# QuickBeam
# Radar Simulation Software

## User's Guide

v 1.1

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# Introduction

QuickBeam is a meteorological radar simulation package. It is capable of simulating vertical radar reflectivity profiles at any common microwave frequency, from either the top-down (i.e. satellite-based radars such as CloudSat) or the bottom-up. The user provides information about the state of the atmosphere and the water species contained therein, and the simulator produces profiles of effective radar reflectivity factor that emulate what a physical radar system would observe. The simulator currently includes five preset distributions of hydrometeors from which the user can choose: modified gamma, exponential, power law, monodisperse, and lognormal. The software accounts for attenuation of the radar beam by both atmospheric gases and hydrometeors.

This a quick-start guide, there is nothing comprehensive about this document! It is intended to convey some basic information about the most typical settings a user might need to specify to do some successful calculations. At this time, the closest thing to a comprehensive reference guide that describes the details of the theory behind the simulator is the author's PhD dissertation, and the relevant portions of this are available on request.

An article describing general features of the simulator is published in the November 2007 issue of BAMS (Bulletin of the American Meteorological Society) and is available from the QuickBeam website. This article may be used as a reference for the simulator.

Haynes, J.M., R.T. Marchand, Z. Luo, A. Bodas-Salcedo, and G.L. Stephens, 2007: A multi-purpose radar simulation package: Quick-Beam. *Bull. Amer. Meteor. Soc.*, **88**, 1723-1727.

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The latest version of the simulator is available from:
`http://cloudsat.atmos.colostate.edu/radarsim`

# Contents

# 1 Preliminaries

Although there are a variety of user settings, the following are the most important settings that must be specified for a successful run:

- the radar frequency

- whether the radar is ground-based or space-based

- at least one profile of environmental temperature, pressure, and moisture; however user may supply a different environmental profile for each radar profile

- for each radar profile and range gate, the mixing ratio of each of up to 50 customizable hydrometeor species, and the type of distribution that governs each species

- whether Mie tables are to be used to speed the calculations

The remainder of this document describes the details of how this information is input to the simulator. In this version, the user may use the interface as described in this documentation, or develop their own interface to the code as described in Appendix B.

It should be noted that QuickBeam makes a number of assumptions in producing reflectivity profiles. Ice crystals are modeled as "soft spheres," meaning the diameter of a given sphere is the same as the maximum dimension of the corresponding ice crystal, but the effective density and index of refraction are reduced to represent a mixture of ice with air (see Liu, 2004). This approximation is used because it is computationally efficient, but errors are incurred. A discrete-dipole approximation (DDA) lookup table database for QuickBeam is being developed to help reduce these errors.

Multiple scattering is also neglected; at traditional precipitation radar frequencies this will results in minimal errors. However when simulating higher frequency radars (particularly spaceborne cloud radars like CloudSat), large errors in reflectivity may be expected when rain or precipitating ice more intense then a few millimeters per hour is present. There is no simple in-line fix to this complicated effect at this time, so users should be aware of the limitations of the simulator in this regard.

the program. The program is run by executing the resulting file named 'driver' (or 'driver.exe'). The program has been tested using the pgf90, ifort, and G95 compilers in Linux, and G95 in Windows.

Alternately, if Makefile compatibility is unavailable, try calling your compiler (in this example, g95) and passing the program files as arguments:

```
g95 *.f90 -o driver
```

Note that you may need to repeat this command several times, until it completes without error, to ensure that all dependencies are met and properly linked.

It is recommended that if multiple hydrometeor profiles are to be processed, they should be processed as a set as described in section 5 rather than running the program multiple times. The time needed to initialize the program may be several times longer than the time required to process a given profile, and this is especially significant when Mie tables are read during initialization. Thus, process multiple profiles together whenever possible.

# 3   Runtime settings: settings.dat

Most parameters of interest can be set at runtime in `settings.dat`. This file contains 15 lines of settings, each of which must contain a value.

1. *freq* – The radar frequency in GHz. May be any value unless *use_mie_table* = 1, in which case it must be one of (94, 35, 13.8, 9.6, 3).

2. *surface_radar* – Set to 1 if the radar is surface based (bottom-up) or 0 if the radar is space-based (top-down).

3. *use_mie_table* – Set to 1 to use pre-compiled Mie scattering tables, 0 to do calculations on the fly. See section 7.

