 1.000]$
 - If “NA”...
 - * If **Element** is “Mirror” or “Primary,” then use **Conductivity** and Equation 50 to calculate Ohmic losses in the conductor
 - * If **Element** is not “Mirror” or “Primary,” then use **Thickness, Index, Loss Tangent**, and Equation 49 to calculate loss in the dielectric
- **Reflection**
 - Definition: r_i in Equation 52
 - Description: Reflectivity of the optical element
 - Units: [NA]
 - Allowed Values: A floating point value between $[0.000, 1.000]$
- **Thickness**
 - Definition: t_i in Equation 49
 - Description: Thickness of the dielectric optical element
 - Units: [mm]
 - Allowed Values: A floating point value between $[0.000, 1.000]$
 - Suggested Default: “NA”
 - If **Element** is “Mirror” or “Primary,” then this parameter is ignored
 - If **Absorption** is not “NA,” then this parameter is ignored
- **Index**
 - Definition: n_i in Equation 49
 - Description: Index of refraction of the dielectric optical element
 - Units: [NA]
 - Allowed Values: A floating point value between $(0.000, +\infty)$
 - Suggested Default: “NA”
 - If **Element** is “Mirror” or “Primary,” then this parameter is ignored
 - If **Absorption** is not “NA,” then this parameter is ignored
- **Loss Tangent**
 - Definition: $\tan\delta_i$ in Equation 49
 - Description: Loss tangent of the dielectric optical element
 - Units: [NA]
 - Allowed Values: A floating point value between $(0.000, +\infty)$
 - Suggested Default: “NA”

- If **Element** is “Mirror” or “Primary,” then this parameter is ignored
- If **Absorption** is not “NA,” then this parameter is ignored
- **Conductivity**
 - Definition: σ_c in Equation 50
 - Description: Conductivity of the conductive optical element
 - Unit: [10^6 S/m]
 - Allowed Values: A floating point value between (0.000, $+\infty$)
 - Suggested Default: “NA”
 - If **Element** is not “Mirror” or “Primary,” then this parameter is ignored
 - If **Absorption** is not “NA,” then this parameter is ignored
- **Surface Rough**
 - Definition: σ_r in Equation 51
 - Description: Surface roughness of the optical element
 - Units: [μ m RMS]
 - Allowed Values: A floating point value between (0.000, $+\infty$)
 - Suggested Default: “NA”
 - If “NA” and **Scatter Frac** “NA,” then scattering set to zero.
- **Scatter Frac**
 - Definition: δ_i in Equation 8
 - Description: Scattering loss at the optical element
 - Units: [NA]
 - Allowed Values: A floating point value between (0.000, $+\infty$)
 - Suggested Default: “NA”
 - If “NA,” then use **Surface Rough** and Equation 51 to calculate scattering loss
- **Scatter Temp**
 - Definition: $T_{\delta;i}$ in Equation 8
 - Description: Effective temperature to which power is scattered from this optical element
 - Units: [K]
 - Allowed Values: A floating point value between (0.000, $+\infty$)
 - Suggested Default: “NA”
 - If “NA,” then assume the same value as **Temperature**
- **Spillover**
 - Definition: β_i in Equation 8
 - Description: Spillover loss at the optical element
 - Units: [NA]
 - Allowed Values: A floating point value between [0.000, 1.000]
 - Suggested Default: “NA”
 - If “NA,” then spillover set to zero
- **Spillover Temp**
 - Definition: $T_{\beta;i}$ in Equation 8
 - Description: Effective temperature to which power is spilled over this optical element
 - Units: [K]
 - Allowed Values: A floating point value between [0.000, $+\infty$)
 - Suggested Default: “NA”
 - If “NA,” then assume the same value as **Temperature**

1.3.4 elevation.txt

Given a finite field of view within a camera, the pixels within that camera will have some distribution of elevations on the sky with respect to the camera boresight elevation. One can define such a distribution in one of two ways: either define a Gaussian spread on the parameter **Boresight Elevation**

in the file `camera.txt` or define an explicit distribution in the file `[Camera]/config/elevation.txt`. The columns of the `elevation.txt` file are given as

- *Column 1*: Pixel elevation with respect to camera boresight
- *Column 2*: Fraction of detectors at this pixel elevation with respect to camera boresight

BoloCalc uses Equation 53 to assign elevation values to each simulated detector pixel, and given the number of detector realizations defined in `simInputs.txt`, the distribution in `elevation.txt` is sampled over as a probability distribution when generating Monte Carlo detector realizations.

1.4 Defining Bands

1.4.1 Top-Hat Band

$$B(\nu) = \begin{cases} 0 & \text{if } \nu < \nu_{lo} \\ b & \text{if } \nu_{lo} \leq \nu \leq \nu_{hi} \\ 0 & \text{if } \nu > \nu_{hi} \end{cases} \quad (1)$$

$$\nu_{lo} = \nu_c - \frac{\nu_c f_{BW}}{2} \quad (2)$$

$$\nu_{hi} = \nu_c + \frac{\nu_c f_{BW}}{2} \quad (3)$$

- ν_c is the band center, an input parameter defined in Section 1.3.2
- f_{BW} is the fractional bandwidth, an input parameter defined in Section 1.3.2

1.4.2 Trapezoidal Band

$$B(\nu) = \begin{cases} 0 & \text{if } \nu < \nu_{lo} \\ \alpha(\nu) & \text{if } \nu_{lo} \leq \nu \leq \nu_{hi} \\ 0 & \text{if } \nu > \nu_{hi} \end{cases} \quad (4)$$

- Absorption in a dielectric optic: $\alpha(\nu)$ defined by Equation 49
- Absorption in a conductive optic: $\alpha(\nu)$ defined by Equation 50
- Scattering due to surface roughness: $\alpha(\nu)$ defined by Equation 51

1.4.3 Custom Bands

The band file can be either a TXT file (whitespace delimited) or a CSV file (comma delimited) and has two or three columns

- Column 1 = frequency [GHz]
- Column 2 = quantity central value
- Column 3 = quantity standard deviation/error bar/spread (optional)

In order to flag an input parameter as having a custom-defined band, its value in the input parameter file needs to be “BAND” and the band file name in `Bands/` needs to include the parameter name. Band files for detectors are stored in the directory `[Cam_name]/config/Bands/Detectors/` and band files for optics are stored in the directory `[Cam_name]/config/Bands/Optics/`. Below are the required file formats for the detector and optics band names:

- `channels.txt` BAND: `camName_bandID.txt` or `camName_bandID.csv`
- `optics.txt` BAND: `opticName_paramName.txt` or `opticName_paramName.csv`

where `bandID` is defined by the parameter `[Band ID]` in `channels.txt`.

