Satellite-Radar SIMulator (SR-SIM)
Science Documentation

Version 1
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August, 2017

Introduction

The Satellite-Radar SIMulator is used to compute synthetic satellite radar observations using output data from Numerical Weather Prediction models. In this document, a detailed description of the methodology to generate such simulated observations is described step by step, following the algorithm flow outlined in Fig 1.
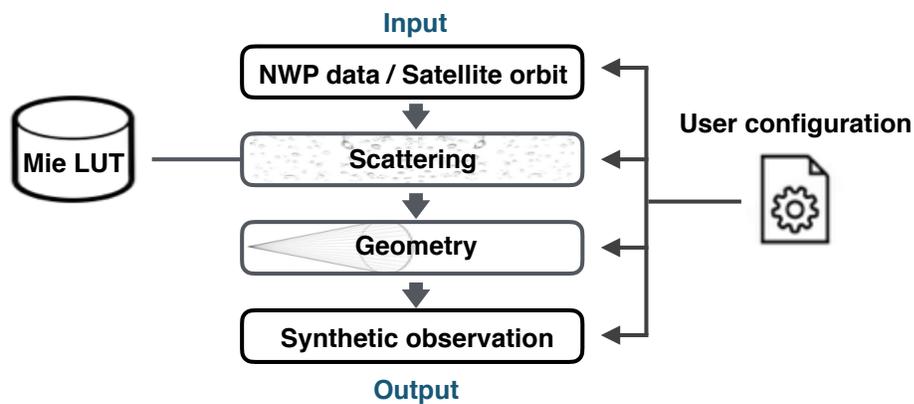

FIG 1. SR-SIM flowchart

The model hydrometeor variables (mixing ratio and number concentration) are initially ingested by the simulator along with other model variables such as temperature, pressure, and relative humidity. The model grid coordinates, latitude, longitude and height are also read. Note that a satellite file can optionally be read as well. The orbit path and the height information will be used in the geometry module later on to interpolate the results.

The scattering module computes the particle size distribution (PSD) using the specifications of the microphysical scheme. Then, the dielectric properties of each hydrometeor category are computed (Klein and Swift (1997), Hufford (1991) and Maxwell-Garnett (1994)). A special treatment for melting hydrometeors has been added, based on Fabry and Szyrmer (1999). The scattering coefficients are then computed following Mie Scattering theory and finally the reflectivity (dBZ) and

attenuation (PIA) fields are generated (Massunaga and Kummerow (2005)). The use of pre-computed lookup tables can be used in that part to speed up computations.

The geometry module performs the antenna beam convolution and interpolates the dBZ and PIA fields taking into account the scanning pointing angle and the satellite orbit path (if provided).

The final product are synthetic observations, written in a NetCDF file in the exact same coordinates as the model or satellite input file (depending on the user configuration). The architecture of the program would allow to easily change the output format, if a different integration of the NWP is ever required.

1. Ingestion of model variables

SR-SIM takes into account up to 6 different hydrometeor categories that must be ingested with their corresponding Mixing Ratio and Number Concentration. These are rain, cloud water, snow, hail, graupel and cloud ice.
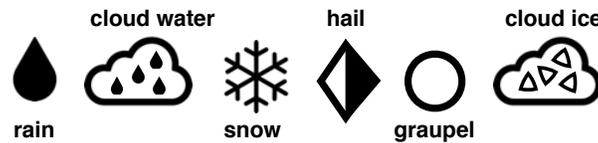

FIG 2. Hydrometeor categories treated by SR-SIM

Note that the synthetic variables reflectivity and attenuation will be separately computed for each one of these hydrometeor types.