4. *use_gas_abs* – Set to 1 to include gaseous absorption in the calculations, 0 to ignore it.

5. *sonde_format* – Specifies how ambient height, pressure, temperature, and moisture profiles are read. 1 – specified in `sonde_file`, 2 - specified in `hydro_file`, 3 - use mid-latitude summer standard profile, 4 - use mid-latitude winter standard profile, 5 - use tropical standard profile.

6. *do_ray* – Set to 1 do include Rayleigh reflectivity computations for comparison, 0 to skip.

7. *melt_lay* – Set to 1 to activate the melting layer/bright band model, 0 to turn it off. See section 9.

8. *output_format* – Set to 1 for full output, 2 for simple output. See section 6.

| Frequency range (GHz) | $\lvert K^2 \rvert$ |
|---|---|
| $13.8 \pm 3$ | 0.925 |
| $35.0 \pm 3$ | 0.88 |
| $94.0 \pm 3$ | 0.75 |
| (All other frequencies) | 0.93 |

Table 1: Default value of the dielectric constant as a function of frequency, used in calculations only if the value *k2* in settings.dat is set to $-1$.

9. *output_disp* – Set to 1 to send output to display as well as file, 0 to send only to file.

10. *k2* – The value of $\lvert K^2 \rvert$, the dielectric constant, used in reflectivity calculations. Set to $-1$ to use the frequency-dependent default shown in Table 1, or specify a value to be used in calculations.

11. *sonde_file* – The file containing environmental sounding information. Only used if *sonde_format* = 1, otherwise set to a dummy value. See section 5.1.

12. *hydro_file* – The file containing hydrometeor information. Format depends on value of *sonde_format*. See section 5.2.

13. *hclass_file* – The file containing hydrometeor class definitions. See section 4.

14. *results_file* – The file that will contain output. See section 6.

15. *mie_table_name* – File containing Mie lookup tables. Used only if *use_mie_table* = 1. See section 7.

# 4   Hydrometeor class settings: hclass_file

The file *hclass_file* contains information about the hydrometeor classes that will be used in the simulation. The user may specify up to 50 different classes of hydrometeors, choosing any of five types: modified gamma, exponential, power law, monodisperse, and lognormal. The number of classes that are used in any given simulation is given by *nhclass*, which is determined from the number of active lines in the file. Each line in the file, with the exception of the first line which contains comments, represents one class of hydrometeor. For each line, fill in the values as follows.

- # – This first column is a list of sequential numbers, one for each class that is to be defined, starting with 1 and ending with *nhclass*.

- *TYPE* – Set to 1 for modified gamma distribution, 2 for exponential distribution, 3 for power law distribution, 4 for monodisperse distribution, 5 for lognormal distribution. Set to a negative number to ignore the hydrometeor class defined in this line.

- *COL* – Reserved for future use, value is ignored.

- *PHASE* – Set to 0 for liquid, 1 for ice.

- *CM* – Set to 0 if hydrometeor profiles will be input in terms of 'true' mixing ratios (g kg$^{-1}$), set to 1 if hydrometeor profiles will be input in terms of liquid or ice water contents (g m$^{-3}$).

- *DMIN* – The minimum drop size for this class ($\mu$m), ignored for monodisperse.

- *DMAX* – The maximum drop size for this class ($\mu$m), ignored for monodisperse.

  **Important note:** These settings for DMIN and DMAX are ignored in the current version for *all* distributions except for power law. Except when the power law distribution is used, particle size is fixed to vary from zero to infinity, a restriction that is expected to be lifted in future versions. A placeholder must still be specified for each.

- *APM* – The $\alpha_m$ coefficient in equation (1) (kg m$^{-\beta_m}$), see section 4.1.

- *BPM* – The $\beta_m$ coefficient in equation (1), see section 4.1.

- *RHO* – Hydrometeor density (kg m$^{-3}$), see section 4.1.

- *P1*, *P2*, *P3* – These parameters that depend on the type of distribution and are defined below.

## 4.1 Hydrometeor mass and density

Hydrometeor mass can be either specified as a constant value that applies to all particles of a given class, or it can be expressed a function of particle diameter.

- To specify a constant density for particles, set *APM* and *BPM* to $-1$, and *RHO* to the constant value desired (kg m$^{-3}$).