1.4.4 Custom Detector Bands

If the parameter **Band Center** in `channels.txt` is defined to be `BAND +/- [SPREAD]`, then an uncertainty in the location of the passed custom band is assumed to be `+/- [SPREAD]` GHz, and when running multiple Monte Carlo realizations of detectors (see Section 3.1 for more details regarding Monte Carlo simulations), the spread is assumed to be the one-sigma uncertainty in the custom band position. Note that you cannot pass “PDF” as a parameter for band shift.

Also, when passing a custom band by setting **Band Center** in `channels.txt` to `BAND` or `BAND +/- [SPREAD]`, the band-integrated efficiency can also be set independently using the parameter **Det Eff**. When both a custom band and **Det Eff** are defined simultaneously, the band-integrated efficiency is set as

$$B(\nu) = \frac{\Delta\nu_{3\text{dB}} \eta_{\text{det}}}{\int_0^\infty B_{\text{input}}(\nu) d\nu} B_{\text{input}}(\nu) \quad (5)$$

- $B_{\text{input}}(\nu)$ is the input custom band
- $\Delta\nu_{3\text{dB}}$ is the bandwidth between the input band’s -3 dB points
- η_{det} is the parameter **Det Eff** defined in Section 1.3.2
- $B(\nu)$ is the adjusted custom bandpass

Note that you can pass “PDF” as a parameter for **Band Eff** if wanting an arbitrary probability distribution for detector efficiency on a custom band.

2 BoloCalc Equation Guide

2.1 Optical Power

The **optical power** on a detector is given as

$$P_{\text{opt}} = \int_0^\infty \left[\sum_{i=1}^{N_{\text{elem}}} p_i(\nu) \right] B(\nu) d\nu \quad (6)$$

- ν is frequency
- $p_i(\nu)$ is the power spectral density of optical element i
- N_{elem} is the number of optical elements in the sky + telescope + camera
- $B(\nu)$ is the detector bandpass, as described in 1.4

The **power spectral density** $p_i(\nu)$ for optical element i is determined by:

$$p_i(T_i, [\eta_{i+1}(\nu), \dots, \eta_{N_{\text{elem}}}(\nu)], \epsilon_i(\nu), \beta_i(\nu), T_{\beta;i}, \delta_i(\nu), T_{\delta;i}) = \quad (7)$$

$$\prod_{j=i+1}^{N_{\text{elem}}} \eta_j(\nu) [\epsilon_i(\nu) S(T_i, \nu) + \beta_i(\nu) S(T_{\beta;i}, \nu) + \delta_i(\nu) S(T_{\delta;i}, \nu)] \quad (8)$$

- its blackbody temperature T_i , an input parameter defined in Section 1.3.3
- the transmission efficiency for all optics between it and the focal plane $[\eta_{i+1}(\nu), \dots, \eta_{N_{\text{elem}}}(\nu)]$, input parameters defined in Section 1.3.2
- its emissivity $\epsilon_i(\nu)$, an input parameter defined in Section 1.3.3
- its spillover coefficient $\beta_i(\nu)$, an input parameter defined in Section 1.3.3
- the effective temperature by which its spilled power is absorbed $T_{\beta;i}$, an input parameter defined in Section 1.3.3
- its scattering coefficient $\delta_i(\nu)$, an input parameter defined in Section 1.3.3

- the effective temperature by which its scattered power is absorbed $T_{\delta;i}$, an input parameter defined in Section 1.3.3

The **power spectral density function** $S(T, \nu)$ of the emitted and scattered power from each element is given by the Planck spectral density for a polarimeter

$$S(T, \nu) = A\Omega \frac{h\nu^3}{c^2} \frac{1}{\exp\left[\frac{h\nu}{k_B T} - 1\right]} = \frac{h\nu}{\exp\left[\frac{h\nu}{k_B T} - 1\right]} \quad (9)$$

where for a diffraction-limited, single-moded detector, the **etendue** $A\Omega$ is given by the square of the detected wavelength

$$A\Omega = \left(\frac{c}{\nu}\right)^2 \quad (10)$$

2.2 Optical Throughput

The **optical throughput** of the instrument is the total transmission through all optical elements and is defined as

$$\eta_{\text{inst}} = \prod_{i=0}^{N_{\text{inst}}} \eta_i \quad (11)$$

- N_{inst} represents all optical elements within in the instrument (which are defined in the `optics.txt` file, and for the detector, whose efficiency is defined in `channels.txt`)
- η_i represent the transmission efficiency for each optical item, an input parameter defined in Section 1.3.2

2.3 Telescope Temperature

The **total power due to emission from the instrument** is a subset of Equation 6 and is defined as

$$P_{\text{inst}} = \int_0^\infty \left[\sum_i^{N_{\text{inst}}} p_i(\nu) \right] B(\nu) d\nu \quad (12)$$

- N_{inst} are elements within the telescope (excluding the sky elements)
- $p_i(\nu)$ is the power spectral density function of each optical element, defined in Equation 8
- $B(\nu)$ is the detector bandpass, defined in Section 1.4

The **telescope temperature** is defined to be

$$T_{\text{tel}} = \frac{P_{\text{inst}}}{k_B \eta_{\text{inst}}} \quad (13)$$

where η_{inst} is the throughput defined in Equation 11. Note that the temperature units are K_{RJ}.