SR-SIM requires hydrometeor water content, this is why Mixing Ratio kg kg^{-1} and Number Concentration [1/kg] are multiplied by air density in order to convert the units to kg m^{-3} and m^{-3} respectively.

$$\rho_{air} = \frac{p}{R_{specific}T}$$

Where:

      p = Pressure [Pa]

      $R_{specific}$ = 287 [specific gas constant for dry air (J/(kg K))]

      T = Temperature [K]

2. Radiative properties

2.1 Particle Size Distribution

The Milbrant-Yau double-moment bulk microphysics parametrization is the microphysics scheme used in the present version (Milbrant et Yau (2005a) and (2005b)). The Particle Size Distribution (PSD) for each hydrometeor category x is represented by a complete gamma function of the form:

$$N_x(D) = N_{0x} D^{\mu_x} e^{-\lambda_x D}$$

Where N_{0x}, λ_x and μ_x are the intercept, slope and shape parameters, respectively, and D is the particle diameter. N_{0x} and λ_x can be computed from the prognostic variables q_x (hydrometeor water content [1/m^{-3}]) and N_x (number concentration [m^{-3}]):

$$N_{0x} = \frac{N_x \lambda^{\mu+1}}{\Gamma(\mu_x + 1)} \qquad \lambda_x = \left[\frac{c_x N_x \Gamma(\mu_x + 4)}{q_x \Gamma(\mu_x + 1)} \right]^{\frac{1}{d_x}}$$

With the following constants parameters:

Hydrometeor	ρ_x [kg m-3]	d_x [-]	μ_x [-]	a_v [m^{1-bv}s^{-1}]	b_v
Rain	1000	3	0	149.1	0.5
Snow	*	3	0	11.72	0.41
Hail	900	3	0	206.89	0.6384
Graupel	400	3	0	19.3	0.37
Cloud ice	440 (π/6)	3	0	71.34	0.6635
Cloud water	1000	3	1	0	0

TABLE 1. Constant parameters used in Milbrant and Yau PSD scheme.

Except for ice, all particles are assumed to be spherical with:

$$c_x = \frac{\pi}{6} \rho_x$$

Where ρ_x is the bulk density of the particles. Ice crystals are assumed to be bullet rosettes, which are believed to be the dominant crystal habit in thunderstorms, and have $c_i = 440$ kg m^{-3}

* For snow, a non-constant bulk density is used, based on disdrometer measurements from Brandes et al., 2007.

$$\rho_s = 0.178 D^{-0.922}$$

The variables a_v and b_v, are used to compute the fall velocity size relationships, but which are not yet implemented in the current version of SR-SIM.

2.2 Dielectric properties

It is necessary to compute the radiative properties of each hydrometeor category which affect how the electromagnetic wave sent from the radar will propagate through each particle. We need to take into account the properties of the atmosphere and each hydrometeor in order to properly simulate the radar measurements.

The reflectance and loss of intensity of the radar wave will be used further on to compute the final synthetic products, reflectivity and attenuation.

The Debye formula for the dipole relaxation process describes the complex permittivity; how an electric field is affected by a medium:

$$\varepsilon(f) = \varepsilon_1 + i\varepsilon_2$$

Where f is the frequency and the parameters ε_1 and ε_2 are real and positive. ε_1 is the real part and often called the dielectric constant, the stored energy within the medium, while ε_2 is the imaginary part, the loss factor.

For water, the model from Klein and Swift (1977) is used:

$$\varepsilon_1 = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + \omega^2 \tau_s^2} \qquad \varepsilon_2 = \frac{(\varepsilon_s - \varepsilon_\infty)\omega\tau_s}{1 + \omega^2 \tau_s^2}$$

Where ε_s is a function of temperature and given by:

$$\varepsilon_s = (87.134 - 0.1949T - 0.01276T^2 + 0.0002491T^3)$$
$$(1 + 1.613 \times 10^{-5} ST - 0.003656S + 3.21 \times 10^{-5} S^2 - 4.232 \times 10^{-7} S^3)$$

and

$$\tau_s = (1.768 \times 10^{-11} - 6.086 \times 10^{-13} T + 1.104 \times 10^{-14} T^2 - 8.111 \times 10^{-17} T^3)$$
$$(1 + 2.282 \times 10^{-5} ST - 7.638 \times 10^{-4} S - 7.760 \times 10^{-6} S^2 + 1.105 \times 10^{-8} S^3)$$

and

ε_∞ = 4.9 [the dielectric constant at infinite frequency]