- To let mass vary as a function of diameter, specify values for *APM* and *BPM* and set *RHO* to $-1$. The mass-diameter relation is given by

$$m(D) = \alpha_m D^{\beta_m} \,, \tag{1}$$

with $\alpha_m, \beta_m > 0$.

For liquid particles, $\beta_m$ will be very close to 3. For ice particles, $\beta_m$ is likely to be less than 3 since the density is a function of both the volume fraction of air trapped in the particle and the bulk density of ice.

The density is used to calculate the index of refraction of ice particles, and for this purpose QuickBeam will automatically ensure particle density derived from equation (1) does not become lower than 5 or greater than 917 kg m$^{-3}$. The mass of ice particles is *not* modified in a similar way for reflectivity and attenuation calculations. This assumption generally results in small error and decreases computation time considerably.

## 4.2   Modified gamma distribution

The modified gamma distribution is defined as

$$n(D) = N_t \frac{1}{\Gamma(\nu)D_n} \left(\frac{D}{D_n}\right)^{\nu-1} \exp\left(\frac{D}{D_n}\right) \,, \tag{2}$$

with $N_t, D_n, \nu > 0$, and

$$\overline{D} = D_n \frac{\Gamma(\nu)}{\Gamma(\nu+1)} \,. \tag{3}$$

One of the parameters (*P1,P2*) must be specified; the one other should be set to $-1$. User must also specify a value for *P3*.

- *P1* – Set to the total particle number concentration $N_t/\rho_a$ (kg$^{-1}$), where $\rho_a$ is the density of air in the radar volume.

- *P2* – Set to the particle mean diameter $\overline{D}$ ($\mu$m).

- *P3* – Set to the distribution width $\nu$.

## 4.3   Exponential distribution

The exponential distribution is defined by

$$n(D) = N_0 \exp(-\lambda D) \,, \tag{4}$$

with $N_0 > 0$. One of the parameters (*P1,P2,P3*) must be specified; the remaining two must be set to $-1$.

- *P1* — Set to a constant intercept parameter $N_0$ (m$^{-4}$). The slope parameter $\lambda$ then follows as

$$\lambda = \left( \frac{\alpha_m \Gamma(1 + \beta_m) N_0}{q_m \rho_a} \right)^{\frac{1}{1+\beta_m}} , \tag{5}$$

where $q_m$ is the hydrometeor mixing ratio and $\rho_a$ is the air density. Note that if hydrometeor density $\rho_m$ is specified as a constant, this reduces to

$$\lambda = \left( \frac{\pi \rho_m N_0}{q_m \rho_a} \right)^{\frac{1}{4}} . \tag{6}$$

- *P2* – Set to a constant $\lambda$ ($\mu$m$^{-1}$). In this case $N_0$ will be calculated from the above equations.

- *P3* – Set to 2 to indicate that $\lambda$ should be evaluated as a function of temperature using the method of Ryan (2000), $\lambda(T) = 1220 \cdot 10^{-0.0245T}$, where T is the temperature in degrees Celsius. Only useful for ice particles.

## 4.4 Power law distribution

The power law distribution is defined as

$$n(D) = A_r \, D^{b_r} , \tag{7}$$

with $A_r, b_r > 0$. Parameter *P1* must be specified.

- *P1* – Either set this to the value of a constant power law parameter $b_r$, set to $-2$ to evaluate $b_r$ according to the method of Ryan (2000) for cirrus type clouds, or set to $-3$ to evaluate with the same method but for frontal type clouds. This method is useful only for ice particles. See Table 2.

- *P2* – set to 0 (zero)

- *P3* – set to 0 (zero)

It is critical that the user specify reasonable values for *DMIN* and *DMAX* since the distribution has no tail, i.e. $n(D)$ increases rapidly with $D$.