2.4 Sky Temperature

Total power due to emission from the sky is a subset of Equation 6 and is defined as

$$P_{\text{sky}} = \int_0^{\infty} \left[\sum_i^{N_{\text{sky}}} p_i(\nu) \right] B(\nu) d\nu \quad (14)$$

- N_{sky} are elements outside of the telescope (which are explicitly CMB, Galactic dust, Galactic synchrotron, Atmosphere, and/or Room, depending on foregrounds and site)
- $p_i(\nu)$ is the power spectral density function of each optical element, defined in Equation 8
- $B(\nu)$ is the detector bandpass, defined in Section 1.4

The **sky temperature** is defined to be

$$T_{\text{sky}} = \frac{P_{\text{sky}}}{k_{\text{B}} \eta_{\text{inst}}} \quad (15)$$

where η_{inst} is the throughput defined in Equation 11. Note that the temperature units are K_{RJ}.

2.5 Photon Noise Equivalent Power

The **photon noise equivalent power** is defined by

$$NEP_{\text{ph}} = \sqrt{2 \int_0^{\infty} \left[h\nu \sum_{i=1}^{N_{\text{elem}}} p_i(\nu) + \left(\sum_{i=1}^{N_{\text{elem}}} p_i(\nu) \right)^2 \right] B^2(\nu) d\nu} \quad (16)$$

- N_{elem} is the number of optical elements
- $p_i(\nu)$ is the power spectral density function of each optical element, defined in Equation 8
- $B(\nu)$ is the detector bandpass, defined in Section 1.4

2.6 Thermal Carrier Noise Equivalent Power

The **thermal carrier noise equivalent power** is defined by

$$NEP_{\text{g}} = \sqrt{4k_{\text{B}} F_{\text{link}} T_{\text{oper}}^2 G} \quad (17)$$

- T_{oper} is the bolometer operating temperature, an input parameter defined in Section 1.3.2
- G is the thermal conductance from the absorbing element to the bath, an input parameter defined in Section 1.3.2
- F_{link} is a numerical factor that depends on the link's thermal conduction index n , an input parameter defined in Section 1.3.2

BoloCalc allows the **bolometer operating temperature** to be determined by

$$T_{\text{oper}} = f_{\text{oper}} T_{\text{bath}} \quad (18)$$

- f_{oper} is the Tc fraction input parameter defined in Section 1.3.2, the ratio of the operating temperature to bath temperature
- T_{bath} is the bath temperature for the bolometer, an input parameter defined in Section 1.3.1

Similarly, the **thermal conductance factor**, an optional input parameter defined in Section 1.3.2, can be theoretically estimated via the equation

$$F_{\text{link}} = \frac{n+1}{2n+3} \frac{1 - (T_{\text{bath}}/T_{\text{oper}})^{2n+3}}{1 - (T_{\text{bath}}/T_{\text{oper}})^{n+1}} \quad (19)$$

- T_{oper} is the operating temperature of the bolometer, an input parameter defined in Section 1.3.2
- T_{bath} is the bath temperature for the bolometer, an input parameter defined in Section 1.3.1
- n is the link's thermal conduction index, an input parameter defined in Section 1.3.2

BoloCalc also provides an option for F_{link} to be set independent of T_{bath} and n , allowing NEP_g to be tuned phenomenologically.

Thermal conductance, G , an optional input parameter defined in Section 1.3.2, can be written as

$$G = P_{\text{sat}}(n+1) \frac{T_{\text{oper}}^n}{T_{\text{oper}}^{n+1} - T_{\text{bath}}^{n+1}} \quad (20)$$

- n is the link's thermal conduction index, an input parameter defined in Section 1.3.2
- T_{bath} is the temperature of the bath for the bolometer, an input parameter defined in Section 1.3.1
- P_{sat} is the bolometer saturation (or the power conducted from the bolometer to the bath), an input parameter defined in Section 1.3.2
- T_{oper} is the operating temperature of the bolometer, an input parameter defined in Section 1.3.2

2.7 Readout Noise Equivalent Power

SQUID amplifier noise is typically characterized in terms of a noise-equivalent current NEI , which has units of $\frac{\text{A}}{\sqrt{\text{Hz}}}$. In order to refer NEI to an NEP , we need to consider the **bolometer responsivity** $S_I = dI_{\text{elec}}/dP$. BoloCalc quantifies **bolometer responsivity** via the relationship

$$S_I = -S_{\text{fact}} \frac{1}{V_{\text{elec}}} \quad (21)$$

- S_{fact} is the bolometer responsivity factor, an input parameter defined in Section 1.3.2
- V_{elec} is the bias voltage across the bolometer, as defined in Equation 26

In the presence of electrothermal feedback, the **bolometer responsivity** can be written as

$$S_I = -\tilde{S}_{\text{fact}} \frac{1}{V_{\text{elec}}} \frac{\mathcal{L}}{\mathcal{L}+1} \frac{1}{1+i\omega\tau} \quad (22)$$

- \mathcal{L} is the bolometer DC loop gain
- τ is the bolometer time constant
- ω is the modulation mode frequency
- V_{elec} is the (DC or AC, depending on multiplexing) bias voltage across the bolometer, as defined in Equation 26
- \tilde{S}_{fact} is a factor that depends on whether V_{elec} is DC or AC, as shown in Equation 23

$$\tilde{S}_{\text{fact}} = \begin{cases} 1 & \text{if } V_{\text{elec}} \text{ is DC} \\ \sqrt{2} & \text{if } V_{\text{elec}} \text{ is AC RMS} \end{cases} \quad (23)$$

In the limit of high loop gain $\mathcal{L} \gg 1$ and at frequencies much slower than the bolometer time constant $\omega\tau \ll 1$, a simple approximate relationship for the **bolometer responsivity factor** is

$$S_{\text{I}} \approx -\tilde{S}_{\text{fact}} \frac{1}{V_{\text{elec}}} \quad (24)$$

- V_{elec} is the bias voltage across the bolometer, as defined in Equation 26
- \tilde{S}_{fact} is a factor that depends on whether V_{elec} is AC or DC

or, equivalently

$$S_{\text{fact}} \approx \tilde{S}_{\text{fact}} \quad (25)$$

where common-use cases for \tilde{S}_{fact} are given in Equation 23.