$\omega = 2\pi f$ [radiant frequency]

S = 0 [salinity]

T = Temperature [C]

For ice, the model from Huffed (1991) is used:

$$\varepsilon_1 = 3.15 \qquad\qquad \varepsilon_2 = \alpha(t)/f + \beta(t)f$$

Where α and β are defined as function of temperature:

$$\alpha(t) = (50.4 + 62(\theta - 1)) \times 10^{-4} e^{-22.1(\theta-1)} \qquad \beta(t) = 10^{-4} \times \left(\frac{0.633}{\theta - 0.131} \right) + 7.36 \times 10^{-4} \left(\frac{\theta}{\theta - 0.9927} \right)^2$$

Where:

$$\theta = \frac{300}{273.16 + t}$$

The Maxwell-Garnett model is used to calculate the dialectic function of the frozen hydrometeors, assumed to be an ice matrix with air inclusions (Olson et al. 2001).

$$\varepsilon_{mix} = \frac{(1 - f_{inc})\varepsilon_{mat} + f_{inc}\zeta\varepsilon_{inc}}{1 - f_{inc} + f_{inc}\zeta} \qquad\qquad \zeta = \left(\frac{2\varepsilon_{mat}}{\varepsilon_{inc} - \varepsilon_{mat}} \right)\left[\left(\frac{\varepsilon_{inc}}{\varepsilon_{inc} - \varepsilon_{mat}} \right)\ln\left(\frac{\varepsilon_{inc}}{\varepsilon_{mat}} \right) - 1 \right]$$

Where *mix* stands for mixture, *mat* for matrix and *inc* for inclusions. The volume fraction of the inclusions is estimated from the particle density.

$$f_{inc} = 1 - \left(\frac{\rho_x}{\rho_{ice}} \right)$$

Where ρ_{ice} is 917 kg/m³ and the refractive index of air is (1.006, 0).

2.3 Generation of melting particles

A special treatment for melting hydrometeors has been added, based on Fabry and Szyrmer (1999). Melting particles substitute for rain and snow within a layer below the 0ºC level. The melting particle PSD is constructed by a weighted average of $N(D)_{rain}$ and $N(D)_{snow}$ in the melting layer, See Fig 3.
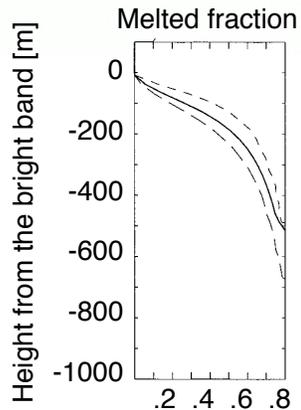
Szyrmer and Zawadzki, 1999

The dielectric properties of the particles are modelled as a sphere composed of a core and a shell with different properties.

An inner core of [water matrix + ice inclusions] matrix + ice inclusions and an outer shell of air matrix + [water matrix + ice inclusions] inclusions.

Fabry and Szyrmer, 1999

FIG 3. Vertical profile of melted snow fraction in function of height, Szyrmer and Zawadzki (1999).

The experiments performed to test the melting particles seem to properly simulate the bright band signature usually observed in stratiform storms.