## 4.5 Monodisperse distribution

The monodisperse distribution contains particles of only one size and concentration:

$$N = N_0$$
$$D = D_0 \tag{8}$$

Parameter *P1* must be specified.

| Temperature (°C) | Cloud type | $b_r$ |
|---|---|---|
| $< -30$ | Cirrus | $-1.75 + 0.09(T_k - 243.16)$ |
| $-30$ to $-9$ | Cirrus | $-3.25 - 0.06(T_k - 265.66)$ |
| $-9$ to $0$ | Cirrus | $-2.15$ |
| $< -35$ | Frontal | $-1.75 + 0.09(T_k - 243.16)$ |
| $-35$ to $-17.5$ | Frontal | $-2.65 + 0.09(T_k - 255.66)$ |
| $-17.5$ to $-9$ | Frontal | $-3.25 - 0.06(T_k - 264.66)$ |
| $-9$ to $0$ | Frontal | $-2.15$ |

Table 2: The power law parameter $b_r$ as a function of $T_k$, the temperature in Kelvin, for both cirrus and frontal type clouds. Based on Table 1 and Figure 3 of Ryan (2000).

- *P1* – Set to a constant diameter $D_0$ ($\mu$m).

- *P2* – set to 0 (zero)

- *P3* – set to 0 (zero)

## 4.6   Lognormal distribution

The lognormal distribution, defined in terms of particle radius $r$ rather than diameter for consistency with the CloudSat 2B-LWC algorithm, is given by

$$n(r) = \frac{N_t}{\sqrt{2\pi}(\ln \sigma_g)r} \exp\left( -\frac{\ln^2(r/r_g)}{2(\ln \sigma_g)^2} \right) , \qquad (9)$$

where $r_g$ is the geometric mean particle radius, $N_t$ is the total particle number concentration, and $\sigma_g$ is the geometric standard deviation, i.e. $\sigma_g^2 = \overline{\ln^2(r/r_g)}$. One of the parameters (*P1,P2*) must be specified; the one other should be set to $-1$. User must also specify a value for *P3*.

- *P1* – Set to the total particle number concentration $N_t/\rho_a$ (kg$^{-1}$), where $\rho_a$ is the density of air in the radar volume.

- *P2* – Set to the geometric mean particle radius $r_g$ ($\mu$m).

- *P3* – Set to the natural logarithm of the geometric standard deviation, $\ln \sigma_g$.

# 5   Input hydrometeor and environmental data

For all the input files, *nprof* is the number of independent radar profiles for which calculations are to be performed, *ngate* is the number of radar range gates in the

given profile (each gate containing its own distribution of hydrometeors), and *nenv* are the number of vertical levels in the environmental sounding profile.

> **Important note:** The simulator must be provided with an environmental sounding for profile that will be simulated, as described below. *It is also important that the user provide hydrometeor mixing ratio data that covers the entire range of the troposphere*, even if most of these values are zero. Failure to do this may result in incorrect evaluation of gaseous attenuation.

## 5.1   sonde_file

Used only if *sonde_format* = 1, this specifies an environmental sounding that will apply to each of the nprof profiles for which calculations are to be performed. The levels at which data is specified need not be the same as the radar range gates. The format is as follows:

```
NENV
HGT     PRES    TT    RH                <-- First height level
. . .
HGT     PRES    TT    RH                <-- Last height level
```

where $HGT$ is the height (m), $PRES$ is the atmospheric pressure (hPa), $TT$ is the temperature (K), and $RH$ is the relative humidity (%). Levels may be input from either the top-down or the bottom-up.

## 5.2   hydro_file

File containing the hydrometeor content of each range gate, and if *sonde_format* = 2 it also contains the environmental profile at each range gate. In the latter case, the environmental profile levels must exactly match the radar gate levels for a given profile, but a different environmental sounding may be used for each of the nprof profiles. The format is as follows:

```
NPROF
NGATE                                   <-- ngate for profile 1
HGT (PRES)(TT)(RH) M1 M2 . . . MN       <-- For profile 1, range gate 1
HGT (PRES)(TT)(RH) M1 M2 . . . MN       <-- For profile 1, range gate 2
. . .
NGATE                                   <-- ngate for profile 2
HGT (PRES)(TT)(RH) M1 M2 . . . MN       <-- For profile 2, range gate 1
HGT (PRES)(TT)(RH) M1 M2 . . . MN       <-- For profile 2, range gate 2
. . .
. . .
```

where *M1*, *M2*, . . . , *MN* are the mixing ratios of hydrometeors in classes 1 through *nhclass* as defined in `hclass_file`, with units of either g kg$^{-1}$ or g m$^{-3}$ depending on the value of the *CM* parameter in that file. Note that *PRES*, *TT*, and *RH* are included only if *sonde_format* = 2. Levels may be input from either the top-down or the bottom-up.