The **bias voltage** is

$$V_{\text{elec}} = \sqrt{R_{\text{bolo}} P_{\text{elec}}} , \quad (26)$$

- R_{bolo} is bolometer resistance, an input parameter defined in Section 1.3.2
- P_{elec} is bias power

and furthermore, the **bias power**, P_{elec} , can be written as

$$P_{\text{elec}} = P_{\text{sat}} - P_{\text{opt}} \quad (27)$$

- P_{sat} is the bolometer saturation power (or the power conducted from the bolometer to the bath)
- P_{opt} is absorbed optical power

Finally, the **readout noise equivalent power** can be written as

$$NEP_{\text{read}} = \frac{NEI}{S_{\text{I}}} = \frac{\sqrt{R_{\text{bolo}} (P_{\text{sat}} - P_{\text{opt}})}}{S_{\text{fact}}} NEI \quad (28)$$

- NEI is the noise equivalent current in the SQUID, an input parameter defined in Section 1.3.2
- S_{I} is the bolometer responsivity
- R_{bolo} is the bolometer resistance, an input parameter defined in Section 1.3.2
- P_{sat} is the bolometer saturation power (or the power conducted from the bolometer to the bath), an input parameter defined in Section 1.3.2
- P_{opt} is absorbed optical power
- S_{fact} is the bolometer responsivity factor, an input parameter defined in Section 1.3.2

Note that a decreased bolometer responsivity factor S_{fact} leads to increased readout noise.

BoloCalc also has an option to define the **readout noise** as a fraction of all other quadrature-summed noise sources, NEP_{other} , as

$$NEP_{\text{read}} = \Delta_{\text{read}} \times NEP_{\text{other}} \quad (29)$$

See Section 1.3.2 for more details about setting channel noise parameters.

2.8 Johnson Noise Equivalent Power

The relationship for **Johnson noise equivalent current**, NEI_{johnson} , is given by

$$NEI_{\text{johnson}} = \frac{1}{\mathcal{L}} \sqrt{\frac{4k_{\text{B}}T_{\text{oper}}}{R_{\text{bolo}}}} \quad (30)$$

- \mathcal{L} is the bolometer DC loop gain
- T_{oper} is the operating temperature of the bolometer
- R_{bolo} is the resistance of the bolometer

The Johnson current noise can be converted to a **Johnson noise equivalent power** as

$$NEP_{\text{johnson}} = \frac{NEI_{\text{johnson}}}{S_{\text{I}}} = \tilde{S}_{\text{fact}} \frac{\mathcal{L} + 1}{\mathcal{L}^2} \frac{1}{1 + i\omega\tau} \sqrt{4k_{\text{B}}T_{\text{oper}}P_{\text{elec}}}, \quad (31)$$

- S_{I} is the bolometer responsivity, which is defined in Equation 22
- P_{elec} is the bias power and is defined in Equation 27
- NEI is the Johnson current noise, as defined in Equation 30
- T_{oper} is the operating temperature of the bolometer
- \tilde{S}_{fact} is a bolometer responsivity factor
- \mathcal{L} is the bolometer DC loop gain
- τ is the bolometer time constant
- ω is the modulation mode frequency

BoloCalc, as of v0.10.0, assumes that the bolometers have a high enough loop gain to render **Johnson noise equivalent power** negligible compared to other noise sources, i.e.

$$NEP_{\text{johnson}} = 0 \quad (32)$$

2.9 Detector Noise Equivalent Power

Assuming that the all detector noise sources add in quadrature and that Johnson noise is zero, as explained in Section 2.8, then the total **detector noise equivalent power** is given as

$$NEP_{\text{det}} = \sqrt{NEP_{\text{ph}}^2 + NEP_{\text{g}}^2 + NEP_{\text{read}}^2} \quad (33)$$

- NEP_{ph} is photon noise equivalent power, as defined in 16
- NEP_{g} is the thermal carrier noise equivalent power, as defined in 17
- NEP_{read} is the readout noise equivalent power, as defined in 28

2.10 Noise-equivalent Temperature

The total noise-equivalent power is described in Section 2.9, and the conversion to **noise equivalent temperature** is given by

$$NET_{\text{det}} = M \frac{NEP_{\text{det}}}{\sqrt{2} (dP/dT_{\text{sky}})} \quad (34)$$

- NEP_{det} is total detector noise equivalent power as described in Equation 33
- M is a 'margin factor' applied to the expected per-detector NET, an input parameter defined in Section 1.2.1
- dP/dT_{sky} is the conversion factor to the total sky temperature, which takes into account two different sky temperature units—the 2.725 K blackbody (K_{CMB}) of the CMB and a 1 K Rayleigh-Jeans source (K_{RJ})

- $\sqrt{2}$ comes from a unit conversion from output bandwidth $\frac{1}{\sqrt{\text{Hz}}}$ to integration time \sqrt{s}

The **conversion factor for CMB temperature** is

$$\frac{dP}{dT_{\text{CMB}}} = \xi \int_0^\infty \left[\prod_{i=1}^{N_{\text{elem}}} \frac{1}{k_B} \left(\frac{h\nu}{T_{\text{CMB}} (\exp[h\nu/k_B T_{\text{CMB}}] - 1)} \right)^2 \exp[h\nu/k_B T_{\text{CMB}}] \right] B(\nu) d\nu \quad (35)$$

- ξ is an overall signal degradation factor (e.g. from poor far-field image formation at the focal plane) and an input parameter defined in Section 1.3.1
- $B(\nu)$ is the detector bandpass, defined in Section 1.4

Note that Equation 35 has units of W/K_{CMB}.