2.3 Mie scattering

With the dielectric coefficients being computed, the radiative properties of hydrometeors are calculated based on the Mie scattering theory.
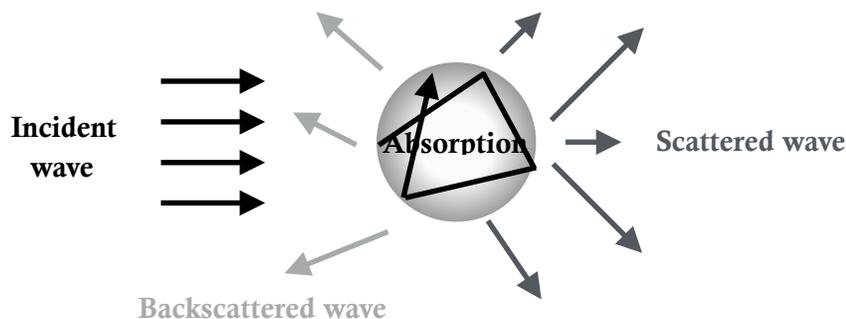

FIG 3. Schematic representation of the Mie Scattering model

Note that Mie theory assumes spherical particles, a constraint which is respected by the Milbrant and Yau microphysical scheme.

The output of the Mie Scattering module gives the extinction coefficient k_{ext} (attenuation), which is the energy loss by the process of absorption and scattering [km^{-1}], and the backscattering coefficient σ_b, the reflected energy [km^{-1}].

The total coefficients are computed integrating for all diameters (0.1 to 10mm with increments of 0.05mm):

$$\overline{\sigma_b} = \int_0^\infty \sigma_b^s(D)N(D)dD \qquad \overline{k_{ext}} = \int_0^\infty k_{ext}^s(D)N(D)dD$$

2.4 Atmospheric attenuation

In order to compute the total attenuation in the atmosphere, we need to consider the attenuation due to gasses (mostly oxygen), water vapour and cloud water. The following equations summarize:

$$A_{total} = A_{dry} + A_{term}W + A_{term\_sq}W^2 + A_w W_{cld}$$

With:

$$A_{dry} = \frac{A_{standard}\,(p - c_1 W)}{p}\left(c_2 + \frac{f}{f_{reference}}\right)^{fc\exp_1}\left(\frac{p}{p_{standard}}\right)^{pc\exp_1}\left(\frac{T}{T_{standard}}\right)^{Tc\exp_1}$$

$$A_{term} = c_2\left(\frac{f}{f_{reference}}\right)^{fc\exp_2}\left(\frac{p}{p_{standard}}\right)^{pc\exp_2}\left(\frac{T}{T_{standard}}\right)^{Tc\exp_2}$$

$$A_{term\_sq} = c_3\left(\frac{f}{f_{reference}}\right)^{fc\exp_3}\left(\frac{T}{T_{standard}}\right)^{Tc\exp_3}$$

$$A_w = c_4\left(\frac{f}{f_{reference}}\right)^{fc\exp_4}\left(\frac{T_{hyd}}{T_{standard}}\right)^{T\exp_{4a} + (Tc\exp_{4b}\,(T_{hyd}-T_{standard}))}$$

Where:

$A_{standard}$ = Standard Atmospheric Attenuation at a given reference frequency

$p_{standard}$ = Standard Atmospheric Pressure = 101325 [Pa]

$T_{standard}$ = Standard Atmospheric Temperature = 288.15 [K]

W = Water Vapour Pressure [Pa]

W_{cld} = Cloud liquid water content [g/m^3]

T = Atmospheric Temperature [K]

T_{hyd} = Hydrometeors Temperature [K]

The rest of parameters are constants and depend on the frequency of the radar simulator. See Table 2 for more details