# 6 Output format

Output is written to the file `results_file`. If *output_format* = 1, then full output is written in the following format:

```
NPROF NGATE
HGT Z_EFF Z_RAY A_TO_VOL G_TO_VOL Z_COR        <-- profile 1, gate 1
HGT Z_EFF Z_RAY A_TO_VOL G_TO_VOL Z_COR        <-- profile 1, gate 2
. . .
HGT Z_EFF Z_RAY A_TO_VOL G_TO_VOL Z_COR        <-- profile 2, gate 1
HGT Z_EFF Z_RAY A_TO_VOL G_TO_VOL Z_COR        <-- profile 2, gate 2
. . .
. . .
```

where *HGT* is the volume height (km), *Z_EFF* is the non-attenuated volume reflectivity (dBZ), *Z_RAY* is the volume Rayleigh reflectivity (dBZ), *A_TO_VOL* is the hydrometeor attenuation between the radar and the volume (dBZ), *G_TO_VOL* is the gaseous attenuation between the radar and the volume (dBZ), and *Z_COR* is the final attenuation-corrected volume reflectivity (dBZ). If the volume contains no hydrometeor, the reflectivity is set to −999. Similarly, if *do_ray* = 0, the Rayleigh reflectivity is not calculated and is set to −999.

   If *output_format* = 2, then simplified output is written as above, expect only *HGT* and *Z_COR* are output to `results_file`.

# 7 Mie tables

Mie tables are pre-compiled tables used to speed code execution time. They contain information for a variety of frequencies, temperatures, and ice fractions (the ice fraction is determined directly from the hydrometeor mixing ratio; although it is not user specified, it is essential that it is allowed to vary across the range of drop sizes to account for changes in the dielectric function of ice crystals that contain a mixture of ice and air). The tables cover values of these parameters that fall in the following ranges:

   Frequency: 94, 35, 13.8, 9.6, 3 GHz
   Temperature: −60 to 35°C, liquid; −90 to 0°C, ice; increments of 5°C
   Ice fraction: 0.01 to 1.0, various increments

Since these parameters have been discretized, some loss of accuracy can be expected when using Mie tables. However their use can decrease execution time by 50% or more if a large number of profiles are to be processed. It is recommended that the user run some sample calculations with and without the use of the Mie lookup table feature, and then compare the results to determine if the errors that occur are acceptable.

# 8 DDA tables

*The DDA lookup tables have not yet been implemented in this version.*

Future versions of QuickBeam will include scattering calculations performed using the Discrete Dipole Approximation. This will allow the user to calculate the radar reflectivity of collections of ice crystals with a variety of habits (such as dendrites, columns, stellar plates, and so on).

# 9 Melting particle model

*The melting particle model has not yet been implemented in this version due to some bugs and that still need to be worked out before a general release.*

The bright band, a region of enhanced reflectivity near the melting level, is not well represented by even the most sophisticated cloud resolving models. The optical effects necessary to simulate a bright band, specifically the gradual melting of snow and its transition into rain, can not be represented by hydrometeors which are constrained to contain either liquid water or ice, but not both at the same time. For this reason a simple model of the melting layer has been included to produce a bright band effect, and can be activated by setting melt_lay = 1 in settings.dat.

Note that use of this flag will introduce a modification to the microphysics that attempts to emulate how frozen particles become coated with liquid water as they fall. Thus the simulated reflectivity profiles no longer truly represent the microphysics input to the simulator, but a hybrid of the input microphysics and the modifications made by the melting layer model.

# 10 Running the sample case

To test the simulator, you may wish to run the example case. It is provided in the `example` directory of the installation. To use, copy the files in this directory to the main directory where the executable is located, and then run the executable.

The example profile contains six different types of hydrometeors, the mixing ratios of which are shown in Figure 1 and contained in `hydromet_example.dat`. The environmental profile is a typical tropical profile and is not shown. You will notice in the file `hclass.dat` (*hclass_file*) that five of these classes are distributed according to the modified gamma distribution, and one of them, the cloud ice, is a power law distribution. The settings in `settings.dat` specify that the simulation should be a space-based 94 GHz radar simulation with Mie calculations performed at runtime.