The **conversion factor for Rayleigh-Jeans temperature** is

$$\frac{dP}{dT_{\text{RJ}}} = \xi \int_0^\infty k_B B(\nu) d\nu \quad (36)$$

- ξ is an overall signal degradation factor (e.g. from poor far-field image formation at the focal plane) and an input parameter defined in Section 1.3.1
- $B(\nu)$ is the detector bandpass, defined in Section 1.4

Note that Equation 36 has units of W/K_{RJ}.

2.11 Array Noise-equivalent Temperature

We defined “array NET” as the inverse-variance-weighted average of the NETs of all yielded detectors within a given frequency channel. Thus, **array noise equivalent temperature** is

$$NET_{\text{arr}} = \frac{NET_{\text{det}}}{\sqrt{Y N_{\text{det}}}} \Gamma \quad (37)$$

- N_{det} is the number of detectors in this frequency channel, an input parameter defined in Section 1.3.2
- Y is the detector yield, an input parameter defined in Section 1.3.2
- Γ is a factor which quantifies the degree to which white noise is correlated between detector pixels on the focal plane, defined in Equation 42

2.12 Correlation Factor

The **optical correlation coefficient** between detector i and detector j when observing a source through the aperture stop is given by

$$\gamma_{i,j} = \frac{\langle |e_i|^2 |e_j|^2 \rangle - \langle |e_i|^2 \rangle \langle |e_j|^2 \rangle}{\text{RMS}(|e_i|^2) \text{RMS}(|e_j|^2)}, \quad (38)$$

- e_i is the integral of the source electric field for detector i

$$e_i = \iint dx dy e^{2\pi i \ell_i(x,y)} b_i(x,y) a(x,y). \quad (39)$$

- $a(x,y)$ is the aperture plane
- $b_i(x,y)$ is the beam for detector i
- $\ell_i(x,y)$ is the optical path length to the source

The **cumulative correlation coefficient** γ is given by a summation of the correlation coefficients between all N_{pix} detector pixels on the focal plane

$$\gamma = \frac{1}{N_{\text{pix}} - 1} \sum_i \sum_{j \neq i} \gamma_{i,j} . \quad (40)$$

Correlations then propagate to MS by suppressing the degree to which wave noise is averaged down when inverse-variance averaging the detector data, giving **array noise equivalent temperature** as

$$\text{NET}_{\text{arr}} = \sqrt{\frac{\text{NET}_{\text{shot}}^2 + (1 + \gamma)\text{NET}_{\text{wave}}^2 + \text{NET}_{\text{g}}^2 + \text{NET}_{\text{read}}^2}{Y N_{\text{det}}}} \quad (41)$$

- NET_{shot} is the noise equivalent temperature associated with photons due to their discretized nature, where the associated noise-equivalent power is defined in Equation 16
- NET_{wave} is the noise equivalent temperature associated with photons due to their wave nature, where the associated noise-equivalent power is defined in Equation 16
- NET_{g} is the thermal carrier noise equivalent temperature, where the associated noise-equivalent power is defined in Equation 17
- NET_{read} is the readout noise equivalent temperature, where the associated noise-equivalent power is defined in Equation 28
- Y is the detector yield, as defined in Section 1.3.2
- N_{det} is the number of detectors

We can now write the **array NET correlation suppression factor** Γ defined in Equation 37 as

$$\Gamma = \sqrt{1 + \frac{\gamma \text{NET}_{\text{wave}}^2}{\text{NET}_{\text{shot}}^2 + \text{NET}_{\text{wave}}^2 + \text{NET}_{\text{g}}^2 + \text{NET}_{\text{read}}^2}} \quad (42)$$

- NET_{shot} is the noise equivalent temperature associated with photons due to their discretized nature, where the associated noise-equivalent power is defined in Equation 16
- NET_{wave} is the noise equivalent temperature associated with photons due to their wave nature, where the associated noise-equivalent power is defined in Equation 16
- NET_{g} is the thermal carrier noise equivalent temperature, where the associated noise-equivalent power is defined in Equation 17
- NET_{read} is the readout noise equivalent temperature, where the associated noise-equivalent power is defined in Equation 28

2.13 Map Depth

Finally, array NET—white noise in the time domain—is converted from units of $\text{K}\sqrt{\text{s}}$ to units of $\text{K}\text{-arcmin}$ —**white noise in the map domain**— using the equation

$$\sigma_{\text{S}} = \sqrt{\frac{4\pi f_{\text{sky}} \text{NET}_{\text{arr}}^2}{\eta_{\text{obs}} t_{\text{obs}}}} \left(\frac{10800 \text{ arcmin}}{\pi} \right) \quad (43)$$

- f_{sky} is the (effective) fraction of sky observed, an input parameter defined in Section 1.2.1
- NET_{arr} is defined in Equation 37
- η_{obs} is the telescope observation efficiency, an input parameter defined in Section 1.2.1
- t_{obs} is the total operation time of the telescope, an input parameter defined in Section 1.2.1

Note that BoloCalc computes Map Depth in both units of $\text{K}_{\text{CMB}}\text{-arcmin}$ and $\text{K}_{\text{RJ}}\text{-arcmin}$.