Radar band	S	C	X	Ku	Ka	W
f_{range} [GHz]	2 - 4	4 - 8	8 - 12	12 - 16	34 - 36	93 - 95
$f_{reference}$ [GHz]	2.8	5.5	9.4	13.6	35	94
$A_{standard}$	0.00700642	0.007421098	0.007984311	0.008916323	0.02947889	0.037341399
c_1	0.9	0.9	0.9	0.9	0.5	1.8
c_2	1	1	0	0	0	0
f_{cexp1}	0.103	0.09	0.207	0.417	3.05	-1.97
p_{cexp1}	1.943	1.98	1.995	2	2	2
T_{cexp1}	-2.93	-2.97	-2.98	-2.97	-2.83	-3.25
c_2	3.215E-07	1.2895E-06	4.2563E-06	1.199E-05	5.704E-05	2.773E-04
f_{cexp2}	2.025	2.11	2.42	3.42	0.18	2.04
p_{cexp2}	0	0	0	0.937	0.975	0
T_{cexp2}	-2.9	-2.88	-2.7	-2.4	-2.7	-3.16
c_3	8.08E-11	3.14E-10	9.303E-10	2.026E-09	1.282E-08	8.797E-08
f_{cexp3}	2	2	2.08	2.18	1.75	2
T_{cexp3}	-9.9	-9.9	-10	-10	-10	-10.1
c_4	0.004728313	0.01822807	0.05312521	1107939	0.7058844	4.018882
f_{cexp4}	2	2	1.99	1.99	1.91	1.53
T_{cexp4a}	-7.2	-7.3	-7.16	-7.1	-6.6	-3.5
T_{cexp4b}	0.059	0.062	0.058	0.058	0.028	-0.45

TABLE 2. Constant parameters used in the computation of attenuation.

2.5 Computation of reflectivity and attenuation

The computation of the final reflectivity (Z) and path integrated attenuation (PIA) fields are given by equations (Massunaga and Kummerow (2005)):

$$Z = \frac{\lambda^4}{\pi^5 |K|^2} \overline{\sigma_b} \tau_{ext}(z, \infty) \qquad\qquad PIA = 20\,\tau_{ext}(0, \infty)\log e$$

Where

$$\tau_{ext} = e^{-2\overline{k_{ext}}L'}$$

is the extinction of optical thickness according to the Beer-Lambert Law for uniform attenuation (2-way), with L' being the path length of the radar beam taking into account the incident angle of the antenna.
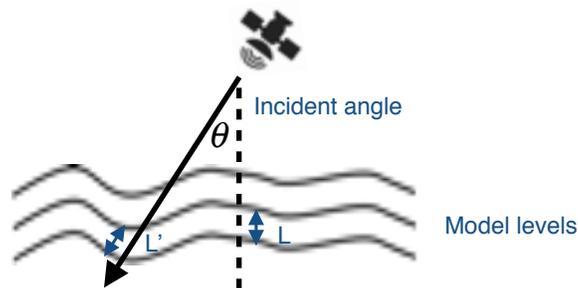
$$L' = \frac{L}{\cos\theta}$$

FIGURE 4. Representation of the satellite radar beam

3. Geometry

3.1 Antenna beam convolution

SR-SIM includes the option to smooth the data over a sensor field of view (FOV), convoluted with a Gaussian antenna pattern. The cross-track and down-track distances can be defined in the general settings file (see the User Documentation for more details).

This part of the simulation, also called beam convolution, is a very important step to compare the simulated and observed satellite data, particularly when the grid size of the input model data and the FOV are very different.

3.2 Orbit interpolation

Once the reflectivity and attenuation fields have been computed and smoothed, an orbit interpolation can be applied (if a satellite file containing such information is provided).

The main idea of this procedure is to interpolate the final measurements to the satellite data coordinates to be able to directly compare the simulated and observed data. The interpolation is computed using the latitude, longitude and height information from the model and satellite files.

Nearest neighbour interpolation is used in the horizontal dimensions while linear interpolation in linear units is performed in the vertical. Note that all distances are computed taking into the curvature of the earth.

4. Synthetic observations

In this part of the program the output synthetic observations are written to a NetCDF file. The final result can be visualized using the GPMVis visualization software, available at http://www.meteo.mcgill.ca/~bernat/sr-sim/

References

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