The program should run and display output to both the screen and the file `results.dat`. The results should be identical to those shown in Figure 2, which shows both the attenuated and unattenuated radar reflectivity at 94 GHz. In particular, the final line of output displayed on your screen should contain these numbers:

```
     0.02       9.54    -999.00        1.87        4.06        3.60
```

# 11  User support

The author is able to provide limited support by email, my email address is given near the top of this document. I am especially interested to hear from users of the software, including bugs you have found and features that you would like to see implemented.

*If you use the software to process data used in a publication, an acknowledgment or reference to the BAMS article shown on Page ii of this document would be appreciated.* If you feel the contribution made by this software is particularly significant or would like to further collaborate, please feel free to contact me.

Figure 1: Mixing ratios of the six hydrometeor species in the example profile: cloud water, rain, snow, aggregates, graupel, and cloud ice.
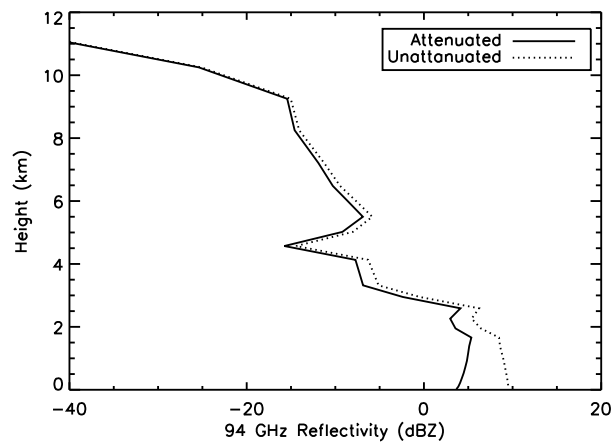


Figure 2: Resulting 94 GHz reflectivity of the example profile, both attenuated and unattenuated.

# Appendices

## A   What's new

– v1.1 (2007 Oct 23)

○ Changed method of calculating index of refraction of ice-air mixtures, favoring the Bruggeman approach. Mie table binary file is changed.
○ Fixed bug where ice density used to calculate index of refraction became unreaslitically large, now restrict ice effective densities to the range of 5 to 917 kg m$^{-3}$.
○ Various speedups, minor bug fixes, some code restructuring in preparation for inclusion of melting particle effects.

– v1.03 (2006 Oct 06)

○ Introduced scaling factors to more quickly calculate DSDs, resulting in a significant speed increase.
○ Streamlined Mie table calculations.
○ Fixed bug in referencing Mie table with monodisperse distribution.
○ Fixed bug that caused NaN in constant-density calculations.
○ Fixed bug whereby Rayleigh reflectivity was reported as NaN.
○ Fixed bug in gamma distribution that caused errors when the distribution width was other than two. (v1.03d, 2007 Apr 12)
○ Hyrometeor mixing ratios may now be specified in either grams per kilogram or grams per cubic meter. Changed meaning of the CM parameter in hclass_file. (v1.03c, 2007 Mar 7)
○ Removed functionality of the COL parameter in hclass_file, as it no longer has a purpose. Input mixing ratios in the same order they are defined in hclass_file. (v1.03c, 2007 Mar 7)
○ Various minor bug fixes. (v1.03c, 2007 Mar 7)
○ Fixed bug processing multiple profiles with different numbers of range gates (v1.03b, 2006 Nov 22)
○ Fixed bug in gamma function scaling factor, fixed compiler compatibility issue in driver (v1.03a, 2006 Nov 08)

– v1.02 (2006 Aug 23)

○ There is now only one array of discrete drop sizes; this array is set on a log-linear scale so there is adequate coverage for both small and large particles.
○ Changed the way hydrometeor classes are defined and input; require file hclass.dat
○ Added monodisperse, exponential, and lognormal distributions.
○ Compartmentalization of the simulation portion of the code into its

own routine separate from the driver. (v1.02a, 2006 Sep 29)

○ The file settings.dat is now mandatory.

○ Fixed bug where N was not properly initialized.

○ Fixed calculation of gaseous attenuation.

○ Fixed situation where hydrometeor phase was not set to proper value after changing from one type to another.

– v1.01 (2006 Jun 1)

○ Initial pre-release.

# B  Guide to radar_simulator.f90

The subroutine `radar_simulator.f90` may be used independently of the the interface described in this documentation. This may be useful, for example, if you wish to run QuickBeam "on-the-fly" as your model produces output. The inputs and outputs of `radar_simulator.f90` are provided in this section to aid in this endeavor.