2.14 Auxiliary Optical Calculations

2.14.1 Synchrotron Emission

The **synchrotron power spectral density** for a single polarization in units of $\text{W Hz}^{-1} \text{sr}^{-1}$ is given by the equation

$$p_{\text{synch}}(\nu) = A\Omega \frac{\nu^2}{c^2} k_{\text{B}} T_{\text{s}} \left(\frac{\nu}{\nu_{\text{s}}} \right)^{n_{\text{s}}} = k_{\text{B}} T_{\text{s}} \left(\frac{\nu}{\nu_{\text{s}}} \right)^{n_{\text{s}}} \quad (44)$$

- ν_{s} is the pivot frequency, an input parameter described in Section 1.1.1
- T_{s} is the synchrotron brightness temperature in K_{RJ} at ν_{s} , an input parameter described in Section 1.1.1
- n_{s} is the synchrotron spectral index, an input parameter described in Section 1.1.1
- $A\Omega$ is the etendue for a diffraction-limited detector, given by Equation 10

This spectral density is included in the summation described in Equation 6 when the **Foregrounds** parameter in `BoloCalc/config/simInputs.txt`, as described in Section 3.2, is set to **True**.

2.14.2 Dust Emission

The **dust power spectral density** in units of $\text{W Hz}^{-1} \text{sr}^{-1}$ is given by the following equation

$$p_{\text{dust}}(\nu) = A_{\text{d}} A\Omega \left(\frac{\nu}{\nu_{\text{d}}} \right)^{n_{\text{d}}} \frac{S(T_{\text{d}}, \nu)}{S(T_{\text{d}}, \nu_{\text{d}})} \times 10^{-20} = A_{\text{d}} \frac{c^2}{\nu^2} \left(\frac{\nu}{\nu_{\text{d}}} \right)^{n_{\text{d}}} \frac{S(T_{\text{d}}, \nu)}{S(T_{\text{d}}, \nu_{\text{d}})} \times 10^{-20} \quad (45)$$

- ν_{d} is the pivot frequency, an input parameter described in Section 1.1.1
- A_{d} is the dust amplitude in MJy sr^{-1} at ν_{d} , an input parameter described in Section 1.1.1
- n_{d} is the dust spectral index, an input parameter described in Section 1.1.1
- $S(T_{\text{d}}, \nu)$ is the blackbody spectral density function defined in Equation 9
- T_{d} is the dust temperature, an input parameter described in Section 1.1.1
- $A\Omega$ is the etendue for a diffraction-limited detector, given by Equation 10

Note that the conversion from MJy to W is $\times 10^{-26} \text{W/MJy}$. This spectral density is included in the summation described in Equation 6 when the **Include Foregrounds** parameter described in Section 3.2 is set to **True**.

2.14.3 Atmosphere Emission

BoloCalc utilizes atmospheric simulations of the atmosphere at the Atacama and South Pole sites, as well as from the high altitude of a balloon, generated by the AM atmospheric modeling code ¹, which uses data from the MERRA-2 meteorological reanalysis ² as input. The output from the AM simulation produces a spectrum of physical sky temperature and sky efficiency/transmission, and the band-integrated values produce loading results consistent with measure sky loading in existing Atacama experiments.

2.14.4 Aperture Stop Spillover Efficiency/Absorption

Aperture efficiency can be specified explicitly, or, if it is defined as “NA,” it can be derived from a combination of other detector pixel parameters

¹<https://www.cfa.harvard.edu/spaine/am/>

²<https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/>

$$\eta_{\text{stop}}(\nu) = 1 - \exp \left[-\frac{\pi^2}{2} \left(\frac{D_{\text{pix}}}{F \lambda w_f} \right)^2 \right] \quad (46)$$

- $w_f = D_{\text{pix}}/w_0$ where D_{pix} is the pixel diameter and w_0 is the beam waist, input parameters described in Section 1.3.2
- F is the F-number at the focal plane, an input parameter defined in Section 1.3.1
- $\lambda = c/\nu$ is the observation wavelength

This quantity is integrated over the observation band when calculating the in-band optical power and signal attenuation referenced to the detector.

Aperture reflection is assumed be zero

$$r_{\text{stop}} = 0 \quad (47)$$

and the **aperture absorption**, in terms of aperture stop spillover efficiency, is assumed to be

$$\epsilon_{\text{stop}} = 1 - \eta_{\text{stop}} \quad (48)$$

2.14.5 Dielectric Absorption/Emission

Absorption in a refractive optical element can be specified explicitly, or, if it is defined as “NA,” it can be derived using the following equation

$$\epsilon(\lambda) = 1 - \exp[-2\pi t n (\tan \delta) \lambda] \quad (49)$$

- t is the thickness of the dielectric substrate, an input parameter defined in Section 1.3.3
- n is the refractive index, an input parameter defined in Section 1.3.3
- $\tan \delta$ is the loss tangent, an input parameter defined in Section 1.3.3
- λ is the observation wavelength

This quantity is integrated over the observation band when calculating the in-band optical power and signal attenuation referenced to the detector.

2.14.6 Reflector Absorption/Emission

Absorption in a reflective optical element can be specified explicitly, or, if it is left as “NA,” it can be derived using the following equation

$$\epsilon(\nu) = 4 \sqrt{\frac{\pi \nu \mu_0}{\sigma_c}} \frac{1}{Z_0} \quad (50)$$

- ν is the observation frequency
- μ_0 is the permeability of free space
- $Z_0 = \sqrt{\mu_0/\epsilon_0}$ is the impedance of free space
- σ_c is the reflector conductivity at the reflector’s operating temperature, an input parameter defined in Section 1.3.3

This quantity is integrated over the observation band when calculating the in-band power and signal attenuation referenced to the detector.

2.14.7 Ruze Scattering

Scattering off of a reflective or refractive optical element can be specified explicitly, or, if it is defined as “NA,” it can be derived using Ruze’s equation

$$\delta(\nu) = \exp \left[\left(\frac{4\pi\sigma_r}{\lambda} \right)^2 \right] \quad (51)$$

- σ_r is the RMS surface roughness of the optical element, an input parameter defined in Section 1.3.3
- λ is the observation wavelength

This quantity is integrated over the observation band when calculating the in-band power and signal attenuation referenced to the detector.

2.14.8 Efficiency

Efficiency can be defined explicitly for any optic by the total power loss as

$$\eta(\nu) = 1 - r(\nu) - \epsilon(\nu) - \beta(\nu) - \delta(\nu) \quad (52)$$

- $r(\nu)$ is the reflection spectrum, an input parameter defined in Section 1.3.3
- $\epsilon(\nu)$ is the dielectric absorption, an input parameter defined in Section 1.3.3
- $\beta(\nu)$ is the spillover spectrum
- $\delta(\nu)$ is the scattering spectrum

This quantity is integrated over the observation band when calculating the in-band power and signal attenuation referenced to the detector.

2.15 Auxiliary Detector Calculations

2.15.1 Pixel Elevation

In order to calculate the expected loading on each detector, we need to know the **elevation of its detector pixel** projected onto the sky

$$\theta_{\text{elv}} = \theta_{\text{tel}} + \theta_{\text{cam}} + \theta_{\text{pix}} \quad (53)$$

- θ_{tel} is the telescope boresight elevation, an input parameter described in Section 1.2.1
- θ_{cam} is the camera boresight elevation with respect to the telescope boresight, an input parameter defined in Section 1.3.1
- θ_{pix} is the pixel elevation with respect to the camera boresight

2.15.2 Saturation Power

BoloCalc has an option to set the saturation power P_{sat} explicitly, or, as another option, as fraction of the optical power P_{opt} , as defined in Equation 6. If the parameter **Saturation Power** is set to “NA,” then **saturation power**, P_{sat} , is calculated as

$$P_{\text{sat}} = f_{\text{psat}} \times P_{\text{opt}} \quad (54)$$

where f_{psat} represents the parameter **Psat Factor**, an input parameter defined in Section 1.3.2.

2.15.3 Operating Temperature

BoloCalc has an option to set the operation temperature T_{oper} explicitly, or, as another option, as a fraction of the bath temperature T_{b} . If the parameter **Tc** is set to “NA,” then **operating temperature** is defined using the equation

$$T_{\text{oper}} = f_{\text{oper}} \times T_{\text{bath}} \quad (55)$$

where f_{oper} represents the parameter **Tc Fraction**.

2.15.4 Fractional Readout Noise

BoloCalc has an option to calculate readout noise using Equations 27 and 28. However, if either the parameter **Bolo Resistance** or **SQUID NEI** is defined as “NA,” and if the parameter **Read Noise Frac** is not “NA,” then **readout noise** is calculated via the equation

$$NEP_{\text{read}} = \sqrt{(1 + \Delta_{\text{read}})^2 - 1} \times \sqrt{NEP_{\text{ph}}^2 + NEP_{\text{g}}^2} \quad (56)$$

- Δ_{read} represents the parameter **Read Noise Frac**, an input parameter defined in Section 1.3.2
- NEP_{ph} is the photon noise equivalent power, as calculated in Equation 16
- NEP_{g} is the thermal carrier noise-equivalent power, as calculated in Equation 17

2.15.5 Number of Detectors

The **number of total detectors** in a given channel N_{det} is given by

$$N_{\text{det}} = N_{\text{det/waf}} \times N_{\text{waf/OT}} \times N_{\text{OT}} \quad (57)$$

- $N_{\text{det/waf}}$ is the number of detectors per wafer, an input parameter defined in Section 1.3.2
- $N_{\text{waf/OT}}$ is the number of wafers per optics tube (or equivalently, per camera), an input parameter defined in Section 1.3.2
- N_{OT} is the number of optics tubes per telescope, an input parameter defined in Section 1.3.2

3 Simulation Parameter Guide

BoloCalc has one executable `calcBolos.py` that has several options which we will outline in this section.

3.1 Monte Carlo

BoloCalc is set up to iterate over uncertainties or probability distributions for experiment, observation, and detector parameters. Below is the basic structure of the calculation

- Generate N_{exp} experiment + telescope + camera realizations
- For each experiment realization, generate N_{obs} observation realizations
- For each observation realization, generate N_{dets} detector realizations

In all the number of frequency channel realizations is

$$N_{\text{sims}} = N_{\text{exp}} \times N_{\text{obs}} \times N_{\text{dets}} \quad (58)$$

3.2 Simulation Inputs

Simulation inputs are stored in the file `BoloCalc/config/simulationInputs.txt`. Each parameter is defined in the following list

- **Experiments**
 - Definition: N_{exp} in Equation 58
 - Description: Number of experiment realizations in the Monte Carlo simulation
 - Allowed Values: Integer value between $[1, \infty)$
 - Suggested Default: “1”
 - If set to “1,” then take the median value for all experiment parameters. If greater than 1, then sample the experiment parameter distributions the set number of times
- **Observations**
 - Definition: N_{obs} in Equation 58
 - Description: Number of observation realizations in the Monte Carlo simulation
 - Allowed Values: Integer value between $[1, \infty)$
 - Suggested Default: “1”
 - If set to “1,” then take the median value for all PWV + telescope elevation parameters. If greater than 1, then sample the PWV + telescope elevation parameters distributions the set number of times
- **Detectors**
 - Definition: N_{dets} in Equation 58
 - Description: Number of detector realizations in the Monte Carlo simulation
 - Allowed Values: Integer value between $[1, \infty)$
 - Suggested Default: 1
 - If set to “1,” then take the median value for all detector parameters. If greater than 1, then sample the detector parameters distributions the set number of times
- **Resolution**
 - Description: Frequency resolution used for the simulation
 - Allowed Values: Integer value between $(0, \infty)$
 - Units: [GHz]
 - Note that reducing the resolution—by increasing this parameter’s value—is an efficient way to speed up BoloCalc calculations
 - Suggested Default: “0.5”
- **Foregrounds**
 - Description: A boolean value to specify whether or not to include foregrounds
 - Allowed Values: “True” or “False”
 - Suggested Default: “True”
- **Correlations**
 - Description: A boolean value to specify whether or not to include white-noise correlations
 - Allowed Values: “True” or “False”
 - Suggested Default: “True”
- **Percentile**
 - Description: A list of percentiles to display on output parameter distributions
 - Allowed Values: A list of two values using the format “[A, B]” where both A and B must be floating point values between $(0.0, 100.0)$
 - Units: [%]
 - Suggested Default: “[15.9, 84.1]” which corresponds to one-sigma deviations for a Gaussian distribution

4 Output File Guide

Running `calcBolos.py` generates several output files, which quantify the performance of the simulated experiment.