## Inputs

- *freq*, 8-byte real
  The radar frequency (GHz). It may be any value unless Mie tables are being used, in which case it must be one of (94,35,13.8,9.6,3).

- *k2*, 8-byte real
  The dielectric constant to be used in reflectivity calculations. Set to $-1$ to use the frequency-dependent default as described in Table 1.

- *do_ray*, 4-byte integer
  Set to 1 to do Rayleigh calculation, 0 to skip them.

- *use_gas_abs*, 4-byte integer
  Set to 1 do include gaseous absorption, 0 to ignore it.

- *mt*, structure of type *mie*
  The Mie table returned from a previous call to `load_mie_table.f90`.

- *nhclass*, 4-byte integer
  Number of hydrometeor classes returned from a previous call to `load_hydrometeor_classes.f90`.

- *hp*, structure of type *class_param*
  The hydrometeor properties table returned from a previous call to `load_hydrometeor_classes.f90`.

- *nprof*, 4-byte integer
  Number of hydrometeor profiles for which to calculate reflectivity.

- *ngate*, 4-byte integer
  Number of range gates in each profile.

- *nsizes*, 4-byte integer
  Number of discrete particle sizes to consider.

- *D*, 8-byte real, dimension(*nsizes*)
  An array of increasing discrete particle sizes that represents all particles with diameters between zero and infinity.

- *hgt_matrix*, 8-byte real, dimension(*nprof,ngate*)
  Height at the hydrometeor level (km). [1]

- *hm_matrix*, 8-byte real, dimension(*nhclass,nprof,ngate*)
  Mixing ratio of the hydrometeors (g kg$^{-1}$). [1]

- *p_matrix*, 8-byte real, dimension(*nprof,ngate*)
  Pressure at the hydrometeor level (hPa). [1]

- *t_matrix*, 8-byte real, dimension(*nprof,ngate*)
  Temperature at the hydrometeor level (°C). [1]

- *rh_matrix*, 8-byte real, dimension(*nprof,ngate*)
  Relative humidity at the hydrometeor level (%). [1]

## Outputs

- *Ze_non*, 8-byte real, dimension(*nprof,ngate*)
  Non-attenuated radar reflectivity (dBZ).

- *Ze_ray*, 8-byte real, dimension(*nprof,ngate*)
  Rayleigh reflectivity (dBZ), set to $-999$ if *do_ray* $= 0$.

- *h_atten_to_vol*, 8-byte real, dimension(*nprof,ngate*)
  Attenuation due to hydrometeors between radar and volume (dB).

- *g_atten_to_vol*, 8-byte real, dimension(*nprof,ngate*)
  Attenuation due to atmospheric gases between radar and volume (dB).

- *dBZe*, 8-byte real, dimension(*nprof,ngate*)
  Radar reflectivity (dBZ).

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[1]Note that these variables must, for each profile, be ordered from closest to the radar to farthest, e.g. *p_matrix*(:,1) is closer to the radar than *p_matrix*(:,*ngate*).

# C   References, acknowledgments, usage

**External Fortran routines used in QuickBeam**

Some of the routines included in this package are from other sources. These are gratefully acknowledged here.

ORDERPACK 2.0 – An excellent library of public domain Fortran utilities by Michel Olagon. The array ranking routine MRGRNK is from this library. Distribution available at: http://www.fortran-2000.com

SLATEC — A library of public domain mathematical Fortran routines. The integration subroutine AVINT is from this library. Distributed by the Energy Science and Technology Software Center, P.O. Box 1020, Oak Ridge, TN, 37831.

MIEINT — Mie scattering code written by R.G. Grainger, University of Oxford, used with permission.

M_WAT,M_ICE — Subroutines that calculate the index of refraction of liquid and ice. Based on the work of Ray (1972) and Warren (1984), respectively.

**Referenced journal articles**

Liu, Guosheng (2004), Approximation of single scattering properties of ice and snow particles for high microwave frequencies, *J. Atmos. Sci.*, **61**, 2441-2456.

Ryan, B. (2000), A bulk parameterization of the ice particle size distribution and the optical properties of ice clouds. *J. Atmos. Sci.*, **57**, 1436-1451.

**Acknowledgments**

**Disclaimer and Usage**

Last updated 2007 October 23: J. M. Haynes