4.1 `sensitivity.txt`

BoloCalc generates sensitivity tables at three levels of the experiment directory structure. The most informative of these is `[Experiment]/[Telescope]/[Camera]/sensitivity.txt` and contains 15 output parameters

- **Chan**
 - Description: Frequency channel name, constructed as `[Cam name]_[Band ID]`
- **Num Det**
 - Definition: N_{det} in Equation 57
 - Description: total number of detectors in this frequency channel + camera + telescope
- **Optical Throughput**
 - Definition: η_{inst} in Equation 11
 - Description: optical throughput for this frequency channel + camera + telescope
- **Optical Power**
 - Definition: P_{opt} in Equation 6
 - Description: optical power sensed by the detector in this frequency channel + camera + telescope
 - Units: pW
- **Telescope Temp**
 - Definition: T_{tel} in Equation 13
 - Description: telescope temperature for this frequency channel + camera + telescope
 - Units: K_{RJ}
- **Sky Temp**
 - Definition: T_{sky} in Equation 15
 - Description: sky temperature for this frequency channel + camera + telescope
 - Units: K_{RJ}
- **Photon NEP**
 - Definition: NEP_{ph} in Equation 16
 - Description: photon noise equivalent power for this frequency channel + camera + telescope
 - Units: aW/ $\sqrt{\text{Hz}}$
- **Bolometer NEP**
 - Definition: NEP_{g} in Equation 17
 - Description: thermal carrier noise equivalent power for this frequency channel + camera + telescope
 - Units: aW/ $\sqrt{\text{Hz}}$
- **Readout NEP**
 - Definition: NEP_{read} in Equation 28
 - Description: readout noise equivalent power for this frequency channel + camera + telescope
 - Units: aW/ $\sqrt{\text{Hz}}$
- **Detector NEP**
 - Definition: NEP_{det} in Equation 33
 - Description: detector noise equivalent power for this frequency channel + camera + telescope
 - Units: aW/ $\sqrt{\text{Hz}}$

- **Detector NET_CMB**
 - Definition: NET_{det} in Equation 34 assuming $dP/dT_{\text{sky}} = dP/dT_{\text{CMB}}$
 - Description: detector noise equivalent CMB temperature for this frequency channel + camera + telescope
 - Units: $\mu\text{K}_{\text{CMB}}\sqrt{\text{s}}$
- **Detector NET_RJ**
 - Definition: NET_{det} in Equation 34 assuming $dP/dT_{\text{sky}} = dP/dT_{\text{RJ}}$
 - Description: detector noise equivalent RJ temperature for this frequency channel + camera + telescope
 - Units: $\mu\text{K}_{\text{RJ}}\sqrt{\text{s}}$
- **Array NET_CMB**
 - Definition: NET_{arr} in Equation 37 assuming $dP/dT_{\text{sky}} = dP/dT_{\text{CMB}}$
 - Description: array noise equivalent CMB temperature for this frequency channel + camera + telescope
 - Units: $\mu\text{K}_{\text{CMB}}\sqrt{\text{s}}$
- **Array NET_RJ**
 - Definition: NET_{arr} in Equation 37 assuming $dP/dT_{\text{sky}} = dP/dT_{\text{RJ}}$
 - Description: array noise equivalent RJ temperature for this frequency channel + camera + telescope
 - Units: $\mu\text{K}_{\text{RJ}}\sqrt{\text{s}}$
- **Correlation Factor**
 - Definition: Γ in Equation 42
 - Description: array NET correlation factor for this frequency channel + camera + telescope
- **CMB Map Depth**
 - Definition: σ_s in Equation 43 assuming $dP/dT_{\text{sky}} = dP/dT_{\text{CMB}}$
 - Description: map depth in CMB temperature units for this frequency channel + camera + telescope
 - Units: $\mu\text{K}_{\text{CMB}} \text{ amin}$
- **RJ Map Depth**
 - Definition: σ_s in Equation 43 assuming $dP/dT_{\text{sky}} = dP/dT_{\text{RJ}}$
 - Description: map depth in RJ temperature units for this frequency channel + camera + telescope
 - Units: $\mu\text{K}_{\text{RJ}} \text{ amin}$

There are also output sensitivity files at levels `[Experiment]/[Telescope]/sensitivity.txt` and `[Experiment]/sensitivity.txt` which contain the parameters

- Array NET_CMB
- Array NET_RJ
- CMB Map Depth
- RJ Map Depth

which combine the sensitivities of all frequency channels within it that have the same **Band ID**.

4.2 optical_power.txt

`calcBollos.py` also generates a table for each frequency channel of the following

- **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, as defined between the detector band's -3 dB points
- **Power to Detect**: power emitted from the optical element onto the detector. This quantity is integrated over the detector bandpass

- **Cumulative Eff**: cumulative efficiency between this optical element and the sky, integrated over the detector bandpass

4.3 `output.txt`

The file `[Camera]/output.txt` holds the parameter outputs for every Monte Carlo simulation, for each frequency channel within the camera. These numbers form the histograms behind the central values and spreads in the `sensitivity.txt` file; see Section 4.1 for more details about the sensitivity outputs.